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# An operating system for 5G Edge Clouds

Antonio Manzalini

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## Doctor of Philosophy (PhD) Thesis

**Institut Mines Télécom, Télécom SudParis and Université Pierre  
& Marie Curie - Sorbonne Universités**

Specialization

### **Computer Networks**

Presented by

**Antonio Manzalini**

**An Operating System for 5G Edge Clouds**

8<sup>th</sup> July 2016

Thesis no: **2016TLE0013**

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**Informatique et réseaux**

Présenté par

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Special thanks to my Committee.

Antonio Manzalini  
8th July 2016



# Abstract

Technology and socio-economic drivers are creating the conditions for a profound transformation, called “Softwarization”, of the Telecommunications and ICT ecosystems. As a matter of fact, fixed and mobile broad-band diffusion and IT performance acceleration, coupled with the related costs reductions, are boosting innovation and convergence of Network and IT domains. Moreover the number of the terminals, machines, devices and smart things connected to the network is growing at an exponential rate, whilst at the same time, the capabilities of processing, storage and communication embedded in these terminals are impressively increasing.

Software-Defined Networks (SDN) and Network Functions Virtualization (NFV) are two of the most important enabling technologies paving the way towards this profound transformation of telecommunications. More in general, it is argued that SDN and NFV are two of the facets of the same overall systemic transformation called “Softwarization” of Telecommunications, which is steering the evolution not only of Networks, but also Service Platforms (e.g., Cloud and Edge Computing architectures) and future terminals. In fact, it is argued that in the near future most (if not all) network and service functionalities will be virtualized and executed dynamically part in the Network, part in the Cloud Computing - which is evolving rapidly towards the Edge and Fog Computing - and part in the terminals.

This radical transformation will enable the development of new service paradigms (e.g., cognition as a service, etc.) creating the conditions for new ecosystems to emerge. One example is the possibility to actuate, through the network, remote control of mobile robotic systems with complex cognitive capabilities and high characteristics of autonomy (e.g., operating also in unstructured and very dynamic environments). Truly mobile robots, remotely controlled with ultra-low latencies, can have an enormous impact on industry, agriculture and several social applications (for example, at home and in the Smart City of the future).

Softwarization of Telecommunications will allow – most probably in less than five years – to virtualize all the network and services functions of a Telecommunication infrastructure and executing them onto a software platforms which could be even fully decoupled from the underneath physical infrastructure (almost based on standard hardware). Any ICT and Telecommunication services will be provided by using a “continuum” of virtual resources (of processing, storage and communications) with practically very limited upfront capital investment and with modest operating costs.

In this future scenario, the border between Cloud computing and Network will disappear, and the two domains will merge together, offering flexibility, adaptability but at the same time a new complexity in the global Operations, i.e., management and control, of the converged infrastructure. Network and Service orchestration will become an essential part of the Operations of Telecommunications infrastructures.

Also the border between the Network and all the terminals and devices (which we call generically Edge) connected to it will disappear. Smart future terminals, autonomous machines, robots and drones will perform “cognitive loops” (with sensors, processing, communications, actuators) embedded into reality.

This will have huge impacts in industry, in agricultural automation and in optimizing almost any socio-economic process of our Society.

From a strategic perspective, it is likely that this profound transformation will drive the emergence of a single converged industrial structure offering end-to-end services, such as voice, Internet access, what today we are calling OTT (Over The Top) services and future services. This converged industrial structure will leverage on a Telecommunications virtualized infrastructure where the provision of the end-to-end services is likely to become decoupled from the operations.

It is likely that there will be a split between Players owning and operating the infrastructure (Infrastructure Providers) from those enabling, operating and provisioning the services (Service Enablers and Service Providers). This will bring a split also in the Vendors supplying the Telecommunications infrastructure: i.e., Players supplying high volume, highly reusable hardware, (server, switch/routers, transport nodes) from Players supplying all the software modules which are eventually used and combines to create the services to residential consumers.

This vision will see a first concrete instantiation with the 5G, expected to exploit this radical techno-economic transformation of Telecommunications. In fact, 5G will be a massively dense distributed infrastructure, integrating processing, storage and (fixed and radio) networking capabilities, capable of producing radical socio-economic impacts. Digital Society and Economy will be radically “transformed” by a faster radio access, by larger bandwidth connections, and above all, by the pervasive availability of processing and storage capabilities integrated by an ultra-low latencies fabric.

“Immersive Communications” and “Anything as a Service” are often mentioned of two attractive examples of future service paradigms, which are posing challenging requirements for future 5G infrastructures. In a nutshell, “Immersive Communications” looks beyond the “commoditization” of current communication paradigms (e.g., voice, messaging, etc.), by pursuing new advanced forms of social communications and networking (e.g., through artificially intelligent avatars, cognitive robot-human interactions, etc.).

In summary, the overall goal of this thesis has been investigating technical challenges and business opportunities brought by the “Softwarization” of Telecommunications, a “game changer”, being exploited with the 5G. In particular, this thesis proposes that the 5G will have to have a sort of Operating System capable of operating the converged fixed and RAN and core infrastructures. The 5GOS will be an extension of the concept of Network OS for a 5G infrastructure. It should be a sort of overarching multi-level orchestration system, spanning from the Cloud, to the Network nodes up to the Users’ terminals and Equipment.

5GOS is an “overarching global orchestrator”. When comparing 5GOS with the ETSI NFV model, it can be seen as a global “overarching orchestrator”, extending the capabilities of the VNF Manager. On the other hand, the Virtual Infrastructure Manager (VIM) plays the role of a 5GOS subsystem.

Specifically, the architecture of the 5GOS is structured into two main functional blocks: the local 5G Edge Cloud Operating Systems (5G Edge Cloud OS) which are local instantiations of the 5G OS in charge of specific edge domains; the centralized 5G Global Operating Systems (5G OS) which is responsible for centralized functionalities in order to provide the overall integration.

Eventually the overall goal and contributions of this thesis has been: 1) defining a vision for future 5G infrastructures, the scenario, use-cases and the main requirements; 2) defining the functional architecture

of an Operating System for 5G; 3) designing the software architecture of a local implementation of 5G for the “Edge Cloud”; 4) understanding the techno-economic impacts of the vision of 5GOS and the most effective strategies to exploit it.

## Keywords

*SDN; NFV; 5G; Operating System; Orchestration; Softwarization; Edge Computing; Fog Computing*

# Résumé

La technologie et les motivations socio-économiques sont en train de créer les conditions d'une transformation profonde, appelée "Softwarization", des télécommunications et des écosystèmes de TIC. En effet, la diffusion fixe et mobile à large bande et l'accélération de performance des systèmes informatiques, conjuguée aux réductions de coûts liés, stimulent l'innovation et la convergence des réseaux et des domaines. De plus, le nombre de terminaux, des machines, des appareils et des choses intelligentes connectées au réseau se développe à un rythme exponentiel, tandis que dans le même temps, les capacités de traitement, de stockage et de communication intégrées dans ces terminaux sont impressionnante augmentation.

Les Réseaux définis par logiciel (Software-Defined Networking, SDN) et la Virtualization des fonctions de réseau (Network Functions Virtualization, NFV) sont deux des technologies les plus propices, qui vont ouvrir la route à cette transformation profonde des télécommunications. Plus généralement, il est considéré que le SDN et le NFV sont deux des facettes de la même transformation systémique globale appelée "Softwarization" des Télécommunications, qui gouverne l'évolution non seulement des réseaux, mais aussi des plates-formes de services (par exemple, les architectures pour l'informatique nuagique au cœur et au bord des réseaux – appelées également "Cloud and Edge Computing") et des futurs terminaux. En fait, on affirme que dans un proche avenir la plupart (sinon la totalité) des fonctionnalités de réseau et de service seront virtualisés et dynamiquement exécutés en partie dans le réseau, en partie dans le "Cloud Computing" - qui va à évoluer rapidement vers le "Edge and Fog Computing" - et en partie par les terminaux.

Cette transformation radicale permettra le développement de nouveaux paradigmes de services (par exemple, la "Connaissance en tant que Service", etc.) en créant les conditions pour l'émergence de nouveaux écosystèmes Un exemple est la possibilité d'actionner, à travers le réseau, le contrôle à distance des systèmes robotiques mobiles dotés de fonctions cognitives complexes et de caractéristiques élevées d'autonomie (par exemple, capable de fonctionner aussi dans des environnements non structurés et très dynamiques). Vraiment robots mobiles, contrôlés à distance avec des latences ultra-bas, peut avoir un impact énorme sur l'industrie, l'agriculture et plusieurs applications sociales (par exemple, à la maison et dans la ville intelligente du futur).

La Softwarization de Télécommunications permettra - très probablement en moins de cinq ans - de virtualiser toutes les fonctions de réseau et de service dans une infrastructure de télécommunication et de les exécuter sur un plates-forme logiciel qui pourrait, elle-même être totalement découplée de l'infrastructure physique sous-jacente (presque basée sur du hardware standard). Tous les services de TI et de télécommunications seront fournis par l'aide d'un «continuum» des ressources virtuelles (de traitement, de stockage et de communication) avec un investissement en capital initial pratiquement très limité et avec des coûts d'exploitation modestes.

Dans ce scénario futur, la frontière entre le "Cloud computing" et le Réseau va disparaître, et les deux domaines vont fusionner ensemble, en offrant une flexibilité, une adaptabilité, mais aussi une nouvelle complexité dans les opérations globales, c'est à dire, la gestion et le contrôle, de l'infrastructure de TIC conver-

gente. Le réseau et l'orchestration de services deviendront un élément essentiel des opérations des infrastructures de télécommunications.

Aussi la frontière entre le réseau et tous les terminaux et les appareils (que nous appelons génériquement "bord") connectés à elle disparaîtra. Les futurs terminaux intelligents, les machines autonomes, les robots et drones vont effectuer des «boucles cognitives» (avec des senseurs, le traitement, les communications, les actionneurs) intégrés dans la réalité. Cela aura des énormes répercussions dans l'industrie, dans l'automatisation agricole et dans l'optimisation de presque tous les processus socio-économiques de notre société.

Du point de vue stratégique, il est probable que cette transformation profonde va conduire à l'émergence d'une seule structure industrielle convergant, qui offrent des services de bout en bout, comme la voix, l'accès à Internet, ce que aujourd'hui nous appelons services des OTT (Over The Top) et services du future. Cette structure industrielle convergant mettra à profit sur une infrastructure virtualisée des télécommunications où la fourniture des services de bout en bout sera probablement découplé des opérations. il est probable qu'il y aura une scission entre les acteurs qui possèdent et opèrent l'infrastructure (les fournisseurs d'infrastructure) et ceux qui facilitent la réalisation ou réalisent les services (les facilitateurs de services et les fournisseurs de services). Cela apportera une scission aussi dans les vendeurs qui fournissent l'infrastructure des télécommunications: c'est-à-dire, entre les acteurs qui fournissent un volume élevé de matériel hautement réutilisable (serveur, commutateur / routeur, nœuds de transport) de acteurs qui fournissent tous les modules logiciels qui sont utilisés et combinés pour créer les services aux consommateurs résidentiels.

Cette vision verra une première instanciation concrète avec le 5G, qui devrait exploiter cette transformation techno-économique radicale des télécommunications. En fait, 5G sera une infrastructure massivement dense distribuée, en intégrant le traitement, le stockage et des capacités de réseau (fixe et radio), capable de produire des impacts socio-économiques radicales. Les sociétés numériques et économiques seront radicalement "transformées" par un accès radio plus rapide, par des connexions à bande plus large et, surtout, par la disponibilité généralisée des capacités de traitement et de stockage intégrés par un tissu qui offre une latence extrêmement modérée. "Immersive Communications" et "Anything as a Service" sont souvent mentionnés comment deux exemples intéressants de futurs paradigmes de service, qui posent des requêtes ardues pour les futures infrastructures 5G. En un mot, "Immersive Communications" regardent au-delà de la "banalisation" ("commoditisation" en anglais) des paradigmes de communication actuels (par exemple, voix, messagerie, etc.), en poursuivant nouvelles formes avancées de communications sociales et de télécommunications (par exemple, à travers des avatars artificiels intelligents, des interactions cognitive entre les robots et les humaines, etc.).

En résumé, l'objectif général de cette thèse est étudier les défis techniques et les opportunités économiques apportées par la "Softwarization" des Télécommunications, un «changeur de jeu" qui peut être exploité avec le 5G. En particulier, cette thèse propose que le 5G devra avoir une sorte de système d'exploitation capable de faire converger le RAN, le accès fix et le réseau de base. Le 5GOS sera une extension de la notion de système d'exploitation de réseau pour une infrastructure 5G. Il devrait être une sorte de système global d'orchestration multi-niveaux, allant du Cloud, au réseau des nœuds jusqu'à terminaux et les équipements de l'utilisateur.

Pratiquement, l'5GOS est une "orchestrateur supérieur globale". Si l'on compare avec le modèle 5GOS ETSI NFV, il peut être considéré comme un "orchestrateur supérieur" global, qui entend les capacités du gestionnaire VNF. D'autre part, les fonctions d'administration d'infrastructure virtuelle (VIM) jouent le rôle d'un sous-système du 5GOS.

Plus précisément, l'architecture du 5GOS est structurée en deux grands blocs fonctionnels : "5G Edge Cloud Operating System" (5G Edge Cloud OS), des modules au bord du réseaux qui sont instanciés localement du 5G OS en charge de contrôler et administrer des domaines d'accès spécifiques; les modules en réseaux du "5G Global Operating Systems" (5G OS) qui sont responsables de fonctionnalités centralisées afin de fournir l'intégration globale.

Finalement, l'objectif global et les contributions de cette thèse ont été: 1) définir une vision pour les futures infrastructures 5G, le scénario, les cas d'utilisation et les principales exigences; 2) définir l'architecture fonctionnelle d'un système d'exploitation pour 5G; 3) projeter l'architecture logicielle d'une mise en œuvre locale de 5G pour le "Edge Cloud"; 4) comprendre les impacts technico-économiques de la vision du 5GOS et les stratégies les plus efficaces pour l'exploiter.

## Mots-clés

*SDN; NFV; 5G; Operating System; Orchestration; Softwarization; Edge Computing; Fog Computing*

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# Chapter 1 Introduction

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This Chapter briefly describes the research context of the thesis, the problem formulation, the objectives pursued and the methodology. It describes also the scientific contributions and the organization of the contents.

## 1.1 Research context

Technology and socio-economic drivers are creating the conditions for a profound transformation of ICT ecosystems.

ICT technology is progressing at an impressive rate: computing is still following the Moore's curve, doubling in capability roughly every 18 months, whilst costs are decreasing rapidly; also storage capability is doubling every 12 months, fueling the connectivity demands for big data transmission; optical and radio bandwidth are, in turn, continuously increasing, and more pervasively adopted.

The number of the terminals, machines and smart things connected to the network is growing at an exponential rate. Given that the capabilities of processing, storage and communication embedded in these devices are impressively increasing they will become, from a functional perspective, like nodes of a pervasive telecommunications infrastructure. In view of that, more and more network and service virtual functionalities will be executed part in the network and part in the edge, fog and end-Users terminals. Here it comes the change of paradigm. If today, Telecom Operators are still keeping a distinction between their "Network" and what is connecting to it (any sort of terminal and machine or smart thing), in the future this distinction or border will disappear.

At the same time, we are witnessing a rapid increase in scale, dynamicity, heterogeneity of ICT infrastructures; the virtualization of IT and Network resources, coupled with software defined networking, which are extending Cloud computing service paradigms to the network functions of the entire infrastructure.

As a matter of fact, we are witnessing a growing attention on how Cloud computing is evolving towards the development of new paradigms (heterogeneous, federated, distributed clouds), with tight interactions between the computing and networking infrastructures.

Softwarization of Telecommunications will allow to virtualize all the network and services functions of a Telecommunication infrastructure and executing them onto a software platforms which could be even fully decoupled from the underneath physical infrastructure (almost based on standard hardware). Any ICT and Telecommunication services will be provided by using a "continuum" of virtual resources (of processing, storage and communications) with practically very limited upfront capital investment and with modest operating costs.

In this future scenario, the border between Cloud computing and Network will disappear, and the two domains will merge together, offering flexibility, adaptability but at the same time a new complexity in the global Operations, i.e., management and control, of the converged infrastructure. Orchestration, which is key to exploiting the potential of Cloud computing, will then become an essential part of the Operations of Telecommunications infrastructures.

Also the border between the Network and all the terminals and devices (which we call generically Edge) connected to it will disappear (figure 1). Smart future terminals, autonomous machines, robots and drones will perform “cognitive loops” (with sensors, processing, communications, actuators) embedded into reality. This will have huge impacts in industry, in agricultural automation and in optimizing almost any socio-economic process of our Society.

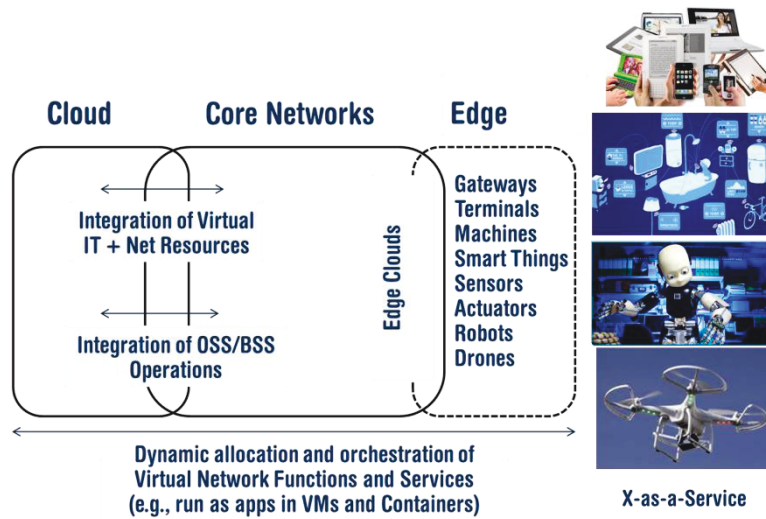


Figure 1 - Disappearing borders between Cloud, Network and Edge<sup>2</sup>: Virtual Network and Service Functions could run as “applications” on Virtual Machines (VMs) and Containers

Software-Defined Networks (SDN) **Erreur ! Source du renvoi introuvable. Erreur ! Source du renvoi introuvable. Erreur ! Source du renvoi introuvable. Erreur ! Source du renvoi introuvable. Erreur ! Source du renvoi introuvable.**and Network Functions Virtualization (NFV) [2] are two of the most important enabling technologies paving the way towards this transformation. In fact, SDN and NFV basic principles have been known for the past couple of decades, even if they were with different names (e.g., Active Networking, Programmable Networks, etc).

Today, these paradigms are garnering a new radical attention as the current technological and socio-economic drivers are making them exploitable and most probably sustainable in the Telecommunications ecosystems. In fact we know that besides technology, also business sustainability and regulation rules are the main variables driving the adoption of any impactful progress.

<sup>2</sup> From the presentation of the paper: A. Manzalini, N. Crespi et alii, “Manifesto of Edge ICT Fabric”, ICIN2013 (Venice, October 2013).

It can be argued that SDN and NFV are two of the facets of an overall systemic transformation called “Softwarization” which is steering the evolution not only of Networks, but also Service Platforms (e.g., Cloud and Edge Computing architectures) and future terminals, machines and smart things. Service providers and network operators embracing this vision will have to face risks and opportunities: on one side cost reductions, improved operations efficiency and dramatically reduced time to market when providing today and future services; on the other side a radical change of the value chain.

Ultimately we are not talking about just another technological upgrade of Telecommunications infrastructures, at least the ones that we’ve seen in the last two, three decades; this time it will be a systemic transformation impacting also several other industries, and much more intertwined with socio-economic sustainability and policy regulations.

This systemic transformation is radically accelerating the pace of innovation Telecommunications infrastructures (as it started doing before in the IT domain) whilst reducing the overall costs.

It is likely that Softwarization will transform future Telecommunications networks by bringing a radical fixed-mobile convergence leveraging on a less hierarchical architecture, with a limited number of big core nodes, co-located with (inter-connecting) big data Centers. In turn, the edge (distribution and access segments) is going to become densely meshed with by hundreds of thousands of small-medium aggregation nodes (e.g., router enriched with processing and storage capabilities), at very low cost.

The “ossification” of current legacy infrastructures is hampering this wave of innovation. In fact, current architectures are limiting the development and deployment of new functionality, services, security and management policies and approaches, and other elements that are essential to cope with an increasingly dynamic ICT and Telecom market.

One concrete example is represented by the number of middle-boxes deployed in current networks: not only these nodes are contributing to the “network ossification”, but also they represent a significant portion of the network capital and operational expenses (e.g., due to the management effort that they require). Basically, a middle-box is a stateful node supporting a narrow specialized network functions (e.g., layer 4 to 7); it is based on purpose-built hardware (typically closed and expensive). Examples of said functions are Wide Area Network (WAN) optimizers, Network Address Translation (NAT), performance-enhancing-proxies, intrusion detection and prevention systems, any sort of firewalls, other application-specific gateways, etc. The virtualization of these middle-boxes and managing them as appliances would determine several advantages, such as cost savings and increased flexibility: this is an example of the transformation being brought by Softwarization.

For sure, it will not be possible anymore adopting traditional management approaches for said networks. Complexity and dynamism will be too high. Dynamic or static modeling for (open or closed loop) control will become very complicated and unstable if not supplemented with a variety of methods and control techniques, including (nonlinear) dynamic systems,



computational intelligence, intelligent control (adaptive control, learning models, neural networks, fuzzy systems, evolutionary and genetic algorithms), and artificial intelligence.

Even more we proposed that the evolution of Control, Orchestration, Management and Policy (COMP) is one of the most important and strategic challenges to be faced to make this transformation sustainable from a business point of view.

In fact, rather than closed pieces of equipment, COMP will have to address a sheer number of software processes, such as virtual functions and service components, deployed from the Cloud, to the Network up to the Users' Equipment and Terminals. As such, future infrastructures will have an high level of "complexity" (J. Doyle): the increasing influence of software \*everywhere\* will increasing pervasively of virtualized resources and as such volatility/uncertainty (Robust Yet Fragile). In this sense "taming this increasing complexity" is one the most challenging requirements. Example of challenges, are:

- Where allocating and executing what functionality for meeting the Quality of Experience (QoE), Quality of Service (QoS) and business requirements ?
- What's the balance between the top-down (centralized) intelligence and bottom-up (local) self-organization (e.g., enabled by heuristics or algorithms executed in the nodes) ?
- How controlling and managing real and virtual resources ?
- How structuring the required multi-level "orchestration" ?
- How taming the "complexity" ?

## 1.2 Problem formulation

The main problem addressed by this thesis manuscript is: how Softwarization will transform ICT ecosystems in the next few years ? Which are the main strategic and technological means to face this transformation ? What are the emerging service models and potential new business roles ?

This thesis proposes a vision where Telecommunications infrastructures will evolve to become a distributed software platform allowing any sort of services (e.g., including network services) and applications (e.g., including also management, traffic engineering services) to be executed over a decoupled "continuum" of resources, extended up to the terminals, or Users' Equipment (UE).

Eventually, the overall architectural model will look like an extension of what has been defined for the Cloud computing domain, i.e., a service-driven platform supporting Software as a Service (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS), revisited in view of the Softwarization of Telecommunications.

IaaS will assume a new meaning as the CPU, storage, and network resources are supplied not only by a collection of Data Centers but also by the CPU, storage, and network resources deployed into the Point of Presence (PoP) of the Telecommunications network (in its Core, Edge and Access segments). In fact, the PoP are already being transformed by some Telecom Providers into medium-small Edge Data Centers.

The PaaS layer will feature a pool of software appliances that facilitate the end-to-end lifecycle of developing, testing, deploying, and hosting service and applications. Example of said appliance are database, Web server, application server, Apache Hadoop, Apache Storm, load balancers... that can be integrated with other network appliances (e.g., middleboxes) for designing complex service chains, functions and applications.

SaaS will integrate multiple, interoperable PaaS and IaaS resources to deliver services and applications to the very end Users. It will be the goal of the orchestrator to select, assemble, deploy, and manage a set of appliances delivering a particular service or application.

In this direction also the concept of orchestration has to be enhanced. The term has been used in the IT domains, to refer to the automation of tasks involved with arranging, managing and coordinating services deployed across different applications and enterprises. In network softwarization environments the orchestration has a much more challenging role because it involves the interworking services running across heterogeneous systems in geographically distributed Data Centre locations.

In this broader perspective, orchestration should satisfy both horizontal and vertical interoperability requirements: horizontal, when considering the interoperability between the same tiers in different infrastructure stacks (such as cross-SaaS, cross-PaaS, or cross-IaaS); and vertical when addressing downstream-compatible infrastructure tiers in different stacks — such as SaaS to PaaS and PaaS to IaaS.

Orchestration functionalities could be seen as an extension of the concept of Network OS.

In order to explain better the metaphor, let's see the main characteristics of a Network OS: it is system software that controls the various devices on a computer network and how they communicate with each other. Some of the tasks of a network OS are similar to those of an OS for individual computers, such as memory management and hardware control. Moreover, a network OS also has some further specialized tasks: for example, when network devices are used, the network OS ensures these resources are used correctly and efficiently. Other specialized functions also include network security and network administration. A Network OS resides normally on a server. Example of Network OS software includes Linux, Mac OS X Server and Windows Server.

A Network OS includes sophisticated tools for network management. For example, a network administrator can monitor the performance of various parts of the network and try to address problems before they can have a serious impact. Network management can also be used to update software on the individual computers on the network. Rather than having to visit each individual computer for a manual installation, changes can be made directly over the network. This allows for automated software updates and installation, and it helps with maintaining compliance with software licensing.

Today's computer networks include devices with many different personal operating systems, so a Network OS should be able to manage multi-platforms, so they can all have to work together seamlessly. One of the critical tasks of network management is security. Network

security refers to preventing unauthorized access and misuse of the network and its resources. Computer networks face a number of security threats. Many of these threats are common to all computer systems, but computer networks are particularly vulnerable since many of them are used by a large number of users.

It is likely that this vision will see a first concrete exploitation with the 5G.

The concept of an Operating System for the 5G (5GOS) indicates an extension of the concept of the concept of Network OS for a 5G infrastructure. It should be a system software that controls the various 5G resources and how they communicate with each other. It should be a sort of overarching multi-level orchestration system, spanning from the Cloud, to the Network nodes up to the Users' Terminals and Equipment.

### 1.3 Thesis objectives and principles

The overall goal of this thesis has been investigating technical challenges and business opportunities brought by the "Softwarization" of future Telecommunications (e.g., 5G), recognised as a "game changer" of the Digital Society and Economy.

This overall goal has been articulated in a number of objectives: **1) defining a vision for future 5G infrastructures, the scenario, use-cases and the main requirements; 2) defining the functional architecture of an Operating System for 5G; 3) designing the software architecture of a local implementation of 5G for the "edge cloud"; 4) understanding the techno-economic impacts of the vision and 5GOS and the most effective strategies to exploit it.**

### 1.4 Research questions and methodology

In this section we decompose the previous problem statement into eight research questions (RQ), each of them leading to one or more contributions.

*RQ 1: What is the impact of exploiting SDN and NFV in Telecommunication infrastructures ?*

***Contribution 1: Analysis of the state of the art on SDN and NFV, with particular reference to the ongoing activities international bodies and open source initiatives***

*RQ 2: What is the role of Cloud, Edge and Fog Computing in shaping the future of Telecommunication?*

***Contribution 2: Analysis the state of the art on Cloud, Edge and Fog Computing***

*RQ 3: Will SDN, NFV paradigms and Cloud, Edge and Fog Computing converge in the future ?*

***Contribution 3: Developed the vision of "Softwarization" of Telecommunications, where SDN, NFV, Cloud, Edge and Fog Computing are seen as facets of an overall systemic transformation in Telecommunications. Producing arguments that 5G will be a first concrete exploitation of "Softwarization".***

*RQ 4: What will be the impact of the “Softwarization” on the Operations (e.g., management, control) ? What will be the main challenges to be faced ?*

***Contribution 4: Understanding the requirements for the management and orchestration of virtual network functions and services in a future virtualized infrastructure.***

***Contribution 5: Analysis of DevOps and submission of a contribution for IETF (for the contribution see annex)***

***Contribution 6: Analysis of the state of Autonomic and Cognitive capabilities which could increase the level of automation in the Operations of a future virtualized infrastructure.***

*RQ 5: If 5G will be a first concrete exploitation of “Softwarization”, what are the scenarios, use-cases and main requirements ? Will a new concept/model of 5G service emerge ?*

***Contribution 7: Analysis and definition of 5G scenarios and use-cases, from which the main functional and non-functional requirements for 5G have been derived.***

***Contribution 8: Definition of a unifying concept/model of 5G service, valid across IaaS, PaaS and SaaS.***

*RQ 6: How can we concretely design an OS for 5G infrastructures?*

***Contribution 9: Developed the scope and functional architecture of an OS for 5G, with local and centralised functions. Designed the software architecture of an example of OS for the Edge Cloud. Submission of a contribution, on 5GOS, for ITU-T Focus Group on “Network Softwarization” (for the contribution see annex)***

*RQ 7: What will be the techno-economic impact of “Softwarization” ? What are the strategies being adopted by Telco Service Providers ?*

***Contribution 10: Analysis the current value chain and developed a model of the future value chain.***

***Contribution 11: Analysis the main initiatives of the Telco Network Operators/Service Providers in order to infer the strategies most adopted.***

#### 1.4.1 Research methodology and scientific contributions

This section presents the methodology adopted to address the research questions. This is complemented by an overview of achieved scientific contributions.

In order to address the first research question **RQ 1** about the potential impact of exploiting SDN and NFV in Telecommunication infrastructures, an analysis of the state of the art and trends about SDN and NFV has been made; particular attention has been paid to the ongoing activities international bodies and open source initiatives.

The second research question **RQ 2** about role of Cloud, Edge and Fog Computing in the future of Telecommunications, has been covered by analyzing of the state of the art and trends about Cloud, Edge and Fog Computing.

After the above analysis it has been possible to address the third research question **RQ 3**, about the potential convergence of SDN and NFV paradigms with Cloud, Edge and Fog Computing. In this case the main contribution has been the development of the vision of “Softwarization” of Telecommunications, where SDN, NFV, Cloud, Edge and Fog Computing are seen as facets of an overall systemic transformation. This vision, presented for the first time in [5], is the result of the convergence of a number of drivers such as ultra-broadband diffusion (i.e., high bandwidth and low latency connections), IT techno-economic drivers (e.g. increasing performance of chipsets, at continuously decreasing costs), more and more advances terminals and eventually the diffusion of open source software and hardware. It has been also argued that 5G will be a first concrete exploitation of this vision by 2020.

The **RQ 4**, concerning the impact of the “Softwarization” on the Operations (e.g., management, control) of Telco infrastructures, had been addressed by an analysis of the requirements for the management and orchestration of virtual network functions and services in a future virtualized infrastructure. The study has been consolidated in a contribution to IETF on the analysis of opportunities and challenged for the adoption of DevOps by the Network Operators. Moreover, RQ 4 has been addressed by the analysis of the state of Autonomic and Cognitive capabilities which could increase the level of automation in the Operations of a future virtualized infrastructure.

In order to address the fifth research question **RQ 5**, an analysis and definition of 5G scenarios and use-cases has been carried out. Starting from this analysis, a list of the main functional and non-functional requirements 5G have been derived. Also a second contribution addressing this question concerned the definition of a unifying concept/model of 5G service, valid across IaaS, PaaS and SaaS.

The sixth research question **RQ 6** has been answered by defining the scope and functional architecture of an OS for 5G, characterized by local instantiations (5G Edge Cloud OS) and centralized functions (5G Global OS). As a further contribution, the software architecture of an example of OS for the Edge Cloud has been designed. Eventually the the scope and functional architecture of an OS for 5G has been submitted as a contribution for ITU-T Focus Group on “Network Softwarization” (for the contribution see annex).

The contributions to address **RQ 7** highlighted the techno-economic impact of “Softwarization” in the telecommunications ecosystem: new emerging business roles and transformation of the value chain has been drawn. A second contribution for this research question has been the analysis the main initiatives of the Telco Network Operators/Service Providers in order to infer the strategies most adopted.

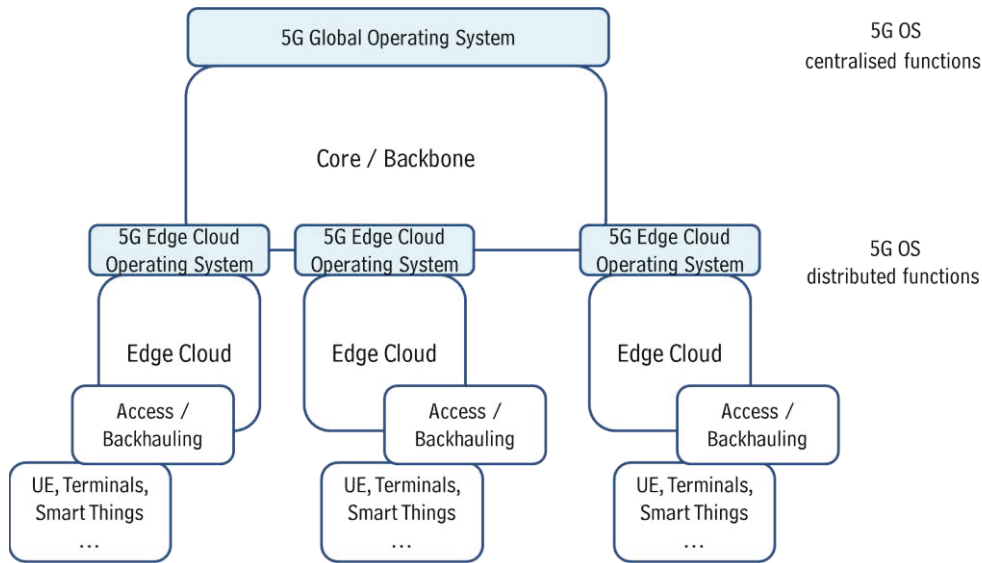


Figure 1- 5G Operating System

### 1.4.2 Thesis organization

The outline of the thesis is the following:

Chapter 2 makes an overview of the state of the art of SDN, NFV, Cloud, Edge and Fog Computing.

Chapter 3 presents the vision of “Softwarization” of Telecommunications, specifically focusing on the 5G infrastructure as a first concrete industrial exploitation of it. Some scenarios and use cases are also described.

Chapter 4 presents the design principles, architectural model and requirements of an Operating System for 5G.

Chapter 5 describes a possible implementation of the Edge OS for the Edge Clouds of 5G.

Chapter 6 elaborates about the main the techno-economic impact of “Softwarization” and provide an analysis of the strategies being adopted by Telco Service Providers to face this business transformation.

Chapter 7 draws the closing remarks and proposes next steps for future developments by leveraging on the achievements of this thesis.

Annex 1 provides a list the published papers.

Annex 2 reports some key published papers.

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# Chapter 2 State of Art on SDN, NFV and Edge-Fog Computing

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## 2.1 State of Art on SDN and NFV

This section will report a short overview of the state of the art of SDN and NFV, considered to be two key enabling technologies capable of shaping the Softwarization of Telecommunications infrastructures towards 5G.

### 2.1.1 SDN

ONF (Open Networking Foundation) defines Software Defined Networks (SDN) as an architectural paradigm based on *“the physical separation of the network control plane from the forwarding plane, where the control plane controls several devices”* [6]. In simpler words SDN leverages on the separation the hardware (forwarding plane) are from software (control plane) in Telecommunications equipment. Moreover the execution of said software not necessarily has to be done in the equipment, but potentially it could be on Cloud-Edge Computing, or in any standard processing resources (e.g., IT servers). For example, most of the routers and switches in current Telecommunication infrastructures are based on specialized hardware and “closed” software. According to SDN paradigms, in the future, routers and switches could be built with a clear separation of the hardware and software, and the control planes could be allocated – in centralised and/or local standard processing resources (e.g., IT servers).

Another key aspect about SDN is about providing abstractions and Application Programmable Interfaces (API) to program/control the functions and the services of the network resources. As a matter of fact, API will allow the dynamic programming of network equipment to achieve operations and business requirement and/or in response to changes in the network state. The control plane for a group of network equipment, being decoupled from the forwarding plane, could be even migrated or centralized in the Cloud or Edge Computing. There are several examples of APIs (e.g., REST API) defined as northbound interfaces.

In SDN there are three main abstraction: forwarding abstraction, distribution abstraction, and specification abstraction. Forwarding abstraction consists in the separation of data and control plane by adopting a higher-level namespace and exploiting a logically-centralized controller to enforce the network policies by communicating them to generic forwarding hardware (via the southbound interface). Distribution abstraction consists of embedding logically the intelligence in the control plane, being decomposed in sets of controllers. Eventually, the specification abstraction consists in specifying the network behavior through network applications running on the application plane through commands sent to the control plane which are in turn translated into low-level specific commands delivered to the data plane via to the southbound protocol.

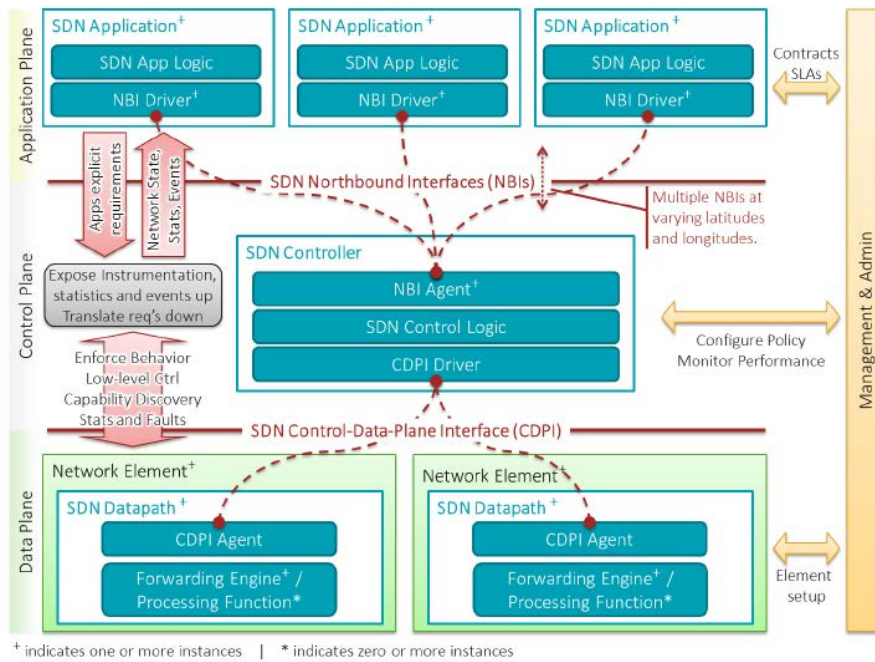


Figure 2 - SDN reference architecture (source ONF)<sup>3</sup>

Figure 1 shows the SDN reference architecture as under development in the Open Networking Foundation (ONF). Two key interfaces are the SDN Northbound interface (NBI) and the SDN Southbound interface (SBI)

As far as the SBI is concerned, today, the most popular one is probably the OpenFlow protocol [2]. OpenFlow is an open standard protocol managed by ONF. It specifies a protocol through which a remote controller can modify the behaviour of networking devices through a well-defined “forwarding instruction set”.

NBI of any controller, through which applications are supposed to interact with the network, are normally proprietary. There are also open descriptions of NBI such as the ones being developed in OpenDaylight [3] (ODL) aim to bring some alignment in the plethora of specifications.

ODL is an Open Source Software project under the auspices of the Linux Foundation. The project has designed an architecture which defines separated layers, several, extensible north- and southbound interfaces to applications and infrastructure as well as a modular set of functions of the controller platform. OpenDaylight supports the Java based OSGi framework and bidirectional REST for the northbound API and for example OpenFlow, OVSDB as south bound interfaces. Another aspect is that the business logic and algorithms reside in either of these (northbound) applications, which use the controller to gather network intelligence, run algorithms to perform analytics, and finally use to orchestrate the new rules.

<sup>3</sup> White paper on “Software-Defined Networking: The New Norm for Networks” <https://www.opennetworking.org/>;

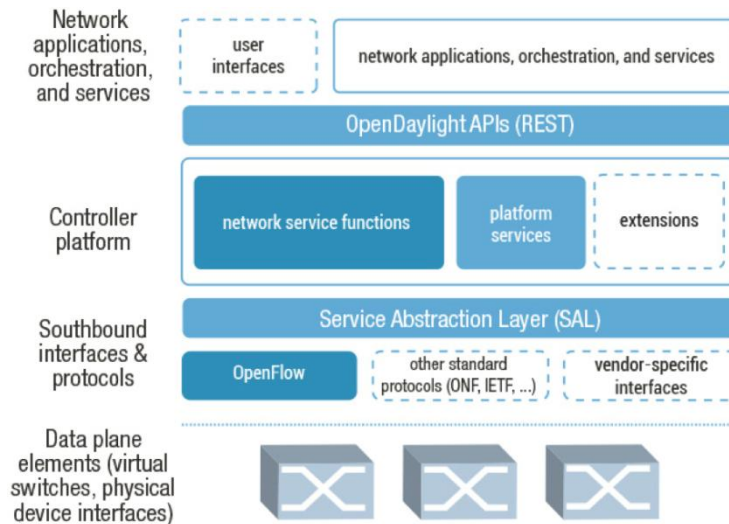


Figure 3 - ODL reference architecture

As another example, Floodlight Open SDN Controller [4] is an enterprise-class, Apache-licensed, Java-based OpenFlow Controller. Floodlight is designed to work with the growing number of switches, routers, virtual switches, and access points that support the OpenFlow standard.

ONOS is another example of controller for a SDN fabric, or better a sort of distributed network operating system. Developed by ONLab (a non-profit organization founded by SDN inventors and leaders from Stanford University and UC Berkeley), ONOS has released in open source, with features such as scale-out design, high availability, and network graph as a north bound abstraction. ONOS has been built using Floodlight for the OpenFlow controller, Cassandra for distributed key-value store for network state, Titan for network graph abstraction, and Zookeeper for coordination among ONOS instances. Initial use cases for ONOS focus on services and applications for service provider and WAN networks, e.g.,: multi-layer optimization and traffic engineering over packet optical core; seamless peering of SDN islands with the Internet; SDN-based WAN control with segment routing; bandwidth calendar-ing; bandwidth and network provisioning.

### 2.1.2 NFV

Today most of network functions (e.g., firewall, load balancers, WAN accelerators, DNS, video optimizers, etc) of current Telecommunications infrastructures are implemented with closed software running on dedicated customized hardware (middleboxes).

Network Function Virtualization (NFV) is an innovative architectural paradigm [5] proposing that network functions (L2-L7, i.e., from a software switch/router to a software middle-box) can be virtualized, dynamically allocated and executed (on virtual resources as Virtual Machines, Containers) in centralized (Cloud Computing) or distributed in commodity hardware. SDN and NFV are mutually beneficial but are not dependent on each other: network functions can be virtualized and deployed without an SDN being required and vice-versa.

ETSI NFV ISG is defining the NFV reference architecture<sup>4</sup>.

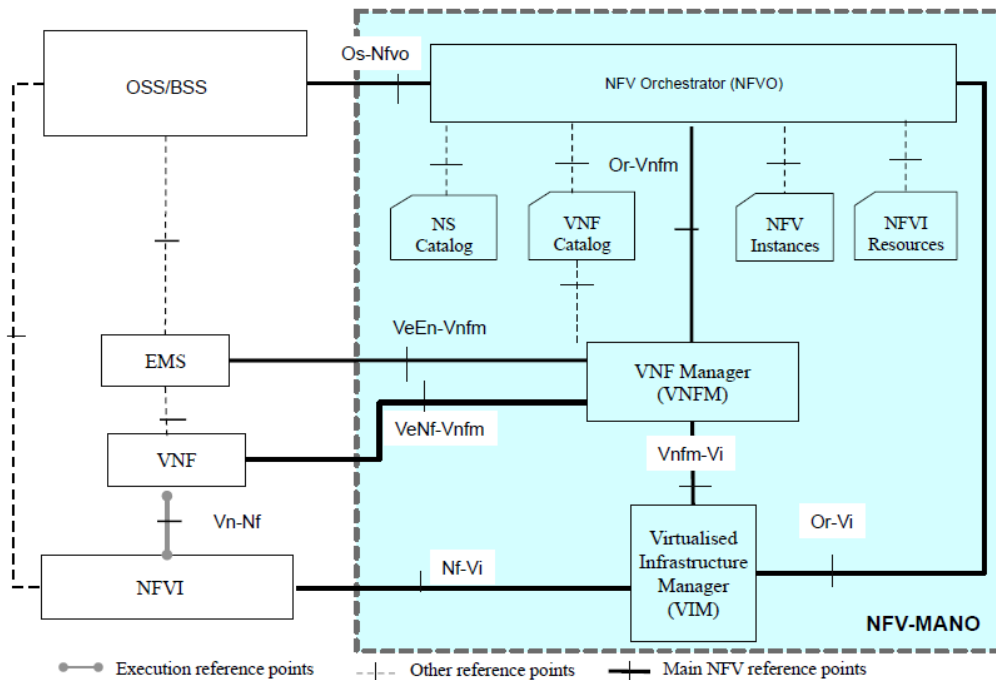


Figure 4 - NFV reference architecture

The NFV reference architecture is made of: the NFV infrastructure (NFVI), the NFV Management and Orchestration (MANO), and the OSS/BSS. The NFV Infrastructure is composed of the virtual and physical computing, network, and storage resources. The virtual resources of the NFVI rely on a virtualization layer which in turn relies on the physical substrate.

MANO is composed of the Virtualized Infrastructure Manager (VIM), the VNF Manager, and the NFV orchestrator. Specifically:

- The VIM has the goal of controlling and managing the NFVI resources, providing compute, storage and network capabilities. It exposes northbound APIs to allow creating the underlying virtual links and virtual networks necessary to ensure the network services. It also keeps updated a database (e.g., performance measurements and events) with the allocation of virtual resources on the physical substrate.
- VNF Manager: This block is responsible for managing the life-cycle of the VNF instances, providing overall coordination and adaptation role for configuration and event reporting between NFVI and the E/NMS. It is in charge of managing, modifying, healing, terminating, updating, upgrading, scaling, and migrating the VNFs.
- NFV orchestrator is in charge of ensuring the life-cycle management of network services (including instantiation, scale-out/in, performance measurements, event correlation, termination). NFV orchestrator also provide global resource management, validation and authorization of NFVI resource requests and policy management for NS instances.

<sup>4</sup> White paper on “Network Functions Virtualization” [http://portal.etsi.org/NFV/NFV\\_White\\_Paper.pdf](http://portal.etsi.org/NFV/NFV_White_Paper.pdf);

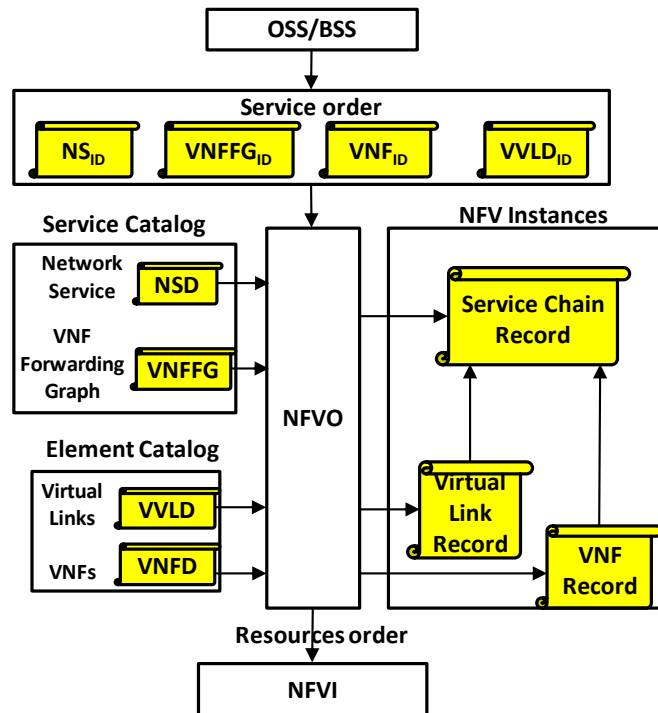


Figure 5 - Network service instantiation in the NFV architecture (Source ETSI)

As an example, a network service is instantiated in NFV by following these three steps: reception of the service order, instantiation of the VNFs, and instantiation of the virtual links.

**Reception of the service order:** NFVO receives a service order from the OSS/BSS. This service order is a data model which consists of parameters such as the identifiers of the network service to be instantiated, the identifiers of the VNFFG, the identifiers of its composing VNFs, or the identifiers of the Virtual Links (VL) interconnecting the VNFs.

The NFVO then consults the service catalog where it reads the NSD (network service descriptor). The NSD provides with the VNFs and the Virtual Links (VL) to be instantiated, which are contained in the associated VNFFG (VNF forwarding graph) to that network service. The VNFFG describes how traffic is forwarded among VNFs composing this network service. The NFVO will instantiate the corresponding VNFs and VFs composing that network service.

**VNF instantiation:** NFVO consults the element catalog to read the VNF Descriptor (VNFD). The element catalog contains all the on-boarded VNF packages the NFV architecture can provide. The VNFD contains the requirements of each VNF composing the network service such as the VNFC (VNF component) composing that VNF as well as their intra connections, the computer requirements and Service Level Agreement parameters. The requirements of VMs (required storage, compute parameters, scaling limits, etc.) are given by their respective VDU (Virtual Deployment Unit) descriptors.

The VNF Manager instantiates each VNF. It first reads the VNFD of the VNF to be instantiated, which contains information of the VNFC composing that VNF. The VNF Manager then gets the number and types of the VNFC to be instantiated. For each VNFC, the VNF Manager reads the VDU of each VNFC and requests a new VM for that VNFC and network and storage

resources to the NFVI. Depending on the number of VNFC composing the VNF, this instantiation process can be more or less complex. For instance, if there are several VNFCs, firstly the different VNFC are instantiated and secondly those are connected to each other. Once those VNFCs are connected, a series of messages are sent among VNFCs in order to find a suitable VNFC to play the role of master and coordinate all the VNFCs (master function). Only the master function communicates with the VNF Manager. After the resources of the VNFC are allocated, the VNF Manager asks to start that VM and it then informs that the VNF is ready for configuration.

**VL instantiation:** The NFVO consults the element catalog to read the Virtual Links Descriptor (VULD). The VULD contains the type of virtual link (point-to-point, point-to-multipoint, etc.), the associated KPIs (QoS, latency, bandwidth), and the network type (hypervisor vSwitch, etc.).

The VIM allocates the necessary components in the NFVI for each VL. The virtual links connect the VNF in that network service. The VNF NCT (Network Connectivity Topology) is a set of VLS to connect the different VNFs. These VNFs are connected through connection points (CP).

Next section will address how SDN and NFV will impact the Operations of future infrastructures.

## 2.2 How SDN and NFV will impact the Operations of future infrastructures?

The ossification of Telecommunications networks is creating several difficulties for Service Providers (SP) and Network Operators (NO) to develop and deploy, flexibly, any innovative network functionalities, services and management policies, which are essential to benefit from the increasing dynamicity of the ICT markets. Launching new services, for example, is still time-consuming and requires expensive efforts: this is preventing any rapid roll-out of new businesses models and opportunities.

A major requirement for SP and NO is thus making the innovation cycles of networks and services features faster and simpler. Moreover there is a need, for both SP and NO of reducing Operational Expenditures (OPEX) and Capital Expenditures (CAPEX): concerning the OPEX, for instance, automated operation processes (e.g. configuration of networks and services systems and equipment) could limit human intervention, reducing also wrong operations; on the other hand, concerning the CAPEX, a flexible and optimal provisioning of network functions and services could reduce systems and equipment costs and allows postponing investments.

These requirements are likely to be met by a combined exploitation of SDN and NFV. Most (if not all) network and service functions can be virtualized and dynamically allocated into a standard IT resources (e.g., in the Cloud, Edge or even Fog Computing). This would mean a deeper integration of networks and IT (e.g. Cloud) domains, including the related Operations (now mainly carried out separately), which are a likely to be fully automated.

It is evident that the complexity and dynamism of an SDN-NFV infrastructure will require re-designing current management systems (OSS/BSS) to handle, rather than closed pieces of equipment, an impressive number of software processes, which have to be dynamically orchestrated, executed and moved.

Automation of operations processes (e.g., introducing autonomic and machine learning capabilities crunching networks and services big data) will be mandatory to make business sustainable. Moreover, management needs to be complemented with new capabilities such as programmability and orchestration of the life-cycles of virtual network functions and services.

With Softwarization of Telecommunications (and any critical infrastructure), cyber security will become even more important. Interestingly A.I. solutions for security are emerging. For example recently a group of researchers at MIT's Computer Science and Artificial Intelligence Laboratory (CSAIL) are working with machine-learning startup PatternEx to develop an Artificial Intelligence system that can detect 85 % of attacks by reviewing data from more than 3.6 billion lines of log files each day and informs anything suspicious<sup>5</sup>.

Their analyst-in-the-loop security system<sup>6</sup>, combines analyst intuition with state-of-the-art machine learning to build an end-to-end active learning system. They have called this system AI2 (AI Squared) as it learns and automatically creates models that, when executed on new data, produce predictions as intelligent as those deduced by human analysts. In other words the human analyst then identifies which events are actual cyber attacks and which aren't. This feedback is then incorporated into the machine learning system of AI2 and is used the next day for analysing new logs. The system has four key features: a big data behavioral analytics platform, an ensemble of outlier detection methods, a mechanism to obtain feedback from security analysts, and a supervised learning module.

Other potential solutions for cyber security are being analysed from the application of blockchain architectures<sup>7</sup>.

### 2.3 State of art on Edge-Fog Computing

If software-hardware decoupling and the virtualization of functions and services can be seen as the "common denominator" of Softwarization, the potential differentiation and evolution of Cloud towards Edge and Fog Computing represents another interesting and synergic expressions of the same overall transformation.

The growing interest for Edge-Fog Computing comes from the need of reducing the end-to-end application latency: in fact, this requirement can be achieved by moving the processing nearer to the Users.

As known, TCP is a serious performance bottleneck for video and other large files (as it requires receiver acknowledgement) and throughput is inversely related to Round Trip Time

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<sup>5</sup> <https://www.patternex.com/>

<sup>6</sup> <http://ieee-sdn.blogspot.it/2016/05/ai-humans-ai2-for-cyber-security.html>

<sup>7</sup> <http://ieee-sdn.blogspot.it/2016/04/blockchain-game-changer-also-for.html>

(RTT) or latency. It is impossible to provide HD-quality streams if the servers are not relatively close to the Users; at the same time, just best effort traffic will not allow achieving the low latency requirements pose by services such caching or interactive applications.

In fact, the "last mile" connection between a user and the ISP is a significant bottleneck. According to the FCC's Measuring Broadband America report [6] , during peak hours "Fiber-to-the-home services provided 17 milliseconds (ms) round-trip latency on average, while DSL-based services averaged 44 ms".

It should be mentioned that PON and DSL delays are intrinsic in the access protocols. Achieving lower delays means either changing said protocols or locating all of the necessary data at the subscriber, including content caches and databases.

Another example is Mobile Cloud Computing, a paradigm where both data storage and data processing are outsourced from the mobile phone to the cloud [7] . Mobile Cloud Computing [8] aims at integrating the cloud computing into the mobile environment and overcomes obstacles related to the performance (e.g., battery life, storage, and bandwidth), environment (e.g., heterogeneity, scalability, and availability), and security (e.g., reliability and privacy) debated in mobile computing.

In particular, ETSI [9] defines Mobile Edge Computing as the way of providing IT and cloud-computing capabilities within the Radio Access Network (RAN) in close proximity to mobile subscribers.

Dew Computing, described in [10] is another approach based on a structural layer in the existing distributed computing hierarchy, which is positioned as the ground level for the Cloud and Fog computing paradigms. Dew Computing is based on a micro-service concept in vertically distributed computing hierarchy. pushing the frontiers to computing applications, data, and low level services away from centralized virtual nodes to the end users. DC addresses a wide range of technologies including wireless sensor networks, mobile data acquisition, cooperative applications on distributed peer-to-peer ad hoc networking and processing environments.

Fog Computing is one of the latest trend of computing aimed at computation and storage very close to end Users at the edge of network [11] . Fog nodes includes in fact the end Users terminals, the smart machines, the gateways which are assumed becoming capable of executing local service tasks and storing local information.

The main distinguishing characteristics of Fog Computing is its close distance to end users, in order to support latency-sensitive applications and services. Another property is location-awareness; the geo-distributed fog node is able to infer its own location and track end user devices to support mobility. Finally, fog computing can process and reduce data volume at a very early stage, thus limiting propagation delay and bandwidth needs.

The paper [12] offers a comprehensive definition of fog computing, even if it points out the unique connection to the cloud. A more general definition of fog is the following [13] "*Fog computing is a geographically distributed computing architecture with a resource pool con-*



*sists of one or more ubiquitously connected heterogeneous devices (including edge devices) at the edge of network and not exclusively seamlessly backed by cloud services, to collaboratively provide elastic computation, storage and communication (and many other new services and tasks) in isolated environments to a large scale of clients in proximity”.*

There are a few approaches similar to fog computing. The Cloudlets, for example, are also called “a data center in a box”, are implementing the same cloud computing paradigm but in a more concentrated way, relying on high-volume local servers [14]. Typically a Cloudlet has a three-layer design, in which the bottom layer is Linux and data cache from cloud, the middle layer is an evolution of OpenStack [26] for the fog, and the top layer is applications isolated by different virtual machine (VM) instances. Cloudlet are designed to provide services to delay-sensitive, bandwidth-limited applications nearer to the Users.

For example, IOx is a fog device from Cisco: it works by hosting applications in a Guest Operating System (GOS) running in a hypervisor directly on the Connected Grid Router (CGR)" [15]. On IOx platform, developers can run python scripts, compile their own code, and even replace the operation system with their own.

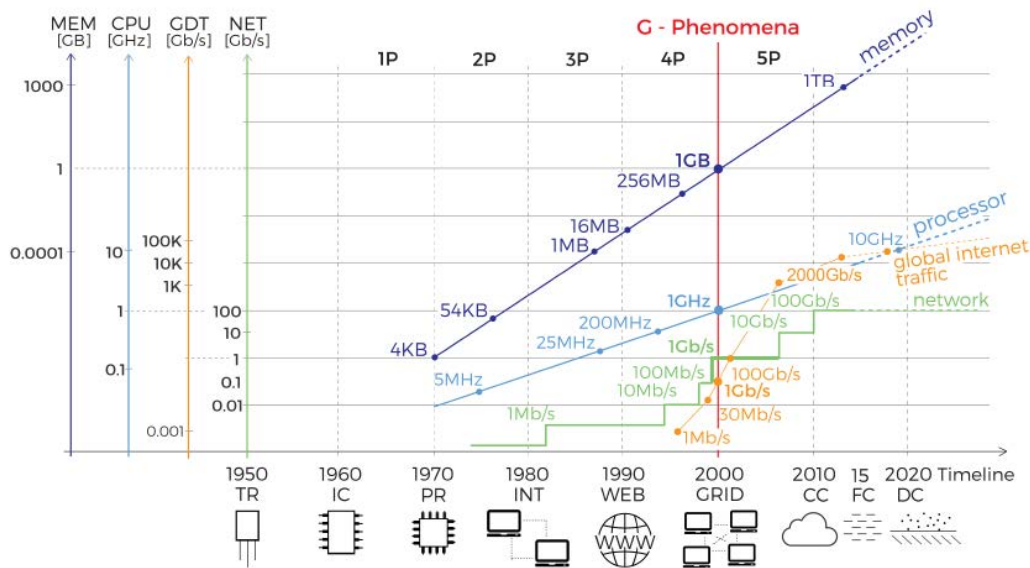
For more references for these examples and more examples, please see an initial list of over 100 recent publications on eight different topics under Fog Networking [16].

In general Edge and Fog Computing will not replace the Cloud, obviously: they are beneficial. A main research question is what tasks have to be allocated to the Edge and Fog (e.g., those that require real-time processing, end user objectives or low-cost leverage of idle resources) and what go to Cloud (e.g., massive storage, heavy-duty computation, or wide-area connectivity). In this sense it will be important to define the Fog-Cloud and Fog-Fog interfaces: the specification of information passage, from its frequency to granularity, across these interfaces.

Moreover because of the proximity to end users and locality, Edge and Fog nodes can often act as the first node of access control and encryption, provide contextual integrity and isolation, and enable the control of aggregating privacy-sensitive data before it leaves the edge.

Another key open question is the convergence and consistency arising out of local interactions: concerns of distributed control, divergence/oscillation and inconsistency of global states, become more acute in a massive, under-organized, possibly mobile fog with diverse capabilities.

Interestingly, it is argued in [10] that the biggest boost in the development of distributed computing occurred around year 2000 when the processor clock rate, network bandwidth and RAM (Random Access Memory) capacity reached the Giga range. This occurrence has been denoted as the G-phenomena [17] and started the fifth phase of development of computing systems (see following figure).



G (GIGA) - Phenomena, TR - Transistor, IC - Integrated Circuit, PR - Processor, INT - Internet, BD - Big Data, CC - Cloud Computing, FC - Fog Computing, DC - Dew Computing, 1P...5P - Development Phases

Figure 6 - The decade phases of the development of ICT and its relations to the G-phenomena and Distributed Computing Hierarchy: Cloud Computing (CC), Fog Computing (FC) and Dew Computing (DC) [10]

## 2.4 Edge Fabric (Cloud)

Beyond the state of the art, we propose, in this section, the concept of Edge Fabric. The term “fabric” has been used in the past to indicate a distributed system of loosely coupled storage, networking and processing functions interconnected by high bandwidth links. More recently it has been also used to indicate the Data Centre networks, optimized for “server-to-server connectivity”.

The data center network fabric is a network capable of interconnecting thousands of servers, storage and other network ports in a flat, ultra-low latency, high bandwidth infrastructure that provides any-to-any connectivity. A flat fabric-based network architecture eliminates the need for multiple layers, switch-to-switch interactions: it simplifies network management and operations while improving performance. Other nodes can be seamlessly added given the fabric’s high degree of scalability.

Edge Fabric has been coined in the paper [18] as a synonymous of Edge Clouds, leveraging on these concepts and extending them on a network wide perspective

Softwarization will allow virtualizing network and service functions which are provided today by expensive L4-L7 functions middle-boxes, and moving them in the Data Centers or even better at the edge (where this huge amount of resources is accumulating), as close as possible to the Users.

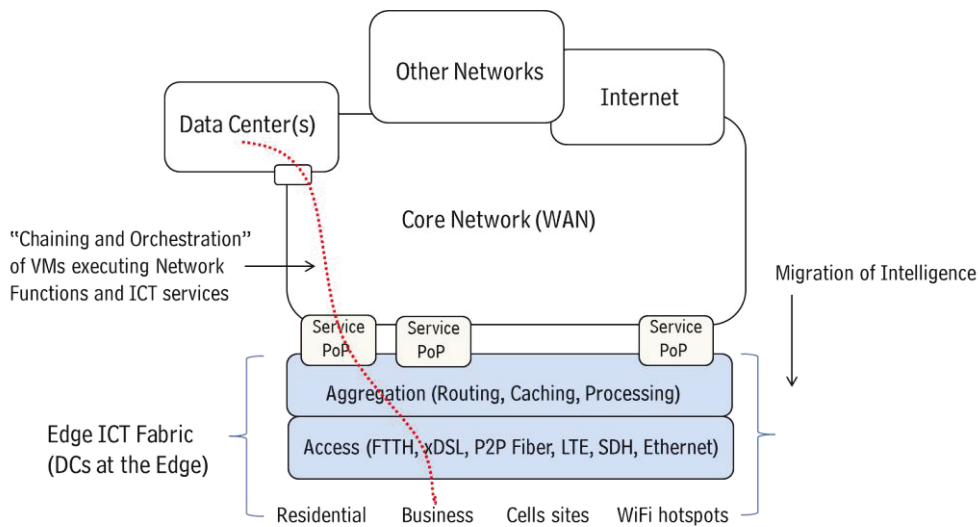
Edges will look like a data center network fabrics capable of interconnecting thousands of standard hardware servers, storage and other network nodes. Edges will become like mas-

sively distributed network computing infrastructure (creating the so-called Edge Clouds or Fabrics).

End Users (applications) will be more and more able to “drive the network dynamics”, flooding the network by the edges: by Users it is meant not only people by also machines, smart objects, things and any device which is attached to the network at the edge.

Edge Fabrics will be characterized by high flexibility, performance and self- adaptation at run-time (e.g. dynamic flocking of resources computing, storage and network I/O according to needs). Importantly, it will be also possible harnessing and combining all unused resources (e.g. computing and storage power at end Users’ home and in the edge micro data centers). Through the Edge Fabrics, it will be possible programming, allocating and moving a variety of virtual architectures (spanning across diverse edge networks or even across today Data Centers) on-demand, based on Users’ applications, also meeting governance and biz requirements (no more ossified networks structures).

Today a smart phone has a processing power of about 200 megaflops, a laptop is offering some tenth of gigaflops, a PlayStation hundreds of gigaflops. Imagine to find the way for orchestrating millions of Users’ devices, harnessing their idle processing and storage power: we could achieve bigger capacity than a supercomputer, like Titan (today number one, capable of 18 petaflops).



“Clouds of Virtual Machines at the Edge”. IEEE Com. Mag. Future Carriers Networks, July, 2013

Figure 7 – Architecture of the Edge Fabric presented at ICIN2013 <sup>8</sup>

<sup>8</sup> From the presentation of the paper: A. Manzalini, N. Crespi et alii, “Manifesto of Edge ICT Fabric”, ICIN2013 (Venice, October 2013).

## The “power of the edge”



- A Smartphone has 200 Mflops, a PC some tenth of Gflops, a PlayStation hundreds of Gflops... → **hundreds of petaflops of distributed processing capacity “at the edge”**;
- Near future Users’ devices having 100 GB of memory: a density of 5000 people/km<sup>2</sup> → **500 TB/km<sup>2</sup> of distributed storage capacity**.



Titan: 18 Petaflops



...a few Petaflops



...hundreds of Petaflops

Flops: floating point operations per second

15-16 Oct 2013

Session / Manifesto of Edge Fabric

13

Figure 8 – Vision of the Edge Fabric presented at ICIN2013<sup>9</sup>

This distributed platform of edge devices can indeed create a sort of processing and storage fabric that can be used to execute any network function and to provide any sort of ICT services and applications. The components of this fabric can be seen as: CPU/GPU, SSD (Solid State Drive), HDD (Hard Disk Drive) and link (and this is perfectly in line with the “disaggregation of resources” targeted by the Open Compute Project).

A perfect storm of pieces of software (even open source) executed on general purpose hardware allowing to abstract all network functions and services.

One may imagine these components aggregating dynamically in an application-driven “flocking”. And, in the same way as birds with simple local behaviors are optimizing the aerodynamics of the flock (which is solving a “constraints optimization problems” by using very simple local rules), the flocking of component can follow dynamically application-driven network optimizations.

The problem is finding these local rules. Not only, but also the optimal way to allocate and dynamically migrate Virtual Machines and to access/store data (which are representing also states). The latter one (access/store data) is very impactful on performances: let’s make an example. Imagine, just for didactical reasons, to consider the equivalence between the time of one CPU cycle and the time of a step in a walk. The latency in accessing a SSD (Solid State Drive, e.g., DRAMs) can be estimated as around tenths of CPU cycle, tenths of steps in our example. But if you wish estimating the latency in accessing the HDD, i.e. the stored data (also including the latency of the network links, RTT), then overall it results the time to make a walk of about 10 000 km.

<sup>9</sup> From the presentation of the paper: A. Manzalini, N. Crespi et alii, “Manifesto of Edge ICT Fabric”, ICIN2013 (Venice, October 2013).

### 2.4.1 Clustering and group communication in Edge Fabrics (Clouds)

Clustering and group communication will be two of the most important requirements for the Edge Fabric (Cloud)

The evolution of these requirements in enterprise systems exemplifies the challenges posed by these developments. Group communication is essentially concerned with who is in the group (membership) and reliable communication between group members (for a good survey see [19] ). As systems grew in size, protocols evolved from master-slave replication, to synchronous replication in cohorts, and then to protocols that allow asynchronous progress, such as Virtual Synchrony [20] , [21] .

Those group communication protocols employed strong consistency semantics, which limited their scalability. As systems grew in size even further, peer-to-peer techniques and gossip protocols were introduced, relaxing consistency semantics, yet increasing the scale by an order of magnitude [22] [23] [24] , [25] .

In an effort to increase scalability even further, and reach Internet scale deployments, peer-to-peer overlays were stacked hierarchically [26] , allowing Census [27] for example, to support membership of 10000 nodes. The advent of cloud computing and the increase in size and complexity it represents brought P2P techniques to the doorstep of almost every large scale enterprise system [28] , [29] .

Chubby [30] and ZooKeeper [31] represent another approach for managing large distributed systems. Here a distributed hub is deployed, and all other group participants connect to it and coordinate their actions through it. Chubby and ZooKeeper were designed for coordinating data-center based distributed systems and provide strong consistency guarantees. ZooKeeper builds upon a restricted variant of Paxos [32] , [33] but has the crucial drawback of using a static member set. FRAPPE [34] improves upon that drawback by implementing a high performance version of reconfigurable Paxos.

One of the fundamental communication services that needs to be offered for efficient group communication is multicast – the ability to send a message from one member to a subgroup.

A popular abstraction for that service is publish-subscribe (pub/sub) messaging [35] Pub/sub systems may be centralized or distributed; for scalable setups, generally distributed versions are employed [36] . Distributed pub/sub is generally based on overlay networks [37] [38] [39] [40] [41] and has gained traction in major enterprise systems [42] , and even HPC environments [43] .

### 2.4.2 A Global Workspace for an Edge Fabric

If we look at Nature, there is a complex and dynamic network which is considered the most effective structural basis for coexistence of informational processing (both segregation and integration) and communications: it is the network of neurons in the brain. Several analogies between brain and pervasive dynamic networks are stimulating the idea of taking inspiration from Neuroscience advances for designing future communication networks.

In this direction, we propose that the understanding of human brain will provide valuable elements for building future networks and proposes a long-term approach for management and control Edge Fabrics.

Understanding brain functioning is one of the grand challenges of Science: interest is clearly motivated by the fact that some general principles of brain functioning seem governing also many other networks, including social, biological and communications networks. Activity dynamics in brain neuronal networks basically depends on patterns of synaptic connections (excitation and inhibition) between neurons. There has been a great deal of research showing that, for humans, emotions are key elements for achieving a neuronal connectivity capable of supporting “rational” behaviour (meant as the behaviour that avoids non-pleasurable states and/or pursues pleasurable states).

Global Workspace Theory and Pandemonium represents an interesting set of brain modelling approaches that could be seriously considered for designing principles for the Edge Fabrics (Clouds).

There is considerable empirical evidence from fMRI (functional Magnetic Resonance Imaging) that individual human consciousness involves a single global workspace. Global Workspace Theory (GWT) [44] argues that human cognition is implemented by a multitude of relatively simple, special purpose processes (processors). Interactions between them are based on cooperation-competition, thus allowing, at the end, coalitions of processes find their way into a global workspace.

Workspace acts to broadcast messages of certain coalitions to all processors, in order to recruit others to join. All this takes place in a certain contexts which is itself a coalition of processes. In other words, brain can be viewed as a collection of distributed specialized processing networks. The global workspace serves to integrate many competing and cooperating input networks of processors: similar principles could inspire the design of bottom-up approaches for the self-organization capabilities of Edge Fabrics (Clouds).

Pandemonium Theory [45] is a connectionist architecture originally used for pattern recognition. Multiple independent processes called demons work simultaneously recognizing specific conditions (or a set of them). Demons have links that allows them to “call” other demons. J. Jackson [46] extended the original Pandemonium theory by creating the stadium metaphor, organizing demons in two different locations, the equivalent of stands and arena of a stadium. A system consists of a crowd of usually dormant demons located at the stands, from where a few demons could go down to the arena and start exciting the crowd. Some demons in the crowd get more excited and start to yell louder. If a demon yells loudly enough, it gets to go down to the playing field and become active.

Whenever a demon enters the playing field, the arena creates associations (if they do not already exist) between the incoming demon and any demons already on the field. These connections between demons are created or strengthened according to the time they are together on the arena, following a Hebbian learning scheme.

Arena can perform the actual input and output functions of our network. It can also calculate a “gain”, i.e., a variable to measure how well the network is performing. Gain is up (goals achieved) if things are going well, down when doing poorly. The higher the gain, the more links are a strengthened by time together on the field. Gain determines how to strengthen or weaken associations between components and network steers towards goals.

It is easy to observe that processes of the Global Workspace Theory correspond to demons of the Pandemonium theory and that the arena looks like the global workspace.

#### 2.4.2.1 Example

Let’s consider first abstracting all management entities, functions, rules, methods and associating them to lightweight components (or an aggregation of components) in charge of representing them (and eventually executing or triggering the execution), if certain preconditions are met. Then, let’s imagine a cooperation-competitive workspace populated with a myriad of all said abstractions behaving for example according to the Global Workspace or Pandemonium Theories.

Emergent network representation will be driven by a myriad of micro-behaviours rather than in traditional systems, where knowledge representation is driving the behaviour. Global workspace performs the actual input and output functions of our network logic. A network efficiency or gain indicator will up (minimizing costs whilst meeting goals) when things are going well, down when doing poorly. The higher is the indicator, the more components aggregations and links are a strengthened by time together.

In other words, management logic permits to rehearse network behaviours prior enacting them; said behaviours are evaluated, and the relative salience of a set of concurrently executable actions is modulated as a result. Network behaviours whose outcome is associated to a gain (or reward) become more and more salient and, at the end, selected and executed (e.g. with winner-take-all-strategy). Figure 8 shows an embodiment of this management architecture.

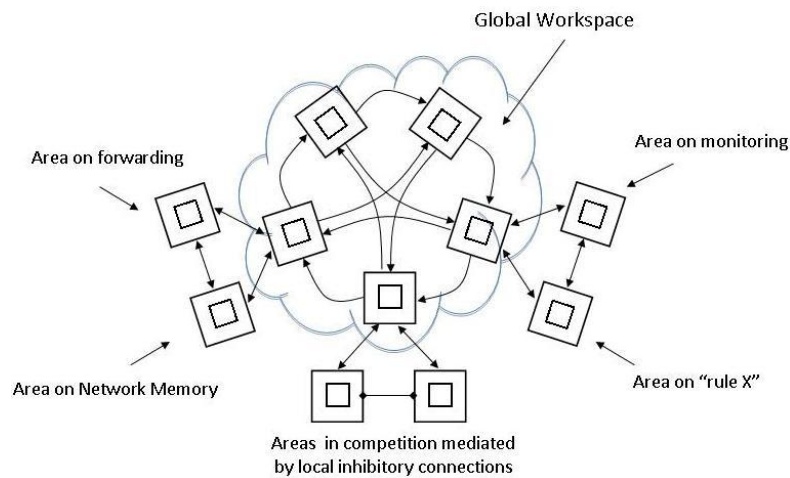


Figure 9 - Example of an embodiment of the management network

In an experimental assessment, this Global Workspace has been implemented by means of minimal middleware substrate deployed on top of the physical resources [47]. Middleware substrate supports the execution of individual local components which act, for example, as sensors (e.g. providing monitoring data) and effectors (e.g. actuating the selected configuration actions). Local components interact with other remote components running on a processing infrastructure like a Cloud Computing, where the Global Workspace can be implemented. In figure 8 shows an example of embodiment of the architecture. Each box in the diagram (like a brain cortical area) represents a sub-network of remote components (implementing Finite Automata) grouped into hierarchies; excitatory and inhibitory interactions between components have been introduced. Also boxes might be in competitive relationships, mediated by local inhibitory connections. Cortical areas can include also various rules and methods: they can be dynamically plugged-in depending on the scenario, assuring a good separation of concerns. As mentioned in [47] one important requirement is the absence of a common unifying component model going in the direction of middleware-deconstruction for management platforms.

Eventually, it should be noted that the network logic and the final actuation of said management operations are separated. The former runs into the space where all the myriads of the described micro-behaviors will take place (for example in a Cloud, independently if this will be deployed with a centralized or distributed or mixed approach); the latter is effected directly into physical nodes (which become very simple and low cost without any embedded logic into protocols).

### 2.4.3 Open Mobile Edge Cloud (OMEC)

OMEC vision [48] could be considered as an extension of the Edge Fabric towards integrating fixed and mobile functionalities in future 5G infrastructures.

A lot of efforts are addressing the evolution of RAN, also through its integration with the fixed access, and the Edge, Core networks.

One of the promising RAN architectures is the so-called CRAN which is providing a cloud computing based architecture for the RAN where most of the radio network functionalities are moved in Data Centre. CRAN architectures have been in trials in various countries and research labs for the past few years to determine the major benefits, challenges and solutions to those. Major challenges are fronthaul interface requirements (e.g., delay, jitter, cost, technology) and the ability of centralized BBUs to provide adequate signal processing in performance targets. These basically determine the spectral and energy efficiencies targeted.

One promising architectural direction is to decouple user and control planes which is in line with the SDN paradigm. This also allows a major rethinking of the mobility edge (and subsequently the converged wireline/wireless edge). This is essentially requiring a deconstruction, virtualization and following aggregation of basic functions of RAN and Core networks.

For example, a new type of functional node, called Open Mobile Edge Cloud, could be deployed to provide seamless coverage and execute various control plane functions as well as



some of the Core “functions” currently placed in various nodes of EPC. Moreover, other IT functionalities will enable truly cloud capabilities in User proximities. Since many location based applications are on the rise, social, analytics, video etc. fronthaul load will be considerably higher in the future and requirements on local storage, compute and networking processing of “edge” services almost forces a new architectural desing.

As a matter of fact, ETSI MEC<sup>10</sup> and “Fog computing<sup>11</sup>” are moving in this direction, leveraging on the substantial amount of processing, storage, communication resources being placed at the “edge” of a network. This idea is based on the premise to certain extensions of cloud computing architectures to the Edge and Fog Computing.

Next figure is showing the functional decomposition of UE, RAN and core functions for a 5G architecture.

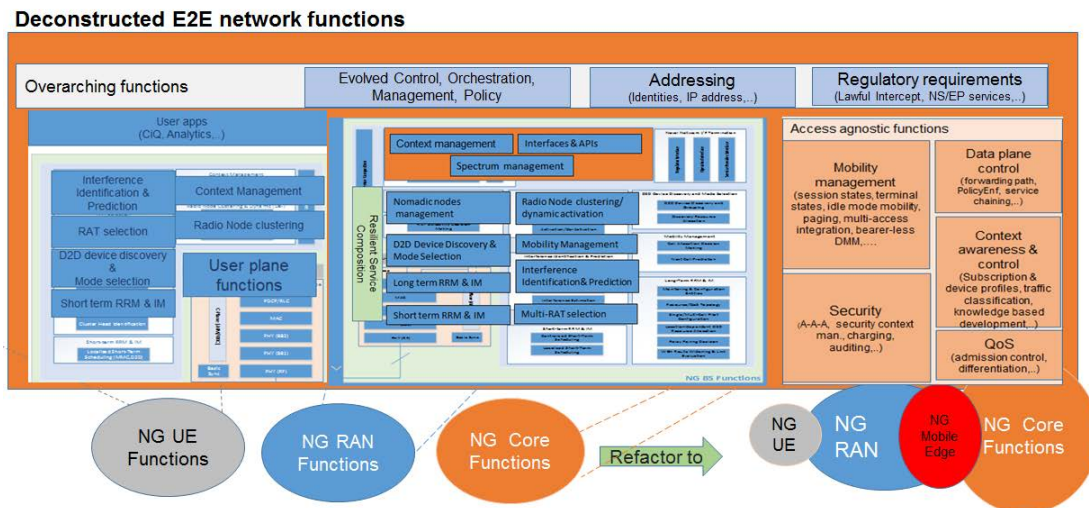


Figure 10 -The functional decomposition of UE, RAN, core and end-to-end functions [48]

The deconstruction of functions is a prelude to reconstruction and optimal placement and orchestration of virtual functionalities, to refactored nodes to better address requirements.

In the IEEE SDN workshop that took place in November 2015<sup>12</sup>, the Open Mobile Edge Cloud (OMEC) was defined as:

*An open cloud platform that uses some end-user clients and located at the “mobile edge” to carry out a substantial amount of storage (rather than stored primarily in cloud data centers) and computation (including edge analytics, rather than relying on cloud data centers) in real time, communication (rather than routed over backbone networks), and control, policy and management (rather than controlled primarily by network gateways such as those in the LTE core).*

<sup>10</sup> ETSI/MEC: <http://www.etsi.org/technologies-clusters/technologies/mobile-edge-computing>

<sup>11</sup> <http://www.openfogconsortium.org/>

<sup>12</sup> IEEE SDN: <http://sdn.ieee.org/>

One distinguishing characteristic is the ability to address varying degrees of requirements (in delay, throughput, types and quantities of devices, etc.) concurrently with a unified framework. This almost dictates a new functional node that is in close proximity to end users/devices with at most 10 km distance to provide the new control and steering applications brought by new use cases.

Eventually, the concept of Edge Fabric that we proposed in 2013 is perfectly in line with the concept of Open Mobile Edge Cloud, currently being investigated by IEEE SDN.

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# Chapter 3    Softwarization: Vision, Scenario and Use-cases for 5G

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### 3.1 Introduction

In very beginning of Telecommunications, around 1880, the business seemed to be limited to the sale of telephones; it should have been the buyer of the telephone who would need to roll out the needed wires to connect with another telephone. Soon it was realized that the “connectivity fabric” was actually the most important and the most expensive part of telecommunications. Thus, Network Providers undertook the investments and the operational cost of creating and managing such network infrastructure as was needed. The Telecommunication business did not change much from that model for the following 130 years, but it will change radically in the next few coming few years.

With the exploitation of SDN and NFV, Telecommunications infrastructures will be transformed from a fabric of interconnected closed boxes (today’s nodes, e.g., switches, routers, middle-boxes, etc.) into a continuum of logical containers executing millions of intelligent software processes, interacting each other. Smart terminals, autonomous machines, drones and robots will become just like “nervous terminations” embedded into reality.

5G will bring into reality this transformation. Space-time dimensions of Digital Society and Economy will be “morphed” by the 5G faster access and larger bandwidth (increase of 2-3 orders of magnitude) connections, by the pervasive availability of processing and storage capabilities eventually supporting any sort of ultra-low latencies end-to-end applications.

It has been already mentioned that Service Providers and Network Operators have the need of making cost savings, both in terms of CAPEX and OPEX. On the other hand, saving expenditures will not be enough to assure the future sustainability of the Telecommunications and ICT industries: it is key to design 5G to be scalable, flexible and programmable to support any innovative service paradigms emerging in the future.

“Immersive Communications” and “Anything as a Service” are often mentioned of two attractive examples of future service paradigms, which are posing challenging requirements for future Telecommunications infrastructures. In a nutshell, “Immersive Communications” looks beyond the “commoditization” of current communication paradigms (e.g., voice, messaging, etc.), by pursuing new advanced forms of social communications and networking (e.g., through artificially intelligent avatars, cognitive robot-human interactions, etc.).

“Anything as a Service” is about providing (anytime and anywhere) a wider and wider sets of ICT services by means of new terminals, machines, smart things, robots, toys going far beyond our today imagination [7].

Robots, drones, autonomous machines, A.I. interfaces will be the 5G terminals of the future. The development of more and more complex cognitive capabilities through advances terminals (increasingly powerful and sophisticated) attached at the edges of the 5G infrastructure, offer interesting opportunities not only to automate processes and optimize costs, but also to develop new service scenarios (Cognition as-a-Service). This will pose challenging requirements for ensuring ultra-low latencies in closing the interaction “loop”.



Today, the local computing power of a robot is not enough (for reason of consumption, space, dissipation, etc.) to implement strong cognitive characteristics of autonomy: tomorrow, thanks to 5G, it will be possible to make use of solutions of Cloud Robotics, which offer the huge amount of resources, at low cost through Cloud/Edge Computing. In fact, with the 5G, the data collected from the several sensors of robotic systems, thanks to high bandwidth connections with very low latency, will be transmitted where there are adequate computing power and memory resources (with a proper balance centralization - distribution); this data will be then transformed quickly in cognitive "decisions", transferred back locally and actuated by the robot within a few milliseconds (ms). It will be possible, for example, to perform highly accurate operations at a distance, to optimize real-time control of any transportation system, manage business processes in a highly dynamic and flexible.

In summary, it is argued that 5G will allow: 1) sensing and collecting massive data (by any sensor, terminal, smart thing and intelligent machine); 2) exchanging/accessing quickly sets of data (via optical and mobile networks with ultra-low low latency); 3) using A.I. methods, algorithms, heuristics for elaborating big data (with Cloud/Edge and Fog Computing resources) in order to infer decisions used eventually actuating local actions (by any actuator).

Smart future terminals, autonomous machines, robots and drones will perform "cognitive loops" (with sensors, processing, communications, actuators) embedded into reality. This will have huge impacts in industry, in agricultural automation and in optimizing almost any socio-economic process of our Society.

Importantly there is a need of understanding how the three variables Technology, Biz Sustainability and Regulation will be deeply intertwined in such future Digital Society and Economy.

### 3.2 5G Scenario and Use cases

The 5G Infrastructure Public Private Partnership, in short 5G PPP [7], has been initiated by the EU Commission and industry manufacturers, telecommunications operators, service providers, SMEs and researchers. The 5G PPP has the main scope of delivering solutions, architectures, technologies and standards for the ubiquitous next generation communication infrastructures of the coming decade.

The 5GPPP has delivered a number of White Papers [8] – [13] describing some key vertical use cases for 5G. These use cases are:

- eHealth
- Factories-of-the-Future
- Energy Vertical Sector
- Automotive
- Specialized Services
- Media & Entertainment



Figure 1 - 5G scenarios and use cases (Picture credits: 5GPPP)

### 3.2.1 Intelligent Cities and *Connectography*

Statistics are showing that about 30% of the world's economy are concentrated in just 100 cities. By 2030, more than two thirds of the world's population will live in cities. A strategic question is: can technology progresses in Telecommunications and ICT help managing population expansion, optimizing resources utilization, while nurturing cities' role as an socio-economic driver ?

Interestingly, in a TED [14] it is argued that we are crossing a "*global connectivity revolution*", that in all of its forms -- transportation, energy and communications -- has enabled "*a quantum leap in the mobility of people, of goods, of resources, of knowledge, such that we can no longer even think of geography as distinct from it*". This is called "*Connectography*."

*Connectography is an evolution of the world from political geography, which is how we legally divide the world, to functional geography, which is how we actually use the world, from nations and borders, to infrastructure and supply chains.*

As a matter of fact, there are a number of projects concerning a pervasive exploitation of ICT for the developments "smart cities". In general, most of these projects are combining the use of sensors, actuators and Telecommunications-ICT capabilities in order to deploy a sort of "distributed intelligence" capable of automating and optimizing public and private processes.

As previously mentioned 5G will embed cognitive loops into the reality, to automate and optimize any process. In the context of intelligent cities, this cognition is coordinating and managing communications and interoperations of different active elements deployed on the city, also including people into the loop.

### 3.2.2 Robotics in Industry, Agriculture and Households

Already today we are witnessing a growing interests in using drones, robots and autonomous machines in industry, agriculture, mining, security and other domains. In agriculture, for example, autonomous machines can be used for tasks like crop inspection, targeted use of water and pesticides, actions and monitoring to assist farmers, as well as in data gathering, exchanged and processing for optimizing the production and distribution processes. Cloud Robotics and Industry 4.0 paradigms are full of other potential use-cases. In general, these are ideal contexts where an OS can control and operate in real time autonomous machines (as they were nodes) for a number of different applications. Interestingly, APIs can be opened to end-Users and Third Parties to develop new types of services.

Besides agriculture and industry, it is likely that we'll see robotic applications also in the domestic environment: It is estimated that by 2050-2060 the European demographics will be represented for about one third by people over 65. The cost of the combined pension and health care system will top about 29% of the European GDP. Remotely controlled and operated robots will enable remote medicine and open up a new world of domestic applications

which may be taken uniformly by the entire population (e.g. cleaning, cooking, playing, communicating, etc.).

### 3.2.3 Automotive and Self-Driving Vehicles

The automotive sector is expected to pose very challenging requirements for 5G, with several use cases based on vehicle-to-vehicle communications, vehicle-to-cloud/edge. Other use cases may concern services based on augmented reality dashboards installed in the vehicles: for example, displays overlaying information on top of what a driver is seeing through the front window, identifying objects in the dark, or in the fog by showing the distances and movements of the objects.

Many car manufacturers are already adding driver assistance systems based on 3D imaging and built-in sensors and first prototypes of self-driving vehicles are being tested. The technical requirements for self-driving cars call for ultra-low latencies and ultra-high reliability.

At the end of the day, a self-driving Vehicle is a sort of complex robotic system equipped with sensors, actuators and ICT capabilities. Driving a car in real traffic is a very challenging task for machine intelligence: unit of milliseconds of reaction time are required (for example to avoid sudden and unpredictable obstacles), and maybe a sort of “common sense” is also necessary. This means a lot of computing power (minimizing the application latencies) and very low network latencies.

Today, the local computing power that can be embedded in a vehicles is not enough (for several reasons, e.g., space, dissipation, costs etc.) for executing machine learning, heuristics or A.I. methods required for exploiting such levels of autonomy; on the other hand, the availability of enormous computing and storage power in the Cloud, is encouraging to consider the execution the “cognition” of the vehicle in the Cloud, or at the Edge.

### 3.2.4 5G enabling Pervasive Machine Intelligence

The physical direct presence of humans will be less and less required to perform certain production jobs or professional, educational tasks. “Machine intelligence”, controlled by 5G, will allow, for example, improving industrial and agricultural efficiency, developing new models of decentralized micro-manufacturing (e.g. also through 3D printers), improving efficiency in public processes, energy consumption, supporting better citizens' lives (e.g. with machines and robots).

Today, robots with full mobility are still a challenge, as most of them are static or connected with cables, limiting the flexibility; 5G will not only enable monitoring and control of truly mobile robots, but also the development and provision of “cognition services” or “Cognition-as-a-Service”. Robot sensors could collect data from the environments, which will be transferred through 5G infrastructure to the cloud where a variety of methods and techniques will execute the intelligence of the robot remotely. The availability of APIs will allow users and third parties to develop, program and provide any related services with robots. So, the next generation of 5G-enabled robots will work alongside humans also in Smart Cities, collaborating with them in far more articulated ways in the daily life.

In general, this “Second Machine Age” [15] will bring a number of consequences: reduction of human manual efforts in jobs (subject to computerization, robotization); increase of local production; reduction of long distance transportation; optimization in electrical power production and consumption; and industries will not need migrating, as today, where humans labor costs are lower [16].

In the short-term basis, this transformation will create a ripple on the current socio-economic ecosystems. On a long-term basis, the increased automation will provide better quality and cheaper goods and services for consumers and higher opportunities for specialized workers. According to the [International Federation for Robotics \(2016\)](#), robots “will be a major driver for global job creation over the next five years,” while a study conducted by Metra Martech credited the one million industrial robots currently in operation with being directly responsible for the creation of close to three million jobs.

On the other hand, this evolution will require developing different business models, and different kinds of jobs, workers and skills should be created. As mentioned in this report [17] “...as technology races ahead, low-skill workers will have to reallocate to tasks not-susceptible to “Computerization” – i.e., tasks requiring “creative and social intelligence”.

Finally, because of this evolution, several economists, as well as technologists, have started to wonder if the usual representation of relationships among a myriad of players in a certain industrial area can still be modelled on the bases of value chains. There is a growing consensus that value chains modelling shall be complemented by a broader view considering business ecosystems.

### 3.3 Some key requirements for 5G

The scenarios and use-cases described in the previous sections are shaping the 5G infrastructures requirements. The 5G PPP, for examples, addresses these key challenges and requirements for the 5G Infrastructure:

- Providing 1000 times higher wireless area capacity and more varied service capabilities compared to 2010
- Saving up to 90% of energy per service provided. The main focus will be in mobile communication networks where the dominating energy consumption comes from the radio access network
- Reducing the average service creation time cycle from 90 hours to 90 minutes
- Creating a secure, reliable and dependable Internet with a “zero perceived” downtime for services provision
- Facilitating very dense deployments of wireless communication links to connect over 7 trillion wireless devices serving over 7 billion people
- Ensuring for everyone and everywhere the access to a wider panel of services and applications at lower cost

Already today people have wearable devices, phones, tablets, laptops: the number of smart devices with embedded communications, processing and networking will radically increase in the coming years, also due to the fact that new type of terminals will appear. In the next

20 years it is likely that the carried data traffic will increase three to four order of magnitude. This will request that 5G be designed in a way that enables deployment in new frequency bands.

5G will need to be flexible to handle efficiently very simple devices sending small, rare bursts of data, but more advanced future terminals that send large amounts of data quickly.

Peak data rates of a 5G system will be higher than 10 Gbit/s but more importantly the edge data rate (for the majority of Users) should be at least 100 Mbit/s: this will allow the use of the mobile Internet as a reliable replacement fixed connectivity where and when it is needed. Using higher frequency bands, large transmission bandwidth combined with low transmit power automatically limits the coverage, so what will be strategically important for the new radio access design are the total costs of the ultra-dense deployment.

Another requirement will be the “Zero latency”, which does not mean no end-to-end latency at all: it requests that the overall latencies (including both network delays, IT response time and application latency) will be low enough (around units of milliseconds) to meet the QoS requirements of the most challenging use cases. In fact, 5G will not be used only for humans mobile communications. As mentioned several use-cases are envisaged based on machine type communications, sometimes referred to as the ‘Internet of Things’ but also including advanced robotics.

If in the past human voice communications were setting up delays in the order of several tenths of milliseconds, already for multimedia applications, these requirements were lowered to less than 10 milliseconds. Future “tactile internet”, leveraging on an increasing use of touch interfaces, will reduce the latency requirements as low as a few units of millisecond.

In summary, the highly demanding requirements of 5G require an outstanding research and innovation effort to reach orders of magnitude of improvement over the current technology and infrastructure. 5G targets are currently discussed worldwide in several Fora, SDOs (e.g. ITU-R, 3GPP, NGMN...).

Several other additional requirements are also common to all the Vertical sectors imagined today. Among these requirements there are:

- Faster Service Deployment Time: duration required for setting up an end-to-end 5G service with the respective QoS level guarantees (such as bandwidth guarantees, overall latency, ...);
- High Data Volume: Quantity of information transferred (downlink and uplink) per time interval over a dedicated area (e.g., Tb/s/km<sup>2</sup>);
- Automation of operations processes (as current OSS/BSS cannot easily scale);
- Security: System characteristic ensuring globally the protection of resources and encompassing several dimensions such as authentication, data confidentiality, data integrity, access control.

A key strategic requirement for 5G will be its business sustainability. In fact, it will that not be a matter of identifying the best technologies and solutions for 5G, but on the other hand having solutions “good enough” for a sustainable 5G ecosystems.

“Softwarization” (and Hardware commoditization) has to be combined with the “algorithmic revolution” in order to create the conditions for the development sustainable ecosystems.

As mentioned, 5G will be able to chain network functions and services, to execute and orchestrated them on virtual resources, from the Cloud to the Fog. This will enable verticals application platforms of platforms (e.g., providing services for IoT, Robotics, Industry4.0, Tactile Internet, etc.).

It should be notes that, deep inside in 5G there will be a “fabric of algorithms”, so the core of this transformation will be mathematics. In fact, mathematics will be language, computation will be about executing said language (coded in software), storage will be about saving the related exchanged information and, eventually and networking will be about creating relationships between, combining – at almost zero latency - said sets of functions and services.

Interestingly this paper 15addressed the historical evolution of mathematical thinking and its spatial spreading. They have identified two important transitions in the 20th century. A first occurred between 1930 and 1940, when the disciplines of statistics and probability merged and began to attract other applied fields, such as information theory, game theory, and statistical mechanics. The result was the emergence of the field of applied mathematics. The second transition occurred between 1970 and 1980, when computer science and statistics merged to form one community.

It appears that mathematical evolution is not made of smooth transitions, but instead, it is a maelstrom, characterized by tipping points, just like “phase transitions” in complex systems.

Eventually I argue that current technology drivers (e.g., what’s behind Softwarization) are steering Computer Science, Telecommunications-ICT, Artificial Intelligence and Applied Mathematics to merge into a new Community.

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# Chapter 4 5G Operating System

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## 4.1 Introduction

Chapter 3 presented some scenarios and use cases from which some high level functional requirements have been derived.

In summary, several Bodies and industry initiatives identify a set of requirements for 5G such as:

- 1-10Gbps connections to end points in the field (i.e. not theoretical maximum)
- 1 millisecond end-to-end round trip delay (latency)
- 1000x bandwidth per unit area
- 10-100x number of connected devices
- (Perception of) 99.999% availability
- (Perception of) 100% coverage
- 90% reduction in network energy usage
- Up to ten year battery life for low power, machine-type devices

This Chapter first addresses some non-functional requirements for 5G and then aims at deriving the high level functional architecture of the 5GOS.

## 4.2 5G Non Functional Requirements

There is no a clear distinction between functional and non-functional requirements. In general, *“functional requirements define what a system is supposed to do and non-functional requirements define how a system is supposed to be. Functional requirements are usually in the form of “system shall do <requirement>”, an individual action of part of the system, perhaps explicitly in the sense of a mathematical function, a black box description input, output, process and control functional model. In contrast, non-functional requirements are in the form of “system shall be <requirement>”, an overall property of the system as a whole or of a particular aspect and not a specific function<sup>13</sup>.*

This section will report some key non-functional requirements for 5G.

### 4.2.1 5G shall be “secure”

Softwarization of Telecommunications will increase even more than today the attention towards cyber security.

It has been already mentioned that 5G will require security solutions “by design”. Advances A.I. applications and the exploitation of approaches like “blockchain” might provide very effective solutions. At the same time it is necessary also to define appropriate control authorities and responsibilities.

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<sup>13</sup> [https://en.wikipedia.org/wiki/Non-functional\\_requirement](https://en.wikipedia.org/wiki/Non-functional_requirement)

In a legacy “non-virtualized environment”, the domains of control of various entities are generally fairly clear: network administrators manage the network, systems administrators manage the hardware systems, OS stacks and patching, storage administrators manage the storage, etc. With the Softwarization, the separation between different domains becomes less clear. However, the importance of maintaining appropriate control authorities and responsibilities does not diminish. In fact, it is a key security requirement that trust domains are well defined between, for instance, the various components of a Virtual Network Function (e.g., virtual machines, containers or hardware). .

It is not only Virtual Network Function which are being virtualized, of course: there is also the softwarization of other management and orchestration (MANO) components. Trust domains need to be considered not only for the MANO components, but also for the infrastructure – physical and virtual – that underpins them. SDN controllers is an example, as compromise of an SDN controller may mean loss of control of significant portions of a Service Provider’s network.

Network slices for should be an expression of operational – and security – policy. This implies at least three challenges:

1. The creation of a resilient policy;
2. The mapping and application of the policy to real hardware and software;
3. The visualisation and enforcement of the policy, typically through visualisation and enforcement tools.

In fact, once any trust domain has been defined, establishing and maintaining it will require use of a variety of monitoring and enforcement tools, including attestation, IDS (Intrusion Detection System) and careful management of software (including vendor-provided image) provenance and integrity.

Definition – and the mapping and enforcement – of these trust domains is not simple, and further complicated by the need for some trust domains which span others. Security monitoring, management and application of policy, for instance, will need to cross multiple trust domains. Added to this complication is the fact that some will span geographical boundaries.

With Open Source software making up a significant part of many deployments, it is important to have a good view of the security of such software. The first point that should be made is that, for many service providers and operators, the provision of Open Source software will not be directly by them, but by a vendor who will undertake to support it. To some extent, then, liability for the security of the software will lie with another party. A firm understanding of the liability and support arrangements behind use of Open Source software are important in any deployment, but where that software has particular security functions, it is even more vital. The openness of Open Source software doesn’t necessarily guarantees its security.

#### 4.2.2 5G shall be “stable”

The risks of instabilities are already experiences in today’s networks (and also cloud computing infrastructures).

Ensuring stability of a strategic asset like a network of ICT resources is of paramount importance for society. In fact, occurrence of instability in a network may have primary effects both jeopardizing dramatically the performance and compromising an optimized use of resources.

The potential instability of an end-to-end path is a cross-layer issue: in fact, it might depend on the unwanted combination of diverse control and optimization mechanisms acting on either the underlying transport network or on the higher layers’ components (e.g. flow admission control, TCP congestion control and dynamic routing).

As an example, it has been widely demonstrated that even with resource over-provisioning; a network without an efficient flow admission control has instability regions that can even lead to congestion collapse in certain configurations. Congestion control mechanisms represent another example. Currently available mechanisms (e.g. TCP Reno and Vegas) are examples of large distributed control loops designed to ensure stable congestion control of resources. On the other hand, these mechanisms are expected to be ill suited, from a stability viewpoint, for future dynamic networks where transients and capacity will potentially be much larger. A further example is the instability risk typical of any dynamically adaptive routing system: this can be (informally) defined as the quick change of network reachability and topology information, has a number of possible origins, including problems with connections, router failures, high levels of congestion, software configuration errors, transient physical and data link problems, and software bugs.

Prior art analysis about network stability issues offers other interesting examples. In [19], for example, starting from a simple model of a traditional network traffic dynamics, it is shown that a phase transition point appears, separating the low-traffic phase (with no congestion) from the congestion phase as the packet creation rate increases. In [20], an enhanced model has exhibited nontrivial scaling properties close to the critical stability point, which reproduce some of the observed real Internet features. In [21] they discuss the possibility of phase transitions and meta-stability in various types of complex communication networks as well as the implication of these phenomena for network performance evaluation and control. Specific cases include connection-oriented networks with dynamic routing, TCP/IP networks under random flow arrivals/departures, and multiservice wireless cellular networks. Wang et al. [22] presents an investigation of the dynamics of traffic over scale-free networks: results have indicated the existence of the bi-stable state in traffic dynamics; specifically, the capacity of the network has been quantified by the phase transition from a free flow state to a congestion state. Interestingly [23] addresses the risk of instabilities in Cloud Computing infrastructures. That study points out some analogies of Cloud Computing infrastructures and complex systems and elaborates on the emergence of instabilities due to the unwanted coupling of several reactive mechanisms.

Telecommunications networks will become more and more ubiquitous and dynamic, hooking together a sheer number of heterogeneous real/virtual resources. So, one of the major challenges will be managing said resources in a cost effective way in order to meet technical and business requirements whilst ensuring stability and performance. Development and exploitation of self-organization capabilities in network management (and even into nodes) appears to be an answer to face such challenges in spite of the ever growing complexity of networks.

Practically, network self-organizing capabilities can be achieved through the exploitations of “constrained optimizations” (CO) solvers (i.e. through protocols, control loops, methods , algorithms...) spread across network layers. On the other hand these CO solvers have to be properly orchestrated to avoid unwanted couplings or interactions, potentially bringing to non-linearity in the network behavior. This is even more true in future SDN/NFV infrastructure.

Let’s assume that Virtual Machine (VM) and Virtual Router (VR) can be moved from one physical node to another (the physical node merely serves as the carrier substrate on which the actual virtual node operates). Actually VR is a logical router that separates its functionality from the physical platform that hosts the entity, including mechanisms for management, configuration, monitoring and maintenance.

In principle, a dynamic provisioning of virtual resources (VMs and VRs) [24] [25] could allow load and traffic engineering in order to improve performance (e.g. limiting hotspots in the IT resources) and to reduce power consumption in the routers network.

In particular, in case of hotspots in the IT resources, operators can change the allocation or migrate VMs to improve performance (e.g. response time). At the same time, as the network traffic volume decreases, operators can migrate VR to a smaller set of physical routers and shutdown or hibernate unneeded physical routers to save power. When the traffic starts to increase, physical routers can be brought up again and virtual routers can be migrated back accordingly).

In summary, in this example we can see the interactions of two main methods, that have to be coordinated to ensure stability and proper levels of performance: the former is in charge of allocating VM across multiple networks for performance optimization; the latter is in charge of migrating VR a smaller set of physical routers for saving power (by shutting down or hibernating unneeded physical routers). It should be noted that although both methods would be stable if operating alone, without a proper coordination, the combination of the two methods might risk a positive feedback loop.

#### 4.2.3 5G shall be “learning” ...

The need of achieving (almost) real time operations in 5G future infrastructure will strongly rely on actionable data in order to automate and optimize the OSS/BSS processes. Big Data should be used for achieve that. It’s not a matter of data quantity, but rather quality, accuracy, persistency...and other characteristics making them “actionable”, which means making

them valid and representative for a particular context or situation and as such adequate input for making a decision. Big Data will have to be crunched by “cognition”, i.e., Machine Learning, A.I., analytics methods, algorithms, heuristics... all those Industrial Mathematics instruments (implemented in software) necessary for inferring decisions (using the enormous IT power now available at low costs). Then these decisions will be used actuating actions which, in turn, are aiming at optimizing processes, for example.

Machine learning algorithms, for example, are used today to process large amounts of data for tasks such as image and speech recognition, pattern identification or optimization. So Machine Learning is obviously not new but, there are the conditions, for a revamped interest for the use of Machine Learning in the operations for future 5G infrastructures. Machine learning can be applied to solve problems about resource allocation problem(s) and management which are outstripping human ability (literally  $10^9$  of interacting dynamic processes in typical hyper-scale Data Centre).

Two of the most widely adopted machine learning methods are supervised learning and unsupervised learning:

- Supervised machine learning: the machine is of correct input-output relations and has to infer a mapping therefrom. Probably the most important task is pattern classification, where vectors of input data have to be assigned to different classes.
- Unsupervised machine learning: machine is given a bunch of data and must find patterns and the relationships therein

There also another category of learning, which is reinforcement learning: given a framework of rules and goals, an agent gets rewarded or punished depending on which strategy it uses in order to win.

#### 4.2.4 5G shall support “X-as-a-Service”

The innovation power of Softwarization will be fully exploited only if service model unification will be reached capable of cutting across either resources (Compute, Network, Storage) or the infrastructure (DC, WAN, Access/Edge, Terminals/Fog) or the service levels (IaaS, PaaS, SaaS).

As a matter of fact, there are the conditions for reaching this unification: in SDN, a controller can be seen as service running on a IT platform, e.g., an operating system as ONOS; in NFV, a network function can be seen as a virtualised service and running on IT resources centralized and/or distributed; and, at the end of the day, there is no difference with respect to a service executed by the Cloud-Edge Computing: a CDN managing a caching can be seen as a controller or a proxy can be seen as a network function.

This is why in virtualised infrastructures makes sense referring to “X-as-a-Service” as a unifying paradigm.

Generally speaking a service is becoming a “unit of orchestration”, running in one or more infrastructure slices. A service which should:

- provide a function (both “global” and “local”)
- export APIs (e.g., REST)
- be available anywhere and anytime (location-time independent)
- be scalable, elastic, and resilient
- run in in one (or more) network slices (a set of VMs connected by one or more VN)
- build new services by composing with existing services (e.g, building blocks (NoSQL DB), user-facing (Facebook), and both (DropBox) )

In the following part of this section a short overview of the different service descriptions is provided, as from ETSI NFV, IETF and OASIS.

In ETSI the Network Service (NS) is a *“composition of Network Functions and it is defined by its functional and behavioural specification”*, being a Network Function (NF) a functional block within a network infrastructure that has well-defined external interfaces and well-defined functional behaviour. Specifically, as reported in [26] *“the Network Service contributes to the behaviour of the higher layer service, which is characterized by at least performance, dependability, and security specifications. The end-to-end network service behaviour is the result of the combination of the individual network function behaviours as well as the behaviours of the network infrastructure composition mechanism”*.

VNFs are associated to deployment templates, called VNFD (Virtual Network Function Descriptors): these template could be used also to describe Network Services that consist of two or more VNF with an optional “forwarding graph” describing the connectivity between them (in this case it is called Network Service Descriptor).

In IETF [27] the term Service Function Chaining (SFC) is used *“to describe the definition and instantiation of an ordered list of instances of such service functions, and the subsequent “steering” of traffic flows through those service functions”*. Middle-boxes are example of service functions. *“The sets of service function chains reflects Network/Service Operator service offerings and is designed in conjunction with application delivery and service and network policy”* .

SFC deployments are coupled to infrastructure topology: for example, a firewall requires that traffic flow through the firewall, which means placing the firewall on the network path (often via creation of VLANs) or architecting the network topology to steer traffic through the firewall. In highly dynamic service scenarios, this is creating a complexity in the entire configuration tasks.

TOSCA (Topology and Orchestration Specification for Cloud Applications) is a standard from OASIS that target interoperable deployment and lifecycle management of cloud services.

In a nutshell, TOSCA uses the concept of service templates to describe cloud workloads as a topology template. The topology template describes the structure of a service as a set of

node templates and relationship templates modelling the relations as a directed graph. Node templates and relationship templates (linking different nodes) in fact specify properties and operations (via interfaces) to manipulate the service components. For example, both node and relationship types may define lifecycle operations to implement the behaviour an orchestration engine can invoke when instantiating a service template. As another example, a node type for some software product might provide a 'create' operation to handle the creation of an instance of a component at runtime, or a 'start' or 'stop' operation to handle a start or stop event triggered by an orchestration engine.

Plans define the process models that are used to create and terminate a service as well as to manage a service during its life time.

TOSCA NFV [28] define the NFV data model using the TOSCA language and aligned with ETSI: the Network Services correspond to Service Templates of TOSCA, and the Nodes Templates are used to describe the remaining elements, including the virtual links.

NFV introduces Network Service Descriptors (NSDs) in order to enable dynamic composition of network services. NSDs specify the network service to be created, and typically include Virtualized Network Function Descriptor, VNF Forwarding Graph Descriptor, Virtual Link Descriptor and Physical Network Function Descriptor.

The mapping between TOSCA and NFV can be seen as:

- NSD can be seen as a service template;
- VNFD, VNFFGD, VLD and PNFD can be seen as node templates with appropriate node types;
- VNFD can be further described by using another service template with substitutable node type.

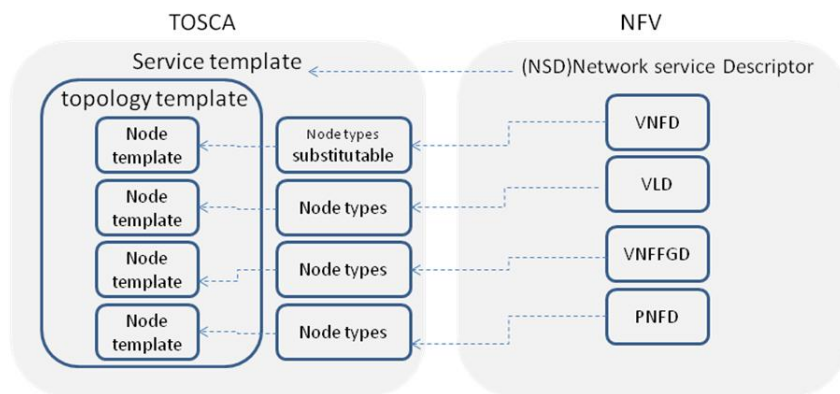


Figure 1 - Mapping relationship between TOSCA and NFV [28]

TOSCA uses XML today but it is moving to the YAML<sup>14</sup>, a expressive and more natural language for describing high level complex services.

<sup>14</sup> <http://yaml.org/spec/current>



#### 4.2.5 5G shall be “autonomic”

Softwarization of Telecommunications will radically increase the level of “flexibility” and “programmability” of an infrastructure. The cost which has to be paid is an increase of “complexity”. This will require introducing automatic and autonomic capabilities in management, control and orchestration.

Autonomic solutions took inspiration from the biological characteristics of the human Autonomic Nervous System: this part of the nervous system, which acts and reacts to stimuli independent of the individual’s conscious input, regulates the behaviour of internal organs (e.g., heart to control blood flow and heartbeat, the stomach and intestines to control digestive movement and secretions). It sends commands to the organ, and, via sensory fibers receive feedbacks on the condition of internal organs, information that helps maintain “homeostasis”. In this way the Autonomic Nervous System implements a control loop, through which it can react, according to “predefined policies”, to the changes of the internal organs and the environmental conditions (e.g., external temperature), by hiding the complexity of the control to the conscious part of the Nervous System.

The prior art is very rich of research and innovation efforts: a few example are mentioned here just to give the flavour of what is meant by autonomic.

IBM [29] , as part of its autonomic computing initiative, derived from the metaphor of the Autonomic Nervous System, a management architecture able to cope with the increasing complexity of IT systems. This architecture is based on the so-called MAPE-K (Monitor Analyze Plan Execute – Knowledge) that is implemented in autonomic managers (in charge of controlling any resources). Essentially sensors, probes, etc, feed information to a Monitor function; the system then proceeds to Analyze the information, form a Plan, and then Execute it. This is then fed back to the effectors which exploit the plan of action. Knowledge is fundamental aspect for the correct functioning of this cycle: it consists of data shared among the MAPE-K functions of an autonomic component, such as symptoms and policies.

A system that implements a MAPE-K cycle is capable of sensing the environment changes and sending commands to adapt the behavior of the environment; in this way it is possible to achieve the self-\* autonomic capabilities (e.g. self-CHOP: configuration, healing, optimization, protection).

In this proposal, there is a separation between the supervisor, which implement the MAPE-K cycle, and the system under supervision. This model can be recursively applied, so as to create a cascade of supervisors/system under supervision, in a hierarchical way.

This original MAPE-K model is not suitable to exploit a fully autonomic behaviour: in fact, components are structured in strict hierarchies; on the other hand, in nature, such manager-managed relationships are much less relevant to those established in a peer-wise way. Moreover, individuals are able to react independently, i.e., “autonomously”, to most of the external events they perceive, and are able to cooperate by activating peer-to-peer relationships among them.

Therefore, this approach requires to overcome the distinction between supervisors/supervised systems, by embedding in each of the system components an autonomic control loop, in charge of monitoring its internal behaviour and adapting it to internal events and to the changes in its external environment. In this way, the components themselves become “self-aware”, by integrating self-CHOP features in their behaviour. In this way, the strict distinction between managed and managing components is removed, as all the components can implement self-management logic, by possibly cooperating through interactions with other components in the system.

The embedding of autonomic control loop in the components also enables grassroots approaches: in this case, the control loops are extremely simple, e.g., based on the monitoring and adjustment of just few local variables, and oriented to handle simple exchange of information with the environment through local interactions: the local interactions of larger numbers of components, embedding much simpler control-loops, enable the emergence of global system properties.

In particular, the control loops can introduce self-awareness, oriented to achieve self-CHOP features internally to each element, and self-organization, oriented to create, maintain and tune cooperation inside ensembles of elements, and to rule the emergence of properties.

Specifically, unpredictable events may cause a system to drift away from the desired, so it is necessary that the system is able to configure its parameters, at run time, to enable the optimal response to any changes. An autonomic system is capable of deciding on the fly which elements to update, remove or aggregate in the new configuration. This requires knowledge about the local and global state and configuration of the single components and of the system as a whole, as well as a model of the external environment.

Eventually, autonomic control loops can introduce local self-awareness and global self-organization properties.

Self-awareness of a single element could be defined as the component awareness of being a single entity of a global autonomic system, at any point in time. This implies that the component knows certain internal/external data, transforming them in knowledge (e.g., with reasoning) and using that knowledge for controlling its behaviour according to plans. The process to maintain the homeostasis is an example of self-awareness.

Self-organization of ensembles of components derives, instead, inspiration from biological processes where pattern at the global level of a system emerges from numerous interactions among the elements in the system: the rules specifying interactions among the components and the reaction to them are executed by using only information local to the components.

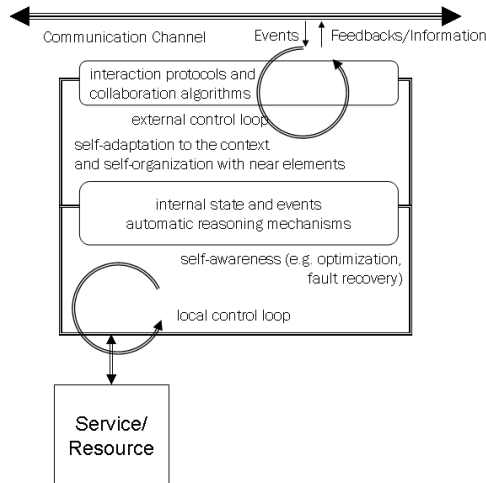


Figure 2 - Self-awareness and self-organization through autonomous control loops.

Self-awareness and self-organization can be achieved by means of two complementary types of control loops implemented by computing elements:

- *Internal/Local Control Loop* to tune the behavior according to the planned and unplanned internal events, e.g., for improving performance of internal functions or for detecting and recovery from internal faults; it introduces self-awareness features in the elements, by encompassing reflection, self-control, planning and reasoning;
- *External/Global Control Loop* to react to environmental changes and adapt the internal behavior and coordinate it with those of other elements according to information exchanged with them; it enables self-organization features for achieving the emergence of global properties/behavior through simple cooperative interactions (inspired to biological, social metaphors), and self-adaptation of the internal behavior to environmental changes.

The concept of self-organising networks is derived by the above principles: the network becomes able to set itself up and then manage the resources to enable the optimum performance to be achieved at all times

Even ETSI has developed a group specification on “Autonomic network engineering for the self-managing Future Internet”. Main objective of [30] has been to define, iteratively, a generic, conceptual architectural reference model intended to serve as guideline for the design of the future generation networks exhibiting autonomic characteristics or capabilities. In particular, document consists of a set of fundamental design principles elaborating on the functions, processes and interfaces of autonomic networks and systems.

### 4.3 5G OS: architectural model

SDN offers the possibility to make use of a logically centralized control plan to manage a domain of packet processing and forwarding nodes in the data plane. In this direction, [31] proposed the adoption of a sort of network operating system with interfaces for programming the network: control and management applications on top of said operating system could perform different tasks using proper interfaces.

Operating system concept has been a useful unifying metaphor but, in spite of that, there is still a fragmented effort in developing SDN controllers and, moreover, most of said controllers are missing features like full ability to run across multiple machines/domains (i.e., a distributed controller). Some example controllers include Onix, ONOS, Floodlight and OpenDayLight. At the same time NFV emerged with its ETSI reference architecture offering the opportunity of combining the two paradigms (SDN and NFV) to amplify the innovation potential of “Softwarization” or paving the way to 5G.

As mentioned in Chapter 1, it is argued that in the same way, as a computer network have Network Operating System (OS) such future 5G infrastructure will have to have a an OS capable of operating the converged fixed-mobile infrastructures (5GOS).

Generally speaking a Network OS is a software platform capable of controlling the various elements of a network and how they communicate with each other. Some of the tasks of a network OS are similar to those of an OS for individual computers, such as memory management and hardware control. A Network OS also has some further specialized tasks, including optimization of used resources, network security and network administration. A Network OS includes sophisticated tools for network management. For example, a network administrator can monitor the performance of various parts of the network and try to address problems before they can have a serious impact. Network management can also be used to update software on the individual computers on the network.

A Network OS should be able to manage multi-platforms, so they can all have to work together seamlessly. One of the critical tasks of network management is security for preventing unauthorized access and misuse of the network and its resources.

The 5GOS will be an extension of the concept of the concept of Network OS for a 5G infrastructure. It should be a system software that controls the various 5G resources and how they communicate with each other. It should be a sort of overarching multi-level orchestration system, spanning from the Cloud, to the Network nodes up to the Users’ Terminals and Equipment. The following picture is showing the high level architecture of the 5GOS instantiated on a 5G infrastructure. The 5G Edge Cloud Operating Systems are local instantiations of the 5G OS in charge of specific edge domains, whilst the 5G Global Operating Systems exploits centralized functionalities in order to provide the overall integration.

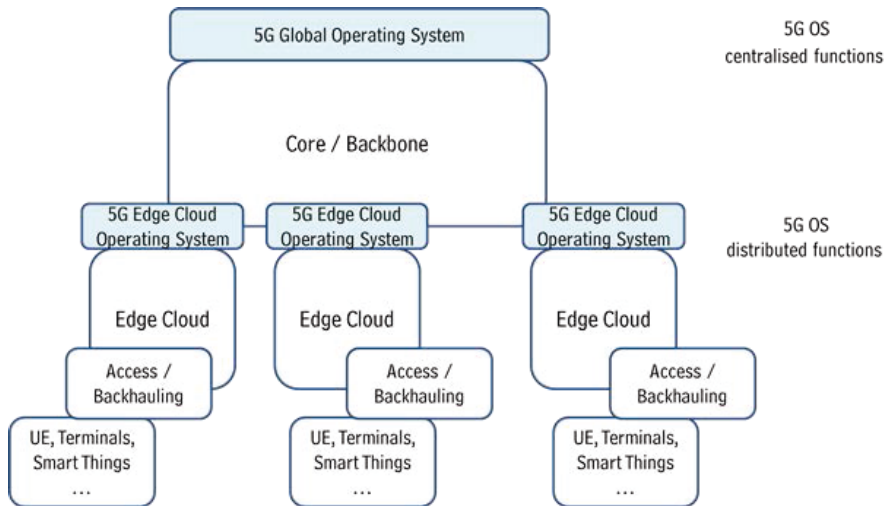


Figure 3 – 5G Edge Cloud OS and the 5G Global OS onto a 5G infrastructure

The following figure is showing the functional layering of a 5G infrastructure, in line with ETSI NFV reference architecture. When comparing 5GOS with the ETSI NFV model, it can be seen as a global “overarching orchestrator”, extending the capabilities of the VNF Manager (from the terminals to the Cloud). At the same time, the Virtual Infrastructure Manager (VIM) plays the role of a 5GOS subsystem (an example is the combination of OpenStack and ONOS).

5GOS facilitates also the functional decoupling with respect to the capabilities of the NFV Orchestrator (NFV-O). Service orchestrators can be executed as “services” on top of the 5GOS, leveraging on the APIs that the 5GOS is offering.

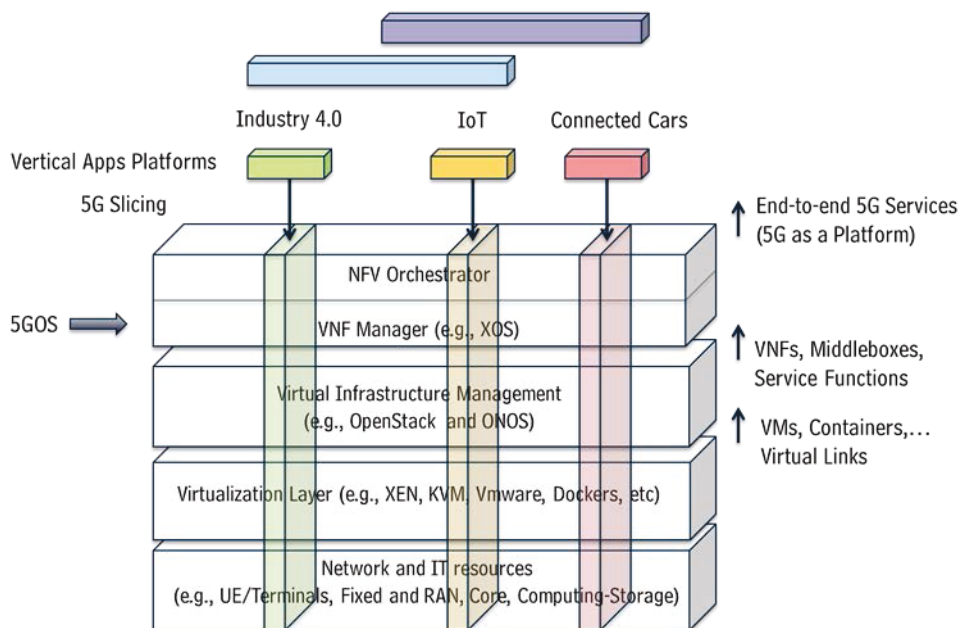


Figure 4 – 5G layered model and 5GOS

The overall functional design of 5GOS will have to define:

- logical resources (e.g., Virtual Machines, Containers) in which programs (services) run;
- communication primitives and mechanisms for services to communicate with each other;
- conventions about how services are named, configured, started/stopped;
- a programming environment: with a view abstraction (e.g., Unix shell);
- an abstraction to incorporate new hardware into the 5G (e.g., drivers).

Eventually 5GOS is distributed software platform (exploitable with the Cloud, Edge and Fog Computing) to ease the development, execution, management-control and orchestration of any 5G end-to-end service executed on the 5G virtualised infrastructure.

Any 5G end-to-end service is a piece of software that implements a network functionality or a service over the 5G virtualized infrastructure. It encompasses any VNFs (Virtualized Network Function) as defined in ETSI NFV, any control applications (a la SDN) and Cloud/Edge/Fog services. As shown in the following picture the service tasks composing an end-to-end service can be executed either in the Cloud Computing, or in the processing power of Network nodes (Edge-Fog Computing) or in the Terminals.

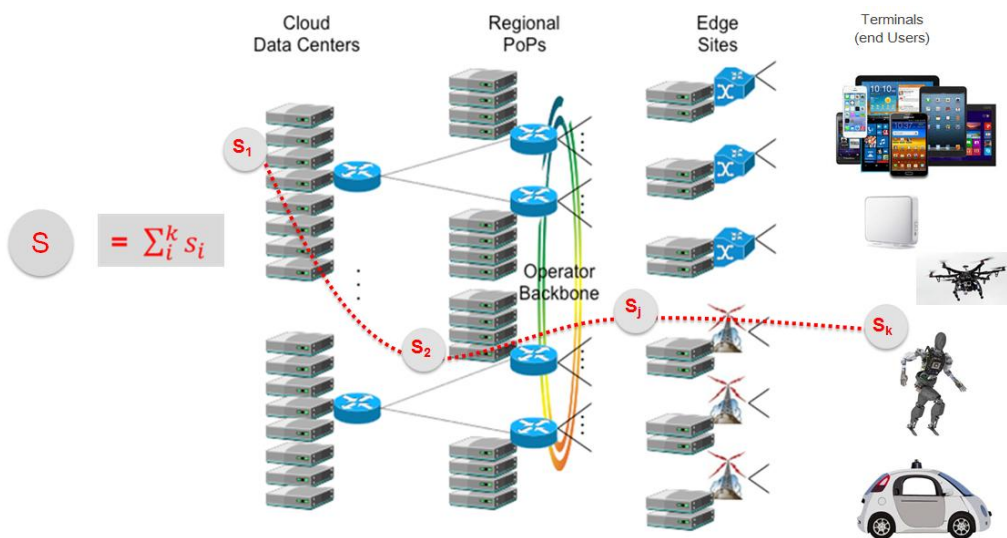


Figure 5 – Distributed execution of 5G end-to-end services

Horizontal and vertical extensions of the 5GOS are related to the business model of the Operator. As previously mentioned, the vertical dimension concerns to what extent the 5GOS will include levels of hierarchy of orchestration capabilities enabling, through API, corresponding to IaaS, PaaS and SaaS. The horizontal dimension concerns how it may be extended up to the UE/terminals.

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# Chapter 5 Systems Design of the Edge Operating System

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### 5.1 Why an Operating System for the Edge Clouds?

It is argued that the first impact of Softwarization will occur at the “edge” of current Telecommunications infrastructure. We define the “edge” as the peripheral part of current infrastructures, ranging from the distribution and access segments up to the direct proximity to Users (e.g., home, office) 32

The exploitation of SDN and NFV will start at the “edge” first, extended up to the User’s Equipment and terminals. In fact, this is making the evolution possible at the micro scale. It cost less, it scales more gracefully, and leads to immediate revenues. Evolution in User’s Equipment and terminal is much faster than in network equipment, for their sheer number (a new cell phone appears on the market every week!) and its virality. This creates a volume and an economic market that will drive investment outside of the network infrastructure boundary and stimulate the advent of new communications paradigms.

The “edges” will be transformed into distributed virtualized fabric, consisting of a number of diverse and autonomous, but interrelated nodes, devices, machines chained/aggregated in an application driven way. The term “fabric” has been used in the past to refer to a distributed computing system consisting of loosely coupled storage, networking and processing functions interconnected by high bandwidth links. It has also been used to describe a flat, simple intra data centers network optimized for horizontal traffic flows, mainly based on a concept of “server-to-server connectivity”. Leveraging on these meanings, the term fabrics is extended, in this thesis, to indicate that the edges of the current networks will become like to distributed Data Centers consisting of loosely coupled processing and storage resources interconnected by pervasive wired and wireless 5G links.

It should be noted that the concept of Edge Cloud is in line with the position paper of GSMA “Operator Required Capabilities in Future Mobile Systems Operator Required 5G Capabilities” (April 2016, Version 0.3) reports the following picture.

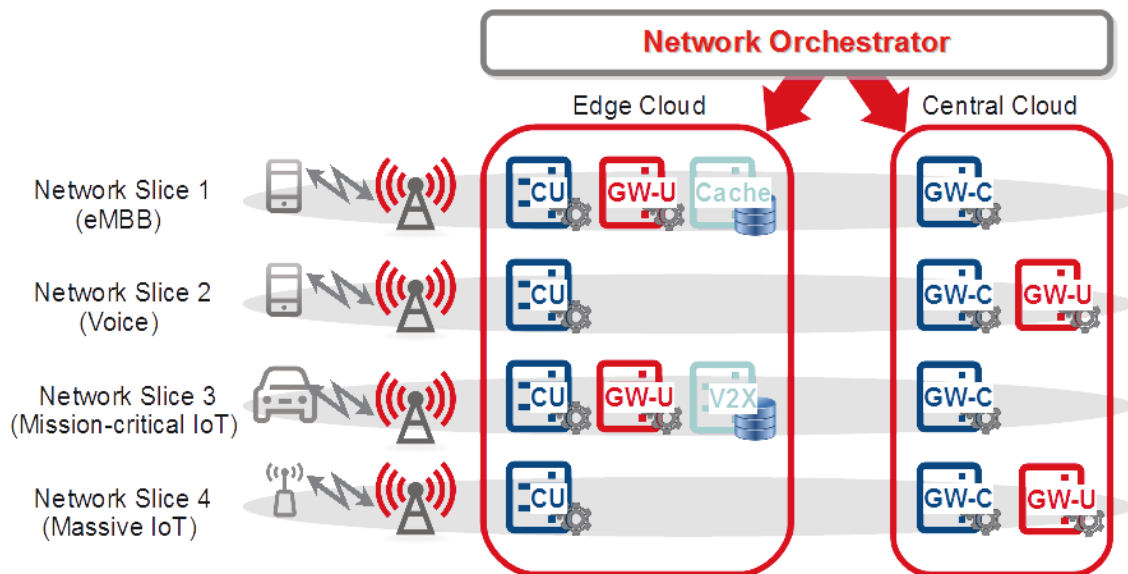


Figure 11 - 5G network orchestration to support various service slices [GSMA White Paper]

If Edge Clouds will become like distributed Data Centres at the edge, then several processes or activities normally carried out in Data Centers, such as allocation, migration and cloning of VMs (e.g. for server consolidation, load balancing, etc.) will be also performed in the aggregation nodes, even up to Users’ devices.

It has been mentioned in Chapter 2 33 The execution of network and service functionalities at the edge may have several advantages: one of them is an increase of performances. In fact, it is recognised that TCP is a serious performance bottleneck for video and other large files (as it requires receiver acknowledgement) and throughput is inversely related to Round Trip Time (RTT) or latency 34 even if it should be recognised that PON and DSL delays are intrinsic in the access protocols. Achieving lower delays means either changing said protocols as well or locating all of the necessary data at the subscriber, including content caches and databases.

In summary, it is very likely that the techno-economic drivers and the emerging technologies will create the conditions for exploiting very powerful network and service platforms at the edges of 5G infrastructures: such peripheral platforms will be able to carry out a substantial amount of storage and real time computation, thereby supporting a wide range of innovative communications and ICT services.

## 5.2 Main functional characteristics of the 5G Edge Cloud Operating System

5GOS will be an extension of the concept of the concept of Network OS for a 5G infrastructure. It should be a system software that controls the various 5G resources and how they communicate with each other. It should be a sort of overarching multi-level orchestration system, spanning from the Cloud, to the Network nodes up to the Users' Terminals and Equipment.

5GOS is structured into two main functional blocks:

- the local 5G Edge Cloud Operating Systems (5G Edge Cloud OS) which are local instantiations of the 5G OS in charge of specific edge domains;
- the centralized 5G Global Operating Systems (5G OS) which is responsible for centralized functionalities in order to provide the overall integration.

5G Edge Cloud OS plays the same overall role of the VNF Manager (defined in ETSI NFV [35]) for an Edge Cloud: a VNF Manager is in charge of the VNF lifecycle management, in terms of instantiation, update, query, scaling and termination and an overall coordination and adaptation role for configuration and related events . As multiple VNF manager could be deployed, in the same way, multiple 5G Edge Cloud OS may be deployed.

Still according ETSI NFV, underneath the VNF Manager (as shown in figure 2) there is the Virtualised Infrastructure Manager (VIM), which is in charge of controlling and managing the compute, storage and network resources. Today, a VIM could be implemented by combining open source software products such as, OpenStack and ONOS : the former for managing the Virtual Machines and the latter for controlling the network fabric.

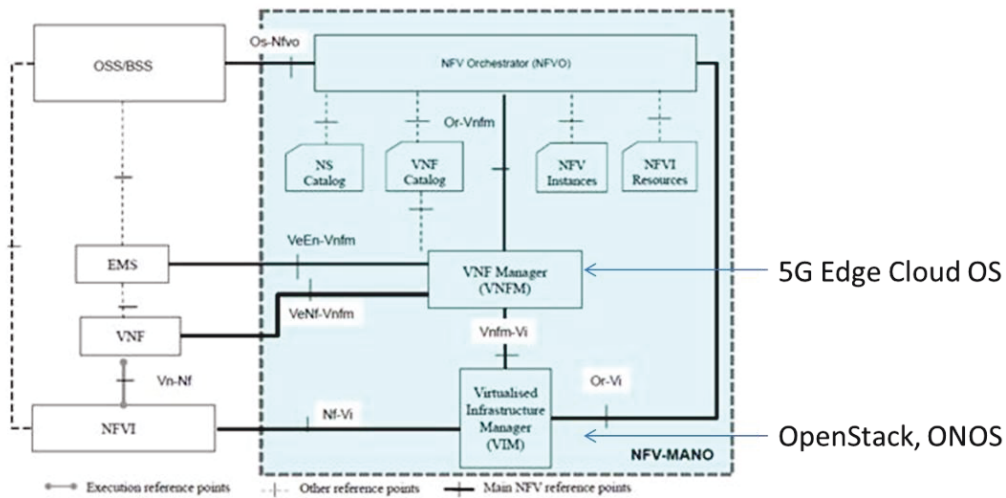


Figure 12– Analogies between the roles of the 5G Edge Cloud and the VNF Manager of the ETSI NFV MANO Architecture [35]

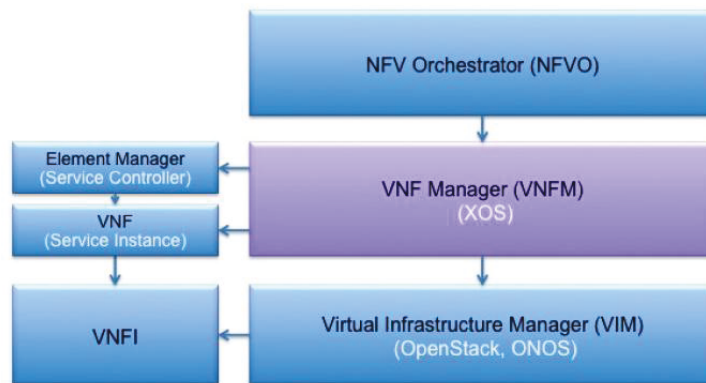


Figure 13 – Analogies between the VNF Manager of the ETSI NFV MANO Architecture and the X-OS of CORD (source ONLab)

Figure 4 provide a simplified view of the analogies of functional roles of the ETSI NFV and CORD architectures: again the Virtual Infrastructure Manager (VIM) corresponds to OpenStack and ONOS, whilst the VNF Manager correspond to X-OS which is a sort of service orchestration layer that runs on top of OpenStack and ONOS.

Interestingly X-OS adopts much the same design philosophy as Unix: everything is a file in Unix and Everything is a Service (XaaS) in X-OS. Four are the main abstractions:

- Resource Containers: X-OS provides a Slice abstraction (Unix process) in which Services (apps) can run, with low level mechanisms managing a service in a slice.
- Application Programs: X-OS defines a Service abstraction (application programs), along with a Tenancy abstraction that provides a means by which Services can be composed to create new functionality (Unix pipes).
- Programming Environment: X-OS provides a View abstraction (Unix shell), a RESTful API (kernel interface), and a convenient userlevel library which can be used to extend XOS with new capabilities.
- Importing Resources: X-OS defines a Controller abstraction that can be used to import new resources into XOS (device drivers).

From a purely architectural view point, 5GECOS looks similar to XOS of CORD project. On the other hand, there major differences which should be highlighted.

XOS is a service orchestration layer to manage scalable services running in a Central Office. On the other hand, 5GECOS is a highly pervasive software architecture, i.e., it is extended up to the terminals (current and future ones), smart things and elements of capillary networks (e.g., aggregations of sensors, actuators, etc).

XOS unifies management of a collection of services that are traditionally characterized as being NFV, SDN, or Cloud specific. 5GECOS addresses also services that can be executed also at the edge (leveraging also Edge and Fog Computing). This difference dictates profound implications: 5GECOS is implemented with a scalable software architecture leveraging on a trade-off between top-down and bottom-up intelligence.

Eventually we can argue that 5G Edge Cloud OS provides an alternative perspective of X-OS in implementing a VNF Manager for the Edge Clouds, and as such reaching the terminals.

### 5.3 Definition and design assumptions

Let's start by generalizing the concept of physical Infrastructure Element (IE) as reported in figure 4.

An IE is defined as a physical entity – providing and consuming services - which may include a dynamic combination of sensors, actuators, processing-storage resources and data forwarding capabilities. The term dynamic combination indicates that an IE may include all or part of said capabilities. It could be just a sensor, or an actuator, or the data plane of a router-switch capable of data forwarding capabilities. On the other hand, an IE could be also a robot or a drone and as such it could include sensors, actuator, processing and communication capabilities.

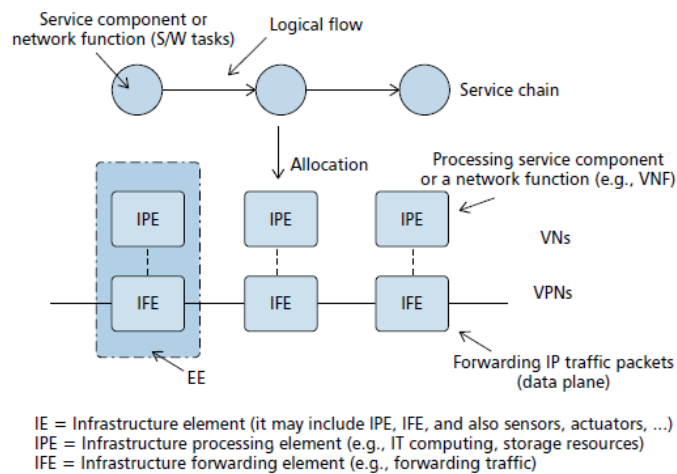
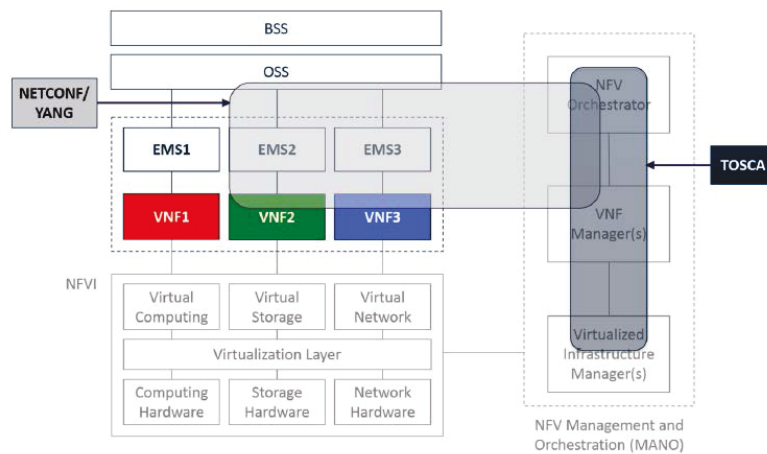


Figure 14– Infrastructure Element

YANG declarative data modelling language can be used for both to describe deployable instance of a service (e.g., a VNF) and to configure a network device/element (in our model an IE) at run time. It should be also noted that TOSCA and NETCONF/YANG can also be considered as complementary instruments: deployment templates may trigger the NETCONF/YANG configurations during the instantiation of a service, whilst in the Operations the OSS can take over configurations at run time [36].



Source: Tail-F Systems

Figure 15– TOSCA deployment templates and NETCONF/YANG can be seen as complementary instruments [36]

As an example if the IE is a robot, it may implement also cognitive loop, (through Artificial Intelligence methods, machine learning techniques, heuristics, algorithms, etc. executable locally or centralised). In fact, it should be possible:

- sensing, collecting and storing (even locally) massive data sets (through terminals, smart things, intelligent machines);
- transporting quickly huge sets of data (through high bandwidth and ultra-low low latency connections) where it is more convenient (allocation of virtual functions);
- elaborating big data (Cloud and Edge/Fog Computing) to infer decisions for actuating/controlling local actions.

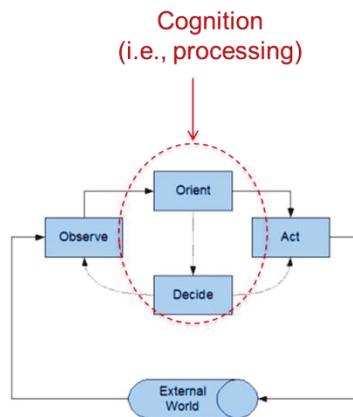


Figure 16– Cognitive loop implementable by an IE as a robot

5G Edge Cloud OS leverages on the concept of services as an “unifying” abstraction across across multiple domains and across different infrastructure levels.

In fact a service is seen as providing a function across the ISO-OSI layers (e.g., it could be an infrastructure service, a middle-box up to a cloud service), it should exports an API, it should be available anywhere and anytime (location-time independent), scalable, elastic, and resilient and it could be dynamically composed with other existing software components (e.g., to create a service chain, or more articulated service logics). Services could be executed into one or more virtual slices, which are made of a set of logical resources (e.g., Virtual Machines, Containers) connected through Virtual Networks.

The allocation and orchestration of logical resources, in charge of executing a certain service chain or logic, requires solving constraint-based double optimization problems: not only VMs or container have to be properly allocated (to

avoid hot-spots), but also the traffic crossing the VMs also has to be properly routed (to avoid congestion). This is a NP-hard problem which normally is solved with some metaheuristics. From this perspective, also the term orchestration [37] which has long been used in the IT domain to refer to the automated tasks involved with arranging, managing and coordinating higher level services, assumes increasing importance as a multi-level capability across the different level of the infrastructure.

### 5.3.1 Taking inspiration from Robot Operating System

One of the most stringent requirements of 5G Edge Cloud OS is about scalability. The number of heterogeneous nodes, systems, terminals and devices at the edge of current infrastructure is growing day by day. Internet of things, pervasive robotics and machine to machine services scenarios are calling for control, orchestration, management and policy solution which should be able to face high level of dynamism of a sheer number of entities.

In this sense the study of the functional architecture of the Robot Operating System (ROS) [38] has provided interesting elements for the design of the 5G Edge Cloud OS. In particular, ROS is an open source, widely adopted meta-operating system for robotic systems.

The ROS is a widely adopted meta-operating system for robots: the full source code of ROS is publicly available and currently only runs on Unix-based platforms.

Among the merits of ROS there is the variety of processes (called nodes), executed on a number of different hosts, connected at runtime with logical topologies. Moreover, another main reason for that design choice is the observation that a robot, generally speaking, can be considered as a dynamic aggregation of resources such as sensors, actuators and processing-storage capabilities implementing a cognitive loop. These are the same categories of resources that will populate the edges of current infrastructures, named Infrastructure Elements (IE).

It is recognised, obviously, the domain contexts and the requested performances of ROS and 5G Edge Cloud OS might be quite different: in this sense, the design of the 5G Edge Cloud OS software architecture has taken only inspiration from ROAS and it has been extended to meet the requirements of 5G Edge Clouds.

### 5.3.2 ROS in a nutshell

In ROS, a robotic system built consists of a number of processes (called ROS nodes), potentially on a number of different hosts, connected at runtime in a peer-to-peer topology.

ROS has a lookup mechanism (ROS Master) to allow processes to find each other at runtime.

ROS Master acts as a name-service: it stores topics and service registration information for ROS nodes. Nodes communicate with the Master to report their registration information. As these nodes communicate with the Master, they can receive information about other registered nodes and make connections as appropriate (bypassing messages, structuring data).

Nodes connect to other nodes directly; the Master only provides lookup information, much like a DNS server. Nodes that subscribe to a topic will request connections from nodes that publish that topic, and will establish that connection over an agreed-upon connection protocol (e.g., standard TCP/IP sockets). This is represented in figure 4.

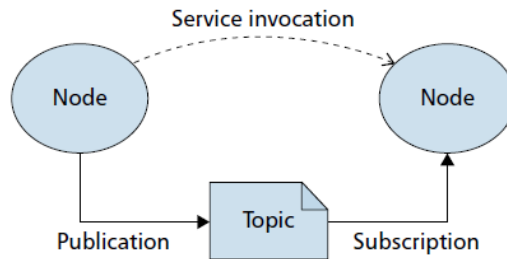


Figure 17 – Pub-Sub

An ROS node sends a message by publishing it to a given topic, which is simply a string such as “map.” A node that is interested in a certain kind of data will subscribe to the appropriate topic. There may be multiple concurrent publishers and subscribers for a single topic, and a single node may publish and/or subscribe to multiple topics.

Although the topic-based publish-subscribe model is a flexible communications paradigm, it is not appropriate for synchronous transactions, which can simplify the design of some nodes.

Therefore, ROS developers have introduced the concept of services, defined by a string name and a pair of strictly typed messages: one for the request and one for the response. This is analogous to web services, which are defined by URIs and have request and response documents of well-defined types.

The special characteristics of the ROS architecture allow for decoupled operation, wherein names are the primary means by which larger and more complex systems can be built.

This decoupling is very much important and it is perfectly in line with the similar need for the 5G Edge Cloud OS, whose main goal is allowing decoupled operation of the Edge Cloud resources. One of the interaction primitives of 5GECOS is the publish-subscribe model, which is adopted as a basic way to distribute software task execution requests. As described in the next section, each software task execution request is coded as a tuple and written on the tuple space, named blackboard, whilst a take operation is used by IEs to offer their process capability.



## 5.4 Functional architecture of the Edge Operating System

This section describes the main characteristics of the 5G Edge Cloud OS (5GECOS), whose high level architecture is reported in the following figure.

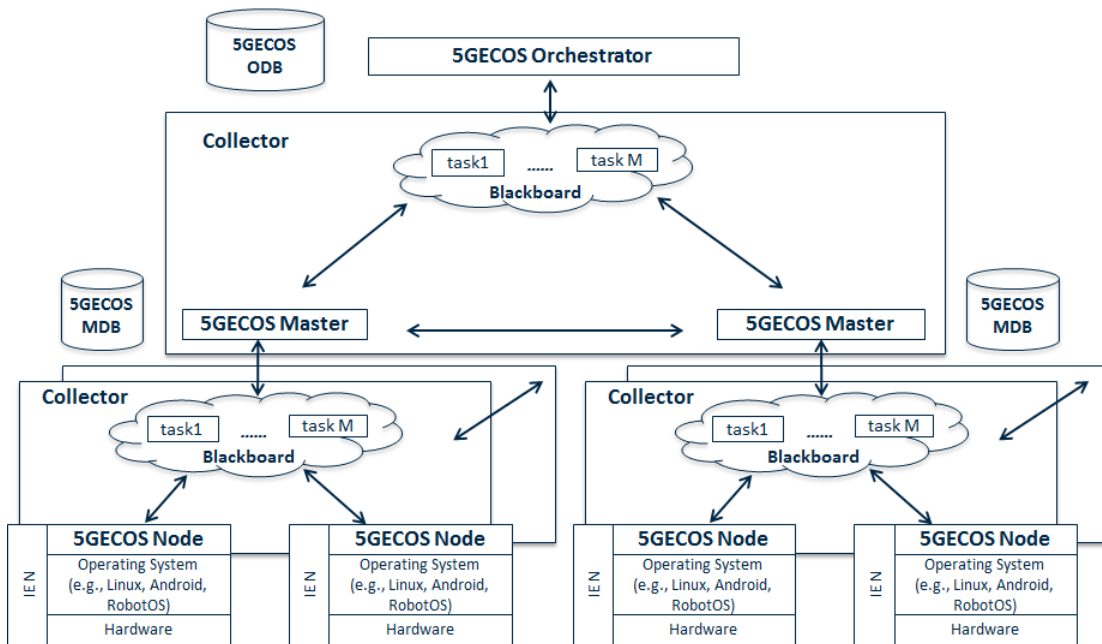


Figure 18 – High-level functional architecture of the 5G Edge Cloud OS (5GECOS)

The main elements of the 5GECOS are listed below:

- An 5GECOS Node is an S/W module which can be executed on top of any Operating System (e.g., Linux-based OS, Android, Robot Operating System, etc.) of an IE. Similarly to ROS, any 5GECOS Node communicates with an 5GECOS Master to whom it registers (e.g., services that can provide) and updates the status (e.g., resources utilization) of its associated IEs: this data is stored in the 5GECOS Master Data Base (5GECOS MDB). IE Nodes are interconnected on the data plane via fixed and virtual radio links (these links could be either local, in a single edge domain, or across a WAN).
- An 5GECOS Master is dynamically allocated to a specified edge domain. It is responsible for the local creation (and deletion) of the slice(s) where service chains are executed in order to provide the requested services. It has to interact with a higher level 5GECOS Orchestrator and with other 5GECOS Masters, in case the service chain has to be allocated across multiple edge domains. The 5GECOS MDB stores the data related to the IEs belonging (assigned) to the specified domain.
- The Master blackboard is a sort of virtual repository shared among the 5GECOS Master and the 5GECOS Nodes. The 5GECOS Master publishes (using the pub primitive) the task/component of the service chain which has to be allocated. In turn, 5GECOS Nodes subscribe (using the sub primitive) to the S/W task/component if the associated IE can provide the logical resources to execute it (i.e., can serve the specific task of the chain). Multiple subscriptions are possible, so in a next stage the 5GECOS Master will make an optimized selection of the IEs to whom the S/W task/component will eventually be allocated.

- The Collector abstraction [39] has been introduced to make Master blackboards recursive thus overcoming scalability limitations. In this sense, a Collector can be seen as an agent acting as an ensemble of IEs together with their shared blackboard. A Collector thus can act towards other Collectors as a super-IE as it can take tasks on its blackboard from other overloaded Collectors.
- The 5GECOS Master includes a capability called the Selection Method, which makes it possible to select the proper IEs to assign the execution of the service chain tasks. Selection is done according to specific criteria, for example through the minimization of specified KPI, as with end-to-end application latency. Interacting with the 5GECOS Node, the 5GECOS Master can configure the logical resources hosted by the IEs at run time.
- The 5GECOS Orchestrator is a higher level S/W module which is set up to receive the service request that must span multiple edge domains. It decomposes the request into a service chain, selecting and interacting with the appropriate 5GECOS Masters for the end-to-end allocation of IEs across multiple domains. 5GECOS Master can communicate with the 5GECOS Orchestrator to whom it registers and updates its status: this data is stored in the 5GECOS Orchestrator Data Base (5GECOS O-DB).
- The Orchestrator blackboard is a higher-level virtual repository shared between the 5GECOS Orchestrator and the 5GECOS Masters. As above, for the Master blackboard, Collector concept can be applied also at this level for Orchestrator blackboard.

Eventually 5GECOS should be based on the following main abstractions:

- Infrastructure Slice in which the X-as-a-Services are executed: this abstraction should include the low level mechanisms allowing to handle a service in a slice;
- X-as-a-Services abstraction (as an application program);
- Programming Environment based on APIs;
- Drivers which can be used to include new resources into 5GECOS.

Let's see an example of that shows the high level functioning of 5GECOS. At the start-up of an IE, the 5GECOS Node sends the 5GECOS Master a description of the associated IE services and the status (including the configuration) of the resources. The description can adopt a variety of formats, for example YANG modelling.

Users' service requests are sent to the 5GECOS Master through their terminals (which run 5GECOS nodes): if a service request can be executed just locally, within the 5GECOS Master domain, then it is simply decomposed into a sequence of service component and required network functions (i.e., a service chain).

The 5GECOS Master then publishes (pub primitive) the software tasks of the service chain; 5GECOS Nodes subscribe (sub primitive) to said tasks if the related IEs can execute them. At the end, the 5GECOS Master must make an optimized selection of the IEs (Selection Method). On the other hand, if the 5GECOS Master realizes that the service request cannot be executed locally, it forwards it to the 5GECOS Orchestrator. In turn, the 5GECOS Orchestrator decomposes the service request and publishes it on its Blackboard. The flow of actions then proceeds as above within each edge domain.

The 5GECOS is a distributed software architecture where the states of the resources are stored in distributed DBs. The well-known CAP theorem [40] will dictate some limitations: in fact, it states that any networked shared-data system

can have at most two of the following three properties: 1) Consistency (C) equivalent to having a single up-to-date copy of the data; 2) high Availability (A) of that data (for updates); and 3) tolerance to network Partitions (P).

The general idea is that 2 of the 3 properties have to be privileged: CP favours consistency, AP favours availability, and with CA there are no partitions. A trade-off that will be needed then for storing/configuring the states of the infrastructure while achieving specific performance levels. End-to-end latency (or delay) and partitioning are deeply related, and such relations become more important in the case of widely distributed infrastructure. This situation contributes even more to the requirement of minimizing the application end-to-end latency. These specific aspects require further investigation.

## 5.5 Example of a possible prototype

Already today we are witnessing growing interest in using drones, robots and autonomous machines in agriculture, industry, security and several other domains. For example, the advent of robots remotely controlled via 5G connections would create a tremendous impact on the Industry 4.0. Also the contexts of Tactile Internet and Cyber Physical Systems envisage several applications for cognitive machines.

The development of a 5GECOS prototype could leverage on available open source software complemented with the development of other required software modules.

In particular, the two main pieces of opens source software to start with are OpenStack and ONOS. The former will be used to manage the Virtual Machines executing the network and service functions of the virtual infrastructure; the latter will be in charge of managing the fabric of connections, whilst executing the control applications. 5GECOS can be seen as an overarching operating system that runs on top of both OpenStack and ONOS.

Software architecture of 5GECOS prototype is shown in figure 9. Code additions are required for example to address the capability of OpenStack of handling chains of VMs (i.e., service chains) and the Nova-scheduler of OpenStack which currently uses algorithm (i.e., Filter&Weight) for scheduling VMs in isolation, without considering the status of the underneath network links. Code additions are required also for the controller, obviously. Actuations sent by ONOS and OpenStack are handled locally by the 5GECOS agents.

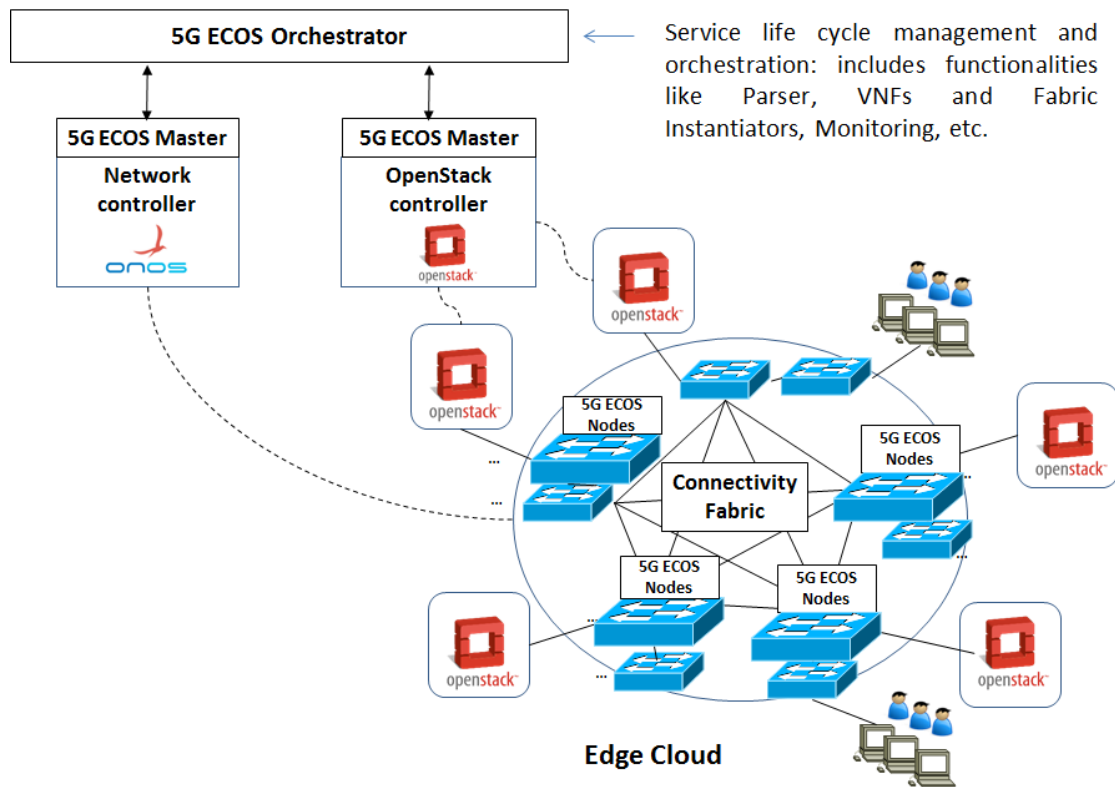


Figure 19 – 5GECOS example of prototype

A very similar conceptual architecture has been implemented (by the Politecnico of Turin) in the EIT-Digital funded Activity “SDN At the Edge” (which I coordinated in 2015). A preliminary demonstration of the FROG prototype<sup>15</sup> has been shown in ETSI (see appendix).

### 5.5.1 On the use of Blockchain for trust and security

Let’s spend some consideration about Security, even if this is outside the scope of this work. Security is one of the biggest challenges for 5GECOS. As mentioned the expected high levels of programmability of the future 5G will allow creating and customizing dynamically “slices” of virtual resources spanning from the Terminals through the Network up to the Cloud Computing.

In order to achieve the desired levels of dynamism and openness of the future service ecosystems (running upon these virtualized Telecom infrastructures) whilst ensuring security, the control, management and orchestration processes require to be trusted (as there will be interfaces exposed to public access).

A way to achieve that is ensuring that any control, management and orchestration commands will have to be properly traced (associated to the “reason why”) and authenticated. The “infrastructure slice” will have to become a sort of trusted entity, operated with automated processes. Message authentication in Network and IT is not a new story.

<sup>15</sup> FROGv4 orchestration software is available at <http://github.com/netgroup-polito/frog4>

The applicability of “blockchain technology” for these future security requirements might create an impact in this direction: for example for the authentication of Users (humans and/or agents), of commands and messages, of APIs, of resources belonging to other domains, etc.

A block chain or blockchain is a distributed database that maintains a continuously-growing list of data records hardened against tampering and revision. The blockchain is seen as the main technological innovation of Bitcoin, since it stands as proof of all the transactions on the network. A block is the ‘current’ part of a blockchain which records some or all of the recent transactions, and once completed goes into the blockchain as permanent database. Each time a block gets completed, a new block is generated. The blockchain database is shared by all nodes participating in a system.

The applicability of blockchain for security requires further investigations.

### 5.5.2 On the adoption on “intent interfaces”

Application developers would like to focus on the development of functionality of an application, as such the use of the infrastructure service should be as easy as the cloud services. This requires the infrastructure to have a set of service oriented, declarative, and intent based NBI (e.g., “create a connection between site A and B”).

The general idea of having The general idea of "intent-based interfaces" is to make the Apps Developers or the Users to tells the network what he wants, but not how to do it.

- Intent description is declarative, not designates the way for execution: the SDN controller is a “black box” for resource allocation and management. Intent NBI must become an universal language , the only interface to the SDN controller.
- Intent is completely abstract. It does not include references to specific instances of infrastructure devices or state.
- Intent request is independent of the controller platforms and implementations. It only expresses the requirements for the application layer, using application related vocabulary and information. This enables portable applications.
- Intent NBI helps applications to reduce conflict on higher level, so that increases the success of requests. The application only expresses the requirement and the SDN controller is responsible for the automatic setting of the path.
- All Intent based networking could be said to be policy based, but not all Policy based infrastructure or networking is Intent Based.
- Intent brings context: key to detecting and resolving conflicts is to be able to examine the “what I need” description, rather than the “how to do it” description.

The IETF, “Intent-Based Nemo problem statement” (July 05, 2015) represent a first example.

The applicability of intent interfaces requires further investigations.

### 5.5.3 A simple use case

In the example of use case shown in the following figure, a mobile cognitive machine can be seen as an IE, with its own operative system.

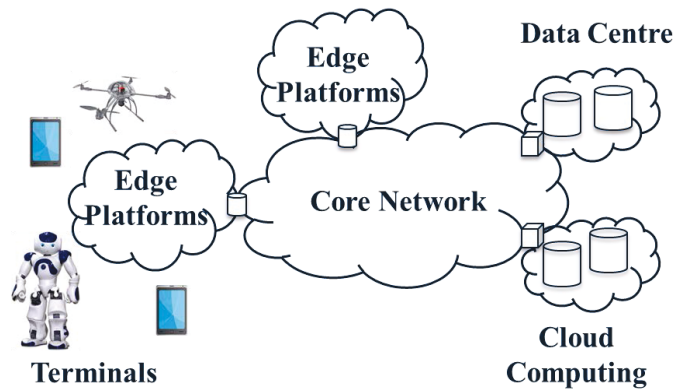


Figure 20 – Example of use case

The control system of a mobile cognitive machine usually comprises several ROS nodes: for example, one ROS node controls a laser range-finder, one controls the wheel motors, one performs localization, one node performs path planning, one provides a graphical view of the system, one for the cognitive service logics, and so on. Other remote ROS nodes may be required, in order to provide other services. In this example, said ROS nodes can be seen as service components of a end-to-end service chain orchestrated and executed over the 5GECOS.

Let's focus on a service request for allowing a mobile cognitive machine to perform some articulated task (e.g., in a scene of a disaster) with ultra-low reacting times (e.g., a mobile robot remotely control acting in an environment which is changing dynamically).

These requirements are dictating the need of executing of a certain cognitive service by using a proper balance of local, edge and centralized processing-storage resources: in fact the machines' reaction times are very much depending on IT response time and network latency. In fact, even small changes in the area's layout, or delays in the actuation commands, can lead to catastrophic failures.

5GECOS should be able exploiting this intelligence: for example, the Selection Method makes it possible to select the proper IEs to assign the execution of the service chain tasks minimizing end-to-end network and application latencies.

A User wishes to control a remote a mobile cognitive machine providing a specific service in a certain area (e.g., in a museum, in a firm, etc).

Mobile cognitive machine can be considered an IE with sensors and actuators having also local (but limited) processing and storage capabilities; the mobile cognitive machine is connected to the 5G infrastructure.

Intent based interfaces will allow the Users to ask what service is requested (not how to get it). The so-called "intent" [41] should be in fact completely abstract: it should not include references to specific instances of infrastructure devices, nodes or state.

A User (with his/her own controlling IE device, e.g., a terminal for remote control) sends the service request (with the associated KPI) to the 5GOS and a 5GECOS Master is instantiated. The 5GECOS Master decompose the service

request into a sequence or service component and the required network and service functions (i.e., it creates a service chain associated to the service request).

5GECOS Master then publishes (pub primitive) the required service components (and the KPI) on a board; a number of 5GECOS Nodes subscribe (sub primitive) to said service components (if the related IEs can execute them, respecting the performance KPI). 5GECOS Master makes the best selection of the IEs (with a specific optimization method) in order to meet the performance KPI. Practically, this best selection will decide in what VM execute what service component (of the machine cognition) and which route/network function set-up to interconnect/chain all said VMs.

In case the service request should span across multiple edge domains, the 5GECOS Orchestrator is invoked for the end-to-end allocation of IEs across multiple domains. In fact, any 5GECOS Master communicate with the 5GECOS Orchestrator to whom it registers and updates its status (stored in the 5GECOS O-DB). 5GECOS Orchestrator makes use of the an orchestrator blackboard, which is a higher-level virtual repository shared between the 5GECOS Orchestrator and other 5GECOS Masters. Also at this level, the concept of Collector is an abstraction to make Master blackboards recursive thus overcoming scalability limitations. In this sense, a Collector can be seen an agent acting as an ensemble of IEs together with their shared blackboard. A Collector thus can acts towards other Collectors as a super-IE as it can take tasks on its blackboard from other overloaded Collectors.

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# Chapter 6 Techno-economic impact and Exploitation Strategies

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## 6.1 Techno-economic impact

Softwarization is enabling a substantial convergence between IT and Telecommunications industry structures. In brief summary, it is likely that the transformation will drive the emergence of a single converged industrial structure offering services, such as voice, Internet access, and what today we are calling OTT (Over The Top) services.

This converged industrial structure will leverage on a Telecommunications virtualized infrastructure where the provision of the end-to-end services is likely to become decoupled from the operations of the infrastructure itself. This is likely to bring a split between the Players owning and operating the infrastructure (Infrastructure Providers) and those Players, operating and provisioning the services (Service Enablers and Service Providers).

DC will become the new network nodes (notably the CORD project of AT&T and ONLab is going in this direction). Wholesale telecoms supply and datacentre hosting are likely to merge as well.

Retailing of telecoms services as a separate industry sector will disappear. The telecoms services will become increasingly packaged with other services. Telecoms retailing is likely to join with OTT service providers and voice telephony will increasingly become just another OTT service.

This disruption will occur also on the telecoms vendor supply industry, where there will be a split between the supply of common hardware from the supply of software components. At the same time while the supply of the telecoms hardware merges into the supply of Data Centre IT hardware, some telecoms equipment suppliers may decide to reposition themselves as principally software supply companies

When focusing on the telecoms service for businesses the analysis might be a little bit different but the overall picture remain the same: a common infrastructure with a splitting in the supply of infrastructure hosting services from the supply of managed business solutions.

In the next sections, a comparison has been made between the value chains of three industry structures for: 1) delivery voice services; 2) delivery Internet services; 3) delivery of commodity services in the age of Softwarization.

### 6.1.1 Value Chains comparisons

The first major consumer service offered by the telecoms industry was voice telephony. In those times when this was the telecoms industry only primary service, there was reasonably clear industry structure. The following picture [42] is showing this value chain.

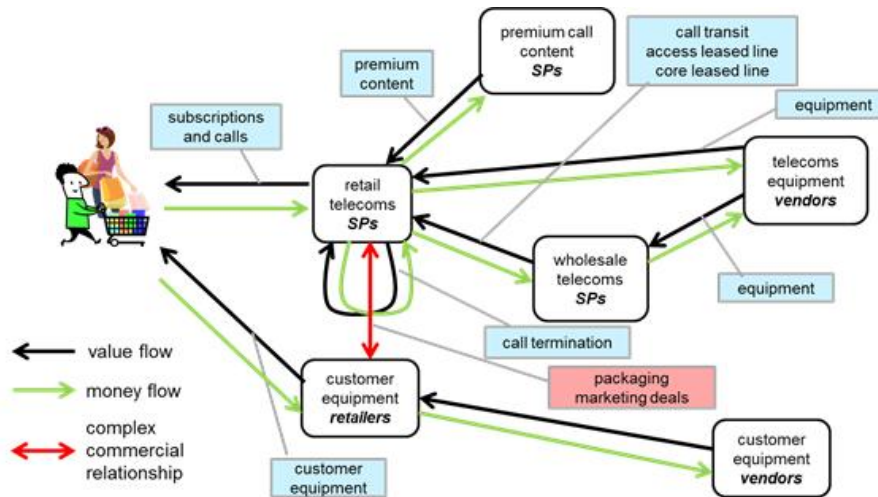


Figure 21 - Value chain for voice services [42]

In this case, not all the retail telecoms service providers may will to build and operate all segments of the infrastructure so they may buy in wholesale services from other providers. These wholesale services include:

- Leased Access – where a telecoms service provider does not have access infrastructure, it can lease access from a third party ;
- Leased Core – where a telecoms service provider does not have core infrastructure (e.g., for global connectivity), it can lease core capacity from a third party.

The other major consumer telecoms service is broadband Internet access: it has been a fundamental telecoms service alongside voice telephony over 15-20 years.

The industry structure associated with broadband Internet has evolved 15-20 years with substantial changes. Also new Players has emerged and grown up with the Internet to become some of the world’s biggest companies such Google, Facebook, Amazon, etc. In addition, some very large product supply companies, e.g., Apple and Microsoft, have diversified into providers of Internet based services.

These of these ‘Over The Top’ (OTT) companies don’t own telecoms access infrastructure. They built their success on a global availability via the Internet, in fact, any linkage to any particular access service, technical or commercial, would limit this global reach. They form an independent relationship with the end consumer: this relationship is not mediated by the telecoms service provider.

In many cases, the OTT does not charge the end consumer – the service is offered free of charge, or better the end consumer is ‘paying’ for the service by providing with detailed personal information which then can be used/sold as marketing information to other companies.

There are other distinguishing characteristics about the OTT service providers:

- OTT services are normally based on Data Centre (Cloud Computing).
- OTT tends to be establish relationships with the CPE vendors rather than retailers : e.g., Google with their relationships with CPE vendors for their use of Android.
- OTT services are characterised by the ‘network effects’ : attractiveness of any one player is strongly related to the number of Users already using that player’s service. This means that for each OTT service, there is dominant player – a ‘winner takes all’.

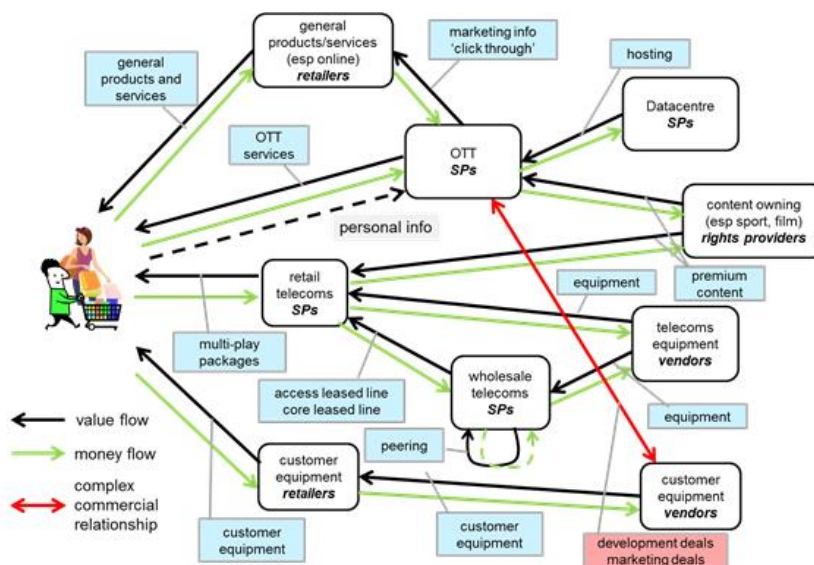


Figure 22 - Value chain for Internet based services [42]

Figure 2 illustrates the value chain associated with the broadband Internet access and related services.

As mentioned, Softwarization will enable a common hosting infrastructure which can host a wide variety of network services (e.g., middle-boxes) and functionality (e.g., content distribution networks, content policing and filtering, content based routing and QoS management). These functions and others can be dynamically combined into complete services by constructing specific chaining of functions – service chains – using the virtualised infrastructure with its control and orchestration capabilities.

Following figure 3 is showing the related value chain.

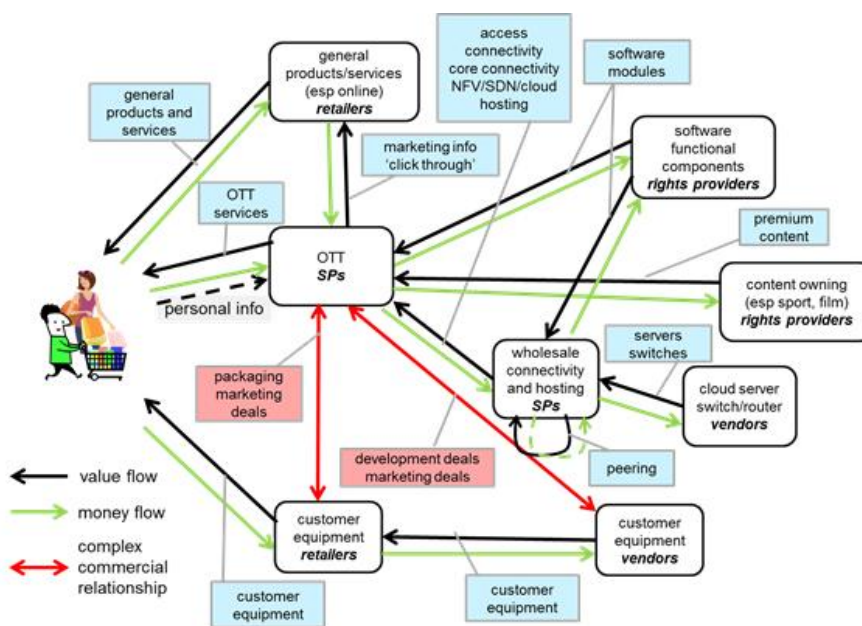


Figure 23 - Value chain for Internet based services [42]

Eventually, Softwarization of Telecommunications is moving the competition from a CAPEX-oriented models (e.g., based on physical infrastructure, hardware) to an OPEX ones (e.g., based on renting virtual resources, software).

## 6.2 Social Impact

With Softwarization of Telecommunications, smart terminals, autonomous machines, drones and robots will become just like “nervous terminations” embedded into reality. This will have huge impacts in industry, in agricultural automation and in optimizing almost any socio-economic process in smart cities.

We mentioned in chapter about scenario and use case several examples. In agriculture, for example, autonomous machines may be used for tasks like crop inspection, the targeted use of water and pesticides, and for other actions and monitoring activities that will assist farmers, as well as in data gathering, exchange and processing for optimizing processes. Interestingly, APIs can be opened to end-Users and Third Parties to develop, program and provide

any related services and applications for pursuing specific tasks. In industry, softwarization will pave the way to process automation, data exchange and robotics manufacturing technologies. It draws together Cyber-Physical Systems, the Internet of Things and the Internet of Services applied to industrial processes and the value chain.

Education and cultural implications should be considered, with particular reference to the new skills which will be eventually required by the Softwarization. The future of creativity may depend on younger generations being taught mastering the software skills just as they are taught foreign languages, mathematics, and science. As we integrate digital devices and products deeper and deeper into our lives, from smartphones to wearable, from drones to robots and self-driving cars - which are largely run and driven by telecommunications and ICT - dreaming up new ideas will depend on our ability to understand and master the software.

This is the coming of the true Digital Society and Economy, where the network will literally play the role of a “nervous system” embedding cognitive loops into reality, automating and optimizing any process. At the end of the day, any open ecosystem is pursuing (and always reaching, otherwise it will disappear) “optimization” as the best possible adaptation to the environment. This optimization is always subjected to constraints: it might appear to be chaos at the micro-scale, but at the macro-scale the emerging properties are leading to optimizations.

Let us consider an example from statistical mechanics: the behavior of a gas can be described, at the micro-scale level, in terms of the position and velocity of each molecule, which appear as random processes. At a macro-scale level, the emerging property of the gas, described by the state equation, is solving a global constrained optimization problem.

Similarly, the behavior at the micro-scale level of electrons in an electrical network can be described in terms of random walks. This leads to rather sophisticated behavior at the macroscopic level: for example, the patterns of potentials in a network of resistors minimizing the heat dissipation for a given level of current. Again, this is like saying that the local random behavior of the electrons causes the network as a whole to solve a large scale constrained optimization problem. At the quantum level, another more complicated model could be applied, but still leading to the same conclusion.

Looking at living entities, a termite colony can be seen as a (self-) optimized ecosystem. Termites interact with each other, and with the environment, whilst living in their colonies. Again, this is like saying that the termites’ own simple behaviors and cross-interactions are solving constrained optimization problems, and which appears as an emergent self-organization.

In summary, one may say that any large-scale ecosystem tends to move from a state with higher energy (i.e., higher cost) to a state with lower energy (i.e., lower cost), usually related to the stable stationary states. We could apply this metaphor also for the case for Telecommunications: clearly this trend is unstoppable given the continuous acceleration of technology.

We could even add that the shifting of the focus from the network to smart terminals will boost the techno-economic evolution of Internet at the micro-scale, at the “edge” (where by the way start-ups are already booming). This will drive even more investments (at the macro-scale) outside of the network infrastructure itself, stimulating the advent of new communications and service paradigms.

Eventually Softwarization could be seen also as the new tool for humanity, offering new ways for communicating- producing-consuming ICT services, creating the Digital Society and Digital Economy. This new “tool” will be capable of distorting and reducing the space-time dimensions of Digital Society, not only making the world hyper-connected, but reducing the need of travelling or enabling distributed production models.

From an anthropological perspective, this also very much resonates with what R. Bandler and J. Grinder [43] called “distortion”, as one of the processes that allow us to survive, grow, change... a process which allows us to make shifts in our experience of sensory data. Indeed, future Telecommunications and ICT services will allow us to include morphing in our experience of sensory data! Softwarization is a tool that will offer humans a potential new world of communications and services. The creation of a new socio-economic development will depend very much on our ability to manipulate symbols; that is, to create-models.

Marshall McLuhan [44] argues that the web, media, and Telecommunications in general are bringing us to a sort of social "implosion" as people and processes are more closely connected and interworking. For McLuhan, this unification, through implosion, will allow the idea of living in a "global village" to emerge and become full-fledged.

This "global village" will be also populated with digital beings such as virtual and embodied agents or software processes, becoming characters of their socio-economic surroundings and life conditions. It will not just be a matter to technology: ICT is reaching such a level of maturity that it will fade into the physical reality, virtually merging with it.

It will become crucial to realize (sooner rather than later) how to make this merger of the natural and softwarization worlds sustainable from a socio-economic viewpoint, making the best of the compatibility between people and the digital worlds they have created with this new tool.

There is a reverse side of the coin: in principle, in the future, any job that can be broken down into a series of routine tasks is susceptible of being digitalized, automated and done by any of a variety of robots or cognitive-autonomous terminals, thus replacing humans.

So, what is left to humans tomorrow? Or better, how can we leverage on the differences between robots and humans to create a more human-valued society and economy?

We need to leverage on the integration between robots and humans to create a new society and economy.

### 6.3 The role of Open Source

It is well recognized that open source software is a powerful instrument for accelerating innovation. A number of successful examples of development and adoption of Open Source software occurred, producing a strong impact on the market, even in short span of time (e.g., less than 5 years).

Linux kernel is one prominent example: it is a Unix-like operating system released (around 1994) under the GNU General Public License version (GPLv2). The Linux kernel is used by a variety of operating systems based on it, which are usually in the form of Linux distributions. An example of “good enough” but simpler and cheaper operating system. The popularity of Linux virally diffused across developers and users. Linux servers now represent about 29% of all server revenue (which means, given their lower costs with respect to other commercial servers, a much larger market share).

Apache is another example. Apache has been the most popular web server on the Internet since April 1996. Apache adoption diffused virally reaching about 60% of the market in about 5 years. Today, 385 million sites are now powered by Apache, landing today on a 38% share of the market.

Coming to Cloud and Edge Computing, SDN, NFV, there are several open source software tools and platforms.

OpenStack, for example, is an open source platforms that can be used to provide Cloud services. OpenStack has been developed by the OpenStack Foundation, now comprising a large group of technology companies. Several companies in the Foundation run public cloud services on the OpenStack platform (comparable with Amazon’s Elastic Computing Cloud EC2). OpenStack has been launched in 2010 and today dominates the market with a 69% adoption rate of IT Enterprises offering Cloud Computing services.

No need mentioning the long list of open source SDN controllers which have been released and are being tested. ONLAB has released in open source an operating systems (ONOS) for SDN-like networks: interestingly, after the release some Telco Network and Service Providers immediately announced that they will start testing it for assessing a future potential deployment in production environments.

The lesson learnt from the past is that if an open source software solution (tool or platform) will be developed and released with the support of a critical mass of enterprises and technical communities, it is likely that in about 5-7 years it will reach at least 50%-60% adoption in the related market.

It is a reasonable to expect that path also for open source platforms and tools for SDN and NFV, provided that there will be the support of a critical mass of industries. It should be noted that this is quite a short span of time, considering the huge potential impact that this transformation may have on the current ecosystems.



## 6.4 Some examples of Strategies

In this section the strategies adopted by DT and AT&T have been analysed.

### 6.4.1 DT: the Software Defined Operator

Internet traffic will continue to grow exponentially and Deutsche Telekom argues that the old way of building networks and producing services will hardly scale for the future.

Google, Facebook and other Internet companies have proven that a new software and data-center-based production model can deliver high flexibility, agility and highest availability, so DT argues [45] that network operators have to implement a similar approach in their production chain in order to be competitive. At Deutsche Telekom, they have called this strategy under the name *Software Defined Operator*.

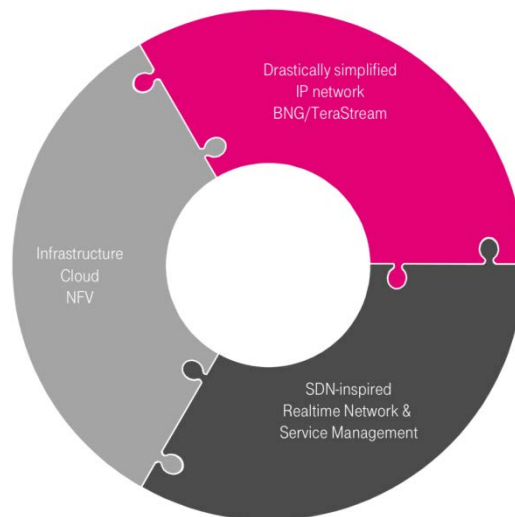


Figure 4 - The Software Defined Operator (source DT)

The Software Defined Operator has three main elements - the drastically simplified IP Network, the Infrastructure Cloud and a SDN-inspired Realtime Network and Service Management.

#### 6.4.1.1 Drastically Simplified IP Network

Today most Operators are running a two-tiered IP/MPLS core on top of an Optical Transport Network (OTN) and a rather complex aggregation for broadband customers, including the termination of customer PPP over Ethernet connections on Broadband Remote Access Servers (BRAS).

DT is driving the simplification with the current implementation of a Broadband Network Gateway into the production networks (e.g. in Germany and Greece). In parallel, they are developing a revolutionary long-term approach under the name TeraStream (they have two customer pilots in two countries).

TeraStream only has two types of routers - R1 as customer facing edge router and R2 as Datacenter and Peering facing edge router. Optical transmission is fully integrated into the IP

routers using 100Gb/s Coherent interfaces and an extremely simple optical drop and waste concept. TeraStream does not use any OTN - the only optical components in the network are amplifiers and very cheap optical splitters. TeraStream is agnostic to access technologies, covering both fixed and mobile access.

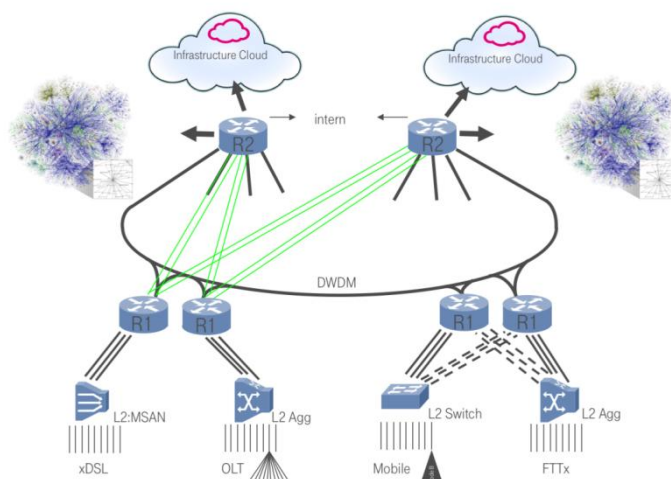


Figure 5 - The TeraStream Architecture (source DT)

R1s are IPv6-only routers, IPv4 is delivered as a service - produced in the datacenters attached to the R2s, encapsulated using the standardized Lightweight 4over6 technology [46] and terminated on the customer premise equipment. TeraStream does not use any MPLS. The efficient IP+Optical approach allows us to overprovision the core. QoS is applied at the Edge towards the customer. To simplify the routers to the bare minimum, DT has tightly integrated network I/O optimized datacenters with the IP network. The operation of these datacenters at the R2 locations follows the Cloud paradigm, called the *Infrastructure Cloud*.

#### 6.4.1.2 Infrastructure Cloud

Traditionally, IT-orientated datacenters are optimized for compute performance and storage access. Network traffic in a datacenter supporting traditional applications (e.g., ERP) typically flows in east-west direction. This is not optimal for producing virtualized network functions (VNFs) in a telco environment. For VNFs, traffic typically flows north-south, from the server in the datacenter directly towards the network. TeraStream Infrastructure Cloud model represented the first network I/O optimized approach adopted in the industry.

In the TeraStream pilots, launched in December 2012 in Croatia [47] each server was connected using 6 10 Gb/s Ethernet connections directly to the R2 routers. Most IT-optimized datacenters have this as a total capacity towards the network. High availability in the Infrastructure Cloud is achieved using geo-redundancy and a tight integration into the IP routing system.

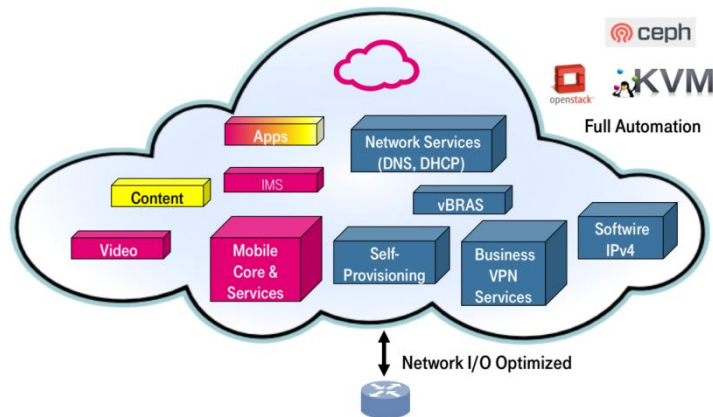


Figure 6 - The Infrastructure Cloud (source DT)

In order to avoid a single vendor dependency, the Infrastructure Cloud is fully based on Open Source. KVM is used as Hypervisor, Openstack as Cloud Orchestration and CEPH for the software defined storage.

Above figure shows a view on the Infrastructure Cloud: blue boxes represent network functions required to run the network like DNS, DHCP, virtualized routers for VPN services, the Lightweight 4over6 Softwire solution or for a migration a virtualized BRAS. The magenta boxes are representing traditional core services for fixed and mobile networks, including a packet core, IMS or video distribution systems. The yellow boxes represent options for future partnerships, e.g. on the content or application side.

The Infrastructure Cloud fully follows cloud paradigms, including a Continuous Development / Continuous Integration / Automated testing cycle (in the direction of the Telco DevOps model).

Overall, Open Interfaces and Open Standards are recognized as crucial for the success of the Infrastructure Cloud and the Cloudification of Network Functions. The role of traditional standards is in many areas replaced or at least complemented through Open Source, even if DT believes that Open approaches require a community or standardization organization behind. The initial version of the Infrastructure Cloud is built using standard x86 server hardware.

DT argues that the move to virtualized or, better, cloudified network functions produced in the Infrastructure Cloud represents a major transformation for the telco industry. This is impacting the suppliers who need to partially rearchitect their network functions to make them cloud-ready, but it is also impacting the Network Operators teams.

As part of its strategy, Deutsche Telekom announced to join the Open Compute Project (OCP) [48] forming a TelCo working group within OCP (established in 2012 with the strong

support of Facebook). Applying the Open Source approach, OCP proposed to decompose IT systems into elementary units (CPU, Storage, I/O) and to open specifications developed in a community effort. OCP is going to revolutionize the Datacenter architectures, leading to a significantly lower Capex and Opex. The OCP approach has been recently complemented through the Telecom Infrastructure Project (TIP) [49] applying the same Open Source approach to the overall Telco infrastructure, including Fixed and Mobile Access, Aggregation, IP Core.

### 6.4.1.3 Realtime Network and Service Management

DT argues that all the simplification in the IP network, and the Infrastructure Cloud is of limited value without a radical change in the way networks and services are managed. TeraStream adopts a new realtime network and service management approach.

Importantly DT don't believe in re-architecting the network or operational support systems for new services – main requirement is to be able to "program" service and fully automate the operation.

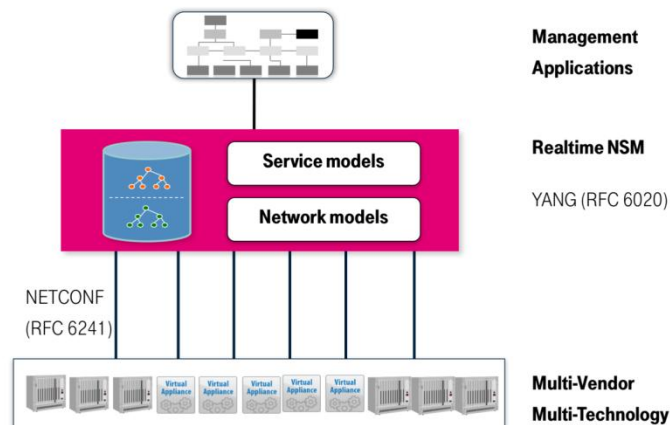


Figure 7 - YANG-based Realtime Network and Service Management (source DT)

DT Realtime Network and Service Management approach (RT-NSM) is fully based on YANG, a generic schema description language standardized within the Internet Engineering taskforce (IETF).

Southbound, element managers or specific integration into OSS systems have been replaced by using standardized YANG datamodels to access the physical or virtualized network elements, NETCONF is used for the communication.

YANG datamodels can also be used northbound towards the business support systems. Describing services in YANG leads to a fully automated YANG-based RT-NSM, addressing both the traditional fulfillment as well as the assurance space.

## 6.4.2 AT&T: CORD Project

The CORD project [9], run jointly by AT&T and ONLab, aims at transforming today Central Offices in Data Centres by unifying the three related but distinct threads:

- **SDN**, which is about separating the network’s control and data planes. This makes the control plane open and programmable, and that can lead to increased innovation. It also allows for simplification of forwarding devices that can be built using merchant silicon, resulting in less expensive white-box switches.
- **NFV**, which is about moving the data plane from hardware appliances to virtual machines. This reduces CAPEX costs (through server consolidation and replacing high-margin devices with commodity hardware) and OPEX costs (through software-based orchestration). It also has the potential to improve operator agility and increases the opportunity for innovation.
- **Cloud**, which defines the state-of-the-art in building scalable services—leveraging software-based solutions, micro-service architecture, virtualized commodity platforms, elastic scaling, and service composition, to enable network operators to rapidly innovate.

### 6.4.2.1 Commodity Hardware

The hardware architecture of CORD consists of a collection of commodity servers and storage, interconnected by a leaf-spine fabric constructed from white-box switches, as shown in the following figure:



Figure 8 - Target hardware, constructed from commodity servers, storage, and switches [9].

The switching fabric is optimized for traffic flowing east-to-west, between the access network that connects customers to the CO and the upstream links that connects the CO to the operator’s backbone. There is no north-south traffic in the conventional sense.

The racks of GPON OLT MACs commoditize connectivity to the access network. They replace proprietary and closed hardware that connects millions of subscribers to the Internet with an open, software-defined solution. (GPON is the example access technology in the reference implementation of CORD, but the same argument applies to other access technologies as well).

### 6.4.2.2 Software Building Blocks and Virtualization

CORD [9], is based on three open source projects: OpenStack, ONOS and XOS. OpenStack is responsible for creating and provisioning virtual machines (VMs) and virtual networks (VNs).

ONOS is the network operating system that manages the underlying white-box switching fabric. It also hosts a collection of control applications that implement services. ONOS is also responsible for embedding virtual networks in the underlying fabric, which is in turn accessed via OpenStack’s Neutron API. XOS is a service abstraction layer that unifies infrastructure services (provided by OpenStack), control plane services (provided by ONOS). It provides explicit support for multi-tenant services, making it possible to create, name, operationalize, manage and compose services as first-class operations.

Main concept is to virtualize existing hardware systems, transforming them into its software service counterpart and running it on commodity hardware. Functionality is likely disaggregated and re-packaged in new ways. The following figure is showing an example concerning Optical Line Termination (OLT), Customer Premises Equipment (CPE), and Broadband Network Gateways (BNG). For a GPON this will produce on GPON technology and virtualizing the OLT to produce vOLT; there are also virtualized counterparts to the CPE (vCPE) and BNG (vBNG).

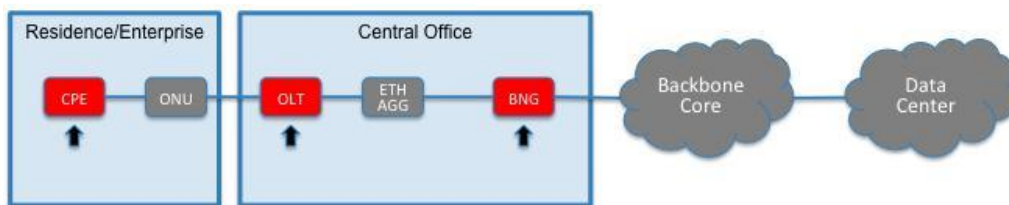


Figure 9 - Legacy CO, including three physical devices to be virtualized [9].

AT&T has developed an open specification for a GPON MAC 1RU “pizza box,” as shown in Figure 10. This board includes the essential GPON Media Access Control (MAC) chip under control of a remote control program via OpenFlow. This replaces an existing closed and proprietary OLT chassis (not shown) that integrates this GPON MAC chip with GPON protocol management, 802.1ad-compliant VLAN bridge, and Ethernet MAC functions.

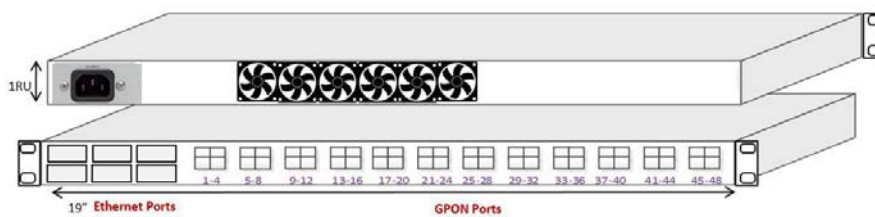


Figure 24 - GPON OLT I/O Blade [9].

In other words, virtual OLT (vOLT), is implemented as a combination of: (1) Merchant Silicon (i.e., commodity GPON interface boards) and (2) an SDN control function that sets up and manages control plane functions of an OLT (e.g., 802.1X, IGMP Snooping, and OAM). The vOLT control application running on top of ONOS facilitates attachment and authentication (AAA), establishes and manages VLANs connecting consumer devices and the CO switching fabric on a per-subscriber basis, and manages other control plane functions of the OLT.

### 6.4.2.3 Service Orchestration

Replacing hardware devices with software running in virtual machines is a necessary first step, but is not by itself sufficient. Software counterparts must also be managed as a collective. This is achieved through the *service orchestration*.

CORD approach is to adopt *Everything-as-a-Service (XaaS)* as a unifying principle. This brings the disparate functionality introduced by virtualizing the hardware devices under a single coherent model. The control functions run as scalable services (these functions run on top of ONOS), the data plane functions run as scalable services (these functions scale across a set of VMs), the commodity infrastructure is itself managed as a service (commonly known by the generic name IaaS), and various other global cloud services running in the CO are also managed as scalable services.

Each service is structured in exactly the same way: it supports a logically centralized interface, called a *service controller*; it is elastically scale across a set of *service instances* (corresponding to VMs and OpenFlow switches); and it is multi-tenant with an associated *tenant abstraction*.

For example, while vOLT, vCPE, and vBNG refer to the virtualized counterpart of the three physical devices, they are not complete and “pluggable” elements in CORD until they are packaged as services—each includes a multi-tenant service controller, and each scales independently across a set of service instances.

Because, the new architecture no longer requires functionality to be bundled along the same boundaries as before, it is more intuitive to think of the virtualization process as resulting in three generic, multi-tenant services:

- **Access-as-a-Service (ACCaaS):** Implemented by a vOLT control application running on ONOS, where each tenant corresponds to a *Subscriber VLAN*.
- **Subscriber-as-a-Service (SUBaaS):** Implemented by a vCPE data plane function scaled across a set of containers, where each tenant corresponds to a *Subscriber Bundle*.
- **Internet-as-a-Service (INTaaS):** Implemented by a vBNG control application running on ONOS, where each tenant corresponds to a *Routable Subnet*.

If a Content Distribution Network (CDN)—itself a scalable cloud service deployed throughout the operator’s network, including caches in the CO—is added to these three new services, we have an example of the three kinds of services outlined: a cloud service (CDN), a data plane service (Subscriber-as-a-Service), and two control plane services (Access-as-a-Service, Internet-as-a-Service). This results in the legacy CO being re-architected into the datacenter version shown in Figure 12.



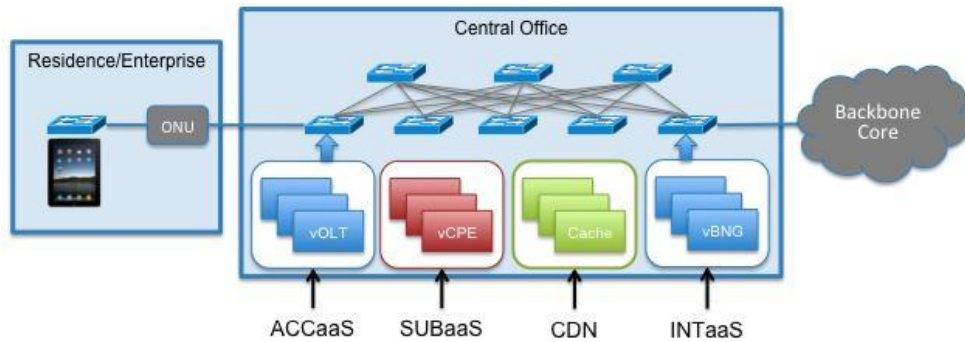


Figure 11 - Four scalable services running in a CO, with a bare-metal switch located on the customer premises [9].

### 6.4.3 Summary

This section reports a brief summary of the main lessons learnt from an analysis of the innovation initiatives carried out by the main Telco Operators.

- Telco Operators are adopting different strategies (e.g., bi-modal, inertial, etc) to pursue a digital business transformation, basically oriented to exploit technologies such as NFV, SDN and Edge Computing. Most of the analyzed Telcos are adopting a “bi-modal” transformation approach, essentially implying the deployment and exploitation of a parallel infrastructure.
- Open source software support and partnerships with multiple vendors (both startups and established suppliers) are the most common collaboration approaches. Nevertheless, standardization of open source software solutions is still recognized as an hot issues.
- Software mastering is recognized a must for a successful exploitation of SDN, NFV: most of the analyzed Telcos are developing / co-developing key functionalities.
- Several Telcos consider strategic to focus innovation efforts on the orchestrators and OSS/BSS capable to manage the complexity and heterogeneity of NFV and SDN solutions.
- Cultural and organization change is one of the biggest challenge of the digital business transformation. SDN and NFV exploitation will require a radical change for the Telco’s operations: from design to planning to executions, all operations processes (OSS/BSS) should be totally changed to cope with the complexity and heterogeneity of future software-based infrastructures (current processes cannot be simply updated);
- OSS/BSS must be able to dynamically cooperate with the control and orchestration capabilities;
- Workforce needs to be completely retrained in this new environment, and new skills have to be developed.



- Open - standard interfaces are needed but related standards are not yet stable: it's still a moving target in the industry, with vendors' lock-ins.
- This digital transformation is impacting not only Telcos but also equipment suppliers (for both Telco and IT domains) who are trying to position themselves with different interpretations on how/when SDN and NFV will impact future infrastructures. This is an influencing factor in the overall biz transformation strategies of Telcos.
- Eventually it should be noted that SDN and NFV are lowering the thresholds for new Players to enter in the Telecommunications and ICT ecosystems: it is likely that current Telcos and equipment suppliers will see new Competitors (even Start-ups) in their business segments.
- Regulation will be another determinant factor influencing the overall biz transformation strategies of Telcos.

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# Chapter 7 Closing Remarks and Future Work

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## 7.1 Summary of contributions

Broad-band diffusion and ICT performance acceleration, coupled with costs reductions, are boosting innovation in several industrial and society sectors thus creating the conditions for a socio-economic transformation, which is called Softwarization (sometimes IT-zation or Cloudification).

Softwarization will allow to virtualize all the network and services functions of a Telecommunication infrastructure and executing them onto distributed software platforms fully decoupled from the underneath physical infrastructure (almost based on standard hardware).

Any ICT and Telecommunication services (X-as-a-Service) will be provided by using a “continuum” of virtual resources (of processing, storage and communications) with practically very limited upfront capital investment and with modest operating costs.

This vision will see a first concrete instantiation with the 5G, expected to exploit this radical techno-economic transformation of Telecommunications. In fact, 5G will be a massively dense distributed infrastructure, integrating processing, storage and (fixed and radio) networking capabilities, capable of producing radical socio-economic impacts.

Eventually, it is argued that in the same way, metaphorically, as a computer network have Network Operating System (OS) such 5G will have to have an OS capable of operating the converged fixed-mobile infrastructure (5GOS).

5GOS should be a system software that controls the various 5G resources and how they communicate with each other. It should be a sort of overarching multi-level orchestration system, spanning from the Cloud, to the Network nodes up to the Users' Terminals and Equipment.

The overall goal of this thesis has been investigating technical challenges and business opportunities brought by the “Softwarization” of future Telecommunications (e.g., 5G), recognised as a “game changer” of the Digital Society and Economy.

This overall goal has been articulated in a number of objectives: 1) defining a vision for future 5G infrastructures, the scenario, use-cases and the main requirements; 2) defining the functional architecture of an Operating System for 5G; 3) designing the software architecture of a local implementation of 5G for the “edge cloud”; 4) understanding the techno-economic impacts of the vision and 5GOS and the most effective strategies to exploit it.

Let's summarize the main contributions provided by this thesis:

- Contribution 1: Analysis of the state of the art on SDN and NFV, with particular reference to the ongoing activities international bodies and open source initiatives
- Contribution 2: Analysis the state of the art on Cloud, Edge and Fog Computing
- Contribution 3: Developed the vision of “Softwarization” of Telecommunications, where SDN, NFV, Cloud, Edge and Fog Computing are seen as facets of an overall

systemic transformation in Telecommunications. Producing arguments that 5G will be a first concrete exploitation of “Softwarization”.

- Contribution 4: Understanding the requirements for the management and orchestration of virtual network functions and services in a future virtualized infrastructure.
- Contribution 5: Analysis of DevOps and submission of a contribution for IETF (for the contribution see annex)
- Contribution 6: Analysis of the state of Autonomic and Cognitive capabilities which could increase the level of automation in the Operations of a future virtualized infrastructure.
- Contribution 7: Analysis and definition of 5G scenarios and use-cases, from which the main functional and non-functional requirements for 5G have been derived.
- Contribution 8: Definition of a unifying concept/model of 5G service, valid across IaaS, PaaS and SaaS.
- Contribution 9: Developed the scope and functional architecture of an OS for 5G, with local and centralised functions. Designed the software architecture of an example of OS for the Edge Cloud. Submission of a contribution, on 5GOS, for ITU-T Focus Group on “Network Softwarization” (for the contribution see annex)
- Contribution 10: Analysis the current value chain and developed a model of the future value chain.
- Contribution 11: Analysis the main initiatives of the Telco Network Operators/Service Providers in order to infer the strategies most adopted.

## 7.2 Closing Remarks and next steps

In summary it is argued that techno-economic drivers are creating the conditions for the Softwarization. As one of the main consequences of this transformation, the Internet will enter deeper and deeper into the socio-economic processes of the our Society and as such it is becoming a more integral part of our daily life. This trend that will undoubtedly continue into the future so that it is argued that the “Internet will disappear”.

In the near future, the way the Telecommunications will be used and perceived will change radically.

Telecommunications infrastructures will be transformed from a network of interconnected closed boxes (today’s nodes and IT systems, e.g., switches, routers, middle-boxes, servers etc.) into a continuum of logical containers executing millions of intelligent software processes, interacting each other. A massive use of standard hardware (instead of specialized one) – in principle - will reduce the CAPEX.

This transformation will radically increase flexibility, programmability eventually robustness but also the level of complexity of future Telecommunications infrastructures. Human made configurations will not be able to face such level of complexity. Control, Management, Orchestration and Policy will be have to acquire an high level of automation, which in turn will reduce OPEX.

Smart terminals, autonomous machines, drones and robots will become the natural extension of Telecommunications infrastructures, embedded, “closing the loops” into the reality. This will have huge impacts in industry, in agricultural automation and in optimizing almost any socio-economic process in smart cities.

This radical transformation will enable the development of new service paradigms (e.g., security as a service, cognition as a service, etc.) creating the conditions for new ecosystems to emerge.

### 7.3 A glimpse into the future

The technology trends and the transformation discussed in this thesis are bringing to a convergence Computer Science, Telecommunications Artificial Intelligence and Industrial Mathematics: in fact, autonomous machines are starting learning<sup>16</sup> as humans, they are becoming globally interconnected and today terminals, such as smart-phones, in the near future will be replaced by new forms of A.I. interfaces<sup>17</sup>.

One of the most challenging future trends of A.I. will be really developing machines acquiring a certain level of “artificial consciousness”: means to get there will be networking and then combining sets of functions capable of encoding, processing and storing very specific “informational structures”, received and exchanged with the world. Some interesting studies about entangling consciousness agents<sup>18</sup> are moving in this direction.

In summary: mathematics will be language, computation will be about running said language (coded in software), storage will be about saving this encoded information and, eventually, the Network will be creating relationships – hopefully at almost zero latency - between said sets of functions. Consider, for example, Google funding researches about how converting language into a problem of vector space mathematics: basically this is about using data mining techniques for modeling the structure of a language and compares it to the structure of another language. It is likely that, advances in this direction will concern bringing this “intelligence” into the Operating Systems to empower devices with the capacity for logic and natural conversation<sup>19</sup>.

Already today, we are coupling our mind/body with laptops, tablets, smartphone, wearable, avatars, cognitive agents, etc...: in the future we’ll see different forms of intertwining humans and machines intelligence and consciousness, through the advances of A.I., future Internet and 5G.

Eventually the future entanglement of humans-machines intelligence and consciousness will be one of the most exciting and challenges directions of research and innovation, requiring multi-disciplinary approaches with far reaching implications for our Society and Economy.

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<sup>16</sup> [http://www.kurzweilai.net/when-machines-learn-like-humans?utm\\_source=KurzweilAI+Daily+Newsletter&utm\\_campaign=13e4d36e28-UA-946742-1&utm\\_medium=email&utm\\_term=0\\_6de721fb33-13e4d36e28-281953201](http://www.kurzweilai.net/when-machines-learn-like-humans?utm_source=KurzweilAI+Daily+Newsletter&utm_campaign=13e4d36e28-UA-946742-1&utm_medium=email&utm_term=0_6de721fb33-13e4d36e28-281953201)

<sup>17</sup> <http://www.ericsson.com/res/docs/2015/consumerlab/ericsson-consumerlab-10-hot-consumer-trends-2016-report.pdf>

<sup>18</sup> [https://www.youtube.com/watch?v=6eWG7x\\_6Y5U](https://www.youtube.com/watch?v=6eWG7x_6Y5U)

<sup>19</sup> <https://wtvox.com/robotics/google-is-working-on-a-new-algorithm-thought-vectors/>

## 7.4 Next steps

As next steps for extending the contributions provided will include:

- continuing a critical analysis of the state of the art on SDN, NFV but also Cloud, Edge and Fog Computing as it is argued that all these paradigms are converging quickly as expressions of a same systemic transformation in Telecommunications;
- pursuing a deeper and deeper analysis of the impact of Softwarization on the value chain of Telecommunications, considering also the strategic role of regulation; contributing to the convergence of the plethora of standards on SDN and NFV;
- finding scalable, secure and resilient solutions for Control, Orchestration, Management and Policy of future «software infrastructures» (e.g., 5G), which will be characterised by randomness, heterogeneity and modularity. «Complexity» will reach such high levels that radically new approaches will be required in the architectural design and the operations;
- implementing pre-commercial solutions of a « plug and play » 5G Operating System, and creating the conditions for the development of new ICT ecosystems around it.



## Annex 1 – List of published papers

1. A. Manzalini, N. Crespi, “Mitigating Systemic Risks in Future Networks”, Computer Aided Modeling and Design of Communication Links and Networks (CAMAD), 2012 IEEE 17th International Workshop on;
2. A. Manzalini, N. Crespi, R. Minerva, Uddin Shan Muhammad Emad, Chapter “Software Networks At the Edge” IGI Book title: Evolution of Cognitive Networks and Self-Adaptive Communication Systems; , 2012;
3. A. Manzalini, R. Minerva, F. Callegati, W. Cerroni, A. Campi “Clouds of Virtual Machines at the Edge”, IEEE Com Mag Future Carriers Networks, 2013;
4. D. Darsena, G. Gelli, A. Manzalini, F. Melito and F. Verde “Live migration of virtual machines among edge networks via WAN links”, paper # 159, [www.FutureNetworkSummit.eu/2013](http://www.FutureNetworkSummit.eu/2013);
5. A. Manzalini “Future ICT Networks” MMTC E-Letter: SDN Industrial Column for the May Issue at <http://committees.comsoc.org/mmc/e-news/E-Letter-May13.pdf>; , 2013;
6. A. Manzalini “Self-Organization and Stability in Software Networks Maximization of Ecosystems Utility Functions in Vol. 3 Iss. 2 of the International Journal of Information Engineering (IJIE). <http://www.vkingpub.com/Journal/ijie/Archive.aspx> American V-King Scientific Publishing;
7. A. Manzalini, N. Crespi et alii, “Manifesto of Edge ICT Fabric”, ICIN2013 (Venice, October 2013);
8. A. Manzalini, R. Minerva, V. Gonzales, "Halos Networks: A Competitive Way to Internet of-Things" Communications & Strategies, No. 87, 3rd Quarter 2012, pp. 41-55, ERN Economics of Networks eJournal, Vol. 5 No. 62, 09/09/2013;
9. R. Minerva, C. Moiso, A. Manzalini, N. Crespi, Virtualizing Platform, In Evolution of Telecommunication Services, a cura di E. Bertin, N. Crespi, T. Magedanz, LNCS 7768 (Springer Berlin Heidelberg, 2013), 203-226, ISBN 978-3-642-41568-5;
10. R. Minerva, A. Manzalini, C. Moiso, N. Crespi, Virtualizing Network, In Evolution of Telecommunication Services, a cura di E. Bertin, N. Crespi, T. Magedanz, LNCS 7768 (Springer Berlin Heidelberg, 2013), 227-256, ISBN 978-3-642-41568-5;
11. M. di Bernardo, E. Maini, A. Manzalini and N. Mazzocca, “Traffic dynamics and vulnerability in hypercube networks”, submitted to ISCAS2014;

12. M. Ulema, N. Amogh, R. Boutaba, C. Buyukkoc, A. Clemm, M. Vuran, L. J. Xie, A. Manzalini and R. Saracco, "IEEE Software Defined Network Initiative", IEEE Workshop SDN4FNS, Trento, 11-13 Nov.2013;
13. A. Manzalini and R. Saracco, "Software Networks at the Edge: a shift of paradigm", IEEE Workshop SDN4FNS, Trento, 11-13 Nov.2013;
14. W. John, K. Pentikousis, G. Agapiou, E. Jacob, M. Kind, A. Manzalini, F. Risso, D. Staessens, R. Steinert and C. Meirosu, "Research Directions in Network Service Chaining", IEEE Workshop SDN4FNS, Trento, 11-13 Nov.2013;
15. F. Risso, A. Manzalini and M. Nemirovsky "Some Controversial Opinions on Software-Defined Data Plane Services", IEEE Workshop SDN4FNS, Trento, 11-13 Nov.2013;
16. A. Galis, S. Clayman, L. Mamas, J. Rubio-Loyola, A. Manzalini, S. Kukliński, J. Serrat and T. Zahariadis, "Softwarization of Future Networks and Services - Next Generation SDNs", IEEE Workshop SDN4FNS, Trento, 11-13 Nov.2013;
17. D. Soldani, A. Manzalini, et al. "Software defined 5G networks for anything as a service [Guest Editorial]." *Communications Magazine*, IEEE 53.9 (2015): 72-73;
18. Kim, Juhoon, A. Manzalini, et al. "Service provider DevOps for large scale modern network services." 10th International Workshop on Business-driven IT Management, part of IM2015, the IEEE International Symposium on Integrated Network Management (BDIM 2015). 2015.
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29. A. Manzalini, N. Crespi, "A Global Operating System for SD-Infrastructures", IEEE NCCA 2015, Munich, June 2015;
30. A. Manzalini, N. Crespi, "An Edge Operating System enabling Anything-as-a-Service", IEEE Communication Magazine's feature Topic: Semantics for Anything-as-a-Service, March 2016;
31. C. Buyukkoc, A. Manzalini, L. Peterson, "From CORD to the 5G era"; Notiziario Tecnico Telecom Italia Mobile, April 2016;
32. F. Callegati, W. Cerroni, C. Contoli, R. Cardone. M. Nocentini, A. Manzalini "SDN for Dynamic NFV Deployment", approved for publication on IEEE Communication Magazine, October, 2016;
33. A. Manzalini, N. Crespi, "An Operating System for the Digital Society and Economy", Submitted to Communications of the ACM (June 2016);
34. A. Manzalini, C. Buyukkoc, P. Chemouil, N. Crespi "Towards 5G Software-Defined Ecosystems Technical Challenges, Business Sustainability and Policy Issues" 2<sup>nd</sup> White Paper of IEEE SDN.

## Annex 2 – Selection of papers

1. Paper “Clouds of VMs at the Edge”, IEEE Com Mag Future Carriers Networks, 2013 ;
2. White Paper for IEEE SDN “Software-Defined Networks for Future Networks and Services”, January 2014;
3. Contribution to ITU-T “A Global Operating System for 5G Infrastructures” (Seoul/Bejiin, March/May, 2016) ;
4. Draft IETF “DevOps for Software-Defined Telecom Infrastructures” draft-unify-nfvrg-devops-02.txt (March, 2016) ;
5. White Paper for NetWorld 2020 (5GPPP) “5G Experimental Facilities in Europe”, v11, (February, 2016) ;
6. Description of demonstration “Exploiting Infrastructure Capabilities to Dynamically Orchestrate NFV Services across Multiple Domains” (ETSI, May 2016).

# Clouds of Virtual Machines in Edge Networks

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**Abstract**— This paper addresses the potential impact of emerging technologies and solutions, such as Software Defined Networking and Network Function Virtualization, on carriers' network evolution. It is argued that standard hardware advances and these emerging paradigms can bring the most impactful disruption at the networks' edge, enabling the deployment of clouds of standard hardware nodes: it will be possible virtualizing network and service functions, which are provided today by expensive middle-boxes, and moving them at the edge, as much as possible near the Users. Specifically, this paper identifies some of key technical challenges behind this vision, such as the dynamic allocation, move and orchestration of ensembles of Virtual Machines across wide area interconnections between edge networks. This evolution of the network will impact profoundly the value-chains: it will create new roles and business opportunities, totally reshaping the entire Telco-ICT world.

**Index Terms**— Software Defined Networks, Network Function Virtualization, Edge Networks, Virtual Machines Migration.

## 1 INTRODUCTION

The original Internet paradigm focused on packet forwarding based on the IP address, to reach a given final destination. This is not true anymore, in current IP networks packets are processed in intermediate nodes not only for address lookup, but also for a number of additional functions, i.e. middle-boxes for network address translation, packet filtering, application acceleration over WANs, network monitoring, QoS management, load balancing, etc. Each middle-box typically (closed and quite expensive) supports a narrow specialized function (layer 4 or higher) and it is mostly built on a specific hardware platform.

Middle-boxes are deployed along most paths from sources to destinations: that's why networks lost the initial end-to-end principle of Internet (with packets being just forwarded). Not only, middle-boxes are also representing a significant fraction of network capital and operational expenses (due to management complexities).

The *ossification* of the Internet makes difficult for operators to develop and deploy new network functionality, services, management policies, etc. essential to cope with the increasing complexity and dynamicity of networks.

Launching new services requires time-consuming and expensive efforts, thus preventing a rapid roll out of new revenues, which is an important business requirement in a very dynamic market. The network operators' innovation cycles should be simplified by improving network flexibility and adaptability to market dynamics.

Future networks should reduce operational expenditures (OPEX) and capital expenditures (CAPEX): for instance, automated management and configuration of network equipment will reduce the need for human intervention, thus limiting the chances of wrong configurations, whereas flexible provisioning of network functionality on top of an optimally shared physical infrastructure will reduce equipment costs and allows to postpone network investments.

Progresses in the performance of standard hardware and emerging paradigms such as Software Defined Networking (SDN) [1] and Network Function Virtualization (NFV) [2] may help in fulfilling the aforementioned requirements.

This paper argues that future networks infrastructures will be made of a sheer number of resources (compute, storage and network I/O) being controlled dynamically based on Users' demands, QoS and business objectives, or any other changing conditions. Data analytics systems and methods should then allow exploiting a global autonomic loop capable of orchestrating virtual functions allocated to this fabric of resources.

This paper argues that the edge of the networks is the starting point from which this innovation wave will start: this is also fuelled by pervasiveness of embedded communications, computing and storage power in User's devices. In less than a decade, Edge Networks will create distributed environments made of clouds of virtual resources (operated even by diverse players) interconnected by a simpler, less hierarchical and core network.

Core network will then become stateless (as Internet in former days) and the Edge Networks (and the Data Centers) will become the only stateful parts of the networks. This transformation will enable new roles and business opportunities, completely reshaping the value chains in the entire Telco-ICT world.

In essence, the key enablers of this evolution will be the advances in processing, storage and networking technologies that will allow the development of networks nodes based on standard off-the-shelf hardware, cheap but powerful enough to run virtualized network functions and services.

Edge Networks will encompass a sheer number of inexpensive nodes and Users' devices capable of collapsing the OSI layers (e.g. L2 to L7) on standard hardware solutions.

One of the main challenges behind this vision is the capability of dynamically instantiating, orchestrating and migrating multiple Virtual Machines (VMs) across the providers' transport networks. Ensembles of VMs will be strictly related and intertwined to implement sets of virtual functions and services that network operators, and even Users, must be able to configure and program.

The rest of this paper is structured as follows. Trends and enabling technologies are described in Section II. Examples of network scenarios are discussed in Section III. A survey of the related works is reported in Section IV. Section V presents the experimental results of a use-case, demonstrating the feasibility of the vision and pointing out the current technical limitations. Section VI elaborates about the role of network operators in the

envisioned future scenarios and draws some conclusions.

## 2 TRENDS AND ENABLING TECHNOLOGIES

Progresses on the SDN paradigm have recently sparked a significant industrial interest in rethinking network architectures, control and management [1]. The SDN vision consists in decoupling the control plane logic from the forwarding hardware and moving the network states to a component, called *controller*. This basic idea is not a new concept, but for the first time processing, storage and network throughput performance may realistically support this disruption for carrier grade services.

Virtualization of physical resources will also have a significant impact on network evolution. In the IT field, virtualization is already well known and widely deployed in data centers to execute multiple isolated instances of a software entity on top of a single physical server. Virtualization has several advantages: for example, it increases resource utilization and improves state encapsulation. The extension of IT virtualization principles to network equipment (such as routers and switches) offers several advantages in terms of optimized use of the physical resources and allows a deeper integration of IT and network resources [2], [3].

Moreover, as proposed in the NFV initiative, implementing network processing functions in software (possible today) allows to execute them on standard hardware [4]. As a consequence of this evolutions, operations, normally carried out in data centers, such as allocation, migration and cloning of virtual resources and functions (e.g. for server consolidation, load balancing, etc.) could be also applied in the network. This means that it should be possible to leverage, with proper enhancements, those management tools which are used today in Data Centers.

Network virtualization, for example, allows to collocate multiple instances of network functions in the same hardware, where each function is executed by one or multiple VMs, as illustrated in Fig. 1.

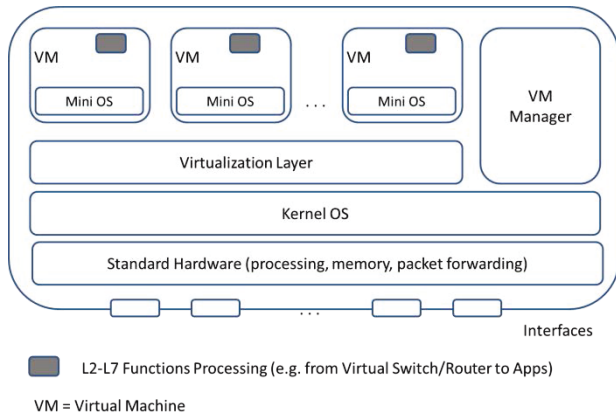


Figure 1. Example of generalised node architecture.

As a result, network operators may dynamically instantiate, activate and re-allocate resources and functions, as well as program them according to dynamic needs, requirements and policies.

*It should be noted that NFV is complementary to SDN but not depending on it: the two concepts should not be mixed even though they can be combined in several ways that can potentially create a great value.*

To make such a combination feasible and exploitable, some technical challenges are still to be solved. The capability of moving and orchestrating sets of VMs across wide area connections (not just locally, as in data centers) is one of such challenges. Available virtualization tools, used for intra-data center applications, offer just a limited support for WAN live migration of VMs, due to the lack of signaling and control tools spanning over multiple technologies and domains and because of the strict constraints in terms of throughput and delay. This is a point of weakness over which future research and development activities should focus. Section V presents some experimental results of a use case addressing these issues and showing its potential feasibility and limitations.

Furthermore, network operators should be able to face the increasing complexity of the network management and control, exacerbated by the aforementioned needs. This will require the integration of autonomic and cognitive capabilities within virtualization solutions [5]. As an example, one may imagine an Edge Network

capable of self-organized learning, i.e. capable of extracting knowledge from the environment and using such knowledge to improve the performance. This means to embed into its nodes and devices a number of autonomic and cognitive methods with a set of local rules capable of changing, for instance, the “characteristics” of the local interconnections of a node with the immediate neighbors.

### 3 APPLICATION SCENARIOS

This Section reports some application scenarios that could be of particular interest for network operators all fitting into the reference network scheme depicted in Fig. 2.

One example is *Networks Portability*: network services and functions could be initially deployed and tested by using a certain network and cloud environment (e.g. in a given domain or country); in a second phase the whole services and functions (i.e., networks and servers configurations, states, etc.) could be moved to another physical network and cloud environment (e.g. in another domain or in another country) even by leasing processing and network physical resources from other local cloud and infrastructure providers.

Another example is *Networks Federation*: different virtual networks (putting together virtual IT and communication resources) can be seamlessly federated, despite being geographically remote. This is the ideal scenario for an operator wishing to provide de-perimetrised services across different domains or countries.

*Networks Partitioning* is another possible scenario: a virtual network, providing certain services, can be seamlessly partitioned into smaller sub-networks to simplify administrative tasks. Maintenance can be performed on a subset of the infrastructure without causing any noticeable downtime in the provided services.

In a longer term perspective, this network transformation will create the conditions whereby Users will literally “decide and drive” future ICT networks and services. This will have big impacts. This floating “fog” of ICT resources at the edge will give rise to new biz mod-

## 4.1 Survey of Related Work

VM live migration should be essentially transparent to applications: in principle this is already supported by most virtualization platforms for data centers [6]. For example, most virtualization environments support live migration, allowing administrators to move a VM between physical hosts within a LAN platform while running (e.g. XenMotion and VMotion)<sup>20</sup>.

However, when considering to move a VM across WANs, low bandwidth and high latencies over network connections may dramatically reduce the performance of the VM migration, and as such, the QoS/QoE of applications. Some commercial solutions have been recently announced for WAN migration, but only under very constrained conditions, i.e. 622 Mbps link bandwidth and less than 5 ms network delay.

The challenge of live migration of VM across WAN has been analyzed in [7], where the proposed solution (CloudNet) interconnects local networks of multiple data centers at Layer 2; so that WAN-based cloud resources look like local LAN resources, allowing LAN-based protocols to seamlessly operate across WAN sites.

An overlay approach to create private groups of VMs across multiple grid computing sites has also been investigated; but this approach can hardly scale for NFV in a carrier class network [8], [9].

A WAN migration system focusing on efficiently synchronizing disk state during the migration was described in [10]; the Xen block driver has been modified to support storage migration, and VM disk accesses are limited when the write requests occur faster than what allowed by the network.

A solution for high fault tolerance using asynchronous VM replication was reported in [11]. This method im-

els based on new forms of competition and cooperation between existing Providers, and new ones entering the arena, including utilities, car manufacturers, consumers' electronics, public administrations, communities, etc.

A galaxy of new ecosystems will be created, rewarded directly by the market itself, which will be essential encouragement for further investments.

We are already witnessing that the declining costs of computation, communication, and storage are moving the means of information and entertainment production from a limited number of companies to hundreds of millions of people around the planet.

So, ideally, at the edge it will be possible creating, programming, instantiating or migrating dynamically different types of virtual functionalities and services as well as alternatives of the same. No more ossified architectures, but sort of ephemeral virtual networks of resources capable of self-adapting plastically to humans' dynamics.

Also, we should not forget the rise of large-scale cooperative efforts under the form of open source software and hardware development and production, which might soon create a further ripple in the Telco-ICT vendor markets.

These trends, in turn, will influence the network transformation itself by making open source software and hardware available for carriers' class pieces of equipment.

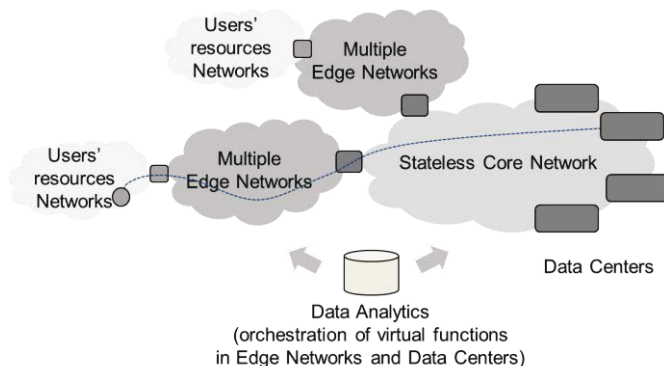


Figure 2. Future network scenario.

<sup>20</sup> See the respective websites at <http://www.xenserver5.com/xenmotion.php> and <http://www.vmware.com/products/vmotion/>.



plements a quick filter of clean pages and maps the guest domain's entire physical memory to reduce mapping overhead.

Finally a scheme for VMs migration in a federated cloud environment was presented in [12]. It is used to detect the overloaded servers and automatically initiate the migration to a new location in the cloud, thus eliminating the hotspots and balancing the load considering CPU, memory and network as a whole.

In summary, results from prior art and commercially available solutions are still showing insufficient performance levels, as required by a carrier class network: so we argue that the vision of an Edge Network made of clouds of VMs is actually feasible, although there are open challenges yet to be addressed by research and development activities.

## 4.2 Open Challenges

One of the major challenges is to make the migration of VMs as much seamless as possible, to have no (or very limited) impact on the Users' QoE. Such migration can be seen from two different perspectives. The former considers the migration of VMs running an application (e.g. video streaming, interactive multi-media gaming). Motivations to migrate a VM running an application could be intra or inter data center load balancing (e.g., to avoid performance degradations due to hot spots), or following Users moving to other network attachment points (e.g. for QoE optimization). The second perspective considers the migration of VMs running a virtual middle-box function (fully developed in software): this might be even more challenging, especially when the migration is executed while the traffic is flowing. Motivations could be again network load balancing, traffic engineering (avoiding performance degradation due to host spots and congestions), energy consumption various other optimization, etc.

Typically, moving a VM between two hosts involves the following steps:

1. establish connectivity (e.g. layer-2 for intra-data center operations) between the hosts;
2. transfer the whole disk state;

3. transfer the memory state of the VM to the target host, as the source continues running without interruption;
4. once the disk and most of the memory states have been transferred, freeze the VM execution for the final transition of remaining memory dirty pages and processor states to the target server.

Implementation and performance issues to successfully complete these actions are well understood in LANs, but not in WANs where bandwidth constraints and latency will impact steps 2 and 3, and IP address consistency will be an issue in step 4.

It is important to match the performance parameters (e.g. total migration time and total downtime) of moving a VM, running applications characterized by a given dirty page rate, with the network performance indicators (e.g. throughput, latency, etc). For example, the total migration time is roughly given by the number of dirty pages (depending on the VM workload) that should have been sent during the whole migration process divided by the available connection bandwidth. A complete analysis of these challenges is still missing and requires further investigation.

Another challenge that must be added to the previous ones is the problem of migrating a batch of VMs. The scenario here considered envisages networks of intertwined VMs, implementing IT and network resources.

Moreover, network operators will have to face the increased complexity of management and control as well as the orchestration of said virtual functions and resources. This will require also the exploitation of automatic "local vs global" capabilities in order to create a sort of overall Operating System.

Eventually, a creation environment, with open API's, allowing to program the network at various levels, will complete the vision.

## 5 USE CASE AND EXPERIMENTAL RESULTS

This section discusses, with a practical example, the degree of feasibility of the scenarios defined above. A use case is designed to implement a test-bed supporting the network function migration. The experiment demonstrates that the orchestration can be successfully

implemented by extending existing protocols (i.e. SIP in this case), spanning different logical layers and network functions, whereas the migration of VMs still represents a performance bottleneck for carrier grade operations, which require further investigation and engineering effort.

## 5.1 Use case

The basic scenario is a simple example of networks portability and federation, as depicted in Figure 3. A User is watching a video available on a video server, through both a physical (wireless or wired network access) and a virtual network infrastructure (virtual router). The former is responsible for the pure connectivity between the User and the data center where the service is hosted; the latter is responsible for the additional service profiling which may be required by the specific application, i.e. bandwidth reservation, traffic shaping and/or isolation, etc.

It is assumed that the network operator, at some stage, considers more efficient to migrate the network service, state and virtual infrastructure to a different data center. This could be motivated by many reasons: for example, initially the User could be watching the video on the move using mobile access, whilst, at a later time, he/she reaches home and connects to the fixed broadband access network. In this case the operator decides to move the virtual resources, which were hosted in a data center serving the mobile network, to another data center optimally connected to the fixed User access network; this will allow, for example, the

User to take advantage of the larger bandwidth available and watch the video stream at a higher definition.

The main actions necessary to perform this migration are depicted in Figure 3. Basically what is needed is a kind of orchestration of the migration procedure, involving the whole set of VMs that compose the virtual network infrastructure and that must be moved from one data center to another one over the WAN, in a way that should appear as seamless as possible to the user. In other words, we expect the migration to be completely transparent to the User, who should continue to retrieve the same video stream from the same video server at the same network address.

Such an orchestration requires a signaling platform which is able to carry cross-layer information used to coordinate the whole actions to be performed. An example of this orchestration was recently reported in [13], where a video server is migrated while reconfiguring the underlying network in order to keep the reservation of the bandwidth sufficient for a good customer's QoE. The use case reported here exploits the same signaling, but with the additional complexity of orchestrating the migration of a whole set of Virtual Machines and related network state. This use case focuses mainly on network and IT virtualization. Nonetheless SDN could be part of this scheme: for instance, in case of a more complex physical network topology, SDN can be the key component of the orchestration of network resources that must be properly reconfigured to successfully complete the migration.

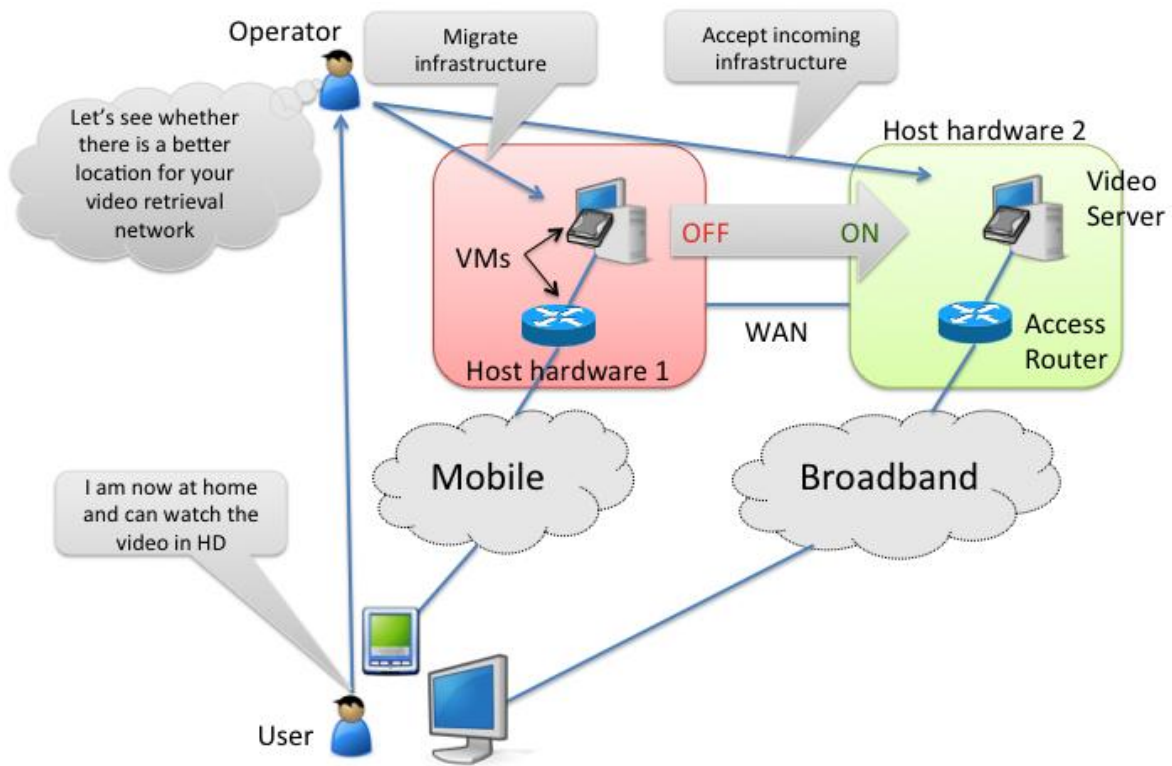


Figure 3. Schematic graphical example of the service and network migration experiment.

## 5.2 Experimental Set-up

The experimental test-bed used to prove the concept was implemented on purpose using off-the-shelf technologies. The aim is to understand the weak points and the areas where ad-hoc development and engineering are required to meet carrier grade standards in the overall operation.

The signaling platform for service management and orchestration is implemented using the SIP protocol, just as an example (for more details see [14]). In summary, taking advantage of the SIP session management capability, it is possible to create and maintain the network state necessary to guarantee full consistency during the migration, while the body of the SIP messages is able to carry the information used to specify what has to be migrated, where to and when. The signaling scheme is supported by a SIP proxy implemented with the OpenSIPS platform with minor add-ons to allow the correct stripping of the message body with the additional information. The signaling terminals at the User and network operator sides consist of SIP user agents

implemented as web applications using the PHP language.

The hosting infrastructure is implemented by two multi-core servers equipped with a Linux CentOS distribution running VirtualBox as the VM hypervisor. The VMs used in the experiment include two virtual single-core Linux boxes, one acting as the video server, the other as the access router connecting the User to the server. In order to keep the migration latency as small as possible, the two VMs have been dimensioned with the minimum amount of memory (512 MB for both) and disk space (7.2 GB for the video server, 1.3 GB for the access router) needed to perform their functions. Live migration of the whole network infrastructure is performed through the VM teleporting function natively available in VirtualBox.

The two hosting servers emulating two remote data centers are connected by an ad-hoc link between interfaces that are separate from those used to communicate with the User. This set-up emulates the WAN interconnection between data centers. In the experiment reported here, this link is implemented with a Gigabit

Ethernet (1000baseT) point-to-point interconnection with negligible propagation delay. This choice again is motivated by the fact that the goal of this preliminary experiment is to prove that the concept is feasible with reference to the overall system architecture. A detailed investigation of the role of the WAN parameters on the performance is left to further studies.

In the experiment the signaling platform executes the full live migration of network and IT resources, in the sense that both video server and access router VMs are migrated together with the corresponding virtual network. Once the migration is completed, the same signaling platform triggers a live reconfiguration of the stream from Low Quality (LQ) to High Quality (HQ), since the User is now connected to the video source with broader bandwidth.

### 5.3 Experimental Results

Figure 4 reports the video throughput (i.e., the measured video stream bit rate) as seen by the final User during the whole experiment. The blue solid line represents the Variable Bit Rate (VBR) LQ video stream, which fluctuates around 1 Mbps, whereas the red dotted line represents the VBR HQ stream, with an average bit rate between 2 and 3 Mbps, although some peaks reach 6 Mbps. The inset in Figure 4 shows an enhanced view of the interval when the live migration occurs. The vertical arrows indicate the time instants when the live migration of the video server starts (T1) and ends (T2), when the live migration of the router starts (T3) and ends (T4), and when the stream switches from LQ to HQ (T5).

When the migration starts at T1, the User receives the LQ stream from the video server VM instance still

running at the source host. However, as soon as the video server migration is complete at T2, the LQ stream is interrupted because there is no connectivity between the access router still running on the source host and the video server now running on the destination host. The interruption lasts for about 5 seconds, which is the time needed in our test-bed to complete the migration of the access router VM (from T3 to T4) and restore the connectivity between the User and the video server. Then the LQ stream resumes, as measured by the blue solid curve rising again after T4. After a few seconds, at T5 the stream switches from LQ to HQ, as shown by the end of the blue solid curve replaced by the red dotted one.

The system outage caused by the live migration in another experiment is reported in detail in Figure 5, which shows the packet capture of a ping session where ICMP ECHO messages are sent every 100 ms. The video server is at IP address 172.16.3.100 while the User terminal is at IP address 192.168.107.197. This capture shows that the packets with sequence number from 216 to 245 are missing. These 30 packets are lost during the VM migration, which counts for a network outage of about 3 s. It is worth noting that, apart from this, the ping packet flow is exactly the same before and after the migration, showing that IP addresses and network state are kept unchanged.

Finally, Figure 6 reports a capture of the SIP signaling that triggers the VM migration. The capture shows the dialog between the SIP user agent at the source (IP: 10.10.10.66, UDP port: 50601, controlled by either the end User or the network/service manager), the SIP proxy (IP: 10.10.10.66, UDP port: 5060) and the SIP user agent at the destination (IP: 10.10.10.67, UDP port: 5060).

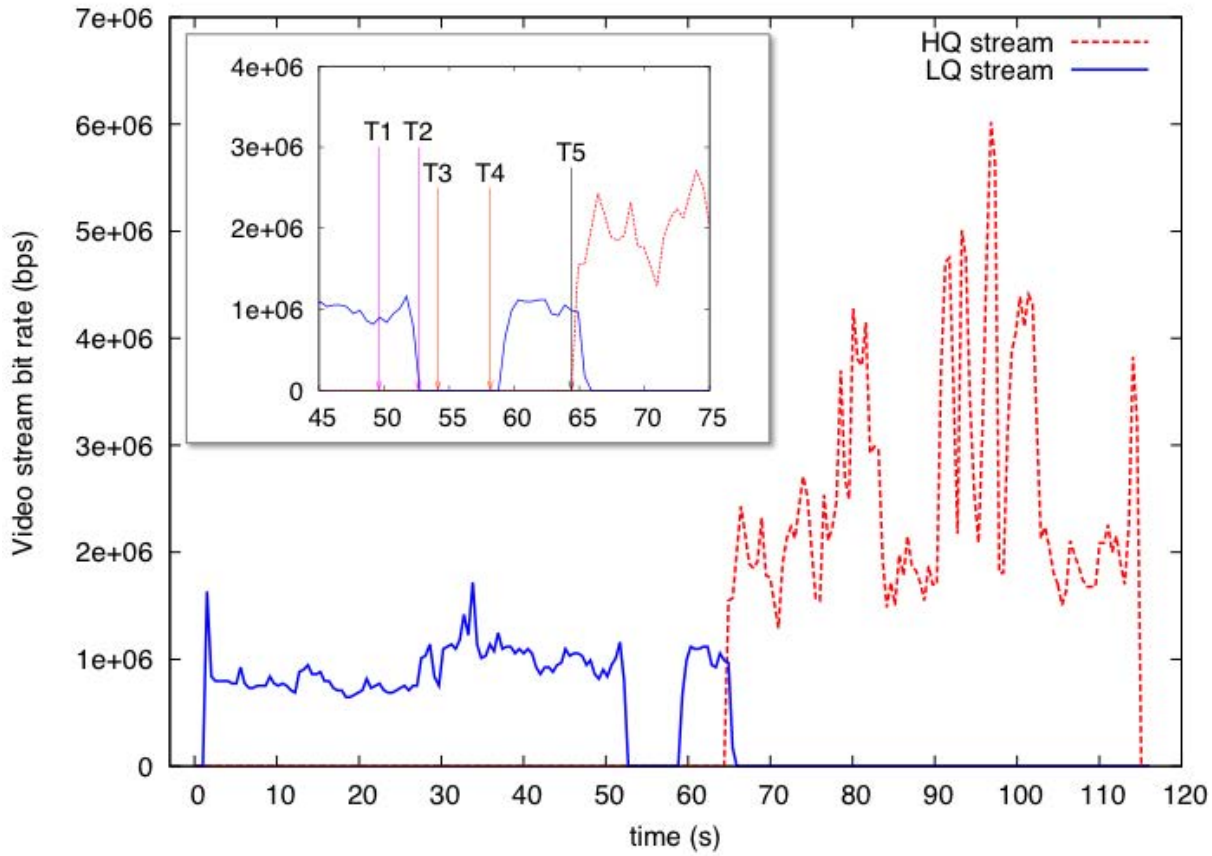


Figure 4. The video data flow as seen by the User terminal.

| No. | Time      | Source          | Destination     | Protocol | Length | Info   |
|-----|-----------|-----------------|-----------------|----------|--------|--|
| 422 | 21.048197 | 192.168.107.197 | 172.16.3.100    | ICMP     | 98     | Echo (ping) reply id=0x0654, seq=211/54016, ttl=64   |
| 423 | 21.149379 | 172.16.3.100    | 192.168.107.197 | ICMP     | 98     | Echo (ping) request id=0x0654, seq=212/54272, ttl=63 |
| 424 | 21.149399 | 192.168.107.197 | 172.16.3.100    | ICMP     | 98     | Echo (ping) reply id=0x0654, seq=212/54272, ttl=64   |
| 425 | 21.250333 | 172.16.3.100    | 192.168.107.197 | ICMP     | 98     | Echo (ping) request id=0x0654, seq=213/54528, ttl=63 |
| 426 | 21.250381 | 192.168.107.197 | 172.16.3.100    | ICMP     | 98     | Echo (ping) reply id=0x0654, seq=213/54528, ttl=64   |
| 427 | 21.351039 | 172.16.3.100    | 192.168.107.197 | ICMP     | 98     | Echo (ping) request id=0x0654, seq=214/54784, ttl=63 |
| 428 | 21.351081 | 192.168.107.197 | 172.16.3.100    | ICMP     | 98     | Echo (ping) reply id=0x0654, seq=214/54784, ttl=64   |
| 429 | 21.451944 | 172.16.3.100    | 192.168.107.197 | ICMP     | 98     | Echo (ping) request id=0x0654, seq=215/55040, ttl=63 |
| 430 | 21.451980 | 192.168.107.197 | 172.16.3.100    | ICMP     | 98     | Echo (ping) reply id=0x0654, seq=215/55040, ttl=64   |
| 431 | 24.869291 | 172.16.3.100    | 192.168.107.197 | ICMP     | 98     | Echo (ping) request id=0x0654, seq=246/62976, ttl=63 |
| 432 | 24.869357 | 192.168.107.197 | 172.16.3.100    | ICMP     | 98     | Echo (ping) reply id=0x0654, seq=246/62976, ttl=64   |
| 433 | 24.969890 | 172.16.3.100    | 192.168.107.197 | ICMP     | 98     | Echo (ping) request id=0x0654, seq=247/63232, ttl=63 |
| 434 | 24.969943 | 192.168.107.197 | 172.16.3.100    | ICMP     | 98     | Echo (ping) reply id=0x0654, seq=247/63232, ttl=64   |
| 435 | 25.070627 | 172.16.3.100    | 192.168.107.197 | ICMP     | 98     | Echo (ping) request id=0x0654, seq=248/63488, ttl=63 |
| 436 | 25.070688 | 192.168.107.197 | 172.16.3.100    | ICMP     | 98     | Echo (ping) reply id=0x0654, seq=248/63488, ttl=64   |
| 437 | 25.170760 | 172.16.3.100    | 192.168.107.197 | ICMP     | 98     | Echo (ping) request id=0x0654, seq=249/63744, ttl=63 |
| 438 | 25.170818 | 192.168.107.197 | 172.16.3.100    | ICMP     | 98     | Echo (ping) reply id=0x0654, seq=249/63744, ttl=64   |

Figure 5. Packet capture of a continuous ping session from the video server (172.16.3.100) to the User terminal (192.168.107.197) during the live VM migration.

| No. | Time      | Source      | Destination | Src Port | Dst Port | Protocol | Length | Info  |
|-----|-----------|-------------|-------------|----------|----------|----------|--------|---|
| 1   | 0.000000  | 10.10.10.66 | 10.10.10.66 | 50601    | 5060     | SIP      | 391    | Request: REGISTER sip:user2@10.10.10.66                     |
| 2   | 0.000210  | 10.10.10.66 | 10.10.10.66 | 5060     | 50601    | SIP      | 436    | Status: 200 OK (1 bindings)                                 |
| 3   | 0.012952  | 10.10.10.66 | 10.10.10.66 | 50601    | 5060     | SIP/XML  | 1743   | Request: INVITE sip:user2@10.10.10.67                       |
| 4   | 0.013343  | 10.10.10.66 | 10.10.10.66 | 5060     | 50601    | SIP      | 349    | Status: 100 Giving a try                                    |
| 6   | 0.013450  | 10.10.10.66 | 10.10.10.67 | 5060     | 5060     | SIP/XML  | 406    | Request: INVITE sip:user2@10.10.10.67                       |
| 8   | 0.031972  | 10.10.10.67 | 10.10.10.66 | 5060     | 5060     | SIP/XML  | 334    | Status: 200 OK  |
| 9   | 0.032130  | 10.10.10.66 | 10.10.10.66 | 5060     | 50601    | SIP/XML  | 1755   | Status: 200 OK  |
| 11  | 0.050975  | 10.10.10.66 | 10.10.10.67 | 50601    | 5060     | SIP      | 221    | Request: ACK sip:user2@10.10.10.67:5060                     |
| 14  | 10.889623 | 10.10.10.66 | 10.10.10.67 | 33807    | 7001     | TCP      | 76     | 33807 > afs3-callback [SYN] Seq=0 Win=5840 Len=0 M          |
| 15  | 10.889746 | 10.10.10.67 | 10.10.10.66 | 7001     | 33807    | TCP      | 76     | afs3-callback > 33807 [SYN, ACK] Seq=0 Ack=1 Win=1          |
| 16  | 10.889795 | 10.10.10.66 | 10.10.10.67 | 33807    | 7001     | TCP      | 68     | 33807 > afs3-callback [ACK] Seq=1 Ack=1 Win=5888 L          |
| 17  | 10.889845 | 10.10.10.66 | 10.10.10.67 | 33807    | 7001     | TCP      | 73     | 33807 > afs3-callback [PSH, ACK] Seq=1 Ack=1 Win=5          |
| 18  | 10.889938 | 10.10.10.67 | 10.10.10.66 | 7001     | 33807    | TCP      | 68     | afs3-callback > 33807 [ACK] Seq=1 Ack=6 Win=14592           |
| 19  | 10.944860 | 10.10.10.67 | 10.10.10.66 | 7001     | 33807    | TCP      | 88     | afs3-callback > 33807 [PSH, ACK] Seq=1 Ack=6 Win=1          |
| 20  | 10.944880 | 10.10.10.66 | 10.10.10.67 | 33807    | 7001     | TCP      | 68     | 33807 > afs3-callback [ACK] Seq=6 Ack=21 Win=5888           |
| 21  | 10.945098 | 10.10.10.66 | 10.10.10.67 | 33807    | 7001     | TCP      | 70     | 33807 > afs3-callback [PSH, ACK] Seq=6 Ack=21 Win=          |
| 22  | 10.945192 | 10.10.10.67 | 10.10.10.66 | 7001     | 33807    | TCP      | 68     | afs3-callback > 33807 [ACK] Seq=21 Ack=8 Win=14592          |
| 23  | 12.063601 | 10.10.10.67 | 10.10.10.66 | 7001     | 33807    | TCP      | 72     | afs3-callback > 33807 [PSH, ACK] Seq=21 Ack=8 Win=          |
| 24  | 12.104139 | 10.10.10.66 | 10.10.10.67 | 33807    | 7001     | TCP      | 68     | 33807 > afs3-callback [ACK] Seq=8 Ack=25 Win=5888           |
| 25  | 17.114230 | 10.10.10.66 | 10.10.10.67 | 54140    | 1234     | TCP      | 76     | 54140 > search-agent [SYN] Seq=0 Win=5840 Len=0 MS          |
| 26  | 17.114371 | 10.10.10.67 | 10.10.10.66 | 1234     | 54140    | TCP      | 76     | search-agent > 54140 [SYN, ACK] Seq=0 Ack=1 Win=14          |
| 27  | 17.114427 | 10.10.10.66 | 10.10.10.67 | 54140    | 1234     | TCP      | 68     | 54140 > search-agent [ACK] Seq=1 Ack=1 Win=5888 Le          |
| 28  | 17.114568 | 10.10.10.67 | 10.10.10.66 | 1234     | 54140    | TCP      | 94     | search-agent > 54140 [PSH, ACK] Seq=1 Ack=1 Win=14          |
| 29  | 17.114598 | 10.10.10.66 | 10.10.10.67 | 54140    | 1234     | TCP      | 68     | 54140 > search-agent [ACK] Seq=1 Ack=27 Win=5888 L          |
| 30  | 17.114668 | 10.10.10.66 | 10.10.10.67 | 54140    | 1234     | TCP      | 73     | 54140 > search-agent [PSH, ACK] Seq=1 Ack=27 Win=5          |
| 31  | 17.114765 | 10.10.10.67 | 10.10.10.66 | 1234     | 54140    | TCP      | 68     | search-agent > 54140 [ACK] Seq=27 Ack=6 Win=14592           |
| 32  | 17.114776 | 10.10.10.67 | 10.10.10.66 | 1234     | 54140    | TCP      | 72     | search-agent > 54140 [PSH, ACK] Seq=27 Ack=6 Win=1<br>..... |

Figure 6. The SIP signaling sequence triggering the VM migration. The source SIP user agent is at 10.10.10.66:50601, the SIP proxy is at 10.10.10.66:5060, the destination SIP user agent is at 10.10.10.67:5060.

## 6 CONCLUSIONS AND OPEN CHALLENGES FOR TELCO OPERATORS

In this paper it is argued that future networks infrastructures will be made of a sheer number of virtual resources (compute, storage and network I/O) being controlled dynamically based on Users' demands, QoS and business objectives, or any other changing conditions. In particular, standard hardware advances and emerging paradigms, such as SDN and NFV, will start this impactful disruption at the edge of current networks. It will be possible virtualizing network and service functions, which are provided today by expensive middle-boxes, and moving them at the edge, as much as possible near the Users.

The amazing increase of smart nodes and devices at the edges will provide globally enough processing power, data storage capacity and communications bandwidth to provide several services with local edge resources.

Actually, we are already witnessing this evolution, if we consider the current shift of value from the network to the terminals. Services are more and more often provided at the edge of the network, and this trend will consolidate in the future.

This transformation will turn the edge into a business arena composed by a multiplicity of interacting sub-domains, operated by diverse (both private and public) players and User communities.

Network operators should closely follow this transformation and evolve their business models accordingly: pursuing a traditional approach, or adopting walled gardens, will be detrimental for their business on the long run reducing the offering to a mere pipe connectivity. On the other hand, enabling open virtual environments at the edge will offer several business opportunities: in fact, future services and data will be virally delivered through multiple devices, machines, objects, mostly by using local resources.

Network operators could also play the role of infrastructure providers of Edge Networks, in conjunction with public administrations or other players willing to cooperate. The role is to help reducing the complexity

and to act as an "anchor" around which to organize complex and dynamic edge systems.

In this scenario, operations, normally carried out in data centers, such as allocation, migration and cloning of virtual resources and functions could be advantageously applied at the network's edges. This means that it should be possible to leverage, with proper enhancements, those techniques and management tools which are used today in data centers. Nevertheless this implies to overcome several technical challenges, among them the seamless allocation and migration of VMs across multiple distributed servers.

In this sense it will be also possible to overcome routing processing limitation by optimizing the use of the huge amount of processing power made available today in large data centers, and tomorrow at the edge of the networks. Software router architectures, for example, could be capable of parallelizing routing functionality both across multiple servers.

This would change, in principle, the (economic) equation of the network: overprovisioning connectivity rather than just overprovisioning bandwidth. Overprovisioning connectivity pays off better than overprovisioning capacity: it will be possible to create very large numbers of topologies to choose from, even almost randomly, or program and control the QoS at higher levels. Up today, to overprovision connectivity in a network is more expensive than to overprovision capacity, but tomorrow this equation may change.

This paper reports an experimental test-bed to demonstrate the feasibility of this vision under some practical application scenarios, taking advantage of existing technologies to implement the session-based signaling platform required to maintain the network state while migrating the virtual resources.

The experiments proved that future Edge Networks made of clouds of VMs (running virtualized network functions and services) are potentially feasible, as long as the performance limitations imposed by the current technology will be solved. Next steps will consider also the applicability of data analytics to create a global autonomic loop (complementing local actions)

to orchestrate these clouds of VMs at the edges and in the Data Centres.

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# Software-Defined Networks for Future Networks and Services

## Main Technical Challenges and Business Implications

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**Abstract** — In 2013, the IEEE Future Directions Committee (FDC) formed an SDN work group to explore the amount of interest in forming an IEEE Software-Defined Network (SDN) Community. To this end, a Workshop on “SDN for Future Networks and Services” (SDN4FNS’13) was organized in Trento, Italy (Nov. 11<sup>th</sup>-13<sup>th</sup> 2013). Following the results of the workshop, in this paper, we have further analyzed scenarios, prior-art, state of standardization, and further discussed the main technical challenges and socio-economic aspects of SDN and virtualization in future networks and services. A number of research and development directions have been identified in this white paper, along with a comprehensive analysis of the technical feasibility and business availability of those fundamental technologies. A radical industry transition towards the “economy of information through softwarization” is expected in the near future.

**Keywords**—*Software-Defined Networks, SDN, Network Functions Virtualization, NFV, Virtualization, Edge, Programmability, Cloud Computing.*

### I. INTRODUCTION

The ossification of Internet and Telecom networks is creating several difficulties for Service Providers (SP) and Network Operators (NO) to develop and deploy, flexibly, any innovative network functionalities, services and management policies, which are essential to benefit from the increasing dynamicity of the ICT markets. Launching new services, for example, is still time-consuming and requires expensive efforts: this is preventing any rapid roll-out of new businesses models and

opportunities. A first requirement is thus making the innovation cycles of networks and services features faster and simpler. Moreover there is a need, for both SP and NO of reducing OPERational EXPenditures (OPEX) and CAPital EXPenditures (CAPEX): concerning the OPEX, for instance, automated operation processes (e.g. configuration of networks and services systems and equipment) could limit human intervention, reducing also wrong operations; on the other hand, concerning the CAPEX, a flexible and optimal provisioning of network functions and services could reduce systems and equipment costs and allows postponing investments.

Emerging paradigms such as Software-Defined Networks (SDN) [1] and virtualization, for instance Network Functions Virtualization (NFV) [2], if properly designed and deployed, could help in fulfilling the above mentioned requirements: as a matter of fact, a deeper integration of networks and IT (e.g. Cloud) domains, and the related Operations (now mainly carried out separately), could allow huge savings, and the acquisition of greater flexibility in services provisioning.

In particular, according to a widely accepted definition, SDN concerns the decoupling of the software-based control plane from the hardware-based data plane (e.g., packets forwarding) of networking and switching pieces of equipment; in principle, this would allow moving control logic (and states) to logically centralized controllers. NFV is one of the most innovative expressions of virtualization, and specifically it implies the virtualization of network functions and services that could run on general purpose hardware; this would allow dynamically placing and moving said functions in various locations of the networks and services infrastructures.

Importantly, it should be noted that different developments and deployment scenarios of SDN and NFV could be envisioned, depending on network segments (e.g., core or edge) and, consequently, on time horizon (e.g., medium-long term or short term). These deployment scenarios, in turn, could require different amounts of investments (e.g., less investments in the edge), expected revenues and impacts on the Operations of NO and SP. Nevertheless, we are witnessing an overall trend of networks and services “softwarization” which is unstoppable as it is mainly due and driven by the continuous IT technology evolution and cost reductions.

In 2013, the IEEE Future Directions Committee (FDC) formed an SDN work group to investigate and determine the amount of interest in assembling an IEEE SDN community. In order to achieve this goal, a Workshop on Software-Defined Networks for Future Networks and Services (SDN4FNS’13) was held in Trento, Italy, on Nov 11-13<sup>th</sup> 2013 [3]. Around 70 international experts from industry (e.g., NO, SP, Technology Providers, etc), SMEs and academia gathered together to present visions, pieces of results and to discuss and draw the key challenges about the potential adoption of SDN and virtualization. Three keynote speeches, thirty presentations and three panel discussions provided a comprehensive overview of current and future research and development work, socio-economic aspects and impacts.

In this white paper, leveraging the results of the workshop, the authors have further analyzed scenarios,

prior-art, state of standardization, and reviewed the main technical challenges and socio-economic aspects of SDN and virtualization in future networks and services.

The rest of the paper is organized as follows. Section II reports some of the widely adopted terms and definitions of SDN and NFV, in order to align with the nomenclature; Section III summarizes the main outcomes of the IEEE Workshop SDN4FNS. Section IV describes some thought-provoking scenarios and use-cases. Section V provides an analysis of some of the more debated conceptual and functional models for SDN and related challenges. A brief status report on the main standardization activities is presented in Section VI. Conclusions and next steps are drawn in Section VII.

## II. TERMS AND DEFINITIONS

According to the Open Networking Foundation (ONF)[1] [4] a SDN is a network where the control (software-based) and data forwarding planes (hardware-based) are decoupled, so that, in principle, the network infrastructure could be abstracted from functions and business applications [4]. The proposed concept and architecture for SDN is illustrated in Figure 1.

In a SDN, for example, the decisions concerning flows switching and engineering are taken by a so-called SDN controller which interacts with SDN switches via the OpenFlow protocol (as defined by ONF). The protocol procedures are mostly related to data flows, queues and ports, while applications and functions, running on top of the controller, (not defined by ONF) may be developed by other implementers.

Nevertheless, above SDN definition is still evolving in order to enrich said networks with functionality, for example, to provide support for mobility, to add control and programming capabilities of other abstractions and even of physical or virtual resources.

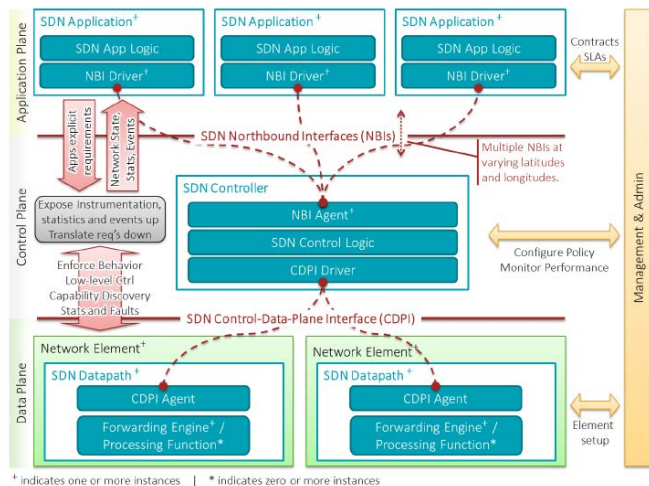


Figure 1 – SDN architectural model (Source: [4])

This evolution aims to cope with some specific problems and requirements such as scalability, performance, management, robustness or ability to adapt to multi-operator environment in which multiple SDN controllers or SDN domains have to co-exist. As high level functional definition may determine the elaboration of different systems and software architectures (with the related implementation for different networks' areas) there are, currently, several viewpoints in considering and assessing future deployments of SDN.

It has also to be noted that in the past other attempt have been made to decouple software from hardware and to achieve network programmability: an overview of such a concept was presented in [5] [6]. At present, several latest attempts, such as PCE [7], ForCES [8], or i2rs [9] are also denoted as in line with SDN principles and an effort to consolidate them under the SDN umbrella can be perceived. Such integration would be justified by some similarities of these concepts, especially the programmability of some operations and the separation of control and data planes. However some concerns related to the overall complexity and cost of such integrated solution could arise. Moreover between these concepts some substantial differences also exist, as “distributed i2rs driven by real-time management” versus “centralized SDN with fundamental role of con-

trol plane”, which make the integration of those troublesome.

It should be noted that SDN should not be confused with NFV, which is about the virtualization of some network functions that could be executed on standard of the shelf hardware.

In principle, this approach could allow introducing in network operations, those features which are today normally carried out in Data Centers (DC), such as dynamic allocation, migration and cloning of virtual resources and functions (e.g. for server consolidation, load balancing, etc.).

In the IT context, virtualization is already well known and widely deployed in Data Centers for enabling the execution of multiple isolated instances of a software entity on top of a single physical server. IT Virtualization has several advantages, for example it increases resource utilization and improves state encapsulation.

These principles have not been fully extended to networks. Network virtualization already exists in virtual private networks (VPNs) which generally use the multi-protocol label switching (MPLS) technology, operating on the link level layer. Another form of virtualization is to segment the physical local area networks into virtual local area networks (VLANs). An overlay network is yet another form of network virtualization which is typically implemented in the application layer, though various implementations at lower layers of the network stack are also being used. Extension of IT virtualization principles to network equipment (such as routers and switches) could determine several advantages as well, i.e. optimizing the use of physical resources and allowing a deeper integration of IT and network resources.

NFV could bring the ability to co-locate multiple instances of network functions on the same hardware – each running in one (or more) different Virtual Machine (VM). This could provide NO and SP with the ability to dynamically instantiate, activate, and re-allocate resources and functions, and even program those accord-

ing to needs and policies. SDN and NFV could be seen as mutually beneficial, but they are not dependent on each other: e.g., network functions can be virtualized and deployed without an SDN being required and vice-versa. An example of functional architecture from ETSI is depicted in Figure 2.

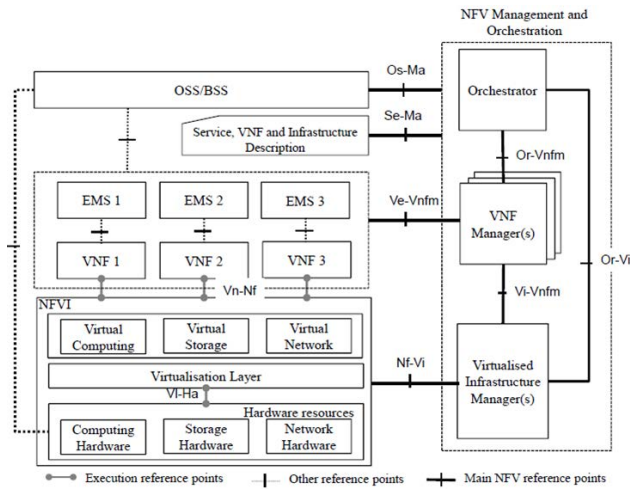


Figure 2 – Example of functional model for NFV (Source: ETSI).

### III. SUMMARY OF THE SDN4FNS' 13 WORKSHOP

This section intends to provide a brief overview of the most important topics covered by papers and discussions during the IEEE Workshop SDN4FNS. The Workshop was organized in three tracks: 1) Telecom and Internet SDN Scenarios, 2) Hardware and Software 3) Regulatory, Biz, Techno-Economic Sustainability. The main takeaways are briefly summarized in the following sub-sections.

#### A. Track 1: Telecom and Internet SDN Scenarios

There an emerging understanding that the disruptive potential of SDN and virtualization could provide a number of new opportunities to NOs, SPs, software developers and equipment vendors. However, all these new potential opportunities carry also a new set of challenges to cope with this transformation. State-of-the-art SDN and virtualization implementations have

already shown many issues to be addressed, and a significant number of those are related to security aspects [10]. In general, SDN could be seen as a paradigm helping in overcoming ossification of current layering and protocols stacks. For example, [11] argued that, in the future, the TCP/IP layering itself may represent just one of the ways to deployment of a truly flexible software-defined networking environment.

Several interesting SDN applications scenarios have been presented and discussed, for both wired and wireless-radio and networks. For instance, SDN can be envisioned as a potential solution for efficient and scalable implementation of control functions in extremely dense and heterogeneous wireless networks [12]. According to this vision, a novel network architecture, accounting for MAC control and Mobility Management, was proposed as part of the activities of the EU-funded FP7 CROWD project [13].

SDN and virtualization could also enable a flexible and more efficient implementation of the LTE Evolved Packet Core by splitting its main functions between a virtualized cloud environment and an SDN-based transport infrastructure [14]. SDN could provide key functions such as load balancing over different wireless technologies and related flow admission control in heterogeneous 5G mobile networks [15].

Finally, the issues to enable switch mobility, while enforcing robustness against network attacks were addressed in [16], by introducing an enhanced transport layer, based on standard IP mobility techniques for OpenFlow controller-to-node communications.

One of the key challenges that could be faced with SDN is the optimization of (virtual) resource allocation and usage. Relevant case studies include: inter-data center communication for service brokerage over large scale distributed and heterogeneous cloud environments [17]; performance evaluation of virtual network functions migration across cloud-based edge networks [18]; dynamic traffic engineering and adaptive network

design to efficiently map logical/virtual topologies on physical network infrastructures [19], [20].

## B. Track 2: Hardware and Software

Hardware performance advances and costs reductions are creating the mass market favorable conditions to a large adoption of the software-defined principles and virtualization.

Nevertheless this will create an high level of complexity in future networks and services platforms. As such, SDN and NFV will require to enhance current management systems with new capabilities, for example concerning the orchestration of virtualized functions and resources.

Moreover, in order to tame the growing complexity and the dynamism proper levels of software abstractions should be timely introduced, simplifying also the views of the architecture (e.g. slicing). Elasticity and flexibility could be achieved through systems and methods for VMs placement, move and traffic routing between VMs (i.e., solving double constrained optimization problems in almost real time).

In general, there are several efforts in this avenue, which appears to be very strategic.

Inter-domain SDN controller integration could be enforced by means of compatible east-west bound interfaces, based on either service-oriented architectures [21] or inter-platform signaling for distributed flow processing [22].

Most of the ongoing discussions about SDN typically focus on control plane aspects. However, many unresolved issues arise when considering the programmability of the data plane, such as the relative importance of data plane vs. control plane services, the relevance of the underlying hardware platform, and the need for standardized northbound and southbound interfaces in the data plane [33].

Another very important aspect of SDN concerns service provisioning with guaranteed QoS: leveraging network programmability features provided by SDN, specific platforms addressing the QoS monitoring and enforcement issues were developed with managed [23] or autonomic [24] approaches.

Then, considering the increasing deployment of OpenFlow-enabled equipment, a smart platform capable of detecting OpenFlow rules interactions and determining possible inconsistencies could be extremely useful as a sort of “debugger” for OpenFlow application development [25].

SDN can be considered as a powerful enabler for many emerging networking paradigms. It is indeed vital to deploy inter-cloud communication services over existing network infrastructures in a scalable and feasible way, as proposed within the European Future Internet initiative [26]. It is also the key technology that can foster the implementation of multipath inter-data center communication architectures, building on emerging standard protocols [27]. Finally, SDN may ease the deployment of Information-Centric Networking (ICN) in existing IP networks by effectively decoupling forwarding information from object names [28].

As mentioned, virtualization is one of the most important technologies intertwined the growing interest in SDN: the capability of virtualizing practically any network function and service and SDN principles are mutually beneficial. This is also the rationale behind the so-called “hyperconnected telecommunications environment”, where most of the intelligence is moved to the network edges, eventually evolving into a fully interconnected Internet of Everything [29]. It is of course intended that virtualizing networks at any scale would require some level of orchestration: technical challenges and potential architectural approaches to edge-to-edge virtualization, abstraction, control, and optimization of heterogeneous transport networks with packet- and circuit-switched technologies were discussed in [30].

Test-beds and proof-of-concepts of virtualized network functions can provide an insight into the major feasibility issues of network virtualization and a viability check of NFV performance. Good examples include: EmPOWER experimental test-bed for wireless network virtualization [31]; an OpenFlow-based prototype of routing function virtualization [32]; CONTENT project approach [33] to infrastructure virtualization over heterogeneous wireless and optical networks. Last, but not least, the internal structure of a network node capable of function virtualization, which is also a critical aspect of SDN, may be implemented through a plug-in interface architecture as presented in [35].

### C. Track 3: Regulatory, Biz, Techno-Economic Sustainability

Although SDN is still considered to be in its infancy, medium to long-term visions on how it will possibly evolve in the future can set the grounds for strategic research and investigations on the techno-economic sustainability.

Dynamic Network Service Chaining is, for example, one key research topic showing several challenges, considering the many aspects to be dealt with during the typical lifecycle of a network service [36]. This is in alignment with the concept of “Forwarding Graph”, which is used sometimes in preference to “Service Chain”, in order to account for the fact that end-to-end forwarding within virtualized overlay service networks is not exclusively a one dimensional chain: instead they may, and often will, have branches.

From the techno-economic perspective, a wider and wider introduction of “software” in networks and services infrastructures [37] will accelerate the pace of innovation (as it is doing continuously in the IT domain) and will reduce operational costs (e.g., through optimizations exploiting big data and automation). This trend will move “competition” from hardware to software, lowering the threshold for several Players to enter into

the ICT – Telco arena. It is likely that the so-called “softwarization” will to enter more and more in all socio-economic processes.

Finally, the vision of a future network where most of the intelligence resides at the network edge was brought one step further. This is especially true, considering the vision that SDN and NFV solutions will be able to create a sort of distributed communication “fabric” around the users, covering all network equipment available at the edge (including any type of hyper connected devices, such as smartphones, robots, cars, drones, etc.), which can offer huge processing and storage capabilities to execute and consume practically any virtualized function and service [38].

### D. Main Takeaways

Socio-economic drivers and technology progresses (with their down-spiraling costs) are steering the evolution of current networks towards a highly dynamic and flexible environment of virtual resources, interconnected by virtual links that are set up and torn down to serve multiple applications.

SDN and NFV are likely to represent a first step to this direction. In general, in the future, a growing number of industries and small medium enterprises will rely more and more on “digitalization” and “software”. In this sense SDN and NFV could be seen as powerful enablers to create and develop new ecosystems capable of aggregating and driving investments, even outside the traditional Telco-ICT contexts. This requires embracing this crucial industrial transformation from a broader perspective.

This transformation is an unstoppable trend, because of the continuous technology evolution and cost reductions by lowering operating costs through simplified hardware, software, and management will definitely enable new economic paradigms. For example, SDN and NFV are claiming network cost reductions, due to the adoption (and consolidation) of standard hardware, capable of running virtualized network functions/applications. Nevertheless, we found wide con-

sensus on the fact that this model will be successful only if SDN and NFV are really based on open source software solutions. (Closed software solutions, in fact, would move costs from hardware CAPEX to software OPEX, probably erasing the claimed advantages of SDN and NFV in terms of cost saving.)

The analysis is obviously more complex as it should take into account to which level the performance should be managed as well, and how all these virtual network functions should be efficiently orchestrated. Moreover, it was argued by several people that this r-evolution would happen at the edge, first, as it would require fewer investments, it would scale much more gracefully, and it would lead to immediate revenues. Evolution in Users' devices, terminals, Customer Premises Equipment (CPE) or aggregation edge nodes is much faster than in core or WAN equipment, especially due to the impact of SDN and NFV on traditional Operations Support Systems (OSS)/Business Support Systems (BSS).

Next sections will provide further analysis of scenarios, prior-art, state of standardization, and further discussions on technical challenges and socio-economic aspects.

#### IV. SCENARIOS AND HIGH LEVEL REQUIREMENTS

In this section, some scenarios (wired and radio, core and access/distributions, edge) are provided from the points of view of NOs and SPs, as well as from other players' angle, such as OTTs, Enterprise Networks Providers, Consumer Electronics Providers, etc.

##### A. Examples of core scenarios

Core networks scenarios typically consider SDN as a paradigm providing incremental improvements (in terms of flexibility, programmability, etc.) of current networking concepts; practically, it is recognized that the concept of the separation of hardware from (control) software is not really new, but the point is that the

decoupling is made possible today thanks to the hardware technology advances.

In the context of these core scenarios, Dynamic Network Service Chaining is one of the most mentioned classes of use cases, where IT and networks resources are integrated: network services are provided by "chaining" the executions of several service components.

SDN is often assessed as an opportunity reducing CAPEX and OPEX costs. As previously mentioned, savings may derive from centralizing and, above all, automating processes and postponing investments through optimized usage of resources (provided that carriers' class performances are still achieved by the adoption of general purpose hardware).

On the other hand a deeper integration of networks and IT (e.g. Cloud) domains, and the related Operations requires also a deep "change of culture" in NOs and SPs, and maybe the development of new skills for mastering "software". This might require some time, also to define new models of business sustainability.

Seamless integration with legacy equipment and the related management systems might represent other critical issue, mainly demanded to the standardization of interfaces, which might be delayed. In summary, it remains to be seen whether SDN exploitation in core scenarios will be really followed, and what the time horizon will be.

##### B. Examples of edge scenarios

Edge scenarios concerns the exploitation of SDN principles for creating very dynamic virtual networks out of a variety of aggregation nodes, devices, elements located at the edge of current networks, up to around Users. Some of these elements usually are not considered yet as network nodes: for example, cars, robots, drones, any Users' devices, smart things with embedded communications, etc. In other words, this is about

developing a “fabric” made of an enormous number of nodes and elements aggregated in an application driven way, as depicted in Figure 3.

In the past, the term “fabric” has been used to refer to a distributed computing system consisting of loosely-coupled storage, networking and processing capabilities interconnected by high-bandwidth links. It has also been used for describing flat, simple intra data center networks optimized for horizontal traffic flows, mainly based on a concept of “server-to-server connectivity”. Based on these previous meanings, in this context, the term fabrics is extended to indicate the edges of the metro networks, becoming like as distributed Data Centers consisting of loosely coupled processing and storage resources interconnected by pervasive high speed wired and wireless links.

An example of use case is that of a SP that may want to provide end-to-end ICT services to users who are attached to edge networks, even if belonging to different infrastructure providers or NOs. This could be achieved by operating an overlay service platform capable of chaining, managing and orchestrating virtualized resources and functions made available by the different edge networks.

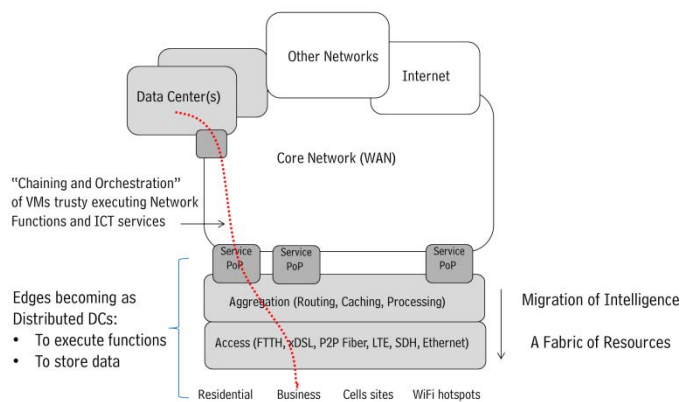


Figure 3 – Example of scenario where the “edge” is becoming a “fabric” of resources to execute networks functions and store data.

Another use case is that where Data and ICT services (seen as apps executed via chains of VMs) will follow the users when they are moving from one network attachment point to another one, even across different edge networks.

Management and orchestration capabilities should allow this “follow-me” service whereby personal data and ICT services will be moved seamlessly with little or no impact on the Quality of Experience (QoE) of users. Moreover, data and services associated to users can be even federated to build distributed virtual data center at the edge (ideal for example for universities, enterprises, etc) at costs which are a small and a fraction of traditional clouds.

### c. Other Expectations and Requirements

In general, NOs and SPs expectations related to the SDN/NFV frameworks are much broader than the currently addressed Telco’s requirements. One far-reaching circumstance is that the carriers have made huge deployment investments in legacy networks. Hence, many of the novel SDN capabilities need to enable the transformation of the current nodes to the new infrastructure vision the research community is creating.

This is a fundamental requirement: developing a radical simplification on how carrier networks are designed, built, deployed, operated and managed. End users should have the desired QoE, new services should be easily introduced, and resources should be optimally used for meeting all performance requirements of the new complex applications. The networks will transform into a new “market” where all actors’ (users, applications, networks) requirements are appropriately addressed with the new supported and deployed capabilities.

This transformation is a big task, and the existing paradigm is not quite ready in achieving this objective, but



the capabilities at hand should allow the research community to work in this research direction.

In the IEEE SDN4FNS Workshop, several contributions were given towards this goal. Yet, some other key areas would need to be addressed in the upcoming period by the research community, including, but not limited to:

(a) Development of an end-to-end SDN framework for Collaboration (Coordination, Cooperation, Communication Orchestration) taking into account the current and new actors (prosumers/functions/applications), in order to agree and achieve global goals (i.e., utility maximization, resource optimization QoE, Policy, Security...). There is an ongoing work with this broad aim, but new capabilities are definitely needed. As an example, Identity, Security, Mobility and QoS Management are key high level objectives; providing these in a modular way, across the network/s and all layers need corresponding abstractions from all, as well as new concepts and architectures of Access and Non Access Strata. In the security context, perimeter defenses do not usually work, instead of firewalls at the perimeter, using internal modular firewalls to define enclaves within the network, and using secure protocols [e.g., Secure Sockets Layer (SSL) or Transport Layer Security (TLS)] and service validation at their inputs to prevent attacks might be a better approach. Similarly, E2E QoS and mobility objectives should be apportioned and relegated to the corresponding domains and layers to provide the necessary carrier grade performance.

(b) Development of an SDN/NFV framework for Service Providers. The existing paradigm would need to be extended beyond data centers and enterprise networks. This would require longer geographic reach and diversity. All different access, core, and link technologies (e.g., RAN, cellular, Wi-Fi, optical, etc.) should be brought into the framework as well, to create an end-to-end infrastructure, where these domains could be offered as a Service. It also requires fundamental rethinking on how the current network may evolve (typically, delivery of new network-based services takes weeks and in some cases months) and how new services may be provi-

sioned using a much more dynamic business process, characterized by the configuration and management of all virtual resources to provide even network services, as previously introduced. Dynamic network provisioning and configuration needs to be coordinated and orchestrated, in order to efficiently direct the assignment, creation and configuration of virtual resources, and, especially, to satisfy customer requests and manage customer experience per SLA. Network Orchestration will play a key role in implementing these requirements at various levels and will be responsible for coordinating the delivery of the resources and attributes of a customer request into an operational service that embodies the runtime requirements of that request. Network Services Orchestration is expected to provide highly reliable and scalable capabilities to enable these expectations. SDN would require a new set of capabilities that would work with the existing networks. Legacy networks should gracefully evolve to the future network through an evolution. Key control and management functions should interoperate with existing frameworks. This is a key requirement for SP that cannot afford a clean slate approach.

Looking at Flexible Service Control, the virtualization technologies for telecommunication infrastructures enable more opportunities in terms of flexibility, scalability and efficiency for on demand driven dynamic network dimensioning and traffic engineering. For instance, the flexible control of radio (Cloud-RAN/evolved-NodeBs) and core network (Evolved Packet Core, IP Multimedia Subsystem, Service Delivery Platform) resources enables novel lifecycle management and control possibilities.

The main advantages for virtualization, with respect to today's telecommunications architectures are:

(a) Data path optimization for signaling and user data plane. The influence of SDN and NFV on the control and data plane within Telco architectures allows a precise and particular optimization in overloaded parts of the network. Energy consumption and carbon footprint are playing an important role in the ICT in general and tele-

communication in particular, since clouds, data center, network elements and base stations are responsible for a large amount of the total energy consumption. Therefore, the influence of virtualization on Telco networks, as a method for enabling optimized network design and traffic engineering instead of over-provisioning the Telco network, arise. High performance, flexible, elastic and demand-driven solutions are addressed in European research projects (MCN [39], iJOIN [64], etc).

(b) Network aware service enablement / QoS on demand. Flexible QoS control is one of the key denominators in emerging future telco environments. Features such as user demanded QoS, QoS level per subscriber base, and differentiation between multiple Mobile Virtual Network Operator (MVNO) on top a physical network infrastructure all require flexible QoS control to ensure connectivity for dedicated service types. These service types might be emergency calls, public safety services or critical infrastructures such as smart metering.

## V. CONCEPTUAL AND TECHNICAL CHALLENGES

This Section describes a list of the most important technical challenges for the development and deployment of SDN.

### A. Management and Orchestration

The fundamental feature of SDN is the decoupling of the network control plane from the network forwarding (data) plane. Such separation is well-known in telecommunication networks. However, network architectures always include an additional plane, namely the management plane. Such plane and their functions are defined and standardized by the TeleManagement Forum and ITU-T. The functions include fault management, configuration management, accounting management, performance management and security management.

The role of management (including fault, configuration, accounting, performance and security areas) is especial-

ly critical in large, production networks. Typically, in such networks, the operators interact with the network via the management system. After network deployment, the most typical network operator's actions are usually related to network reconfiguration, as a result of network enlargement or topology changes. It is commonly agreed that in order to cope with future demands and the ever-growing number of managed devices, the network management should be automated.

Hence the network availability is expected to be improved and OPEX related to the network management significantly reduced. This type of management lies on performing selected management operations in "real-time", which is often referred to as autonomic.

The management of SDN can reuse some well-known network management concepts and it should incorporate the latest trends in network and service management as well. So far it is not the case. In fact, the management issues of SDN have been as of today ignored. This situation can be explained by the experimental status of deployed networks.

In the current SDN approaches, the usage of existing IP network management systems combined with OpenFlow is often assumed. The analysis of the OpenFlow protocol leads to the conclusion that it lacks primitives that are able to cope with network management operations. In order to support management functions, ONF has defined the OF-Config protocol. This protocol is used for configuration of links between the OpenFlow switches and the controller. In the short term, the SDN management operations could be supported by the existing network management protocols (SNMP [63], NETCONF [62]).

The openness of OpenFlow enables the implementation of some network management functions, but the lack of standardization of a management interface makes impossible to use third-party management solutions in a way as they are used in legacy management systems.

SDN-based networks have some specific properties. Their owner or operator has not only the ability to

manage them but also the possibility of defining their functionality.

There are several management issues that appear to be specific to SDN only. Most of them are related to the critical role of the controller, which has to perform most of its operations in a real-time manner. It means that the performance of the controller has to be monitored, and the controller processes should be categorized and handled according to their real-time requirements. In case of controller failure, a hot swap operation is necessary. Controller programmability requires special care. In order to fully use such capability, the network operator should be able to remotely add new controller functions and to update the existing ones. Such functionality means on-the-fly re-programmability of the controller. The management operations should be able to start, stop and monitor each software module. Moreover abnormal behavior of such modules has to be monitored and cure taken. Last but not least, the security of the controller platforms is critical and has to be handled accordingly. This includes also the authentication of newly added switches. It has to be combined with the security of the management platform.

It is important to determine a border line between the SDN network operations (implemented in the controller) and SDN-based applications implemented in application servers. Such a separation can help in the definition of the management system role. In order to cope with scalability and complexity, separate platforms for the control and the management of SDN networks are highly recommended. A proper information exchange between these platforms is necessary, and it could be provided by programmable interfaces.

It is an open issue whether the management will be fully centralized, or implemented by distributed functionalities. There is however no doubt that the added complexity should not significantly increase the cost of the SDN nodes and that the distribution of functionalities should still give a centralized view of the network.

## 1) Adaptive and Autonomic Methods and Systems

This research challenge deals with the critical nature of developing the methods, enablers and systems for autonomic management functions applied not only to the physical resources, but also virtual resources located inside the physical / virtual network.

In this avenue, even if the requirement of unification of all autonomic functions might be highly desirable, it will be almost impossible to achieve it, as the number of functions is expected to be large. New approaches probably should be developed, allowing separated autonomic managers to coordinate and resolve conflicts in their activities autonomously with minimal disruption.

One example is that where management and control functions would be distributed and located or hosted in or close to the managed network and service elements, enabling control of CAPEX and significant operational costs reduction for physical (i.e. OPEX) and virtual (i.e. VPEX) systems. These may include adaptive re-allocation of virtual resources according to changing network conditions or service demands. Additionally, this challenge deals with the critical nature of developing autonomous actions that provide network stability and optimizations in absence of higher-level control.

## 2) Optimised allocation and orchestration of resources

It has been mentioned several times that one major challenge will be the capability of dynamically instantiating, orchestrating and migrating multiple VMs across the networks and services infrastructures. Orchestration, in this context, means also lifecycle management of physical and virtual resources.

Specific optimization techniques are required for both the placement of the VMs into the physical networks and the traffic routing between VMs (e.g., this means solving double constrained optimization problem in "almost" real time).

In the case of wireless infrastructures, other characteristics and capabilities have to be considered, e.g. limited bandwidth, processing capabilities, storage, energy (battery), type of interfaces supported of the mobile nodes and mobility, conflicting requirements. As the mapping of virtual to physical resources should be transparent to higher control layers, mechanisms have to be developed that allow the seamless hand-off between different wireless devices. Additionally, algorithms will be identified that optimize the coverage of wireless radio connections to provide access to enough physical resources while avoiding unnecessary energy consumption.

In the case of wireline networks, optimized allocation will involve a wide variety of resources available from the underlying wireline network, including communication, execution and storage capabilities. The mapping will take into account the top-level service/operational requirements such as the demanded QoS requirement and resilience capability to be embedded into the resulting virtual network. By addressing this challenge virtual networks will be customized with optimally allocated capabilities such as virtual nodes (with computing and storage capabilities), virtual links and paths for specific networked services.

As an example, the Cross Layer Optimization paradigm as outlined in [65] maps top-level service/operational QoS requirements against underlying network capabilities and thus enhances network management and traffic engineering sustainable. Individual characteristics of user profiles, service descriptions and network topologies have to be optimized given a connectivity with certain requirement on the transport system in order to guarantee QoS. Algorithms and concepts for realizing a network-awareness for services through Cross Layer Optimization are required in the scope of SDN and NFV for dynamic service chaining and optimal network function placement.

### 3)Energy Management

Finally, looking at the management aspects of energy consumption, we may relate this challenge to the critical nature of developing mechanisms for energy-aware networking, including the optimization of energy consumption within the limits of a single domain and/or multiple domains. Such energy-aware capabilities would include the optimal dynamic distribution of VMs across the set of networks and servers and providing stabilization of the local networks in response to variable electricity demand-response requirements.

### 4)Security and Safety

Security in terms of privacy, integrity has to be guaranteed in a virtual environment [41] in at least a similar or a higher level than in today's networks to foster the acceptance. Even more security challenges arise in a virtualized environment due to shared hardware, processor, memory, system bus and control interface. Virtualization enables new charging models, which require precise monitoring, policy control and charging from the virtualized system. Existing Operation and Management system need to be adapted or renewed for facing the challenges of virtualized environments. The safety of SDN systems requires redundancy and reliability of the controller, the real and virtual resources and other ad-hoc engineering solutions [42]. The flow paradigm offers interesting opportunities for security processing: one example is traffic steering for automated malware quarantine. Another area to be explored is how SDN could also bring to network security the ability for security policies to follow logically specific network applications or VM.

## B. Interoperability and federation

SDN solutions count already on numerous Open Source and commercial OF software and hardware switches and controller. Already the large heterogeneity of OF Switches, OF Controller and OF versions challenges interoperability. Evolution of OF protocol and the use of

other protocols than OF will require to make sure that interoperability is guaranteed.

In general interoperability between the different NOs and different domains with the same NO is extremely important. This challenge would include:

- interfaces that will allow a servicing /networking virtual function to federate. Using this interface, the networking function should be able to cooperate in order to provide inter-domain communication;
- authentication for other NOs, and the different NOs to confirm with each other the identity of the different users of a particular service;
- mechanisms for communication and programmability of service modules deployed by different operators for the same service;
- mechanisms for end-to-end service management, monitoring, and accounting.

### c. Networked and Computing Services Operations

Service Operation deals with keeping the service infrastructures (and the services it provides) up and running smoothly. It includes, for example, monitoring the services execution environments to spot problems, provisioning of services, ensuring programmability, etc.

#### 1) Performant and Safe Network Execution Environments

This challenge refers to the network hosting virtual environments and virtual machines to overcome the problem of having several execution environments implemented in various technologies, and providing different abstractions, interfaces, and so on. This challenge could be faced by developing a unified network execution virtual environment and by having groups of virtual machines which are managed (creation, change/update, deployment, migration, orchestration, deletion) as one. The advantage of having an explicit notion of a virtual environment is to provide generic

means to manage access and resource control on the node-level. While execution environments support the installation, instantiation, and configuration of services code in various ways, the virtual environment puts a uniform management layer on top. This allows external clients to interact with services through the interface of the virtual environment in a generic way, and the interactions will be mapped to specific interfaces of the execution environments. Several execution environments can be attached to a virtual environment, just the same way as other resources. This leads to another aspect of virtual environments: the partitioning of resources. The network provider can set up virtual environments on selected network nodes, and assign them to a particular service provider, in order to offer a virtual network. Access to the virtual environments will be made available to the respective service provider so that it can manage its own virtual network. The resource partitioning implemented among virtual environments will prevent interference with other service providers and, additionally, allow an accounting per service provider.

#### 2) Programmability in Future Networks and Services

This challenge refers to solutions for the fast, flexible, and dynamic deployment of new network services through programmable enablers and primitives for all planes of SDN environments (e.g. application, operation, management, control and forwarding planes). This is also aimed to provide easy introduction of new network services by realizing the dynamic programmability of the network and its devices such as routers, switches, and applications servers. Dynamic programming refers to *executable code* that is injected into the network element in order to create the new functionality at run time. The basic idea is to enable third parties (operators, service providers and other authorized users) to inject application-specific services (in the form of code) into the network. Applications may utilize this network support in terms of optimized network resources and, as such, becoming network aware. Hence, network programming provides unprecedented flexibility in tele-

communications. However, viable architectures for programmable networks must be carefully engineered to achieve suitable trade-offs between flexibility, performance, security, and manageability.

The exploitation of such flexibility for the benefit of both the operator and the end user would require guarantees against jeopardizing the integrity and stability of the network based on solutions for

- Rapid deployment of new services;
- Customization of existing service features; optimization of network resources;
- Scalability and cost reduction in network and service management;
- Independence of network equipment manufacturer;
- Information network and service integration;
- Guarantees for Quality of Service;
- Diversification of services and business opportunities in particular for virtual environments and clouds.

#### D. Architectural and Functional Models

The current developments in SDNs and NFVs are highlighting new and critical research topics related to what and how create the conditions to effectively and continuously update and change the networking functions (e.g., softwarization of future networks and services without reinventing every time the network architectures or network layering).

This means the use of software to program individual network devices, network systems and services dynamically and therefore control, manage and operate programmatically the behaviour of the network as a whole. Key software features of the future networks and services are already identified [43], [44] and include: service diversity, functional flexibility, programmability, ease of new services introduction, virtualisation of resources, energy consumption, service universalization, network management, mobility, optimisation, identification, reliability and security would need to be realised

as part of the future network services and continuously updated.

The future networks and services need to move from being merely defined by software to be programmable by software and must be capable of supporting a multitude of providers of services that exploit an environment in which services are dynamically deployed and quickly adapted to heterogeneous physical wire, wireless and smart object infrastructure(s), according to evolving and sometimes conflicting customer requirements.

Programmability is a key property that SDN framework enables, but it does not make it “easier”, as the proper abstractions and a set of layering have not been completely defined yet.

#### 1) Architectural Models

Different abstractions, layering, conceptual models and architectural approaches have been proposed in the research literature. Some of them are discussed in the following.

Programmability of network elements (switches, routers, and so forth) was introduced about a decade ago, this set the basis for rapid deployment and customization of new services, as illustrated in Figure 4..

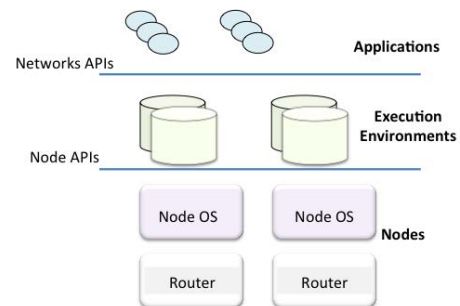


Figure 4 – Example of model of a programmable router network

Advances in programmable and virtual networks have been driven by the adoption of Open-Flow, which has led to refined high level architectural model, as in Figure 1.

We are now witnessing a growing interest moving from the centralized control and “monolithic” approaches, where systems are vertically integrated, towards a component-based approach, where systems are made of multiple components from different manufacturers, interacting with each other through open interfaces to form new services [45].

As depicted in Figure,, the expected results would make it possible to achieve a level playing field, where different stakeholders, such as infrastructure and services providers, would compete with each other, while users may select and customize services according to their needs [46],[47][48].

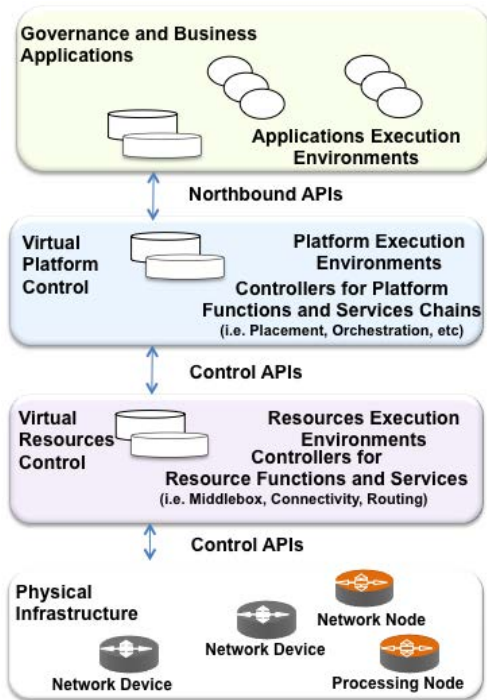


Figure 5 – Example of model of a unified environment integrating connectivity, computational power and storage

A fundamental characteristic of the architectural model of Figure 5 is the evolution towards a unified environment integrating connectivity, computational power and storage. This is requiring proper enhancement of current control and management planes and the introduction of orchestration capabilities.

Before that, there is a need of defining a meaningful functional model capable of abstracting and represent-

ing all network functions and capabilities which will appear in SDN and NFV (which means including processing and storage).

Realizations and instantiations (with proper adaptations) of the above model to Cloud [49] and in RAN [50] and cellular-wireline [51] domains (figure 6).

One of the main problems with the earlier models is that the richness and diversity of applications and technologies prevents a simple model to be representative for all approaches (just a simple northbound API might not be enough).

A recursive approach is needed, where a new set of abstractions are developed, depending on the area or domain and the set of layers as necessary.

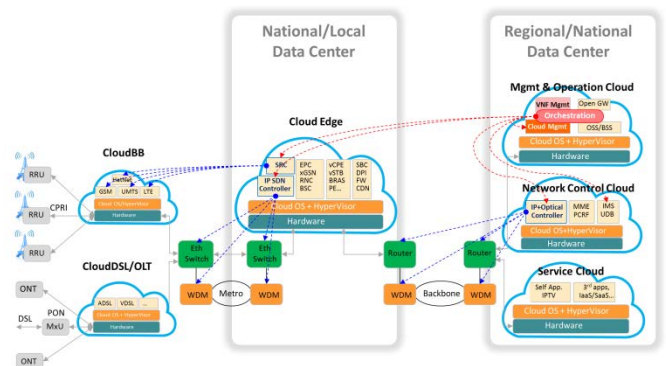


Figure 6 – Example of instantiations of SDN in Cloud, RAN and Cellular/Wireline domains (SDN4FNS Workshop)

In addition as a result of users shifting to mobile environments and devices, the need to create denser networks and more efficient usage of wireless resources are vital. (i.e., usage is rapidly growing on the demand side, on the resources side). Generalizing a set of abstractions to mobile networks and applying the SDN framework, would presumable bring additional benefits in management, converged resources control and agile deployment areas of increasingly dense networks.

In these scenarios, there is a need for efficient resource control and management across various wireless protocols, ability to tie and coordinate these capabilities with other core network functions, creating a common and programmable data plane, and creation of a wireless network operating system.

This will be only possible by rethinking the 3GPP architectures, starting from the definition of the logical network domains; session, mobility and identity management concepts and architectures, as well as Access and Non-Access Stratum protocols. For instance, it remains to be seen how mobility will be ultimately handled in SDN without tunnels, and whether the protocols implementing the bearer service (3GPP layer) will converge with the protocols in the transport network layer, which have been evolving separately.

In summary, as previously pointed out, SP's networks require a much more complex set of controls and layered abstractions, which can be iteratively realized. A lot of details are still in need of development but a key piece, a coordination/collaboration proxy, that needs to receive policy directives from "above", i.e., from non-functional requirements (i.e., business, technology and quality) and translates them into the domain of applicability is a key function that is missing to achieve a global goal.

An overarching architectural model should include shared virtualised resources, and all the corresponding abstractions, including those in wired, wireless and resource-constrained mobile devices and smart objects. Such an model would need to be engineered to facilitate the integration and delivery of a variety of ICT services, computing and network Clouds and to enhance integration of the key enabling technologies: programmability, networks, network virtualization and network function virtualisation and self-management.

## 2)Functional Modeling

Starting from the OSI Layering [52] integration of the software infrastructures and traditional communication / telecommunication technologies has been always a

challenge for network and service operators, as far as service deployment and management are concerned [53][54]. This is due mainly the fact that OSI layers were designed to address IP packet delivery paradigm of early Internet days.

Interestingly, to overcome this problem, ITU-T developed a functional formalism capable of modelling transport networks in a technology independent way. ITU-T Recommendation G.805 describes the modeling of connection oriented (point to point) transport networks; then G.809 has been developed to model connectionless network and, eventually, G.800 reports a model for unified connection oriented/connection less architecture.

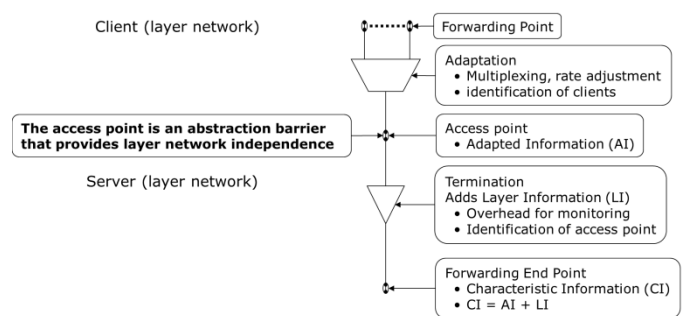


Figure 7 – G.805 components for functional modeling

The main characteristics of this functional modeling has been the capability of describing recursively any transport networks in terms of information transfer capability, in a technology-independent manner, and by using a small set of components. Moreover the model is capable of relating the equipment/logical resource/management views.

This approach has been very effective for the design and the management of networks. It is argued that a similar approach, obviously with proper enhancements, should be adopted for the functional modeling of SDN.

The key point will be definition of a small set of functional components capable of modeling recursively a SDN in all its aspects (i.e., including also processing and storage features).



### A. Standardization Bodies and other Fora

The theoretical concept of SDN has been realized by multiple standardization organizations (ONF, IETF/IRTF, ETSI, ITU-T, IEEE, etc.) into practical solutions (ONF's OpenFlow, CISCO's OpenPK, IBM's DOVE, NEC's Programmable Flow and more).

Several working and discussion groups of the Open Networking Foundation (ONF) are covering various SDN related topics. These are currently Active Working Groups, Architecture and Framework, Configuration and Management, Forwarding Abstraction, Market Education, Migration Discussion Group, Northbound Interface, Optical Transport, Testing and Interoperability, Discussion Groups, Wireless & Mobile. The OpenFlow protocol in version 1.4.0 and OpenFlow Config protocol version 1.1.0 have been standardized by ONF. Both have the largest market share and influence at this point in time, since most vendors and manufacturers support at least OpenFlow as part of their portfolio.

IRTF Software Driven Networks focuses within SDNRG on areas of interest covering the classification of SDN models, relationship to work ongoing in the IETF and other SDOs, SDN model scalability and applicability, multi-layer programmability and feedback control systems, system complexity network description as well as security [55].

The IETF working group Forwarding and Control Element Separation (ForCES) defines an architectural framework and associated protocols to standardize information exchange between the control- and data plane in a ForCES Network Element (ForCES NE). ForCES defines Network Elements (NE), Control Element (CE) and Forwarding Element (FE). In comparison to the SDN concept, which strictly separates forwarding from control in different functional elements, ForCES allows each NE to consist of multiple NE's and FE's. A NE is therefore more complex and is controlled through a CE Manager and FE Manager -each managing the referring Control or Forwarding Element(s) [56].

ITU-T Study Group 13 ITU (Future networks including cloud computing, mobile and NGN) is standardizing FNs with the objectives of service, data, environmental and socio-economic awareness as part of the topic Software-defined Networking (SDN) [57]. Standardization efforts include support network virtualization, energy saving features for FNs, and an identification framework. Future plans are to develop different facets of the smart ubiquitous network, requirements of network virtualization for FNs, framework of telecom SDN and requirements of formal specification and verification methods for SDN.

The standardization activities of the Object Management Group (OMG) aim to set a vendor-neutral global standard for SDN through the investigation of opportunities to foster the development of open SDN specifications.

### B. Open Source Software Initiatives

A great number of Open Source communities are working on SDN, NFV, and Network Virtualization projects. As a matter of fact, the number of open-source projects is rapidly growing. SDNCentral aims to capture a list of the main Open Source SDN projects [58].

OpenDaylight is an example of forum created through the combination of open community developers and open source code and project governance that guarantees an open, community decision making process on business and technical issues. The main goal is to help accelerate the development of technology available to users and enable widespread adoption of Software-Defined Networking [59].

Currently we are already witnessing a growing number of Industries (big but also SME) which are starting adopting Open Source (e.g. OpenStack, Avana, etc) - properly customized - for real production environments. It is a sort of bottom-up move that could change the rules of the game, as it is lowering the thresholds to new Players (even with little investments) to enter the market. Arguably this will happen first at the edge, thus

creating a fertile environment for creating and developing new ecosystems. Also this will create new roles and new ways of cooperating and competing. "Competition" will move more and more at the software level, so there is also a great value in testing, assessing and certifying Open Source component, systems or platforms for security, trust, performances and interoperability.

### c. Need for Certification

It seems that there are very limited certification related activities on SDN. The Cisco Certified Network Professional (CCNP) Service Provider certification program, which is aimed at developing the skills and knowledge of IT professionals to deploy and manage next-generation networks; however, this is not specifically tailored for SDN, There is also Indiana University's InCNTRE Lab, which is a sort of certification lab for Open Flow.

Certification can be provided in the following three areas:

- Professional Certification (SDN-P): This may consist in the establishment of Body of SDN knowledge (BoSK); creation of BoSK Learning Tools that should include the curriculum, books, newsletters, classes, as well as the support. In addition, development of BoSK Examination Tools including SDN-P Certification Exam and Renewal is needed.
- Components Certification (SDN-C): This will require that components requirements, application areas, and benchmarks need to be developed by solicitations and interactions with the industry. Revisions need to be managed. Also, evaluation tools for SDN Certification test-bed, SDN-C Benchmark tests, and SDN-C Certification need to be established. The process for certification renewals needs to be established as well.
- Internal SDN-test bed development: Certification procedures should be developed based on the initial test bed evaluations. Implementation of a test bed via Internet 2.0 and local data centers/supercomputer centers is necessary to utilize state-of-the-art resources. Education activities will be included in the SDN-test-bed for education/curriculum activities. Third party requirements which require SDN test-bed specs and heavy Industry relations need to be established. Finally, an evaluation board for test-bed certification need to be formed.

## VII. CONCLUSIONS

Socio-economic drivers, IT technology progresses, hardware down-spiraling costs and availability of open source software are steering the evolution of future networks and services infrastructures. It is likely that a

wider and wider adoption of "software" in said infrastructures will accelerate the pace of innovation of processes (as it is doing continuously in the IT domains) and will reduce operational costs (e.g., through optimizations exploiting big data) for NOs and SPs.

Emerging paradigms as SDN and NFV represent a first concrete step to this direction, catalyzing the idea of decoupling software defined control plane from hardware driven data plane and the virtualization of network functions on general purpose hardware. This will influence significantly the future developments of 5G technologies and architectures.

As a matter of fact, we are witnessing a growing number of other industries moving to the same direction. In this sense, SDN and NFV could be seen as powerful enablers for new ecosystems capable of aggregating and driving investments beyond the traditional Telco-ICT contexts. It is argued that this transformation is unstoppable, because of the continuous hardware technology evolution and cost reductions, which will enable new economic paradigms. In facts, this will move the competition from hardware to software, creating the favorable conditions for a sustainable "economy of information".

This will require different business rules, and different kinds of jobs, workers and skills than the economy of the 20<sup>th</sup> century, mostly based on industrial factories, manufacturing and manual work. Economic and cultural values in the economy of information are, and will be, placed on information, knowledge, creativity and intelligence to cope with the fast-changing socio-economic environment. To this end, the development of new skills, mindsets and education are required to face this transformation.

In synthesis, a number of research and development avenues are envisaged:

*Core-Edge split.* SDN deployment strategies for Core and Edge networks should be distinguished in terms of technical approaches, business models and time horizons [60]. Details and control frameworks for end-to-end networks with core/edge functional split require

fundamental rethinking in the fabric designs. This implies impactful aspects such as addressing the virtualization of L4-L7 middle-boxes and the RAN evolution. NOs and SP's spend 60-80% of CAPEX on RAN technologies that are not keeping up with the changing application requirements. In SDN, it remains to be seen whether we need the classical core network functionalities at all, as most of the intelligence will be placed in terminals for handling mobility and at the Edge (data centers) for hosting any type of service, from basic connectivity to Internet and applications.

*Functional modeling and architecture.* A proper functional architecture would accelerate the development and the standardization of SDN. (In facts, there is an urgent need to standardize interfaces.) The main characteristics of the functional architecture should make it possible to model recursively all SDN features, in a technology-independent manner, using a small set of components. The model should be capable of relating the equipment/logical resource/management-control views. It might be advisable to follow the effective philosophy of the ITU-T G-805 functional modeling, with proper enhancements to take into account the nature of a SDN (i.e., processing, storing and transferring information).

*Management and Orchestration.* Complexity and dynamism of SDN will require enhancing current management systems (OSS/BSS) to cope with of a sheer number of real and virtual ICT resources. The border between IT and network resources will blur, requiring the integration of the operations of the two domains. Another major requirement will be the automation of business management processes (e.g., introducing autonomic and learning features exploiting networks and services big data) and adopting decentralized approaches (at the current centralized model will not scale properly). Moreover, the SDN management needs to be complemented with new capabilities such as programmability and orchestration of the life-cycles of virtual network functions and services. Security is one of the key areas of management which should be deeply investigated in SDN.

*Distributed computing.* SDN and virtualization will offer the opportunity to enhance and adopt in the network infrastructures means and methods today widely used in Data Center. At the same time Data Center concepts need to be evolved reliably and efficiently, especially looking at the integration with networks. Achieving scale by using collections of distributed components (e.g., out of the shelf) and devices will enable reliability and create a more competitive Technology Providers ecosystems. Major issues on consistency and reliable distribution for various network tasks remains to be tackled. Distributed sets of data representing states of network resources and functions demand for carriers' class solutions in compliance with the limits imposed by the CAP (Consistency, Availability, Partition tolerance) theorem.

*Taming heterogeneity, geographic distribution and scale.* NOS' and SPs' networks will become far more distributed and capillary, geographically and technologically. The way of putting all this diversity under a common end-to-end framework remains a major challenge, especially to cope with the rigid performance requirements in terms of QoS and QoE, for instance. SDN could be a powerful enabler to meet the above requirements but proper levels of abstractions and recursive control and management planes needs to be achieved

*Pursuing Open Source Software.* There will be a great value in testing, assessing and certifying Open Source component, systems or platforms for security, trust, performances and interoperability.

*Peering and Software Defined Internet Exchange.* Current inter-domain routing protocol, BGP, is lacking in simplicity of management, security and flexibility in defining relationships. SDN could allow the evolvability of BGPs independently of from the underlying nodes hardware. SDN programmability could mitigate the main problems in inter-domain routing: security and accountability; pricing and contracts; and traffic management [61].

*Edge Self-Organization.* In the future, the edge of the network will see a sheer number of nodes and devices (i.e. aggregation nodes, terminals, machines, sensors, actuator...): each of these elements with sufficient processing, storage and communication capacities will become like a network node, capable of sharing its capabilities. Then these nodes will be able to aggregate to create local self-organized networks, which, selecting appropriate gateways, will connect to the big network. Nodes decisions will be made based on local conditions, adopting autonomic and self-organization capabilities [38], [66].

*Socio-economic impacts.* In general, SDN and virtualization appear to be expressions of a softwarization trend in Industry. In ICT, this is lowering the thresholds for new Players to enter the market. This will also create new business roles and new ways of cooperating and competing. Competition, in fact, will move to the software level, whilst the hardware will no longer be a differentiator. New business models and value chains and networks should be defined. As an example, in the long term, one could even imagine scenarios with a galaxy of ecosystems, where "trusted" network services and functions could be provided by different Developers, exchanged and traded like in stocks exchange.

#### GLOSSARY AND DEFINITIONS

|      |  |
|------|--|
| AAA  | Authentication-Authorization-Accounting  |
| ADN  | Application-Defined Networking is an enterprise data network that uses virtual network and security components to provide a dedicated logical network for each application, with customized security and network policies to meet the requirements of that specific application. |
| AP   | Application Plane – It is plane where applications and services reside and execute.  |
| API  | Application Programming Interface (a set of routines, protocols, and tools for building software applications)   |
| ASIC | Application Specific Integrated Circuit  |
| BNG  | Broadband Network Gateway  |
| BRAS | Broadband Remote Access Server   |
| BSS  | Business Support System  |

|           |  |
|-----------|--|
| CDN       | Content Delivery Network   |
| CP        | Control Plane - Control Plane – It is responsible for taking and executing decisions on how packets should be forwarded. It focuses mostly on the forwarding plane and less on the operational plane. It could use operational and management planes information for fine-tuning and modification of the forwarding plane actions. |
| CPU       | Central Processing Unit  |
| DHCP      | Dynamic Host Configuration Protocol  |
| DNS       | Domain Name Service  |
| DPI       | Deep Packet Inspection   |
| FP        | Forwarding Plane – It is responsible for controlling actions on packets in the data-path, including dropping, changing and forwarding packets. It contains forwarding resources such as classifiers and actions.   |
| HV        | Hypervisor   |
| I/O       | Input/Output   |
| LAN       | Local Area Network   |
| LB        | Load Balancer  |
| MP        | Management Plane is responsible for monitoring, configuring, optimizing, maintaining state of systems, equipment, devices and the overall networks. It maintains and executes the processes that modify the operation of the control plane and it configures the forwarding and control planes.                                    |
| M2M       | Machine-to-Machine communications  |
| MVNO      | Mobile Virtual Network Operator  |
| NFV       | Network Functions Virtualization   |
| NGN       | Next Generation Network  |
| NIC       | Network Interface Controller   |
| NMS       | Network Management System  |
| NO        | Network Operator   |
| OAM       | Operations Administration & Maintenance  |
| OGF       | Open Grid Forum  |
| ONF       | Open Networking Foundation   |
| OpenFlow  | Specifications developed by the Open Networking Foundation   |
| OpenNaaS  | Specifications developed by the OpenNaaS community   |
| OpenStack | Specifications developed by the OpenStack Foundation   |
| OSS       | Operations Support System  |
| OTT       | Over The Top   |
| PCE       | Path Computation Element   |
| PoP       | Point of Presence  |

|         |  |
|---------|--|
| RAN     | Radio Access Network   |
| QoE     | Quality of Experience  |
| SLA     | Service Level Agreement  |
| SP      | Service Provider   |
| SDN     | Software Defined Network   |
| VN      | A virtual network (VN) is a network that consists of virtual resources (e.g. processing) and virtual network links. The two most common forms of network virtualization are protocol-based virtual networks, (such as VLANs, VPNs, and VPLSs) and virtual networks that are based on virtual devices (such as the networks connecting virtual machines inside a hypervisor). |
| VM      | Virtual Machine  |
| VPN     | Virtual Private Network  |
| vswitch | Any Ethernet switch implemented in software alongside or inside a hypervisor. There are proprietary and open implementations of vswitch.   |
| WAN     | Wide-Area Network  |
| Xen     | Open Source Hypervisor   |

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WG(s):

Seoul, 8-11 March 2016

**DOCUMENT****Source:** Telecom Italia**Title:** A Global Operating System for 5G Infrastructures**1. Introduction**

This contribution proposes the development of a Recommendation about the Global Operating System for 5G Infrastructures in the area of IMT-2020.

|                   |  |                                |
|-------------------|--|--------------------------------|
| Title             | A Global Operating System for 5G Infrastructures |                                |
| Lead Organization | Telecom Italia                                   |                                |
| Completion Date   | 2017-MM-DD                                       | Includes end-of-year demo? TBD |

**2. Scenarios and Motivations**

Softwarization (e.g., SDN-NFV) is going to make telecommunications infrastructures very flexible and pervasive, capable of hooking billions of processing network and service functions with ultra-low latency connections. It is argued that Softwarization will find a first concrete exploitation in the 5G infrastructure. In fact, 5G will be a massively dense distributed infrastructure, integrating processing, storage and (fixed and radio) networking capabilities, capable of producing radical socio-economic impacts. Digital Society and Economy will be radically “transformed” by a faster radio access, by larger bandwidth connections, and above all, by the pervasive availability of processing and storage capabilities integrated by an ultra-low latency fabric.

“Immersive Communications” and “Anything as a Service” are often mentioned as two attractive examples of future service paradigms, which are posing challenging requirements for future 5G infrastructures. In a nutshell, “Immersive Communications” looks beyond the “commoditization” of current communication paradigms (e.g., voice, messaging, etc.), by pursuing new advanced forms of social communications and networking (e.g., through artificially intelligent avatars, cognitive robot-human interactions, etc.). “Anything as a Service” is about providing (anytime and anywhere) a wider and wider sets of ICT services by means of new terminals, machines, smart things, robots, toys going far beyond our today imagination. Robots, drones, autonomous machines, smart things, A.I. interfaces will be the terminals of the future for 5G.

In summary, 5G will become a dense and distributed “fabric” of computational, storage and communication functions, so, in the same way, metaphorically, a computer has an operating system — dictating the way it works and it provides services for developing applications — 5G will have to have a sort of OS capable of operating the converged fixed and RAN and core infrastructures.

This contribution proposes to develop a Recommendation describing the functional architectural model of an Operating System (OS) for 5G.

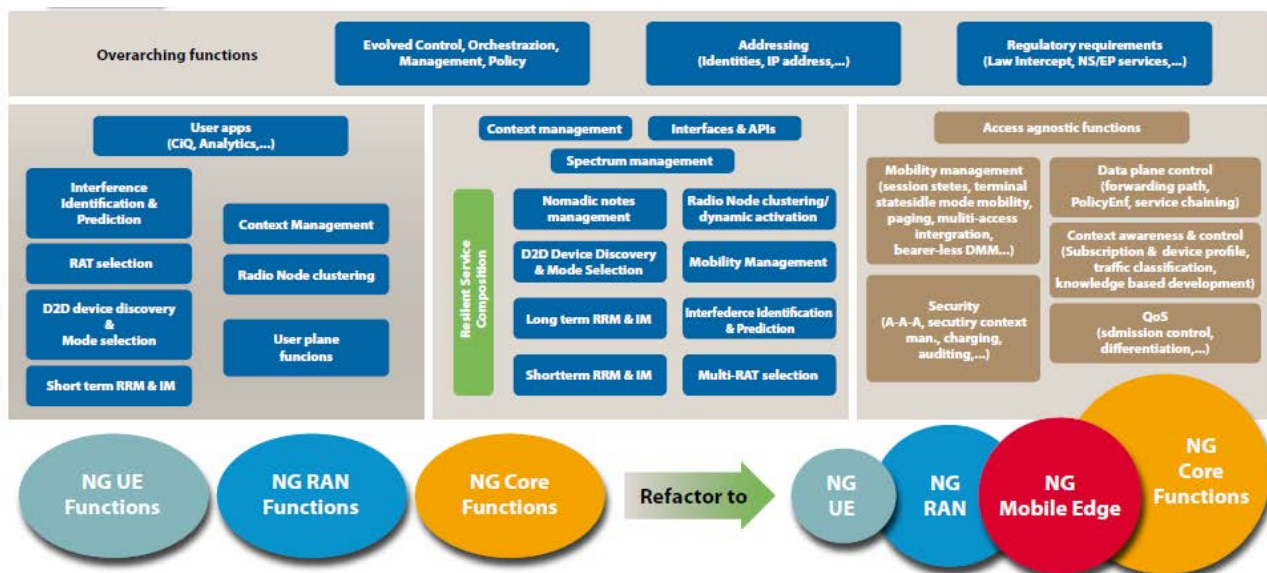
### 3. A Global Operating System for 5G

In a way 5G will be a dense and distributed “fabric” of computational, storage and communication functions, so, in the same way, a computer network has an Operating System (OS) — dictating the way it works and it provides services for developing applications — 5G will have to have a sort of OS capable of operating the converged fixed and RAN and core infrastructures.

Practically, the 5GOS can be seen as a distributed software platform in charge of executing any sort of SDN services, NFV services, and Cloud-Edge Computing services provided by a fully virtualized 5G infrastructure. 5GOS operates from the terminals (executing services tasks and storing local data), through the Network (e.g., Edge Clouds), up to the Cloud Computing (e.g., centralized Data Centers).

### 4. End to End functional decomposition of 5G

Following figure is showing a functional decomposition of NG UE, RAN and core functions for an end-to-end architecture of a 5G infrastructure.



The functional decomposition should be followed by an optimal allocation and orchestration of the virtualised functionalities to refactored nodes to address requirements.

### 5. Infrastructure Common Model and Abstractions

Under preparation

### 6. Unifying Service models

X-as-a-Services is seen as a unifying perspective whereby SDN services (e.g., controllers), NFV services (e.g., Virtual Network Functions), and Cloud services are seen as “application” executed on virtualized resources. In this sense, services can be seen as “units of orchestration” which are executed in one of more 5G “slices”.

A “slice” is made of a set of logical resources (e.g., Virtual Machines or Containers) interconnected by a set of virtual links (e.g., Virtual Networks).





Figure 1 – Example: a service made of a number of service components (S) executed on Virtual Machines (VM) interconnected via Virtual Network (VN)

According to the proposed unifying model, a generic service:

- is made of service components or building block;
- can be composed with other services (e.g., service chain, or more articulated service logics)
- provides a function (both “global” and “local”);
- exports APIs (e.g., REST);
- is available anywhere and anytime (location-time independent)
- is scalable, elastic, and resilient.

## Service Templates and Data Models

TOSCA (Topology and Orchestration Specification for Cloud Applications) [5] is a standard from OASIS that target interoperable deployment and lifecycle management of cloud services. TOSCA uses the concept of service templates to describe cloud workloads as a topology template. The topology template describes the structure of a service as a set of node templates and relationship templates modelling the relations as a directed graph. Node templates and relationship templates (linking different nodes) in fact specify properties and operations (via interfaces) to manipulate the service components.

In ETSI NFV [6], a Network Service (NS) is a “*composition of Network Functions and it is defined by its functional and behavioural specification*”, being a Network Function (NF) a functional block within a network infrastructure that has well-defined external interfaces and well-defined functional behaviour.

In IETF, [7] the term Service Function Chaining (SFC) is used “*to describe the definition and instantiation of an ordered list of instances of such service functions, and the subsequent “steering” of traffic flows through those service functions*”.

Moreover, the YANG declarative data modelling language can be used both to describe deployable instances of a service (e.g., a VNF) and to configure a network device/element at run time.

Eventually, TOSCA and NETCONF/YANG can be considered as complementary instruments: deployment templates may trigger the NETCONF/YANG configurations during the instantiation of a service, whilst in the Operations the OSS can take over configurations at run time [8].

## 7. 5GOS Functional Architecture

The following figure is showing the functional layering of a 5G infrastructure, in line with ETSI NFV reference architecture. When comparing 5GOS with the ETSI NFV model, it can be seen as a global “overarching orchestrator”, extending the capabilities of the VNF Manager (from the terminals to the Cloud). At the same time, the Virtual Infrastructure Manager (VIM) plays the role of a 5GOS subsystem (an example is the combination of OpenStack and ONOS).

5GOS facilitates also the functional decoupling with respect to the capabilities of the NFV Orchestrator (NFV-O). Service orchestrators can be executed as “services” on top of the 5GOS, leveraging on the APIs that the 5GOS is offering.

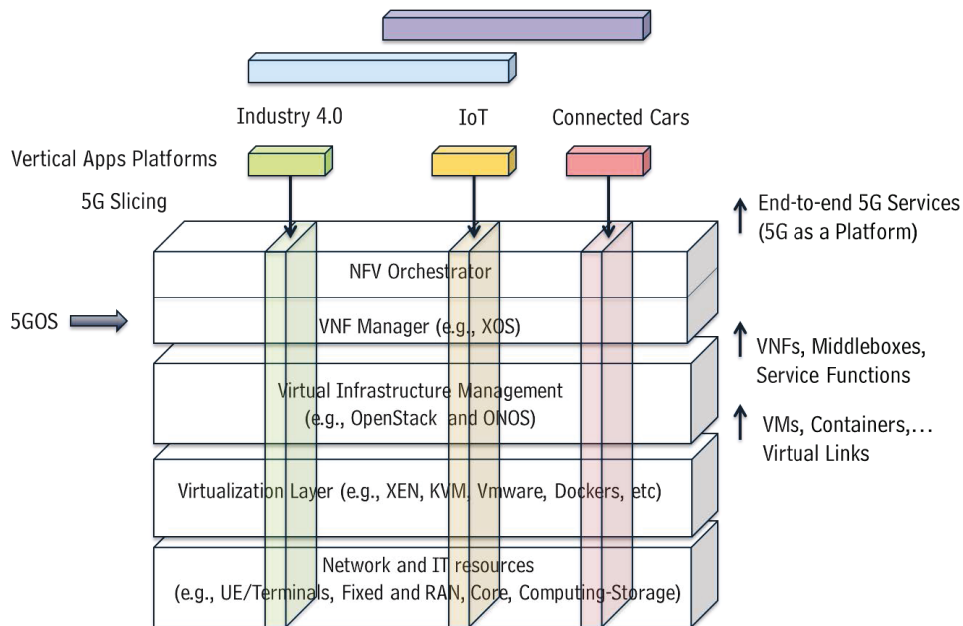


Figure 3 – 5GOS

The overall functional design of 5GOS will have to define:

- logical resources (e.g., Virtual Machines, Containers) in which programs (services) run;
- communication primitives and mechanisms for services to communicate with each other;
- conventions about how services are named, configured, started/stopped;
- a programming environment: with a view abstraction (e.g., Unix shell);
- an abstraction to incorporate new hardware into the 5G infrastructure (e.g., drivers).

5GOS can be seen structured into two main functional blocks (Figure 4):

- the local 5G Edge Cloud Operating Systems (5G Edge Cloud OS) which are the local instantiations of the 5G OS capabilities for a specific Edge Cloud domains;
- the centralized 5G Global Operating Systems (5G Global OS) which is responsible for centralized functionalities of 5GOS, this providing the overall integration.

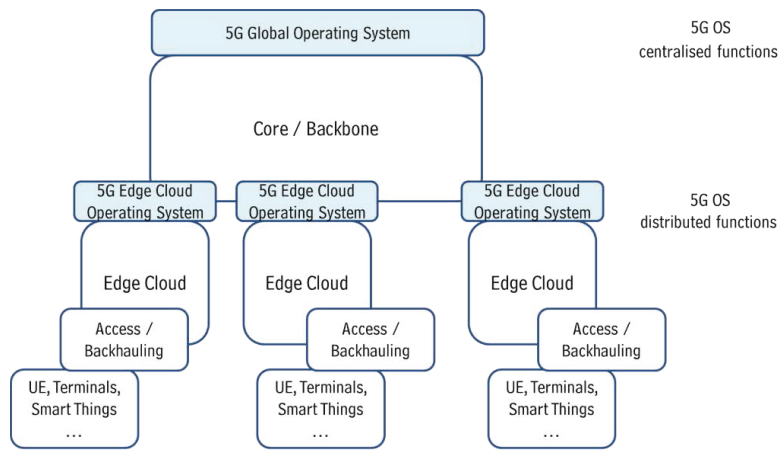


Figure 4 - 5G OS: local vs global capabilities

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DevOps for Software-Defined Telecom Infrastructures  
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## Abstract

Carrier-grade network management was optimized for environments built with monolithic physical nodes and involves significant deployment, integration and maintenance efforts from network service providers. The introduction of virtualization technologies, from the physical layer all the way up to the application layer, however, invalidates several well-established assumptions in this domain. This draft opens the discussion in NFVRG about challenges related to transforming the telecom network infrastructure into an agile, model-driven production environment for communication services. We take inspiration from data center DevOps regarding how to simplify and automate management processes for a telecom service provider software-defined infrastructure (SDI). Finally, we introduce challenges associated with operationalizing DevOps principles at scale in software-defined telecom networks in three areas related to key monitoring, verification and troubleshooting processes.

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## 1. Introduction

Carrier-grade network management was developed as an incremental solution once a particular network technology matured and came to be deployed in parallel with legacy technologies. This approach requires significant integration efforts when new network services are launched. Both centralized and distributed algorithms have been developed in order to solve very specific problems related to configuration, performance and fault management. However, such algorithms consider a network that is by and large functionally static. Thus,

management processes related to introducing new or maintaining functionality are complex and costly due to significant efforts required for verification and integration.

Network virtualization, by means of Software-Defined Networking (SDN) and Network Function Virtualization (NFV), creates an environment where network functions are no longer static nor strictly embedded in physical boxes deployed at fixed points. The virtualized network is dynamic and open to fast-paced innovation enabling efficient network management and reduction of operating cost for network operators. A significant part of network capabilities are expected to become available through interfaces that resemble the APIs widespread within datacenters instead of the traditional telecom means of management such as the Simple Network Management Protocol, Command Line Interfaces or CORBA. Such an API-based approach, combined with the programmability offered by SDN interfaces [RFC7426], open opportunities for handling infrastructure, resources, and Virtual Network Functions (VNFs) as code, employing techniques from software engineering.

The efficiency and integration of existing management techniques in virtualized and dynamic network environments are limited, however. Monitoring tools, e.g. based on simple counters, physical network taps and active probing, do not scale well and provide only a small part of the observability features required in such a dynamic environment. Although huge amounts of monitoring data can be collected from the nodes, the typical granularity is rather coarse. Debugging and troubleshooting techniques developed for software-defined environments are a research topic that has gathered interest in the research community in the last years. Still, it is yet to be explored how to integrate them into an operational network management system. Moreover, research tools developed in academia (such as NetSight [H2014], OFRewind [W2011], FlowChecker [S2010], etc.) were limited to solving very particular, well-defined problems, and oftentimes are not built for automation and integration into carrier-grade network operations workflows.

The topics at hand have already attracted several standardization organizations to look into the issues arising in this new environment. For example, IETF working groups have activities in the area of OAM and Verification for Service Function Chaining [I-D.aldrin-sfc-oam-framework] [I-D.lee-sfc-verification] for Service Function Chaining. At IRTF, [RFC7149] asks a set of relevant questions regarding operations of SDNs. The ETSI NFV ISG defines the MANO interfaces [NFVMANO], and TMForum investigates gaps between these interfaces and existing specifications in [TR228]. The need for programmatic APIs in the orchestration of compute, network and storage resources is discussed in [I-D.unify-nfvrg-challenges].

From a research perspective, problems related to operations of software-defined networks are in part outlined in [SDNsurvey] and research referring to both cloud and software-defined networks are discussed in [D4.1].

The purpose of this first version of this document is to act as a discussion opener in NFVRG by describing a set of principles that are relevant for applying DevOps ideas to managing software-defined telecom network infrastructures. We identify a set of challenges related to developing tools, interfaces and protocols that would support these principles and how can we leverage standard APIs for simplifying management tasks.

## 2. Software-Defined Telecom Infrastructure: Roles and DevOps principles

Agile methods used in many software focused companies are focused on releasing small interactions of code to implement VNFs with high velocity and high quality into a production environment. Similarly Service providers are interested to release incremental improvements in the network services that they create from virtualized network functions. The cycle time for DevOps as applied in many open source projects is on the order of one quarter year or 13 weeks.

The code needs to undergo a significant amount of automated testing and verification with pre-defined templates in a realistic setting. From the point of view of infrastructure management, the verification of the network configuration as result of network policy decomposition and refinement, as well as the configuration of virtual functions, is one of the most sensitive operations. When troubleshooting the cause of unexpected behavior, fine-grained visibility onto all resources supporting the virtual functions (either compute, or network-related) is paramount to facilitating fast resolution times. While compute resources are typically very well covered by debugging and profiling toolsets based on many years of advances in software engineering, programmable network resources are still a novelty and tools exploiting their potential are scarce.

### Service Developer Role

We identify two dimensions of the "developer" role in software-defined infrastructure (SDI). One dimension relates to determining which high-level functions should be part of a particular service, deciding what logical interconnections are needed between these blocks and defining a set of high-level constraints or goals related to parameters that define, for instance, a Service Function Chain. This could be determined by the product owner for a particular family of services offered by a telecom provider. Or, it might be a key account representative that adapts an existing service template to the requirements of a particular customer by adding or removing a small number of functional entities. We refer to this person as the Service Developer and for simplicity (access control, training on technical background, etc.) we consider the role to be internal to the telecom provider.

### VNF Developer role

The other dimension of the "developer" role is a person that writes the software code for a new virtual network function (VNF). Depending on the actual VNF being developed, this person might be internal or external to the telecom provider. We refer to them as VNF Developers.

### Operator role

The role of an Operator in SDI is to ensure that the deployment processes were successful and a set of performance indicators associated to a service are met while the service is supported on virtual infrastructure within the domain of a telecom provider.

System integration roles are important and we intend to approach them in a future reversion of this draft.

## DevOps Principles

In line with the generic DevOps concept outlined in [DevOpsP], we consider that these four principles as important for adapting DevOps ideas to SDI:

- \* **Deploy with repeatable, reliable processes:** Service and VNF Developers should be supported by automated build, orchestrate and deploy processes that are identical in the development, test and production environments. Such processes need to be made reliable and trusted in the sense that they should reduce the chance of human error and provide visibility at each stage of the process, as well as have the possibility to enable manual interactions in certain key stages.

- \* **Develop and test against production-like systems:** both Service Developers and VNF Developers need to have the opportunity to verify and debug their respective SDI code in systems that have characteristics which are very close to the production environment where the code is expected to be ultimately deployed. Customizations of Service Function Chains or VNFs could thus be released frequently to a production environment in compliance with policies set by the Operators. Adequate isolation and protection of the services active in the infrastructure from services being tested or debugged should be provided by the production environment.

- \* **Monitor and validate operational quality:** Service Developers, VNF Developers and Operators must be equipped with tools, automated as much as possible, that enable to continuously monitor the operational quality of the services deployed on SDI. Monitoring tools should be complemented by tools that allow verifying and validating the operational quality of the service in line with established procedures which might be standardized (for example, Y.1564 Ethernet Activation [Y1564]) or defined through best practices specific to a particular telecom operator.

- \* **Amplify development cycle feedback loops:** An integral part of the DevOps ethos is building a cross-cultural environment that bridges the cultural gap between the desire for continuous change by the Developers and the demand by the Operators for stability and reliability of the infrastructure. Feedback from customers is collected and transmitted throughout the organization. From a technical perspective, such cultural aspects could be addressed through common sets of tools and APIs that are aimed at providing a shared vocabulary for both Developers and Operators, as well as simplifying the reproduction of problematic situations in the development, test and operations environments.

Network operators that would like to move to agile methods to deploy and manage their networks and services face a different environment compared to typical software companies where simplified trust relationships between personnel are the norm. In such companies, it is not uncommon that the same person may be rotating between different roles. In contrast, in a telecom service provider, there are strong organizational boundaries between suppliers (whether in Developer roles for network functions, or in Operator roles for outsourced services) and the carrier's own personnel that might also take both Developer and Operator roles. How DevOps principles reflect on these trust relationships and to what extent initiatives such as co-creation could transform the environment to facilitate closer Dev and Ops integration across business boundaries is an interesting area for



business studies, but we could not for now identify a specific technological challenge.

### 3. Continuous Integration

Software integration is the process of bringing together the software component subsystems into one software system, and ensuring that the subsystems function together as a system. Software integration can apply regardless of the size of the software components. The objective of Continuous Integration is to prevent integration problems close to the expected release of a software development project into a production (operations) environment. Continuous Integration is therefore closely coupled with the notion of DevOps as a mechanism to ease the transition from development to operations.

Continuous integration may result in multiple builds per day. It is also typically used in conjunction with test driven development approaches that integrate unit testing into the build process. The unit testing is typically automated through build servers. Such servers may implement a variety of additional static and dynamic tests as well as other quality control and documentation extraction functions. The reduced cycle times of continuous enable improved software quality by applying small efforts frequently.

Continuous Integration applies to developers of VNF as they integrate the components that they need to deliver their VNF. The VNFs may contain components developed by different teams within the VNF Provider, or may integrate code developed externally - e.g. in commercial code libraries or in open source communities.

Service providers also apply continuous integration in the development of network services. Network services are comprised of various aspects including VNFs and connectivity within and between them as well as with various associated resource authorizations. The components of the networks service are all dynamic, and largely represented by software that must be integrated regularly to maintain consistency. Some of the software components that Service Providers may be sourced from VNF Providers or from open source communities. Service Providers are increasingly motivated to engage with open Source communities [OSandS]. Open source interfaces supported by open source communities may be more useful than traditional paper interface specifications. Even where Service Providers are deeply engaged in the open source community (e.g. OPNFV) many service providers may prefer to obtain the code through some software provider as a business practice. Such software providers have the same interests in software integration as other VNF providers.

### 4. Continuous Delivery

The practice of Continuous Delivery extends Continuous Integration by ensuring that the software checked in on the mainline is always in a user deployable state and enables rapid deployment by those users.

### 5. Stability Challenges

The dimensions, dynamicity and heterogeneity of networks are growing continuously. Monitoring and managing the network behavior in order

to meet technical and business objectives is becoming increasingly complicated and challenging, especially when considering the need of predicting and taming potential instabilities.

In general, instability in networks may have primary effects both jeopardizing the performance and compromising an optimized use of resources, even across multiple layers: in fact, instability of end-to-end communication paths may depend both on the underlying transport network, as well as the higher level components specific to flow control and dynamic routing. For example, arguments for introducing advanced flow admission control are essentially derived from the observation that the network otherwise behaves in an inefficient and potentially unstable manner. Even with resources over provisioning, a network without an efficient flow admission control has instability regions that can even lead to congestion collapse in certain configurations. Another example is the instability which is characteristic of any dynamically adaptive routing system. Routing instability, which can be (informally) defined as the quick change of network reachability and topology information, has a number of possible origins, including problems with connections, router failures, high levels of congestion, software configuration errors, transient physical and data link problems, and software bugs.

As a matter of fact, the states monitored and used to implement the different control and management functions in network nodes are governed by several low-level configuration commands (today still done mostly manually). Further, there are several dependencies among these states and the logic updating the states (most of which are not kept aligned automatically). Normally, high-level network goals (such as the connectivity matrix, load-balancing, traffic engineering goals, survivability requirements, etc) are translated into low-level configuration commands (mostly manually) individually executed on the network elements (e.g., forwarding table, packet filters, link-scheduling weights, and queue-management parameters, as well as tunnels and NAT mappings). Network instabilities due to configuration errors can spread from node to node and propagate throughout the network.

DevOps in the data center is a source of inspiration regarding how to simplify and automate management processes for software-defined infrastructure.

As a specific example, automated configuration functions are expected to take the form of a "control loop" that monitors (i.e., measures) current states of the network, performs a computation, and then reconfigures the network. These types of functions must work correctly even in the presence of failures, variable delays in communicating with a distributed set of devices, and frequent changes in network conditions. Nevertheless cascading and nesting of automated configuration processes can lead to the emergence of non-linear network behaviors, and as such sudden instabilities (i.e. identical local dynamic can give rise to widely different global dynamics).

## 6. Consistency, Availability and Partitioning Challenges

The CAP theorem [CAP] states that any networked shared-data system can have at most two of following three properties: 1) Consistency (C) equivalent to having a single up-to-date copy of the data; 2) high Availability (A) of that data (for updates); and 3) tolerance to network Partitions (P).

Looking at a telecom SDI as a distributed computational system (routing/forwarding packets can be seen as a computational problem), just two of the three CAP properties will be possible at the same time. The general idea is that 2 of the 3 have to be chosen. CP favor consistency, AP favor availability, CA there are no partition. This has profound implications for technologies that need to be developed in line with the "deploy with repeatable, reliable processes" principle for configuring SDI states. Latency or delay and partitioning properties are closely related, and such relation becomes more important in the case of telecom service providers where Devs and Ops interact with widely distributed infrastructure. Limitations of interactions between centralized management and distributed control need to be carefully examined in such environments. Traditionally connectivity was the main concern: C and A was about delivering packets to destination. The features and capabilities of SDN and NFV are changing the concerns: for example in SDN, control plane Partitions no longer imply data plane Partitions, so A does not imply C. In practice, CAP reflects the need for a balance between local/distributed operations and remote/centralized operations.

Furthermore to CAP aspects related to individual protocols, interdependencies between CAP choices for both resources and VNFs that are interconnected in a forwarding graph need to be considered. This is particularly relevant for the "Monitor and Validate Operational Quality" principle, as apart from transport protocols, most OAM functionality is generally configured in processes that are separated from the configuration of the monitored entities. Also, partitioning in a monitoring plane implemented through VNFs executed on compute resources does not necessarily mean that the dataplane of the monitored VNF was partitioned as well.

## 7. Observability Challenges

Monitoring algorithms need to operate in a scalable manner while providing the specified level of observability in the network, either for operation purposes (Ops part) or for debugging in a development phase (Dev part). We consider the following challenges:

- \* Scalability - relates to the granularity of network observability, computational efficiency, communication overhead, and strategic placement of monitoring functions.

- \* Distributed operation and information exchange between monitoring functions - monitoring functions supported by the nodes may perform specific operations (such as aggregation or filtering) locally on the collected data or within a defined data neighborhood and forward only the result to a management system. Such operation may require modifications of existing standards and development of protocols for efficient information exchange and messaging between monitoring functions. Different levels of granularity may need to be offered for the data exchanged through the interfaces, depending on the Dev or Ops role.

- \* Configurability and conditional observability - monitoring functions that go beyond measuring simple metrics (such as delay, or packet loss) require expressive monitoring annotation languages for describing the functionality such that it can be programmed by a controller. Monitoring algorithms implementing self-adaptive monitoring behavior relative to local network situations may employ such annota-

tion languages to receive high-level objectives (KPIs controlling tradeoffs between accuracy and measurement frequency, for example) and conditions for varying the measurement intensity.

\* Automation - includes mapping of monitoring functionality from a logical forwarding graph to virtual or physical instances executing in the infrastructure, as well as placement and re-placement of monitoring functionality for required observability coverage and configuration consistency upon updates in a dynamic network environment.

## 8. Verification Challenges

Enabling ongoing verification of code is an important goal of continuous integration as part of the data center DevOps concept. In a telcom SDI, service definitions, decompositions and configurations need to be expressed in machine-readable encodings. For example, configuration parameters could be expressed in terms of YANG data models. However, the infrastructure management layers (such as Software-Defined Network Controllers and Orchestration functions) might not always export such machine-readable descriptions of the runtime configuration state. In this case, the management layer itself could be expected to include a verification process that has the same challenges as the stand-alone verification processes we outline later in this section. In that sense, verification can be considered as a set of features providing gatekeeper functions to verify both the abstract service models and the proposed resource configuration before or right after the actual instantiation on the infrastructure layer takes place.

A verification process can involve different layers of the network and service architecture. Starting from a high-level verification of the customer input (for example, a Service Graph as defined in [I-D.unify-nfvrg-challenges]), the verification process could go more in depth to reflect on the Service Function Chain configuration. At the lowest layer, the verification would handle the actual set of forwarding rules and other configuration parameters associated to a Service Function Chain instance. This enables the verification of more quantitative properties (e.g. compliance with resource availability), as well as a more detailed and precise verification of the abovementioned topological ones. Existing SDN verification tools could be deployed in this context, but the majority of them only operate on flow space rules commonly expressed using OpenFlow syntax.

Moreover, such verification tools were designed for networks where the flow rules are necessary and sufficient to determine the forwarding state. This assumption is valid in networks composed only by network functions that forward traffic by analyzing only the packet headers (e.g. simple routers, stateless firewalls, etc.). Unfortunately, most of the real networks contain active network functions, represented by middle-boxes that dynamically change the forwarding path of a flow according to function-local algorithms and an internal state (that is based on the received packets), e.g. load balancers, packet marking modules and intrusion detection systems. The existing verification tools do not consider active network functions because they do not account for the dynamic transformation of an internal state into the verification process.

Defining a set of verification tools that can account for active network functions is a significant challenge. In order to perform veri-

fication based on formal properties of the system, the internal states of an active (virtual or not) network function would need to be represented. Although these states would increase the verification process complexity (e.g., using simple model checking would not be feasible due to state explosion), they help to better represent the forwarding behavior in real networks. A way to address this challenge is by attempting to summarize the internal state of an active network function in a way that allows for the verification process to finish within a reasonable time interval.

## 9. Troubleshooting Challenges

One of the problems brought up by the complexity introduced by NFV and SDN is pinpointing the cause of a failure in an infrastructure that is under continuous change. Developing an agile and low-maintenance debugging mechanism for an architecture that is comprised of multiple layers and discrete components is a particularly challenging task to carry out. Verification, observability, and probe-based tools are key to troubleshooting processes, regardless whether they are followed by Dev or Ops personnel.

### \* Automated troubleshooting workflows

Failure is a frequently occurring event in network operation. Therefore, it is crucial to monitor components of the system periodically. Moreover, the troubleshooting system should search for the cause automatically in the case of failure. If the system follows a multi-layered architecture, monitoring and debugging actions should be performed on components from the topmost layer to the bottom layer in a chain. Likewise, the result of operations should be notified in reverse order. In this regard, one should be able to define monitoring and debugging actions through a common interface that employs layer hopping logic. Besides, this interface should allow fine-grained and automatic on-demand control for the integration of other monitoring and verification mechanisms and tools.

### \* Troubleshooting with active measurement methods

Besides detecting network changes based on passively collected information, active probes to quantify delay, network utilization and loss rate are important to debug errors and to evaluate the performance of network elements. While tools that are effective in determining such conditions for particular technologies were specified by IETF and other standardization organization, their use requires a significant amount of manual labor in terms of both configuration and interpretation of the results; see also Section **Erreur ! Source du renvoi introuvable**.

In contrast, methods that test and debug networks systematically based on models generated from the router configuration, router interface tables or forwarding tables, would significantly simplify management. They could be made usable by Dev personnel that have little expertise on diagnosing network defects. Such tools naturally lend themselves to integration into complex troubleshooting workflows that could be generated automatically based on the description of a particular service chain. However, there are scalability challenges associated with deploying such tools in a network. Some tools may poll each networking device for the forwarding table information to calculate the minimum number of test packets to be transmitted in the network. Therefore, as the network size and the forwarding table size

increase, forwarding table updates for the tools may put a non-negligible load in the network.

## 10. Programmable network management

The ability to automate a set of actions to be performed on the infrastructure, be it virtual or physical, is key to productivity increases following the application of DevOps principles. Previous sections in this document touched on different dimensions of programmability:

- Section 6 approached programmability in the context of developing new capabilities for monitoring and for dynamically setting configuration parameters of deployed monitoring functions
- Section 7 reflected on the need to determine the correctness of actions that are to be inflicted on the infrastructure as result of executing a set of high-level instructions
- Section 8 considered programmability in the perspective of an interface to facilitate dynamic orchestration of troubleshooting steps towards building workflows and for reducing the manual steps required in troubleshooting processes

We expect that programmable network management - along the lines of [RFC7426] - will draw more interest as we move forward. For example, in [I-D.unify-nfvrg-challenges], the authors identify the need for presenting programmable interfaces that accept instructions in a standards-supported manner for the Two-way Active Measurement Protocol (TWAMP) protocol. More specifically, an excellent example in this case is traffic measurements, which are extensively used today to determine SLA adherence as well as debug and troubleshoot pain points in service delivery. TWAMP is both widely implemented by all established vendors and deployed by most global operators. However, TWAMP management and control today relies solely on diverse and proprietary tools provided by the respective vendors of the equipment. For large, virtualized, and dynamically instantiated infrastructures where network functions are placed according to orchestration algorithms proprietary mechanisms for managing TWAMP measurements have severe limitations. For example, today's TWAMP implementations are managed by vendor-specific, typically command-line interfaces (CLI), which can be scripted on a platform-by-platform basis. As a result, although the control and test measurement protocols are standardized, their respective management is not. This hinders dramatically the possibility to integrate such deployed functionality in the SP-DevOps concept. In this particular case, recent efforts in the IPPM WG [I-D.cmzrjp-ippm-twamp-yang] aim to define a standard TWAMP data model and effectively increase the programmability of TWAMP deployments in the future.

Data center DevOps tools, such as those surveyed in [D4.1], developed proprietary methods for describing and interacting through interfaces with the managed infrastructure. Within certain communities, they became de-facto standards in the same way particular CLIs became de-facto standards for Internet professionals. Although open-source components and a strong community involvement exists, the diversity of the new languages and interfaces creates a burden for both vendors in terms of choosing which ones to prioritize for support, and then de-

veloping the functionality and operators that determine what fits best for the requirements of their systems.

## 11. DevOps Performance Metrics

Defining a set of metrics that are used as performance indicators is important for service providers to ensure the successful deployment and operation of a service in the software-defined telecom infrastructure.

We identify three types of considerations that are particularly relevant for these metrics: 1) technical considerations directly related to the service provided, 2) process-related considerations regarding the deployment, maintenance and troubleshooting of the service, i.e. concerning the operation of VNFs, and 3) cost-related considerations associated to the benefits from using a Software-Defined Telecom Infrastructure.

First, technical performance metrics shall be service-dependent/-oriented and may address *inter-alia* service performance in terms of delay, throughput, congestion, energy consumption, availability, etc. Acceptable performance levels should be mapped to SLAs and the requirements of the service users. Metrics in this category were defined in IETF working groups and other standardization organizations with responsibility over particular service or infrastructure descriptions.

Second, process-related metrics shall serve a wider perspective in the sense that they shall be applicable for multiple types of services. For instance, process-related metrics may include: number of probes for end-to-end QoS monitoring, number of on-site interventions, number of unused alarms, number of configuration mistakes, incident/trouble delay resolution, delay between service order and deliver, or number of self-care operations.

Third, cost-related metrics shall be used to monitor and assess the benefit of employing SDI compared to the usage of legacy hardware infrastructure with respect to operational costs, e.g. possible man-hours reductions, elimination of deployment and configuration mistakes, etc.

Finally, identifying a number of highly relevant metrics for DevOps and especially monitoring and measuring them is highly challenging because of the amount and availability of data sources that could be aggregated within one such metric, e.g. calculation of human intervention, or secret aspects of costs.

## 12. Security Considerations

TBD

### 13. IANA Considerations

This memo includes no request to IANA.

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# **NetWorld 2020 ETP**

## ***5G Experimental Facilities in Europe***

### ***White Paper***

Version 11.0

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# White Paper for NetWorld 2020 (5GPPP) “5G Experimental Facilities in Europe”, v11, (February, 2016)

## Executive Summary

The recent advances in Information Technologies (IT), the diffusion of ultra-broadband (fixed and radio) connectivity, the continuous reduction of hardware costs and the wider and wider availability of open source software solutions, are creating the conditions for introducing a deep innovation in the architectural design and in the operations of future telecommunications networks and services.

We are witnessing a period of rapidly growing interest on the part of industry and academia in Software-Defined Networks (SDN) [1] and Network Function Virtualization (NFV) [2]. The growing interest in these paradigms (re-proposing principles that have been well-known) is most probably motivated by the novelty of the overall context, specifically their techno-economic sustainability and high-level performance. Thanks to these techno-economic trends, SDN and NFV principles will soon impact not only current telecommunications fixed and mobile networks, but also service and application platforms. In fact, SDN and NFV, together with Cloud, Edge and Fog Computing, can be seen as facets of a broad innovation wave, called **Softwarization**, which will contribute to automating processes, optimising costs, reducing time-to-market, providing better services. At the same time, the Internet of Things (IoT), Tactile Internet, Machine Type Communications (MTC), Cloud Manufacturing, Cloud Robotics, etc. will generate a new plethora of services and applications, ranging from industrial (e.g., Industry 4.0) and mission critical ones to precision agriculture, to Smart Cities, etc.

5G (which is not just one step beyond 4G) will be the main “collector” of this coming wave of innovation, bringing a number of different technologies to maturation, convergence and socio-economic impact, thus accelerating the transition towards the Digital Society and the Digital Economy. Europe should be prepared to face this important transformation, ready to capture all the socio-economic opportunities that it will bring.

In order to bring this vision into reality, Europe needs developing and aggregating a “critical mass” of **5G experimental facilities**, capable of exploiting synergies and collaborations, both within and outside Europe, e.g., with similar initiatives in US, China, Korea, Japan. This will go in the direction of joining forces for strengthening Europe in the development and exploitation of 5G infrastructures. There are several ways for pursuing this aggregation of **5G experimental facilities**: for example by interconnecting test-beds and field-trials at different levels (hierarchically), by making interoperable open and closed experimental islands, by exploiting the service “platforms of platforms” on top of virtual labs, etc.

Though many efforts have been made in the past in similar directions, a real “critical mass” of **experimental facilities** has not been fully reached yet, thus determining a certain level of **fragmentation**, bringing – in turn - the risk of delaying the socio-economic impacts of 5G.

5G will have to become the pervasive, highly flexible and ultra-low latency infrastructure capable of “networking” the enormous processing and storage power available in the Cloud/Edge with the sheer number of smartphones, tablets, things, wearable and the Fog Computing devices around Users.

From the infrastructure side, this “critical mass” of **experimental facilities** should increase collaboration on interoperability testing of different architectural approaches (e.g., SDN, NFV), their deep integration with Cloud/Edge/Fog Computing (e.g., validating the delicate balance of centralised versus distributed control and execution of functions) and the interworking of new operations processes. For example this includes testing of (and operating) the interoperability of different **Core and Radio Access** solutions (by using frequencies above and below 6 GHz, spectrum cognitive approaches (for specific applications), novel and traditional transmission techniques); it also includes the integration of Core and Radio Access solutions with Optical Networks (also strictly required to minimize latencies) and Satellite Networks.

To accomplish this goal, the fragmentation of experimental activities needs to be tackled through focused and concerted actions, aiming at collaborations between all projects and stakeholders.

Europe needs strong investments in this direction, both to innovate and also to ensure the maintenance and operation of experimental test beds. Investments are required both from the public and private sectors, in order to create a EU critical mass, which should be designed together with and for the specific goals of all industry players. In fact, this “critical mass” of **experimental facilities** will act as an “accelerator” for boosting the businesses of both **large, small, medium industry players and entrepreneurs**.

The challenge is bringing exploitation in Europe to concreteness, by creating new socio-economic opportunities and business ecosystems (e.g., in the sectors from industrial and agricultural mobile robotics, to new service paradigms such as “anything as a service”, from “full immersive experience and communications” to “Cognition-as-a-Service” for EU Citizens and Smart Cities, from Self-Driving Transportation Systems to the Internet of Things).

Moreover, in order to enable a sustainable and scalable experiment facility, it is recommended to dedicate joint efforts to the development of the vision of an **overarching Operating System** (OS) for 5G. This OS, spanning from the terminals, across the network to the Cloud, will be a sort of “glue” for “sticking” together different experimental domains and islands, making them interoperable. For example, this overarching OS should be seen as platform of platforms capable of executing network services and applications; it does not manage the 5G infrastructure itself, but it provides APIs supporting a broad spectrum of control and management applications.

This White Paper does not discuss the possible **verticals** of relevance to the development of 5G. Many of the facilities listed can be used to test technologies for several of the application areas currently envisaged for 5G. In few cases the test beds are specifically focused towards a specific vertical. In this case, this is specified in the short description.

## Rationale

Developing and aggregating a “critical mass” of **5G experimental facilities** has to, foremost, support the visions that major stakeholders are proposing for 5G, in order to allow proper interoperability testing and comparison of the different architectural frameworks. This should have the ambition to let European companies create the basis for a **shared vision** on what 5G will really be, not only from the technological viewpoint, but also from a business sustainability and regulations perspectives.

The shared vision, proposed by this White Paper, is:

- 1) embedding 5G into the reality as the “nervous system” of the Digital Society and the Digital Economy;
- 2) defining a “critical mass” of **5G experimental facilities** to facilitate synergies in the whole community of industries, including SMEs, and academia;
- 3) pursuing efforts in developing an overarching OS as a “glue” for “sticking” together different experimental domains and islands, making them interoperable.;
- 4) producing concrete impacts through a number of use-cases overcoming the fragmentation and lack of collaboration between separate Communities and Research Groups (e.g., IT/Cloud Experts, Network Engineers, Robotics Experts, etc).

While this strategy should be put in action to feed the European economy, at the same time cooperation should be found with regions like Korea, China, Japan and the US, to support the vision of a unique global network for the 5G era.

On the one hand the process of creating this critical mass should leverage on existing experimental infrastructures in Europe, created in the past years through National or EC funding (for example: the FIRE projects). On the other, necessary steps forward have to be taken, in order to reduce **fragmentation** and to ensure a better sustainability.

Proper **integration** needs to be sought in order to create a hierarchical experimental ecosystem with interoperable coordination and management. Many of the contributions received to this document describe existing test-beds and facilities of enormous value and potential. However, none of them has the capability to cover all aspects considered as possible technology bricks of 5G, and has the size needed to ensure proper environments for testing 5G in real heterogeneous conditions.

With respect to 2G, 3G and 4G, the 5G network will need a much higher degree of **flexibility and adaptability**, to serve applications with extremely diversified requirements (e.g. units of ms latency, more than 100 Mbit/s throughput per user) that will require separate and co-existing network and cloud approaches.

Moreover, from the radio access network side, the envisaged massive use of small cells, with distributed or centralised coordination and control, the novel backhaul paradigms based on multi-hop links, the many different frequency bands and physical layer techniques under investigation, require the deployment of test beds that in some cases will need to offer **large-scale** experimental facilities with thousands of programmable radio nodes.

From the optical network side, the rapid growth of user demand for increased connectivity, mobility and bandwidth, fibre capacity and reduced latency offered by new spectrally efficient, adaptive transmission,

networking, control and management approaches, also require the deployment of large-scale experimental facilities for advanced optical networking experimentation. Moreover, in order to ensure that the 5G network infrastructure can also serve low populated areas (emerging countries, rural areas and possibly suburban areas) as well as maritime and aeronautical markets, seamless integration with Satellite Networks is to be envisaged. These Satellite Networks can offer direct access or backhaul services and may be integrated at the access or at the metro network segments.

The overarching OS will integrate such experimental ecosystem in order to use both existing (e.g. 2G, 3G, 4G, WiFi) and novel radio technologies, both traditional and new networking and cloud paradigms; it should be designed according to criteria based on openness, ease of use whilst being secure in intellectual properties, with repeatable testing capabilities as well as being scalable. Though devised ultimately for serving industry and standardisations processes, its design requires **forward-looking approaches and knowledge of both fundamental and experimental approaches to research**. To this aim, the role of academia should be relevant, to provide proper methodological approach to the design of such ecosystem.

In summary, this proposal will be, able to serve the European industry in the next decade, becoming a sort of “accelerator” to create a socio-economic impact and developments in Europe. However it requires a number of conditions:

- i) huge investments from both the public (i.e. EC and National bodies) and private sectors, to collaborate in the design and development of what (e.g., software and hardware components) is required to pursue this goal;
- ii) true commitment from the main industry stakeholders, which have to perceive such critical mass of experimental facility as an opportunity where to make interoperability testing of their solutions, even under a certifiable framework: service providers, network operators, manufacturers should be involved, whether large, mid-sized or small enterprises. This will create the conditions for a pre-industrial adoption of the tested solutions;
- iii) strong support from academia, especially in the design phase;
- iv) enormous coordination effort, to let this experimental critical mass to really become ecosystems of ecosystems where the inter-play among the different components follows smooth and clear processes;
- v) open and transparent operations of hardware and software resources, with fair play of all players of the 5G roadmap;
- vi) proper dissemination tools to increase the EU visibility in pursuing this vision and to attract the largest number possible of small and medium enterprises, for testing of their solutions;
- vii) attention paid to the training of a new generation of researchers with 360° degree knowledge of the different technologies involved in 5G and prone to both fundamental and experimental research;
- viii) forward-looking approach; Europe needs to go one step forward, investing in its future.

# Requirements

A large-scale and hierarchical aggregation of experimental facility/islands for 5G should fulfil a number of requirements; it should be:

- **flexible** enough in order to accommodate many different options in terms of technologies (including separate physical layers, frequency bands, etc.) at the different layers and components of the network;
- easily **reconfigurable** so that experimenters can shape it for the sake of testing their own solutions;
- based on **open source** solutions, to magnify its potential exploiting the competences of the largest possible scientific community;
- able to provide **reproducible** results, in order to guarantee fair and scientific testing and comparison of separate technologies (this might require the inclusion of emulation components);
- **complete**, to allow the inclusion of all components of the 5G ecosystem, from the MNO to the virtual operator, from the end-user to the M2M application field and the IoT, etc;
- **heterogeneous** in terms of radio and optical interfaces tested, as well as of contexts, including body centric communications, vehicular networks, advanced robotics, etc.;
- **site-agnostic**, as far as this is possible, in order to test technologies and solutions in different contexts and to be easily accessible by researchers throughout all Europe;
- **topology-agnostic**, in order to cover all wireless solutions (including cellular and satellite technologies) and topologies (from small cells to macro-cells);
- **pan-European**, crossing several countries in Europe and serving stakeholders and research centers from all EC countries and beyond.

Moreover, it should constitute the basis for the development of 5G technologies in Europe, as well as for **training** a new generation of engineers and researchers prepared to such development. And above all, it should create concrete socio-economic impacts.

In terms of **performance**, the experimental facility should be able to allow testing of 5G technologies having in mind the need to meet some expected levels for KPIs to be properly defined; as a reference list, those mentioned in the Networld2020 White Paper “What is 5G (Really) About” can be considered: throughput, latency, coverage, battery lifetime, harnessing challenge, QoS, service creation time. The same document provides additional elements that should be considered as “soft” requirements (not directly quantifiable): privacy by design, open environment challenge, location and context information, manageability, harvesting challenge, hardening challenge, resource management, flexibility, authentication, charging, energy efficiency.

# Components

From a more technical viewpoint, these are the needed components:

- **designing and developing an overarching OS (leveraging from what is available in open source);** feasibility of OS concept might be first evaluated over small clouds of testbeds;
- **integration of legacy and novel physical access and backhaul evolutions,** including all those listed in the Networld2020 White Paper “Next Generation of Wireless Networks”: millimetre waves, flexible spectrum usage, visible light communications, distributed antenna systems, C-RAN, massive MIMO, hetnets, cooperation techniques, etc.;
- **exploitation of software-defined paradigms and virtualization,** including concepts mentioned in the Networld2020 White Paper “Network and Service Virtualisation” like NFV and SDN, both for the access and the core network;
- **integration of network and cloud based technologies** to help the network fulfil the stringent requirements of 5G in terms of latency, coverage and throughput and to manage the enormous amount of data that will be carried by 5G networks;
- **development and validation of novel 5G innovation services (e.g. based on IoT/M2M, Robotics, etc),** as also emphasized in the Networld2020 White Paper “Mobility/Connectivity and Networking Layer”, including the application of software defined networking approaches to IoT, specific solutions for low-complexity devices, cash-based networking, delay tolerant and social based networking, cloud robotics, etc.;
- **deployment of a rich application ecosystem,** where the continuously evolving trends of the end-user needs and new service models can be tested. Examples are from industrial and agricultural mobile robotics, to new service paradigms such as “anything as a service”, from “full immersive experience and communications” to “Cognition-as-a-Service” for EU Citizens and Smart Cities, from Self-Driving Transportation Systems to the IoT and MTC.

These core aspects find their supporting framework on the following three main 5G network components:

- a) the **terminals**, including smart devices with high computational capabilities (smartphones, tablets, pcs, etc.), things (sensors, actuators, tags carried by objects and humans) and machines (robots, drones and industrial devices), all acting as “nodes” providing users and applications with any services, or as routers for other nodes;
- b) the **network**, including the Radio Access component, backhauling and the Core, which will be indistinguishable;
- c) the **cloud**, with its storage and processing capabilities that – in the future - will not just be centralized in big Data Centers but it will be also distributed over a number of network sites (e.g., ex-



changes becoming mini-Data Centers at the edge) and possibly up to terminals, car, machines, robots.

We are now moving towards **fully software-enabled** automated infrastructures. The experimental facility however, should integrate such three components under a fully unified perspective. An overarching OS should be designed and developed, able to hide the complexity of the network to operators and service providers offering a unique platform with a distributed architecture spanning from terminals to the network to the cloud.

# Existing Facilities

A number of existing facilities for experimental purposes have been created in the past years in Europe. Some of them are mentioned below; the list is not exhaustive, being the result of the bottom-up contributions to this document. The order of presentation is random.

These resources offer immense opportunity for the European research community to progress research in this area and help to establish the European research community as main player in the development of 5G. However to fully take advantage from this existing infrastructure, a deeper integration that goes beyond basic federation is needed. An overarching OS can provide such integration.

- **EuWIn: European Laboratory of Wireless Communications for the Future Internet** – This joint and distributed laboratory has been created in the framework of the Network of Excellence Newcom# and will be maintained after its end through the participation to subsequent networking projects (COST Action IRACON). EuWIn integrates the competences and test-beds of three sites; one at the University of Bologna/CNIT, Italy (IoT protocols and indoor localization), one at EURECOM, France (including the OpenAirInterface) and one at CTTC, Spain (radio interfaces for 5G systems and indoor/satellite localization). The individual lab sites are also described as separate items below.
- **Openair5GLAB@EURECOM (EURECOM, France)** – This laboratory is part of EuWIn and it provides truly open-source solutions for prototyping 5th Generation Mobile Networks and devices. EURECOM has created the OpenAirInterface (OAI) Software Alliance (OSA), a separate legal entity from EURECOM, which aims to provide a similar ecosystem for the core (EPC) and access-network (EUTRAN) of 3GPP cellular systems with the possibility of interoperating with closed-source equipment in either portion of the network. OAI will be used in several EC funded project after Call 1 for 5G.
- **RadioNetworks@UniBO (University of Bologna, Italy)** – This laboratory is part of EuWIn, and is partly developed in collaboration with Telecom Italia Labs; it provides facilities for testing network architectures, protocol stack and air interfaces for the Internet of Things with particular emphasis to the comparison of architectures for the integration of the IoT into 5G networks. More than 200 devices (partly fixed and partly mobile) are available and share the same programmable software architecture including 802.15.4 systems, 802.15.4a UWB devices and LoRa systems.
- **EuWIn@CTTC (CTTC, Spain)** - The laboratory is part of EuWIn, and it explores key future challenges faced by radio interfaces in wireless systems with particular emphasis on energy efficiency, spectral efficiency and the interplay with positioning capabilities. Three testbeds are available: 1) the GEDOMIS® testbed, which comprises a complete set of baseband prototyping boards (FPGA and DSP-based), signal generation equipment, RF front-ends, signal analysis instruments, and a channel emulator for the prototyping of PHY layer of 5G systems such as FBMC; 2) a GNSS receiver lab station, including a set of GNSS antennas and LNAs, a reference GNSS multi-constellation receiver, a benchmark of COTS GNSS receivers, an SDR radio interface and a GNSS signal generator; 3) OpenInLocation - an Indoor localisation testbed.
- **5GTNF (5G Test Network, Finland)** – It coordinates and combines the research and technology development activities from the 5G infrastructures built under Tekes' 5th Gear programme. TNF creates a single coherent entity from the numerous smaller test networks around Finland (5GTN, CORE++, TAKE-5 and FUHF, below) and represents them as an integrated innovation platform to the research community, industry and other interested parties on both national and international level. With this approach, the 5GTNF covers all relevant 5G research areas ranging from the programmable core network infrastructures (including the utilization of the Software Defined Networking and Network Functions Virtualization concepts) to dense and heterogeneous access network configurations (including small cells and Internet of Things use cases). More efficient and intelligent use of the available spectrum (including different spectrum sharing techniques and utilization of

the Ultra-High Frequency band in cellular communications) is also covered together with the related business and regulation issues.

- **5GTN (VTT Technical Research Centre of Finland Ltd, University of Oulu, Nokia Networks, Finland)** is a research project, building a 5G test network at Oulu, Finland. In the test network, critical new technologies can be developed and it will allow testing of the performance of the novel technologies in a realistic environment. The Mission is to build a scalable 5G test network enabling future business models and service development as well as testing and developing a key 5G technology components and related support functions. Main focus is in 5G radio and IoT and 5G test network feature evolution follows 5G research and standardization progress, acting as a verification platform for theoretical 5G research.
- **CORE++ (VTT, Nokia Networks, Centria University of Applied Sciences, Finland)** - CORE++ trial environment provides a unique environment for spectrum sharing trials with live LTE networks on several frequency bands (licensed, unlicensed and shared bands). The trial environment consists of capabilities for demonstrating the feasibility of latest spectrum sharing concepts (e.g. Licensed shared access (LSA)) including adjustment of live LTE networks according to varying spectrum availability.
- **TAKE-5 (Aalto, VTT, Nokia Networks, Finland)** - TAKE-5 creates of a multidisciplinary and open research platform for investigation and experimental evaluation of innovative ideas in networking and services for 5G. The platform and 5G network functions are incrementally built and refined after each implemented extension. TAKE-5 objectives consist of research and initial test-bed setup for piloting new 5G business and services. TAKE-5 will optimize and verify the cloudification concepts of network functions and 5G radio solutions as the key enablers for efficient and cost effective mobile broadband infrastructure. TAKE-5 will address security and software defined networking (SDN) technology to control 5G and verify end to end services performance, agility while maintaining strict requirements on delays and reliability.
- **FUHF (Turku University of Applied Sciences, VTT, Nokia Networks, Finland)** - The objectives of the FUHF project, are to research the changing media environment, long-term media consumption formats, and especially evaluate and strategize around their impact on business models for different actors, that is, mobile operators, broadcasters, mobile network manufacturers, and broadcast network providers/operators. From a technical perspective, the FUHF project studies Supplemental Downlink (SDL) and LTE broadcast technologies. Test environment consists of DVB network and mobile network.
- **Netleap (Nokia Networks, Aalto University, Finland)** network is fully functional real life Cloud based LTE evolution network with both outdoor and indoor coverage in Finland. It supports both research and innovation projects. It is part of Nokia Innovation Laboratory ecosystem hosted by Nokia Networks. Net Leap Network offers a real-life lab and testing environment, especially suited for Industrial Internet and Cloud edge computing research.
- **IMB5 (Nokia Networks, Germany)**: Integration of Broadcast and Mobile Broadband in LTE/5G – Two test beds located in Munich and Erlangen, Germany for the purpose of testing the capabilities and limitations of current LTE eMBMS for nationwide broadcast infrastructure. Results will be used to create an optimized system architecture for eMBMS based networks and to develop input for modifications of the standards, esp. in 3GPP. The project started in March 2014 and is driven by a consortium including Nokia, IRT (Institut für Rundfunktechnik), Bayerischer Rundfunk, Fraunhofer IIS, University of Erlangen and Rohde & Schwarz.
- **5G Lab Germany (TU Dresden, Germany)** is an interdisciplinary team with more than 500 researchers and aims to deliver key technologies for enabling 5G. The 5G Holistic Testbed consists of several connected test-beds which enable holistic research approaches for areas from silicon, wireless, networks, edge clouds and applications. The 5G Physical Layer test-bed consists of a core hardware platform with four NI PXI units and several USRP-RIOs, spectrum analyzers, channel emulator, networking hardware, which enable test and evaluation of novel physical layer schemes, in indoor as well as outdoor environments. The 5G Network layer test-bed consists of 150 meshed mobile devices (e.g. smartphones, drones, mobile robots) with a research focus on networking coding to enhance meshed, multi-hop, multi-path and secure communication. Several 5G tactile application test-beds are also used.
- **Flexible testbed for 5G millimeter wave communications (SINTEF-ICT-CS, Norway)** - The purpose of the testbed is to test and demonstrate MIMO techniques and PHY and MAC communication protocols for 5G systems at millimetre wave frequencies. It is based on flexible SoC platforms from Xilinx and 60 GHz transceivers from Hittite. In particular, emphasis is put on the evaluation of the effects of realistic hardware impairments and propagation conditions on the performance, in order to limit power consumption and complexity of beamforming algorithms while ensuring fast network discovery.
- **mHOP: Experimental testbed for device-centric wireless networks (Universidad Miguel Hernandez de Elche, Spain)** - mHOP is a real-time experimental platform for the study of the connectivity and end-to-end perfor-

mance of device-centric wireless networks, in particular Multi-hop Cellular Networks (MCN) using mobile relays and Device-to-Device (D2D) communications; D2D communications are based on the 802.11 standard. The platform operates using live cellular networks, and allows evaluating the performance benefits of MCN over traditional cellular systems, and the operating conditions under which such benefits can be obtained. The mHOP nodes include sniffer and GPS software tools to monitor and geo-reference all the performance measurements both at the cellular and D2D links. mHOP has been evolved to integrate opportunistic networking both at the D2D and cellular connections. The code for the link-aware opportunistic (multi-hop) D2D communications scheme is released open source to the community at [www.uwicare.umh.es/opportunities/Opp-D2D.html](http://www.uwicare.umh.es/opportunities/Opp-D2D.html)

- **Antelia (University of Vigo, Spain)** – Antelia is the antenna test laboratory of the University of Vigo that is under the supervision and operation of the Radio Systems research group. The facilities available at Antelia include an anechoic chamber where a spherical far field measurement system is implemented. The measurement system is based on a Rohde-Schwarz ZVA67 4-port Vector Network Analyzer. Antelia has implemented a quality system according to ISO/IEC 17025:2005 “General requirements for the competence of testing and calibration laboratories”. ENAC (the Spanish national accreditation entity) has granted Antelia the accreditation ENAC 1141/LE2222 to perform the test “Antenna gain measurement (1 GHz – 50GHz)”.
- **PhotonLab (ISMB, Italy)** – It is a joint initiative by Istituto Superiore Mario Boella and Politecnico di Torino (Italy); it is a large experimental facility focused on the study of the physical layer of optical communications networks. Thanks to a fruitful cooperation with an Italian alternative telecom operator, the PhotonLab has access to a dark fiber infrastructure of a total of 240Km of SMF fiber going across the city of Turin and is organized in 8 rings of different lengths, from 10Km to 40Km, whose ends are in the laboratory. Such infrastructure could be used for testing optical fronthaul and backhaul solutions for 5G networks.
- **5G Playground (Fraunhofer FOKUS, Germany)** – It represents a comprehensive environment for the development of 5G technologies, integrating a large set of standard based real implementation toolkits addressing testbeds including radio signaling and core network functionality (Open5GCore), SDN functionality (OpenSDNCore), M2M functionality (Open5GMTC and OpenMTC) as well as an overarching virtual network environments orchestration and federation functionality represented by the OpenSDNCore orchestrator and the in-development OpenBaton toolkit. 5G Playground provides the functionality for easy development of new product prototypes, benchmarking and validation, testbed-as-a-service and the means to completely replicate the infrastructure at customer premises (Testbed-to-Go).
- **Comnets (TUHH, Germany)** - The wireless sensor network testbed at Hamburg University of Technology Institute of Communication Networks (ComNets) aims at performance evaluation for safety critical communication. It was motivated by the group’s experience in project with the aircraft industry (Airbus, Lufthansa Technik) and their approach to model, test and certify components and systems.
- **OVNET Experimental Overlay Network (CBA UPC BarcelonaTECH, Spain)** - The OVNET is a joint effort among academics, research laboratories, major companies (e.g., Microsoft, Facebook, and Verisign) and operators (e.g., Level3) to provide a worldwide experimental facility. The experimental network has around 200 nodes in 27 countries and has its own IP address space (one /16 IPv4 and one /32 IPv6 prefix). The network uses Open Overlay Router (<http://openoverlayrouter.org>) technology which is controlled by a NIB and it is integrated with OpenDayLight. Such overlay technologies are key drivers of Over-the-Top overlay services.
- **Communications Research Laboratory (Universidad Carlos III de Madrid, Spain)** - The Communications Research Laboratory has the goal of developing, analysing and prototyping wireless communications systems with applications to mobile communications, space and security. Wireless applications include next generation cellular (LTE-A and beyond), metropolitan access (WiMAX), wireless area networks (WLAN) and wireless sensor networks (WSN).
- **Fit/CortexLab (INRIA Socrate Team, France)** - CorteXlab counts with more than 80 nodes in two main types, namely Wireless Sensor Networks (WSN) and Software Defined Radio (SDR). The test-bed can be used remotely to run radio experiments in state-of-the-art future communications techniques, such as the ones considered for the 5<sup>th</sup> generation of cellular systems.
- **JOLNet: a geographical SDN network test-bed (Telecom Italia, Italy)** - The JOLNet network test-bed is aimed to deploy an SDN geographical overlay network facility, in order to extensively and concretely assess the SDN and virtualization technologies and its operational impact.
- **Real-Time Emulation, Characterization, and Validation of Millimeter-Wave Front-/Backhauling Links (Fraunhofer IIS labs, Germany)** - The objective of the facility is to allow full system validation of wireless high-rate links. It comprises equipment for high-rate signal generation, validation and characterization of millimeter-wave transmission, as well as data-analysis and validation.

- **Over-the-Air Testbed in the city of Erlangen (Erlangen, Germany)** - The objective of the facility is to allow field testing, characterization and validation of waveforms and software applications of 4G systems and beyond. Different environments (urban, suburban, highway, rural, forest) are covered by the experimental network, to perform live testing under various conditions and transmission types (unicast LTE-A, broadcast/multicast eMBMS).
- **FORTE: Facility for Over-the-air Research and Testing (Technical University Ilmenau, Germany)** - SatCom: Main objective for SatCom on the move system tests is the overall system performance under realistic but repeatable conditions. OTAINVEE: The objective of the facility is to allow full validation and characterization of complex wireless communication systems under reproducible conditions in a virtual electromagnetic environment using wave field synthesis.
- **AINE: Advanced IP Network Emulator (INDRA Sistemas, Spain)** - AINE is a real time emulation software running as a user process on a Linux based platform, used for performance characterization of communication networks, particularly satellite communication systems, providing IP over Ethernet interfaces to test real applications on the modelled packet networks. This emulation tool includes ETSI-TISPAN standardized functional blocks (RCEF and RACS) to integrate it within an IMS (IP Multimedia Subsystem) service provision with end-to-end QoS guarantee. This allows the integration of the tool in environments where satcom-terrestrial networks convergence is under test.
- **5TONIC: 5G Telefonica Open Innovation Center (IMDEA, Spain)** - The test-bed is designed for partner companies to evaluate the feasibility and costs of a given technology, via a realistic evaluation of technology choices. Its core functionality is divided in two main areas; 1) 5G Virtual Software Network Area, with a specific focus on: Network Function Virtualization, Software Defined Networking, security services, network control and management planes, cloud services, signaling; and 2) 5G Wireless Systems Area, with emphasis on: air interface, duplexing, multiplexing, media access control, spectrum, interference, mobility tracking, all considering single- and multi-RAT scenarios. The testbed consists of four main components: terminals (smart devices, things, sensors), network (both radio and Core), a distributed cloud architecture, and services (with end-to-end integration).
- **P2E: Patras Platforms for Experimentation (University of Patras, Greece)** - P2E since its first operation have been transformed to a remote experimentation facility. The latest years P2E follows ITU-T Y.30012 recommendations on Future networks, objectives and design goals. P2E evolves into the design objectives of Service awareness, thus broadening the range of offered services.
- **PerformNetworks (University of Málaga, Spain)** - PerformNetworks (formerly PerformLTE) is a testbed integrated in the Future Internet Research and Experimentation (FIRE) EU initiative, designed to offer a realistic environment to allow controlled and automatic experimentation in LTE, LTE-A and beyond networks. The testbed is based on COTS solutions (both in the radio and core network), SDR and conformance testing equipment; and supports the combination of these elements to generate an hybrid deployment mixing cutting edge research developments with commercial equipment. PerformNetworks offers different layers of abstraction, i.e.: different exposure of network functionality, in order to support experimenters coming from many different domains (namely app developers, vendors, operators, service providers, etc.).
- **Wireless Networking Laboratory (University of Oulu, Finland)** - The WNL is intended to become an important infrastructure for enabling real-life testing of the existing and perspective radio and optical wireless communication technologies for 5G (WMAN, WLAN, WPAN/WBAN, VLC), their interoperability and ways of integration, and experimental characterization of the physical communication channels.
- **5G Experimental Facilities (University of Bristol, UK)** - The facility aims to create a unique, fully flexible, programmable and open experimental platform for all networks and IT technologies. It enables user-defined experimentation with physical and emulated technologies under realistic, controllable, predictable, secure and repeatable conditions.
- **CTTC 5G end-to-end experimental platform (CTTC, Spain)** – The existing experimental facilities cover complementary technologies from terminals, sensors and machines to radio access networks, aggregation/core networks, and cloud/fog computing,. Specifically, the existing experimental facilities involved are: i) the ADRENALINE Testbed® for wired fronthaul/backhaul (SDN-enabled packet aggregation and optical core network, distributed cloud and NFV services in core and metro data-centers); ii) the EXTREME Testbed® and LENA LTE-EPC protocol stack emulator for wireless fronthaul/backhaul and mobile core (SDN-enabled wireless HetNet and backhaul, edge datacenter and distributed computing nodes for cloud and NFV services); iii) LTE/5G PHY prototyping based on FPGA (GEDOMIS® testbed) and software-defined radio (GEDOMIS® testbed and CASTLE simulator for rapid prototyping and highly reconfiguration), and Satellite (CASTLE simulator), iv) LTE/5G analog front-end  $\mu$ wave & mmwave (antenna, power amplifier, filter, mixer, ...) including digital

predistortion (SHAPER testbed), and finally; v) the IoTWorld Testbed (sensors, actuators and wireless/wired gateways) combined with energy harvesting devices.

- **AMAZING: Advanced Mobile wireless Network playground (Univ. of Aveiro, Portugal)** - Free access wireless testbed composed by 24 fixed nodes located at the rooftop of Instituto de Telecomunicações – Aveiro, complemented with 50 additional mobile devices which can roam freely.
- **VISTA: Virtual Road Simulation and Test Facility (Technical Univ. Ilmenau, Germany)** - The objectives of VISTA are the characterization and test of automotive communication systems and antennas with a special focus on Over the Air and MIMO measurement techniques. Also electromagnetic compatibility (EMC) analysis issues of communication and vehicle systems are addressed. VISTA allows the emulation of communication scenarios in combination with a simulated driving scenario, therefore enabling tests of these systems under realistic driving conditions.
- **DIWINE: Dense Cooperative Wireless Cloud Networks (Univ. of York, UK)** - This testbed is currently under development within the DIWINE project funded by the EU FP7 framework, with some interim implementation showing proof-of-concept already available. It will demonstrate a future Smart Meter Network (SMN) system which will exhibit a number of characteristics that will also be required by 5G systems.
- **Experimental Facilities for Optical Wireless Trials towards 5G (Fraunhofer HHI, Germany; Czech Technical University, Czech Republic; Scuola Superiore Sant’Anna, Italy; Univ. of Edinborough, UK)** - It is proposed to use optical wireless to accelerate implementation, test and validation in particular of advanced 5G interference management techniques.
- **CARMEN: A Cognition Network Testbed (Univ. of Padova, Italy)** - CARMEN is to build a flexible testbed that makes it possible to observe and act upon both in-stack and out-stack parameters, i.e., both on the communication protocols and the device sensorial peripherals. The final objective is to exploit this rich set of information to improve the whole network performance experienced by mobile users by applying cognitive-network techniques.
- **UoP’s Association to Experimental Facilities (Univ. of Peloponnese, Greece)** - The objective of the facility is to integrate and experimentally validate novel as well as legacy access network solutions with respect to their ability to support heterogeneous LAN/last-mile systems in the access. The facility includes the integration and demonstration of data-plane (DP) systems as well as the corresponding activities in opensource SDN-oriented control-plane developments and its associated integration to carrier-grade control and management plane (CP/MP) frameworks.
- **Computer and Communication Systems laboratory (CCSL)** – CCSL has installed a Remote EMF Monitoring System (REMS) in the majority of Greek islands in order to monitor the level of electromagnetic radiation as well as the occupancy of licensed and unlicensed wireless spectrum bands. From each remote station we acquire a dense set of 240 measurements per day which gives us an accurate view of the usage of the entire available spectrum throughout the coverage area.
- **VirNet@Unibo: Cloud Virtual Networking and SDN Experimental Facility (University of Bologna, Italy)** - The primary goal of VirNet@Unibo is to provide a platform to test and analyse architectures to provide networking services in a virtual environment in the cloud. It exploits both SDN and NFV concepts and the full openness of the infrastructure allows to experimentally assess future-oriented solutions and improvements in network virtualization technologies, SDN controllers, network service chaining as well as end-user SDN-enabled applications.
- **5GIC campus testbed (Univ. of Surrey, UK)** - The main objective of the 5GIC testbed is to facilitate experimentation of algorithms, techniques and novel concepts for the future 5G wireless system; the test facility will allow testing of all aspects of a future system in a real-life network deployment. In addition to advanced radio access technologies, the test-bed is designed to experiment new ICN/CDN techniques for both IoT and 5G mobile traffic. The whole test-bed covers an area of more than 4km<sup>2</sup> comprising rural, urban, dense urban and motorways.
- **Future Networks Innovation Lab (Italtel, Italy)** - The facility is aimed to the application of the NFV and SDN concepts for improving multimedia real time communications and M2M/IoT services. The facility is based on a distributed architecture under SDN control, based on the interconnection of different sites hosting multimedia and M2M traffic sources and/or Datacenters hosting cloud applications, including edge Datacenters, i.e. distributed infrastructures implementing service wherever they are most effective.
- **WST: Wireless Actuator and Sensor Network Testbed (Univ. of Parma, Italy)** - The main objective of the WASN Lab Testbed is to create an innovative Internet of Things experimental environment. Its purpose is to support the design, development and test of applications and services on real hardware. In contrast with

available testbeds for IoT, WST will hide low-layer details to end users, and it will offer a simple, high-level programming framework to develop final applications on top of the IP layer (IPv6 and IPv4).

- **i2CAT's OpenFlow-enabled islands (i2CAT, Spain)** - The I2CAT Island's main objective, as part of the OFELIA facility, was to address the need to test and evaluate innovative solutions and ideas in real network environments, in addition to simulations or laboratory setups. This is achieved by means of building and operating a multi-layer, multi-technology and geographically distributed Future Internet test-bed facility, where the network itself is precisely controlled and programmed by the experimenter using the OpenFlow technology. The FIBRE Island follows the same principle since it is designed as an extension of the OFELIA island, but with focus in the federation with heterogeneous test-beds.
- **OpenSAND** is an user-friendly and efficient tool to emulate satellite communication systems, mainly DVBS2/RCS2. It provides a suitable and simple means for performance evaluation and innovative access and network techniques validation. Its ability to interconnect real equipment with real applications, provides excellent demonstration means. Initially developed by Thales Alenia Space in the frame of European Commission R&D projects, R&T CNES studies and internal research, it is now promoted by CNES (French Space Agency) as a reference open-source software tool. See <http://opensand.org/>
- **SICS ICE (SICS North, Sweden)** – It is a full scale datacenter testlab planned to be built in 2 phases at Luleå University of Technology, Sweden, campus. First phase is operational. Consists of compute pods with 200 servers, 3600 cores, 4 TB RAM, up to 7 petabytes hard disk. Owner/host of the testlab is the Swedish Institute of Computer Science (SICS). This laboratory/test facility meet the needs of the new booming datacenter industry along the complete value chain. Driving development of IoT, big data, cloud, 5G networks, it all ends up in a mega-datacenter. The offering include for example an open Hadoop platform, bare-metal servers, datacenter measurements data monitoring and automation. **B<>COM (France)** – B<>COM provides a testbed to test security aspects of SDN based networks. Moreover, it provides a scalable, flexible and accessible framework for testing 5G network components, working on OpenStack and OpenDayLight. B<>COM is focusing on Network Function Virtualization and is also working at radio physical level especially on Multi-Radio Access Technologies.
- **KU Leuven Networked Systems (KU Leuven, Belgium)** - The test facility consists of 45 FPGA-enabled software radios (90 antennas) that can be configured in various ways to explore the benefits of many networking architectures relevant to 5G and beyond: from central antenna configuration for Massive MIMO to distributed configurations representing small cells or distributed antenna systems (cloud-RAN). The testbed can hence be used to explore the benefits of central versus distributed control, and centralised versus distributed antenna placements.
- **OneLab (UPMC, France)** - The OneLab facility provides single entry point for federated infrastructures, a common API and a Portal to browse and reserve resources of different technologies, from Wireless or IoT based to Cloud based like OpenStack or distributed at a global scale on Internet. The federated platforms include FIT-IoT, FIT-CortexLab, FIT-Wireless, III IoT-Lab, PlanetLab Europe, NITOS Volos, FUSECO Playground, Virtual Wall and w-ILab.t.
- **5G Wireless Innovation Center, Argela, (Istanbul, Turkey)** - 5GWiN based in Istanbul and Silicon Valley focuses on software defined future radio access technologies. Current projects listed as ULAK to develop 4G base station, short and long range Small Cell, programmable C-RAN. The center holds expertise more in radio technologies, self-organization, programmability and NFV. 5GWiN has a full access to Türk Telekom and several other operators to test and validate the findings in real network environments in addition to simulations or laboratory setups. Current expertise and facilities are converging towards a multi technology federated test bed facility that can be remotely connected and programmed through SDN.
- **EHU-OEF (University of the Basque Country, ES)** – The OpenFlow Enabled Facility is one of the oldest OpenFlow based facilities that is currently being used both on production and for research activities. It physically consists in a 10 Gbs backbone with 1 Gbps trees linked with OpenFlow Switches that implement a layer 2 virtualization mechanism that frees to the experimenter every

part of the Ethernet Layer except MAC source and destination addresses to experimenters. It's connected to the Basque and Spanish NRENS (I2Basque and RedIRIS) through 10Gbps. It has recently been upgraded to support the deployment of services through the use of Service Graphs and with Universal Nodes to support and hybrid SDN based Network Function Virtualization mechanism. The facility provides to each experimenter's slice the possibility to deploy their own OpenFlow controller. The facility is particularly well suited to experiment with networking applications that require full control over the frame format, or in which VLAN or other Layer 2 headers.

- **iMinds (University of Ghent, Belgium)** - iLab.t technical testing offers access to the hardware, measurement equipment, user-friendly software tools and professional technical expertise needed to efficiently prototype, develop, and test innovative ICT innovations. iMinds has 3 generic testbeds: (1) The Virtual Wall (<http://ilabt.iminds.be/iminds-virtualwall-overview>) for all testing and experimentation activities related to wired networks and solutions (e.g. distributed software and service evaluation, scalability evaluation, validation of protocols, stress testing, ...), (2) The w-iLab.t testbed (<http://ilabt.iminds.be/iminds-wilabt-overview>) for testing and experimentation activities in the field of wireless networks and solutions covering different technologies and platforms (Wi-Fi, embedded sensors, Bluetooth, LTE, various SDR platforms), and (3) iMinds Homelab (<http://ilabt.iminds.be/homelab>) offering a residential test environment and innovation incubator for stimulating collaboration and cross-fertilisation between stakeholders in the field of research, development and innovation.
- **Network Implementation Testbed using Open Source platforms - NITOS (University of Thessaly, Greece)** – It is a remotely accessible and configurable testbed established through the EU Future Internet Research and Experimentation (FIRE) initiative. The testbed is equipped with cutting edge fully programmable networking equipment (LTE-A, LTE, WiMAX, WiFi, ZigBee, Software Defined Radio equipment, hardware OpenFlow switches, Cloud Computing infrastructure). The testbed is deployed in three different locations. The equipment provided is based on both Open Source software, enabling the deployment of novel services and protocols towards 5G communications, and commercial solutions. The testbed can be parameterized in order to setup a multitude of different topologies, whereas GEANT connectivity is provided as well.
- **5G-EmPOWER testbed (Create-Net, Italy)** - 5G-EmPOWER developed by Create-Net is a unique and open toolkit for SDN/NFV research and experimentation over wireless and mobile networks. Its flexible architecture and the high-level programming APIs allow for fast prototyping and validation of novel services and applications. 5G-EmPOWER blurs the line between radio and core segments introducing the concept of Programmable Network Fabric which abstracts the radio and packet processing resources available in a network. Our architecture builds upon a single platform consisting of general purpose hardware (e.g., x86) and operating systems (e.g., Linux) in order to deliver three types of virtualized network resources, namely: forwarding nodes, packet processing nodes, and radio processing nodes. The platform currently supports programmable LTE/LTE-Advanced eNodeBs and WiFi Access points in the radio access and a mixed wired (Ethernet) and wireless (mmWave) mesh backhaul.
- **5G Center for Innovative Networks (NETAŞ, Turkey)** - 5GNET based in Istanbul focuses on wireless access technologies and performs combined functionalities with a wide function equipped laboratory and venture capital. 5GNET focuses to develop 4G base station, Mobile Edge Computing (MEC), LTE core network, IMS core with VoLTE, DRS-Diameter Route Server, RCS, VoWiFi, IOT, Cyber Security and multimedia applications. 5GNET has an access to operators and several other test suites to validate the findings in real network environments in addition to simulations or laboratory setups. The test bed facility in the center holds several cutting edge radio equipment and simulators.
- **5G:haus (Deutsche Telekom, Germany)** – DT has set-up a European wide program for the coordination, planning, and carrying out of 5G related experiments, tests, and field trials. As Deutsche Telekom is present in many European countries, branches such as Czech Republic, The Netherlands, Austria, and Germany will participate in the 5G:haus. Testing topics are amongst others base line



technologies, 5G radio access technologies, service creation mechanisms, control plane issues, and network management.

- **Com4innov** is a consortium providing the framework for testing solutions and services on next generation networks and technologies, including M2M applications.
- **Imaginlab** is an open platform thought for interoperability tests in fixed and mobile networks.

A special mention is needed with respect to the outcomes of the INFINITY project, and in particular the XiPi portal. Information on more than 230 ICT infrastructures are described in the XiPi portal with all relevant details. Furthermore, the INFINITY project delivered the INFINITY roadmap for investment into infrastructures, and the Common Description Framework, which can be used to describe infrastructures in a harmonized manner. These tools should be further considered as useful elements for the definition of a 5G experimental facility. In addition, current 5GPPP/phase1 projects may have already now several useful 5G testing environments.

# Summary and Conclusions

The current fragmentation of experimental activities in Europe needs to be tackled through a shared and concerted effort, aiming at creating a critical mass of experimental facilities for reinforcing EU-wide cooperation, synergies, for making 5G interoperability testing and for accelerating 5G to concrete socio-economic exploitations. After listing a number of requirements, this White Paper argues that in order to put in place concretely this vision for example by interconnecting test-beds and field-trials at different levels (hierarchically), by making interoperable open and closed experimental islands, by exploiting service "platforms of platforms" on top of virtual labs. An overarching OS is a possible means to get there. The two main distinguishing characteristics of this overarching OS will be: 1) leveraging on what is available in terms of open source developments; 2) developing what is missing with an incremental approach, not only addressing fixed and mobile networks (including satellite), but reaching also the smart terminals (e.g., even the more advanced ones, such as machines or robots) and the Cloud Computing facilities. With this OS, in the future, we can imagine one consolidated 5G infrastructure abstracted out by virtualization. The very same infrastructure can be the servicing layer of everything that is needed. Costs, speed to market and paradigms are differentiating factors. Benefits are tremendous; the system will function with fewer pieces of hardware that are less specialized and cheaper variety.

Though aimed at serving (large, medium and small) industry in Europe, an effort from all research stakeholders (industry, academia, research centres) is needed.

# Recommendations

The advances and diffusion of ultra-broadband (fixed and radio) connectivity and Information Technologies, the dramatic reduction of hardware costs and wider availability of open source software, the development of novel application fields driven by the revolution of the IoT, Tactile Internet, MTC, Cloud Manufacturing, Cloud Robotics, etc. are creating the conditions for introducing a deep innovation in telecommunications and ICT networks and services. 5G (which is not just one step beyond 4G) will be the main “collector” of this coming wave of innovation, bringing a number of technologies to maturation and socio-economic impact, accelerating the transition towards the Digital Society and the Digital Economy. Europe should be prepared to face this important transformation, ready to capture all the socio-economic opportunities that this will bring.

In particular, the following actions are recommended:

R1) EC should invest in facilitating the aggregation of a “critical mass” of **5G experimental facilities**, capable of exploiting synergies and collaborations, both within and outside Europe, e.g., with similar initiatives in US, China, Korea, Japan. This will go in the direction of joining forces for strengthening Europe in the development and exploitation of 5G infrastructures. There are several ways for pursuing this aggregation of **5G experimental facilities**: for example by interconnecting test-beds and field-trials at different levels (hierarchically), by making interoperable open and closed experimental islands, by exploiting service “platforms of platforms” on top of virtual labs, etc.

R2) The major industries should support this “critical mass” of **5G experimental facilities**, in order make interoperability tests of their solutions in a certified environment; this will help facilitating the exploitation and adoption of 5G services in the EU;

R3) Academia should invest in experimental research training a new generation of researchers prone to both fundamental and experimental activities;

R4) Efforts should be made to have small, medium enterprises and entrepreneurs involved in the 5G experimental platform in order to create and develop new ecosystems (e.g. in areas from industrial and agricultural mobile robotics, to new service paradigms such as “anything as a service”, from “full immersive experience and communications” to “Cognition-as-a-Service” for EU Citizens and Smart Cities, from Self-Driving Transportation Systems to Internet of Things, from Tactile Internet to Machine to Machine, to Cloud Manufacturing, etc.).

As a document that is complementary to the other White Papers delivered by Networld2020, all recommendations included in the latter should be implicitly added to the list above.



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## Exploiting Infrastructure Capabilities to Dynamically Orchestrate NFV Services across Multiple Domains

*ETSI Workshop, "From Research To Standardization," Sophia Antipolis, France, 10-11 May 2016*

### **Abstract**

The FROG is a software that is able to orchestrate NFV/cloud services across multiple heterogeneous domains. The FROG is based on multiple domain orchestrators, each one responsible of a single infrastructure domain, that cooperate by timely exporting the capabilities and the available resources in each domains to an overarching orchestrator, which has to coordinate the deployment of the service across the entire infrastructure. Supported domains include not only traditional infrastructures with network (e.g., OpenFlow only) or compute (e.g., OpenStack) capabilities, but also resource-limited SOHO home gateways, properly extended to make it compatible with the FROG orchestrator. The set of capabilities and resources exported by each single domain, coupled with the constraints specified by the service itself (e.g., the IPsec client endpoint must stay on the tenant home gateway and not on the data centre) determines how the orchestrator splits the service graph, originating the proper set of sub-graphs that are deployed on the selected infrastructure domains.

This demo shows the FROG overarching orchestrator that will receive a service request, will query the different infrastructure domains for their capabilities/resources and it will dynamically partition the requested service graph across the selected available infrastructure domains, determining also the network parameters that have to be used in the interconnections between domains. For instance, the orchestrator will be able to set up either the proper GRE tunnels, or VLAN-based connections, or OpenFlow paths, based on the resource exported by the involved domains, the cost of the solutions, and the constraints given by the service.

This demo shows also the possibility to integrate resource-constrained devices, such as existing home gateways, in the controlled infrastructure. For instance, we will show how an home gateway, extended with NFV support, can dynamically recognize a new user connecting to it and consequently create a GRE tunnel to deliver that traffic to the proper set of VNFs that are instantiated in the operator data centre. Furthermore, some more powerful home gateways are shown as well that can execute a limited number of VNFs that are implemented as a "native software", i.e., applications running on the bare hardware, in addition to the traditional VM-based or Docker-based VNF support.

Finally, the FROG architecture relies on an intermediate message bus instead of using the traditional REST API to interconnect the different components. This solution provides a clear advantage when the recipient of the information published is not known such as in the bootstrapping process, or when different components (e.g., service layer and orchestrator) need to know the same information coming from the infrastructure domains to perform their job.

In summary, our distributed orchestration software will show the following concepts:

- The capability to deploy service graphs across different heterogeneous domains;
- The possibility to create an orchestration logic that is split across multiple domain orchestrators, coordinated by a single overarching component, which enables future services based on the concept of *federated* (and not only *hierarchical*) domains;
- The support of NFV on (existing) resource-constrained devices, enabling the overarching orchestrator to dynamically adapt to their capabilities and deploy the service based on the available resources;
- The use of a message bus to interconnect the different components together.

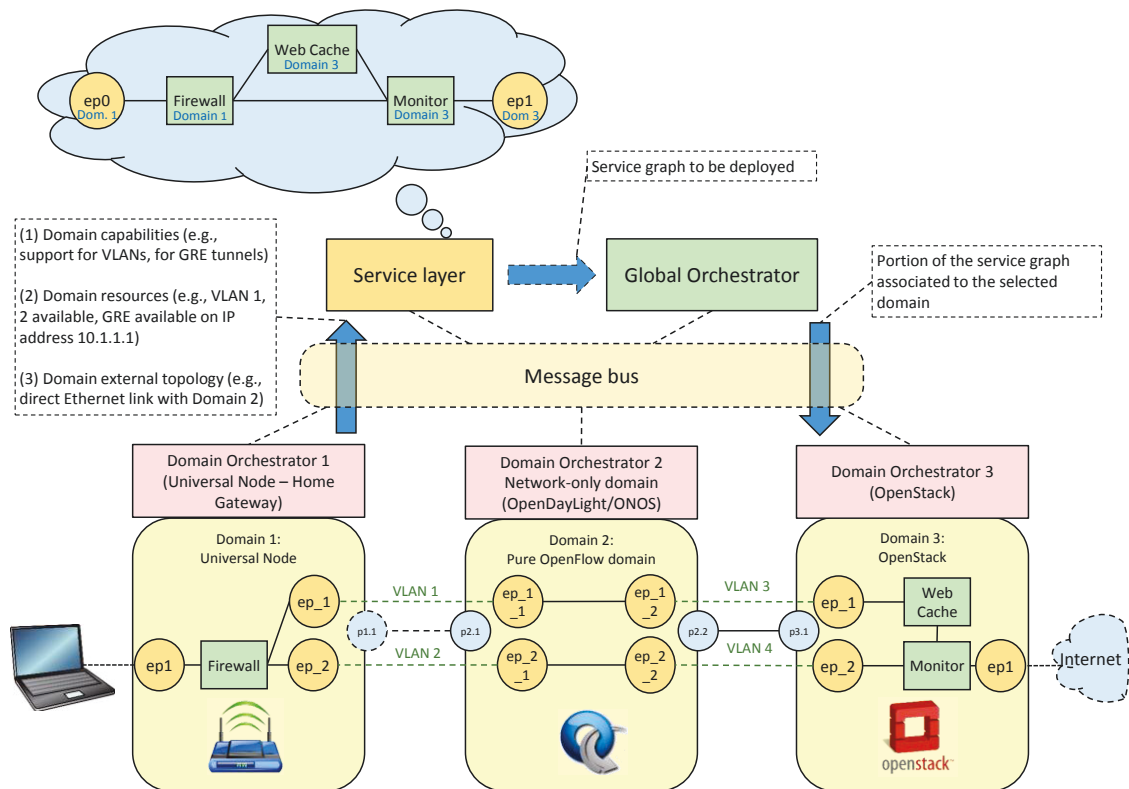


Figure 25. Example of possible orchestration of a user-defined service with the FROGv4 orchestrator

The demo will show how users can define their own service based on a set of building blocks (e.g., VNFs), how the service is dynamically deployed on the network, and how the network will recognize the traffic of *each* user and deliver it to the proper set of network functions; in other words, each user, attached dynamically to the same home gateway, will experience a different service.

## Contacts

- Antonio Manzalini and Mario Ullio (TIM), Fulvio Rizzo (Politecnico di Torino)

## References

- The FROGv4 orchestration software: <http://github.com/netgroup-polito/frog4>
- The UN Orchestration: an NFV node with support to resource-constrained hardware: <http://github.com/netgroup-polito/un-orchestrator>
- The EU-FP7 UNIFY project <http://fp7-unify.eu/>
- The EIT Digital CC4BA project: <https://www.eitdigital.eu/innovation-entrepreneurship/future-networking-solutions/cc4ba/>