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Flexible 5G Edge Server for Multi Industry Service Network

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***Abstract*— The Telecom world is converging with IT rapidly in order to address users demands in a more agile and personalized way and is a once in a generation inflection point in the telecommunications industry. But how can a 5th generation wireless system architecture framework also conforms to the new demands from the major areas Internet of Things and Networked Society? The Software defined Network – Network Function Virtualization matches the 5th generation wireless system framework, it has the concepts and the key components for deploying a service at the edge of the Radio Access Network. But with a different approach: moving Software Defined Network-Network Function Virtualization into the Radio Access Network which is conceptually different than moving the Radio Access Network into the Cloud. This paper is an extension of Server at the Edge concept introduced recently and depicted with its key characterizations. Resources and meters handling are also considered fundamental for the new architecture using analytics feedback for a more efficient and autonomous deployment of new services. Business cases examples are added to highlight why the proposed components for the edge of the network are considered important.**

Keywords-component; 5G; IoT; SDN-NFV; Edge Network OS; SON; Analytics.

I. INTRODUCTION

The server at the edge concept has been presented as “SEED, a Server Platform for the Edge of the Network” [1]. Today, the Telecom realm is facing an epic moment, a technology step that will drive the evolution of the

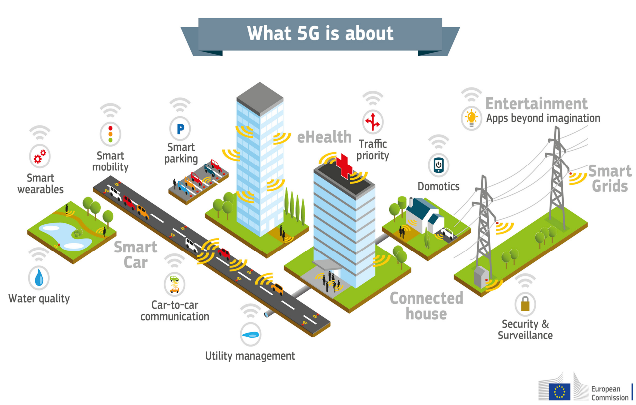

Figure 1. 5G is about digital society (source [2])

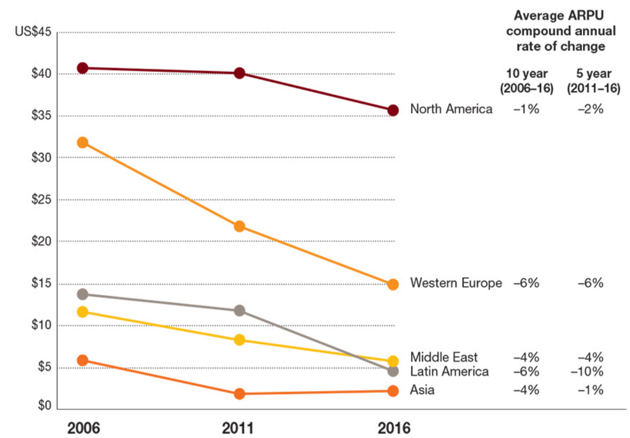

Figure 2. Average revenue per user in telecom industry (source [4])

networked system in the future and, at the end of the day, the End User services and life style. The entire world of communication is driving the strong requirement for new services, where End User is at the center of the business case of a digital society (see Figure 1), and Telecom operators could make the difference. Mobility is dominating the area with significant smartphone penetration growth, it has changed the usage of connectivity [3][5]. With the emerging 5th Generation wireless system (5G) new great benefits opens up for the Telecom operators.

In the last years, Telecom operators have seen an exponential growth of data traffic and, at the same time, a significant income reduction from the “golden eggs goose” voice and Short Message Service (SMS). Today the majority of the operators have most of their Average Revenue Per User (ARPU) coming from data traffic where voice and SMS is often offered at a very cheap price just to attract new customers and increase revenue from data traffic. The trend is not supposed to change in the next years. Ericsson prediction shows that, by 2021, there will be 28 billion connected devices around the world [3].

With that trend prediction, there are at least two aspects; The first is Mobile data offloading [6] and in this context for the operator a strive to find alternative for the backhaul and core network offloading. This not only affects the business model and the type of services provided. It would also require an interworking standardization between cellular and Wi-Fi to create a seamless user experience. The second would be for the operators to increase network capability and thereby increase income. But the picture is not complete, most mobile users are not prepared to spend too much for using their smartphones. However, it is not a case that the revenue from new subscriber dropped down dramatically in the last years, as reported in Figure 2. Such a condition would result in a significant reduction of operator margin in a way that some pessimistic vision [7] is predicting a possible "end of profitability" condition for their business. But it is a fact that even in a more optimistic prediction the current business model is not sustainable. Operators need a new direction where their margins can start to increase again [8].

A common understanding is that Software Defined Network – Network Function Virtualization (SDN-NFV) is a key to reduce Operating expenses (Opex) and Capital expenditures (Capex) and thereby increase margin for operators. But it looks like that statement is not enough to make operators change strategy. Just to avoid any misunderstanding, SDN-NFV architecture will reduce Opex and Capex, but it is not actually that huge of an incentive for the business of the operators. In fact, Opex and Capex have been reduced during the latest years. Mostly thanks to the cost reduction of technology, and the truth is that today total cost and revenue are so close that one can hardly imagine a new golden era thanks only to Opex and Capex reduction. It seems enough for surviving in the Telecom market battlefield, but surely not enough to justify a new infrastructure investment.

Eventually, let us consider the life cycle of a new Telecom technology: the delivery rate between a technology step (from 2G to 3G, from 3G to 4G and so on) has an aggressive pace, in most of the case "forcing" operators to make a new infrastructure investment. But reduced revenue and delivery interval is concurrently reducing the business case window. Thus operators are not actually too keen to join a new technology in such conditions and for sure they are looking at any new investment very carefully. So, what are the actual needs of the operators then?

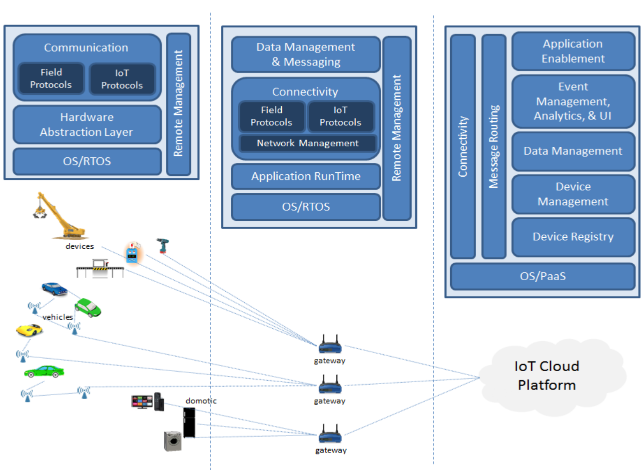

Figure 3. IoT architecture and its software stack (source [9])

So far, their effort has been focused on a market where improvement of capacity and quality of the connectivity has been enough. But the richest market today is fully in the hands of the Over-The-Top (OTT) content media delivery companies (Google, Facebook, Netflix, etc.). A real shift of business for the operators is the key to enter such a rich market. Eventually, that will be a win-win condition, since OTT is perfectly aware that reducing the end-to-end (E2E) data contents latency will improve their business. They are also aware that accessing User Metadata (very well known by Telecom operators) will increase even more such a market thanks to new business cases.

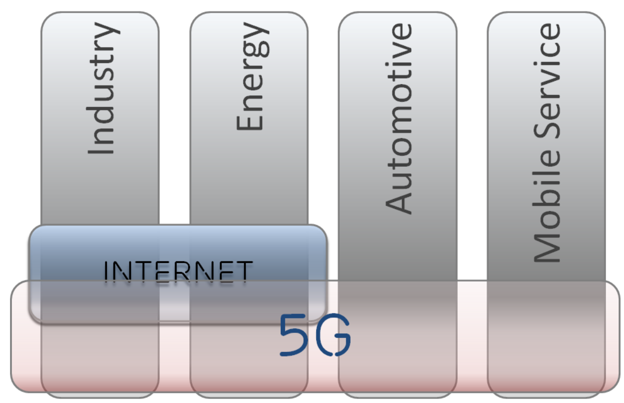

Figure 4. 5G is a common accelerator

II. IOT AND MACHINE TYPE COMMUNICATION

A clear huge opportunity for operators comes from the Internet Of Things (IoT). Telemetry, sensors and infrastructure monitoring have been visible for the last ten years, but cost reduction of semiconductors, system on chips, and new radio technology opens the door to smarter devices. Security, enhanced health, manufacturers fully connected, intelligent and with autonomous data handling are today very attractive business opportunities and promise great benefits for the consumers. The IoT is part of the Industry 4.0: an instrumented and data-driven world, a world where Data is the new oil. But a business is valid only if it is sensible. It is not realistic to expect operators investing and maintaining different infrastructures and limiting the operation agility. So the IoT infrastructure, as described in Figure 3, needs a system solution where IoT is considered as a vertical service more than a different infrastructure. This leads to the conclusion that the requirement for the next generation of mobile system is to concurrently support different areas of industry, from new End User services to IoT (Figure 4). Once devices and machines are connected, the traditional vision of data flow into centralized cloud repositories will not work any longer. The solution is to move intelligence close to those devices and machines. That will reduce latency in decision control loops for time-critical applications and

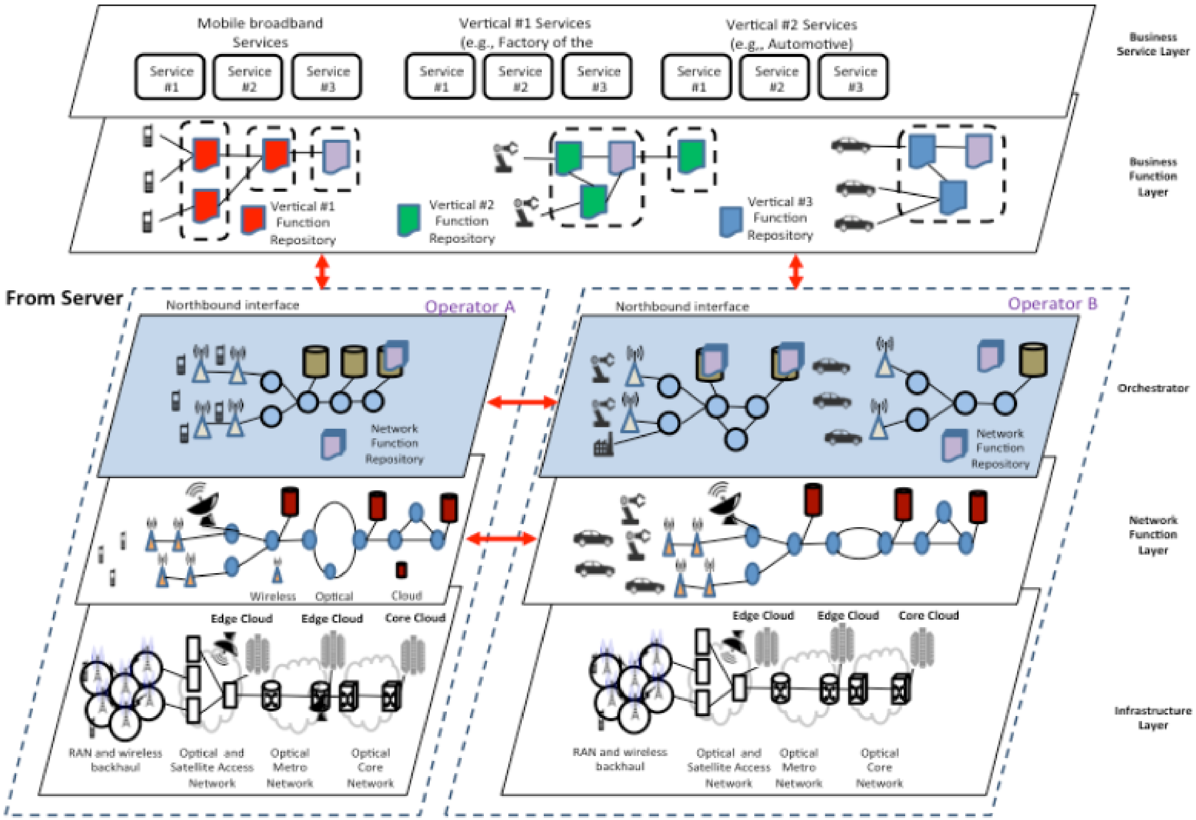

Figure 5. 5G Architecture (source [10])

the backhaul bandwidth drawback caused by that massive data flow.

III. 5G

5G is the answer. It is not a bare new radio technology. 5G has the ambition to be a new framework, covering the system architecture, the network management and the software deployment to act as the enabler of the new business opportunity mentioned. Massive broadband, machine-type communication and time-critical autonomous control are the three groups where to find 5G requirements, with the declared scope to offer an eco-system for business innovation. 5G solution wants to support vertical markets, such as IoT, automotive connectivity, Mobile broadband.

The vertical deployment approach is based on a complex integration of: distributed computing, storage, networking and spectrum capabilities. Slicing those underlying resources is fundamental. A vertical service deployment needs a system where it is possible to have: multi-tenancy and multi-service, respecting the Service Level Agreement (SLA), providing different Quality Of Service (QoS) level to achieve different Service characterization and different network policy. The diversity of that system needs an orchestrator responsible to allocate computing, storage and networking resources to the network functions. Then allocate those network functions to the vertical services.

Security, Reliability and Power Consumption efficiency are very challenging in this scenario and need special focus.

Automation of service deployment is also very important. In the traditional system, installation of a new service required months because it depended on a number of installation parameters. That traditional way of working is very expensive and often the root cause of performance drawback or bad reputation for infrastructure providers. The 5G system needs to be more autonomous, self-organizing resources when and where needed. These characterizations are important enablers to a successful system, but they explain very well the complexity of the new architecture too.

The 5G architecture is based on five pillars:

- Radio Technology: Massive Multiple Input, Multiple Output (MIMO);
- SDN/NFV Technology;
- Radio Protocol split: The Mobile Edge Computing;
- Management and Orchestration (MANO);
- Self-organizing Network (SON)

The concepts behind the 5G architecture are summarized in Figure 5. This paper is mainly focusing on the Mobile Edge Computing, identifying the critical technologies needed. For the other bullets above only a recall is provided though with an emphasis taken for Edge Analytic handling.

IV. SDN-NFV: A Recall

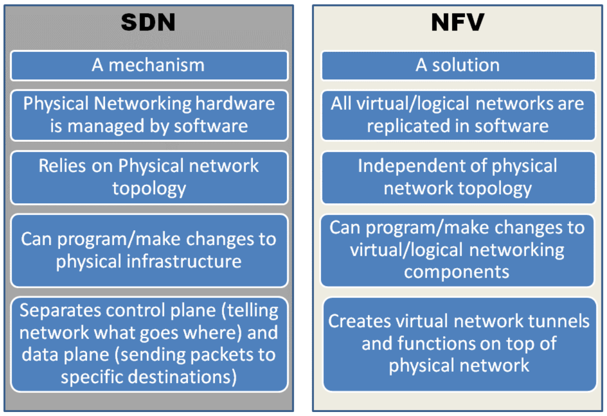

Figure 6: SDN-NFV in a nutshell

An SDN-NFV introduction should start from the reason behind the SDN-NFV architecture. In fact, following this approach, it will be clear why SDN-NFV is a pillar of 5G. SDN-NFV has been designed to cope with the reality that, in the next decades, enterprises will increasingly make their specific applications available on mobile devices. The next wave of mobile communication is to mobilize and automate industries and industry processes. This is widely referred to as Machine-Type Communication (MTC) and IoT. OTT players will move to deliver more and more applications that require higher quality, lower latency, and other service enhancing capabilities. The SDN-NFV target is to allow vertical multiservice deployment and, at the same time, reduce Opex and CapEx; thereby creating a more green-power environment and allows an easy deployment of a new technology in a shorter, safer and comfortable new way. The "core" promise of SDN-NFV is to guarantee a new "business environment" where telecom operators are a stakeholder in service creation. SDN-NFV architecture is built over three layers [16], as logically shown in Figure 7:

- Business Application Layer – where the enterprise business value model is defined
- Business Enablement Layer – where the enabling and capabilities value are defined
- Infrastructure Resources Layer – where the resources needed by the value are defined

The SDN-NFV layered vision is the most useful to understand the service oriented approach supported by the architecture itself. The comparison between Figure 5 and Figure 7 is self-explaining: it is the same concept. The European Telecommunications Standards Institute (ETSI) has set regulations and indications to design and define SDN-NFV architecture [12][13].

The Architecture Framework is showed in Figure 8 [11], where any block has specific role, briefly summarized below:

- Virtual Infrastructure Manager (VIM)
  - Manages life cycle of virtual resources in an Network Function Virtualitazion Infrastructure (NFVI) domain. That is, it creates, maintains and tears down virtual machines (VMs) from physical resources in an NFVI domain.
  - Keeps inventory of virtual machines (VMs) associated with physical resources.
  - Performance and fault management of hardware, software and virtual resources.
  - Keeps north bound Application Program Interfaces (APIs) and thus exposes physical and virtual resources to other management systems.

- Virtual Network Function (VNF) Manager (VNFM)
  - VNFM manages life cycle of VNFs. It creates, maintains and terminates VNF instances.

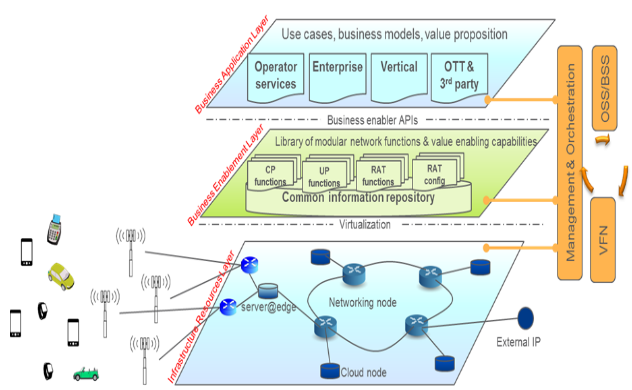

Figure 7. SDN-NFV: the Layered Architecture

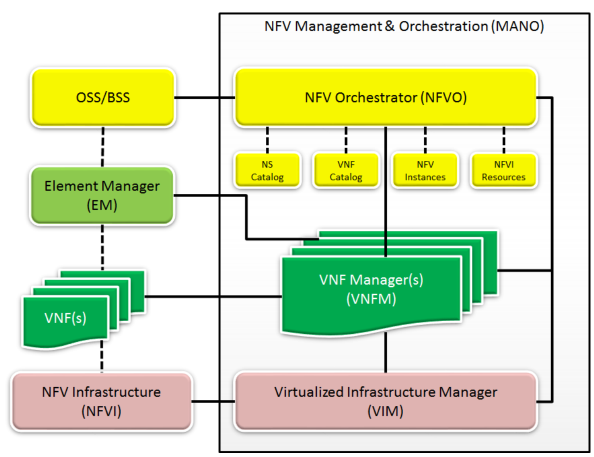

Figure 8. NFV Architecture Framework

(Which are installed on the VMs which the VIM creates and manages)
- It is responsible for the Fault, Configuration, Accounting, Performance and Security (FCAPS) of VNFs.
- It scales up/scales down VNFs which results in scaling up and scaling down of CPU usage.

- NFV Orchestrator (NFVO)
  - Resource Orchestration
  - NFVO coordinates, authorizes, releases and engages NFVI resources among different Point of Presence (PoPs) or within one PoP. This does so by engaging with the VIMs directly through their north bound APIs instead of engaging with the NFVI resources, directly
  - Service Orchestration
  - Service Orchestration creates end to end service between different VNFs. It achieves this by coordinating with the respective VNFMs so it does not need to talk to VNFs directly. Example would be creating a service between the base station VNFs of one vendor and core node VNFs of another vendor.
  - Service Orchestration can instantiate VNFMs, where applicable.
  - It does the topology management of the network services instances.

- NFV Catalogs
  - A VNF Catalog is a repository of all usable VNF Descriptors (VNFDs).
  - Network Services (NS) Catalog is the list of the usable Network services.
  - NFV Instances list holds all details about Network Services instances and related VNF Instances.
  - NFVI Resources is a repository of NFVI resources utilized for establishing NFV services.

- Element Management (EM)

EM is not part of the MANO but, if it is available, it needs to coordinate with VNFM so it is important to know about it. Element Management System is responsible for the FCAPS of VNF. If you recall, VNFM does the same job. But EM can do it through proprietary interface with the VNF in contrast to VNFM. However, EM needs to make sure that it exchanges information with VNFM through open reference point (Ve-Vnfm-em). The EM may be aware of virtualization and collaborate with VNFM to perform those functions that require exchange of information regarding the NFVI resources associated with VNF.

- Operations Support System (OSS)/Business Support System (BSS)

NFV is supposed to work in coordination with OSS/BSS.

It is useful to finish this recall for the SDN-NFV with a clarification: SDN and NFV are mentioned together because they need to be considered concurrently in the implementation of the architecture: the NFV system is the solution matching Figure 5 and Figure 7, while SDN is the tool used to deploy the NFV framework.

V. Radio Protocol Split And Mobile Edge Platform

Despite the effort done by ETSI, some parts are left for others to design. One of those parts is the so-called NFVI (see Figure 8), where the Radio Network vendors could play their significant role, both contributing to the SDN-NFV best deployment and improving their own business. The first discriminating condition to succeed in this challenge is their ability to integrate the traditional IT world with the Telecom (as explicitly required by the new business case), that is, their ability to provide full SDN-NFV architecture up to the edge of the network; into the Radio Access Network (RAN). ETSI group defined the deployment of the SDN-NFV for the mobile network in their Use Cases study report [11]. According to that scenario, the current base station is actually split into two main objects: the Remote Radio Header (RRH), that is antenna and eventually the basic Layer 1, and the virtualized Baseband Unit (vBBU) as a service housed in a specific server implementing Layer 2 and Layer 3 of mobile protocols. Then, from an infrastructure point of view, the challenge is to understand what SDN-NFV deployment into the RAN really means, identifying how the server at the edge of the network should look like. The questions that initially need to be answered are: what are the characterizations and technologies that must be considered as key components of the server itself, which hardware characteristics are matching the requirements, which functions are clearly new components (services) of the platform housed into the server@edge (SEED) and which ones need more attention and effort to remove possible obstacles and limitations?

It is a long journey where the infrastructure designers must remember the real needs behind the SDN-NFV. Moreover, the expectation of operators must be fulfilled and a more complete understanding of other opportunities, like footprint and energy consumption, play their important role. For these reasons, it is worth to focus on the SEED concept, identifying its characterization to cope with the radio function requirements.

In fact, the starting point of this paper is that it could be very difficult to move the RAN into the cloud and it is more suitable to port SDN-NFV into the RAN. This will give all the benefits of SDN-NFV described in the introduction, and at the same time answer the specific requirements needed at the edge of the network.

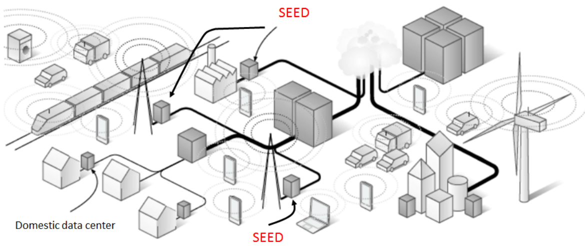

Figure 9. Distributed computing in the next infrastructure (source [17])

The reference deployment model has been described [14][15] and ETSI made some progress in the same area [12] introducing the so called Mobile-Edge Computing (MEC) server. It offers application developers and content providers cloud-computing capabilities and an IT service environment at the edge of the mobile network. The reference system architecture in this paper is depicted in Figure 9. Another aspect is to consider SDN-NFV as an overall system solution, an end-to-end solution and, from that perspective, to avoid not fulfilling the fundamental requirements.

There are also some concepts on the splitting of the current Base Station in RRH and vBBU and what it means for the current implementation of the Base Station Controller (BSC). As an example, one can refer to the Long Term Evolution (LTE) protocol deployment, to figure pros and cons out, while moving LTE function from RRH to the vBBU (see Figure 10).

The deployment of Radio Technology between RRH and BBU could be done in several ways; mostly by deciding the point in the protocol chain where the split is done and so defining the interface typology between RRH and BBU. Depending on the decision taken one can face different types of issues or constraints. An ETSI-based vBBU implementation, for example, might guarantee the highest possible service flexibility. Thus, also achieving the highest level of operational agility (indeed very useful for Telecom Infrastructure providers as well, since deployment of a new technology could be handled in the same shape as of a new service deployment), but it is challenged by very aggressive latency time requirement.

On the other hand, a “smooth” porting of the existing BSC solutions into the cloud could be attractive in term of legacy software or reduced latency time and would simply the first deployment. But it is a poor answer to the strong request of operation agility, because, in this case, the protocol splitting is done on the highest protocol layer only. In a similar way, splitting BSC between RRH and BBU could have important impacts by means of Fronthaul and Backhaul capacity demand [18].

There is not a common trend between proposed solutions of operators. For example, KT (Korea Telecom) has recently set its target for 2020 to Radio Link Control (RLC) [19], emphasizing the need of reducing the Fronthaul bandwidth requirement. However, SK Telecom is pointing to L2, so

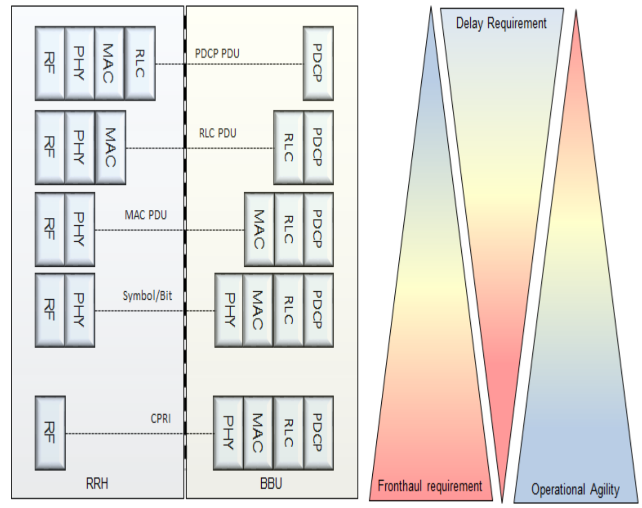

Figure 10. Pro and cons of splitting Radio Technology

somewhere between Medium Access Control (MAC) and RLC [20]. The uncertain trend is supposed to be fixed by 3GPP standardization group and it is out of the scope of this paper to point to any splitting point. Pro and cons have been listed before. For the nature of the radio technology, the design of the server at the edge of the network makes the difference; by means of feasibility and performance.

It is worth to mention that all network functions should be handled as a service, according to the layer architecture described in Figure 7. In SDN-NFV network, the deployment is based on Service Availability Concept: meaning, Radio Access must be a function deployed on the Business Enablement Layer and published to be used as component in a service chain at the Business Application Layer. The service chains capability [21] is considered a key accelerator of the SDN-NFV usage, since it is introducing a high level of operational agility, which is already mentioned as mandatory requirement. Note how the service chain is also a mindset in ETSI use case description of the BS [11] and it is at the very fundamental of SDN-NFV architecture description [22][23].

VI. SEED, A SDN-NFV SYSTEM ELEMENT

In order to understand the needs for the SEED, it is important to recall the vertical services concept as introduced in Figure 4. This is only possible if the system can define and handle “slices” of network that can be univocally assigned to different services. Slicing requires the capability to virtualize the underlying resources.

Virtualization is the core of the SDN-NFV architecture and there is no alternative to conform to such an architecture. All resources must be virtualized, with no exception. Functions are virtualized, and every single physical resource is virtualized as well. To downsize the virtualization is against the operational agility characterization, which has been already mentioned previously as the key incitement for the business model behind the SDN-NFV. Downsizing the virtualization means to downsize the operational agility. This affects the business capacity of the operators and eventually misses the expectation they have for the new business opportunity. Applications are services and handled as services into the new architecture. That means there is no software deployment as traditionally intended, but instances of services as VMs (or containers) deployed over the architecture to provide a network value. The MANO (see Figure 8) must concurrently be able to handle containers and VMs in a very elastic way. There will be services with strong real-time requirement that do not need any guest OS, and cannot accept the cost of non-OS based virtualization; among other services that will be deployed in the system as "standard" VMs. The SEED should be able to house both.

It would be convenient to use Common Off The Shelf hardware (COTS), but it should not be a restriction. There are cases where implementation of complex traffic protocols or functions in software has not acceptable performance drawback and requires usage of Hardware Accelerators (HA). Moreover, the cost of the virtualization could be significantly reduced if the server is armed by a full set of Hardware Assisted Virtualization (HAV) features. Sometimes, HAV is the only chance to reduce the virtualization layer drawback with an acceptable result, and they can help avoiding unwanted dependencies between services. Which hardware for the SEED should be used? It is a decision that is based on a few requirements:

- remove the latency obstacles to strengthen the operational agility, using HA and full set of HAV.
- improve connectivity and direct services communication bypassing the virtualization layer thanks to the HAV.
- structure a server to deploy both SDN-NFV objects, distributed computing capabilities, distributed storage and Radio interface.

For the edge of the network, there is also a non-hardware need to consider: design to ensure Quality of Service (QoS) resource usage for Service Level Agreement (SLA) handling. The above set of different capabilities is defining the SEED as described in Figure 11. The number of the capabilities for the SEED will define its size, which is a pure dimensioning calculation. The solution is fully aligned to the

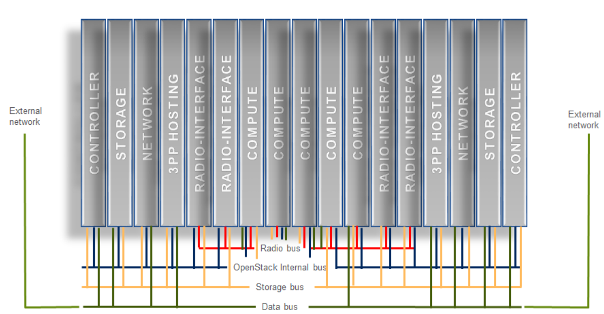

Figure 11. The SEED structured per function capabilities

most common cloud platform (ref. User's Guide indication [24][25]).

Traditional Data Center usage is considering slice allocation in computer domain, that is computation, storage and network capabilities. The SDN-NFV open source community created a solution with a data center way of working in mind and that drives the range and the "granularity" of resources while defining the slice. The characterization of applications running in a data center is on the opposite range of telecommunication applications: which are more sensitive to real-time constrains and, by definition, they need to have access to Radio Interfaces. Moreover, the distribution of computing into the system (see Figure 9) requires a more optimized usage of the resources, introducing the need of a different resource granularity definition. A better definition of resource slicing for the Radio Access is available in [26] and [37] and summarized in Figure 12.

The optimized usage of the resources will require a different computational granularity. By introducing a more flexible usage of scheduling policies [27] it is possible to achieve better resources utilization and still have strong temporal isolation. In such case, the guaranteed QoS based on SLA protects the business case of the operators. The above consideration, about the need of a slice approach to point to new requirements:

- The MANO should be able to manage resource allocation with a better elasticity, allowing the allocation of the resources per scheduling policies.
- Once using HA to cope with real-time constrains, the engines shall be designed to provide slice access to the services, without the need of software layers that create useless performance drawback.

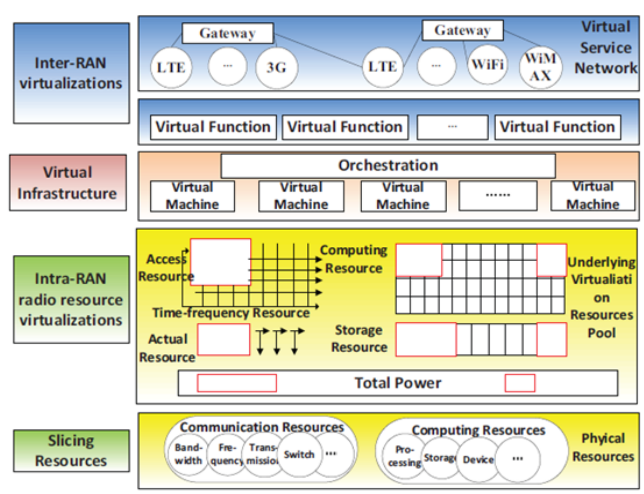

Figure 12. The slicing resource scheme for the Radio Access (source [26])

VII. STRUCTURING THE SEED

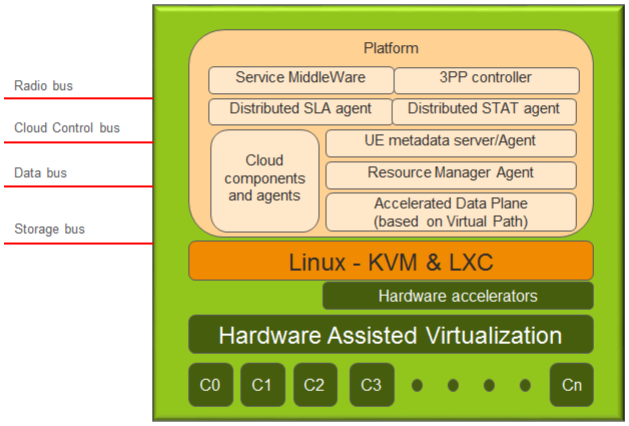

Figure 13. The SEED structured per function capabilities

Looking at the state of the art, Intel architecture seems to have better performance and virtualization features than other architectures: the management of virtualized objects requests less capability and introduce less latency in the system. Moreover, SDN-NFV implementation is strongly supported by the Open Software Community, and as a matter of fact a lot of functions and features in SDN-NFV are designed on Intel architecture first and then eventually ported to other targets. Though, power consumption needs to be considered, especially while referring to the edge of the network. Here power consumption really is a big issue and it seems that other hardware architectures would be more efficient. Figure 13 is summarizing the main objects housed in a SEED board, where differences are described in the next paragraphs.

A. *Compute Platform for the Edge*

The compute platform for the edge shall support Linux Containers (LXC) and be based on 64-bits Linux Operating system (OS). Both hardware and software support the virtualization layer, which points to a very specific set of needed features:

- reduce the cache pollution (e.g., Huge Page or Rapid Virtualization Indexing – RVI, depending on hardware architecture),
- support multi-core system,
- guarantee low power consumption,
- full set of hardware and software feature in order to speed up VM context switch,
- Virtual Interrupt Handling,
- hardware assisted trace & debug capability for a virtualized environment, and
- virtual path (Single Root Input/Output Virtualization, SR-IOV).

The OpenSoftware Cloud components and agents are obviously there (OpenStack, OpenDayLight, ONOS, M-CORD and whatever is requested by MANO). Accelerated Data Plane in User Space (virtual path, direct interrupt delivery, etc.) is needed to design an efficient connectivity solution. Security is a critical aspect for a computing distributed system and this requires HA for encryption/decryption, cryptography and data compression. A Resource Manager Agent is needed and must be able to handle the resources reference points as described in the SDN-NFV architecture. Distributed SLA and Statistics (STAT) agents are also needed and they shall interwork not only with each other, but according to higher hierarchical SLA and STAT objects in the architecture. This point will be discussed further in next session.

B. *Third Party Product (3PP) Hosting Platform for the edge*

The hardware board is just the same as the one for compute and likewise we can say about OS and virtualization layer, even if 3PP applications will be deployed as standard VMs. Platform components are the same; or agents of the same functions in the compute board. For example, User Equipment (UE) metadata agent interworks with its server in order to provide the complete list of metadata info. 3PP bridge is the active component of its controller, providing connectivity channel between 3PP application and external internet/radio channels and, for that reason: responsible for security check, registration, authorization and encryption/decryption. The available connectivity channels are not the same; 3PP hosting - for security reason - shall not have a possibility to use the radio bus directly. This will allow resource control according to the SLA in the compute board, thereby avoiding any possible malicious or faulty behavior of the 3PP applications themselves.

C. *Radio-Interface Platform for the Edge*

The board could be armed with dedicated hardware accelerators, needed to speed up the radio access protocols handling. It is not a limitation, as long as they are designed to be controlled as virtualized resource by the resource manager. With such differentiation, the board and the platform components/functions are not different from the components/functions mentioned so far for the SEED platform.

D. *SEED Characterization*

Connectivity and the efficient implementation of it is the critical key of the SEED. It is fundamental to avoid any bottleneck and additional overhead that will cost a lot for latency time. At the same time, the connectivity handling shall never be an obstacle for the service chain deployment concept (the operational agility is a mandatory requirement for the server at the edge of the network). Once one decides to share resources between different actors, it is crucial that they can access them without creating disturbances to each other and also acting according to the resource sharing agreement. It is like job scheduling where one wants threads continuously working and not starve them out. In case that happens, the thread may steal a job from someone else, and thereby maybe using another set of resources. The virtual path concept is trying to do the same with the connectivity access. Different running VMs should be able to access connectivity, based on the maximum available bandwidth defined in its SLA (the virtualized slice of connectivity assigned to it) and avoiding performance drawback due to system overhead (minimum or zero cost of virtualization layer, VM walkthrough data handling).

The nature of SEED sets a specific requirement for the platform; provide a wide range of computing characterization and also guarantee the agreed slice of computing resources, that should not be affected by other VMs running on a board. This is clear once one starts thinking on a platform where there are strong time constrains application types, like: radio services, relaxed time-constrains application types, video or audio services, no time-constrains application types, and general services. But that is not enough. If someone pays for a specific bandwidth and computing, the platform shall assure those resources. Again, the macro effect should be that, no matter if the VM is working alone or not, it can always count on the resource slices assigned by SLA. For that reason, the platform shall schedule VM jobs according to the following rules: a) Provide strong isolation for VMs with strong time-constrains; b) Provide maximum Central Processing Unit (CPU) utilization for VMs with relaxed time constrains using SCHED_DEADLINE policy.

VIII. Self-Organizing Network – An Obvious Simplification?

The term "Self-Organizing" appears in many science fields, already in 1962 Ross Ashby a pioneer in cybernetics gave his first principles [39]. It might seem a little bit far-fetched when speaking about Self-Organizing Network which already was introduced by the Next Generation Mobile Networks (NGMN) [40] and now a part of the 3GPP standard [28]. But it gives a historical perspective of a trivial question; how do we know that the developed organization is "good"? The simple answer is; we must decide a criterion to distinguish between "good" and "bad" and then we must ensure that the appropriate selection is done!

As simple as it might sound the truth is that in a Self-Organizing Network we are heavily relying on an Operations Administration and Management (OAM) that in every selection makes the right decision. For that we need a Configuration Management with verified operations, Diagnostics capability with strict classification and a scalable Analytic infrastructure.

What is the rationale for Self-Organizing Network? From the 3GPP standard Technical Specification [41] it is stated as follows:

a) The number and structure of network parameters have become large and complex;
b) Quick evolution of wireless networks has led to parallel operation of 2G, 3G, Evolved Packet Core (EPC) infrastructures;
c) The rapidly expanding number of Base Stations needs to be configured and managed with the least possible human interaction;

Thus, the technical challenges. But the business target of SON is a transition from an operator controlled role to an autonomous operation environment to reduce the OPEX and shifts the management from an open loop to a close loop. The actions are taken by the SON functions and are dedicated of giving the best resource optimization, autonomous configuration and suitable setting of installation parameters. The ambitious target of the 5G framework, as shown in Figure 5, implies a higher network complexity and so a management overhead. If the target is to allow easy deployment of vertical service, it is mandatory to remove this management overhead from duties for operators. This means that SON in SDN-NFV is not only a simplification, but a crucial key technology to achieve the business purposes mentioned in the introduction of this paper.

To resolve the different optimization and deployment scenarios the SON architecture comes in three types (see Figure 14).

- Centralized – All SON functions are implemented close to the OAM;
- Distributed – All SON functions are implemented at the edge;
- Hybrid solution – The complex schemes are implemented close to OAM, and the simpler schemes are implemented at the edge;

There is nothing that prevents that all three scenarios can co-exists and varies over time too.

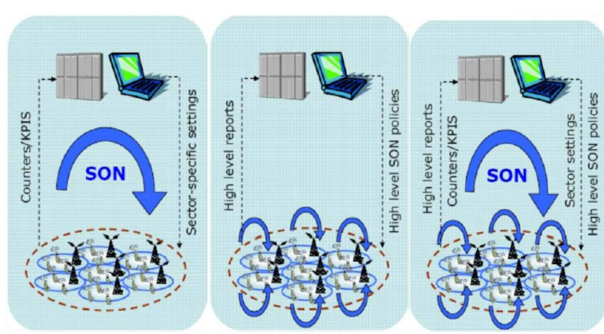

Figure 14. 3GPP, features delivery (source [44])

3GPP releases	Content	Type
Release 8	• Automatic Inventory • Automatic Software Download • Automatic Neighbor Relation (ANR) • Automatic Physical Cell ID (PCI) assignment	Procedures
Release 9	• Mobility Robustness/Handover optimization (MRO) • Random Access Channel (RACH) Optimization • Load Balancing Optimization • Inter-Cell Interference Coordination (ICIC)	Use cases
Release 10	• Coverage & Capacity Optimization (CCO) • Enhanced Inter-Cell Interference Coordination (eICIC) • Cell Outage Detection and Compensation • Self-healing Functions • Minimization of Drive Testing • Energy Savings	Use cases
Release 11	• Automatic Neighbor Relations • Load Balancing Optimization • Handover Optimization • Coverage and Capacity Optimization • Energy Savings • Coordination between various SON Functions • Minimization of Drive Tests	Features
Release 12	• Small cell and heterogeneous networks • Multi-antennas (e.g., MIMO and beam forming) • Proximity services • Procedures for supporting diverse traffic types	Features
Release 13	• Active Antenna Systems (AAS) • Enhancements for inter-site Coordinated Multi-Point Transmission and Reception (CoMP) • Support for up to 32 CA • DC enhancements • RAN sharing improvements • Indoor positioning enhancements • Downlink (DL) Multi-User Superposition Transmission (MUST) • LTE Wireless Local Area Network (WLAN) Aggregation (LWA) radio integration • Licensed Assisted Access (LAA)	Features

Figure 15. 3GPP, features delivery (source [44])

SON solutions can be divided into three categories: Self-Configuration, Self-Optimization and Self-Healing, each containing a wide range of decomposed use cases. When the 3GPP standardization work started it was with the respect to eNodeB and as such focused with releases on the first LTE network deployments. Thereafter the releases have followed the LTE evolution and the maturity of commercial networks (see Figure 15).

As the SON only have taken a half step forward so far (even though a vital step) basically an automatic configuration system, it needs to be extended to meet the 5G requirement. The relation to the "good" organization has to be concrete and should be based on the resources and its behavior which are controlled and formalized in the shape of SLA and guaranteed QoS. This will require a fully automated SON and functions that is more Self-oriented and able to make their own decisions. That means providing intelligence in the network which opens up for technologies like Machine Learning (ML) and Artificial Intelligence (AI).

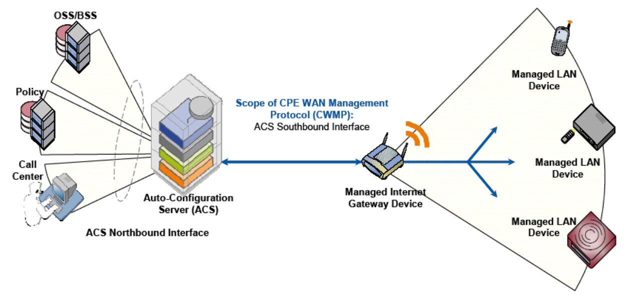

Figure 16. CPE WAN Management Protocol

From standard point-of-view one of the crucial work is to identify the set of interfaces to support OAM and one of the important is TR-069 [42] defined by Broadband Forum.

TR-069 describes the CPE WAN Management Protocol (CWMP) (see Figure 16) which is intended for communication between a CPE (Customer Premises Equipment) and Auto-Configuration Server (ACS). The CPE WAN Management Protocol is intended to support a variety of functionalities to manage a collection of CPE, including the following primary capabilities:

- auto-configuration and dynamic service provisioning,
- software/firmware image management,
- software module management,
- status and performance monitoring, and
- diagnostics.

IX. The Correlation Between SON and SLA

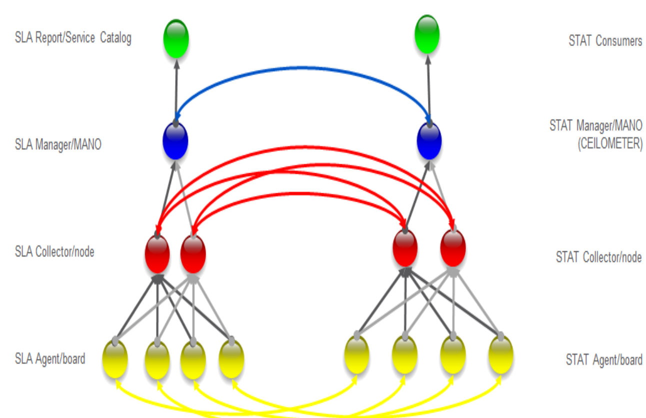

Figure 17. The hierarchical structure and co-relation of SLA and STAT

Concepts introduced in the previous two chapters, SLA and SON, are mutually inclusive. SLA and STATS are strictly correlated to each other and hierarchically spread all over the system (this concept is also emphasized in Figure 17).

Indeed, STATs are far from being a passive snapshot recording, they are actively interworking with SLA and resource manager to deploy the best resource utilization of the network. The hierarchical implementation of resources and metrics handling is fully devoted to simplifying the SON. SON brings a set of self-configuration and self-optimization use cases that allow a better control of the operational cost for the complex radio access technologies. Here, the role of the real-time data analysis makes the difference. It involves all resources of the system, removing the over-allocation, which today is dominating the dimensioning of RAN and causes a huge wasting of money in most of the operational time [29][30]. The hierarchical approach for meters and resources handling, as described in Figure 17, is crucial to avoid massive signaling. Moreover, the local resource-meters agents can by applying the right taxonomy create a resources relationship between different logical layers, from physical resources usage up to QoS, reducing the pressure of meters over the backhaul. This concept is further described in Figure 18 and the DPAC research program (Dependable Platforms for Autonomous System and Control) has designed a suitable framework for QoS control [31]. The model is suitable for debugging too, thanks to the centralized logs hosted as VNF, and it is integrated into the SDN-NFV solution (the so-called vProbe concept [32]).

Concepts like Real-Time and Run-Time are widely abused in literature due to the different domains where such terminologies are used. Radio Access Network is very sensitive to time constrains, considering deadline and latencies in the range of few milliseconds or even less. It is worth to explain the roles behind the different hierarchical analytics.

Real-time Analytics are responsible to collect, elaborate and act on the infrastructure resources usage, that, for the edge of the network, shall include the radio access too. The main target for real-time Analytics is the optimization of the resources allocation respecting the SLA. A function is described by its model, that is, characterization of inter-arrival triggering time (for example, the incoming packets), statistics distribution of computing and temporal constrains, like deadline and latency limitation. Resource reservation for that function could be based on prediction algorithms that identifies the opportunity of resources sharing between different functions, by considering statistics of distribution characterization, constraints and previous allocations. Thus , Real-time Analytics needs to be done as close as possible to the resources location and its data. Another important role for Real-time Analytics is mapping very low-level resources usage into function parameters/characterization, to decrease the pressure of the data into the backhaul. Real-time Analytics can create resources usage report for higher hierarchical Analytics and STATs agents, but in the form of statistical reports.

Run-Time Analytics collect, elaborate and act on the functions characterization. It is responsible to control the function slicing reservation and to scale in/out functions depending on the current usage and SLA. Run-Time Analytics could be based on prediction algorithms to be able to scale in/out function slicing and avoid resources conflicts. Depending on the outcomes of a prediction algorithm, Run-Time Analytics can set different SLA to the lower hierarchical Analytics and STATs agents. It will translate function slices reservation, usage and prediction into Key Performance Indicators (KPI) to higher hierarchical STATs. A special case is the trace&log control. In this case, the Run-Time Analytics will aggregate and correlate the data to set a contextual trace setting and thereby provide a “fault-detection” log. Trace&log can be supported with dedicated vProbe at NFVI level, dynamically set by the run-time analytics and collect important data on the fly. Note how different logs can be considered and aggregated to provide a layered view of the system covering more or less of the topology.

Statistics Analytics is probably the closest to data center analytics concept: there is not deadline of latency constrains and the analysis of the data can produce both Network statistics and new requests for the MANO.

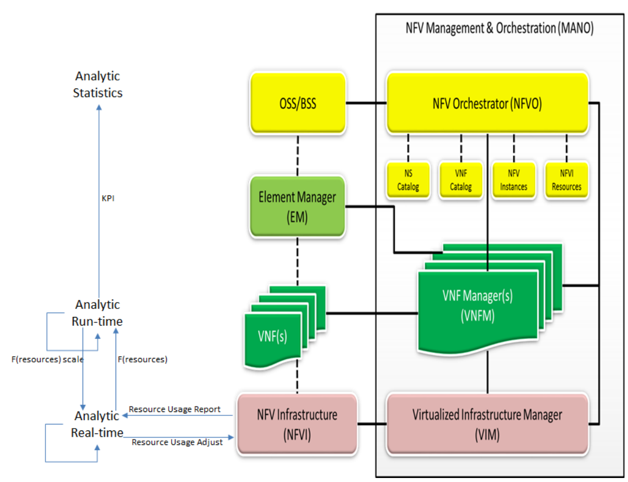

Figure 18. The different Analytic types in the hierarchical data handling

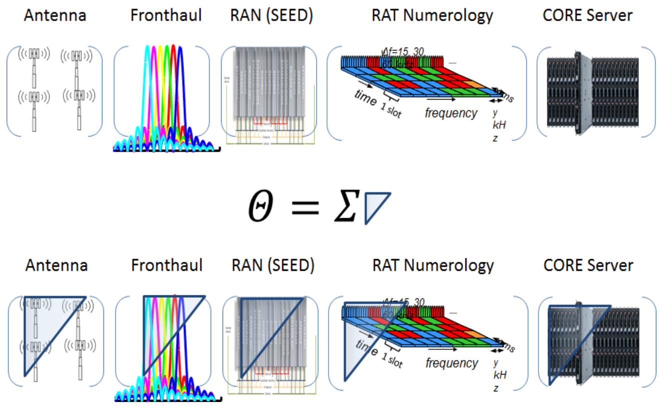

Figure 19. E2E slicing definition

Regardless which level of Analytic considered, a field that is emerging and attracts more attention is AI. Actually, it would be more suitable to talk of Machine Intelligence (MI), that stands for Machine Learning – Artificial Intelligence, in order to emphasize the active and pro-active usage of system data. MI is today one of the most active research topics, but it is important to identify where MI can effectively open new market opportunities rather than be a fascinating technology. In the RAN domain, the amount of data that can be generated is huge. Therefore, MI has become a key technology in the area of prediction models, classification, and optimization problems. The need to analyze large data sets is today actually one of the main obstacles on the strive to achieve efficiency. Machine learning and deep learning is probably the best way to consider MI. As it has been stated before, it is the ability to learn behaviors and anticipate both the system and the End User behaviors (to optimize the use of resources such as the quality of the experience), but also it is the technology to understand how to present the data to the operator, how to use the right data to characterize the system itself. Not least, how to use the data to locate a possible mistake automatically.

The dynamic resources handling as functional component of the network slicing is a critical enabler of the new services. For example, in Figure 12 it is shown how even spectrum is part of the slicing at the edge of the network and that is surely for optimal spectrum usage. But more focus should be put on its nature of E2E vertical deployment enabler, since it allows multiple services with multiple characterizations, from extreme bandwidths demand up to IoT (Figure 19).

Massive MIMO (M-MIMO) has already been addressed in the paper as a pillar of the 5G and probably the most complex part of spectrum dynamic control; like beamforming, cooperative multipoint coverage and swept beams, which are only possible in RRH so it is out of the scope for this paper. However, Figure 20 shows how consideration of spectrum involves hierarchically higher controller, so that spectrum handling and analytics connected is spread on different levels (note how this example is fully compliant to the concept described in Figure 17).

X. BUSINESS CASE OPPORTUNITY EXAMPLES

The availability of distributed computing for the new system is the enabler for new business cases. Since 5G architecture is proposing itself as a new framework, it is the accelerator for new service products. This chapter wants to introduce two examples, already well-known.

The first one is based on the local storage availability. This concept has been mentioned at the beginning of the paper and already described. The second case is considering the high value of the End User metadata. In Figure 13 Agent/Server is considered a characteristic of the SEED. A service able to provide End User data is extremely attractive and valuable for enterprises and vertical services. Handling of such a service, however, shall be done in the proper way. Security, licenses, registration and publication of the service is fully involving MANO and most likely need a certification agreement between OTTs and operators. MANO is also

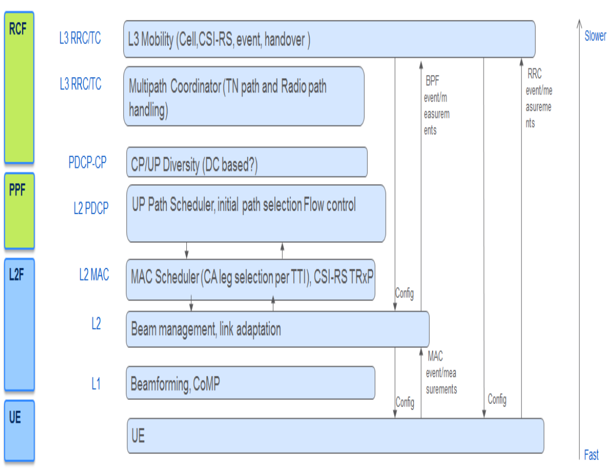

Figure 20. RAN Connected mobility

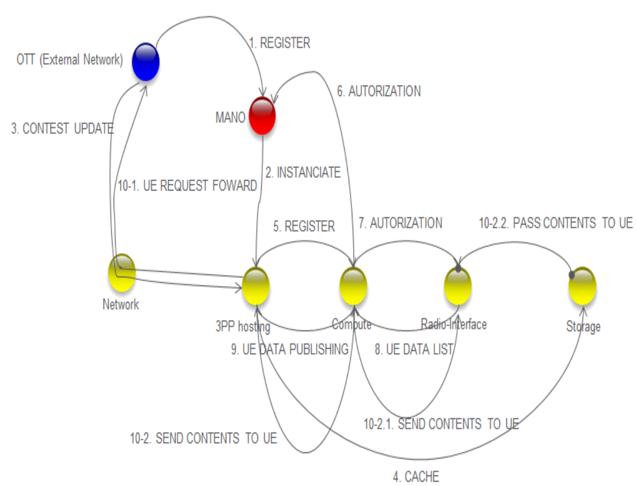

Figure 21. Ue Metadata publishing interwork example

responsible for authorization approval of the SEED 3PP controller, defining which level of End User metadata could be exposed for which 3PP application, as well as if the 3PP application is allowed to send data to the End User. Mainly, the SEED is the bridge between End User and OTTs providing a hierarchical service contents handling that will guarantee a better quality of experience to the consumers. For that reason, storage is a mandatory SEED capability, and one more time, the server dimensioning could be the differentiation of features while offering the solution to the operators (in telco vendors point of view) and while defining SLA to the OTTs (in the point of view of operators). Figure 21 is emphasizing the complexity of End User data publishing in a secure way by defining the different steps needed, from registration to usage.

XI. Conclusion

The opportunity to move SDN-NFV into the Radio Access Network is a crucial objective for the communication system in the next years. Fulfilling the needs of the customers means: to answer on the demand for the next generation mobile, create new business models for the operators and open new service market share for the infrastructure vendors. However, mobile cannot be handled as data center or networking nodes. Location, latency time, End User metadata are unique and added value for the radio access, which means an ad-hoc solution is the enabler for a successful and high performing product. A complete C-RAN solution is not considered suitable due to the fronthaul capacity explosion, the more flexible approach of the Radio Access Network as a Service (RANaaS) looks more promising. The ad-hoc solution is based on the implementation of the ETSI concept called MEC. This paper emphasizes the role of it as server@edge of the network, calling it SEED. SEED is a suitable set of heterogeneous hardware solution, designed to dramatically reduce the cost of virtualization. The engine of the SEED is the so-called C-mobile platform, a horizontal, per sever distributed, platform able to support the main functions characterizing the SEED: SDN-NFV controller, End User Metadata access service, Radio Access as Service solution, 3PP hosting and granted SLA. To be fully dynamic, SDN applications need to be responsive to their environment, therefore, triggers for network changes need to be state-driven. This automated management will be based on real-time network data analysis. Hierarchical Resource Manager and big data handling in the meaning of SON support is a key enabler together with the needed support.

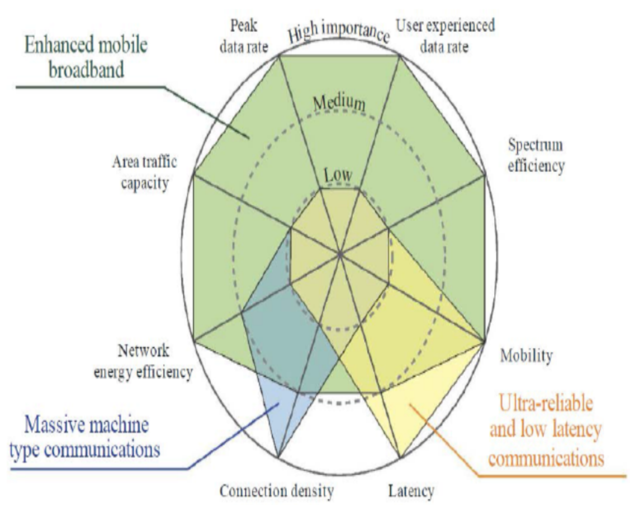

Figure 22. Key capabilities in different service domains (source: [33])

The International Telecommunication Union (ITU) standardization – network and service aspects – group, has set the 5G in that direction too, by emphasizing the diversification of service demands to be the key characterization of the 5G network for 2020 [33]. In fact, similarly as it has been done in the introduction of this paper, ITU identifies Enhanced Mobile Broadband (eMBB), Ultra-reliable and Low-Latency Communications (uRLLC) and Massive Machine Type Communications (mMTC) to be the service domains for 5G. Those services domains have a widely different set of performance and capabilities requirements (see Figure 22), that is only possible to achieve through the strengthening of the resource usage and SLA flexibility handling at the server of the edge.

XII. Future Works

All the concepts in the paper needs investigation and future study. For example, the usage of sched_deadline in a virtualized environment needs c-groups extension for a complete control of thread in containers. Moreover, a Greedy Reclamation of Unused Bandwidth (GRUB)-like mechanism implementation would decrease the Constant Bandwidth Server (CBS) effect of sched_deadline, providing a more performing latency time [34][35]. Usage of resources meters and statistics is a very interesting topic. One of the natural next steps is the evaluation of the taxonomy framework introduced in [36] for the characteristic resources of the Radio Access Network: network slices, load balancing, resource abstraction and resource control as defined in [37].

Similarly, the impacts on SDN-NFV MANO look significant. In fact, the same concept of Point Of Presence (PoP) as defined today is missing the elastic assignment of resources. In a future scenario where MTC and IoT begin accelerating 5G deployment, the slicing of computing, for example assigning different scheduling policies and fraction of a core, looks like a fundamental opportunity even to decrease the power consumption through the optimization of the resource usage. More should be done also in the domain of hardware accelerators. In Chapter VI, it has been stated how HAs, at the state of the art, are mandatory to meet protocols requirements and functions feasibility, but they should be designed in order to support the function slicing concept, that is, the vertical services introduced in Chapter III as fundamental characterization for the 5G system. HAs should provide SR-IOV-like virtualized access to the function as the enabler of needed intra-service resource sharing and isolation.

What has been considered only partially in this paper is the impact with respect to security requirements. Indeed, the strong temporal isolation introduced by the sched_deadline is in the security domain contents, but that is not enough. Even considering a fully slices based resources system, the intrusion avoidance is mandatory in order to protect sensitive data, like the End User data described in Chapter X. The real-time algorithms which are able to supervise, detect and lock unwanted threads are today under deployment [38].

References

[1] C. Vitucci and A. Larsson, "SEED, A server platform for the edge of the network," IARIA 2017, Volume ICN 2017: the sixteenth conference on Networks (includes SOFTNETWORKING 2017), Mestre (Venice), 2017, pp. 118-123.

[2] DG Connect team, "Towards 5G," European commission, Digital Single Market Policies, February 2014. Available from https://ec.europa.eu/digital-single-market/en/policies/5g [retrivied: 06, 2017].

[3] Ericsson AB, "Ericsson mobility report on the pulse of the networked society," EAB-15:037849 Uen, 2015. Available from http://www.ericsson.com/res/docs/2015/mobility-report/ericsson-mobility-report-nov-2015.pdf [retrieved: 03, 2017].

[4] Bahjat el-Darwiche, Pierre Peladeau, Christine Rupp, and Florian Groene, "2017 telecommunications trends," Strategy& pwc, 2017. Available from https://www.strategyand.pwc.com/trend/2017-telecommunications-industry-trends [retrieved: 06, 2017].

[5] Ericsson AB, "Ericsson mobility report on the pulse of the networked society," EAB-15:026112 Uen, 2015. Available from http://www.ericsson.com/res/docs/2015/mobility-report/ericsson-mobility-report-june-2015.pdf [retrieved: 03, 2017].

[6] A Aijaz, H Aghvami, and M Amani, "A survey on mobile data offloading: technical and business perspectives," IEEE Wireless Communications 20(2):104-112 · April 2013

[7] T. Kridel, "The end of profitability," Tellabas Insight Q2, 2011, pp. 14-15.

[8] K. Shatzkamer, "Applying systems thinking to mobile networking," Brocade Communications Webinar, 2015. Available from http://docplayer.net/8990528-Applying-systems-thinking-to-mobile-networking.html [retrieved: 03, 2017].

[9] Eclipse IoT working group, "The three software stacks required for IoT architectures," Sept. 2016. Available from https://iot.eclipse.org/resources/white-papers/Eclipse%20IoT%20White%20Paper%20-%20The%20Three%20Software%20Stacks%20Required%20for%20IoT%20Architectures.pdf [retrivied: 06, 2017].

[10] 5G PPP architecture working group, "View on 5G architecture," EuCNC 2016. Available from https://5g-ppp.eu/wp-content/uploads/2014/02/5G-PPP-5G-Architecture-WP-July-2016.pdf [retrivied: 06, 2017].

[11] ETSI paper, "Network Functions Virtualisation (NFV); Use cases," ETSI GS NFV 001, v1.1.1, 2013. Available from http://www.etsi.org/deliver/etsi_gs/NFV/001_099/001/01.01.01_60/gs_NFV001v010101p.pdf [retrivied: 03, 2017].

[12] Y. C. Hu, M. Patel, D. Sabella, N. Sprecher and V. Young, "Mobile edge computing - A key technology towards 5G," Sept. 2015, availble from http://www.etsi.org/images/files/ETSIWhitePapers/etsi_wp11_mec_a_key_technology_towards_5g.pdf [retrieved: 03, 2017].

[13] ETSI paper, "Network Function Virtualisation (NFV); Network operator perspectives on industry progress," SDN & OpenFlow World Congress, Dusseldorf, 2014. Available from https://portal.etsi.org/Portals/0/TBpages/NFV/Docs/NFV_White_Paper3.pdf [retrivied: 03, 2017].

[14] G. Karagiannis et al, "Mobile cloud networking: virtualisation of cellular network," 21st International Conference on Telecommunications (ICT), 2014, pp. 410-415.

[15] C.Vitucci, J.Lelli, A.Pirri, and M.Marinoni, "A Linux-based virtualized solution providing computing quality of service to SDN-NFV telecommunication applications," In Proceeding of the 16th real time Linux workshop (RTLWS 2014), Dusseldorf, Germany, 2014, pp. 12-13.

[16] NGMN Alliance, "5G white paper," NGMN, 2015 J.S. Harrison, M.M. Do, "Mobile Network Architecture for 5G Era - New C-RAN Architecture and distributed 5G Core", Netmanias, 2015. Available from https://www.ngmn.org/uploads/media/NGMN_5G_White_Paper_V1_0.pdf [retrivied: 03, 2017].

[17] Karl-Erik Arzen et al, "WASP: autonomous Cloud," Lunds Universitet, 2017. Available from http://www.control.lth.se/Research/RealTimeComputing/autonomous-cloud.html [retrieved: 06, 2017].

[18] J.S. Harrison and M.M. Do, "Mobile network architecture for 5G era - New C-RAN architecture and distributed 5G core," Netmanias, 2015. Available from http://www.netmanias.com/en/post/blog/8153/5g-c-ran-fronthaul-kt-korea-sdn-nfv-sk-telecom/mobile-network-architecture-for-5g-era-new-c-ran-architecture-and-distributed-5g-core [retrivied: 03, 2017].

[19] Netmanias, "KT 5G network architecture," NMC Consulting Group, October 2015. Available from http://www.netmanias.com/en/post/oneshot/11146/5g-kt-sdn-nfv/kt-5g-network-architecture-update [retrivied: 06, 2017].

[20] SK telecom network technology R&D Center, "ATSCALE white paper," rev 1.0, 06/2016. Available from http://www.sktelecom.com/img/pds/press/SKT_5G%20White%20Paper_V1.0_Eng.pdf [retrivied: 06, 2017].

[21] G. Brown, "Service chaining in carrier networks," Heavy Reading, 2015. Available from http://www.qosmos.com/wp-content/uploads/2015/02/Service-Chaining-in-Carrier-Networks_WP_Heavy-Reading_Qosmos_Feb2015.pdf [retrivied: 03, 2017].

[22] T.A. Satria, M. Karimzadeh, and G. Karagiannis, "Performance evaluation of ICN/CCN based service migration approach in virtualized LTE systems," IEEE 3rd International Conference on Cloud Networking (CloudNet), 2014, pp. 461-467.

[23] M.J. McGrath, "Network functions as-a-service over virtualized infrastructures," Ref. Ares(2015)3376865, 2015. Available from http://cordis.europa.eu/docs/projects/cnect/0/619520/080/deliverables/001-TNOVAD32InfrastructureResourceRepositoryv10Ares20153376865.pdf [retrivied: 03, 2017].

[24] OpenStack, "OpenStack operations guide," OpenStack Foundation, 2014. Avaiable from https://docs.openstack.org/ops-guide/ [retrivied: 03, 2017].

[25] C. Dixon, "OpenDayLight: introduction, Lithium and beyond," available from http://colindixon.com/wp-content/uploads/2014/05/brighttalk-odl-webinar.pdf [retrivied: 03, 2017].

[26] N. Nikaein et al, "Network store: exploring slicing in future 5G network," in Proceeding of the 10th International Workshop on Mobility in the Evolving Internet Architecture, 2015-09, pp. 8-13.

[27] T. Cucinotta, M.Marinoni, A.Melani, A.Parri and C.Vitucci, "Temporal isolation among LTE/5G network functions by real-time scheduling," in Proceedings of the 7th IEEE International Conference on Cloud Computing and Services Science (CLOSER 2017), 2017.

[28] 3GPP TS 32.500, "3rd generation partnership project; technical specification group services and system aspects; telecommunication management; Self-Organizing Networks (SON); concepts and requirements (Release 11)," v11.1.0, 2011-12.

[29] K.Trichias, R.Litjens, A. Tall, Z. Altman, and P. Ramachandra, "Self-optimisation of vertical sectorisation in a realistic LTE network," Europen Conference on Networks and Communications, 2015, pp. 149-153.

[30] S. Fortes, A. Aguilar-Garcia, R. Barco, F. Barba, J.A. Fernandez-Luque, and A. Fernandez-Duran, "Management architecture for location-aware self-organizing LTE/LTE-A small cell networks," IEEE 53(1) Communications Magazine, 2015, pp. 294-302.

[31] M. Jägemar, A. Ermedahl, S. Eldh and M. Behnam, "A scheduling architecture for enforcing quality of service in multi-process system," (to appear in) Proceedings of Emerging Technologies and Factory Automation (ETFA), 09, 2017.

[32] G. Brown, "Virtual probes for NFVI monitoring," Heavy Reading, 2017. Available from https://builders.intel.com/docs/networkbuilders/virtual_probes_for_nfvi_monitoring.pdf [retrivied: 06, 2017].

[33] ITU-R, Recommendation ITU-R M.2083-0 (09/2015), "IMT vision - framework and overall objectives of the future of IMT for 2020 and beyond," M series, Mobile, radiodetermination, amateur and related satellite services, 2015.

[34] L. Abeni, J. Lelli, C. Scordino, and L. Palopoli, "Greedy CPU reclaiming for SCHED DEADLINE," in Proceedings of the Real-Time Linux Workshop (RTLWS), Dusseldorf, Germany, 2014.

[35] G.Lipari and S. Baruah, "Greedy reclaimation of unused bandwidth in constant bandwidth servers," in IEEE Proceedings of the 12th Euromicro Conference on Real-Time Systems, Stockholm, Sweden, 2000, pp. 193-200.

[36] S. Cai, B. Gallina, D. Nyström, and C. Seceleanu, "A taxonomy of data aggregation processes," IEEE DAGGERS project paper, 2016. Available from http://www.es.mdh.se/pdf_publications/4628.pdf [retrivied: 03, 2017].

[37] VG. Nguyen, TX. Do, and Y. Kim, "SDN and virtualization-based LTE mobile network architectures: A comprehensive survey," Wireless Personal Communications, 2016, Volume 86, Number 3, pp. 1401-1438.

[38] M. Fergurson, "Architecting a platform for big data analytics," 2nd Edition, Copyright © by Intelligent Business Strategies Limited, March 2016. Available from https://www-01.ibm.com/common/ssi/cgi-bin/ssialias?htmlfid=IML14333USEN [retrivied: 07, 2017].

[39] W.R. Ashby, "Principles of the self-organizing system," in Principles of Self-Organization: Transactions of the University of Illinois Symposiu, H. Von Foerster and G.W. Zopf, Jr. (eds.), Pergamon Press, London, UK, 1962, pp. 255-278.

[40] Frank Lehser, "NGMN recommendation on SON and O&M requirements," NGMN Alliance, December 2008. Available from https://www.ngmn.org/uploads/media/NGMN_Recommendation_on_SON_and_O_M_Requirements.pdf [retrivied: 10, 2017].

[41] Technical specification group services and system aspects, "SP-080064: New BB_Level WID on management of Self-Organizing Networks (SON)," 3GPP, 2008.

[42] William Lupton, John Blackford, Mike Digdon, and Tim Spets, "TR-069 CPE WAN management protocol v1.1", Broadand forum technical report, December 2007. Available from http://www.broadband-forum.org/technical/download/TR-069_Amendment-5.pdf [retrivied: 10, 2017].

[43] Magdalena Nohrborg, "SON," 3GPP, 2017. Available from http://www.3gpp.org/technologies/keywords-acronyms/105-son [retrivied: 10, 2017].

[44] 3GPP, "Release 13," 3GPP, 2017. Available from http://www.3gpp.org/release-13 [retrivied: 10, 2017].