Network Function Virtualization in 5G

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Abstract

The fifth-generation (5G) wireless technology is paving the way to revolutionize future ubiquitous and pervasive networking, wireless applications, and user quality of experience(QoX). To realize its potential, 5G must provide considerably higher network capacity, enable massive device connectivity, with reduced latency and cost, and achieve considerable energy savings compared to existing wireless technologies. The main objective of this paper is to explore the potential of network functions virtualization (NFV) in enhancing 5G Radio access networks functional, architectural and commercial viability, including increased automation, operational agility, and reduced capital expenditure. The ETSI Network Function Virtualization (NFV) Industry Specification Group has recently published drafts focused on standardization and implementation of NFV. Harnessing the potential of 5G and network functions virtualization, we discuss how NFV can address 5G critical design challenges through service abstraction and virtualized computing, storage, and network resources. We describe NFV implementation with network overlay and Software Defined Network (SDN) technologies. In our discussion, we give first steps in understanding the role of NFV in implementing Coordinated multipoint (CoMP), Device to Device (D2D) communication, and ultra densified networks.

1 Introduction

In the last decade, wireless technology has emerged as one of the most significant trends in networking. Recent statistics show that mobile wireless broadband penetration has exceed that of fixed wire-line broadband networks. In addition to general broadband access, recent advances in wireless communications and node processing capabilities have made it possible for communication networks to provide support for a wide variety of new multimedia applications and compelling wireless services, that are rapidly and steadily becoming national priorities. This trend is expected to continue in the future at much faster growth rates. By 2018, the global mobile traffic will increase from 2.6 to 15.8 exabytes. Addressing the expected exponential growth of rich media underscores the need to evolve cellular networks. To this end, 5G will support 1000 times the current aggregate data rate and 100 times the user data rate, while enabling 100 times increase in the number of currently connected devices, 5 times decrease of the end-to-end latency, and 10 times increase of the battery lifetime [1].

To meet the expected three-orders-of-magnitude capacity improvement and the massive device connectivity, 5G centers its design objectives around efficiency, scalability, and versatility. To sustain its commercial viability, 5G networks must be significantly efficient in terms of energy, resource management, and cost per bit. Connecting a massive number of terminals and battery operated devices necessitates the development of scalable and versatile network functions that cope with a wider range of service requirements including: low power, low data rate machine-type communication, high data rate multimedia, and delay-sensitive applications among many other services. The efficiency, scalabaility, and versatility objectives of 5G directs the 5G community towards finding innovative but simple implementations of 5G network functions.

5G network functions face critical functional and architectural challenges in spite of their performance superiority. CoMP for instance can improve the cell-edge user experience by using coordinated and combined transmission of signals from multiple antennas, cells, terminals, or sites to improve the Downlink (DL) and Uplink (UL) performance (e.g. by coordinated scheduling, coordinated beam-forming, or interference alignment). However, CoMP achieves this gain with increased computations, increased signaling overhead, and increased back-hauling and equipment cost. Moreover, the massive number of devices requires ultra densified networks, specialized hardware, and device-centric architecture that are not well defined yet. Finally, 5G must coexist with legacy technologies like 2G, 3G, and 4G. This requirement alone increases cost and complexity indefinitely. These challenges can be effectively addressed by implementing the 5G network functions as software components using the NFV paradigm.

A growing group of companies and standardization bodies push research and development of the NFV paradigm to improve cost efficiency, flexibility, and performance guarantees of cellular networks in general[1]. In NFV, vendors implement network functions in software components called Virtual Network Functions (VNFs). VNFs are deployed on high volume servers or cloud infrastructure instead of specialized hardware. For example NFV pools the signal processing resources in cloud infrastructure rather than using dedicated Baseband processing units (BBUs) in every site. Such resource pooling reduces computational and signaling overhead, optimizes cost, and improves flexibility so that a service provider activates a particular signal processing resource for only specific termi-

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[1]`https://portal.etsi.org/TBSiteMap/NFV/NFVMembership.aspx`

nals in the whole network instead of activating all processing resources unnecessarily in each site.

Generally, NFV can overcome some challenges of 5G by: (i) optimizing resource provisioning of the VNFs for cost and energy efficiency, (ii) mobilizing and scaling VNFs from one hardware resource to the other, (iii) ensuring performance guarantees of VNFs operations, including maximum failure rate, maximum latency, and tolerable unplanned packet loss, and (iv) ensuring coexistence of VNFs with non-virtualized network functions [8]. Unlike other work on application of NFV and SDN technologies in generic 5G networking, virtualized LTE evolved packet core, and SDR based sites [10, 12, 6, 3], this work focuses on the implementation of an NFV framework that meets 5G Radio Access Network (RAN) technology requirements and enables several 5G complex functions while smoothing its coexistence with other technologies. We also demonstrate the effectiveness of NFV in reducing the Capital Expenditures (CAPEX) and Operational Expenditures (OPEX) of the 5G RAN.

In this paper, we will first survey service abstraction, architecture of NFV, and network virtualization via the network overlay model. As an NFV enabling technologies, we will describe how to use SDN and OpenFlow to virtualize and interconnect VNFs. Second, we will focus on 5G virtualizable radio functions and describe CoMP, Inter-Cell D2D, and ultra densified network implementation using NFV. Finally, we will discuss open research problems specific to NFV in 5G RAN.

2 NFV and Network Overlay

With NFV, services are described as a forwarding graph of connected network functions. A forwarding graph defines the sequence of network functions that process different end-to-end flows in the network. For example, Figure 1 shows a simplified forwarding graph of a mobile Internet service where data flows traverse network functions from the Evolved NodeB (eNodeb), to the Service Gateway (sGW), to the Internet Protocol (IP) backbone until it reaches the application server. Mobility management and Non-Access Stratum (NAS) protocols flow through different network functions for mobility management, authentication, and policy enforcement. Unlike the current cellular networks where a particular feature is activated network wide, forwarding graphs enable 5G operators to activate features per service (e.g. CoMP becomes active only for predefined service classes). The network functions are virtualized using a separate virtualization layer which decouples service design from service implementation while improving efficiency, resiliency, agility, and flexibility. Network functions that can be virtualized in general include: *i*) the evolved packet core functions such as: the mobility management entity, the serving gateway, and the packet data network gateway, *ii*) baseband processing units functions including: MAC, RLC, and RRC procedures [5], *iii*) switching function, *iv*) traffic load balancing, and *v*) operation service centers.

The NFV reference architecture (Figure 2) supports wide range of services described as forwarding graphs by orchestrating the VNF deployment and operation across diverse computing, storage, and networking resources [8]. As shown in Figure 2, the computing and storage hardware resources are commonly pooled and interconnected by networking resources. Other network resources interconnects the VNFs with external networks and non-virtualized functions, enabling the integration of existing technologies with virtualized 5G network functions. NFV Management and Orchestration comprises resource provisioning modules that achieve the promised benefits of NFV.

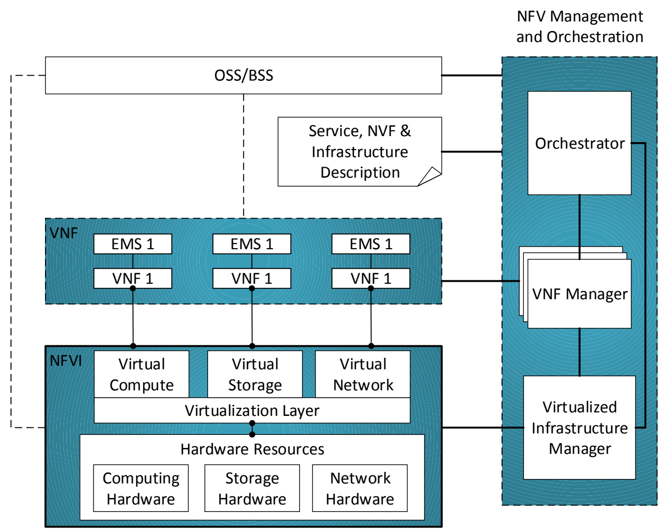


Figure 2: The Network Function Virtualization Reference Architecture.

The VNF Managers(s) (Figure 2) performs two main functions: operation and resource provisioning. VNF operation consists of infrastructure management, fault management, performance management, and capacity planning and optimization. Resource provisioning ensures optimal resource allocation (e.g allocate Virtual Machines (VMs) to servers), optimal connectivity between VNFs, energy conservation, and resource reclamation. Moreover, resource managers discover computing, storage, and network resources in the infrastructure. Efficient design of VNF Manager leverage the peak benefits of NFV to reduce CAPEX and OPEX in 5G by means of dynamic resource allocation, traffic load balancing, and easier operation and maintenance [13].

In the rest of this section, we will detail the NFV design trade-offs and the main networking problems associated with them. Then, we will introduce the network overlay concept as a solution to these problems.

2.1 Networking Problems in NFV

NFV faces several networking problems; some are inherited from multi-tenant data center networking, while others are specific to NFV. Designing NFV platforms for carrier-grade availability that exceeds five nines, requires fail-over times between redundant 5G VNFs in less than a second. Also, almost all cellular services are dynamic in nature and the physical resources must expand and shrink as service demand changes (elasticity). Cellular traffic has regular daily and weekly patterns, but also changes spatially in case of special events (e.g. football matches) so that resources must be as-

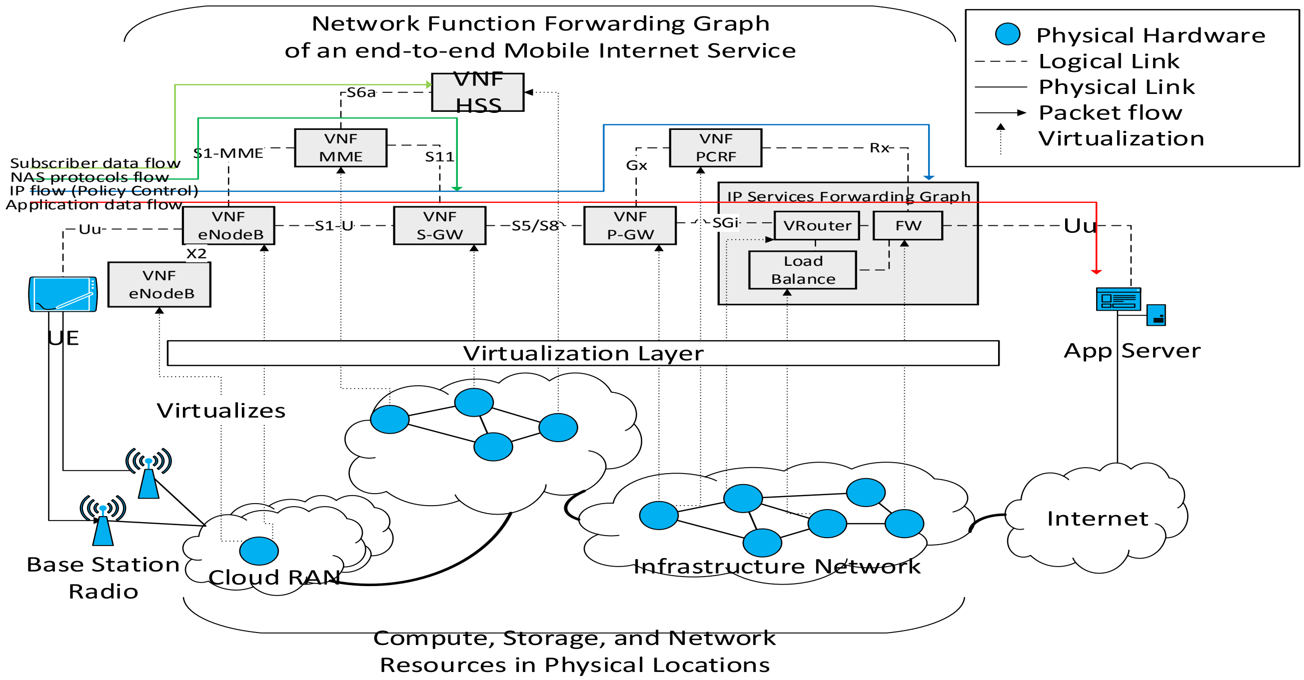


Figure 1: Virtualization of a Forwarding Graph implementing mobile Internet service.

signed optimally to cope with these changes. VMs mobility is one technology that can support these rapid traffic changes, but it comes with *networking* design challenges. First, migrating a VM from one server to another must retain VMs' network states including at least: physical location, and IP and Medium Access Control (MAC) addresses. Second, as the VM implements 5G radio functions, it have access to devices data, radio states, and channel information and it becomes critical that VM migration solutions provide real-time capabilities of distributed state management through localized caching and acceleration agents. Third, from operational efficiency view, resource utilization must be kept as high as possible to ensure profitability. An optimal NFV system design incorporates efficient and flexible allocation of resources and optimal forwarding of traffic by which an operator can realize and mobilize virtual networks of VNFs on any hardware across the infrastructure.

The flexibility of NFV is also associated with overhead. If we place multiple VNFs on the same physical server, the server will not have a single address but many. The switching network will have to learn addresses of individual VMs, and we can witness an uncontrolled increase in forwarding table sizes. Additionally if an infrastructure is shared between multiple service providers, VNFs address separation becomes a must as we need to perceive address use flexibility of a single provider while the address space may overlap between providers. Specifically, as traffic from different providers share the same networking resources, not only security becomes challenging, but also flexibility and optimal forwarding of traffic from one virtual network (network of VNFs) to the other without compromising security and address separation. Additionally, NFV shall maintain the scalability characteristics of the current highly distributed cellular networks while exploiting the discussed benefits of NFV, hence features such as load balancing and VM placement in cloud environment shall become real-time aware and shall support thousands of back-end cellular virtual functions. We will discuss the network overlay concept as a typical solution to the networking problems in such virtualized environment.

2.2 Network Overlay

Network overlay is an approach to address NFV networking problems by implementing virtual networks of VNFs as overlays. The first-hop network device connected to a VNF, called Network Virtualization Edge (NVE), encapsulates the original packets from the VNF and identifies the destination NVE that will decapsulate the packet before delivering it to the next VNF. The network forwards the packet based on the encapsulation header obliviously from the packet payload. The NVE is basically a physical switch, router, or a virtual switch in a network hypervisor.

Network overlay enjoys several appealing characteristics. A key feature of network overlay is the decoupling of the VNF addresses from the physical network addresses, and isolation of traffic from multiple virtual networks. The traffic isolation is achieved by the fact that forwarding traffic between virtual networks requires gateway entity to forward such traffic. If this gateway is missing, forwarding traffic between virtual networks is not possible. With such a feature, the overlay provides both traffic isolation and flexibility to forward traffic between virtual networks (with adequate gateways).

Moreover, overlay works well in environments that are highly distributed which involves thousands of VNFs. The expected number of NVEs required to implement a virtual network is generally low which is important for scalability while these NVEs provide the needed flexibility to mobilize VNFs with highly dynamic traffic. In principle, migrating a VNFs imply quick reconfiguration of a single NVE to maintain routing flows form that VNF.

Looking at its drawbacks, network overlay requires in general changes in the data plane headers by possibly using existing encapsulation or tunneling protocols in order to support packet (en/de)capsulation. For example the Generic Routing Encapsulation protocol (RFC 2784) can be used to encapsulate - in principle - any arbitrary protocol over IP and to create any virtual Layer-2 network on top of a physical Layer 3 network.

SDN is another approach that simplify network overlay implementation. The idea is to program switches at the NVE to modify packet headers from different NFV flows according to a global mapping of virtual network addresses (e.g. MAC and IP addresses) to physical network addresses. This can be done without changes to the data-plane protocols. A central SDN controller maintains global mapping of virtual/physical network addresses and install rules in switches to implement this mapping. We overview SDN via OpenFlow first and give more details on network virtualization using SDN in the next section. In section 4, we will provide specific use cases of SDN in virtualization of 5G RANs functions.

3 Virtual VNFs overlay via SDN

SDN adopts two main ideas: *logically* centralized control of the data plane, and network state management across distributed controllers. Separating control and data plane accustoms increasing traffic volumes and improves network reliability, predictability, and performance. Such separation allows a controller to deploy forwarding-table entries in data plane programmable switches (or routers) and frees switches from performing control functions.

The controlling function needs not to be centralized in principle, but logically centralized. How distributed controllers manage their states to improve performance, reliability, and scalability is a challenging problem. A support from underlying SDN platform is required from one side to achieve distributed state management. This platform incorporates sophisticated algorithmic and protocol solutions for optimized network control and state management[9].

OpenFlow [15] is a standardized protocol for programming data-plane using control-plane Application Programming Interfaces (APIs). Openflow programs the forwarding behavior of the traffic flows in switches based on different packet header fields matching which are specified in flow table rows. An OpenFlow switch matches protocol header fields (e.g. ports, MAC, and IP) in an incoming packet, and perform actions against matched packets. A router matches the specified header fields and either, floods, forwards the packet on a predefined port, or drop the packet. The router is also capable of rewriting header fields before forwarding the packet.

OpenFlow made the idea of Network Operating System possible. A network operating system is a software that controls the behavior and state of the network through: (i) data plane forwarding rules programming, (ii) network state management, and (iii) network behavior control. Network state management is challenging in distributed SDN controllers to maintain network state at different controllers. The open network operating system (ONOS) is an example of a distributed controller [4] that maintains consistent shared network state information across all controllers represented by a graph database. For fast read/write of network states, it maintains the network data in a low latency, distributed key-value storage along with in-memory topology information cache. The question now is: why SDN and OpenFlow are particularly important for NFV?

3.1 OpenFlow and NFV

NFV does not necessarily require SDN and OpenFlow. However, NFV and SDN are related in many folds. First, SDN is an enabling technology to NFV, where it can simplify the implementation of the network overlay model. Second, virtualizing network functions, like routers and switches, is complicated with conventional networking technologies while SDN provides a natural solution. Imagine the complexity of a router that is running several virtual routers, each implements its own control-plane. Third, SDN flexibly allocates pooled computing resources to a particular VNFs, elastically manages these resource allocation according to traffic demands, and easily mobilizes VNFs with quick modification to NVE rules. In this sub-section, we will discuss the first two possibilities and will leave the third one to section 4.

Unlike adding an encapsulation layer to implement network overlay, an SDN controller just rewrites packets' addresses to implement overlays [2]. This idea does not require changing the data plane at all and still leverages the same benefits of separating virtual networks address spaces. A controller maintains mapping between virtual networks and physical networks including routes through which traffic of a virtual network traverse. The controller installs a flow in the OpenFlow switch's (NVE switch at the edge) flow-table with an action to rewrite a matched source and destination IP/MAC address of a packet from a VNF to addresses in the physical network. The controller also installs rules in the OpenFlow switches in the network to implement a particular route between two chained VNFs. In this process, the controller is not aware of every single packet rewriting event, but just installs the flows in the switches that optimally implement a particular network overlay.

A rigorous way of traffic isolation between virtual networks with SDN based virtualization is to define multiple physical IP addresses ranges for the same physical network. Packet addresses from one virtual network are translated to a particular physical IP addresses range, while packet addresses from another virtual network are translated to another physical IP addresses range. This separation allows flexible isolation of traffic between virtual networks as flows from one virtual network can be controlled to follow a disjoint route from another virtual networks' flows. The main drawback of this approach is the increased IP address space that is needed in the physical network, which is not necessarily required in encapsulation approach. Nevertheless, rigid traffic separation is of a paramount importance when the infrastructure is shared between multiple service providers.

The second flexibility of the SDN approach is the independent networking behavior design of different virtual networks of VNFs. Even if network virtualization is not implemented via SDN, a separate SDN controller can control each virtual

[2] `http://ovx.onlab.us/`

network behavior independently from other virtual networks. The network behavior not only includes how traffic flows are routed, but also how individual virtual network functions process traffic (control-plane) flows (e.g. Firewall, load balancing, deep packet inspection). This discussion reveals that SDN, in general, is a natural choice of implementing some VNFs (besides interconnecting VNFs). Using OpenFlow for SDN or not is another arguable choice due to some limitations in OpenFlow standard that we will discuss later.

NFV and its implementation using SDN can be applied to legacy cellular network functions, virtualization of data centers networks, and Infrastructure as Service in cloud computing, etc. What are the network functions that shall be virtualized in 5G RAN?, How does the third advantage of SDN which we mentioned at the beginning of this section benefit 5G related technologies? and How do NFV and SDN meet 5G architectural and functional challenges? We will try to give an answer to these questions by discussing current and forthcoming research activities that leverage the benefits of NFV and SDN towards an advanced but yet simpler 5G network.

4 Virtualization of 5G RAN

Several control and user plane network functions in 3GPP RANs are candidate for virtualization. Figure 3 shows typical 3GPP network functions, which will also be in 5G, that are virtualizable in principle. Virtualizing these functions lowers footprint and energy consumption through dynamic infrastructure resource allocation and traffic balancing. It also eases network management and operations and enables innovative service offering. We will study potential CAPEX and OPEX savings to be incurred from virtualizing BBUs in a typical cellular network.

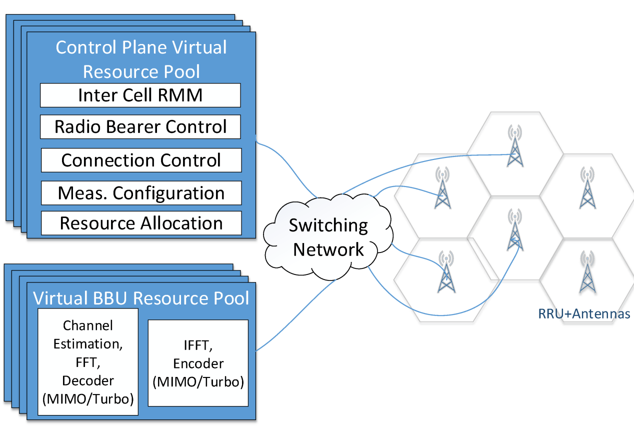


Figure 3: Common RANs network functions in 3GPP control and user plane.

4.1 CAPEX and OPEX in NFV

Consider a scenario in which a VNF implements baseband processing in a virtual BBUs as illustrated in Figure 3. This scenario is known as Cloud-RAN [5], where NFV provides the needed orchestration layer for Cloud-RAN to virtualize layer 2 and layer 3 of the radio interface and the necessary framework to incorporate specialized hardware and accelerators for baseband processing. The Virtualized Infrastructure Manager deploys a pool of virtual BBUs in near the network edge infrastructure. The cell-site in this scenario simplifies to antennas, Remote Radio Units (RRUs), and switching functions. The switching functions interconnect the virtual BBUs pool to the RRUs via optical links and high speed OpenFlow switch to meet strict latency requirement [7, 5]. Every virtual BBU has exactly the same processing capability as the non-virtual BBUs being deployed in every site. According to traffic demand, the VNF Manager allocates particular slices of BBUs VNFs to active cell-sites. For this allocation, the VNF Manager programs an overlay virtual network to switch physical layer flows to/from the RRUs connected to the site and from/to the RRUs to the allocated VM hosting the BBU VNF for processing. We study the impact of VNF on CAPEX by comparing the total number of needed BBUs in virtualized and non-virtualized deployments given the same maximum traffic. We also study the impact of NFV on OPEX by showing the average number of active BBUs in both cases.

We consider real traffic mixture of a cellular network[3]. The network consists of 85 cells, and the traffic traces were collected for a period of six hours. A speech call in these traces requires one processing unit per second and a packet session requires two processing unit per second. This assumption is quite realistic and follows dimensioning rules of major hardware vendors. A single BBU capacity, weather virtualized or not, ranges from 64 to 256 processing units. We assume that a BBU is active if at least one processing unit is active, and when the BBU is idle it consumes no energy.

Figure 4 shows the total number of required BBUs in virtualized and non-virtualized scenarios. As the maximum capacity of a single BBU increases, the total number of required BBUs decreases significantly with VNFs to reach 25% if a single BBU supports 256 processing unit (typically found in major vendors). The saving is attributed to two facts. First, with NFV a single virtual BBU can serve traffic from multiple cell sites by ideal traffic allocation to pooled virtual BBUs instead of specific BBU. Second, the total number of required virtual BBUs depends on the maximum of the aggregate traffic of the network, unlike the non-virtualized case where it depends on the maximum traffic of each individual cell. Since the maximum traffic of each cell occurs at a time interval that varies from one cell to the other, the maximum aggregate traffic of the network becomes significantly less than the sum of maximum traffic of all cells. The saving in total number of required BBUs translates directly to CAPEX saving.

OPEX saving in this study can be observed from the average number of active BBUs shown in Figure 5. The less the active BBUs, the less is the aggregate energy consumption of the whole system (contributed only by BBUs). In the proposed NFV architecture, we allocate traffic from any cell site to an already active virtual BBUs first with sufficient utilization before activating another virtual BBU. At any point in time, a virtual BBU becomes active only if the current aggregate network traffic cannot be served by the already active BBUs. By this approach, we can observe around 30% savings comparing current non-virtualized architecture and VNF. The saving reaches up to 55% with increasing the

[3]The data source is anonymized as per the providing operator request.

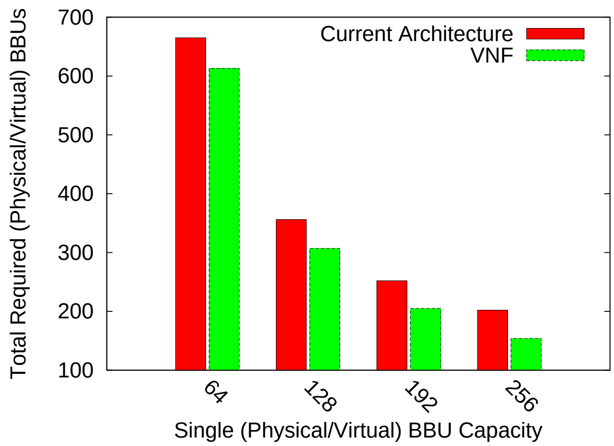


Figure 4: Up to 25% saving in total required BBUs, comparing current (non-virtualized) architecture and VNF.

maximum BBU capacity to 256. The saving in CAPEX and OPEX is clear from this study on a small sized network. We can anticipate more significant impact on networks with thousands of cells and heavier traffic. But the benefit of NFV is not only expenditures savings, but also flexibility in implementing 5G functions.

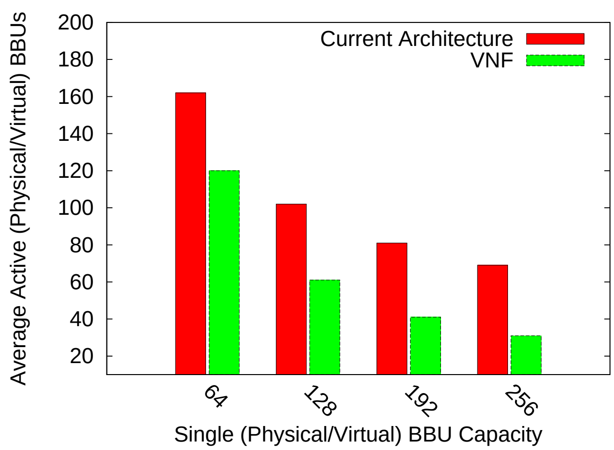
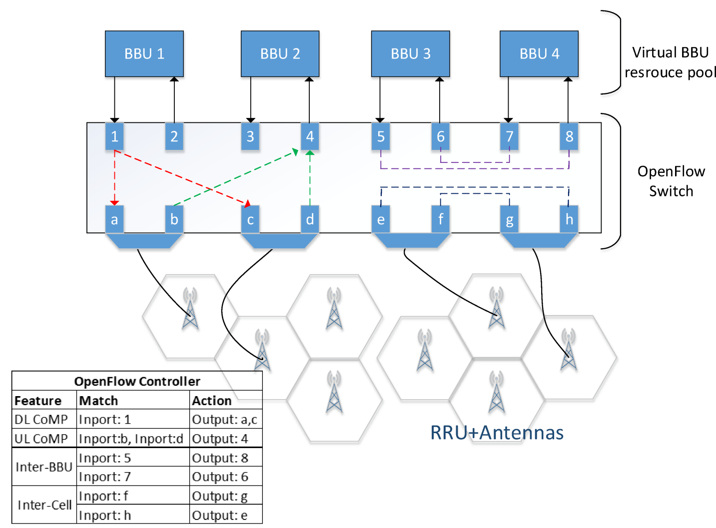


Figure 5: Up to 55% saving in active BBUs, comparing current (non-virtualized) architecture and VNF.

4.2 NFV for CoMP and D2D

NFV and SDN can be viewed as enabling implementations of advanced 5G technologies such as CoMP and D2D communication. Figure 6 illustrates this architecture. The VNF Manager, embodying OpenFlow controller, easily and effectively realizes DL CoMP, UL CoMP, and high speed Inter-Cell D2D connectivity by installing the flows shown in the flow-table in Figure 6 in the switch.

DL CoMP requires all BBUs from multiple 5G cell-sites to communicate while delivering parallel terminal data from one to all involved cell-sites. Similar communication is required in UL CoMP in the reverse direction from multiple cell-sites to single BBU. Additionally, two terminals communicating in Inter-cell D2D require BBUs of the cells to communicate directly and to handle high speed, low latency traffic. That type of D2D communication was requiring exploiting mobile backhaul network in legacy architectures to route traffic through the core network.



OpenFlow Controller

Feature	Match	Action
DL CoMP	Inport: 1	Output: a,c
UL CoMP	Inport:b, Inport:d	Output: 4
Inter-BBU	Inport: 5	Output: 8
	Inport: 7	Output: 6
Inter-Cell	Inport: f	Output: g
	Inport: h	Output: e

Figure 6: NFV/SDN enabling implementation of DL/UL CoMP and Inter-Cell D2D Communication [7].

The NFV/SDN approach in Figure 6 instantiates DL CoMP in which terminal data from BBU-1 are forwarded to two different sites. A flow modification message installs OpenFlow flow that match traffic from input port 1 and take two parallel actions to output flow packets to output port a and c. This realizes both DL CoMP from two cell-sites to a single terminal at aggregate rate and forward the same aggregate message to multiple terminals at user data rate. Two match, single action flow entry realizes UL CoMP similarly. Input flow matched on ports b and d are forwarded in a single action to output port 4.

The OpenFlow controller implements D2D communication in inter-Cell scenario by establishing a high speed, low latency connection of different BBUs. At the same time, another high speed, low latency connection is established between the correspondent cells. This is illustrated by the two multiple match, multiple action flows in Figure 6. Multiple matches and multiple actions are needed in this case as both UL and DL traffic are involved in the connection. We could also use four parallel single match, single action rules in a less optimized flow-table size. In all these scenarios, the NFV manager keeps track of active flows' rules and BBUs allocation.

4.3 Evolving densification with NFV

Another 5G technology where NFV/SDN are of a great benefit is ultra densified networks. 4G networks design was based on the assumption of sparse deployments where cell-sites make nearly-autonomous radio resource management decisions. This is not the case in ultra densified networks. The terminal connects to the network through a cluster of closest cells which cooperatively minimize the impact of interference from neighbor clusters that the terminal is not connected to [14]. The terminal will also exhibit rapid handover decisions, adding and removing cells from its cluster. The solution to this is to logically centralize the radio resource management decision like legacy 3G and 2G networks. However, unlike 2G and 3G, we are challenged by scalability problems which prevents providing a commercially viable centralized controller that manage resources in chaotically deployed massive number of cell-sites.

NFV can provide a solution to scalability issues by deploying all control decisions that require mainly cooperation of large number of cells in VNFs near the network core and that require mainly rapid decisions in NFVs near the network edge. Handovers, transmit power allocation, and cluster selection are control decisions that must be made in cooperation as it impacts inter-cell interference. Alternatively control decision as radio resource allocation are done near the network edge as the decision must be available as frequent as every Transmission Time Interval (TTI) [11].

In addition to the optimized deployment of VNFs, the logical centralization enables advanced algorithms to have access to an accurate and updated view of network status, interference maps, flow parameters, and operator preferences. Mobility management functions can base their decisions on network statuses beyond local radio quality at the cell site (e.g. energy, traffic, and interference awareness), while still provides minimal service interruptions during handovers. For example, operators can implement an efficient VNFs that offload user traffic at the network edge, and load balance traffic at the core. And small cells clustering can be done more efficiently with network supported decisions rather than terminal based decisions.

5 Open Problems

The previous discussion envisioned several research problems to efficiently employ NFV in 5G RANs. RANs rely heavily on digital signal processors in the base station hardware to meet strict real time requirements. Virtualized Software Defined Radio (SDR) technology can virtualize BBUs and generally requires support of real time constraint processing in both VMs and the interconnecting networks. The CoMP example we presented earlier ([7]) uses fiber communication to ensure meeting time constrains of the BBUs. However, OpenFlow does not provide native support of time-critical packet switching and leaves this task to controllers. Performance of virtualized SDR based BBU interconnected to RRU through OpenFlow switches is unexplored.

OpenFlow is currently limited by the lack of programmable data-plane support across different network stacks, by which packet payload can be inspected, modified, or reassembled. The work of Bansal et. al in [2] is an example approach that addresses data plane programmable across the wireless stack by decomposing the data plane into two main components, processing and decision. The processing plane includes data stream processing operation (e.g. signal processing) and the decision plane includes rules that define the sequence of processing operations required to process the data stream.

Moreover, programmable control-plane is currently limited in available solutions (e.g. OpenFlow) as it supports limited protocol spectrum to suite all needs of 5G protocols. Non-Access stratum protocols, Radio Resource Control protocols, and Packet Data Conversion Protocols are examples of protocols above layer-3 that require OpenFlow modifications to match their header fields and specify relevant actions to interconnect VNFs in RANs.

Computing resource allocation is also challenging with strict real time requirements and dynamic allocation according to network traffic demands, service descriptions, and operator cost constraints. One particular challenge that we previously discussed is where to place the VNFs pool initially; i.e., near the edge or near the core of the network. Although this split is somehow intuitive—deploy VNFs with real time constraints near the edge and those with coordination requirements near the core—the deployment scenario where both requirements are present is still unstudied.

Support of deployability and interoperability with legacy and non-virtualized network functions is not investigated yet as the NFV is far from maturity. Possible solutions include: integration of purpose specific hardware in data centers such as digital signal processing and graphics processing units, optimized placement of virtualized network functions in proximity to non-virtualized functions to avoid performance degradation during interworking procedures, and extension of I/O virtualizion beyond Ethernet network interfaces to include other legacy interfaces such as TDM transport interfaces, specialized acceleration units (e.g. crypto hardware accelerators), and SoCs. Performance evaluation of early proof-of-concept deployments along with legacy technologies shall enforce policy and research directions in developing open and standardized protocols, programming interfaces, infrastructure federation, and orchestration algorithms. The orchestration algorithms in particular shall not orchestrate virtualized resources only but also manage dependencies and information flows between virtualized and non-virtualized functions.

6 Conclusions

As mobile computing continues to evolve and access to computing clouds becomes ubiquitous, mobile users expect highly-reliable, anywhere and any-time wireless connectivity and services. The need to evolve future wireless networks toward supporting, reliably and efficiently, a wider range of networking and multimedia services and applications becomes a critical design requirement of next- generation wireless networks. Cognizant of emerging trends in wireless services and applications, the paper focuses on exploring the potential of NFV to address the daunting challenges and design requirements of 5G RANs. The paper underscores that NFV approaches to enable advanced, cooperative, rapidly-changing baseband processing and radio resource management in 5G, must be flexible, cost effective, and elastic. NFV naturally inherits these benefits from virtualization, cloud computing, and SDN paradigms. New challenges, related to carrier-grade network functions, must be addressed. To this end, the paper discusses critical open problems, including the need to adhere to strict real time processing, support programmable data-plane, achieve efficient local and global resource management and orchestration , and explore NFV placement trade-offs.

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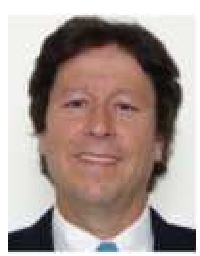

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