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MASTER THESIS

Mobile Network Virtualization: A study of the techno-economic aspects

Sotiria Efthymiadi

Supervisors: **Lazaros Merakos,** Professor
Nikos Passas, Senior Researcher (PhD)
Salvatore Costanzo, Researcher

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Salvatore Costanzo, Researcher

EXAMINATION COMMITEE: **Lazaros Merakos,** Professor

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ABSTRACT

One of the most indubitable challenges faced by the mobile network operators is to provide cost effective solutions to meet the growing demand of the mobile traffic. Whilst every effort has been made to increase the data rates and improve the physical layer performance especially with the introduction of Long Term Evolution-Advanced (LTE/LTE-A) systems, it is not sufficient to meet the exponential increase in traffic demand that is expected to become one order of magnitude larger than the bandwidth that the operators will be able to provide. As a consequence, operators need to achieve a better utilization of the scarce mobile network resources. However, the conventional business model followed by the network operators, based on a dedicated network infrastructure paradigm where each operator have access to a fixed set of network resources is no more considered a valuable approach for efficient radio resource management and utilization. Consequently, the mobile network operators are investigating new and innovative technologies to be able to effectively and efficiently utilize their network infrastructure while increasing the ARPU (Average Revenue Per User) and decrease the capital expenditure (CAPEX) and (OPEX) operational expenditures. To this end, aiming to avoid the underutilization of the physical resources, recently there has been a surge of interest for leveraging the benefits of Network Virtualization in mobile cellular networks. Network Virtualization (NV) has been successfully applied in wired networks as a means to provide abstraction of the network equipment and dramatically simplify the network configuration and resource management. The most prominent NV instances, such as Software Defined Networking (SDN) and Network Function Virtualization (NFV), are also envisioned by the mobile network operators as a way to address the explosive capacity demand of mobile traffic and reduce the costs burden faced to handle the increasing traffic demand. Accordingly, in this dissertation, we will discuss the ways to apply NV in telecoms and especially in mobile networks. This is supported by a techno-economic analysis so as to consider its effect on CAPEX and OPEX expenditures.

SUBJECT AREA: Techno-economic analysis of virtualization case

KEY WORDS: Virtualization, Economic factors, Openflow, SDN, CAPEX, OPEX

ΠΕΡΙΛΗΨΗ

Οι τηλεπικοινωνιακοί πάροχοι σήμερα, έρχονται αντιμέτωποι με την συνεχώς αυξανόμενη ζήτηση δεδομένων ενώ καλούνται να βρίσκουν οικονομικά συμφέρουσες λύσεις για να καλύψουν αυτήν την ανάγκη. Ενώ γίνονται προσπάθειες να αυξηθεί ο ρυθμός που μεταδίδονται τα δεδομένα και να αυξηθεί η απόδοση στο φυσικό επίπεδο, κυρίως με την εισαγωγή της τεχνολογίας LTE, η ζήτηση για χρήση των πόρων είναι πολύ μεγαλύτερη από αυτά που μπορούν να προσφέρουν οι πάροχοι. Για τον λόγο αυτό κρίνεται αναγκαία η καλύτερη αξιοποίηση των δικτυακών πόρων. Το μοντέλο που επικρατούσε μέχρι σήμερα του διαμοιρασμού συγκεκριμένων πόρων δεν θεωρείται εποικοδομητικό. Επομένως κρίνεται απαραίτητη η αξιοποίηση της τηλεπικοινωνιακής υποδομής με νέες μεθόδους αυξάνοντας τα έσοδα ανά χρήστη και μειώνοντας τα έξοδα. Για τον λόγος αυτό γίνεται πλέον λόγος για τον όρο Network Virtualization. Πρόκειται για μία μέθοδο που έχει εφαρμοστεί επιτυχώς στα ενσύρματα δίκτυα και συμβάλλει στην απλοποίηση των δικτύων καθώς και στον καλύτερο διαμοιρασμό των πόρων. Οι όροι Software Defined Networks και Network Function Virtualization έχουν επίσης την ίδια βάση και αποσκοπούν στην καλύτερη αντιμετώπιση της μεγάλης ζήτησης με τον καλύτερο δυνατό τρόπο. Στην παρούσα διπλωματική θα εξετάσουμε τον τρόπο που εφαρμόζονται οι παραπάνω έννοιες στα κινητά δίκτυα και θα γίνει μία προσπάθεια παρουσίασης των τεχνο-οικονομικών μεταβλητών σχετικών με κόστη κεφαλαίου και λειτουργικά κόστη.

ΘΕΜΑΤΙΚΗ ΠΕΡΙΟΧΗ: Τεχνο-οικονομική ανάλυση δικτύων

ΛΕΞΕΙΣ ΚΛΕΙΔΙΑ: Λειτουργικό κόστος, Κόστος κεφαλαίου

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ΠΕΡΙΕΧΟΜΕΝΑ

FIGURES

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PROLOGUE

That dissertation presents a techno-economic evaluation of a virtualization model suitable for mobile networks so as to highlight the possible gains achievable from the operators' perspective.

The dissertation is organized as follows:

At first step, in chapter 1, the concept of Virtualization is introduced, some exemplary solutions suitable for the communication networks are presented.

In chapter 2, we introduce some Network Virtualization tools and architectures focusing on the recent networking paradigm, known as Software-Defined Networking (SDN), and we present the benefits that can reap from its usage. We will concentrate mostly on OpenFlow, which is the basic protocol used to deploy SDN networks. We will see how it works and why its usage is so significant. We will also mention the benefits of applying OpenFlow in wireless and mobile networks that are the target of this dissertation. Finally we will mention an emerging NV technology, known as Network Functions Virtualization (NFV), and we investigate its relation with SDN.

In chapter 3 we will discuss how the concept of network virtualization can be concretely implemented in mobile network scenarios. In particular we will exploit the network sharing aspects of mobile network virtualization and we will focus on RAN (Radio Access Network) sharing solutions that aim to dramatically lower the operator's operative expenses.

After that, the basic techno-economic concepts relative to the mobile network virtualization are presented in chapter 4 and their significance is mentioned. That will help later in the dissertation to results' evaluation.

Finally, in chapter 5, we present a techno-economic model that will help to assess the benefits of virtualization translated in economic values. We will prove that network virtualization is a profitable solution for mobile telecom operators.

1. VIRTUALIZATION IN NETWORKING

With the term virtualization, we refer to the creation of a virtual (rather than actual) version of something, such as a computer hardware platform, a storage device, an operating system or network resources. More specifically, it could be defined as the separation of logic operations from the physical ones. For example, in computer hardware virtualization, the “host” machine creates a simulated computer environment, knows as a “virtual machine” (VM), which acts like a real computer with an operating system. The use of VMs was the base of virtual environments. The first time of that implementation was in 1960 from IBM and the reason was the expensive computer equipment and the desire for simultaneous execution of applications and processes. With this approach, the software executed on the VM is separated from the underlying hardware resources and consequentially it becomes platform-independent. Computer virtualization allows a variety of software configuration settings to be used on a single physical machine and this may provide a much flexible and efficient utilization and sharing of the hardware resources. Virtualization may also be used to enable an efficient aggregation of resources. For example, in the “storage virtualization” a set of storage devices are pooled into what appears to be a single storage unit.

In the networking, virtualization may be used to combine network resources into a single software-based managed entity, known as “virtual network”. More specifically, network virtualization can be categorized in two smaller categories:

- Link virtualization: In that case multiple virtual links are transported over a shared physical link. Virtual links are identified by specific labels or generally by a time slot or wavelength. In Internet, protocols like ATM and MPLS are used for that purpose.
- Node virtualization: This type of virtualization consists of separating and partitioning of the available resources. Physical resources of a node, (CPU, storage, capacity, and bandwidth) are separated in slices and one or more slices are assigned to a virtual node according to demands. These virtual nodes are usually interconnected by means of the aforementioned virtual links so that to enable the creation of virtual networks that are logically equivalent to a concrete physical network.

Today the concept of virtualization in networking is applied in many fields, the most important of which are as follows:

- Virtual Local Area Network (VLAN)
- Virtual Private Network (VPN)
- Active and Programmable Networks
- Overlay Networks

Virtual Local Area Network (VLAN)

A VLAN is a virtual emulation of a LAN network where the end stations can be easily grouped together event they are not placed in the same physical network. The most significant thing in VLAN (Virtual LAN), in contrast to a traditional Local Area Networks (LAN), is that end stations can be grouped together more easily, even if they are not on the same network. A VLAN can be configured through software instead of physically relocating devices or connections. Today, most enterprise-level networks use the concept of virtual LANs to overcome one of the limitation imposed by the traditional LAN networks. In fact, in traditional LANs all the interfaces on a switch are considered to be in the same broadcast domain and hosts in different LANs cannot talk directly with each other since they are in different broadcast domains. Therefore a layer 3 routing is required to enable the communication between nodes placed in different LANs. Conversely, in a VLAN, a single network may be partitioned to create multiple distinct broadcast domains. In this way, it is possible to create a virtual network consisting of group of end stations with a common set of requirements, in such a way that they are independent of physical location. Each VLAN (built upon a local area network) is identified by a VLAN tag, or VLAN ID (VID). The VID is assigned during VLAN configuration. When we configure switches to support VLANs, we need to assign a VID to each port. The VID on the port must be the same as the VID assigned to the interface that connects to the port.

The assignment of VLANs is based on either the following three ways:

- According to the MAC address of the host
- According to switches' ports
- According to the IP address

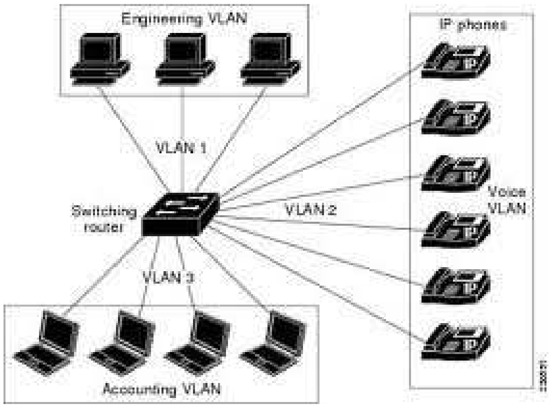


Figure 1: VLAN example [1]

We are not going to see VLAN in detail in the rest of this dissertation but a source in bibliography could be [1].

Virtual Private Network (VPN)

A Virtual Private Network (VPN) makes use of the aforementioned link virtualization concept. The VPNs are used from many enterprises nowadays to let remote users have access to enterprises' networks in a secure way, and to connect together different enterprises' departments that are located in many different countries, by exploiting public telephone networks. Main elements of a VPN are the provider edge routers (PE) and the customer edge devices (CE).

Usually a private virtual network works under the management of a provider, known as "Provider-provisioned VPN (PPVPN)". According to the protocol that is used in the data plane, we have the following PPVPN technologies:

Layer 3 PPVPN: The characteristic of that category is the usage of Layer 3 (L3) protocols (IP, MPLS) for the transfer of information between CEs inside the virtualized network. L3 VPNs are categorized on CE-based and PE-based VPNs. In the first category the network provider ignores the presence of VPN and the creation, the management, and the separation of the channels is under customer's control. The network manages the packets from or to VPNs as if it has to deal with normal packets. So the interconnection nodes demand the use of encapsulation of VPN packets. In the second category, operators' elements recognize that the specific traffic has to do with VPN and treat it accordingly.

<u>Layer 2 VPN:</u> That type, deals with the transfer of layer two protocols (Ethernet, ATM and Frame Relay). The advantage of that type is its simpliness due to ignorance of upper layers. There is no control plane for the management of the access layer.

<u>Layer 1 VPN:</u> After SONET/SDH evolution and optical switching along with GMPLS control, Layer 1 VPN was created from the need for extent L2/L3 packet switching VPN in circuit-switching domains. The basic difference with L2 and L3 VPNs is that in L1 VPNs the interconnection in data plane does not guarantee the interconnection in control plane and the opposite.

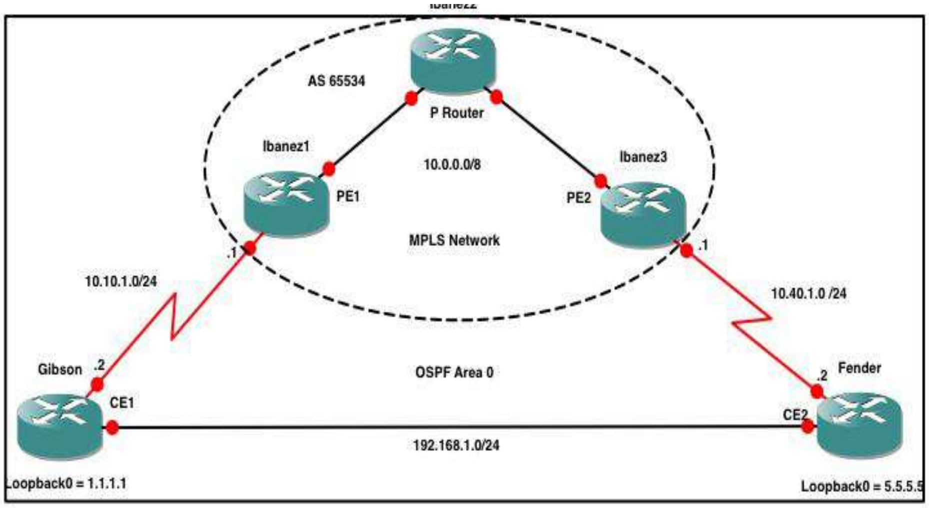


Figure 2: VPN [1]

A more detailed description of the VPN technology can be found in [1].

Active and Programmable Networks

The research on that area was triggered by the willingness for the creation, development and management of new services based on customer needs. Active networking allows the possibility of making real-time changes to the underlying network operation. The behavior of network devices and flow control is handled by software that operates independently from network hardware.

Network programmability is central to an emerging network paradigm, known as Software-Defined Networking. Currently, the most popular specification for creating a software-defined network is a protocol called OpenFlow, which lets network administrators to remotely control routing tables. With OpenFlow, the packet-moving decisions are centralized, so that the network can be programmed independently of the individual switches and data center gear.

Overlay Networks

An overlay network is built on the top of another already existed network. The purpose of that network is to implement network services that are not available in the existing network. Nodes are connected through logical links-paths through many physical links in the underlying network. For example, distributed systems such as cloud computing, peer-to-peer networks, and client-server applications are overlay networks because their nodes run on top of the Internet. The Internet was originally built as an overlay upon the telephone network while today (through the advent of VoIP) the telephone network is increasingly turning into an overlay network built on top of the Internet [2].

In short, with NV it is not more necessary to deploy new equipment to create a new network, but it is sufficient to develop new software on top of existing physical infrastructure nodes and emulate the network behavior in a logic way. These are not all the virtualization paradigms, but are the most important to understand how NV works.

2. NETWORK VIRTUALIZATION TOOLS AND ARCHITECTURES

Today’s telecommunications issues tend to become even more challenging and demanding in contrast with previous years. The already existed networks sometimes fail to cover the needs of enterprises, carriers and end users.

Here comes a new way of implementing network changes relative to customers’ demand. The promising network paradigm, known as Software-Defined-Networking (SDN), consists of a new network architecture, basic elements of which is that control and data plane are decoupled, network infrastructure and state are logically centralized and the underlying network infrastructure is abstracted from the applications [3]. Sometimes, this type of architecture is also referred as split architecture [4].

2.1 Benefits of SDN

Some of the benefits that may derive from this type of networking paradigm are presented in the following:

- *Management of the networks* based on information derived from that. For example, resources may be redistributed based on user’s demand for services.
- *Innovation*, due to massive implementation of new network capabilities that don’t require the relative configuration of individual devices.
- *Rights of network programmability* may be given to operators, enterprises, independent software vendors and that fact enhances the competition in the market.
- *Reliability and security* due to centralized management that results in less configuration errors.
- *Adaptive networks according to users’ needs*. Nowadays, the customers demand high rates of bandwidth that can be achieved only with a more efficient network. Smartphones, tablets, cloud services, dynamic computing and other technologically enhanced means need a reliable network that offers new capabilities.

With SDN we have the ability to identify the amount of traffic that flows through network devices and by that way we could control the network according to real-time changes. For example, a video application would- in a SDN-based network- detect the available bandwidth in that specific time and to manage to adjust it accordingly. As it is mentioned above, SDN separates the control and the data plane, which entails in a centralized control of the network. The centralized approach adopted by SDN aims to simplify the network management by encouraging the replacement of the thousands of protocol standards that today are processed by the network devices.

A non-profit industry consortium, the “Open Networking Foundation” (ONF) [3], is currently dedicated to the promotion and adoption of SDN through the development of open standard APIs. ONF is leading in SDN solutions for multi-vendor management and especially focuses at on-demand resource allocation, network virtualization and secure cloud services. With open APIs, between the SDN control and applications layers, business applications can operate on an abstraction of the network, leveraging network services and capabilities without being tied to the details of their implementation. As a result, computing, storage, and network resources can be optimized [3].

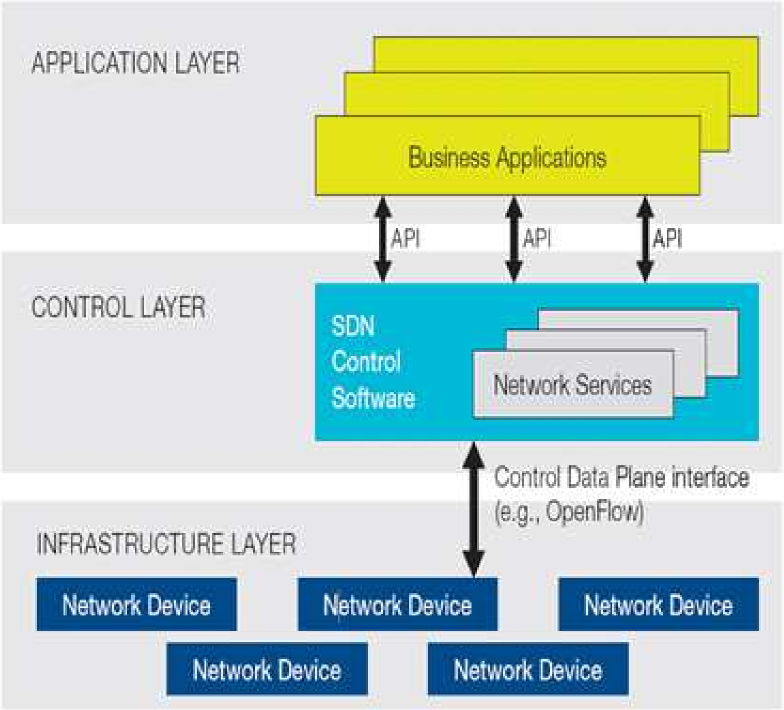


Figure 3: Software-Defined Network Architecture [5]

With SDN, there is a possibility for a logically centralized Controller to monitor an unlimited number of devices. At the same time one single device can be controlled by multiple controllers, too. In SDN, Controllers are periodically kept informed about the status of the network devices. In particular, two different categories of information are maintained by each Controller. The first one is relative to the CPU load, available memory of the network apparatus and generally wireless channels status up to the links characterization (delay, loss rate, stability, etc).The second one is relative to the topology discovery, including the full identification of network nodes [6]. This is how SDN architecture works in general and this abstraction is the key asset of that architecture.

The first well-known instance of SDN is OpenFlow, which is considered as the vital element of an open SDN architecture.

2.2 OpenFlow

OpenFlow implementation began as an idea of Stanford University at United States in 2008. That initiative came from the willingness to exploit the network used by university communities so as to promote innovation and give a chance to investors and stakeholders so create new market assets.

OpenFlow is an open source protocol that works between the control and the forwarding layers of the SDN architecture and it intends to provide an easy programmable, open networking environment for implementation of new technologies, methodologies, routing algorithms and network security. The main advantage of OpenFlow is that it solves a basic problem: the creation and the control of new network methods at already existing and operational networks, without intervening in the operation of active routing and security protocols that work nowadays [1]. A controller can communicate with multiple forwarding devices as it can be seen from the following figure.

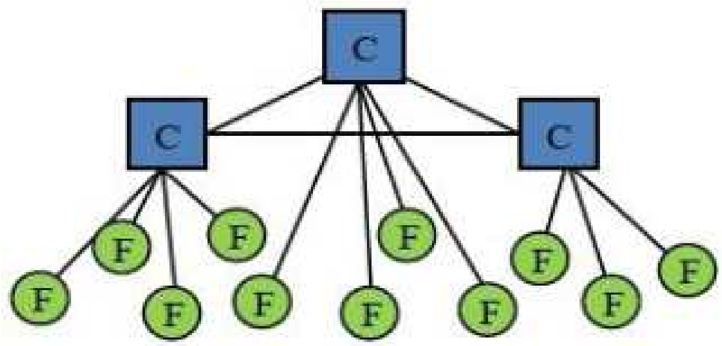


Figure 4: Controller and Forwarding Layers [1]

A logic channel is configured between the controller and the switches. That channel needs to be secure, so as to reassure that the data transmitted through that way, will reach its destination with the proper way and will conform to the OpenFlow protocol rules. For that reason, messages transmitted in the OpenFlow channel use TCP (Transmission Control Protocol) or TLS (Transport Layer Security) to enhance security. The TLS encryption protocol derives from SSL (Secure Sockets Layer). When a switch wants to communicate with the controller it uses the IP address of the controller while the port is defined from the user. OpenFlow protocol supports three types of messages: controller-to-switch, asynchronous and symmetric. At the first category, the controller could find out the characteristics and the abilities of the switch, it could control its parameters, change flow or group entries, select statistical data for the operation and the current state of the switch. Asynchronous messages are sent from the switch to inform the controller about changes in the network and finally symmetric messages are exchanged between both controller and switch.

We will now discuss for OpenFlow switch. OpenFlow switch consists of a device (either switch or router) that processes one or more flow tables, one group table and one separate channel that is used for the direct communication between the switch and the OpenFlow controller. Via that channel, the manipulation of switch take place so as to give the opportunity to the controller to add, remove or update the flow entries of the flow tables.

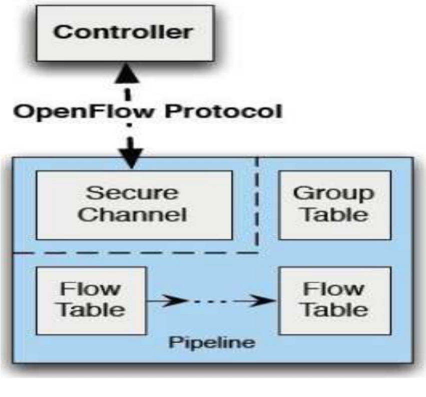


Figure 5: OpenFlow Switch [5]

OpenFlow switches are separated to:

- *OpenFlow-only switches*, which support the OpenFlow operations. Note that all the packets are processed by the OpenFlow pipeline of the switch.

- *OpenFlow-hybrid switches*, that support both the OpenFlow and the Ethernet (for routing in OSI Layer 2 and Layer 3) operation. These switches have a mechanism that redirects the receiving packets either to the OpenFlow or to the normal Ethernet pipeline. That mechanism is based on the in-port of the packets or in a tag at the header of the packets.

In some papers, OpenFlow switches are categorized in two categories: “Type 0" or “Type 1", depending on their capabilities. Type 0 represents the minimum requirements for any conforming OpenFlow Switch. Type 1 requirements will be a superset of Type 0. It is expected that commercial OpenFlow Switches will initially be of Type 0 evolving to Type 1 and that vendors will support additional features over time. However, all switches are expected to use the same OpenFlow Protocol for communication between switch and controller [7].

The OpenFlow Type-0 switch, classifies packets into flows based on a 10-tuple which can be matched exactly or using wildcards (a character that may be substituted for any of a defined subset of all possible characters) for fields. The following fields constitute a 10-tuple:

- Switch input port
- Source MAC address
- Destination MAC address
- Ethernet Type
- VLAN ID
- IP source address
- IP destination address
- IP protocol
- TCP/UDP source port
- TCP/UDP destination port

Flow table entries are matched using this 10-tuple to find the corresponding actions associated with the flow. The OpenFlow Type-0 switch has three required actions:

- Forward to a specified set of output ports: This is used to move the packet across the network.
- Encapsulate and send to the controller: The packet is sent via the secure channel to the remote OpenFlow controller. This is typically used for the first packet of a flow to establish a path in the network.
- Drop: Can be used for security, to curb denial of service attacks, or to reduce spurious broadcast discovery traffic from end-hosts.

If a match is not found for an incoming packet, the packet is sent to the controller which decides on the action(s) that should be associated with all packets from the same flow. The decision is then sent to the switch and cached as an entry in the switch’s flow table. The next arriving packet that belongs to the same flow is then forwarded at line-rate through the switch without consulting the controller. The following figure shows the steps for routing a flow between two hosts across two switches.

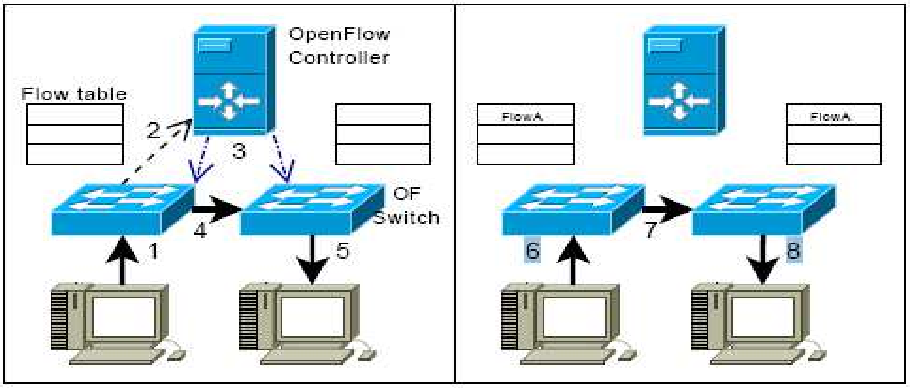


Figure 6: Steps when a new flow arrives at an OpenFlow switch [21]

In the diagram on the left, the switch flow tables are empty. When a new packet arrives to switch (step 1), it is forwarded to the controller (step 2) since no information are still stored in its flow table. The controller examines the packet and inserts entries into the flow tables of the switches on the flow's path (step 3). The packet is then sent through to the receiving host in steps 4 and 5. In steps 6, 7, and 8 any new packets belonging to the same flow are routed directly since they would match the new flow entry that has been previously stored in the flow tables by the controller.

Each flow entry in the aforementioned flow table consists of some fields, discussed in detail in the next section.

The OpenFlow switch, by using the flow entry, forwards the packets from an in-port to an out-port. That port could be a physical port of the switch, or even a virtual one that is selected from a virtual machine that runs on the switch.

There is also the possibility of dedicated ports usage. In that case, we deal with specific forward operations like sending of packets to the controller or massive sending to the devices (flooding) or using non-OpenFlow forward methods-by default device operation. Beyond the management of each packet separately, the switch can use the group table for more massive processing of traffic. One flow entry can be matched with one group table action (that is defined in the group table).

Now we can mention flow tables and OpenFlow entries. OpenFlow uses the concept of flows to identify network traffic due to some pre-defined match rules, which have already dynamically or statistically configured by SDN control software [3]. Inside the OpenFlow switch, there are multiple flow tables containing multiple flow entries. When a new packet arrives in the switch, a procedure starts to verify if the header data matches with one the flow entries. If a match is achieved, the instruction set that is defined from the entry is implemented. The instruction is interpreted as an action to be performed by the switch. If a group table is used, that instruction may also points in another entry of another flow table.

The structure of an OpenFlow entry is the following:

Match Fields	Priority	Counters	Instructions	Timeouts	Cookie

Figure 7: OpenFlow entry [4]

Many of these entries exist in the flow table. The routing of the packets is based on the content of these entries. The "Match Fields" concern the header of receiving packets. "Counters" have a record of the amount of packets that have matched successfully or have been rejected. The “Timeouts” field contains the expiration time after that the entry is expired from the switch and the “Cookie” field are data that the controller save in the entry and can be used to filter the statistics of the entry or its changes. “Instructions” include guidelines for the execution or modification of some actions during the processing of the packet. Finally, the “Priority” field is the value of priority with which the matching procedure is implemented.

When a group table approach is used, a continuous matching of flow entries in the different flow tables is performed following a pipeline-logic as in Figure 8.

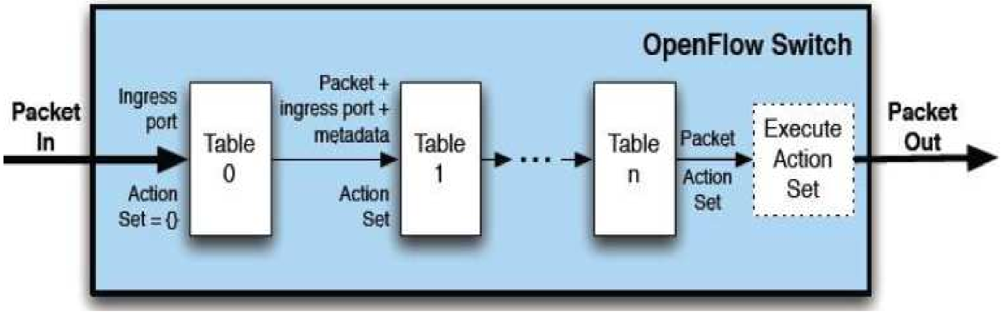


Figure 8: Path of packet via flow tables [4]

At the figure below, we can see a general depiction of flow table entry and some examples of the rules and actions that are used:

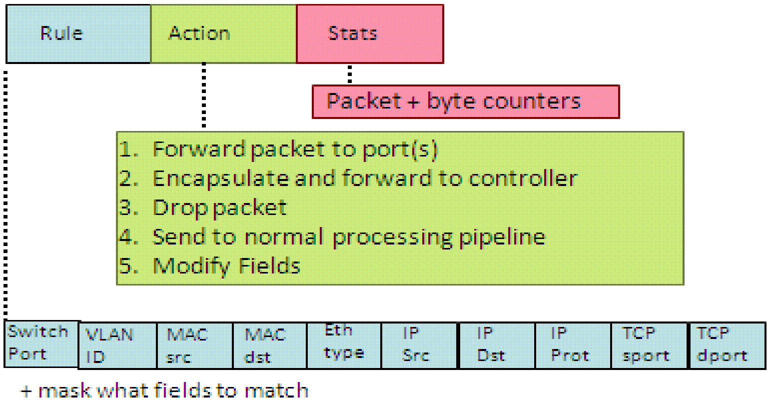
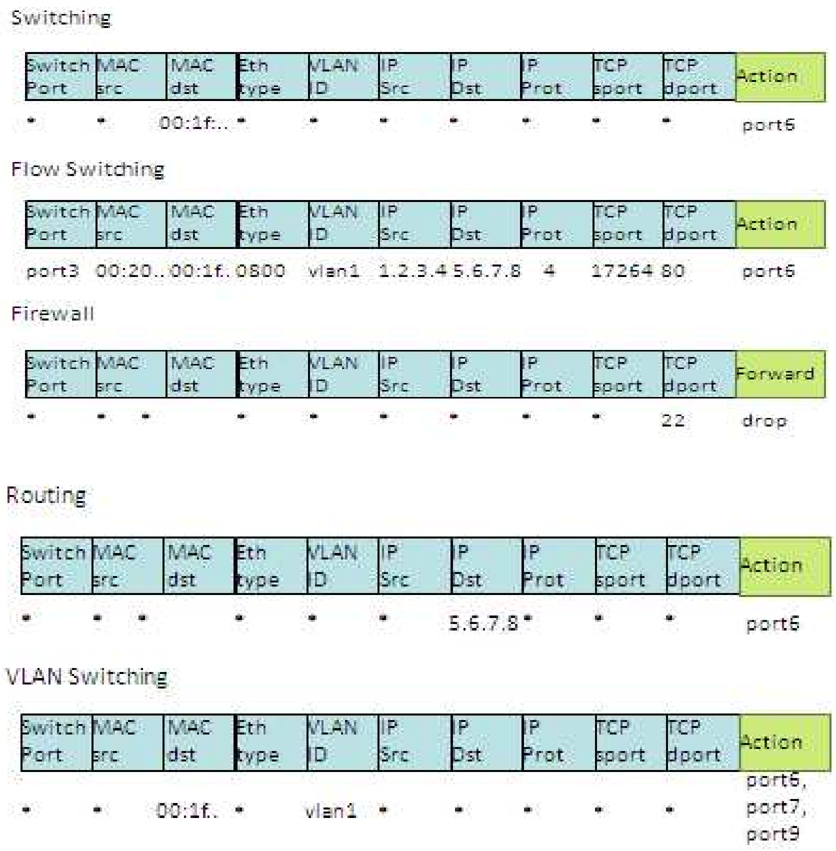


Figure 9: Flow Table Entries [6]

It is preferable to define flows according to lower layer (L2, L3) packet headers since packet parsing complexity is lower compared to processing up to upper layers (L4). Therefore, fields in MPLS between data link and network layer (L2.5), are usually used, although in some cases upper layer header fields may also be required for better packet type discrimination and OpenFlow allows the flexibility of defining flows using upper layer (L4) header fields.



Switching

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
*	*	00:1f:..	*	*	*	*	*	*	*	port6

Flow Switching

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
port3	00:20..	00:1f..	0800	vlan1	1.2.3.4	5.6.7.8	4	17264	80	port6

Firewall

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Forward
*	*	*	*	*	*	*	*	*	22	drop

Routing

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
*	*	*	*	*	*	5.6.7.8	*	*	*	port6

VLAN Switching

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
*	*	00:1f..	*	vlan1	*	*	*	*	*	port6, port7, port9

Figure 10: Examples of Flow Entries [6]

OpenFlow and Network Virtualization usage in wireless networks

Nowadays, we distinguish an attempt to bring the use of OpenFlow in mobile networks, too. However, apply the concept of OpenFlow to achieve the virtualization of wireless resources is a complex challenge. This is mainly due to the vastly heterogeneous infrastructures and topologies, different spectrum bands and different mobility requirements. Moreover, the virtualization of the wireless resources, i.e. to achieve the sharing of them, needs to take into account some challenging aspects as how to manage the resource allocation, i.e. among multiple operators, how to guarantee isolation of the shared network resources and how to obtain an efficient resource utilization to maximize the benefit for both users and network operators. The fairness of the resource allocation is considered as a big issue in that action: i.e. fairness in terms of spectrum used, of power used, products of these two, or even QoS fairness. But despite many challenges that will arise, that type of virtualization can reduce the amount of the required base station equipment and thus reduce the required energy to run wireless networks. Small players can come into market and isolate one virtual network from the best effort Internet access network. Some of the main issues referred in bibliography are as follows:

- Paper [8] concentrates on the LTE in an attempt to show the potential benefits of applying virtualization in LTE. Authors propose to use virtualization to achieve the sharing of the air interface among multiple operators. The conclusion is that through network virtualization, better performance is achieved. The overall resource utilization is enhanced and the performances of both network and end-user are improved.

- Paper [9] proposes a novel approach for virtualizing LTE base stations leveraging on SDN/OpenFlow concepts. Authors propose a framework that permits the virtualization of the LTE evolved eNodeBs and enables an operator to lease the physical infrastructure and resources of additional virtual base stations (usually owned by a different operator).
- Paper [10] proposes the use of Virtualization, as a means to achieve the removing the additional traffic that comes to Packet-Gateway (P-GW element) in the current LTE networks, due to centralization of data-plane functions and the difficulties in communication between different vendor equipment (vendor specific configuration interfaces, complex control-plane protocols).
- Paper [10] also contains some extensions to enable SDN in the core network of the cellular networks. First of all, OpenFlow switches should replace the existing core network nodes. An SDN-approach may be used as follow: A controller may exploit the network information from application modules (mobility management, radio resource management etc), so as to generate the proper attributes that will be distributed through rules, on switches. In addition to this, a switch should have an agent that performs simple actions under the command of the controller (for example, monitoring the traffic and send a message to controller when traffic count exceeds a threshold, or even changing the priority of the queue).

2.3 Benefits of SDN and OpenFlow usage in wireless networks

There may be several advantages in mobile networks if the aforementioned technologies are implemented. Some of these positive effects are presented in the following:

Inter-cell interference

In today’s networks, we can observe that small-cell technology tends to spread with high velocity. It manages to increase the capacity though frequency reuse. Closer physical cell spacing is one of the factors increasing inter-cell interference, which is exacerbated for higher bandwidths such as 4G LTE services. As network traffic increases, subscriber might face degradation in its service quality. So, from the following type:

$$SINR=S/I+N$$

The “I” parameter should be eliminated. That could be achieved by using an SDN orchestration to manage the control of the inference in a centralized manner.

Mobile traffic management

From the predictability of voice services we have nowadays passed in the unpredictability of data services. That fact has resulted in an augmentation of ARPU (average revenue data per user). Dynamic repositioning of resources could be based on individual or aggregate flow rate, flow duration or number of mobile users. The user might have the opportunity to be connected with more than one network (perhaps even ones of his choice). The mobile operator will have the opportunity to monitor the mobile traffic and distribute the resources correspondingly. For example, it would pose the rule that “If the flow rate exceeds 50 Kbps, move the flow from 4G to Wi-Fi”. Distinct criteria and thresholds could be applied for different applications running on the same user equipment or for different users. Thresholds could be based on a wide range of criteria, user profile, service plan, location etc.

Offloading

By that, we mean the movement of traffic from a mobile network (cellular, small cells, femtocell) to a Wi-Fi network. It is also known as Wi-Fi roaming. The most important thing in the wireless technologies is the handover to be seamless, meaning that the user does not confront loss of data/connectivity, loss of IP address etc. It is of paramount importance the maintenance of the user experience. Offloading can also be applied in reverse (reverse offload) when congestion on a Wi-Fi network triggers select mobile users to be moved to another Wi-Fi or onto a mobile data connection (3G or 4G/LTE). To this end an SDN approach can help in achieving a better offload management. For example an OpenFlow controller may interact with the ANDSF (access network discovery and selection function) for discovering wireless networks close to the mobile user and performing a more efficient Wi-Fi offload. The figure below depicts that functionality. Selection of the roaming destination can be based on a QoS metric such as performance, signal strength, or distance. The presence of the controller (probably residing in the mobility management entity (MME)) is crucial for the interworking with the ANDSF.

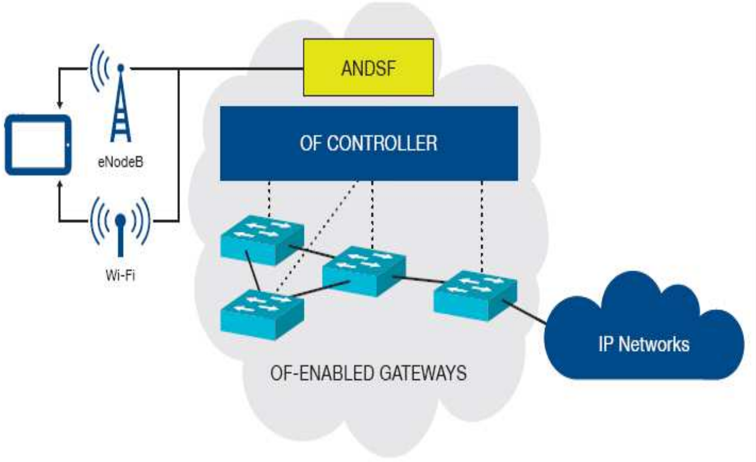


Figure 11: OpenFlow implementation [9]

Mobile offloading has become extremely important with the surge of mobile traffic and devices because it enables mobile operators to optimize RAN resources and improve the quality of experience (QoE) for data-intensive mobile applications.

Wireless link aggregation

It consists of bundling available wireless connections (and bandwidth) to expand the aggregate capacity available to the UE. This requires the UE or mobile device to be capable of simultaneously handling different concurrent wireless connections (for instance, a mix of Wi-Fi, or Wi-Fi and 3G/4G) [5].

Differences in network

Moreover, we have many different types of networks that need to cooperate in a perfect way so that the customer experience should be at the highest possible level. Finally, companies try to focus on new data services to replace the loss from failing voice revenues. Except from that, higher-revenue-producing corporate clients can be offered preference over lower-yielding consumers.

Resource optimization for dynamic environments

The centralized control layer enables radio resource allocation based on a general view of base stations' state, which is more optimal than the distributed radio resource management (RRM), mobility management and routing applications in use today. By centralizing network intelligence, RRM decisions can be adjusted based on the dynamic power and subcarrier allocation profile of each base station. In addition, scalability is improved because as new users are added, the required compute capacity at each base station remains low because RRM processing is centralized in the SDN controller.

Some other benefits in wireless are:

- Middleboxes (a network appliance is a computer networking device that transforms, inspects, filters, or otherwise manipulates traffic for purposes other than packet forwarding) [10] will handle less traffic and by that way can be cheaper.
- The billing processes in SDN, is implemented in real time basis and determine whether a subscriber has reached a usage cap. Nowadays the traffic-monitoring solutions require additional equipment that captures every packet at every interface of S-GW and provide a summary to a backend server every few minutes.
- The mobility management is done much easier. Instead of creating a hop-by-hop path, the controller can modify the rules of multiple switches and by that way lowering the setup delay.
- Virtualization would also be useful to provide isolation and separate control for different classes of traffic. For example, a carrier may want to carry traffic for roaming subscribers on a different virtual network from its own customers, for security reasons.

2.4 Network Functions Virtualization (NFV)

In that section, we will refer to a new trend in telecommunication sector: the one of Network Functions Virtualization (NFV).

NFV officially emerged in October 2012 when the European Telecommunications Standards Institute's (ETSI) "Network Functions Virtualization Working Group" published a white paper defining the NFV concept and its goals. NFV can be divided into two parts: the NFV platform and the Network functions running on top of it. The network functions (software) run on a common shared platform and NFV Platform that is embedded in the network. That architecture allows for agile placement of networking services when and where they are needed. It is applicable to any data plane processing or control plane function in both wired and wireless network infrastructures.

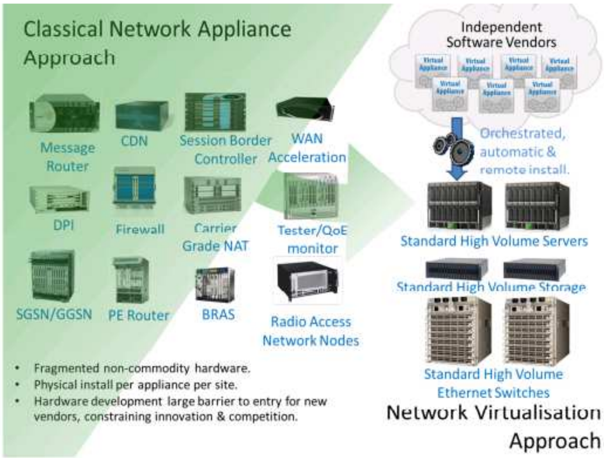


Figure 12: Network Functions Virtualization [11]

The NFV concept is based on building blocks of virtualized network functions (VNFs) that can be combined to create full-scale networking communication services. An end-to-end network service can be defined as a forwarding graph of network functions and end terminals:

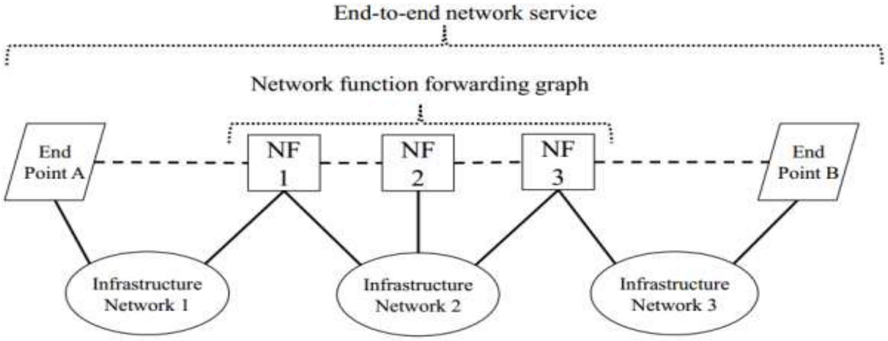


Figure 13: Network Service [12]

A virtualized network function, or VNF, may consist of one or more virtual machines running different software and processes, on top of industry standard high volume servers, switches and storage, or even cloud computing infrastructure, instead of having custom hardware appliances for each network function. By that way, it allows the use of a single physical platform for different applications, users and tenants and service providers will realize significant gains in automation and reductions in costs by driving towards this new model.

Examples of the types of networking functions that can be managed by NFV include network security and firewalls, network address translation (NAT), domain name services (DNS), caching, intrusion detection and more.

NFV presumes and emphasizes the widest possible flexibility as to the physical location of the virtualized functions. Ideally, therefore, virtualized functions should be located where they will be the most effective and least expensive. That means a service provider should be free to locate NFV in all possible locations, from the data center to the network node to the customer premises. This approach is known as Distributed NFV. For some cases there are clear advantages for a service provider to locate this virtualized functionality at the customer premises. These advantages range from economics to performance to the feasibility of the functions being virtualized.

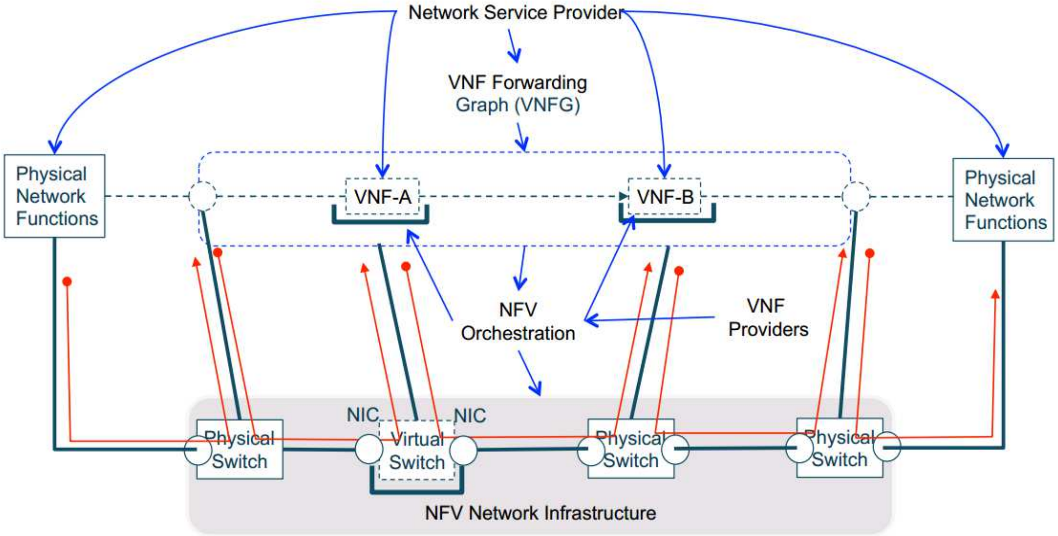


Figure 14: Virtualized Network Functions [13]

Relationship with Software Defined Networks (SDN)

As shown from above, Network Functions Virtualization is similar in nature to software-defined networking (SDN) in that both concepts involve migrating network management from the hardware layer to the software layer. But Network Functions Virtualization focuses more on porting network functions to virtual environments, whereas SDN focuses more on the separation of the network control layer from its forwarding layer, according to ETSI. Network Functions Virtualization is highly complementary to Software Defined Networking (SDN), but not dependent on it (or vice-versa). Network Functions Virtualization implemented without a SDN being required, although the two concepts and solutions can be combined.

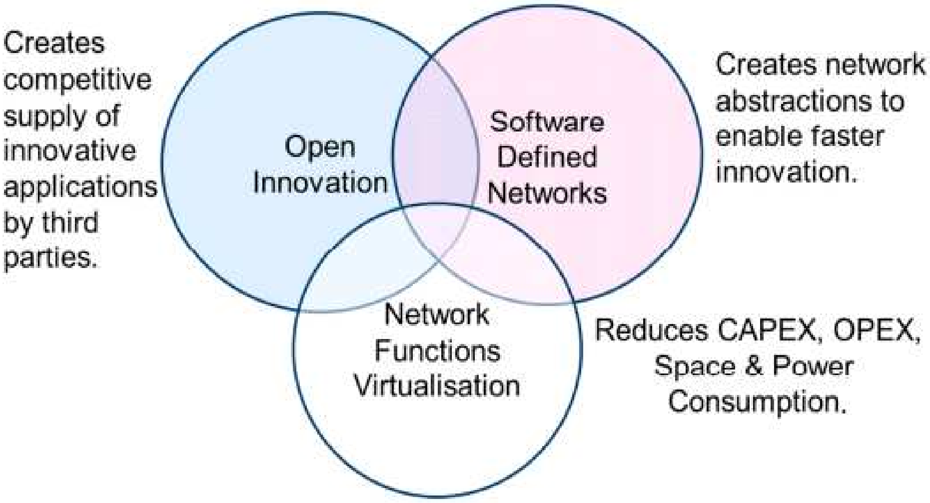


Figure 15: SDN and NFV [11]

Benefits of Network Functions Virtualization

The application of Network Functions Virtualization brings many benefits to network operators, contributing to a dramatic change in the telecommunications industry landscape. Benefits we foresee include (not in any particular order):

- Reduced equipment costs and reduced power consumption through consolidating equipment and exploiting the economies of scale of the IT industry
- Increased velocity of Time to Market by minimizing the typical network operator cycle of innovation. Economies of scale required to cover investments in hardware-based functionalities are no longer applicable for software-based development, making feasible other modes of feature evolution. Network Functions Virtualization should enable network operators to significantly reduce the maturation cycle.
- The possibility of running production, test and reference facilities on the same infrastructure provides much more efficient test and integration, reducing development costs and time to market.
- Targeted service introduction based on geography or customer sets is possible. Services can be rapidly scaled up/down as required. In addition, service velocity is improved by provisioning remotely in software without any site visits required to install new hardware.
- Enabling a wide variety of eco-systems and encouraging openness. It opens the virtual appliance market to pure software entrants, small players and academia, encouraging more innovation to bring new services and new revenue streams quickly at much lower risk.
- Optimizing network configuration and/or topology in near real time based on the actual traffic/mobility patterns and service demand. For example, optimization of the location & assignment of resources to network functions automatically and in near real time could provide protection against failures without engineering full 1+1resiliency.
- Supporting multi-tenancy thereby allowing network operators to provide tailored services and connectivity for multiple users, applications or internal systems or other network operators, all co-existing on the same hardware with appropriate secure separation of administrative domains.
- Reduced energy consumption by exploiting power management features in standard servers and storage, as well as workload consolidation and location optimization. For example, relying on virtualization techniques it would be possible to concentrate the workload on a smaller number of servers during off-peak hours (e.g. overnight) so that all the other servers can be switched off or put into an energy saving mode [14]
- Improved operational efficiency by taking advantage of the higher uniformity of the physical network platform and its homogeneity to other support platforms.

3. BENEFITS OF MOBILE NETWORK VIRTUALIZATION: NETWORK SHARING

As mentioned in the previous chapters of this dissertation, network virtualization promises to dramatically reduce the complexity of the network management as well as the management costs by enabling the sharing of the network resources. In this chapter we define the concept of sharing in mobile network architectures and we will show how it can be applied in an easier and efficient way by means of network virtualization solutions.

3.1 The idea of sharing

The growing demand for new services and generally data traffic renders mandatory new investments to be made so as to meet customers' needs. It is estimated that global LTE infrastructure investment, for example, will reach $14 billion by 2015 [14].

In addition, for marketing purposes the retail prices are continuously diminishing, so the operators are increasingly turned their attention to define new solutions to face the demanded service in a cost effective manner. To this end, network sharing is envisioned as a valuable approach to open new opportunities as that one of partnership. The figure below shows the scope of cooperation and the possible benefits of network sharing.

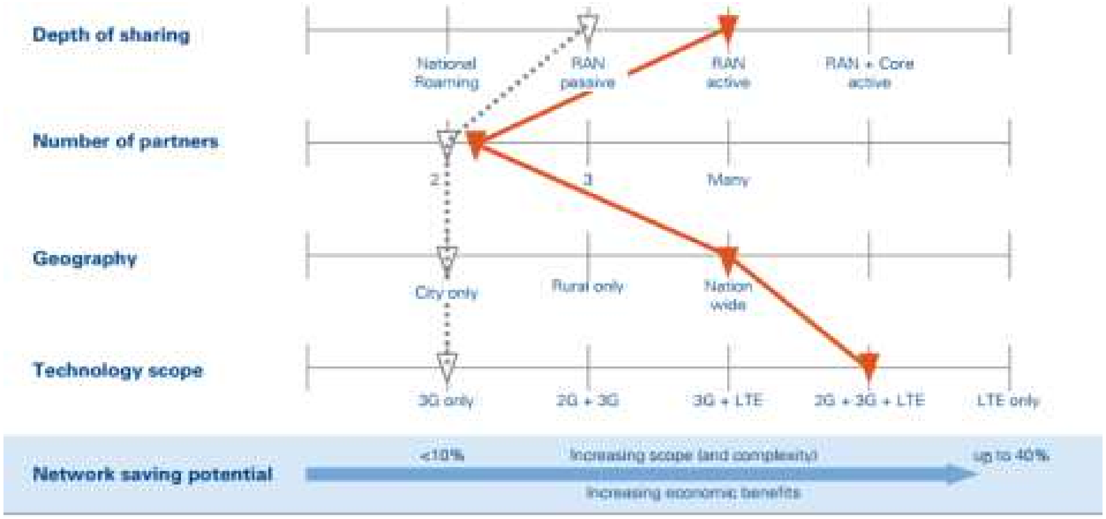


Figure 16: Network sharing benefits [14]

The depth of sharing from passive to active RAN through to core systems yields significant (capital expenditures) CAPEX savings. The geographic extent of the partnership determines the volume of sites that can be pooled and increases opportunities for site rationalization. Further gains can be made if spectrum is pooled where it yields increased utilization of jointly available frequencies. In some cases, the sharing of the mobile network infrastructures is controlled by a third party regulator. Regulatory interest in infrastructure sharing is to regulate the competition and environmental aspects [15]. Before granting approval to infrastructure sharing, national regulatory authorities (NRAs) typically weigh up the positive efficiency and consumer gains against the possible competitive harm.

To this end, regulators may intervene to create frameworks which force the mobile network operators (MNOs), (usually the infrastructure owner- OTE in Greece) [16], to open their networks to mobile virtual network operators (MVNOs). Termination charges, wholesale rates were capped by the regulator.

Regulators must:

- Distinguish cases where dominant firms harm competition, because that fact consists of a barrier between that one and a healthy competitive market.
- Determine the relevant timeframe. Regulatory measures aiming to foster competition in the short term may harm it in the longer term. For example, imposing shared access in short term may decrease the possibility in long-term incentives for network rollout.
- Consider both retail and wholesale mobile markets.

Passive and Active sharing

Basically, network sharing can be achieved by means of passive and active sharing solutions:

- Passive sharing refers to the reuse of components such as sites, masts, cables, ducts, splitters, shelters, generators, air-condition equipment, diesel electric generator, battery, electrical supply, technical premises.
- Active sharing refers to the reuse of backhaul, base stations and antenna systems. The reuse of the latter two is labeled as active radio access network (RAN) sharing which might involves sharing antennas/base stations across multiple mobile (virtual) network operators with either separate spectrum resources for each entity or shared spectrum resources through spectrum pooling.

Generally active sharing can be divided in the following three categories:

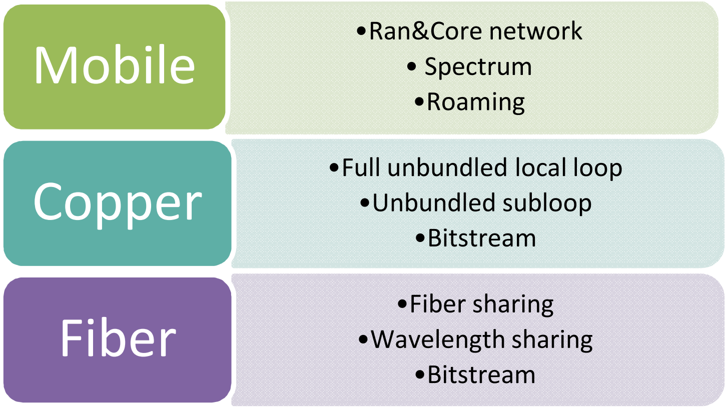


Figure 17: Categories of active sharing

In short, there are three ways of sharing: sharing of mobile resources, sharing of cooper infrastructure and sharing of the fiber used in the cabled networks. Operators can make use of the most profitable for them, and combine different sharing methods together.

RAN sharing

In this section we focus mainly in the use of the active sharing in the RAN, as a way to enable the sharing of network nodes, such as base stations and gateways.

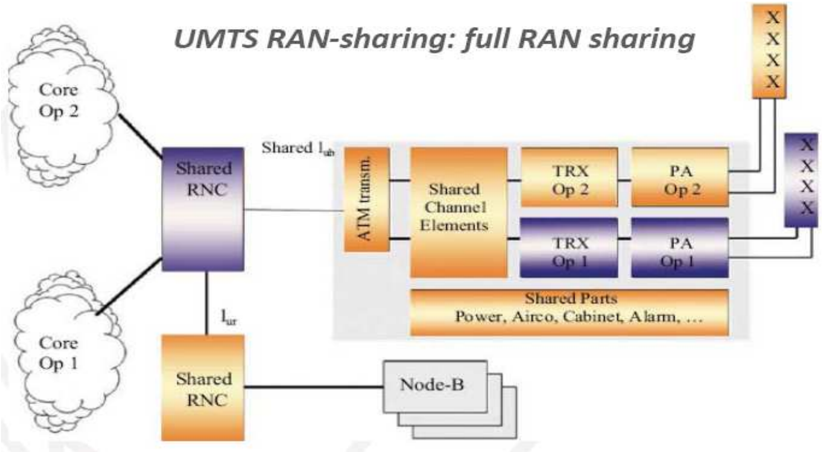


Figure 18: RAN Sharing [17]

Active RAN sharing can enable different scenarios [18]. For example, one MNO may become MVNO on another MNO's network during traffic surges so that to reduce cost for the first MNO, while generating revenue for the second one. In another exemplary use case a service provider (e.g. YouTube) may be enabled to lease resources from an MNO in order to improve service quality to its customers or to share the infrastructure costs with other MVNOs. This model generates new revenue streams for the MNO.

Active RAN sharing can be done in several ways:

- In the MORAN (Multi Operator RAN) approach, the operators share RAN gateways and some parts of the base stations such as processing elements, whereas the radio and power amplifiers remain physically independent to enable the entities to use their different assigned frequencies.
- In the MOCN (Multi Operator Core Network) approach, operators share both the RAN gateways and the base stations, and may also pool their frequencies.

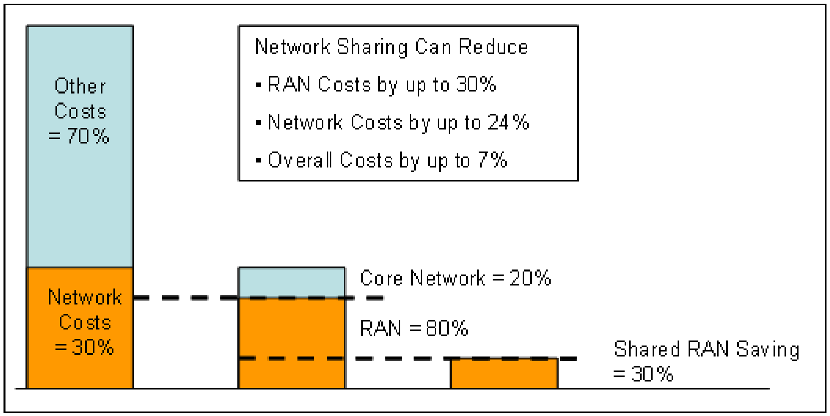
Some 3GPP guidelines have defined some possible RAN sharing use cases:

- Scenario 1 corresponds to multiple core networks (CNs) sharing a common RAN. For operators that have multiple frequency allocations, it is possible to share the RAN elements, but not to share the radio frequencies. In this case the operators connect directly to their own dedicated carrier layer by means of a shared radio network controller (RNC).
- Scenario 2 corresponds to two or more operators with individual frequency licenses with which their respective RANs cover different parts of a country, but together provide coverage of the entire country.
- Scenario 3 corresponds to one operator deploying coverage in a specific geographical area, and other operators being allowed to use this coverage for their subscribers. Outside this geographical area, coverage is provided by each of the operators independently.
- Scenario 4 corresponds to common spectrum network sharing when one operator has a frequency license and shares the allocated spectrum with other operators or if a number of operators decide to pool their allocated spectra and share the total spectrum.

- Scenario 5 corresponds to multiple RANs sharing a common CN. The multiple RANs can belong to different public land mobile networks (PLMNs) and network operators. Due to operators' deployment choices, different nodes or part of the common CN can be shared.

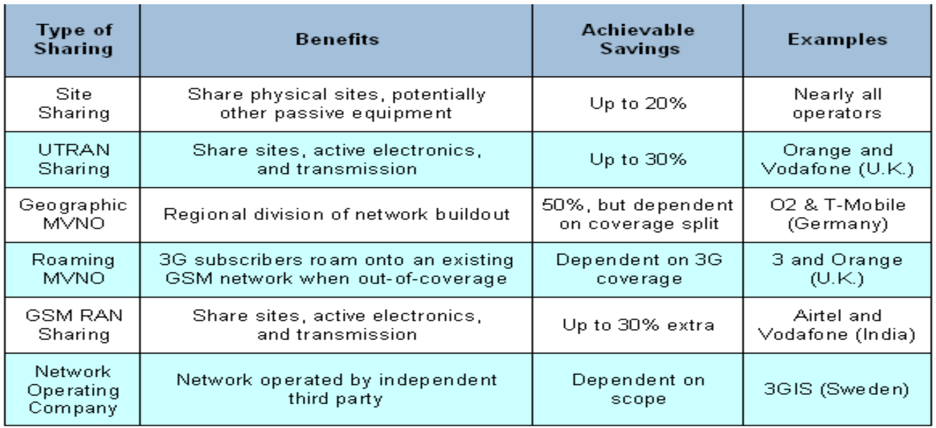
Based on these scenarios, 3GPP has also defined a network sharing architecture with the objective of allowing different CN operators to connect to a shared RAN. In all configurations, the network sharing agreement between operators should be transparent to the users. To this end some technical specifications have been released. These specifications define the way to allow different users to receive service from shared base stations. According to the 3GPP guidelines, the shared base stations broadcast multiple PLMN-ids according to the number of mobile (virtual) network operators. Mobile stations that support network sharing functionality are able to discriminate among operators in a spectrum network sharing configuration based on the PLMN ids. Non-supporting UE devices ignore the broadcast system information, and the shared network selects a CN operator from the available ones. PLMN-ids are used for routing and handover purposes within the network.

RAN sharing is used in today's networks, because the operators can ripe benefits of implementing a sharing framework. The basic one is that CAPEX can be further reduced either by extending the cooperation beyond two operators or by including equipment vendors or financial investors. Figures below show some results of RAN sharing usage in networks.



Source: Unstrung Insider

Figure 19: Potential Savings from RAN Sharing



Type of Sharing	Benefits	Achievable Savings	Examples
Site Sharing	Share physical sites, potentially other passive equipment	Up to 20%	Nearly all operators
UTRAN Sharing	Share sites, active electronics, and transmission	Up to 30%	Orange and Vodafone (U.K.)
Geographic MVNO	Regional division of network buildout	50%, but dependent on coverage split	O2 & T-Mobile (Germany)
Roaming MVNO	3G subscribers roam onto an existing GSM network when out-of-coverage	Dependent on 3G coverage	3 and Orange (U.K.)
GSM RAN Sharing	Share sites, active electronics, and transmission	Up to 30% extra	Airtel and Vodafone (India)
Network Operating Company	Network operated by independent third party	Dependent on scope	3GIS (Sweden)

Source: Unstrung Insider

Figure 20: Types of RAN sharing, savings and examples of implementation

Some additional benefits of sharing can be summarized as follows:

- There are also opportunities for economies of scale, such as increasing the potential for exclusive deals for devices and content.
- A study by ABI (Allied Business Intelligence) research indicates that operators could save up to $60 Billion through active RAN sharing in a period of 5 years.
- Optimization of scarce resources and positive environmental impacts.
- Decrease in duplication of investment, reducing capital and operational expenditure.
- Positive incentives to roll out into underserved areas.
- Improved quality of service, particularly in congested areas.
- Product and technological innovation as operators compete on service differentiation.
- Increased consumer choice as entry and expansion become easier.
- Reductions in wholesale and retail prices for mobile services.
- Allowing networks of different generations be combined on the same site make their upgrade relatively inexpensive.

Early movers can shape deals with partners of their choice and manage to achieve significant cost reduction in their markets [19]. More network sharing deals have been made in emerging markets, but that’s because the larger situations requiring entirely new networks in these markets make ripe for collaboration among new entrants.

It is mentioned that through sharing there is a reduction of about 30-40% of the cost. In Europe savings may mount in 20-40 billion Euros and in USA about 25-50 billion dollars annually. Operators will reach the break-even point after two or three years. With the term “break-even point” we mean the point at the time where revenue exceeds the total costs.

Best-practice guidelines:

Reasonable terms and conditions in the deals are of primary importance. Infrastructure-sharing terms should not impose price or non-price discrimination, meaning that the same attitude should be kept to all customers. On the other hand, pricing for shared facilities or network elements should provide the right economic signals to help market players make the right “build-or-buy” decisions. In addition to these, infrastructure sharing need not be limited to telecommunication or ICT sector players, but can also embrace other industries with viable assets, including utilities (gas, electricity, water etc). Finally, as a scarce resource, radio spectrum can be shared, as long as harmful interference is controlled.

3.2 Virtualization-based networks

One of the main limitations of the existing wireless networks technologies is that they cannot be easily interconnected to each other. It wastes plenty of wireless infrastructures and spectrum resources. Although there may be considerable wireless networks around us, the users cannot access the most appropriate one or select multiple networks to support them simultaneously. Currently, users can access only a specific network all the time, even if this network performs quite poorly. However each service usually requires different network characteristics. Ignoring these differences and just supporting them with the same network characteristics leads to low QoS and QoE [20]. Network sharing together with the employment of NV tools may help operators to improve the QoS and QoE by allowing users to have access to the most appropriate radio access technology.

While sharing has to do especially with cooperation at the physical layer, allowing operators to share the cost of infrastructure, virtualization takes networks one step further: it deals not only with sharing network equipment, but also with the bandwidth and the slices. The definition of a “slice” is defined in bibliography as a group of user flows that belong to a single entity such as an MVNO, and require a chosen fraction of spectrum resources to be allocated for satisfying the SLAs. The adoption of virtualization can have several advantages as follows:

For infrastructure providers

Nowadays, large companies have to play both roles: system operator as well as infrastructure provider. With virtualization, the two roles can be separated explicitly. In that way infrastructure providers can concentrate only on the maintenance of the physical equipment and save manpower for running the networks [21].

For virtual mobile operators

Currently, deploying and operating a mobile system such as GSM or UMTS require enormous investments. Infrastructure sharing is very attractive, where the huge investment on the hardware and fundamental construction could be saved. It also enables the small companies to enter the market without huge investments. In addition, by using virtualization, the deployment, maintenance, migration and upgrade of the mobile systems will be flexible and even on-the-fly.

For end users

The increased number of operators will bring a diversity of services to the end users. This means more options to satisfy the user’s personal demand and subsequently enjoy the services with reasonable pricing.

Several sources for virtualization scenarios exist in bibliography. In the follow we discuss some of them so as to make a clean picture of what architecture are used in some use cases, and how this kind of network works. In paper [22] three ways of virtualization are presented: local, remote and hybrid.

- In a local virtualization approach, a single physical base station (BS) is sliced in multiple virtual BSs (VBSs). The hypervisor, a supervising entity, is in charge of allocation of physical resources between different virtual instances.
- In the remote virtualization approach, a data center approach is adopted. In particular the radio equipment of the BS is segregated from the baseband processing unit.
- Hybrid virtualization is a combination of the local and remote virtualization approaches. In this approach, the baseband processing is distributed among a data center and a local enhanced remote radio head which have augmented capacity for processing delay sensitive data (e.g. voice, live video traffic). This can alleviate the QoS problem for the delay sensitive traffic that can be experienced in the remote virtualization approach.

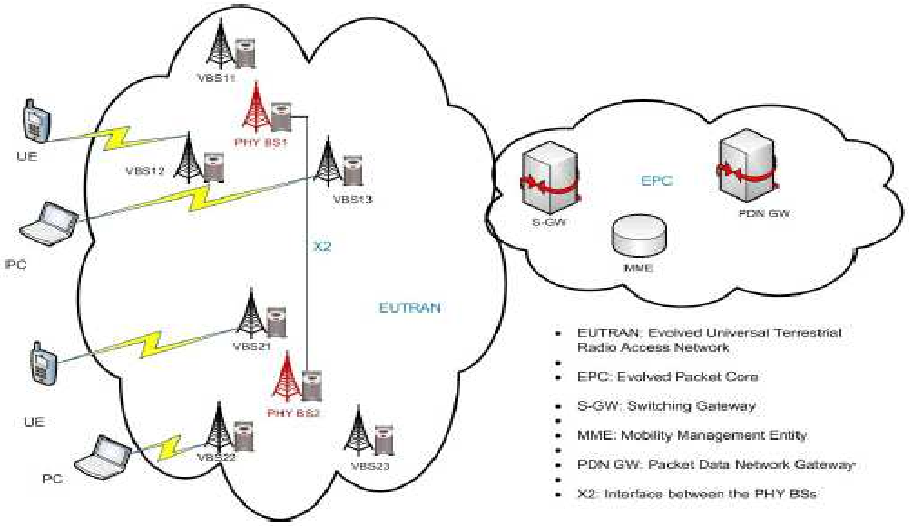


Figure 21: Local virtualization framework [22]

In [22], authors provide an evaluation of the CAPEX for each of the aforementioned approaches. More specifically they refer to the cell-site construction cost as well as the cost of the radio BSs needed to cover a certain geographical area. They also evaluated the OPEX as a function of the power consumption of the network. (It is worth noticing that, although in the CAPEX analysis the parameter of concern was relative infrastructure cost per user, in the case of OPEX, the parameter of interest was power per bit).

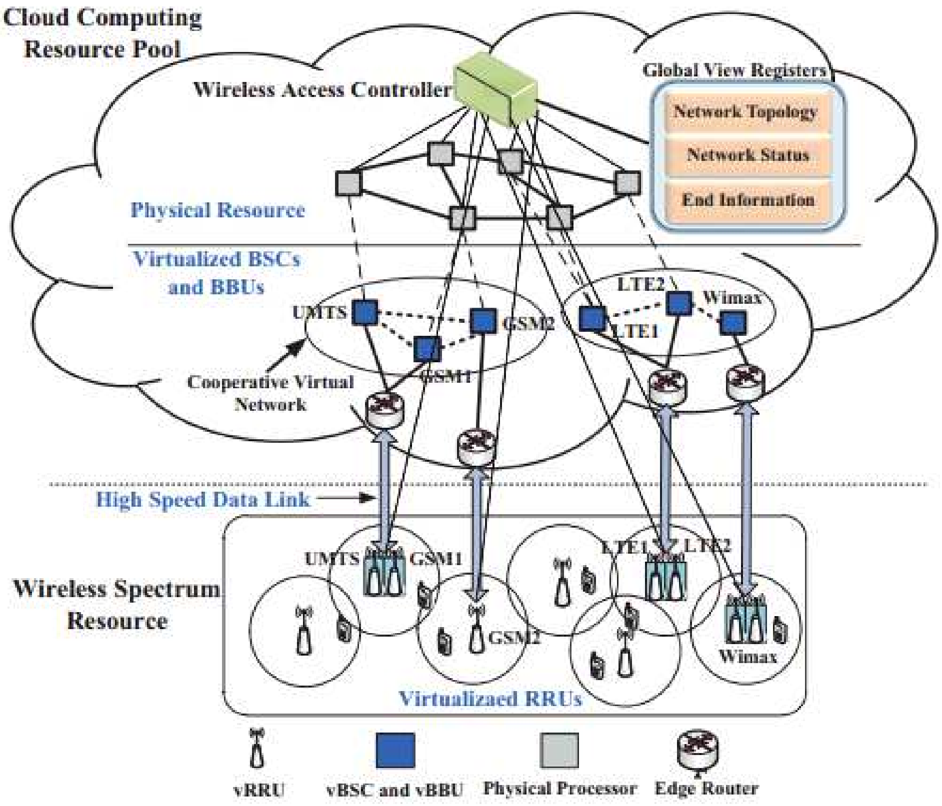


Figure 22: Architecture Overview of OpenRAN [20]

In paper [20], authors present a novel architecture, called OpenRAN. In this architecture a software-defined approach is used to achieve a complete virtualization and programmability of the RAN.

As from the figure above, OpenRAN architecture consists of three main parts: wireless spectrum resource pool (WSRP), cloud computing resource pool (CCRP) and SDN controller.

The WSRP consist of multiple physical remote radio units (pRRUs) that are distributed in various locations. WSRP virtualizes network by RF virtualization technology, which enables several virtual RRUs (remote radio unit) (VRRUs) with different wireless protocols to coexist in one shared pRRU.

The CCRP is comprised of a large amount of physical processors, which construct a high speed cloud computing network. BBUs (base band units) and BSC are replaced by vBBUs and vBSCs.

That architecture contains four levels of virtualization: application level, cloud level, spectrum level, and cooperation levels.

- In application level virtualization, flow space is divided and each virtual space operates and manages its own control strategies. In this case, virtual spaces correspond to several network operators or services.
- In cloud level virtualization, an SDN controller creates vBBUs and vBSCs by virtualizing physical processors and allocating appropriate computing and storage resources.
- Spectrum level virtualization refers to the virtualization of spectrum by RF virtualization technology, which enables several vRRUs with different wireless protocols to coexist in one shared pRRU.
- Cooperation level virtualization constructs several virtual networks, including virtual nodes and virtual links. Such approach is based on cooperative communication among multiple vRRUs and between different vBBUs and vBSCs. This level of virtualization aims to achieve the inter-cell interference elimination.

As a possible use case where to apply the OpenRAN approach is described in the sequel. We suppose that one carrier wants to establish a UMTS network and two GSM networks in two adjacent areas. To this end, the following operations are needed to be performed. First, the SDN Controller estimates the resources that each network needs in view of the requirements and actual network characteristics. Second, it creates vRRUs, vBBUs and vBSCs by allocating appropriate spectrum, computing and storage resources to them via spectrum level and cloud level virtualization. Third, it sends flows to configure the data processing rules in vBSCs and deploy corresponding wireless protocols in vBBUs by programmable scheme. Forth, since three vRRUs are distributed in neighboring cells, in order to eliminate the interferences among them, the SDN Controller deploys one cooperation virtual network. Fifth, by application level virtualization, the SDN Controller provides an operating virtual network that satisfies the requirements of the carrier.

In paper [21] two different key assets of network virtualization are exploited: spectrum multiplexing and multiuser diversity gain.

It is assumed that different mobile operators experience their peak load at different times, so multiplexing gain can be achieved through spectrum sharing. This can lead to better resource utilization. This is investigated by comparing two different setups, legacy and virtualized setup. In the legacy setup, which is most used today, each operator owns a frequency band which is cannot be shared with other operators. In the Virtualized setup, multiple operators can share the same infrastructure through virtualization and the total combined respective spectrum is shared between the different operators. By using such approach the multiplexing gain is achieved.

On the other hand, a multiuser diversity gain can be achieved. User channels are normally frequency selective, which means that each user experiences different channel conditions on different PRBs. With such approach it is possible to have access to a wider number of PRBs so that to allocate the best one to each user and improve the average channel conditions.

In the paper [23] is displayed a way for partial resource reservation. In that way of reservation, each operator is guaranteed a specific minimum share of radio resources while the remaining "common" part is shared among all operators..Based on above works, we can assume that RAN virtualization goes one step further in contrast to RAN sharing. It gives the opportunity of further exploitation of resources and that enhances network capabilities. Spectrum resources are often underutilized on an average and hence regulatory bodies consider spectrum sharing for better statistical multiplexing. There still exist, however, fears from operators' point of view that make them consider that they might lose from such a deal (sharing or virtualization). Some incumbents believe that via sharing, they may lose their competitive advantage and they will not be able to control the direction their network would take in the future, their rollout strategies and their choices about hardware and vendors [19].Operators demand a certain degree of autonomy, which will give them the ability to keep independent control of strategically important sites. These doubts exist in every technological innovation, the early movers reap first the benefits of their quick positive response and after a time period the market is mature enough to welcome that innovation.

4. COSTS FACED BY MOBILE NETWORK OPERATORS

An operator needs to cover a large amount of expenses so as to be able to survive in the market competition. As already mentioned in the previous chapters, these expenses can be categorized in the two main categories: CAPEX and OPEX.

CAPEX costs are relative to infrastructure costs and are depreciated over time. For a network operator, they include the purchase of land and buildings (e.g. to house the personnel), network infrastructure (e.g. optical fiber and IP routers, radio and transmission equipment, installation of equipment), and software (e.g. network management system).

OPEX costs are more relative to running and operational costs. They represent the cost of keeping the company operational and include cost of technical and commercial operations, administration, etc. For a network operator, OPEX are mainly constituted of the expenses for rented and leased infrastructure, marketing and personnel wages.

In the rest of that chapter we will define the basic economic values that are used in telecommunications to obtain the right estimation of an investment plan. These values will be used in the rest of this dissertation to evaluate the potential benefits of an investment plan on a network virtualization sharing business model. Note that in order to make a profitable investment, an operator should also take into account social and political issues in the country that is interested on, so that to be able to make forecast and predict future marketing circumstances. In that way, no surprises will arise and the deviation from its initial prospects will be small. Therefore, proper movements will define who will be the operator with the highest percentage of market share.

4.1 Economic values

An important economic value that needs to be considered for calculating the possible benefits of an investment plan is the Discounted Cash Flow (DCF).

More specifically, a DCF model is a basic economic value that calculates revenues, investments, installed first cost, as well as cash flows and other financial results for the tagged network scenarios and architectures for each year of the study period.

The basic economic values, used on bibliography, can be summarized as follows:

- The ***NPV (net present value)*** is the present value of an investment's future net cash flows minus the initial investments for a given period.

$$NPV = -I + \sum_{t=1}^{n} CF_t / (1+r)^t$$

Where:

I=is the initial amount needed for investments

CFt=Cash Flow at the end of the year

r=the discount rate (the rate of return that could be earned on an investment in the financial markets with similar risk.); the opportunity cost of capital.

In particular, a DCF analysis is needed to compute the NPV. Note that the NPV takes as input cash flows and a discount rate and gives as output a price; the opposite process—taking cash flows and a price and inferring a discount rate—is called the yield.

- The ***IRR (Internal rate of return)*** is the discount rate resulting from an investment and income, which brings the present value of the future net cash flows to zero. To find this solution, several iterations of the proposed plan will have to be carried out. Bearing that in mind we can calculate.

$$\sum_{t=1}^{n} CF_t \,/\, (1+r)^t = \mathrm{I}$$

The IRR gives a good indication of the value achieved with respect to the money invested.

- ***The PI (Profitability Index)*** is calculated from equation:

$$PI = \frac{\sum_{t=1}^{n} CF_t \,/\, (1+r)^t}{I}$$

And using NPV value we can have:

$$PI = \frac{NPV}{I} + 1$$

Note that, in order to have a profitable n investment, the NPV to be positive, IRR more than r and PI more than 1.

- The ***Cash Balance (accumulated discounted cash flow)*** is relative to the difference between the cost and the profit. Its curve generally goes negative in the early part of the investment project because of initial capital expenditures. Once revenues are generated, the cash flow turns positive, and the cash balance curve starts to rise. The lowest point in the cash balance curve gives the maximum amount of funding required for the project. The point in time when the cash balance turns positive represents the payback period for the project.

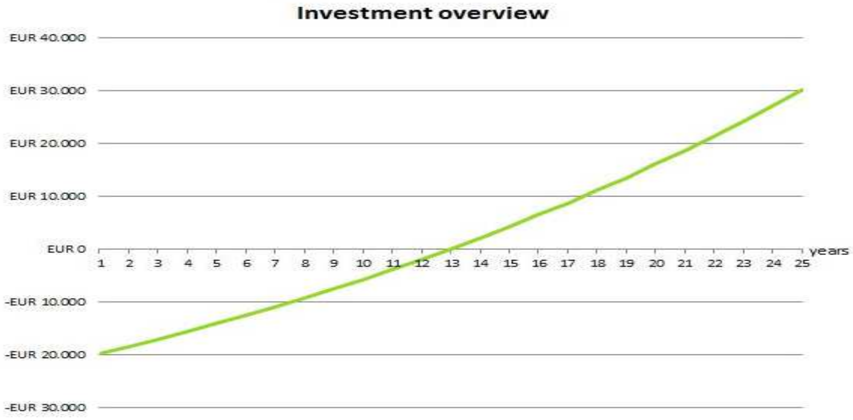


Figure 23: Cash balance [24]

All the economic values described so far, will be used in our model and will contribute to the final result concerning the evaluation of an investment plan for a network sharing scenario.

4.2 Cost Models

In this section we present two of the cost models that are used in the literature toward the estimation of an investment plan: the Top-Down and Bottom-Up cost models.

Top-Down: That model is based on empirical information, statistical on data that already exist in company's cost books. First of all the cost for the basic services is calculated. After that, the cost for more complicated services will be calculated without considering the demand for these services in the whole procedure.

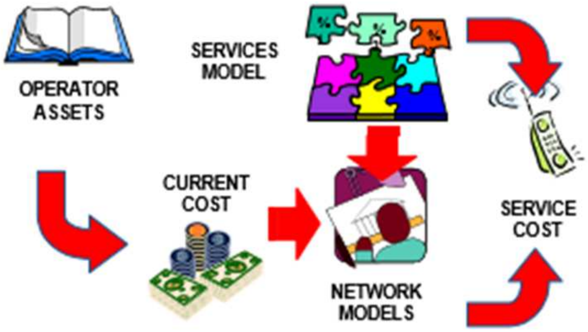


Figure 24: Top-down techno-economic model [24]

Bottom-Up: This type of cost model starts from "a blank page". The primary element that drives that model is the demand. According to that, a network that will meet the needs of the customers will be created.

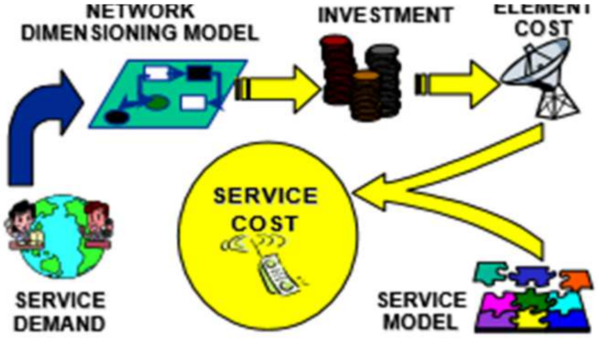


Figure 25: Bottom-up techno-economic model [24]

Generally speaking, a combination of these two cost models should be used. Top-down contains real information about costs and incumbent operators mostly use that model. On the other hand, bottom-up is usually used from national regulatory bodies that want to check the reliability of declared incumbents' costs. However, it can be used also from companies that enter in the telecommunication market and they don't possess any means to be informed about real costs so as to design their strategic plans. Many times although, deviations exist due to false estimation or e.g. demand, that usually concludes to overestimation and wrong movements and implementations of network structure.

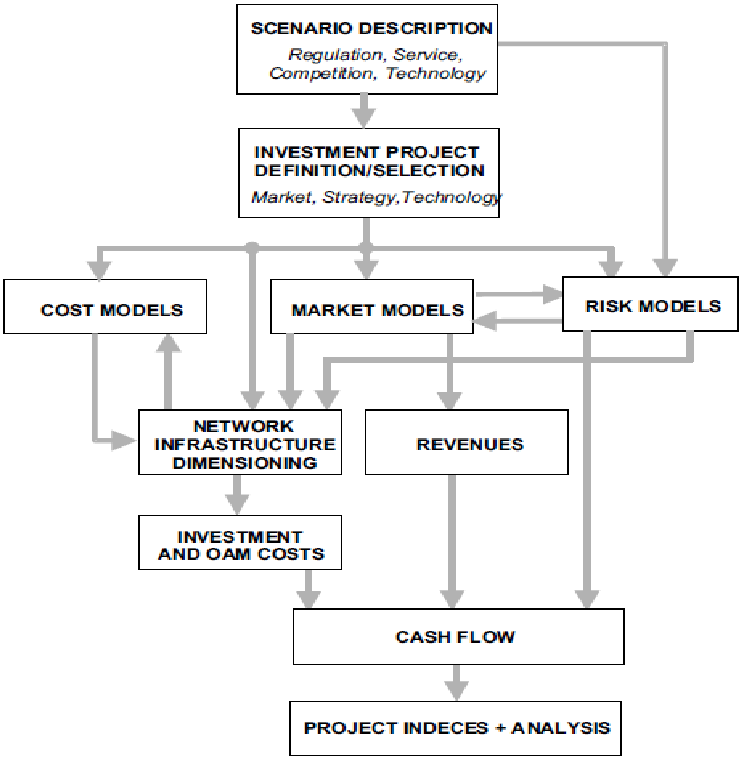


Figure 26: An example of a techno-economic model [24]

The diagram in fig. 24 represents a techno-economic model and the key steps that should be estimated so as to have an overall idea of all the aspects of the investment that figure indicates, the proper way to create a techno-economic model is to have information of regulation, competitors, and technological breakthroughs so as to form a strategy that will match with customers' demands.

4.3 Business Models

Generally, in bibliography two types of business models are described. The first category consists of the description of business model as a game theory and the other one is more techno-economic and consist of network dimensioning while making use of economic values to reach a conclusion. The second way is more focused on CAPEX and OPEX analysis. In the rest of that chapter we are going to mention different techno-economic approaches and generally present what affects costs in today's networks. In one approach [25] three possible scenarios corresponding to SDN and sharing are described. In the first, the classic one, the network control is bound with network devices. In the second, SDN architecture take place and according to the theory mentioned in previous chapters, we have independence between devices and control. OpenFlow contribute on that direction being the communication interface of that scenario. In the third scenario, an extension of SDN is described. Except for SDN implementation, network virtualization between operators is used. From the results we can demonstrate differences in CAPEX and OPEX through these three scenarios, concentrating on the SDN scenario:

- CAPEX: The devices are much simpler and cheaper. Thus we have cost reduction from CAPEX expenditures. However the cost for OpenFlow controllers, line cards and transceivers should be calculated. The main sharing gains in a mobile network can be achieved in the access networks through radio base station sharing. In core network we have less sharing mechanisms because at that point the aggregations have already happened.

- OPEX: We have less cooling energy and power as there is no more energy consumption by the control plane in the network switches. Furthermore, SDN allows for better traffic-steering reducing the number of network devices and their power consumption. In sharing scenario energy consumption will be even lower as a result of higher utilization of network equipment. We should also take into consideration the energy consumed by additional OpenFlow controllers. Maintenance cost in SDN scenario will be lower, because in classic scenario we had to deal with a bunch of independent autonomous devices. Cost of repair can be reduced also in SDN scenario because of better testing possibilities ahead of rollout which will reduce the number of bugs that can reach actual production traffic. The central point of failure though, could be the OpenFlow controllers because a drawback there could destabilize the entire network. Cost of service provisioning will be lowered in SDN networks due to automated configuration of the network and in addition to this, human errors will be diminished. Today's networks demand very experienced and specialized personnel in order to set up, administrate, change and maintain the network. Finally, cost of first time installation of network equipment will be reduced in SDN scenario.

In paper [26], authors demonstrate that infrastructure costs increase almost linearly with the capacity required. As the site density increases, operational and transmission costs tend to dominate rather than radio equipment and site costs.

From the following figure, we can see that running costs dominate the total cost structure of a mobile operator and they correspond to roughly 75% of the total costs for a large country.

	Large country	Small country
Site rental	5%	5%
Transmission	5%	25%
Terminal subsidies	15%	15%
Marketing	25%	15%
Employees	50%	40%

Table 1: Running costs [26]

Radio access network consist the largest percentage of investment infrastructure:

	Large country	Small country
Core network	30%	10%
Site buildout	30%	50%
Radio access network	40%	40%

Table 2: Operator Investment Structure [26]

The results from that paper show how, for different capacity requirements, the costs can be minimized by a proper selection of for example macro, micro and pico base stations. Small micro or pico base station implies a low cost for equipment, site leases and installation whereas a large macro base station costs much more. On the other hand, fixed costs not directly related to the capacity of the base station are divided between many users in a macro base station so the cost per user may still be lower. This fact indicates that coverage is an important parameter when designing wireless.

The macro base station is naturally much more expensive than the smaller base stations, because of its higher output power and capacity, but also due to that it has to be more reliable since more users are served per base station. This clearly affects the costs for sites, installation and O&M (Operations & Maintenance).

	Macro BS	Micro BS	Pico BS
Performance			
Sectors	3	1	1
Carriers(2*5Mhz)	1	1	1
Maximum cell range	1km	0.25km	0.1km
Minimum cell range	0.25km	0.1km	0.025km
Capacity(Wmax)	2.25Mbps	1.25Mbps	1.75Mbps
Initial costs:			
Equipment	50k	20k	5k
Site buildout	70k		
Site installation	30k	15k	3k
Annual costs			
Annual Q&M	3k	1k	1k
Site lease	10k	3k	1k
Transmission	5k	5k	5k

Table 3: Base station performance and costs [26]

From that figure we can assume that, as the base station range decreases the cost is driven by transmission, rather than by radio and site costs.

In the same paper also, two possible tracks are analyzed in the direction of reducing the costs. The first one is to re-use existing sites, or even reduce the number of sites by extending the capacity of existing solutions. This can in principle be done by the following ways:

- Allocating more spectrum for third generation networks,
- Increase spectral efficiency, e.g. by utilizing adaptive antennas which have been developed to help mitigate the effects of multi-path interference. By using spatial selectivity may considerably enhance link performance, increase signal strength and quality. To adjust for frequency and channel use, the adaptive antenna uses multiple antennas and an algorithm in order to maximize the strength of the signals being sent and received while eliminating, or at least reducing, interference.

- Introduce multi-hop technology in the cellular networks, or using a combination of those.

Another way would be to actually allow for denser deployment by decreasing the cost per base station. There is a potential in lowering transmission and O&M costs for pico cell base stations. Instead of the expensive leased lines (El/Tl) or microwave radio links, cheaper transmission technologies could be introduced, e.g., wireless fixed broadband or xDSL. The costs for O&M and sites could be reduced by allowing for privately owned and deployed base stations, possibly connected to existing fixed broadband or local area networks. Similar to Wireless LAN access points, one could imagine small 3G base stations owned by individuals or enterprises.

In paper [27] the same concept is provided. A system which provides only partial coverage shows a more favorable cost structure. Results from that research show that for each offered user bandwidth and user demand, there exist a number of base stations that minimizes the cost of service provision per user which (mostly) yields systems with only partial coverage. Except from this, it is declared that in order to achieve a reasonable transmission costs for wireless multimedia services, "hot-spot" covering wideband schemes seems to be the only way to go.

Paper [28] highlights a combination with wide area coverage through UMTS and the delivery of broadband services hot spot areas via Wireless LANs. While UMTS provides mobile customers with wideband capabilities, WLANs are aimed at customers who require broadband communications capabilities, being away from their office or home. It is generally recognized that the two systems are complementary: WLANs being Ethernet-oriented for data only, and UMTS encompassing both voice and data. Users will be able to benefit from true personal mobility – logging in from a variety of terminals – and service mobility – obtaining access to a common set of services.

However, for such solutions to be economically feasible, some significant modifications are required also in the core network equipment (simply to handle a large increase in the number of base stations). It also requires slightly modified business models and value chain constellations for the mobile operators.

In paper [29] two wireless internet data service categories are selected: asymmetrical upstream and downstream. It is assumed that the percentage of high or low speed data service required by potential users is 20-80% percent. The first case mentioned is the baseline case. It has to do with the concept that the coverage for the entire region is provided in the first year. Densely populated areas have high ROI and short period to break even, while rural area has a negative NPV. That model shows that the wireless network cost is dominated by the large number of access points that are needed to cover the rural areas. The second case has to do with providing access points with high-gain antennas to extend the coverage range, while still limiting the maximum effective isotropic radiated power (EIRP) for each access point in the output power, when a signal is concentrated into a smaller area by the antenna.

In paper [30], two scenarios are studied. In the first one, it is assumed that an existing GSM operator implements GPRS as an evolutionary path towards UMTS. In the second case, a new operator (probably the incumbent) invests directly in UMTS in a competitive environment. There are mentioned different kinds of areas, for example rural, suburban.

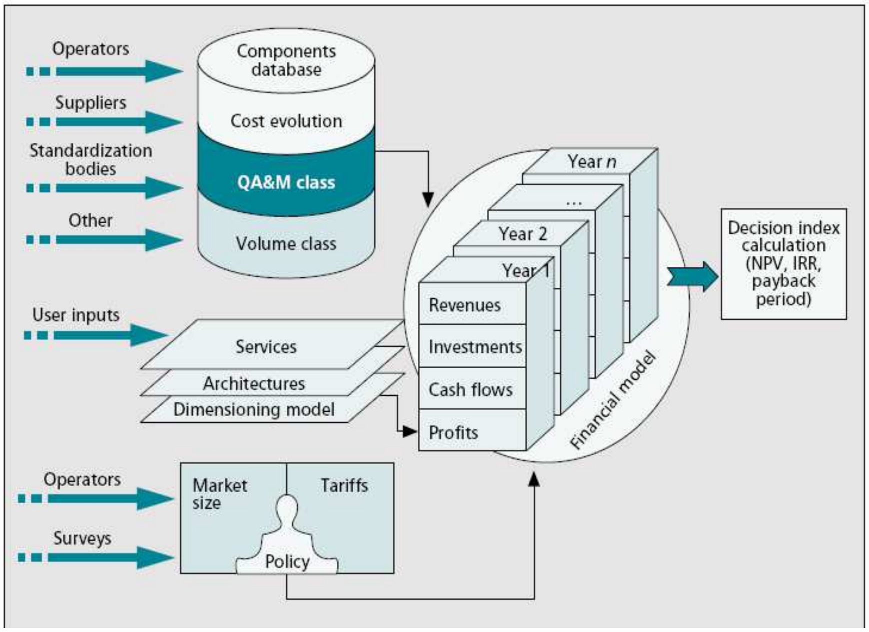


Figure 27: Techno-economic model used [30]

For GPRS upgrade we should calculate the addition of transmitter-receivers to handle the increased traffic load. The TRXs also require a software upgrade, which is actually performed at the base station controller level.

The radio dimensioning procedure takes into account first coverage, then capacity. This process is entirely independent of the existing GSM infrastructure. To ensure physical coverage, the cell radius is determined from link budgets (transmitter output power, transmit antenna gain, path loss, receive antenna gain, receiver noise power, link margin) calculated on the uplink, which is more restrictive since the transmitter power from the mobile is lower than that of the base station.

The results showed that many operators in the market lower the market share and the NPV. In addition to that, the concentration to coverage results in high costs of the base stations (BTSs). That cost in conjunction with low tariffs and competition, renders UMTS implementation not a very viable solution.

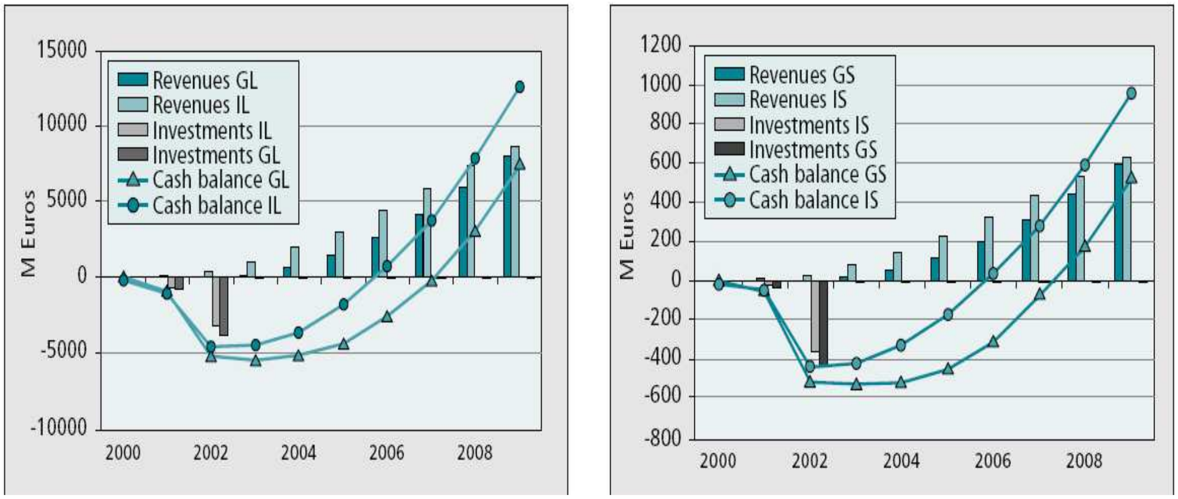


Figure 28: Outcome from and investment in a large country (left) and a small country (right) [30]

The diagrams depicted in fig.28 show the difference between the outcome from investing in a large country and investing in a small country.

The lowest point of the cash balance indicates the amount of investment funding required from the operator (payback period). The large country has much larger potential revenues (and a larger initial cost) than the same investment in a small country due to the greater potential market size.

Paper [31] analyses the impact of the various services on network dimensioning and revenue for the operator, service classes in terms of bandwidth and quality of service (QoS) have been defined. Each bandwidth class (narrowband, wideband, and broadband) is characterized by an average bit rate, which corresponds to the average air interface capacity required by a subscriber when using the given service. There are four QoS classes as defined by the Third Generation Partnership Project (3GPP): conversational, streaming, interactive, and background. In addition to this, services are divided into circuit-switched and packet-switched services. Results from that paper, suggest that 3G and WLAN will be complementary within a total mobile data services portfolio. While WLAN services will not be substitutes for 3G services, they can become a strong source of competitive differentiation and therefore mobile operators should offer WLAN services to their customers, either by themselves or through partnering. Whatever the selected technology of layer 2 (Ethernet or ATM), there is no impact on the cost level and profitability of the cases. The hybrid fixed and wireless access system, is a realistic alternative and possibly a complementary solution in urban areas. In some cases political actions are required if the ambition is to provide the broadband services in all rural and noncompetitive areas.

By analyzing the bibliography on the domain of techno-economic issues we can affirm that many papers have focused on the technical aspects of network virtualization in generally, but only a few discuss the telecom’s economical point of view. In order to fill this gap, in the next chapter we will present an exemplary techno-economic model to evaluate the case where network virtualization is used for allowing the sharing resources among multiple operators.

5. TECHNO-ECONOMIC MODEL

In this chapter we present a techno-economic analysis of a mobile network scenario where virtualization is employed. In particular we focus on the potential benefits from an economic perspective. That analysis is supported by a techno-economic model which is based on the basic economic values described in a previous chapter.

5.1 Reference Model

The model we are going to create is based on the one presented in [32]. In particular, that work presents a techno economic analysis of 3G Long-Term Evolution (LTE) evaluating the cost/benefits of employing this technology in a large Western European country for a period of time of 10 years. The 3G LTE architecture includes several enhancements to the 3G radio interface, i.e. OFDM modulation, MIMO, and smart antennas. These improvements should enable 3G LTE to achieve a significant increase in the throughput of the mobile network. Another key goal of 3G LTE is a much lower latency in the network. In fact the adoption of a simpler network structure (depicted in the figure 29), with less architectural layers compared to the classic 3G architecture, results in a reduced network latency, e.g. less than 20 ms.

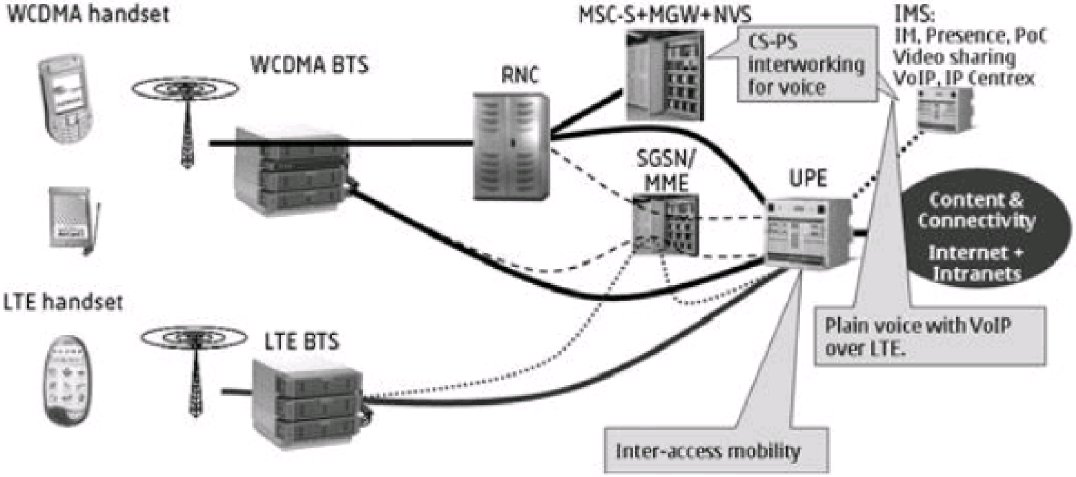


Figure 29: Architecture used in paper [32]

In figure 29 the classic 3G network architecture is compared with the 3G LTE architecture. As it can be seen the core network of the 3G LTE architecture presents a lower number of entities. This is in line with the aim of simplifying the complexity of the network management and the operational costs as well. For example, we can note that the Radio Network Controller (RNC), that in 3G is responsible for controlling the BTS that are connected to it, is no longer used in 4G since its functionalities are included in the LTE BTS.

In [32] the role of base stations (BTSs) in a network is highlighted. Optimizing the BTS cost structure is crucial to the network operator. One way to do this is to increase the coverage area of each BTS, i.e. by using as low a frequency as possible. It should be noted that the actual number of sites drives a number of base station related costs. Additionally, the reuse of existing cellular sites of the 3G infrastructure network could be highly significant in optimizing costs.

The reference model analyzed in [32] considers a total land area of 338000 km^2 and a population of 73 million residents. 25% of these people live in, or close to, densely built urban areas, 58% in suburban areas and 17% in rural areas. The data capacity is initially set to 10 Megabytes and doubles every 24 months. It is assumed that the user acquisition cost is 150 Euros per each new user. We use the term “user acquisition cost” to indicate the cost associated in convincing a customer to buy a product/service of the network operator. The initial market is set to 10 million users and it is assumed a 4% annual increase. Moreover, it is assumed that the urban and suburban coverage is 100% while the rural coverage is 80%. The total number of BTSs required to cover the whole network area is approximately 2300. Of the 2300 base stations, 520 would be situated in urban areas, 1050 in suburban areas, and 730 in rural. Small investments are also necessary for the transport network and core site elements.

The following diagrams depict the CAPEX, OPEX and revenues in the mobile case (3G LTE case) that we mentioned above.

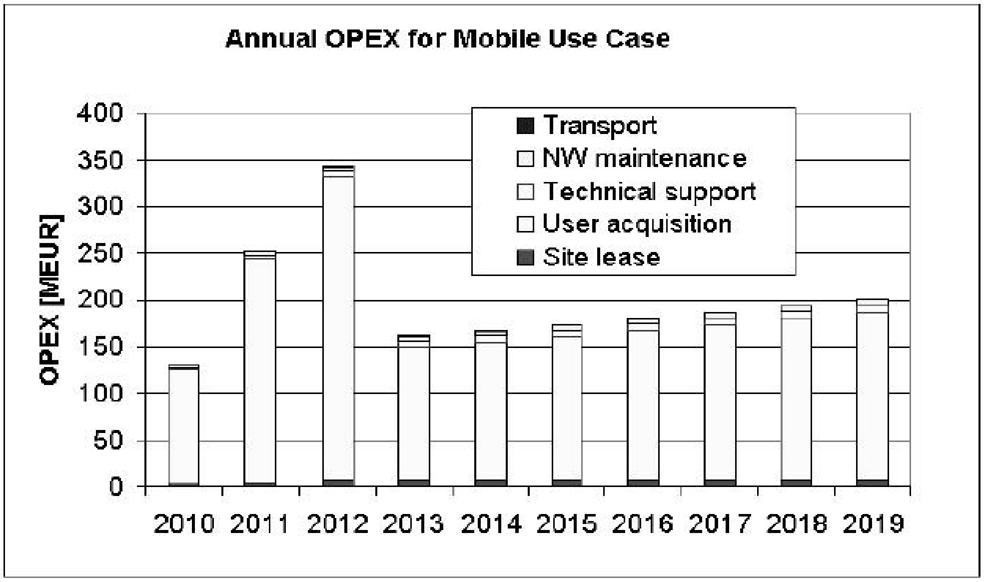


Figure 30: OPEX expenditures in mobile case [32]

Looking at the figure 30, it is important to note that user acquisition costs are considered to be the main factors that dominate in the OPEX cost calculation. Therefore, it is of utmost importance for the operator to optimize its marketing efforts, as well as minimize customer churn. The user acquisition costs of the mobile user case can be compared with the possible revenues by introducing an ARPU (Average Revenue Per User), e.g. 15 Euros per month.

From figure 31 we can assume that the majority of CAPEX is incurred in the BTS sites. Moreover more than 90% of CAPEX is attributable to the base stations while the rest of the CAPEX costs can be attributable to the core network components. Note that in the sequel we will focus only on the CAPEX costs derived by the BTS used for coverage proposes, termed as coverage BTS in fig.31.

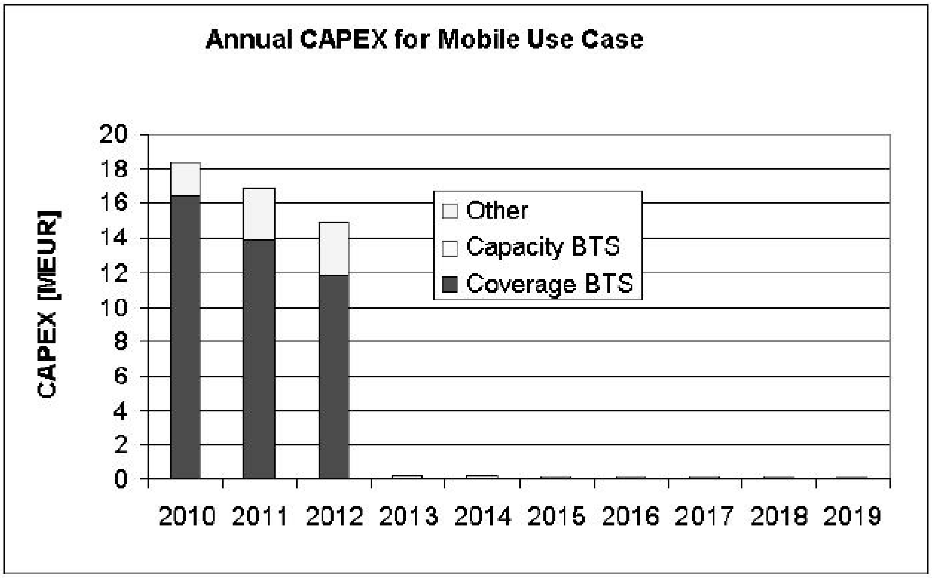


Figure 31: CAPEX expenditures in mobile case [32]

As shown in figure 32, the profits become larger, if the number of users and cash flows become larger. The following we can see the values of the revenue the CAPEX and OPEX cost for a 10 year time frame, as referred in [32].

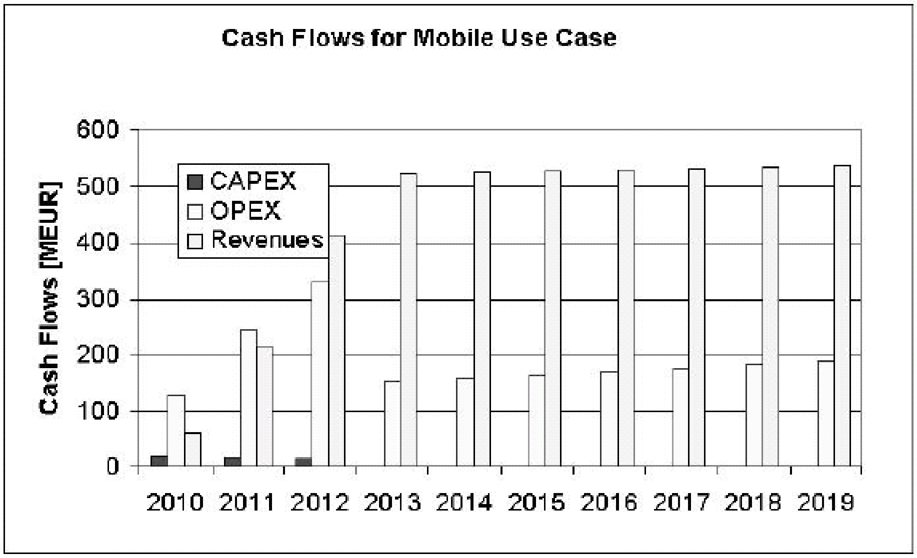


Figure 32: Cash flow in mobile case [32]

As we can see from figure 32, the third columns of the right refer to revenues. As the time goes by, revenues increase. The early years the increase is quicker. That is probably due to the new technology that after few years it goes in mature state and another innovative technologies come to replace the old one.

In the model we are going to create and present, we will take the values of the last figure as input and we will compute the values like PI, IRR and NPV so as to estimate the investment plan which we want to analyze (the mobile network virtualization scenario) and finally to compare PI, IRR NPV values from the [32], with the respective values entailed from our investment plan.

We should note that CAPEX is counted at costs after its depreciation. This means that CAPEX is divided by 10 which is the number of years that the asset (capital investment) is used. Cash flow is calculated by each year's revenue and total cost. Discount rate is assumed to be 10% and IRR and PI are calculated by the equations described in the previous chapter. As already mentioned, initial market is 10 millions, with 4% increase per year. So the first year it will be 10, second 10.4 etc., for time frame 10 years. We will decode somehow the figures 30-32 so as to estimate the number of coverage BTSs used each year. We can see for the figure 31 that the first year the cost of BTSs is 16.1 millions, the second 14 million and the third 12 millions. Therefore, the total CAPEX (both coverage BTSs and other costs), are calculated as 18.1 the first year, 16 the second, 14.5 the third etc. After that, we should make the depreciation in the CAPEX costs. We divide the CAPEX of each year with 10, because this is the number of the years under investigation. We will refer only to year one for convenience. Thus, the CAPEX cost is 4.92 million (18.1/4).

Total OPEX costs, from figure 30 for year one, is almost 125millions and revenues from figure 32 are almost 50 millions. So, the cash flow for year one is -79.92 millions. We can see that the result is negative, so this means that we have loss due to investment, which is pretty logical. After that, we will calculate the value (1+0.1) ^n (n=year number). So in the first year we have 1.1.

Present value is the cash flow, divided with (1+0.1)^n. Present value parameter is relative to NPV which was discussed in previous chapter, with the difference that NPV is for all the time frame used instead of PV which is calculated per year. As already mentioned, NPV is the sum of all PV of all the years in the time frame. So the first year we have PV=-79.92/1.1=72.65. NPV is the sum of 10 years PV.

According to these results and in combination with the formulas mentioned in previous chapter, we can calculate the following economic values based on graphs presented in [32].

NPV	1181,0705
IRR	97%
PI	10,090752

Table 4: Cost values

5.2 Economic analysis of a mobile network virtualization scenario

In this section we make a techno economic analysis of a mobile network virtualization scenario. Note that in that dissertation, we consider to apply the concept of network virtualization, discussed in the previous chapters, to the reference scenario described in the previous section. So, we will create a new model relative to virtualized mobile network, based on the data used in [32]. According to this, 2300 BTSs are distributed in a large area of 338000 km^2 which includes an urban, suburban and rural sub-area. The number of BTSs deployed in each sub-area is reported in Table 5.

URBAN AREA	520
SUBURBAN AREA	1050
RURAL AREA	730

Table 5: Number of BTSs

Different from [32] we propose to utilize network virtualization a means to enable the sharing of all these BTSs among multiple operators. In particular, we assume that there are three operators working in the same market, coined as operator “A”, “B” and “C” respectively. We also assume that BTS’s resources are utilized by each operator according to the own needs of bandwidth, QoS etc. However some service level agreements (SLAs) are established between the tree operators. We assume that such SLAs define the maximum percentage of usage of the BTS’s resources per each operator.

Operator A	0.2
Operator B	0.5
Operator C	0.3

Table 6: Operators’ percentage of BTS usage

So, until now we know “how much” each operator uses a BTS. Operator B makes most use of it. But the initial market will be divided to all operators. Let’s say that operator A has the bigger part of the initial market. Let’s assume that it uses the 50% of the initial market. (We can assume that the operator B might give better QoS to its customers and that is the reason why he needs more resources from BTS. Conversely, the operator A may have to serve more users but with lower QoS requirements. This differentiation is done so as to distinguish the numbers in our calculations in the sequel).

According to that percentage value we calculate the cost of coverage BTSs in urban, suburban and rural areas. According to [32], the coverage BTS cost is calculated as 25000 Euros. In table 7 is reported the total cost of coverage BTSs after the first three years. More specifically, in the first year the coverage cost includes urban BTSs, the second one the suburban BTSs and the third one the rural BTSs. The total BTS coverage cost for urban area for operator A is 2.6 millions. This value is calculated by multiplying the market share (0.5), the number of BTSs in urban area (530) and the cost of BTS (25000).

The BTS coverage cost is calculated for suburban and rural area too. We assume that in the first year we implement urban BTSs, the second one the suburban and the third one the rural. Of course, the time period under investigation is 10 years. These values are discounted in later step as described earlier in this chapter obtaining the values presented in table 7.

(millions)	2010	2011	2012
Coverage BTS	2,6	5,25	3,65

Table 7: Sum of coverage BTSs the first three years

The “Other” costs that are mentioned in figure 31, are divided by three, because that is the number of the operators that we assume are sharing the BTSs.

Adding all the CAPEX costs, we calculate that the total cost after all the 10 years is about 13.8 million as we can see in table 8. This will be divided by 10 so as to be depreciated and to have the same value every year.

Different from the OPEX costs derived in [32], in our case each year cost is divided by the number 3 because the physical infrastructure is shared among three operators. This is a hypothetical scenario of course, since in the reality additional marketing and other operator-specific activities should be included in the analysis.

(millions)	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
CAPEX TOTAL	3,3	5,9	4,5	0,1	0,1	0,0	0,0	0,0	0,0	0,0
Depreciation	1,4	1,4	1,4	1,4	1,4	1,4	1,4	1,4	1,4	1,4
OPEX TOTAL	41,7	83,3	116,3	53,3	55,0	56,7	58,3	60,0	63,3	66,7

Table 8: Costs

We note that the revenues are the similar to [32], with the exception that here we multiply each year revenue with 50% because that is the market share of operator A that is under our analysis.

(millions)	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
REVENUES	25	105	205	255	257,5	260	262,5	265	267,5	270

Table 9: Revenues

As in [32], we can calculate the cash flow (see table 10) by taking into account the costs and revenue.

TOTAL COSTS	43,1	84,7	117,7	54,7	56,4	58,1	59,7	61,4	64,7	68,1
REVENUES	25,0	105,0	205,0	255,0	257,5	260,0	262,5	265,0	267,5	270,0
	50,0	210,0	410,0	510,0	515,0	520,0	525,0	530,0	535,0	540,0
CF	-18,1	20,3	87,3	200,3	201,1	201,9	202,8	203,6	202,8	201,9

Table 10: Cash flow

The following tables demonstrate that the virtualization scenario is more profitable. IRR and PI values are increased in comparison to [32].

In [32] we have:

NPV	1181,0705
IRR	97%
PI	10,090752

Table 11: Economic values of [32]

But in our case we have:

NPV	804,48911
IRR	262%
PI	19,685873

Table 12: Economic values of dissertation's results

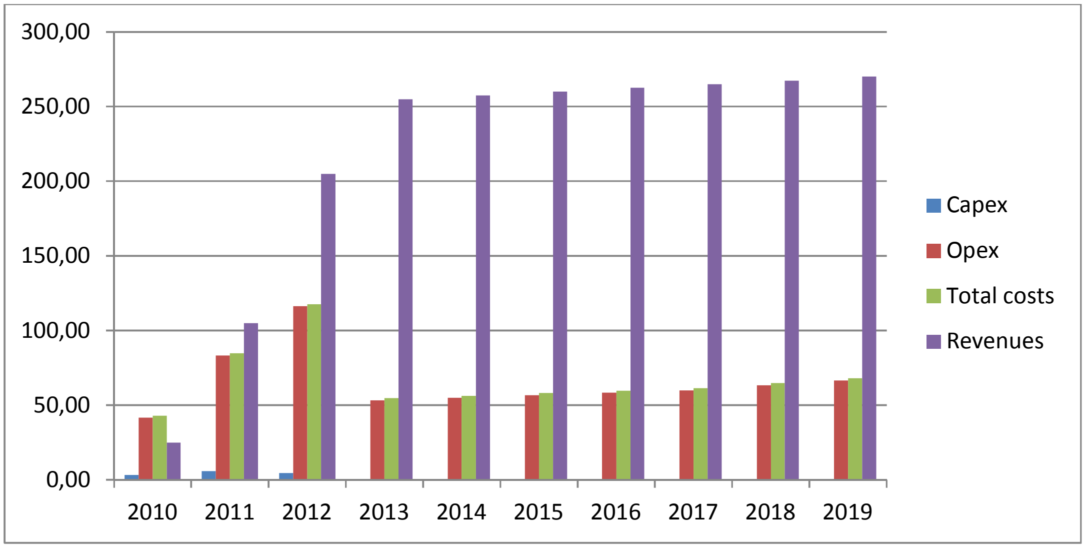


Table 13: Diagram with the basic economic values

From all the above, we can conclude that in the mobile virtualization case we can achieve better results. By having less risk in the investment, we obtain almost the same profit. Looking to the IRR, that is an indicator that shows the values achieved in respect to money invested, it is much augmented in the virtualized scenario so that to make the investment more profitable. Therefore, by virtualizing the network, operators may have many benefits in terms of cost savings.

Note that in this dissertation we have presented both theoretical and practical network virtualization models and our contribution focused in creating a techno-economic model so as to translate the aforementioned theoretical benefits into numbers. Of course this is a relatively simple example since the realistic one, that should be used from companies, is much more complex and accurate because many other specific parameters need to be calculated and estimated.

6. SUMMARY

That dissertation presented a bibliographic research on new trends in today's networks that will help the operators to survive in an era where customers will demand ever new services, with better quality and lower latency and everywhere coverage. The main challenge from the network operator perspective is to face these demands in a cost-effective manner. Moreover the network operators should find ways to offer these new services to their customer in a reasonable price.

Here come the new potentials that new technological breakthroughs will offer. A novel paradigm, known as Software Defined Networking, can be adopted by the operators to manage network services through abstraction of lower level functionalities. By that, it is possible to intervene to the network operation and change it in a dynamic fashion according to the specific needs of both the operators and the customers. Besides SDN, an emerging concept as network virtualization and network sharing can help operators to share resources or physical equipment in order to minimize the capital and operational expenditures.

That dissertation has investigated the benefits of applying virtualization in mobile networks, focusing on the effects on capital and operational Expenditures. In particular, starting from a referenced LTE scenario, the dissertation has presented a new simple techno-economic model to evaluate the use of network virtualization in that scenario. We proved that by using network sharing and network virtualization the final cost values are improved. So that alternative will definitely help each operator who wants to enhance its position in the market place.

7. ACRONYMS

NV	Network Virtualization
VM	Virtual Machine
ATM	Asynchronous Transfer Mode
MPLS	Multiprotocol Label Switching
CAPEX	Capital Expenditures
OPEX	Operational Expenditure
SDN	Software-Defined Networking
NFV	Network Functions Virtualization
VLAN	Virtual Local Area Networks
VPN	Virtual Private Network
PE	Provider Edge Routers
CE	Customer Edge Devices
PPVPN	Provider-Provisioned Vpn
LTE	Long-Term Evolution
ENB	Evolved Node B
P-GW	Packet Data Network Gateway
S-GW	Serving Gateway
ANDSF	Access Network Discovery And Selection Function
MME	Mobility Management Entity
RAN	Radio Access Network
SLA	Service-Level Agreement
BSC	Base Station Controller
VBBU	Virtual Base Band Units
VBSC	Virtual Base Station Controller
O&M	Operations & Maintenance
ROI	Return On Investment
NPV	Net Present Value
ARPU	Average Revenue Per User
WLAN	Wireless Local Area Network
ONF	Open Networking Foundation
eNB	Evolved Node B
API	Application Programming Interface
TRX	Transmitter-Receiver
GBR	Guaranteed Bit Rate

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