Initial Training Network

CROSSFIRE

Uncoordinated network strategies for enhanced interference, mobility, radio resource, and energy saving management in LTE-Advanced networks

FP7 Contract Number: 317126

WP2 – Network Virtualization in LTE-A Networks

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Executive Summary

This deliverable presents an overview the Work Package 2 (WP2) of CROSSFIRE (unCooRdinated netwOrk StrategieS for enhanced interFerence, moblility, radio Resource, and Energy saving management in LTE-Advanced) project. The document provides a comprehensive state-of-art analysis of the main topics including Radio Access Network (RAN) and network sharing, open evolved Node B (eNB) in a multi-tenant environment, RAN programmability for Time –Division Long Term Evolution (TD-LTE) including the concept of virtual cells, and core network function virtualization enabling network operators to share network elements like mobility anchor points. The main challenges and technical requirements are analysed presenting some first details of the architecture enhancements and operations related to network virtualization, which can be incorporated into the overall CROSSFIRE architecture.

Specifically, the work on RAN sharing analyses the 3GPP current state of the art considering the service requirements use cases and architectures before exploring more research work about RAN virtualization considering the virtual eNB and virtualization in wireless resource sharing. Furthermore, it elaborates the architecture scenarios where the work will concentrate considering RAN and network sharing.

The Open eNB proposal examines network virtualization for the RAN based-on the Software Defined (SDN) paradigm. Initially it elaborates the network virtualization concept focusing on mobile networks and summaries the SDN paradigm based-on Open Network Foundation (ONF) Open Flow before analysing the notion of open access and virtualization for certain base station allowing on-demand dynamic resource provision. Architectures, mechanisms and procedures to realize the open eNB are also documented.

RAN programmability investigates methods and mechanisms that allow operators to re-configure the RAN considering resource availability and the application type. In particular, it exploits the logical centralized SDN control to provide new rules about the uplink and downlink resource allocation in a TD-LTE allowing application to program the network, whilst creating also virtual cells. Virtual cells are regions, which are formed by combining resource from different eNBs.

Finally, the core network virtualization is exploring solutions that will allow operators to share certain core network elements, e.g. an anchor point or a mobility management entity,
assuring topology optimization in terms of signalling overhead and mobility patterns. The study focuses on traditional mobility protocols, e.g. Mobile IP, considering also distributed mobility and Proxy Mobile IP, while it also considers as further work its applicability to LTE exploiting the use of the Network Function Virtualization (NFV) to enable certain core functions to be shifted inside the operator’s network.
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1. Introduction

The CROSSFIRE (unCooRdinated netwOrk StrategieS for enhanced interFerence, mobbllity, radio Resource, and Energy saving management in LTE-Advanced) project investigates a number of evolving issues and challenges regarding LTE-Advanced (LTE-A) networks. In particular, it explores network architecture, operations and management aspects as well as mechanisms for enhancing the user performance considering interference mitigation, congestion management and Quality-of-Experience (QoE).

A key enabler for the CROSSFIRE principles is network virtualization, a means for enhancing the efficiency of the network infrastructure by sharing the radio, backhaul and core network. In addition, network virtualization enables network programmability, utilizing Virtual Machines (VM) that can flexibly provide network functions on demand or simply can re-configure certain network functions based-on given optimization objectives, e.g. increase resource efficiency, energy saving, etc. considering also application specific input. The CROSSFIRE Work Package 2 first deliverable “Network Virtualization in LTE-A Networks” brings light into these issues focusing on the following four key areas:

- **RAN and network sharing**: This work explores the 3GPP RAN sharing issues exploring use-cases and architecture aspects as well as other considerations focusing on providing solutions of mapping virtual path requests to substrate physical topology in LTE-A environments consisting of small cells and on the wireless Radio Resource Management (RRM). It further analyzes the challenges and scenarios where this approach can benefit LTE-A networks.

- **Open eNB**: is an alternative approach to radio and backhaul sharing considering eNBs as open entities, which can be shared via the means of Software Defined Networks (SDN). This approach analyzes the SDN architecture and network virtualization highlighting SDN use in mobile networks. The proposed approach intends to offer more flexibility in how virtualized eNBs instances can be managed in cooperative networks. It also provides details regarding the architecture, mechanisms and operations for providing the proposed open RAN access.

- **RAN programmability**: considers efficient radio resource management and RAN re-configuration methods based-on SDN and SON for TD-LTE networks exploiting also the new concept of virtual cells, which are formed among overlapping regions enabling UEs to use sub-frames from different eNBs. The proposed approach introduces a new notion of a cell, which is virtual in the sense that there is no
physical infrastructure but is created on demand based on application demands ensuring flexible in resource allocation.

- Core network function virtualization: investigates the placement and sharing of core network functions, e.g. mobility anchor point, in order to achieve scalability, optimal resource provision and mobility in a multi-tenant scenario. In particular, it details the methodology for achieving the proposed optimization based on Markov chains and analyses the key parameters that should be considered in such an optimization problem.

In this deliverable we also relate our proposals with the CROSSFIRE architecture in order to specify the area of our contribution. The remaining of this document is organized as follows. Section 2 contains the background and analysis of the RAN and network sharing, which is the contributing of UoC, while Section 3 by UoA focuses on the open eNB and SDN based RAN virtualization. The RAN programmability and virtual cell proposal by NEC is described in Section 4, while the core network function virtualization contribution of KCL is contained in Section 5. Finally Section 6 provides the conclusions of our deliverable.

2. **RAN and Network Sharing (UoC)**

Future Networks will be characterized by heterogeneity and they also will be composed of diverse wireless mobile access, home broadband, and core IP/optical networks. As wireless traffic continues to grow, network operators must carry higher volumes of data and support more sophisticated services. To meet the rising and diverse user demands, further improvement in wireless communication technology is required to enhance service delivery for example, through higher data rates, low latency, reduced interference and even greater capacity. Network virtualization, coupled with an effective and efficient approach to manage virtualized resources, is a key solution to this problem. Consequently, it is receiving immense attention in the research community all over the world since it is expected to be a central element of future network architectures.

Generally the concept of network virtualization refers to the architecture and to the related enabling solutions that allow the deployment of multiple virtual networks on top of a common network infrastructure. Network virtualization in essence decouples and isolates virtual networks from the underlying physical network infrastructure. However, the general definition assumes different nuances as a function of the specific context of the current application. In the context of network infrastructure sharing and multi-tenancy, virtualization is conceived as an enabler allowing different virtual radio networks to operate on a common
shared infrastructure and to share the same radio resources with different functionalities and services.

2.1 Reference Architecture of LTE-A

In Long Term Evolution - Advanced (LTE-A) Networks, network virtualization also refers to the capability of partitioning the underlying physical resources or logical elements, such as the Radio Access Network (RAN) and Evolved Packet Core (EPC) nodes, in the existing architecture. Within the CROSSFIRE project, the architecture depicted in Figure 1 is considered.

![Figure 1: LTE-A architecture proposed within the CROSSFIRE project.](image)

According to Figure 1 the latest release of LTE-A ([1], Error! Reference source not found.), defines a heterogeneous environment consisting of E-UTRAN NodeBs (eNodeBs) and small cells (i.e. Pico eNodeBs, Relay Nodes (RNs) and Home eNodeBs (HeNodeBs)). The latest release of LTE-A does not offer the flexibility of providing RAN sharing on demand. The deployment of a large number of smaller cells leads to more frequent handovers among the participant tiers, the boost of the signaling load due to user mobility and to the degradation of application throughput of the perceived call quality.

Nowadays, a single network market with operators competing at the service layer is considered a commercially viable model. Consequently, the efficient management of the heterogeneous environment imposes the need of having separate virtual networks on the same physical infrastructure. Below a brief description of the architecture follows, with main target to identify the proper parts of LTE-A where potential solutions based on network virtualization could be applied.
To start off with, the core network consists of the following nodes: Mobility Management Entity (MME), Service Gateway (SGW) and Packet Delivery Network Gateway (PGW). Generally, MME is responsible for the control plane of the LTE-A architecture and the key control-node for the LTE-A access-network. In more detail, it is responsible for

i. the idle mode User Equipment (UE) tracking,
ii. the paging procedure when retransmissions are required,
iii. activation and deactivation of the bearer process,
iv. user authentication and
v. the provision of the control plane function for mobility between LTE and Second / Third Generation (2G/3G) access networks.

Next, SGW node routes and forwards user data packets by being the mobility anchor for the user plane during inter-eNodeB handovers. It also acts as the mobility anchor for the user plane during inter-eNodeB handovers and as the anchor for mobility between LTE and other 3GPP technologies as well as it manages and stores UE contexts (e.g. parameters of the Internet Protocol (IP) bearer service, network internal routing information). Finally it performs replication of the user traffic in case of a potential lawful interception.

The last node of EPC, PGW, provides connectivity from the UE to external packet data networks by being the point of exit and entry of traffic for the UE. It also performs policy enforcement, packet filtering for each user, lawful interception and packet screening. It is the anchor for mobility between 3GPP and non-3GPP technologies such as Worldwide Interoperability for Microwave Access (WiMAX) standard and 3GPP2 (Code division multiple access (CDMA) One and Evolution-Data Only or Evolution-Data Optimized (EvDO)).

Furthermore, Figure 2 presents the different E-UTRAN network entities included in the latest release of LTE-A ([1],[2]). The E-UTRAN consists of eNodeBs, HeNodeBs and the recently added RNs. These nodes have been introduced in LTE-A for efficient heterogeneous network planning. The RNs are low power eNodeBs that provide enhanced coverage and capacity at cell edges. One of the main benefits of relaying is to provide extended LTE coverage in targeted areas at low cost. The RN is connected to the Donor eNB (DeNB) via radio interface, Un, a modified version of E-UTRAN air interface Uu. DeNB also serves its own UE as usual, in addition to sharing its radio resources for RNs [1].

The RN supports the eNodeB functionality meaning it terminates the radio protocols of the E-UTRA radio interface, and the S1 and X2 interfaces. In addition to the eNodeB functionality, the RN also supports a subset of the UE functionality, e.g. physical layer, layer-2, Radio Resource Control (RRC), and Non – Access Stratum (NAS) functionality, in order to
wirelessly connect to the DeNB. With respect to the RN's usage of spectrum, its operation can be divided into in-band and out-band types.

**E-UTRAN Network Entities**

![E-UTRAN Network Entities](image-source)

*Figure 2: E-UTRAN Network Entities of current release [1].*

The user plane consists of the following protocol layers: Packet Data Convergence Protocol (PDCP), Radio Link Control (RLC), Medium Access Control (MAC) and Physical (PHY). These protocols are responsible for performing functions like header compression, ciphering, scheduling, Automatic Repeat Request (ARQ), and Hybrid ARQ (HARQ). Radio Resource Control (RRC) is the protocol layer responsible for control plane functionalities, such as RRM, admission control, scheduling, cell information broadcast and (de/) compression of user plane data headers. This control and data plane separation in the current architecture is illustrated in Figure 3.

*Figure 3: Simplified LTE network architecture with control and data separation[3].*

Figure 4 presents the detailed functional protocol split between E-UTRAN and EPC, in LTE-A networks. The yellow boxes represent the logical nodes, the white boxes the
functional entities of the control plane and the blue ones the radio protocol layers. This structure is based on the principle that the layers and planes are logically independent of each other. E-UTRAN functions are realized in the Radio Network Layer, and the Transport Network Layer represents standard transport technology that is selected to be used for E-UTRAN.

2.2 Virtualization of the Radio Access Network

Network virtualization in LTE-A architecture can have several meanings. Based on the definition of network virtualization, the main target remains to have several virtual networks sharing the same resources. But the main question is to find the architectural aspects of the network where this idea could be applied.

According to the description of the LTE-A architecture (Figure 1), two options for the application of network virtualization solutions arise: the Core Network and the RAN. In this section the potentials of architectural aspects of network virtualization in LTE-A are investigated. RAN virtualization addresses the partitioning and/or pooling of radio physical resources by enabling more efficient management of RAN capacity. In this context, the imposed challenges require the development of new concepts such as the design of radio resource management algorithms that take into advantage the heterogeneous architecture of

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Figure 4: Functional Split between E-UTRAN and EPC [1].
LTE-A as well as the different traffic characterization. However, even introducing this kind of flexibility can be a challenge as well as aligning RAN and backhaul resources.

2.3 State of the Art

Network virtualization, as a concept, can be applied in several sections of the network; also in the case of cellular networks two options for its application arise: the EPC Network and the RAN. We are going to focus on the RAN side of LTE-A that makes possible the easy creation and management of virtual networks, opening up a range of new business models. RAN offers a wide field for potential solutions based on network virtualization.

The first part of this section, describes the network sharing use case actor roles defined by 3GPP as well as related work in Evolved Radio Access Network Sharing. Moreover, the virtualization of radio spectrum and eNodeB resources make possible the easy creation and management of virtual networks, opening up a range of new business models through which network owners can increase the revenue from their networks. The following two chapters define two broad categories for RAN virtualization in cellular networks:

- eNodeB virtualization and
- Wireless Resources virtualization

The aforementioned categories are presented with some relevant research works in order to explain their significance in cellular LTE-A environments.

2.3.1 Radio Access Network (RAN) Sharing

2.3.1.1 Use-cases and Business Requirements

In this section the general on roles in RAN Sharing as defined in [22] are described. The arrangements for network sharing between the involved entities can vary widely, being influenced by a number of factors including business, technical, network deployment and regulatory conditions. Within all of this variation, there is a set of common roles centered on connecting network facilities between the parties participating in a network sharing agreement. This section presents these common roles to aid in understanding the entities described in the use cases.

Hosting RAN Provider

The Hosting RAN Provider is identified as sharing a hosting RAN with one or more Participating Operators. One of the main characteristics of the Hosting RAN Provider is that it has primary operational access to particular licensed spectrum which is part of the network sharing arrangement. This fact does not necessarily imply that owns licensed spectrum but has agreement to operate in that spectrum. Furthermore, it has deployed a RAN in a specific
geographic region covered under the network sharing arrangement and provides facilities allowing Participating Operators to share the RAN covered under the network sharing arrangement.

**Participating Operator**
The Participating Operator is identified as using shared RAN facilities provided by a Hosting RAN Provider, possibly alongside other Participating Operators. The characteristics of the Participating Operator include:

- It uses a portion of the particular shared licensed spectrum in order to provide communication services under its own control to its own subscribers.
- It uses a portion of the shared RAN in the specific geographic region covered under the network sharing arrangement.

**Roaming operators (Home Public Land Mobile Network (HPLMN) and Visited Public Land Mobile Network (VPLMN))**
Roaming and roaming agreements between operators provides a similar capability to RAN sharing where a subscriber of the HPLMN can obtain services while roaming into a VPLMN. This can be viewed as a form of sharing where the VPLMN shares the use of its RAN with the HPLMN for each HPLMN subscriber roaming into the VPLMN.

The distinction between roaming and RAN sharing is that when roaming, the subscriber uses the VPLMN when outside of the HPLMN geographic coverage and within the VPLMN geographic coverage. In a RAN sharing arrangement, all of the participants (Hosting RAN Provider and one or more Participating Operators) provide the same geographic coverage through the Hosting RAN.

**Operators with multiple roles**
Operators can take on multiple roles at the same time depending on business needs. For the purposes of [22][21], each specific network set (spectrum-region-RAN) can be considered independently and combined with other network sets in various combinations. Indicative examples include:

- An operator has its own spectrum which it does not share and additionally uses the shared RAN in the same region (Participating Operator) provided by Hosting RAN Provider.
- Two operators set up a joint venture to build and operate a shared network. The two operators are both Participating Operators and the joint venture is a Hosting RAN Provider.
• Two operators A & B, divide a region covered by a joint spectrum license and each build and operate the RAN in their portion of the region. In the region covered by operator A's RAN, operator A is the Hosting RAN Provider and at the same time Participating operator while operator B is only Participating Operator. In the region covered by operator B's RAN, operators A and B are the Participating Operators and operator B is the Hosting RAN Provider.

It should be noted that roaming could be considered a form of network sharing where the Visited Operator allows an individual UE to use the visited RAN (VPLMN) in coordination with the Home Operator. However for the purpose of this specification, RAN sharing only applies to deployments where a shared RAN operates as a home network (HPLMN) for each of the Participating Operators.

After presenting these three distinct roles, the study in [22] defines what constitutes a shared RAN. A Hosting RAN Provider may share E-UTRAN resources with Participating Operators in various ways. In the context defined in [22], it is assumed that at least a set of radio Base Stations (BS) are shared for use by Participating Operators. The sharing agreement between Hosting RAN Provider and Participating Operators may or may not include sharing of a part of the radio spectrum of the Hosting RAN Provider. For example, a MVNO as a Participating Operator would use the spectrum provided by the Hosting RAN Provider.

In the context of the study presented in [22], the sharing of Core network nodes, while not excluded, is not considered. Typically RAN sharing arises out of the following situations:

• A Greenfield deployment – two operators jointly agree to build out a new technology (typically 4G). At the outset, the new shared network infrastructure and operations can be based on capacity and coverage requirements of both operators. The operator can e.g. fund built-on 50:50 or according to their expected needs.

• Buy-in – when one of the sharing operator has already built (4G for example) and looking for another operator to share this network. In this case, the second operator would typically either pay a capacity usage fee or up-front fee to acquire in the network.

2.3.1.2 RAN sharing Architectures

The LTE access network consists of eNodeBs, generating a flat architecture. The flat architecture means that only two node types (base stations in the RAN and gateways in the core network) must scale in capacity in order to accommodate large increases in data
volumes. There is no centralized intelligent controller, and the eNodeBs are normally inter-
connected via the X2-interface and towards the core network by the S1-interface [4].

This section presents in detail which parts of the current architecture (Figure 1) can
be shared. 3GPP network sharing architecture allows different core network operators to
connect to a shared RAN. The operators do not only share the radio network elements, but
they may also share the radio resources themselves. Network-sharing existing scenarios
allow operators, without a LTE license, to share the network and supply its customers with
4G services. For example, a 2G operator may supply its subscribers with 4G services using
another operator’s allocated spectrum.

3GPP has identified two general architectures for RAN sharing [4]. In the first architecture
only the radio access network (i.e. E-UTRAN) is shared. This configuration is referred to as
Multi-Operator Core Network (MOCN) configuration. In the second architecture, the evolved
packet core network element MME is shared in addition to the radio access network (E-
UTRAN). This configuration is referred as the Gateway Core Network (GWCN). Figure 5
presents these two distinct configurations [5].

![Figure 5: Current sharing supported by 3GPP [4].](image)

In the MOCN approach the shared eUTRAN is connected to several MMEs entities via
the S1 interface. Each mobile network operator has its own EPC. Thus the MME, the SGW
and the PGW are not shared and are located in the different CN. As shown in Figure 5 the
S1 flex interface allows the eNodeB to be connected to the different CN. It also allows
connecting the eNodeB to several MME and SGW in a given CN. Thus, allowing load
balancing to be supported between MME and SGW of a given CN. In the GWCN approach,
contrary to the MOCN approach, the MME is also shared between the different mobile
network operators. In Figure 6 and **Table 1** a comparison between the two approaches for
network sharing is presented. According to this comparison MOCN configuration is much
more prevalent in current operators.
Figure 6: Comparison between MOCN (left) and GWCN (right) sharing architectures [5][4].

Table 1. Advantages and disadvantages of each sharing solution [5].

<table>
<thead>
<tr>
<th></th>
<th>MOCN</th>
<th>GWCN</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interworking with legacy networks</td>
<td>+</td>
<td>-</td>
<td>To support inter – Radio Access Technology (RAT) mobility, MME needs interfaces with legacy networks. Sharing the MME leads to tighter integration between the shared eUTRAN and each core network operator.</td>
</tr>
<tr>
<td>Support of voice service with Circuit Switched (CS) fallback</td>
<td>+</td>
<td>-</td>
<td>The support of CS fallback in EPS, requires a new interface called SG between the MME and Mobile Switching Center Server (MSC) server. Sharing the MME leads to a tighter integration between the shared eUTRAN and each core network operator.</td>
</tr>
<tr>
<td>Support of voice service with IP Multimedia Subsystem (IMS)</td>
<td>=</td>
<td>=</td>
<td>Support of IMS is the best and future solution for voice transmission over LTE.</td>
</tr>
<tr>
<td>Support of roaming</td>
<td>+</td>
<td>-</td>
<td>In roaming MME in VPLMN needs to interact with Home Subscriber Server (HSS) in HPLMN. Sharing the MME is a drawback in as HSS address of each roaming partner needs to be defined in shared MME for each CN connected to the shared eUTRAN.</td>
</tr>
<tr>
<td>Cost</td>
<td>-</td>
<td>+</td>
<td>Sharing the MME shares the cost. However this depends on the context.</td>
</tr>
</tbody>
</table>

The UE behavior in both of these configurations is the same. No information concerning the configuration of a shared network is indicated to the UE. If the E-UTRAN is shared by multiple operators, the system information broadcasted in each shared cell contains the Public Land Mobile Network (PLMN)-id of each operator (up to 6) and a single Tracking Area Code (TAC) valid within all the PLMNs sharing the radio access network resources.

As far traffic handling is concerned, in the current releases, LTE can isolate different enterprise customers' traffic into virtual private networks using traditional Border Gateway Protocol (BGP) / Multiprotocol Label Switching (MPLS) Virtual Private Network (VPN)
technologies. However, LTE does not allow different carriers to share the infrastructure in order to offer a complete virtual LTE network to the customers [3]. Virtual operators may want to innovate in mobility management, policy and charging, without investing the substantial resources necessary to build and manage a wireless network. For example, content providers could leverage a virtual infrastructure to better deliver content to mobile users.

On the whole, different core network operators (MME/SGW owners) can connect to a shared radio access network (RAN). Furthermore, multiple MMEs can be grouped together in a pool to meet increasing signaling load in the network (using the S1-ex interface between eNodeB and each MME in the pool).

The article in [6] presents a survey of cellular network sharing, which is a key building block for virtualizing future mobile carrier networks in order to address the explosive capacity demand of mobile traffic, and reduce the CAPEX and OPEX burden faced by operators to handle this demand. The authors review the 3GPP network sharing standardized functionality followed by a discussion on emerging business models calling for additional features.

Then an overview of the RAN sharing enhancements currently being considered by the 3GPP RSE Study Item is presented. Based on the developing network sharing needs, a summary of the state of the art of mobile carrier network virtualization is provided, encompassing RAN sharing as well as a higher level of base station programmability and customization for the sharing entities.

Dynamic resources' slicing is another category of solutions based on the concept of RAN virtualization. The authors of [12] have proposed CellSlice; a dynamic framework to achieve active RAN sharing by remotely controlling the scheduling decisions, ensuring that each entity receives its share of the wireless resources. This idea does not require the modification of the Base Station (BS) schedulers but it controls the BS scheduling decisions from a remote gateway.

Currently the 3GPP RAN Sharing Enhancements Study Item of the TSG SA WG1 is defining new scenarios in which multiple operators share network resources [22]. The aim of this work is to formulate the necessary business requirements for sharing common RAN resources, with the goal to provide the following [9]:

- A means to verify that the shared network elements allocate RAN resources according to the sharing agreements and sharing policies
- A means to enable efficient sharing of common RAN resources (e.g. pooling of unallocated radio resources).
- A means to flexibly, dynamically and automatically allocate RAN resources on-demand at smaller timescales that the ones currently supported.

According to the current demands, resource sharing among mobile network operators is a promising way to tackle growing data demand by increasing capacity and reducing costs of network infrastructure deployment and operation. In [43], the authors evaluate sharing options that range from simple approaches that are feasible in the near-term on traditional infrastructure to complex method that require specialized/virtualized infrastructure. They build a simulation testbed supporting two geographically overlapped 4G LTE macro cellular networks and model the sharing architecture/process between the network operators. In this work, they compare Capacity Sharing (CS) and Spectrum Sharing (SS) on traditional infrastructure and Virtualized Spectrum Sharing (VSS) and Virtualized RB Sharing (VPS) on virtualized infrastructure under light, moderate and heavy user loading scenarios in collocated and non-collocated E-UTRAN deployment topologies.

They also study these sharing options in conservative and aggressive sharing participation modes. Based on simulation results, their conclusions are that CS, a generalization of traditional roaming, is the best performing and simplest option, SS is least effective and that VSS and VPS perform better than spectrum sharing with added complexity. The simulation results also showed low effectiveness of inter-operator sharing options for higher UE density factors. The inter-operator sharing options were effective only when there were large differences in resource utilization between the two networks. Their effectiveness also depended on location of the available surplus resources. For higher UE density scenarios in which mobile networks are heavily loaded and surplus resources are scarce, inter-wireless-service-network resource sharing (e.g. dynamically accessing unlicensed/Wi-Fi or DTV spectrum) is likely to be more effective than the intra-service, inter-operator sharing examined in this work. Simulation and modeling of inter-operator resource sharing between cellular and femtocell networks, inter-wireless-service network SS on traditional infrastructure and VSS, VPS and other advanced DSA techniques on virtualized infrastructure are good candidates for future study.

### 2.3.2 eNodeB virtualization

Spectrum sharing is a key technique in LTE virtualization; it can be used at the air interface to adapt to the traffic load variation of different virtual networks. The term eNodeB virtualization refers to the case where multiple virtual networks share the spectrum of the same physical eNodeB.
A preliminary approach towards eNodeB virtualization included the proposal of the scheduling of the physical Resource Blocks (RBs) between the different virtual eNodeBs [7]. This means the splitting of the frequency spectrum between the different eNodeBs of the different operators. A controlling entity called hypervisor was proposed in order to make use of apriori knowledge (e.g. user channel conditions, virtual operator contract, load etc.) to schedule the RBs [8].

The frequency spectrum among the different operators has to be scheduled. This is the most challenging part because of the additional degree of freedom that has been added due to the fact that the scheduling could be based upon different criteria (such as bandwidth, data rates, power, interference, predefined contract, channel conditions, traffic load or a combination of them). According to these requirements, a framework is proposed where the hypervisor has to convert these criteria into a number of RBs to be scheduled for each operator, but also need to make sure that the allocated RBs will be fair and satisfy operators' requirements. Figure 7 presents the proposed virtualized eNodeB protocol stack [7].

![Virtualized eNodeB protocol stack](image)

*Figure 7: Virtualized eNodeB protocol stack proposed by [7].*

In such a scheme, there is the necessity for some mechanisms/contract guidelines to be defined, in order to guarantee the resources to the operators. The time frame that the hypervisor operates in order to guarantee the predefined requirements is crucial. For this purpose, two different types of scheduler algorithms for spectrum allocation are proposed: a static and a dynamic one. The first algorithm defines that the spectrum is divided between the different virtual operators beforehand, and each operator will get his operating spectrum and keep it for the whole time. The second algorithm, is responsible for allocating the resources to the different operators during runtime, and the amount and allocation can be changed over time depending on the operator’s traffic load. This work could be considered as an initial contribution in the wireless network virtualization field but it is not efficient for application in LTE-A systems due to the static handling of the RBs.
As an example of RAN virtualization techniques feasibility, a solution based on spectrum sharing is presented: the Network Virtualization Substrate (NVS), which can be natively implemented in base stations. NVS performance is evaluated in an LTE network by means of simulation, showing that it can meet the needs of future virtualized mobile carrier networks in terms of isolation, utilization, and customization [9]. It is a feature for managing and sharing the radio spectrum and eNodeB processing resources. NEC’s eNodeB product line includes the NVS feature which manages sharing of the radio spectrum and eNodeB processing resources. The OAM server allows each operator’s virtual network to be separately configured and managed.

Furthermore, a scheduler in order to assign efficiently the spectrum resources is introduced. This is practically a slice scheduler which works in conjunction with the MAC scheduler. The slice scheduler monitors the amount of resources that the MAC scheduler assigns to each slice and dynamically adjusts the bearer priorities in the MAC scheduler to maintain the required resource allocation for each operator. In this way, all operators have access to the whole system bandwidth.

In [10] the authors propose a partial resource reservation scheme for LTE networks, addressing both scheduler and admission control aspects. System-level simulation results show: compared to Full Reservation schemes, their proposal can flexibly allocate the shared resources to operators according to their actual traffic loads and traffic priorities, and thus, increase the spectrum utilization and the revenue of the network owner; compared to Complete Sharing scheme, it can provide minimum guaranteed performance for each operator.

In this work ([10]) the provision of active LTE RAN sharing with partial resource reservation is investigated. In particular, the authors extend the NVS solution [8] to support partial resource reservation and propose a two-step AC mechanism. Simulation results show that the proposed scheme enables efficient and flexible utilization of the spectrum while supporting User Equipment (UE) QoS requirements and partial resource reservation.

Virtualization has been explored as a future Internet (wireline network) design approach [25] and with advancements in SDR and Cognitive Radio (CR) technologies it was further extended into Radio/Wireless network virtualization by GENI Error! Reference source not found., VINI / Planetlab [27] and others for experimental testbeds to support large numbers of simultaneous experiments. It was also promoted as a flexible and cost effective solution for rapid deployments of new wireless access technologies [28].

Inter-operator base station sharing based on virtualization has also appeared in the form of Multi-RAN base station [29], Virtual Base Station [30] and others [31][32][33]. Most importantly, [34][35][36][37][38] show increasing interest and willingness by operators,
regulatory and standard bodies to explore and support resource sharing, especially as networks evolve to 4G and beyond. Moreover, various aspects of the inter-operator resource sharing have been studied by [39][40][41][42]. A simple analytical model for dynamic inter-operator resource sharing has been developed to make real-time sharing decisions [41]. Also, [39] and [40] have shown capacity gain using a simple Non-collocated base station layout and a rudimentary round-robin scheduler model for time-slot sharing among operators.

2.3.3 Managing Wireless Resource Sharing

The term wireless resources in the context of network virtualization may refer both to the resources delivered to the eNodeB and in some cases the frequency resources that the eNodeB handles itself. In this section we will be interested into the first case since the latter was described in the previous section. Solutions of this category focus on creating a substrate within the BS for virtualizing the wireless resources of a cellular network delivered to the BS itself.

Virtualizing wireless resources in cellular networks fosters several interesting deployment scenarios that are of interest to both academia and industry [11][12]:

- Active RAN sharing: One radical change that is receiving considerable attention recently is active RAN sharing among Mobile Network Operators (MNOs). RAN sharing enables significant reduction in equipment in low traffic areas and results in at-least 100% increased rollout speed with a given cost.

- Mobile Virtual Network Operators (MVNO): In the recent past, several MVNOs have emerged as strong players in the cellular market providing enhanced services. Such MVNOs often do not own spectrum and rely on sharing the wireless resources of a MNO in that region. Virtualization helps partition the wireless resources in an MNO’s network effectively, thereby encouraging stricter and fine-grained Service Level Agreements (SLAs) between MVNOs and MNOs.

The SLA of today’s utility computing [13][14][15][16] are centered on computation (dollars per hour per virtual machine (VM)), storage (dollars per GB per month), Internet traffic (dollar per GB transferred), and the availability of these resources. Nevertheless, no abstraction or mechanisms and hence no SLAs are available to capture the requirements on the interactions among the allocated VMs, such as bandwidth guarantees among the VMs. This could also be applied in the case of network virtualization.

- Corporate Bundle Plans: Currently, network operators offer data plans to enterprises and corporations that allow sharing of bandwidth dynamically
across their users. However, no bandwidth guarantees are provided.
Virtualization may help realize better guarantees on resource allocation, and hence fosters more sophisticated data plans.

- Controlled evaluation: Virtualization enables MNOs to isolate partial wireless resources to deploy and test novel ideas without affecting the operational networks. Currently, MNOs often use dedicated (small scale) deployments to test new ideas.
- Services with Leased Networks (SLNs): With the increased use of wireless and mobile networks for Internet services, we envision application service providers reserving bandwidth with MNOs and paying on the behalf of their users to enhance users’ quality of experience. Virtualization helps in ensuring that such reservations are met.

One category of virtualization solutions refers to a dynamic way of slicing the resources in order to improve the overall network efficiency. CellSlice, is one proposed dynamic framework in order to achieve active RAN sharing [12]. CellSlice’s goal is the remote control of scheduling decisions ensuring that each entity receives its share of the wireless resources. This idea does not require the modification of the BS schedulers but it constrains the BS scheduling decisions from a remote gateway. Slicing can be done with either a base station-level solution or a gateway-level solution. Compared to BS-level solutions, remotely slicing wireless resources makes the solution easily deployable, enables easier network-wide resource reservations for slices, and enables operation with BS from multiple vendors, some or all of which may not support native virtualization.

Moreover, the work focuses on remote uplink slicing since wireless resource reservation requests from the clients for enabling uplink transmissions terminate at the BS.
and are not visible at the gateways. Although it presents a viable solution, it can be characterized as a slicing solution rather than a solution based on the idea of network virtualization. Figure 8 presents the proposed framework by [12].

Furthermore, another study on virtualizing the wireless resources has been published in the context of FLAVIA project [17]. The key concept of the project's work is to expose flexible programmable interfaces enabling service customization and performance optimization through software-based exploitation of low-level operations and control primitives. Figure 9 shows the separation of control and data plane in LTE networks, which is the principle where the project's idea was based on.

![Figure 9: Functional split where virtualization solution could be applied [17].](image)

In one of the dissemination results of the project, the authors propose a generic MAC architecture for both LTE-A and WiMAX wireless networks [18]. In this paper, both technologies are being analyzed with the goal of finding common functional subsets which can be used as building blocks for a generic and extensible MAC for future mobile cellular networks. To this end, the authors propose a systematic categorization into services, interfaces, functions and primitives as a first step towards achieving generic architecture, as shown in Figure 10.

In this architecture, it is very interesting to notice, a potential solution of virtualization. The upper part of Layer 2 is considered suitable for hosting the functions that would be responsible for virtualization of the resources delivered to the eNodeB. This could support the conclusion that RAN is one of the main proposals where the idea of network virtualization in cellular LTE-A networks could be applied.
2.4 RAN and Network Sharing: Discussion and Open Issues

As mentioned, the open issues in network virtualization area and especially in wireless field require more attention. While being widely regarded as a promising emerging research area, the diversity of the network technologies, network structures, protocols, and applications in virtualized networks creates big challenges on network integration and service integration.

The rollout of LTE networks [1] is currently underway in response to massive increases in mobile traffic. However, the large-scale deployment of LTE networks requires significant investments which may make it unaffordable for small operators to enter this new market and not cost-effective for large operators to cover rural areas. In addition there is an increasing number of mobile virtual network operators who do not own radio spectrum or infrastructure but lease them from network owners to provide customized services to their users [44].

Network sharing is thus attracting growing attention as means to reduce CAPEX and OPEX, expand network coverage and enable fast new network rollout [45]. In passive RAN sharing, multiple operators co-locate the physical sites for antenna towers and share passive elements (such as power supply) whilst installing and operating their own antennas and base stations. In the case of active RAN sharing, operators share the same antennas, base stations and spectrum using network virtualization technology [45] [46]. The 3GPP standardizes the necessary functionalities to enable several core network operators to share one radio access network in [4].

However, the detailed implementation of radio resource allocation is left open. Transport backhaul and core network entities may also be shared by multiple operators using
wired/wireless links, shared nodes and server virtualization technologies [4]. A straightforward solution for radio resource allocation is to partition the spectrum band into multiple sub-bands and assign each operator a sub-band permanently (i.e. a fixed set of physical RBs in LTE).

However, this static reservation solution is sub-optimal in terms of overall spectral efficiency because it reduces the frequency diversity available to each operator and does not allow temporarily unused resources belonging to one operator to be ‘borrowed’ by another operator. A better method is to allow all operators access to the whole bandwidth but apply a mechanism to manage the fraction of resources each operator consumes on average. Although some results have recently been published, there is still a great need for more comprehensive results addressing relevant issues so as to support the emerging content-rich end-user services in a more user-friendly and cost-effective fashion.

These issues start from the more fundamental concepts and technologies such as node/link virtualization and their mapping to physical resources, and then the modeling and performance analysis of virtualized networks. Moreover, different virtual networks should meet requirements of different network services ranging from network layer to application layer service. The virtual networks should provide resource guarantees for different services, and an easy way to operate and manage services. Finally, specific solutions for the LTE-A architecture should be constituted based on the idea of combining SDN as a tool of orchestration and the existing architecture.

The design objectives of such solutions should include isolation, flexibility, programmability, manageability and scalability. First of all isolation should be offered in terms of logical view, resources and operation. As far as flexibility is concerned, the service providers may assemble virtual networks with customized network topology such as control and data plane functionality without the need to coordinate with each other.

The tendency towards programmable networks has the objective to implement in software customized protocols and services in network elements and to open up vulnerabilities. Moreover, manageability of the network is a goal of great importance because there is the target to define policies and orchestration between several network elements, seamlessly between Service and Infrastructure providers. Finally, scalability issues refer to the support of multiple virtual networks and the efficient utilization of resources.

Our work aims to create solutions for an LTE-A network environment in which multiple service providers can share underlying physical resources from multiple infrastructure providers and dynamically compose heterogeneous virtual networks that coexist in isolation within the same physical infrastructure. These multiple service providers should compete with each other by deploying customized end to end services depending on the users' needs,
managing the services on the virtual networks specifically targeted to the end users and effectively sharing and utilizing the physical resources.

In this set-up, each virtual network has its own virtual network controller and can independently specify the end-to-end Quality of Service (QoS) and Quality of Experience (QoE) it expects for its different customer segments. The resource manager can automatically shift resources between services on-demand to meet capacity requirements. Resource allocation can be extremely agile, enabling, for example, an operator to access extra resources to cover a major event.

In the context of CROSSFIRE project we attempt to utilize the concept of sharing resources in terms of RBs in on-demand and self-service way, to achieve the principles of RAN virtualization in LTE-A, and in parallel take advantage of the newly introduced concept of small cells to offload the available data traffic.

We focus on the RAN part of the LTE-A networks and especially the main nodes that consist the RAN; the eNodeB and small cells. CROSSFIRE aims to contribute in this area by creating solutions of mapping virtual path requests to substrate physical topology. This is considered as a step towards RRM in the context of network virtualization without altering the nodes of the existing architecture. Moreover, the utilization of the fractional radio resources spread around on multiple physical small cells using the concept of physical resource transfer is of critical importance. This concept is an efficient way to redistribute the available resources and help small cells to serve seamlessly the maximum possible number of users.

According to the state of the art in RAN virtualization, researchers have a tendency to focus on slicing the available spectrum instead of proposing solutions where the spectrum is delivered on-demand to the participating operators. Since LTE-A is an Orthogonal Frequency Division (OFDM) based system, the whole system bandwidth is available for an eNodeB. However, not all the subcarriers are used simultaneously in a specific set of cells, i.e. according to Inter-Cell Interference Coordination (ICIC) techniques each subcarrier is not usually allocated to more than one BS simultaneously. Actually, the ICIC techniques are aimed to reduce the interference level, particularly in the cell edge. ICIC actually tries to reuse resources only if interference is low enough (i.e. the interfering source is at a minimum distance), but resources are nevertheless reused.

Therefore, an efficient use of the available radio resources can be achieved if a proper coordination / negotiation of the resources is carried out among the BSs. Moreover, to the best of our knowledge, there is no previous work that takes into account the concept of resources negotiation by exploiting the dense LTE-A environment. RENEV presents a practical solution based on network virtualization to implement such resources negotiation.
As the minimum resources unit defined in LTE-A is the RB, our work will be focused on the negotiation of the resources among RAN nodes on RB basis.

The basic scenarios where CROSSFIRE will focus on, would be deployments consisting of numerous small cells with and without the inclusion of an eNodeB. According to [23] below the potential topologies that will be examined in the context of the project are discussed. Figure 11 gives an overview of the two tier deployment with the coexistence of eNodeB and small cells.

![Figure 11: General deployment of two tier scenario with small cells and eNodeB [22].](image)

In Figure 12 the scenario 2a introduced in [23] is depicted. The Outdoor small cells are deployed in the presence of an overlaid macro network. The frequency deployment of the macro cell and small cells is distinct and small cell cluster is considered as well. Both ideal backhaul and non-ideal backhaul are considered for the following interfaces:

- Between the small cells within the same cluster
- Between a cluster of small cells and at least one macro eNB
- Non-ideal backhaul is assumed for all other interfaces
Correspondingly, in Figure 13 indoor small Cells are deployed in the presence of an overlaid macro network. Separate frequency deployment of the macro cell and small cells and a small cell cluster is considered as well. As in the previous scenario was considered, both ideal backhaul and non-ideal backhaul are considered for the following interfaces:

- Between the small cells within the same cluster.
- Between a cluster of small cells and at least one macro eNB.
- Non-ideal backhaul is assumed for all other interfaces

Scenario 3 is the deployment scenario where only small cells on one or more carrier frequencies are connected via non-ideal backhaul (Figure 14).
The above cases are also described in [24] and handled from a higher layer point of view. According to [24], Scenario #1 is the deployment scenario where macro and small cells on the same carrier frequency (intra-frequency) are connected via non-ideal backhaul. One of the main challenges in this type of scenario that we aim to improve within the CROSSFIRE project is to improve per-user throughput by utilizing radio resources in more than one eNodeB (and consequently small cells).

Scenario 3

![Diagram of small cell deployment](image)

**Figure 14: One tier deployment consisting only of small cells [22].**

As described in [24] different services and bearers typically have different QoS characteristics. For example, VoIP traffic has tight delay requirements but does not require high bit rates and can tolerate rather high packet losses. In contrast, best effort traffic benefits from higher bitrates but is less delay sensitive as compared to VoIP traffic. It is desirable to take such QoS requirements into account when multiple cell resources are available. However, if non-ideal backhaul is utilised between macro and small cells a solution, for increasing user throughput by leveraging the utilization of radio resources across those of cells while taking QoS requirements into account, is a challenge.

The other deployment scenario that we investigate throughout our work is Scenario #3 introduced by [24]. This is the deployment scenario where only small cells on one or more carrier frequencies are connected via non-ideal backhaul.

3. **Open eNB (UoA)**

The aim of this research activity is to investigate what may be the benefits of applying network virtualization in a LTE RAN by promoting the use of innovative open access base
stations, capable of allowing the sharing of their resources among multiple operators. The main goal of this work is to devise solutions that use network virtualization as a tool for improving the user performance. This can be done by allocating even more resources to UEs and at the same time by reducing the causes of performance degradation. It is common knowledge that the user performance is affected by various factors, such as the distance to the serving base station, the channel quality or the interference at the cell site. The network layout of the operator is perhaps the most important factor affecting the user performance, e.g., the base station deployment density and layout.

Working in this direction, it has been proposed a framework that, under certain conditions, allows UEs to have access to a larger number of RAN access points, represented by a variable number of virtual base stations. In this way, the average distance between the UEs and their serving base stations can be extremely reduced and this can be reflected in the achievement of better performance. To this end, it has been proposed the use of a novel type of eNodeB, called OpeNB, that allows multiple operators to share on demand their physical resources and available bandwidth.

The OpeNB consists of one or more instances of logical software entities, called VeNBs that emulate the protocol stack of an eNodeB. Such VeNBs can be controlled by different operators in a dynamic fashion, and, essentially, from the operator perspective, they appear as additional (virtual) base stations to be used in case of need. The capability of the OpeNB consists in allowing the coexistence of multiple VeNBs in the same physical infrastructure and in creating and setting up the link between each UE and the appropriate virtual base station. All this operations are transparent from the user perspective, since it gets the impression to receive a service from a real base station.

Figure 15 depicts the CROSSFIRE reference architecture and the part in which the investigated network virtualization technology impacts. The proposed solution can be easily integrated in the CROSSIFRE reference architecture, since it is not invasive from the architectural point of view. Looking at Figure 15, it can be seen that the OpeNBs are placed in such a way to be overlapped with the other RAN base stations (eNodeBs, Pico-eNodeBs, HeNBs).
The OpeNBs can coexist with the Macrocell, Picocell and Femtocell subsystems since they appear as legacy entities, although they are endowed with additional features that allow them to be shared among multiple operators. Note that they can be simultaneously connected to multiple core networks. The main difference between the OpeNBs and the other base stations is that the first ones are logically managed by a software centralized entity, which acts as a SDN Controller (discussed in the next sections). This entity is capable of having a global view of the network and is responsible for establishing which operators and which users can benefit from the additional resources made available by the VeNBs. Moreover, the SDN controller is a non-intrusive entity, since the communication with the OpeNBs is based on a novel protocol, called OpenFlow, that does not interfere with the traditional signaling protocols used in LTE-A.

Further details regarding the operation mode of the proposed RAN virtualization solution will be provided in the section 3.2. In Section 3.1 is provided a review of the state of the art with particular emphasis to the architectures and protocols that have been recently proposed for the RAN virtualization, while Section 3.2 describes the proposed OpeNB framework and gives a description of the entities involved in the virtualization process.
3.1 State of the Art

3.1.1 Network virtualization concept

In recent years, the concept of network virtualization has attracted considerable attention in the debate on how to design the architecture of next generation networks. In fact, network operators need to meet the growing demand for traffic data, by emphasizing on network provisioning, which increases CAPEX and OPEX correspondingly. Network Virtualization is envisioned as a way to reduce both CAPEX and OPEX as it can be used to share the infrastructure and the physical resources among multiple operators. More specifically, network virtualization refers to the creation of a set of overlay architectures built on top of one or more existing physical infrastructures.

This can be done by decoupling the physical infrastructure management from the SPs. In this approach an InP allows the SPs to create virtual networks by aggregating a partition of its physical resources that are mapped in a collection of virtual nodes and a set of virtual links forming a virtual topology. On top of such aggregated resources, SPs can implement arbitrary virtual network topologies, routing and forwarding policies and independent customized protocols providing end-to-end services not just to end users, but also to other providers.

Figure 16 depicts an exemplary network virtualization environment, as described in [47] that is composed by two different virtual networks that are built on top of the same physical infrastructure. Such virtual networks do not require any changes to the underlying physical network and at the same time allow the UEs to utilize the services offered by the SPs in a transparent manner.

The objective of network virtualization is to provide coexistence of multiple virtual networks from different SPs and flexibility in every aspect of networking. In addition, the following challenges need to be addressed for the realization of a network virtualization environment: interfacing and efficient allocation of physical resources. Each InP must be able to provide a standard interface that can allow the SPs to communicate the requests for the allocation of the physical resources. In addition, the appropriate standard interfaces between UEs and SPs need to be designed and standardized. Moreover, the definition of an efficient scheduling scheme for the physical resources allocation among multiple virtual networks is a very challenging task since it is necessary to maximize the utilization of resources in order to satisfy the QoS requirements of the actors involved in the virtualization process.
There are many benefits for considering the virtualization of the physical resources as an important requirement that should be taken into account in the design of the next generation network architectures. The most common ones may be summarized as follows:

- **Sharing**: for an efficient utilization of the available resources, if a resource is too big for a single InP, it is better to share it among multiple SPs.
- **Isolation**: to ensure isolation among multiple users/tenants and to guaranteed confidentiality and privacy among different virtual networks.
- **Aggregation**: to achieve the possibility to construct a large virtual resource from multiple small resources. Aggregation can also increase energy-efficiency of the substrate physical network. In fact, the aggregation and the mapping between physical and virtual resources can be done in such a way to balance the overall load by preferring the most energy efficient nodes. The reduction of the total power consumption can be achieved by aggregating the virtual demands in a consolidated subset of physical nodes and by switching off as many network nodes and link as possible. In order to save energy, as many nodes as possible should be mapped on the same set of active substrate physical nodes. The key idea behind this approach is discussed in the Broadband Forum’s MR-204 white paper [48]. This document discusses how energy efficiency can be addressed by standardizing new technologies that transform the network infrastructures from “always on” to “always available.” This means that the network devices have the opportunity to reduce their
power consumption when not in use. Network Virtualization can be successfully used for this issue, since it offers the opportunity to develop efficiency methodologies that can dynamically adapting the virtual network topology to the energy saving requirements.

- Ease of management: by simplifying the management and administration of the network nodes through the use of an abstract interface that hides the underline physical layer and allows the SPs to control the behavior of the virtual device with a software-based approach.

### 3.1.2 SDN/OpenFlow: network virtualization background

The design and experimentation of network virtualization architectures is the subject of the increasing attention of the industrial and academic research communities. To this end, the latest revolution in networking innovations is represented by the Software Defined Networking paradigm [49]. All components of research academy and networking industry, including network equipment vendors and Internet service providers are working on or looking forward to several aspects of SDN. The basic idea of SDN is to transform network devices in fully programmable nodes and allow the creation of virtual networks independently of the physical networks. More specifically, SDN consists of four innovations:

1. Separation of the control and data planes
2. Centralization of the control plane
3. Programmability of the control plane
4. Standardization of APIs

SDN revolutions the way in which the network protocols have been conceived so far. Traditional networking protocols are usually organized in three planes: data, control, and management. The data plane consists of all the messages that are generated by the end users. The control plane consists of the messages exchanged for establish which paths the user messages will take. The innovation made by SDN consists in decoupling the control plane from the data plane and move intelligence away from edge nodes towards a centralized logic entity, a.k.a. Controller. In this way the network control is logically centralized and it is easier to manage and program the control plane. Moreover is easier to dynamically change the network behaviour by focus only on the software that runs in the Controller. In Figure 17 is shown the logical view of the SDN architecture, as proposed by the Open Networking Foundation [50]. ONF is a user-driven organization dedicated to the promotion and adoption of SDN through open standards development.
At the bottom layer of such architecture the network nodes are placed. These are physical pieces of equipment such as routers, switches, and access points responsible for the forwarding operations only. All control operations are executed in a logically centralized manner by a network Control Layer. Such layer hides the network topology characteristics to the upper layers, providing an abstract view of the network through high level APIs and it is also responsible for collecting and providing to the upper layer information about the state of the individual network nodes. Since the network state is logically centralized, the network managers can easily configure and optimize network resources via customized SDN application programs that run on top of the Control Layer and interact exclusively with it through high level APIs. The Control layer transforms the application demands in appropriate instructions that are sent to the physical devices through a Control Date Plane interface. In short, the aim of this architecture is to facilitate the logically centralized control of heterogeneous physical devices regardless of the technology that is adopted at the physical layer. SDN also significantly simplifies the management of the network devices themselves, since they no longer have to interact with thousands of protocol standards, but simply execute the instructions that are received from the aforementioned Control layer.

The ONF is also promoting the definition of open APIs to encourage multi-vendor management and to open the door for on-demand resource allocation and accurately virtualized networking. To this end, ONF has worked on the standardization of the OpenFlow [51][50] protocol. OpenFlow defines the communication interface between the control and forwarding plane of the network nodes over a SDN network. More specifically, OpenFlow specifies basic primitives that can be used by SDN applications to program the forwarding plane of network devices. This OpenFlow control software instructs the network devices where to send packets based on specific rules. These rules contain a list of actions that must be performed in each device upon packet reception, and, essentially, define the behavior of the entire network. The key feature of OpenFlow is that such rules can be updated on the fly based on the needs of the network (traffic, link congestion, etc.). In this way, a network operator can manage and modify the behavior of the entire network by focusing only on the software that runs on top of the Controller Layer. OpenFlow has been initially designed for a specific wired scenario composed by switches connected to each other via a fixed cable, but the key idea of this protocol can be also valid in other use cases such as mobile and wireless networking.
Figure 17: SDN logical architecture

However, deploying network virtualization in mobile networks is complicated, due to the vastly heterogeneous infrastructures and topologies, different spectrum bands and different mobility requirements as well as because of lack of a converged management system.

To this end, network virtualization for mobile network scenarios arise several technical challenges and requirements, including:

- identification of resources to share
- design solutions for the dynamic resource allocation among multiple operators
- isolation of the sliced network resources
- efficient resource utilization to maximize the benefit for both users and network operators.

The SDN paradigm is also particularly well suited to satisfy the above requirements. Recently, ONF have formed the Mobile Wireless Study Group to investigate the application of the SDN paradigm in wireless and mobile domains. The aim of such working group is to suggest extension of the SDN/OpenFlow specifications to support various issues related to optimization and management of multiple wireless technologies. A possible use case that is currently under investigation regards the use of SDN for multi-tenancy mobile network scenarios. The SDN logically centralized control can allow an efficient base stations coordination, which can be useful for the inter-cell interference and mobile traffic management in order to enable efficient and optimal resource management decisions and improving the utilization of scarce RF spectrum. In addition, SDN makes innovation easier by allowing mobile operators to dynamically re-program the network policies according to
specific needs and user requirements. In addition, network operators can experiment innovative approaches to manage network congestion and new methods to classify and offload traffic. In short, SDN has the potential of allowing the development of higher performance and more efficient mobile networks while also improving the end user experience. To this end, in [52], is analyzed what possible benefits might be obtained by transforming the existing cellular networks in SDN-based architectures. The authors of this paper argue that some potential gains can be achieved and a more efficient inter-cell interference management might be possible by using a centralized SDN controller, endowed with the capability of having a global view of the subcarrier allocation profile of multiple eNBs.

In the next paragraph is presented the current state of the art about other network virtualization schemes for mobile networks while in section 3.2 is described the proposed OpeNB framework for the LTE RAN virtualization in which the benefits of applying SDN and OpenFlow have been explored for introducing network virtualization with an extensible, highly adaptable, and less invasive approach.

### 3.1.3 Network virtualization in mobile networks

In current literature, the discussion about the requirements and the benefits of introducing virtualization in mobile networks is in its infancy. There are primarily two different scopes of virtualization that are foreseen for a mobile network architecture. The first one falls under the scope of virtualization of the air interface between the UE and the eNodeBs and the second one is to virtualize the physical nodes from the base station extending to the backhaul. For cellular networks, base station virtualization is achieved when its hardware and resources can be shared and assigned to different network operators. The sharing of these resources needs to be fair, i.e., in terms of the amount of spectrum to allocate to each operator. Some methodologies for resources allocation in a virtualized base station are discussed in the GENI technical report [53]. More specifically, authors focus on virtualization procedures that provide slice isolation at the virtual base station via FDMA or TDMA techniques. Such procedures can be used for virtualizing a node by partitioning the available frequencies or by partitioning along the time dimension allowing different operators to use a given frequency partition in different time slots. GENI is a virtual laboratory framework for at-scale networking experimentation that have been used in some works for testing network virtualization solutions for mobile network, especially in the context of WiMAX architectures. In one of these works, authors propose a network virtualization substrate [33], called NVS, for virtualizing WiMAX base stations to achieve a shared use of base station’s radio resources between multiple virtual operators. The NVS integrates virtualization into the downlink scheduler software. In order to achieve this, NVS separates the scheduling process
into two steps: a first level of flow scheduler is controlled by each tenant and a second slice scheduler is managed by an additional virtualization layer that hides the virtual instances of the base stations from the concrete physical resources. In [54] authors propose a novel virtual base transceiver system for a WiMAX virtualization architecture that uses instances of the base station firmware on virtual machines. The aim of the proposed system is to emulate a fully functional WiMAX base station Transceiver to every slice user.

Similarly, for LTE virtualization, the architecture proposed in [32] modifies the MAC scheduler of the eNodeB to isolate the traffic of different slices. More specifically, authors investigate network virtualization for the LTE access network to enable multiple operators to share the spectrum and achieve multiplexing gain. The key component is an entity, called Hypervisor, which is placed on top of the physical layer in the eNodeB. The Hypervisor virtualizes the eNodeB into a number of virtual eNodeBs allocating the physical resource blocks among multiple virtual operators with respect to some predefined agreements.

In the Virtual Radio Project [28] is analysed how different radio systems can be realized as virtual networks on a commonly shared physical network infrastructure. It is assumed that a physical network infrastructure is available and provided by an InP while the dimensioning of the availability and capacity of the infrastructure is achieved based on demand requests of one or more virtual network operators. The infrastructure nodes are then responsible for the resource sharing and interference avoidance between the virtual radio networks. Multiple virtual nodes can coexist within a physical network node and each virtual node can have its own transmission procedures and protocols. The coordination and management of physical resource is performed by a resource allocation control function, which performs the multiple access resource allocation among each virtual radio system.

In another project, called FLAVIA [17], it is investigated the design of a new base station architecture with the objective of enabling a higher level of programmability. In the context of wireless access virtualization FLAVIA promotes the concept of a programmable wireless MAC processor that provides a set of open interfaces that can allow each virtual operator to design the desired scheduling protocol.

### 3.2 Multi-tenancy sharing infrastructure

**3.2.1 Open RAN access via OpeNBs**

Future mobile networks capacity requirements have led to network sharing being considered a key business model for reducing future deployment and operational costs. Network sharing solutions are already available and standardized in 3GPP TS 23.251 [4]. These solutions can be divided into passive and active network sharing. Passive sharing refers to the reuse of components such as physical sites and nodes while active sharing
refers to the reuse of backhaul, base stations, and antenna systems. Current solutions, however, have limitations in terms of separating both data and control planes among operators and constraints regarding flexibility and capability for satisfying different requirements per operator.

In the contest of the WP2, a research work has started to investigate what may be the benefits of using a RAN integrated with virtual base stations. The proposed framework, referred to as “OpeNB”, is an attempt to utilize the benefits of SDN and OpenFlow, introducing network virtualization in LTE networks with an adaptable, highly extensible, and less invasive manner. The OpeNB framework permits the virtualization of the LTE eNodeBs depending on the network state and enables an operator to lease on-demand the physical infrastructure and resources of additional eNodeBs (usually owned by different operators). The novelty of this framework is based on the flexibility offered by the use of OpenFlow, which allows for the dynamic virtualization of existing physical eNodeBs. In fact, since in OpenFlow the control plane of the network entities is moved in a centralized Controller, the network virtualization policy can be easily modified or dynamically adapted to new requirements by focusing only on the Controller software. Furthermore, the choice of OpenFlow, as a key tool in the process of virtualization permits to ensure compatibility with the emerging network architectures that are already using OpenFlow in the wired scenario.

![Diagram of OpeNB framework](image.png)

**Figure 18: Physically nearest base station model.**

To illustrate the key idea of the OpeNB framework, it’s convenient to consider an exemplary scenario that is shown in Figure 18, in which a particular eNodeB is owned by a single LTE network operator “A” and serves only the UEs registered to A. Under certain
occasions, A can lease some of the physical resources of its eNodeB to one or more other operators. The number of the non-registered UEs that this eNodeB can host depends of the local availability of physical resources. Now, consider an UE who is registered to another LTE network operator “B”. According to the traditional cell association procedure in LTE, the UE which moves in the area served by its operator is associated with the eNodeB that offers the strongest signal.

What the proposed framework does is to enable UEs registered to B to associate and receive service by additional eNodeBs that are owned by A. If such base stations has available resources to serve the traffic of the tagged UE, the serving eNodeB of operator B can initiate a network virtualization request to the target eNodeB of operator A, in order to host a virtual eNodeB and ultimately serve the tagged UE registered to operator B in a transparent and backwards compatible manner. The coordination among all these base stations is governed by a logically centralized SDN Controller which knows everything about the network state and the network topology. In fact it is periodically informed about the UEs that could improve their performance using the OpeNB framework. For each UE it subsequently identifies if there is a nearest base station endowed with network virtualization capabilities. If so, the UE is associated with the selected base station, even though it may be owned by a different operator. In this way, it can be overcome the limitation that imposes the UEs to utilize only the infrastructure owned by their operators. This approach makes possible to open the road ahead for novel cellular access models, moving from the predominant operator-limited cellular access model to a truly and physically nearest-base-station model. This procedure comes at the cost of a handover execution at the UE and additional core network signaling for coordination among the different operators. In addition, operator B is required to have a certain agreement with operator A for leasing physical resources.

The OpeNB architecture is shown in Figure 19. It consists of physical, software and virtual entities. The physical elements of the framework are the participating eNBs, which are divided in two types:

1) NAeNBs: eNodeBs that are aware of the network virtualization functionality through a simple software update. Even though this type of eNBs do not support network virtualization functionalities under the OpeNB framework, they are capable of communicating with the MC (explained below) and initiating/forwarding the network virtualization signaling towards an OpeNB.

2) OpeNBs: eNodeBs that are both aware of the virtualization functionality and capable of creating VeNBs to support the proposed OpeNB functionality. This type of eNBs allow multiple operators to share their physical resources and available bandwidth,
while they support all necessary control and data plane functions for implementing a VeNB. Each OpeNB integrates a single OFS, and is remotely programmed by a central SDN Controller using the OpenFlow protocol. Note that such OFS is not present in the NAeNBs.

Two types of software entities are also defined, referred to as the Main Controller and the OpeNB Controller, respectively. These entities are responsible for managing the physical elements of the framework as follows:

1) The MC acts as a SDN Controller and manages multiple OpeNBs. It is the place where the network intelligence resides and has the responsibility to activate the virtualization procedure to enable the OpeNB sharing among multiple operators. The MC also programs the Open Flow Switches by sending instructions/rules for handling the link between the UEs and the operators hosted in the OpeNBs.

2) The OC is integrated inside the OpeNB, and is responsible for activating to VeNBs upon request from the MC. The OC acts as a local controller/agent in the OpeNBs and communicates with the MC using a UDP-based signaling procedure.

The virtual entities, referred to as VeNBs, are logical software elements that emulate the protocol stack of an eNB. They are an integral part of the OC.

Figure 19 highlights the physical, software and virtual entities involved in the proposed OpeNB framework. More specifically, the OpeNB performs the functionality of the PHY and MAC layer as a traditional typical LTE base station. What is new is that the packets from/to the MAC layer pass through the OFS, which handles the packets with respect to the instructions provided by the MC. In particular, the output ports of the OFS are connected with the OC entity that implements the eNodeB protocol stack for each different operator. The OC essentially provides the abstraction of the OpeNB physical infrastructure and implements the physical resource sharing functions between the different VeNBs. The OC gives the VeNBs all necessary functionality to handle the allocated physical resources and implements the data/control plane towards the UEs. In addition, the OC coordinates the resource allocation between multiple operators, with respect to proprietary agreements between the operators, while it is also the medium through which the MC updates the entries of the OFS.
The MC decides on the rules required at the OFS based on the operator of each UE. The virtualization initiation procedure is based on measurement reports provided by all UEs to their serving NAeNBs, which in turn, forward these measurements to the MC. Even though, in the first implementation the OpeNB framework focus on the interference experienced from the users, the MC may account for different parameters, such as the traffic, current load, and energy consumption, during the rule making decision. For UEs that experience high interference, the MC identifies the most appropriate OpeNB in proximity and initiates a virtualization request procedure towards the target OpeNB.

Figure 20 depicts the signaling flow used for the activation of network virtualization procedure of the OpeNB framework. The procedure can be summarized as follows. Firstly, each UE sends measurement reports to its serving base station containing information about its network state. Secondly, the serving base station, reports to the MC both the list of the UEs that could improve their performance using the OpeNB framework, as well as the list of measurements performed by each UE. Upon receiving these information, the MC identifies if there is an OpeNB that can improve the performance of the target UE. If so, the MC sends a request to the corresponding OC of the selected OpeNBs, containing the UEs that need to be served by this OpeNB. For each UE, the OC performs Admission Control to check the local availability of resources, identifies the VeNB that refers to the operator of the UE and assigns it a predefined number of PRBs. After the VeNB selection, the OC notifies the MC.
the list of UEs that can be served by the OpeNB and the port number of the OFS on which the appropriate VeNB is connected to. At this step, the MC sends to the OFS an OpenFlow packet containing a pair with rules and actions for the specific UE, according to the signaling protocol used in OpenFlow. Finally, each UE will receive the handover command to the selected OpeNB and all the packets originated from the UE that match the rules contained in the OFS will be delivered to the appropriate VeNB.

**Figure 20: OpeNB signaling Flow**

The main benefits of the opeNB framework can be summarized in the following key points:

- It’s an OpenFlow based framework that make it easy to program the network policy by focusing only on the Controller software.
- It can be used for many purposes: improvement of the interference experienced by UEs, improvement of other UE performance such as throughput, quality of service and quality of experience. What is needed is only to implement a new policy in the software in the controller.
- It can be used for the implementation of load balancing techniques by assigning the user to the opeNBs with low load.
- It can promote new market opportunities by allowing the instantiation of VeNBs for the emerging application service provider (such as Google, Youtube).
- It can allow the sharing of one base stations between multiple core networks. In addition, it can be extended to allow the use of multi technologies in the access
network: in fact, since the protocol stack of the virtual base stations is implemented via software, there are no restriction on the type of the technology to use in the RAN.

4. **Programmable RAN (NEC)**

The crossfire reference architecture is shown in Figure 21. In LTE-A networks, SDN with network virtualization aims to enable efficient sharing of network resources with greater flexibility and finer control over the network to reduce CAPEX and OPEX for the operators. This could be achieved by virtualizing the network through various approaches.

SDN with network virtualization allow the deployment of multiple virtual networks on top of a common network infrastructure. It decouples the control and data plane of the network and isolates the underlying physical infrastructure thereby forming virtual networks. Multiple virtual networks can co-exist and share a common physical network based on pre-defined rules and policies. In LTE/LTE-A networks a number of network functions both physical and logical can be virtualized in the Radio Access Network (RAN), Backhaul and Evolved Packet Core (EPC) for optimized resource usage and management. SDN with network virtualization also enables multi-tenancy enabling isolation, policy-enforcement, and charging of different users i.e. different service providers, with the ability to deploy and test innovative network applications in a very short time.

The latest 3GPP LTE-A release [1] [2], defines a heterogeneous environment consisting of E-UTRAN NodeBs (eNodeBs) and small cells (i.e pico eNBs, Relay Nodes (RNs) and Home eNodeBs (HeNodeBs)) as shown in Figure 21. With increasing mobile traffic the wireless network infrastructure is getting increasingly denser and chaotic. One of the primary reasons to make the networks denser is to increase the network capacity. This way by bringing the wireless infrastructure closer to the users, networks can theoretically improve link quality to each user and decrease the number of users being served by the each base station or wireless access point.
As the spectrum is limited and scarce, sometimes the dense networks are deployed with a frequency reuse factor of one i.e. the neighboring base stations have to operate on the same channel. This could lead to tight coupling in control plane decision making at the neighboring base stations i.e. radio resource management decisions and parameters such as deciding what spectrum to use to transmit at what power to which client) made at one base station have substantial impact on neighboring base stations and vice versa. Thus, due to this tight coupling in control plane decision making, managing dense wireless networks especially with a frequency reuse factor of one is a significantly complex task.

Figure 21: Virtual Cell in the CROSSFIRE architecture.

There are two main aspects of coupling in the control plane decision making. First, the users of one base station experience significant interference from the neighboring base stations due to the high frequency reuse and broadcast nature of wireless communication systems. If this interference is not managed in a proper way it significantly degrades the capacity. Second, as the coverage area is small, the load fluctuates more rapidly due to higher user mobility. Consequently handovers, cell association, and resource (spectrum) allocation have to be managed at each base station in concert with its neighbors to maximize the network capacity by carrying out tasks such as interference management, load balancing, etc.

Conventionally, radio access network is treated as a group of base stations, each largely making independent control plane decisions at the radio layer with some loose
distributed coordination via mechanisms such as SON (self-organizing networks), ICIC, CoMP etc. However, in case of dense network deployments as the size of the cells are small, coordinated control plane decisions have to be made across several neighboring base stations simultaneously often with as low latency as possible. Distributed coordination algorithms do not always scale well as they need to work with larger number of base stations and could be prone to higher latencies. This leads to performance degradation, significantly reducing capacity due to the inability to efficiently manage interference and optimize load. Furthermore, distributed coordination algorithms often require iterative and periodic adjustment of resource allocation decisions at the radio layer that are hard scale and hence these algorithms tend to become more complex.

Therefore, in such a heterogeneous and dense network deployment scenarios, the virtual cell concept based on SDN approach with intelligent and efficient network management and optimization strategies could prove to be very useful in addressing the problems faced by conventional communication networks and to serve the varying UL-DL traffic needs in real time. Virtual cell concept for TD-LTE systems, enable users residing in overlapping coverage regions of different cells to utilize resources from multiple base stations. The virtual cell scheme addresses the problem of pseudo-congestion by efficiently managing, scheduling and sharing the available resources in both UL and DL directions. It provides improved resource flexibility and real time adaptation to serve the varying traffic demands in UL and DL directions with enhanced overall system performance.

The virtual cell concept offers a distributed approach that exploits both spatial and time domain for enhanced load balancing and efficient resource sharing in real time to address varying traffic needs in UL and DL directions. The decision to form the virtual cells and the selection of appropriate UL-DL TD-LTE configuration across multiple base stations with the objective to provide efficient usage and intelligent management of network resources can be controlled with the help of an intelligent and logically centralized entity such as a SDN controller based on several factors for e.g. interference, separate user requirements for the UL and the DL, instantaneous traffic conditions in the UL and DL etc.

4.1 State of the Art

Since the beginning, mobile communication networks have been designed, built and operated as vertically integrated systems, this means that operator owns the network infrastructure and spectrum, applications are well defined for example voice or sms and devices are built with closed architectures. This type of architecture exhibit very tight coupling between all network elements. As a result existing cellular network suffer from expensive and rigid equipment, complex control plane protocols and vendor specific configuration
interfaces. One of the most indubitable challenges for the existing cellular infrastructure is to address the rapid and variable growth in mobile data traffic due to massive increase in the number of mobile devices, data service usage and dynamic traffic patterns. Therefore designing, developing and standardizing new network architectures to support the rising demand in mobile data services without increasing the CAPEX is not just a need but a necessity.

To address such issues, we need a holistic approach to transform the way networks are managed based on real time traffic behavior leveraging the strength of Software Defined Networking (SDN) and virtualization. This approach would simplify network management and provide flexibility to enable new services. SDN offers a logically centralized control model, unprecedented programmability, and a flow-based paradigm that is suited for highly scalable mobile and wireless networks, from access, backhaul to core. This approach would also enable rapid innovation, reduce OPEX and harvest the underlying business opportunities. OpenFlow is considered as one of the enabling communication protocols for SDN that allows access to the forward plane of the network elements over a network [55]. The Open Networking Foundation (ONF) has defined an SDN architecture model that is discussed in [56] with compelling business case for mobile and wireless networks. Here, two use cases have been discussed that illustrate the value proposition: wireless network control for inter-cell interference and mobile traffic management.

Over the past few years, network virtualization and SDN have received a significant attention especially in the mobile network virtualization domain. Virtualization in the field of computer science is a well-known technique and has been studied and used for several years for example virtual memory, virtualizing computer hardware, virtualized operating system etc. In next generation broadband wireless networks and future Internet, one possibility is to have multiple co-existing mobile operators, in which each is designed and customized to fit one type of network with specific requirements. Network Virtualization will play a vital role in diversifying next generation high speed communication infrastructure into for example; separate virtual networks that are isolated from each other and can run different services within. Many research initiatives in the area of network virtualization and SDN have been carried out throughout the globe and several research and development projects are in progress. Some of these projects include 4WARD [57] in Europe, which investigated the concept of network virtualization. CROWD-Connectivity management for eneRgy Optimised Wireless Dense networks (CROWD) [58], an EU FP7 project that focus on SDN based solutions for dense wireless networks (DenseNets). The project aims to use the SDN paradigm to develop flexible control mechanisms to coordinate the wireless access and backhaul network.
Some other approaches to SDN include ODIN which is an SDN framework for enterprise WLAN [59]. CloudMAC [60], it is a new OpenFlow based management architecture for 802.11 MAC layer processing in the cloud. It addresses the challenge of operating large WLAN deployments with heterogeneous hardware and software components that is faced by the network operators. Existing enterprise WLAN management systems support the management of such networks, but are inflexible in implementing new services. CloudMAC attempts to resolve this issue by concentrating most processing and management functionality on virtual access points that can be provided via existing cloud infrastructure. It provides a separation between data and control plane to have more control and flexibility over the network. OpenRoads for wireless is an opensource platform for innovation in mobile networks [61]. It enables researchers to innovate using their own production networks, through providing a wireless extension OpenFlow. It is a test bed approach that allows multiple network experiments to be conducted concurrently in a production network. Virtualization of the mobile network’s radio resources in WiMAX networks have also been studied in [62]. Here, the authors have focused on virtualizing the spectrum resource at the radio interface of a WiMAX network, using a flow based scheduling system in which slices are provisioned by the time-scheduler.

4.1.1 Mobile Network Virtualization
The basic idea is to virtualize the physical elements in a mobile network to ensure maximum flexibility in order to efficiently manage the network resources and adapt to the changing traffic behavior. It creates a system in which the user and control plane are decoupled by an abstraction layer from the services that run on top of it and allows network elements to be controlled, operated and optimized by other entities in the higher layers. This approach supports backward compatibility and has the potential to dynamically deploy innovative services in a very short time.

One of the key motivations behind mobile network virtualization is to enable dynamic and on demand network sharing for both core and access networks. Network virtualization provide operators more independent control over their share of the common physical network this further improves sharing by making it more efficient and provide greater flexibility.

Network consolidation and network slicing are the two different aspects of network virtualization that have been identified and needs to be understood clearly [63]. Network consolidation aims to consolidate separate physical networks into one physical infrastructure as shown in Figure 22. While network slicing refers to partitioning the network resource into several isolated networks with the help of virtualization technology as shown in Figure 23.
Each of these separate networks then could be configured and optimized to deliver specific services and it can be possible to have a multitude of service specific networks.

4.1.2 Virtual eNB

Another approach towards RAN sharing is to virtualize the eNB in LTE [64]. The virtualization of physical hardware in the eNode B that is responsible for transmission and reception of data from an LTE user can be performed by adding a hypervisor layer on top of the physical resources similar to any other node virtualization. This layer is then responsible for allocating and scheduling resources such as air interface or LTE spectrum between different virtual base station instances running on top of it. OFDMA is used as air interface in the downlink in LTE, which implies that the spectrum is divided into a number of sub-bands. Air interface resources are actually the physical resource blocks (PRBs) which are the smallest unit an LTE MAC scheduler can assign to the user. Different policies and scheduling schemes can be applied by the hypervisor to share the resources amongst virtual eNBs. The information such as channel conditions, QoS, priorities, traffic load, contract of each virtual operator etc. is collected by the hypervisor from each virtual eNode B and is used to schedule resources.

Two use cases are considered here each with different versions of the hypervisors as explained in [64]. One use is the multiplexing use case, which exploits multiplexing gain achieved through eNB virtualization and spectrum sharing amongst different virtual network operators. Potential for achieving multiplexing gain via spectrum sharing arises from the fact that different operators experience their peak traffic load at different times. Two different
versions of hypervisors could be employed in multiplexing use case. Static Hypervisor-equal numbers of PRBs are allocated by the hypervisor just once in the beginning to each operator. Each virtual operator keeps its PRBs regardless it is using it or not. Dynamic Hypervisor-PRBs are dynamically allocated to different virtual operators at equal time intervals according to the load that each operator is experiencing during the last time instance.

The other use case is the multi-user diversity use case. This use case arises from the fact that channels are usually frequency selective i.e. each user experience different channel conditions on different PRBs. Multi-user diversity case employs channel aware scheduler which tries to take advantage of the user channel conditions and assigns the PRBs accordingly. As virtual operators share the spectrum, this means that the scheduler has a larger pool of PRBs to exploit the multi-user diversity. This use case provides an opportunity to achieve gains by employing dynamic spectrum allocation based on user channel conditions, even when no multiplexing is allowed and each operator has a fixed amount of spectrum.

### 4.1.3 Programmable SDN-based Mobile Networks

SDN architecture model as defined by Open Network Foundation (ONF) is depicted in Figure 24. It consists of three distinct layers namely the application layer, the control layer and the infrastructure layer that are accessible through open APIs.

In SDN based mobile communication networks, the network is controlled in a centralized manner with network management and optimizing algorithms running as an application or logical entity called an SDN controller in the application layer. The information exchange between different network elements occurs through the control layer via open APIs. The SDN controller running management and optimization algorithms maintain the global state of the network and perform the logical decisions. The underlying infrastructure layer is abstracted from the higher layer and receives instructions from the SDN controller/applications. The decisions are based on the global view of the network and implemented in a distributed manner across the network. In case of LTE/LTE-A the eNBs receive configuration instructions from an SDN controller and the decisions are implemented across multiple eNBs in a distributed manner.

This way the usage of network resources can be optimized and managed based on a global view of the network in an efficient manner in real time with least human intervention. The state of the eNBs can be collected periodically and the global view of the network can then be updated in the form of a database. The information collected can be utilized by the SDN controller/applications running in the application layer for radio resource management and network optimization.
It is worth noting that there is a possibility of inherent delay in sending the optimization decisions or instructions by the centralized SDN controller and implementing those decisions by the eNBs across the network. Hence it is necessary that some control tasks which are based on local network parameters are moved to specific individual radio base stations. Therefore, the control decisions that aspects the neighboring eNBs should be made by the centralized controller, e.g. handovers, power control, interference and mobile traffic management etc. and the decisions that depend on rapidly varying parameters should preferably be made locally by the base station for e.g. resource block allocation.

4.2 Virtual Cells: Enhancing Resources in TD-LTE

Time Division Duplex (TDD) is one of the two variants of 3GPP Long Term Evolution (LTE). TDD utilizes the same radio access scheme as the Frequency Division Duplex (FDD) and uses the same sub-frame format as well as the same configuration protocols. The main difference compared with FDD, is the support of unpaired frequency bands, where downlink and uplink are separated in the time domain. The support of TDD increases the spectrum flexibility allowing operators to utilize both paired and unpaired bands. Besides its spectrum utilization properties, TDD increases the flexibility for the radio resource allocation among uplink and downlink supporting asymmetrical traffic efficiently.

In TDD each frame is composed by downlink (DL), uplink (UL) and special (S) sub-frames, which are used to switch from DL to UL and they are included at least once within each frame. The UL/DL portion of each frame may be configured according to the
specification provided in [1], which defines 7 different UL/DL configurations as shown in Table 1. Such resource flexibility is particularly useful for emerging applications such as video streaming, Machine Type Communication (MTC) etc. that are highly asymmetrical.

Despite the plethora of different UL/DL configuration modes, certain limitations introduce barriers that prevent operators from fully exploiting the TDD resource flexibility. Such limitations are associated with (i) interference when neighboring cells adopt a different UL/DL configuration, limiting the degree of resource flexibility and (ii) admission control when particular overloaded slots may introduce pseudo congestion [65] even when adequate resources exist but in the opposite transmission direction.

### TABLE 2: UPLINK-DOWNLINK ALLOCATIONS

<table>
<thead>
<tr>
<th>Sub-frame Number</th>
<th>UL/DL Config</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>D</td>
</tr>
<tr>
<td>1</td>
<td>D</td>
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<td>2</td>
<td>D</td>
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<td>3</td>
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<td>4</td>
<td>D</td>
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<tr>
<td>5</td>
<td>D</td>
</tr>
<tr>
<td>6</td>
<td>D</td>
</tr>
</tbody>
</table>

#### 4.2.1 Resource Management in TD-LTE

Current TD-LTE systems are configured with a specific UL/DL ratio that matches best long term traffic demands. Neighboring cells typically follow the same UL/DL configuration in order to avoid cross-slot interference, i.e. interference among neighboring eNBs or among UEs residing within a close proximity [66]. However, such synchronization introduces limitations in resource allocation when neighbor cells have different traffic demands. Methods that aim to enhance resource flexibility for TD-LTE systems concentrate on relaxing such synchronization [67] and on introducing dynamic resource management via channel allocation and scheduling [68]. Although such methods may enhance the resource allocation efficiency statistically, they cannot control interference, hence their impact is limited.

An alternative approach that considers interference control and additionally pseudo congestion, concentrates on decoupling the problem into two independent ones that focus on the UL and DL separately [69]. Employing a particular Call Admission Control (CAC) policy for each direction this scheme permits only connection requests that fulfills both UL and DL demands to be established. Treating UL and DL independently is also proposed in [65], which introduces the notion of interlink load imbalance, i.e. the utilization difference among
UL and DL, within a heterogeneous wireless access environment. Its aim is to enhance the resource utilization via an intelligent network selection keeping inter-link load imbalance as low as possible. The idea of configuring independently the UL and DL channels and their coverage jointly with neighbor cells is introduced in [70]. This permits a dynamic provision of asymmetric UL/DL resource allocation, allowing neighboring cells to adopt a different UL/DL configuration and provides a means of load balancing per transmission direction.

A hybrid TD-LTE system presented in [66] combines a static and dynamic resource region. The dynamic region is negotiated among neighboring eNBs specifying the number of UL and DL slots, while cross-slot interference is avoid by introducing power control methods. A similar proposal is also introduced in [71] where the benefits of adaptive UL/DL reconfiguration are verified via simulations. A flexible switching scheme between different TD-LTE frame configurations based on buffer considerations is proposed in [72] providing further UL/DL resource diversity for the cells’ inner regions. With such resource flexibility being the state of the art, the concept of virtual cells examines further the resource management enhancements, taking into account CAC and load balancing, considering the UL and DL separately, while allowing users to utilize resources from multiple eNBs.

The later feature is also supported by the 3GPP Coordinated Multi-Point (CoMP) [73] to enhance the cell edge throughput via joint processing or coordinated scheduling and beam-forming methods. By contrast to our proposal, CoMP requires coherent transmission and detection at physically separated eNBs, which jointly process the transmit/receive signal in order to gain from array and diversity gains. CoMP relies on the fundamental requirement to align the UL and DL resources of multiple cells without providing any means to counteract pseudo congestion as the applied UL/DL sub-frame pattern is assumed to be fixed for all cells, while a UE utilizes resources from different eNBs but in the same transmission direction. The virtual cell proposal concentrates on customizing the TDD frame according to the user traffic demand, which is beyond the use of conventional CoMP advancing the current efforts towards more efficient resource allocation.

### 4.2.2 The Virtual Cell Concept

The concept of the virtual cell refers to a TDD cell specific arrangement that enhances the efficiency of resource allocation. Such virtual cell concept is aligned with TD-LTE flexible frame configuration study carried-out in 3GPP RAN 1 [74] providing also a set of enhancements for regions where neighboring cells overlap. Specifically, virtual cells are formed within overlapping regions enabling residing UEs to use sub-frames from different eNBs. Assuming that the neighbor cells may employ different TD-LTE frame configurations as analyzed in [74] virtual cells can offer a unique type of frame, which is composed from different sub-frames that belong to the set of cells that compose such an overlapping region.
In this way a new notion of a cell is created, which is virtual since there is no physical infrastructure.

Virtual cells may achieve a higher degree of resource allocation flexibility, enabling the network to offer even more diverse UL/DL configurations, which can suit closer the customer needs at particular geographical areas. The adoption of virtual cells could prove particularly useful for densely deployed networks with diverse traffic demands per geographic areas, while its efficiency relies on mechanisms that constantly reflect evolving traffic conditions. To accomplish such resource flexibility, a dynamic frame configuration per cell is needed that match the UL/DL traffic demands at different times. Mechanisms that monitor the traffic demands jointly across the radio access and backhaul may suit best such scenarios, like the evolving Software Defined Network (SDN) management schemes adopted for mobile networks [56], which can be used to estimate the future traffic demands, based on history data and perform the frame reconfigurations for specific eNBs providing also suggestions for creating virtual cells.

Virtual cells offer a novel way of resource management, which allows UEs to utilize sub-frames from multiple eNBs matching better their traffic demands. UEs are no longer restricted to use the frame of a single cell, but can utilize specific sub-frames from different overlapping cells. Hence, eNBs and UEs not only exploit the spatial domain of conventional load balancing but additionally use the time-domain to change the cell-setup. Such an approach may resolve pseudo congestion among neighboring cells by providing more flexible, on demand UE specific virtual frames that utilize resources from multiple cells. Although virtual cells can be configured under a homogeneous environment, with all cells following the same UL/DL ratio, higher resource flexibility is envisioned when neighboring cells adopt a different UL/DL configuration. In this case conventional power control methods, similarly to [68], can be employed to resolve cross-slot interference. Hence, power control coordination among neighboring eNBs ensures that sub-frames with the opposite transmission direction are not provided at the same time within the virtual cell region. It is envisioned that the use of advanced power control mechanisms and interference mitigation techniques could further improve the efficiency and performance of the virtual cell scheme in TD-LTE systems.
For associating UEs to virtual cells, the UL and DL resources should be considered separately, allowing UEs to utilize UL and DL sub-frames from different cells. Figure 25 illustrates a simple example of a UE residing within the virtual cell region, utilizing DL resources from eNB B and UL resources from eNB A in order to match its traffic demand. Specifically, a UE with a high UL and relatively low DL resource demand cannot be served by any of the depicted eNBs solely without experiencing and causing congestion. By assigning the UE to both eNBs and utilizing resources from both, pseudo congestion can be avoided. For instance a UE associated with eNB A to take advantage of the UL resources may switch to the DL of eNB in order to fulfill its DL demand, instead of remaining on the UL of eNB A. Such operation creates a customized or virtual frame for these particular UUEs, which is composed of the shaded UL slots from eNB A and the shaded DL slots from eNB B as shown in Figure 25.

According to the virtual cell concept, adjacent cooperating eNBs appear as one logical cell with each eNB offering a different physical UL/DL configuration. This provides the basis for supporting more diverse applications within smaller geographical areas. It should be noted that UEs cannot utilize UL and DL sub-frames within the virtual cell region at the same time because of device and hardware restrictions. The process of utilizing sub-frames from different eNBs requires enhanced mechanisms to synchronize a UE and to align its transmit/receive mode accordingly. Hence, the proposed method requires additional signaling for control purposes. In general, the process of transmission and reception via multiple eNBs should be synchronized in order to ensure that the data towards and from the UE appears as a single stream. This may be achieved by:

- all eNBs receiving replicated data, which is handled accordingly for transmitting in selected sub-frames,
• a single eNB receiving all data and using the X2 to transfer it towards other eNBs involved in the transmitting process,

• splitting data sessions in the PDN/S-Gw (Packet Data Network/Serving Gateway) before it arrives to the appropriate eNBs,

It should be noted that session transmission and reception via multiple eNBs should be transparent to the user.

4.2.3 Virtual Cell Management: Re-configuration and Maintenance

Once virtual cells are configured, mechanisms to perform maintenance and management are essential to reflect evolving traffic demands. The scope of such an operation is to assess the current UL/DL configuration in combination with virtual cell formations in order to perform potential alternations that enhance the system resource allocation. A key feature is to consider the UL and DL load separately in relation to the UE geographical distribution. UL/DL location based information, may potentially be derived from UE positioning [107]. The proposed resource re-configuration process is envisioned to be hybrid, executed partly on eNBs and on a centralized SDN controller. In particular, the process of managing the formation of virtual cells is handled in a distributed manner by the corresponding eNB, while the UL/DL reconfiguration by the SDN controller. Hence, eNBs need regularly exchange load information associated to UL and DL resources, using the X2 interface.

Once the distributed management cannot ensure adequate resources based on the given traffic demand and/or periodically for maintenance purposes, it notifies the SDN controller. The SDN controller tries to identify an alternative UL/DL configuration considering UL/DL traffic statistics from the network eNBs, cell planning data, i.e. expected throughput, upper bound capacity and specified target KPIs (Key Performance Indicators) as well as the set of eNBs in case the function needs to resolve a specific problem on demand. The core of the reconfiguration function consists of an optimization algorithm that aims to match the input constraints to a specific UL/DL configuration mode for the set of eNBs considered in the process. Local optimization solutions e.g., Simulation Annealing [73]are good candidates, because iteratively try to find a solution based on the current formation introducing small changes and limited overhead. Optimization algorithm could run as an application or software in the application layer of the SDN architecture framework defined by the Open Network Foundation (ONF) in [56].

This approach will logically centralize the intelligence and facilitate the domain/cell specific RRM and allocation decision making based on the global view of the network as opposed to existing networks, which are built on an autonomous system view where nodes
are unaware of the overall state of the network. However, the decisions will be enforced in a distributed manner across many geographically separated eNBs based on the real time traffic and user requirements of the UEs residing in the region of different serving eNBs. The logically centralized control layer enables RRM and radio resource allocation decisions to be made with global visibility across many base stations, which are expected to be far more optimal than the distributed radio resource management (RRM), mobility management, and routing applications/protocols in use today. In addition to this, the centralized control layer is capable of providing enhanced scalability as when the new users are added into the network and the traffic increases, the required compute capacity at each base station remains low. This is because the RRM processing is centralized in the SDN controller, which could be residing in a C-RAN system. As the SDN controller will be able to communicate with the base stations via standard interfaces such as OpenFlow, any RRM upgrades can be achieved independently regardless of the base station hardware configuration. Once an UL/DL configuration mode is specified by the SDN controller, a network performance verification that involves conventional performance management operations is applied.

![Diagram of TDD UL/DL resource configuration process.](image)

**Figure 26: TDD UL/DL resource configuration process.**

Since network management models usually introduce certain deviations between their impact and the expected results a proof of assumptions is an essential step to provide a means of regulation. Such deviations need to be monitored and eventually certain assumptions introduced in the model need to be adjusted accordingly. The fundamental operation elements of the described UL/DL reconfiguration function including the input information and triggering events are illustrated in Figure 26. An operator provides such inputs based on network planning and traffic expectations, which could change on the basis of the different time ranges e.g. minutes, hours or days. Figure 27 shows the overview of the...

Figure 27: Network optimization with a global network view.

5. **Core Network Function Virtualization (KCL)**

The research project entitled "Architectural aspects, algorithms and protocol engineering for network virtualization in wired-cum-wireless LTE-A environments" is part of the second work package of the CROSSFIRE FP7 project and its main objective is the development of algorithms and mechanisms to allow multiple Network Operators to share the same physical infrastructure and optimize network operation. This will be based by utilizing Network Virtualization specific techniques to the characteristics of LTE-A networks to achieve (near) optimal dynamic use and sharing of the available resources (both in terms of radio spectrum and available wired line capacity).

To begin with, network virtualization is gaining an increasing prominence during the last few years in the scope research area. Virtual networks were proposed initially as an innovative concept of creating separate independent networks embedded on the same
network infrastructure in order to improve the network’s flexibility, security and manageability, decrease the power consumption, maximize the total utilization of the existing resources and consequently increase the profit of the network providers.

Although network virtualization was first used in wired networks, increasing forecasted future mobile networks' capacity as well as decreasing mobile operators’ revenue margin due to the data-centric trend and the flat rate charging models (Figure 28) have led network sharing to be a very appealing solution to adapt/deploy and a feasible way to decrease the network operating cost. Enabling network virtualization requires addressing three basic requirements: the maintenance of resource isolation across slices, the customization within different slices and the efficient utilization of the resources.

![Figure 28: Relationship between revenue and traffic (data & voice) [78].](image)

Combining the current literature on wired networks virtualization, the main expectation is to come up with algorithms and mechanisms, which will deal with the aforementioned problems. The research activity will mainly focus on achieving optimal analytical and theoretical solutions to the above problems and can be summarized at the following points:

- Architectural aspects of LTE-A architectures;
- Mobility management in fully IP based wired-cum-wireless networks;
- Optimal radio resource allocation & management;
- Handover procedures mechanisms development and evaluation;
- Validation of the research results with simulations;
- Comparison with previous studies and state-of-the-art solutions.
5.1 State-of-the-art review

5.1.1 Network virtualization in LTE-A networks

Virtualization is the process of creating virtual versions of physical resources that emulate the same physical characteristics. The concept of virtualization was firstly introduced at the beginning of the 1960s by C. Strachey in his paper “Time Sharing in Large Fast Computers” [79] where the main principles of multi-programming were described. Since then there has been significant progress on the virtualization of different resources among the computer world like the memory, the hard disk and whole computing systems. Specifically, the virtualization process of machines is called “Server Virtualization” and its aim is to create several different virtual machines using even only one mainframe computer in order to increase the total utilization of the given physical resources.

The virtualization process as it has been used since nowadays can be summarized in three main categories: the Storage Virtualization which pools storage from multiple storage devices into a common storage pool, the Server Virtualization which was mentioned above and the Network Virtualization which is the main scope of this research project. Specifically, Network Virtualization (NV) is the process of aggregating the created virtual resources in order to form a Virtual Network (VNet). NV allows the created VNets to operate like normal networks without being aware of the virtualization process and coexist without interfering each other. This presumes the virtualization of the network components creating virtual routers/switches, virtual links, network infrastructures and wireless entities such as virtual base stations.

Virtualization in mobile networks, as mentioned above has a lot of benefits. First of all, it increases the flexibility and total utilization of the available physical resources and contributes to hardware cost saving. It is also energy efficient as physical resources have increased utilization and it offers enhanced network management features. More precisely, the fact that thanks to NV it is much easier to recover network resources by adding and deleting nodes without involving the hardware makes possible the instant creation and set up of virtual networks with the needed specifications, ready to address the end-users’ demand. In addition, the virtual network is more sustainable and easily controlled. Another advantage is that NV allows small players (i.e. Mobile Virtual Operators) to enter the market of the telecommunication increasing the competence and in this way, although the physical resources are constant, it allows their total utilization to be more flexible and proportional to the users’ demand.

One of the first times that NV was used was at the beginning of the 1990s with the introduction of the concept of virtual connections in the Asynchronous Transfer Mode (ATM).
Since then, many different scientific projects have contributed to network virtualization: GENI, VINI, PLANTELAB, CABO, Cabernet, 4WRD, AKARI, AsiaFI and others [47].

As for the 4WRD project, it is a European research project among 36 partners, which started at the begging of 2008, and its main objective was to find solutions in order to improve the quality of the communication services. The idea of implementing the network virtualization, as described in one of its work packages [80], was to separate the roles of the infrastructure and service providers into separate entities. As it is shown in Figure 29, three different business models were suggested: the Infrastructure Providers who own and manage the physical network devices and virtualize the physical resources, the Virtual Network Providers who combine the virtual resources in order to form VNets and the Virtual Network Operators who run the VNet and provide their services to the end-users.

![Figure 29: The three different business models in NV [80].](image)

The virtualization process in Long Term Evolution (LTE) networks is a use-case of the mobile network virtualization. As mentioned before, in order to achieve the creation of VNets, all of the available physical resources need to be virtualized: the routers, the servers, the wired and wireless links, the base stations and the host/end systems. Although the virtualization of servers, routers and of wired links has already been a subject of research for a long time, the virtualization of wireless resources is even today an open issue. In accordance, the LTE virtualization process can be summarized into two different categories:
the physical infrastructure (nodes, links, BSs) virtualization and the air-interface (spectrum) virtualization.

Regarding the virtualization of the air-interface, this can be generally considered as a scheduling problem of transmitter/receiver power, frequency, time and code or space allocation in the same concept as in the multiple access schemes FDMA, TDMA, CDMA and SDMA. For the LTE-A networks, in order to achieve the virtualization of the air-interface we have to virtualize the eNodeB, which is the entity that creates the air channel and schedules the air interface resources. One of the proposed solutions for virtualizing the eNodeB is the LTE Hypervisor. In [81], Zaki Y. et al. extend the idea of the PC virtualization solution XEN [82] by developing a hypervisor to the LTE eNodeB. XEN is a PC virtualization solution which introduces the “Hypervisor” which is an entity that schedules the physical resources. The LTE Hypervisor virtualizes the eNodeB into several virtual eNodeBs (the virtual eNodeBs are used by the different operators). The Hypervisor collects information from each node and depending the contract of each operator it schedules the air-interface resources like the OFDMA sub-carriers among the virtual eNodeBs.

In [83] the authors investigate and compare the gain of applying network virtualization in LTE networks and load balancing scheme. More specifically, they propose an LTE virtualization framework, which is responsible for the allocation of the eNodeB spectrum resources to the different virtual operators. Then, they develop a load balancing algorithm which balances the utilization of the spectrum resources among several eNodeBs which belong to the same virtual operator. Both of the aforementioned algorithms offer a significant increase of the total utilization and gain of the user performance.

Kokku R. et al. [11] describe the implementation of a Network Virtualization Substrate (NVS) which addresses efficiently the virtualization of wireless resources in cellular networks ensuring their isolation, the dynamic allocation and the high utilization. NVS’s main innovations are firstly a provably optimal slice scheduler, which enables the co-existence of slices with bandwidth and resource-based reservations, and secondly a generic framework, which allows efficiently customized flow scheduling within the base station on a per-slice basis. The results from simulations show that for both downlink and uplink flows the NV substrate achieves the aforementioned goals.

In [32], the authors validate via analytical and simulative work that the spectrum sharing in LTE virtualization can achieve a significant multiplexing gain. Then, they propose an enhanced model of multi-party spectrum sharing with respect to the accurate estimation (which is also developed as a new method) of the spectrum requirement in order to exploit the multiplexing gain. The spectrum estimation mechanism is based on traffic model of real-time services.
Regarding the mobility management, Xueli An et al. [84] propose the “dMME”, which is a distributed system which implements the mobility management for LTE networks by replacing the LTE Mobility Management Entity (MME). Specifically, it is a software architecture which improves the flexibility and the scalability of LTE cellular networks and performs load balancing. It performs the control plane processing as close as possible to the user and it introduces mechanisms to divert the flow through replicas. The results of their work prove that the distributed architectures are a feasible choice in order to achieve high-throughput, delay-intolerant control plane functions.

Moreover, Melo M. and Sargento S. [85] propose the Virtual Network Clone migration in order to address the virtual resource mobility problem. Their method is independent as for the protocols running inside the virtual networks and this can be very useful because it lets different types of protocols and architectures to be implemented and used in different scenarios. The clone migration procedure is an alternation to the live migration approach [86] and it can achieve elimination to the virtualization process downtime as well as it can be very fast performed. This method can be very useful in scenarios where there many nodes are being added or deleted from the VNet while running.

Regarding the tools in order to enable the virtualization process, the main ones that have been used are the Software Defined Networking (SDN) and the OpenFlow standard. The SDN is a network architecture where a controller monitors traffic data and at the same time is responsible for a distributed pool of switches by applying packet-forwarding rules [87]. OpenFlow is an implementation of SDN which provides an open protocol to program low-tables in switches and routers in the network. The OpenFlow Switch and Controller communicate via the OpenFlow protocol [51].

In [88], the authors analyse the EPC (S-GW and P-GW) nodes and they classify their functions taking into consideration their impact on the data-plane and the control plane processing. Then, they propose an innovative method which enables the mapping for these functions on four alternative deployment frameworks which are based on SDN and OpenFlow. Moreover, they investigate the OpenFlow’s implementation’s capability to realize operations of the core like the QoS, classification of data, tunnelling and charging. Their results show that functions like tunnelling (functions which have to do with high data packet processing) are more likely to be kept on the data-plane network element.

Finally, the Mobile Cloud Networking (MCN) [89] (Figure 300) is a European FP7 project which targets to exploit Cloud Computing as the infrastructure for future mobile network deployment and operation. It proposes the deployment of macro and micro data centers (strategically located across different geographical areas) by mobile operators in order to compose and operate virtual RANs, mobile core networks and data centers and in
that way to be able to provide end user services. Under this project, Staring and Karagiannis, in [90] investigate how three major cloud computing platforms (OpenStack, Eucalyptous and OpenNebula) could be used in order to avoid bottlenecks, to increase the utilization of the available physical resources and to minimize the delay in LTE based cellular networks. However, their results showed that the above platforms cannot satisfy these requirements unless their functions and modules’ extension and enhancing has been previously performed.

Figure 300: Mobile Cloud Networking architecture [89].

5.1.2 Mobility Management schemes description and comparison

As the mobile users increase steadily and there is also a dramatic growth of the data demand, All-IP networks (mobile and fixed) seem to be the dominant trend as they offer to the users the ability to move through different wireless systems without interrupting their service. In order to address the mobility management problem, there have been proposed many different mobility management schemes.

The IETF standards organization proposed Mobile IP in order to support mobility of IP hosts. The mobile node (MN) is given two addresses: the home address (HoA) which is the fixed address to identify the MN and the care of address (CoA) which indicates the current position (IP subnet) of the MN. In Mobile IPv4 (MIPv4) [91], the mapping of the home address to the current CoA is handled only by the home agents (HA). As it is proposed, when a correspondent node (CN) is about to send packets to a MN, it will send the packets to the home address of the MN. Then, in the home network of the MN, this flow will be go through the HA and tunnelled e.g. by IP-in-IP encapsulation [92]. The destination can be either directly the MN or a foreign agent which has a direct link with the MN.

In MIPv6 [93], the home agents are not the only entities which handle the address mapping. Each CN can have its own cache where it can store the binding updates for the MNs. This feature of the MIPv6 offers the route optimization in comparison with the triangle
routing via the HA in MIPv4. This means that when a CN has a relatively recent entry of the MN status in its cache, it can send packets directly to a MN. When this happens, the CN does not encapsulate the packet as the HA but it uses the IPv6 Routing Header Option. On the other hand, when the CN has not any entry for the MN in its corresponding binding cache, it sends the packet to the home address of the MN and then the HA will forward the packet. When the MN receive an encapsulated packet, it will inform the CN about the CoA at this moment. When a MN changes an IP subnet, it has to inform the HA and/or the CNs by sending them a common message format called binding updates (BUs). While the signalling in MIPv4 is performed with UDP, in MPipv6 the signalling is done in extension headers, which can also be piggybacked in data packets.

In order to prevent the end-user service deterioration which can be caused by changes in the MN’s point of attachment, the Fast Handovers for Mobile IPv6 [94] was proposed. In this proposal, the main problem which was addressed was how to allow a MN to send packets the soonest possible as it detects a new subnet link and how to deliver packets to a MN as soon as its attachment is detected by its new Access Router (AR). In order to do so, there was proposed that when a MN has already information about the next point of attachment to which it will move, via a specific signalling procedure, it is triggered a mechanism which has already prepared the binding update and the movement of flow to the next AR.

One of the disadvantages of the Mobile IP protocol is the fact that in cases when there are a lot of handovers and/or the MNs are far away from their home domains, a big BU signalling traffic is produced which can cause to significant network congestion, latency and packet loss. For this reason, Hierarchical Mobile IPv6 (HMIPv6) [95] was proposed as an extension to the previous protocols. HMIPv6 introduces the Mobility Anchor Point (MAP) which is responsible for handling the mobility inside local domains, acting like a local HA, while mobility between different MAP locations (global mobility) are handled by MIPv6. When a MN moves into a MAP region it obtains the Regional care-of-address (RCoA) which will be sent to the HA and the CNs in order to give them its current location. Then, every flow towards the MN will go through the MAP of its domain using inside this domain the on-link care-of-address (LCoA). Regarding the handover procedures, when a MN moves to a new AR inside the same MAP area then only the MAP has to be informed (which means that the signaling load is very low), while when it moves to a new MAP region a BU has to be sent to the HA/CN of the MN in order to notify the change in RCoA and to route the packets through the new MAP. Combining HMIPv6 and FMIPv6 which was discussed above, Fast Handover for Hierarchical MIPv6 (F-HMIPv6) [96] was proposed in order to support seamless mobility and to reduce even more the signaling traffic and the network delay.
In order to eliminate the signalling overhead and to simplify the client’s IP mobility software of the above mobile IP schemes, a network-based protocol for the mobility management was proposed: the *Proxy Mobile IPv6* (PMIPv6) [97]. PMIPv6 (Figure 31) uses network entities in order to handle the mobility instead of MN and in this way there is no need to add any software at the mobile users excluding them from participation in any mobility-related signalling. When an MN is located in its PMIPv6 domain, the serving network gives it a unique home network prefix although it has no awareness of this procedure and it considers the PMIPv6 domain as the home network.

PMIPv6 (Figure 32) introduces the *Mobile Access Gateway* (MAG) and the *Local Mobility Anchor* (LMA). The MAG, which runs on the AR, detects the mobility of the MN and triggers the mobility-related signalling with the LMA, creating a tunnel with it which allows the MN to use an address from its home network prefix and emulates the MN’s home network on the access network for each MN. The LMA, which is an enhanced version of the HA in MIPv6, is responsible to ensure the reachability of the MN’s address while it moves inside a PMIPv6 domain. When a MN first attaches to an access network connected to the MAG, after a successful authentication, the MAG obtains the MN’s profile and then it sends a *proxy binding update* (PBU) message to the LMA. The LMA, after authenticating the sender, it sends back a *proxy binding acknowledgment* (PBA) message and it sets up a route for the MN’s home network prefix over the tunnel to the MAG. The main difference with the MIPv6 scheme is that a tunnel is created between the LMA and the MAG and not the MN. This prevents the MN of wasting bandwidth for mobility-related signalling. Then, the MAG, after receiving the PBA, it has all the information to emulate the home network of the MN and to start sending a *router advertisement* (RA) message to the MN in order the MN to configure its home address accordingly. In this way, all the traffic sent from the MN gets routed to its LMA through this tunnel and all the packets sent by a CN to the MN are received first by the LMA which then forwards them to the MAG. Finally, the MAG, after receiving the packets, it removes the outer header and forwards them to the final destination, the MN.
The fact that in Proxy MIPv6 all of the data and signalling traffic is handling by the LMA may occur some problems. First of all, the centralized anchor can produce undesirable traffic into the core network leading to high congestion and latency of the network. Moreover, the routing is not optimal since the traffic flows through certain nodes (LMAs). Another significant issue is that a failure of one node, the LMA, can lead to global failure, making the whole network vulnerable and easily unstable. In order to find a solution to these problems, the Distributed Mobility Management (DMM) scheme has been proposed. There have been two different proposals under the same scheme: the Partial DMM where only the data plane is distributed and the Fully DMM where both data and control plane are distributed.

Yi L. and Zhang H. in [100] propose a DMM based on PMIPv6 where the MAG still manages the mobility-related signalling messages for the MN and tracks the location of MN, like in PMIPv6, while the data and control plane of LMA is split by introducing a Control plane LMA (CLMA) and Data plane LMA (DLMA). CLMA is responsible to manage the signalling messages of binding registration and allocate the DLMA to MN. The DLMA forwards the data
plane packets. With this kind of separation, the authors prove, by developing simulations, that their proposed scheme addresses the aforementioned problems of PMIPv6.

Furthermore, in [101] the authors propose a distributed mobility management scheme in PMIPv6 introducing a Hash-based Distributed PMIP (PMIP-HD) protocol, in which the control functions for binding update and query operations are performed based on a hash function, distributing in this way the traffic overhead onto the MAG. After numerical investigations, the show that their scheme can be very useful as it can reduce the signalling control and the data delivery costs.

As it is extensively presented at the next section, the current workflow of this project is the mobility management in mobile networks. More specifically, we aim to develop a model, which will address the problem of the optimal number and location of Mobility Agents (MA) across the backhaul network of a cellular network in order to maximize the total utilization. This is an initial investigation to the mobility management problem and our intention is to configure and orient our work towards schemes, which are LTE-A compatible like the PMIP.

First of all, the MA location problem and the assignment of the MAs by the Access Routers (AR) can be parallelized as a facility location problem categorized as capacitated and incapacitated. The authors in [102] investigate the optimal hierarchy level in HMIPv6 with the main objective to minimize the total signaling cost. First, in a tree-like topology with a hierarchy of MAs such that minimizes the signalling costs and the packet delivery costs. As the number of the hierarchies of the MAs increase, the tunnelling costs also become higher having a significant impact to the packet delivery costs. When more hierarchies are available the signaling load tends to decrease but the packet delivery cost increases because of the tunnelling overhead. The authors formulate the location update cost and the packet delivery cost in the aforementioned topology in order to provide the optimal hierarchy. Then, they investigate the impact of the session-to-mobility ratio (SMR) on the total cost. However, the potential deployment cost of the MAs by the network is not taken into consideration, so there is no restriction on the number of the MAs. Furthermore, in [103] a new method was proposed in order to allow an optimal assignment of the base station to the base station controllers in GERAN networks. The main objective is the minimization of the number of handovers between the base station controllers given an upper limit of re-allocations of the base stations. The approach was a graph partition problem which is NP-complete and the main idea is to reduce the number of reallocations of BSs.

A very innovative idea which can be combined with the research on the optimal mobility management is a method proposed by Li Y. et al. in [104] for balancing the network utilization and the quality of routing. The authors investigate the impact of dispersion and
path variation to the quality of oblivious routing. The path dispersion is concerned with how many different paths are available between each origin-destination pair as is indicated by the routing. The path variation is a metric of how much the above paths differ from the shortest path and each other. Then they propose a penalty method, which aims to balance the oblivious ratio and the quality of the oblivious routing and apply this penalty method to the minimization of the maximum utilization problem.

Finally, Pragad D. et al. in [105] investigate the bottleneck impact of MAs on wireless access networks. They use the Maximum Concurrent Flow Problem (MCFP) in order to create a model of the network as a Multicommodity Flow Problem and then they monitor the network’s throughput as it is affected by the adding of MAs. The results prove that when a MA scheme is implemented into a wireless access network in order to manage the local mobility, the network’s capacity becomes lower.

5.2 Current research status

5.2.1 Scenarios and models description

The first part of the research activity of this project concerns the mobility management of the backhaul network of a mobile network. We consider a backhaul network, which consists of two or more mobile operators who serve jointly a geographic area. The VNet can be the result of the combination of physical resources from different infrastructure providers. The final virtual network, which has been created, is the network of our interest. This network consists of one or more source nodes, where it is connected with the Internet, several intermediate routers and the Access Routers (ARs), which are the destination nodes. Each AR may serve several base stations on its area (Figure). In addition, the users in the network move across the different ARs and a Handover Matrix (H) for a specific time window describes the produced traffic. So, there is a given probability of a user to move to a neighbour AR location, or to stay in the same AR (Figure 34). There is also a probability of birth or death procedures in an AR area.

In this scenario the mobility of the users is supported by a Mobility Anchor Point (MAP) scheme. However, the same method can be applied in every fully-IP network, which uses Mobility Agent (MA) based scheme. Mobility management protocols, which have already been proposed and could be adopted, with some alternations, in our work are the HMIP, HMIPv6, PMIPv6 and the DMM, as we efficiently analysed earlier. The main objective is to find an algorithm, which locates the MAs across the candidate routers and minimizes the total cost.

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Each AR has a specific data demand produced by its area of service in the time window we examine. The data traffic originates from the source node (P-WG) and goes
through the mobility agent which serves the destination AR. Every link between two routers has a constant capacity so different paths across the network have a different impact in terms of delay or cost. Since all of the traffic flows through the MAs it is obvious that the number and the location of them can affect the total cost. More specifically, the MAs can be nodes of congestion leading to a bad performance and QoS of the network and also they affect the final performance regarding the handover delays.

In order to estimate the total cost, which is produced by the data traffic, we distinguish two different costs: the total routing cost and the total handover cost. Firstly, as for the routing cost, the flow from the source node to an AR consists of two parts: the path from the source node to the MA and the path from the MA to the destination AR. Taking into consideration that each link has a specific cost, the routing cost for each flow is proportional to the total number of hops. This means that as the number of available MAs is higher the available paths are more and the total routing cost is smaller. In addition, the location plays a significant role in each different case, depending on the given demand. We consider no cost for MA deployment in this model although we consider implementing this in the future.

As for the handover cost, there are two different cases when a user moves to a new AR area: if a user moves to an AR area which is served by the same MA then the handover cost is called intra-MA handover cost - in other case is called inter-MA handover cost. Typically the inter-MA cost is higher than the intra-MA, which means that when there are more MAs in use then the ARs are assigned to many different MAs and there are more inter-MA handovers. However, there are more available paths and the total routing cost is higher. Considering this, it is obvious that the number of the MAs and their location is crucial for the performance of the network. Furthermore, the AR assignment to the MAs, which have been located and enabled, is another important issue as it can significantly affect the total cost.

Finally, the types of networks, which are used in this scenario, are random undirected planar graphs with a high rate of interconnections and a spanning tree-like shape expanding from the source to the destination nodes. The main goal is to simulate as realistically as possible the existent backhaul networks of cellular networks.
6. Conclusions

This deliverable summarizes the state-of-the-art in the field of network virtualization for mobile infrastructures concentrating of LTE-A. Considering RAN and network sharing network virtualization in future cellular networks is one of the very prominent solutions for addressing problems such as heterogeneity and traffic augmentation. It offers all sizes fit into one solution, creating an expandable model where multiple heterogeneous architectures located on shared physical substrate networks. Furthermore, it promotes innovation and customized services / applications. In this deliverable, some connections between current
RAN and network sharing technologies are described focusing on the CROSSFIRE LTE-A architecture. For further work we plan to explore algorithms to enhance RAN and network sharing, by investigating how resources can be shifted between services on-demand to meet capacity requirements. Furthermore, we are planning to create solutions for an LTE-A network environment in which multiple service providers can share underlying physical resources from multiple infrastructure providers and dynamically compose heterogeneous virtual networks that coexist in isolation within the same physical infrastructure. These multiple service providers should compete with each other by deploying customized end to end services depending on the users' needs, managing the services on the virtual networks specifically targeted to the end users and effectively sharing and utilizing the physical resources. In this set-up, we will consider that each virtual network has its own virtual network controller and can independently specify the end-to-end Quality of Service (QoS) and Quality of Experience (QoE) it expects for its different customer segments.

The Open eNB framework, an alternative network virtualization solution for the sharing of LTE base stations has been described. The proposed solution represents a first attempt to utilize the benefits of SDN and OpenFlow, introducing network virtualization in LTE networks with an extensible, highly adaptable, and less invasive approach. The goal of this work is to demonstrate that the performance experienced from the end users are effectively improved. A system-level simulation approach is planned to be used in order to analyse the gains achieved by using this framework. Even though the proposed framework is expected to attain significant performance gains compared to the baseline approach (RAN without virtual base stations), its deployment also comes at the cost of increased core network signaling. This cost follows from the requirement of deploying an additional signaling procedure that is required in a way that virtualization is utilized at the access network in a backwards compatible manner. A complete cost analysis is planned to be part of investigation to realistically assess the performance of the proposed framework.

In the field of programmable RAN we introduced the concept of a virtual cell that enables UEs to utilize resources from multiple eNBs taking full advantage of the TDD resource flexibility and providing a means for efficient resource management. Virtual cell scheme offers a distributed approach that exploits both spatial and time domain for enhanced load balancing and efficient resource sharing in real time to address varying traffic needs in UL and DL directions. We envision virtual cells to evolve dynamically following a self-organized paradigm based on SDN means that combine both coverage adjustments and UL/DL re-configuration processes. We intend to do further study on the use of virtual cells in a cloud RAN scenario and analyze different use cases by means of simulations and analytical means. We also intend to investigate and develop techniques to flexibly centralize...
RAN functionalities based on the need and available computational resources considering different scenarios. Such on demand provisioning, aims to take advantage of resource pooling, improving elasticity and multi-tenancy.

For core network function virtualization, the related work was explored considering also IP mobility solutions, which complements LTE access. A proposal to share core network resources from different operators was investigated and analysed via a Markov-based scheme. As a next step regarding the future research work, the main objective is the development of a realistic model considering the total cost, utilization of the physical resources, energy consumption, while exploring also new parameters like the deployment cost and the delay tolerance of specific flows in accordance with the characteristics of the LTE-A architecture and its virtualization processes. Specifically, we consider the adoption of the latest proposed mobility management schemes, which can be adopted by LTE-A networks, like the PMIPv6 and the DPMIPv6. We, also, intend to investigate how several network operators will share the physical resources like the S-GWs, P-GWs and the MMEs before the formation of the joint network.
### List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>2G/3G</td>
<td>Second / Third Generation</td>
</tr>
<tr>
<td>3GPP</td>
<td>3rd Generation Partnership Project</td>
</tr>
<tr>
<td>API</td>
<td>Application Programming Interface</td>
</tr>
<tr>
<td>AR</td>
<td>Access Router</td>
</tr>
<tr>
<td>ARQ</td>
<td>Automatic Repeat Request</td>
</tr>
<tr>
<td>ATM</td>
<td>Asynchronous Transfer Mode</td>
</tr>
<tr>
<td>BGP</td>
<td>Border Gateway Protocol</td>
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<tr>
<td>BS</td>
<td>Base Station</td>
</tr>
<tr>
<td>BU</td>
<td>Binding Update</td>
</tr>
<tr>
<td>CAC</td>
<td>Call Admission Control</td>
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<tr>
<td>CAPEX</td>
<td>Capital Expenditure</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code Division Multiple Access</td>
</tr>
<tr>
<td>CLMA</td>
<td>Control plane LMA</td>
</tr>
<tr>
<td>CN</td>
<td>Correspondent Node</td>
</tr>
<tr>
<td>CoA</td>
<td>Care of Address</td>
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<tr>
<td>CoMP</td>
<td>Coordinated Multi-Point</td>
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<tr>
<td>CR</td>
<td>Cognitive Radio</td>
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<tr>
<td>C-RAN</td>
<td>Centralized-RAN</td>
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<tr>
<td>CS</td>
<td>Capacity Sharing</td>
</tr>
<tr>
<td>DeNB</td>
<td>Donor eNodeB</td>
</tr>
<tr>
<td>DDM</td>
<td>Distributed Mobility Management</td>
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<tr>
<td>DMME</td>
<td>Distributed Mobility Management Entity</td>
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<tr>
<td>DL</td>
<td>Downlink</td>
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<tr>
<td>DLMA</td>
<td>Data Plane LMA</td>
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<tr>
<td>eNodeB</td>
<td>E-UTRAN NodeB</td>
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<tr>
<td>EPC</td>
<td>Evolved Packet Core</td>
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<tr>
<td>EvDO</td>
<td>One and Evolution-Data Only or Evolution-Data Optimized</td>
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<tr>
<td>FDD</td>
<td>Frequency Division Duplex</td>
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<tr>
<td>FDMA</td>
<td>Frequency Division multiple Access</td>
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<tr>
<td>F-HMIPv6</td>
<td>Fast HMIPv6</td>
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<tr>
<td>FMIPv6</td>
<td>Fast Mobile IPv6</td>
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<tr>
<td>GWCN</td>
<td>Gateway Core Network</td>
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<tr>
<td>HA</td>
<td>Home Agent</td>
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<tr>
<td>HARQ</td>
<td>Hybrid ARQ</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>HeNodeB</td>
<td>Home eNodeB</td>
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<tr>
<td>HMIPv6</td>
<td>Hierarchical Mobile IPv6</td>
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<tr>
<td>HA</td>
<td>Home Address</td>
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<tr>
<td>HPLMN</td>
<td>Home Public Land Mobile Network</td>
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<tr>
<td>ICIC</td>
<td>Inter-Cell Interference Coordination</td>
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<tr>
<td>IETF</td>
<td>Internet Engineering Task Force</td>
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<tr>
<td>InP</td>
<td>Infrastructure Provider</td>
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<tr>
<td>IP</td>
<td>Internet Protocol</td>
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<tr>
<td>KPI</td>
<td>Key Performance Indicators</td>
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<tr>
<td>LCoA</td>
<td>on-Link Care-of-Address</td>
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<tr>
<td>LMA</td>
<td>Local Mobility Anchor</td>
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<tr>
<td>LTE-A</td>
<td>Long Term Evolution – Advanced</td>
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<tr>
<td>MA</td>
<td>Mobility Agent</td>
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<tr>
<td>MAC</td>
<td>Medium Access Control</td>
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<tr>
<td>MAG</td>
<td>Mobility Access Gateway</td>
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<tr>
<td>MAP</td>
<td>Mobility Anchor Point</td>
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<tr>
<td>MCFP</td>
<td>Maximum Concurrent Flow Problem</td>
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<tr>
<td>MCN</td>
<td>Mobile Cloud Networking</td>
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<tr>
<td>MIP</td>
<td>Mobile IP</td>
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<tr>
<td>MME</td>
<td>Mobility Management Entity</td>
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<tr>
<td>MN</td>
<td>Mobile Node</td>
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<tr>
<td>MNO</td>
<td>Mobile Network Operator</td>
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<tr>
<td>MOCN</td>
<td>Multi-Operator Core Network</td>
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<tr>
<td>MPLS</td>
<td>Multiprotocol Label Switching</td>
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<tr>
<td>MTC</td>
<td>Machine Type Communication</td>
</tr>
<tr>
<td>MVNO</td>
<td>Mobile Virtual Network Operator</td>
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<tr>
<td>NAeNBs</td>
<td>NV Aware eNBs</td>
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<tr>
<td>NV</td>
<td>Network Virtualization</td>
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<tr>
<td>NVS</td>
<td>Network Virtualization Substrate</td>
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<tr>
<td>OC</td>
<td>OpenNB Controller</td>
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<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division</td>
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<tr>
<td>OFS</td>
<td>OpenNB Switch</td>
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<tr>
<td>ONF</td>
<td>Open Network Foundation</td>
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<tr>
<td>OpeNB</td>
<td>Open eNB</td>
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<tr>
<td>OPEX</td>
<td>Operational Expenditure</td>
</tr>
<tr>
<td>PBU</td>
<td>Proxy Binding Update</td>
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</table>
PBBA  Proxy Binding Acknowledgment  
PDCP  Packet Data Convergence Protocol  
PGW  Packet Delivery Network Gateway  
PHY  Physical Layer  
PLMN  Public Land Mobile Network  
PMIP  Proxy Mobile IP  
PMIP-HD  Hash-based Distributed PMIP  
PRB  Physical Radio Block  
QoE  Quality of Experience  
QoS  Quality of Service  
RA  Router Advertisement  
RAN  Radio Access Network  
RB  Resource Block  
RCoA  Regional Care-of-Address  
RLC  Radio Link Control  
RN  Relay Nodes  
RRC  Radio Resource Control  
RRM  Radio Resource Management  
SDMA  Space Division Multiple Access  
SDN  Software Defined Networking  
SGW  Service Gateway  
SLA  Service Level Agreement  
SLN  Services with Leased Network  
SMR  Session to Mobility Ratio  
SP  Service Provider  
SS  Spectrum Sharing  
TAC  Tracking Area Code  
TDD  Time Division Duplex  
TD-LTE  Time Division-LTE  
TDMA  Time Division Multiple Access  
UE  User Equipment  
UDP  User Datagram Protocol  
UL  Uplink  
VeNB  Virtual eNB  
VM  Virtual Machine  
VN  Virtual Network
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>VPLMN</td>
<td>Visited Public Land Mobile Network</td>
</tr>
<tr>
<td>VPN</td>
<td>Virtual Private Network</td>
</tr>
<tr>
<td>VPS</td>
<td>Virtualized RB Sharing</td>
</tr>
<tr>
<td>VSS</td>
<td>Virtualized Spectrum Sharing</td>
</tr>
<tr>
<td>WiMAX</td>
<td>Worldwide Interoperability for Microwave Access</td>
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</tbody>
</table>
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