5G Crosshaul

the integrated fronthaul/backhaul

H2020 5G PPP 5G-Crosshaul project
Grant No. 671598

D1.1: 5G-Crosshaul initial system design, use cases and requirements

Abstract

This deliverable describes the set of identified use cases and the final sub-set selected in the project. Furthermore, it reports all the technical and commercial requirements derived along with their priorities for consideration in the 5G-Crosshaul design.

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List of Acronyms

Acronym	Description
5GPoA	5G Point of Access
API	Application Programming Interface
BaaS	Broadcast as a Service
BBU	Baseband Unit
BH	Backhaul
BGP-LS	Border Gateway Protocol - Link State
BS	Base Station
CDN	Content Delivery Network
CPRI	Common Public Radio Interface
C-RAN	Cloud Radio Access Network
CRUD	Create, Read, Update and Delete
DAS	Distributed Antenna Systems
DC	Data Center
EMF	Electro Magnetic Field
ERIP	Equivalent Isotropically Radiated Power
FH	Fronthaul
FSO	Free Space Optics
HD	High Definition
IT	Information Technology
MAC	Medium Access Control
MANO	Management and Orchestration
MBB	Mobile Broadband
MEC	Mobile Edge Computing
MTA	Multi-Tenancy application
MTTR	Mean Time To Repair
NB	North Bound
MVNO	Mobile Virtual Network Operator
NETCONF	Network Configuration Protocol
NFV	Network Function Virtualization
NFVO	Network Function Virtualization Orchestrator
OBSAI	Open Base Station Architecture Initiative
ONF	Open Networking Foundation
OS	Operating System
OTT	Over the Top
OVS	Open Virtual Switch
PCEP	Path Computation Element Protocol
PHY	Physical media
PIP	Physical Infrastructure Provider
PoA	Point of Access
PoC	Proof of Concept

QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
REST	Representational State Transfer
RF	Radio Frequency
RoF	Radio over Fiber
RRU	Radio Remote Unit
SAP	Service Access Point
SBI	South Bound Interface
SDN	Software Defined Networking
SFC	Service Function Chaining
SLA	Service Level Agreement
SNMP	Simple Network Management Protocol
TCO	Total Cost of Ownership
TDD	Time Division Duplex
UC	Use Case
UE	User Equipment
VIM	Virtual Infrastructure Machine
VM	Virtual Machine
VMF	Virtual Machine Function
VN	Virtual Network
VNO	Virtual Network Operator
VNP	Virtual Network Provider
vRAN	Virtualized RAN
VRU	Vulnerable Road User
XCF	5G-Crosshaul Common Frame
XCI	5G-Crosshaul Control Infrastructure
XCSE	5G-Crosshaul Circuit Switching Element
XFE	5G-Crosshaul Forwarding Engines
XPFE	5G-Crosshaul Packet Forwarding Element
XPU	5G-Crosshaul Processing Units

Executive Summary

5G-Crosshaul project aims to develop a 5G transport network solution integrating the fronthaul and backhaul segments of the network. It is expected that 5G-Crosshaul can provide an adaptive, programmable and cost-efficient substrate for advanced services on top of it.

This document is the first deliverable of WP1, investigating use cases and 5G-Crosshaul system architecture. Five key use cases have been selected taking into account the potential benefits that can be derived from Crosshaul architecture, the compatibility with other 5GPPP projects and the demonstrability through experimentation. They facilitate the design of 5G-Crosshaul data plane, control plane and applications, which are the focus of WP2, WP3 and WP4, respectively.

Three of the five use cases are service-oriented, meaning that they are related to specific applications or set of applications. These service-oriented use cases are: (i) vehicle mobility, (ii) media distribution (CDN and TV broadcasting), and (iii) dense urban information society. In addition to them, two more functional-oriented use cases have been considered: (iv) multi-tenancy, and (v) mobile edge computing. A common set of functional and non-functional requirements are identified and mapped to the use cases, including prioritization.

WP1 is not considered a strictly technological work package, but it has the goal to provide the common understanding of system architecture and the harmonization of technical solutions envisaged in WP2, WP3 and WP4 in order to achieve 5G KPIs. This deliverable synthetizes the work provided during the first year of project lifetime focusing, first of all, on providing a complete view of the overall 5G-Crosshaul architecture. Following this line, the document provides the common agreement of the project regarding the architecture of the Crosshaul control plane, which also supports the multi-tenancy characteristics.

The key technical achievements of this document can be summarized as follows:

- Definition of a classification of the different service use cases for the tenants. A taxonomy of three categories has been defined i.e. *Over-The-Top* (OTT), *Mobile Virtual Network Operator* (MVNO) and *Virtual Infrastructure Provider* (VIP). Each of them with different characteristics and requirements from the Crosshaul.
- Application of these service use cases to the different scenarios defined by WP1 and mapping of each scenario to different service use cases.
- Definition of the 5G-Crosshaul architecture for the single *Management and Orchestration* (MANO) scenario, considering the case where different transport technologies in data plane must be orchestrated.
- Definition of the Multi-MANO architecture, in which the *Multi-Tenancy Application* (MTA) plays a central role.

This document also provides a survey in Annex I on the major Open Source projects and softwares e.g., OpenDaylight and ONS for SDN controller and OpenStack,

OpenMANO, OpenBaton and OPNFV for Network Function Vitualization (NFV), that can be used to implement the proposed 5G-Crosshaul architecture.

The inputs and feedbacks between other technical WPs and WP1 are continuously active and lead to the definitions of:

- Applications, from WP4, which will support the 5G-Crosshaul use cases. A mapping of the applications to support all selected use cases is provided, especially enabling a multi-tenant usage of the physical infrastructure.
- Control plane: the 5G-Crosshaul Control Infrastructure (XCI) is designed such that it interacts with external layers through the following interfaces:
  - South-bound interface (SBI): towards the 5G Crosshaul data-plane
  - North-bound interface (NBI): towards the 5G Crosshaul applications
  - East-west interfaces (EBI and WBI): towards core network and RAN domains (out of scope of 5G-Crosshaul project)
- Data plane: the mostly-suitable technologies for the deployment of a 5G-Crosshaul network are investigated, envisaging a unified data plane encompassing innovative high-capacity transmission technologies and novel deterministic-latency framing protocols. The project has also selected a Crosshaul Common Frame (derived from MAC-in-MAC Ethernet technology) as the framing protocol for transporting both fronthaul and backhaul .

Besides the architectural works, WP1 also targets to evaluate the cost and energy consumption perspective of the 5G-Crosshaul network. Therefore WP1 has developed a preliminary methodology and modeling for calculating and analyzing the cost (in terms of investiment and operational expenditures). Also the computation of the energy consumption has been considered since it usually represents a significant portion of yearly expenditures for a network operator and also because the 5G network should contribute to the reduction of carbon emissions.

1 Introduction

Evolution of mobile generation towards 5G is facing the growing demand for better mobile broadband experiences and the future extreme performances. Differently from the 4th mobile generation, which was tailored to provide the high speed mobile broadband service, the 5G system will be designed to serve more use cases. Therefore, the 5G system design needs to cope with a big challenge: to introduce significant improvements in terms of services, user experience, infrastructures and network capacity etc., while keeping low the overall costs.

Cloud Radio Access Networks (C-RAN, also sometimes referred to as Centralized-RAN) have shown a good potential to solve such a challenge and promise considerable benefits in terms of network performance, network flexibility and programmability, but they also put challenging requirements on the fronthaul and backhaul transport networks. The transport network may become a bottleneck in terms of complexity and costs for implementing C-RAN. In 5G-Crosshaul, the idea is to solve this by integrating both backhaul and fronthaul segments into one single, flexible and Software Defined Networking (SDN) based transport network for data exchange between the Radio Access Network (RAN) and its respective operator's core network in an adaptive, cost efficient and sharable manner, as shown in Figure 1.

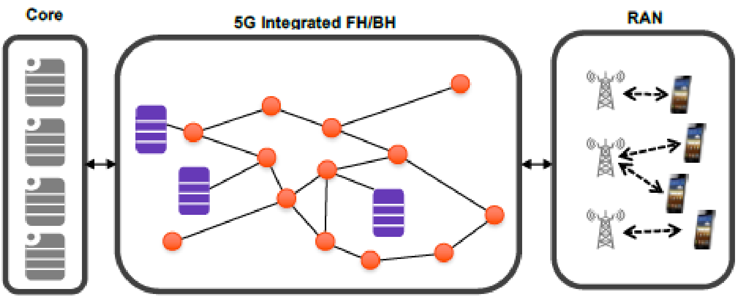

Figure 1: Integration of Fronthaul and Backhaul.

Multiplexing backhaul and fronthaul traffic is highly advantageous, since it enables the use of the same infrastructure and a common control for multiple purposes, with a consequent decrease of the total cost of ownership (TCO). This holds even more in 5G network, where new functional split schemes of the radio interface add a plethora of possible intermediate cases in between the pure fronthaul and backhaul scenarios, which is impossible to manage with dedicated infrastructures for each split.

Furthermore, the integration of the fronthaul and backhaul technologies will enable the use of heterogeneous transport platforms, leveraging novel and traditional technologies to increase the capacity or coverage of the 5G network, removing the need of using specialized fronthaul interfaces and optimizing the location of network functions, in order to dynamically provide the required services in the most efficient manner, according to the variation of traffic demand which is intrinsic to mobile systems.

Different actors will play significant roles in the definition of final services and will take advantage from new technologies: end users who consume the services offered on top of the infrastructure, network operators being in charge of connecting the end-users by providing the access to telecommunication services and external networks, service providers delivering telecommunication services and applications.

The design of 5G-Crosshaul shall be driven by the requirements extracted from realistic use cases with a clear economical target. A large number of use cases have been investigated in literature from other projects, studies, organizations and standardization bodies. With a careful selection, five key use cases have been selected and described in **Chapter 2**, for analyzing the system requirements and the impacts to the system design and also for demonstrating flexible and programmable capabilities, dynamic and cost-effective service provisioning, reduced network deployment costs and energy consumptions of the 5G-Crosshaul network. The selected use cases can be split into three service-oriented use cases and two functional-oriented use cases, where the formers mostly focus on the service layer, which is more related to specific applications or set of applications, while the latters mostly focus on the infrastructure layer.

After the use case description and analysis in **Chapter 2**, **Chapter 3** describes the 5G-Crosshaul system architecture, based on the principles of SDN and NFV, aiming to enable a flexible and software-defined reconfiguration of all networking elements, through the definition of a unified data plane and control plane interconnecting distributed 5G radio access and core network functions, hosted on network cloud infrastructure. It also defines an architectural framework enabling the dynamic request of Crosshaul slices through a multi-provider exchange,, in order to further develop the concept of multi-domain Crosshaul.

5G-Crosshual WP1 has the commitment to elicit the requirements for the 5G-Crosshaul subsystems and components developed by other work packages, i.e. WP2 for data plane, WP3 for control plane and WP4 for network applications, aligned with the viewpoints of the operators and vendors involved in the project, but also those formulated by other 5G stakeholders and projects targeting the 5G Key Performance Indicators (KPIs). Therefore, **Chapters 4**, **5** and **6** respectively extend **Chapter 3** with more detailed inputs and feedbacks from/to WP4, WP3 and WP2, dealing with application stratum (based in particular on NFV), control plane (dealing with SDN-based solutions) and data plane (considering a hybrid packet and optical environment, also defining a common frame structure, i.e. the 5G-Crosshaul Common Frame for packet transport, referred to as XCF).

Chapter 7 describes a methodology for modeling the cost and energy consumption of a transport network for fronthaul and backhaul. This is a work in progress. The later derived cost and energy models based on this methodology will be used to compare a 5G-Crosshaul network to the legacy transport networks.

The document has also included three Annexes chapters, providing more detailed information on the relation to major open source projects (like OpenDaylight, ONS, OpenStack, OpenMANO etc.), the system requirements analysis and the impacts on the selected use cases regarding data plane, control plane and applications.

2 Use cases and mapping into network services

In this chapter, one of the main goals of the project is described, which is the definition of the use cases that will achieve the "rising awareness" of the project together with the consolidation of concepts and objectives, and the definition of requirements obtained from the analysis of the selected use cases.

The idea of the work to be done during the project lifetime is to drive the study from the analysis of use cases, requirements and required functionalities, to a specification of the 5G-Crosshaul system design and its overall network architecture for adoption in standards and implementation in PoC prototypes.

The use cases are the result of a work where a larger set of them has been analysed ordered and prioritized. The selected use cases are fitted to the 5G-Crosshaul framework for demonstrating flexible and programmable capabilities, dynamic and cost-effective service provisioning, reduced network deployment costs and energy consumptions.

The identification and definition of the relevant roles (stakeholders) in 5G-Crosshaul, as well as the network service definition, are also included in this chapter.

2.1 Definition of 5G-CROSSHAUL stakeholders

The deployment of SDN/NFV and the consequent virtualization of network infrastructures and services provides new interfaces which, in turn, introduce new stakeholders and business models in 5G networks.

The 5G-Crosshaul project differentiates among two kinds of stakeholders in terms of Service and Infrastructure provisioning that are grouped into two layers, namely the Service layer and the Transport layer.

At the Service layer distinct actors interact on the delivery of final services to be consumed by end-users attached to 5G networks, as detailed in Figure 2. The following stakeholders are identified:

- End users, who consume the services offered on top of the 5G-Crosshaul infrastructure.
- Network Operator, being in charge of connecting the end-user by providing access to telecommunication services and external networks, like the Internet. The end-user will typically have a contract with the Network Operator for connectivity purposes.
- Service Provider, delivering telecommunication services, either basic or value added ones. The end-user will commonly have a contract with the Service Provider for consuming such kind of services.
- Application / Data Provider, providing specific and complementary services to the ones above (e.g., video, storage), typically relaying on distributed facilities like CDNs or cloud computing. These other services are usually offered in an over-the-top fashion. The end-user will register for those services, but there is not always a contractual relationship among them.

Those three roles can be played by the same actor, but also different providers can coexist.

On the other hand, the Infrastructure layer will consist of a number of actors providing transport and infrastructure services to stakeholders pertaining to the Service layer. The following list summarizes the stakeholders identified by 5G-Crosshaul:

- Radio Access Provider, offering radio access infrastructure where the end-users attach to. The split of RAN functionalities can be considered with the aim of centralizing some of them for efficiency purposes.
- 5G-Crosshaul Transport Infrastructure Provider, enabling the interconnection of the radio access infrastructure with the core network functions. 5G-Crosshaul comprises of the fronthaul and backhaul segments in 5G networks so that both types of traffic are carried over a single infrastructure. The 5G-Crosshaul Transport Infrastructure Provider manages both network and computing resources.
- Core Network Provider, where the mobile control entities typically reside, in a centralized manner. Distribution of mobile core functionalities towards the access can be considered for efficiency purposes.
- Virtual Network Provider, providing abstracted logical infrastructure composed of different physical elements commonly pertaining to distinct physical infrastructure providers.
- Computing Facilities Provider, making available distributed cloud computing capabilities that could be additional to the ones provided by the 5G-Crosshaul Transport Infrastructure provider.

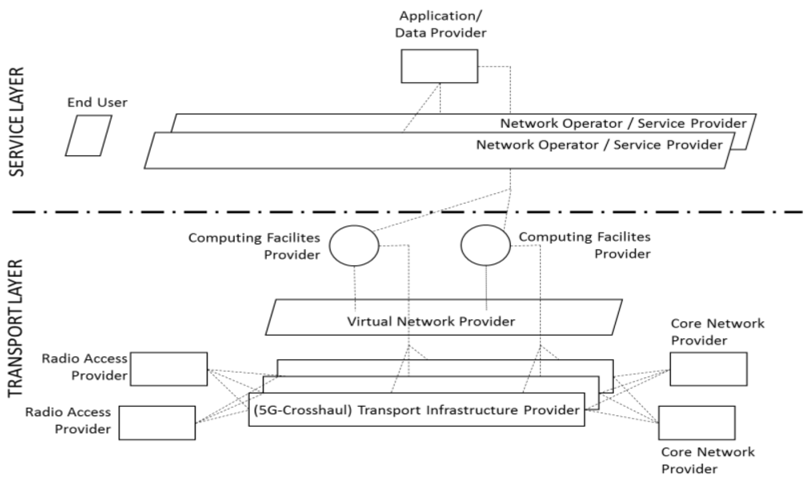

Figure 2: 5G-Crosshaul stakeholders

2.2 Definition of network service

A network service is defined as a composition of network functions defined by its behavior and its functional specification. A network service is characterized by several parameters. The most important ones for the project are reported in the following table.

Table 1: Network service parameters

Nature of connectivity	
Circuit switching / Packet switching	**Circuit switching** is a methodology of implementing a telecommunications network in which two network nodes establish a dedicated communication channel (circuit) through the network before the nodes may communicate. **Packet switching** is a digital networking communications method that groups all transmitted data into suitably sized blocks, called packets, which are transmitted via a medium that may be shared by multiple simultaneous communication sessions.
Connection-oriented communication / Connectionless communication	**Connection-oriented communication** is a network communication mode in telecommunications and computer networking, where a communication session or a semi-permanent connection is established before any useful data can be transferred, and where a stream of data is delivered in the same order as it was sent. **Connectionless communication** is a data transmission method used in packet switching networks by which each data unit is individually addressed and routed based on information carried in each unit, rather than in the setup information of a prearranged, fixed data channel as in connection-oriented communication.
E-LAN / E-Tree / E-Line	Terminology inherited from Ethernet standard. **E-Line**: a service connecting two customers over a Wide Area Network. **E-LAN**: a multipoint service connecting a set of customer endpoints, giving the appearance to the customer of a bridged connection. **E-Tree**: a multipoint service connecting one or more roots and a set of leaves, but preventing inter-leaf communication.
BW variability	Intrinsic ability to transport variable bandwidth, i.e. without the intervention of the control or the management plane
BW capacity	Maximum size of the connection.
Hierarchical containers/frames	Possibility to have indented frames.
Possibility of implementing Quality of Service mechanisms	Possibility to implement prioritized model.
Synchronization	Coordination of events to operate a system in unison.
Monitoring and control	Ability of continuously monitoring and controlling the network.
Max time for modifying	Time necessary to set-up/tear-down or modify connections

connections	parameters (e.g., bandwidth, end-points, QoS…).
SLA verification	Mechanisms to verify if the connectivity satisfy the Service Level Agreement signed by Carrier and Customer (user or tenant).
Failure localization	Mechanism devoted to the localization of failures.
Performance	
Max latency	Network latency is the time taken by data to get from one designated point to another. The network latency takes into account: Propagation time, Transmission time and Processing time.
Max jitter / Max Packet delay Variation	Jitter is the variation in latency as measured in the variability over time of the packet latency across a network. A network with constant latency has no variation (or jitter). Packet jitter is expressed as an average of the deviation from the network mean latency. In standards, it is usually defined as packet delay variation (PDV).
Bit Error Rate	The bit error rate (BER) is the number of bit errors divided by the total number of transferred bits during a studied time interval.
Packet Loss Rate	Packet Loss Rate is defined as the percentage of frames that should have been forwarded by a network but were not.
Resilience	
Time of recovery after failure	Time required to restore service after a failure.
Mean availability	Availability is the probability that a system will work as required during the period of a mission.
Carrier class devices	Carrier class refers to a system that is extremely reliable, well tested and proven in its capabilities. Carrier grade systems are tested and engineered to meet or exceed "five nines" high availability standards, and provide very fast fault recovery through redundancy.

2.3 Set of selected use cases for 5G-CROSSHAUL

As a result of the stakeholder layering explained in section 2.1, 5G-Crosshaul defines two types of use cases: service-oriented use cases and functional-oriented use cases. Though all stakeholders are involved in all of them, the former mostly focus on the service layer, whilst the latter mostly focus on the infrastructure layer.

The result of the selection consists of a total of five use cases, being three of them the service-oriented use cases, which means that they are related to specific applications or set of applications, while other two functional-oriented use cases have been selected in order to represent transversal scenarios considering a particular use of the 5G-Crosshaul network. In the next sections they will be described in detail.

2.3.1 Service-oriented use cases

2.3.1.1 UC1 – Vehicle mobility

This use case is focused on both passengers connectivity needs for mobile Internet when they are inside vehicles and setting up communications among vehicles, e.g., for traffic safety. The most challenging situations are passengers using 5G services (video in particular) on a very high speed train (about 500 km/h) and real time messages among vehicles for emergency and security. These subcases have often similar requirements.

2.3.1.1.1 High speed train

Background / Rationale

High speed train is a common public transportation for inter-city connection. Currently, the train speed can reach up to 300 km/h, and speeds higher than 500 km/h have been tested and demonstrated in Japan. It can be foreseen that more and more people will use high speed trains for traveling or business trips.

Passengers on these public vehicles will need mobile internet for entertainment (such as on-line gaming, HD video, social cloud services), or for business (such as accessing company information systems or having video conferences). Therefore, in this context challenges in providing satisfying Quality of Experience (QoE) to a crowd of passengers (e.g., more than 500 people) need to be identified and addressed in a cost effective way.

Scenario description

Due to the obstacles like Doppler effect caused by high mobility and the penetration loss resulted from the metallic carriage, the direct access from on-board terminals to the base stations will likely be hampered. Therefore, as shown in Figure 3, one or several points of access (PoA), such as small cells or Wi-Fi APs, will be installed on a high speed train to provide broadband access to the passengers inside each car of the train. The mobile backhaul for the PoA is provided via outbound gateway(s) which connect to the land base stations and the 5G-Crosshaul transport network.

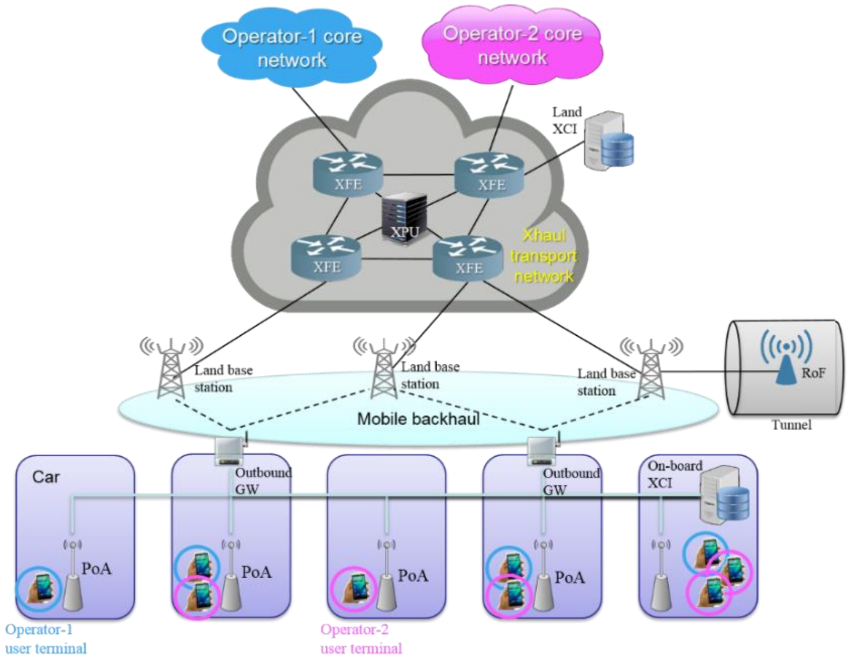

Figure 3: High speed train over 5G-Crosshaul transport network

The on-board 5G-Crosshaul Control Infrastructure (XCI) can be used to manage the multi-tenancy RAN sharing (together with the Land XCI), determine user traffic routing, or even leverage MEC for content caching and traffic offloading. Handover related challenges can be addressed by the proactive setup of paths according to the information about the train trajectory, including its speed, location and direction. There are also some terrestrial related challenges, for example the signal strength of base stations is largely degraded inside the tunnels, and radio-over-fiber (RoF) is one of the promising and cost-effective approaches to extend the coverage of base stations inside the tunnels.

2.3.1.1.2 Traffic efficiency and safety

Background / Rationale

Not only passengers inside vehicles have the necessity to communicate. Information exchange among vehicles will enable the provision of safety hints to the drivers or warnings about the road status, e.g., constructions, weather conditions, road hazards. Consider a vehicle arriving into an intersection with low visibility. In order to aid the driver and avoid the occurrence of an accident, the vehicle could signal to the driver the direction and velocity of any moving vehicle that approaches the intersection. Additionally, the vehicle could communicate with other vehicles and actively intervene in order to avoid accidents. An example could be the autonomous intervention of the emergency braking, based on the notification of the presence of another vehicle, in order to avoid an accident. Figure 4 illustrates dangerous situations that could be avoided.

With the help of advanced radio interfaces for vehicles in 2020, the accident rate is expected to be reduced by 50% and the fatal accident rate is expected to be limited at the same rate.

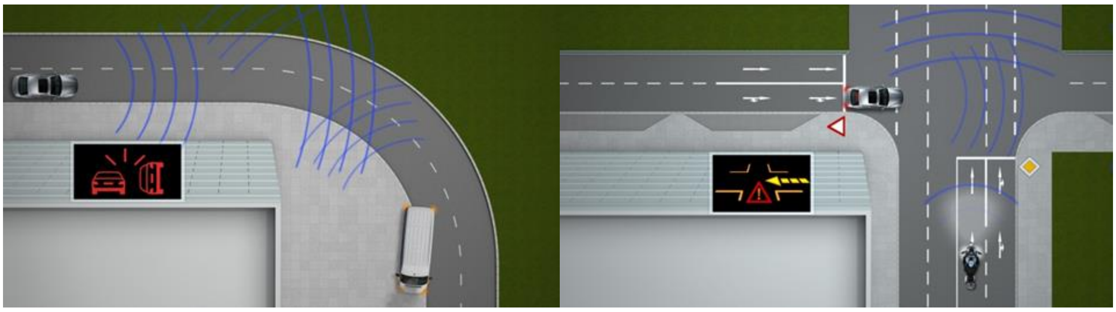

Figure 4: Traffic efficiency and safety

Scenario description

The idea is to collect safety-relevant information directly from the vulnerable road users (VRU). This can be achieved by exploiting the information from an existing and very powerful sensor that almost everyone carries in his or her pocket today: a mobile phone. Information is exchanged between the VRU device and the vehicles in order to warn the driver and the VRU about the presence of each other and actively initiate the necessary actions to avoid an accident.

Besides providing a safer driving environment, information exchange between vehicles can also enhance traffic efficiency. This refers to increasing traffic flows and reducing fuel consumption and emissions. The so-called "platooning" is a promising traffic efficiency application. Vehicles drive close to one another, with an inter-vehicle distance of 3 to 5 meters, in an autonomous manner. The lateral and longitudinal position of a vehicle in a platoon is controlled by collecting information about the state of other vehicles (e.g., position, velocity and acceleration) through communications. Such a cooperative automation system requires high reliable communication and the capability for vehicles to receive and process co-operative awareness messages with other involved vehicles within very short delays (less than 100 ms). Moreover, highly automated vehicles will benefit significantly from additional information delivered via V2X communication, since the vehicle environment model can extend its prediction horizon.

2.3.1.1.3 Addressed objectives and potential benefits

Table 2: Vehicle mobility objectives and benefits

Objectives addressed	**5G-Crosshaul Objectives** • Design of the 5G-Crosshaul Control Infrastructure (XCI), including interaction between controllers • Specify the XCI's northbound (NBI) and southbound (SBI) interfaces • Unify the 5G-Crosshaul data plane • Design scalable algorithms for efficient 5G-Crosshaul resource orchestration • 5G-Crosshaul key concept validation and proof of concept **Other objectives**

	• High mobility support • High connection density • High availability for mobile network
Potential benefits of 5G-CROSSHAUL solution	5G-Crosshaul will implement the concept of multi-tenancy at the infrastructure level. In addition, the XCI architecture can be utilized in assisting high speed train handover by exploiting context information, optimizing routing and allocating resource prior to handover. Therefore, 5G-Crosshaul introduces the following benefits: For network operators: CAPEX and OPEX reduction and increased coverage and capacity. For end users: Good QoE services.
Functions involved	• Multi-tenancy application • Mobility management application • Resource management application
Stakeholders involved	End User, Network Operator, Service Provider, Application/Data Provider, RAN Provider, Core Network Provider, Computing Facilities Providers, Infrastructure Providers.
Pre-conditions	RAN access along high speed rail and vehicles equipped with appropriate software and transmission system
Business model	Business-to-business and retail

2.3.1.1.4 Energy efficiency

The energy efficiency can be achieved in two ways. From the viewpoint of user equipment (UE), it connects to the PoAs on the high speed train instead of outdoor macro base stations. The transmit power can be reduced and the battery life can be extended.

In addition, the RoF deployed along high speed rail can be controlled by XCI to be turned on only during trains passing by, thus saving more energy in operations. In principle, no particular constraints are required. Nevertheless, low-energy operation of all radio nodes including sensors is expected due to energy cost and Electromagnetic Field (EMF) considerations, especially auto-configuration/operation is considered as an important implementation feature, including switch-on/off of radio nodes dependent on traffic load/day time.

2.3.1.2 UC2 - Media distribution: Content Delivery Networks (CDN) and TV broadcasting & multicasting

<u>Background / Rationale</u>

Content distribution, especially video traffic, is expected to be the dominant contributor to the mobile data traffic demand, being more and more present in everyday life communications, anywhere, any time and in end-user multi-device environments. Especially relevant scenarios for content delivery are massive events such as international music festivals or big sport events, such as FIFA World Cup or the Olympic Games, in which high volumes of traffic are needed, maintaining an acceptable quality for the end users. Video consumption is then becoming the most demanding component of the traffic growth observed in current networks. This trend will even increase in the future 5G networks. Thus, providing efficient ways of delivering content to end users is a must.

Content Delivery Networks (CDNs) have evolved to overcome the inherent limitations of the Internet in terms of user perceived Quality of Service (QoS) when accessing the content. CDN end-points can be distributed across the network, saving transport resources and reducing transmission delay.

Another important scenario where the media distribution is relevant is the case of TV broadcasting & multicasting, where the next 5G networks will become a good alternative to classical broadcasting networks, with an additional ability to mix with other media content not coming from the broadcasted TV, using the same network with a controlled quality to offer the Broadcast-as-a-service (BaaS).

The distribution of the content in a BaaS manner is the key for operators to achieve a more efficient TV distribution (in terms of spectrum occupation, cost and performance) , with a new revenue stream that doesn't need an additional dedicated network. Undeniably, operators too will have reasons to look favorably at 5G-Crosshaul broadcast: the existing mobile infrastructure can be reused.

Scenario description

A CDN replicates content from the origin server to cache servers, in order to deliver content to end-users in a reliable and timely manner from nearby optimal surrogates. A CDN would make the media delivery using the 5G-Crosshaul network, deploying replica servers close to the 5G-Crosshaul Forwarding Elements (XFEs).

The request-routing and distribution infrastructure would be based on information from the RAN and the 5G-Crosshaul network, so, it would be able to provide an optimal access to the network. The origin and replica servers would be managed as an additional element in the network, providing different metrics in order to manage their own performance. The CDN end-points can be distributed across the network saving transport resources and reducing transmission delays.

In addition to that, TV broadcasting/multicasting services can be offered. The network described in Figure 5 is configured by selecting the forking nodes of the tree to optimize the content delivery and make sure that a real-time delivery with the lowest possible delay is offered to the users. The content using 5G-Crosshaul architecture is then offered in real-time to a great number of users simultaneously, in the different underlying technologies, with adapted but consistent quality to the end users.

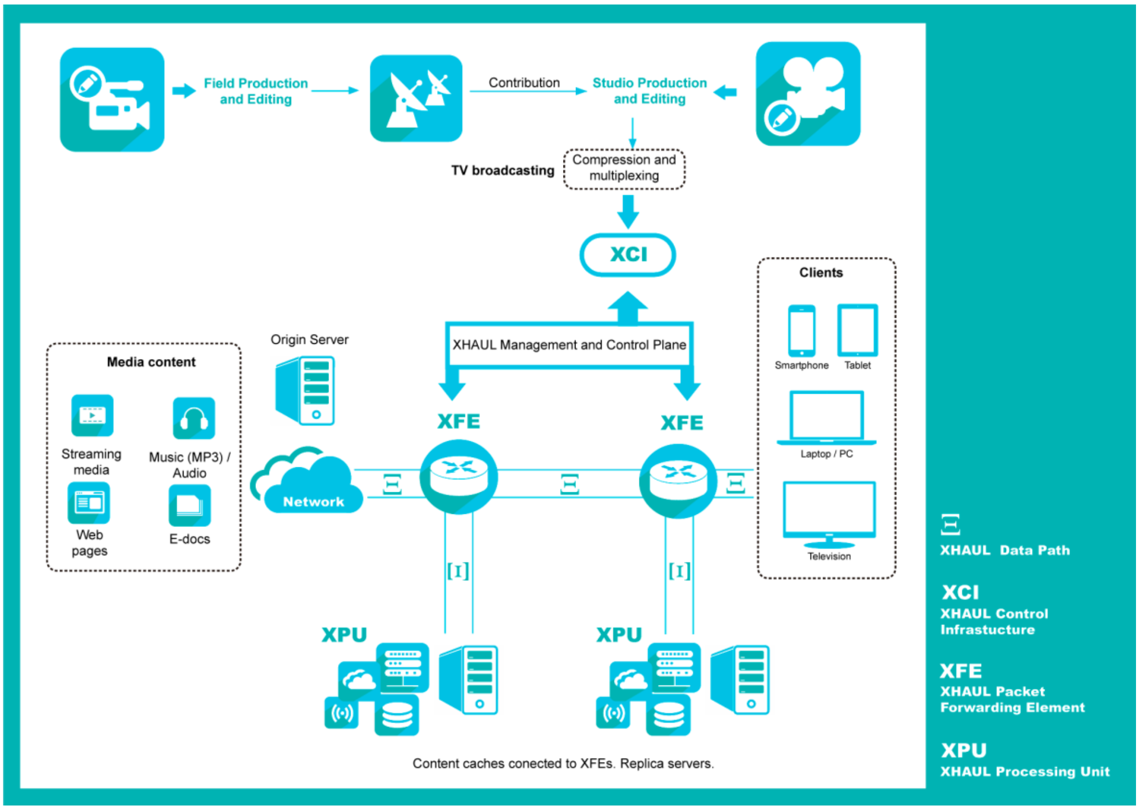

Figure 5: Media distribution over 5G-Crosshaul infrastructure

2.3.1.2.1 Addressed objectives and potential benefits

Table 3: Media distribution objectives and benefits

Objectives addressed	**<u>5G-Crosshaul Objectives</u>** • Deployment/integration of replica and origin servers into the 5G-Crosshaul architecture • Requirements for 5G-Crosshaul on the NBI in order to support a content distribution network • Cost-efficient usage of transport technologies for media distribution by integrating CDN traffic into the 5G-Crosshaul architecture instead of using a separate one • Design scalable algorithms for efficient 5G-Crosshaul resource utilization and orchestration • Design essential 5G-Crosshaul-integrated (control/planning) applications
Potential benefits of 5G-CROSSHAUL solution	Media distribution can provide several advantages: • A CDN service will take advantage of the 5G-Crosshaul infrastructure because it will be network-aware, so it will be able to provide a faster service to the end user, achieving better quality. On one hand, the new transmission media and techniques will provide more speed and bandwidth. On the other hand, the new centralized control architecture will allow better resource optimization and orchestration mechanisms.

	• A TV Broadcast/Multicast service will take advantage of the new 5G-Crosshaul features such as resource optimization, reconfiguration and distribution functions to provide real-time optimized live content to the users, with a control of the network parameters and QoE to provide an enhanced user experience.
Functions involved	• Content distribution functions • Network reconfiguration functions • Joint BH/FH optimization (routing, content scheduling, load balancing, etc.)
Stakeholders involved	Application / Data Provider (CDN/Content providers, including broadcasters), Network Provider, End users or clients, Infrastructure Providers.
Pre-conditions	Physical infrastructure will provide connectivity between all network elements. Content distribution mechanisms (CDN service logic, content replication in data plane for multicast/broadcast)
Business model	Business-to-business
Physical IT and/or network elements participating in the solution	All elements present in the 5G-Crosshaul infrastructure will participate in the solution. Moreover, for the CDN case, the origin content server and the replica servers used for the content delivery will also be required. In the case of broadcast/multicast, the content head-end is required, supported by replication mechanisms in the data plane.

2.3.1.2.2 Energy efficiency

Energy efficiency improvements can be achieved by an efficient utilization of resources. The mere optimization due to a more efficient distribution of the content will reduce the number of content flows across the network.

2.3.1.3 UC3 - Dense urban society

Background / Rationale

In the "Dense urban information society" use case (Figure 6), the connectivity is required at any place and at any time by humans in dense urban environments, considering both the traffic between humans and the cloud, and direct information exchange between humans or with their environment. Furthermore, a particular aspect arising in urban environments is that users tend to gather and move in "dynamic crowds", leading to sudden high peaks of local mobile broadband demand.

In an outdoor environment, an interesting scenario consists of some devices providing information about the surrounding of the users by measuring a certain phenomenon or by providing information about the presence of certain objects of interest. Based on the information harvested from surrounding devices and other sources, the UE could provide the user with contextual information in such a way of helping the users to better understand and enjoy their environment. Furthermore, the data collected by the device can be uploaded to the cloud servers and be shared with others through the cloud, where a tight latency requirement for connectivity will be as important as a high data rate. Since user and traffic densities in such an environment vary in terms of time and events, the Crosshaul resource management should be effective to accommodate peak traffic in dense areas or to improve energy efficiency in sparse areas.

Similar cases might arise as well in indoor environments with a spontaneous crowd concentration in a common part of the building. In fact, people spend over 90% of their times indoors and over 70% of the mobile traffic are generated inside buildings, such as homes, offices, hotels, shopping malls, hospitals, airports etc. In nowadays radio access networks, the indoor coverage and capacity are often a big issue due to high penetration loss from the outside-in approach.

As a result, it is required the deployment of indoor radio systems. Given the regulation of the output power/EIRP and the hostile RF propagation environment, deploying many small cells indoor has been concluded as the right solution to deliver high capacity to indoor users.

In 5G, the indoor problem will be more prominent, as higher frequency bands. In consequence there is a need for new indoor radio solutions providing high capacity and enabling massive and rapid indoor small cell deployment in a cost-effective manner. This scenario also includes the study of FH-based solutions for indoor small cells in the context of 5G requirements and applies the 5G-Crosshaul principle in the solution investigations.

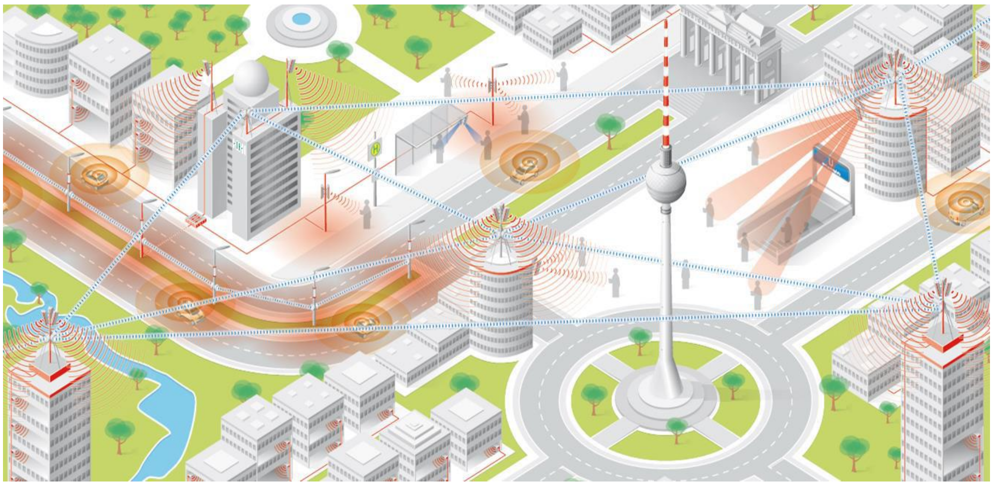

Figure 6: Dense Urban society

Scenario description

Besides classical services such as web browsing, file download, email or access to social networks, there will be a strong increase in high definition video streaming and video sharing, possibly also with higher requirements for image resolution (4K standard). This trend will be fostered, for instance, by the availability of new user interface improvements like resizable portable screens, or screens embedded into watches or glasses. Besides a massive increase in the data volumes connected to the usage of public cloud services, a key challenge in communication systems beyond 2020 will lie in the fact that humans will expect the same reliable connectivity from the cloud anytime and anywhere.

In an urban area, some of these devices might provide information about the surrounding of the users by measuring a certain phenomenon or by providing information about the presence of certain objects of interest. Furthermore, the data collected in, or by the device, can be uploaded to the cloud servers and be shared with others through the cloud, where a tight latency requirement for connectivity will be as important as a high data rate.

As a generic challenge for mobile communication systems beyond 2020, a mobile technology, completely transparent for users, will allow network access at any location and any time with service quality comparable to current wired broadband access with optical fiber.

2.3.1.3.1 Addressed objectives and potential benefits

Table 4: Dense urban society objectives and benefits

Objectives addressed	**<u>5G-Crosshaul Objectives</u>** • Design of the 5G-Crosshaul Control Infrastructure (XCI) • Unify the 5G-Crosshaul data plane • Develop physical and link-layer technologies to support 5G requirements • Increase cost-effectiveness of transport technologies for ultra-dense access networks • Design scalable algorithms for efficient 5G-Crosshaul resource orchestration **<u>Other objectives:</u>** • 10 Gbit/s over 500 meters distance with wireless mmWave • Ease local Cloud-RAN deployment scenario
Potential benefits of 5G-CROSSHAUL solution	In dense urban areas, network densification is necessary because of high traffic volume. 5G-Crosshaul technology will bridge the gap between backhaul and fronthaul technologies, reducing the costs derived from running these two unrelated network segments. Furthermore, the integration of the fronthaul and backhaul technologies will enable the use of heterogeneous transport technologies across the 5G-Crosshaul, leveraging novel and traditional technologies to increase the capacity or coverage of the 5G-Crosshaul and removing the need of using specialized fronthaul interfaces. To cope with the main objectives of the project (backhaul/fronthaul integration), 5G-Crosshaul will explore the capability of managing both fronthaul and backhaul on a single mm-wave wireless link, as well as copper and fiber. The costs for such an operation could be high. Using a single wireless 5G-Crosshaul Mm-Wave link for both backhaul and fronthaul to transmit data will drastically reduce the costs. The backhaul/fronthaul integration concept (5G-Crosshaul) enables mobile network operators to use the same link to transmit data from backhaul and

	fronthaul, introducing the following benefits. For Operators: CAPEX and OPEX savings, ease network densification, increase coverage and capacity and enable statistical multiplexing. For the end users: Better QoE increase indoor system flexibility, make indoor system switchable and coexist with other system like Wi-Fi.
Functions involved	• Mm-Wave 5G-Crosshaul Resources management • Mm-Wave 5G- Crosshaul control management • CPRI optimization • Faults management • FH over Ethernet • FH compression • FH switching
Stakeholders involved	End Users (residential and business), RAN Providers, Core Network Providers, Network Operators, Infrastructure Providers.
Pre-conditions	RAN Access or Cloud RAN available
Business model	Business-to-business and retail

2.3.1.3.2 Energy efficiency

Low-energy consumption is preferred for cost and sustainability reasons. The consumed energy should be very low when not transmitting user data. Generally, the network energy consumption should be comparable to the energy consumption of today's metropolitan deployments, despite the drastically increased amount of traffic.

With respect to the indoor traffic, it is usually unevenly distributed. The traffic hotspots follow where people gather. With the built-in flexibility of the 5G-Crosshaul network, the cell topology and the distribution of resources can be adapted to the changing traffic demand. For low traffic areas, unused resources can be put into idle-mode to save energy. Especially, in the non-office time for enterprise and public places, the capacity provided by the network can be adjusted. This fact can produce the release of the majority of the resources comparing to the required network capacity during the office time.

2.3.1.4 Mapping into network services

The network services to carry service-oriented use cases data should present some characteristics, summarized in the following paragraph:

- Use case 1 – The main parameters to be considered while choosing a network service for this use case are: ultra-low latency, high reliability and dynamic reallocation. In addition virtualization, on-demand adaptation, monitoring capacity, ability of mobility and possibility of data replication are “high importance” functional requirements for this use case. On the other side the high availability and the isolation of traffic are the most tailored non-functional requirements for this kind of use case. No huge bandwidth is required.

- Use case 2 - The main parameters to be considered while choosing a network service for this use case are: monitoring and dynamic reallocation. The network services should have the possibility to be virtualized, dynamically allocated and they should present low errors (BER and Packet loss). It is also important to have a sophisticated monitoring system and the possibility of data replication (multicast). Among the non-functional requirements, programmability and usability are the most important ones.
- Use case 3 - The main parameters to be considered for choosing a network service for this use case are: short physical latency and managing of huge density of connections. It is very important to have also the possibility to virtualize network services. Among the non-functional requirements robustness and resilience are the most relevant ones.

Table 5: Use cases mapped into service-oriented network services

	Use Case 1		**Use Case 2**	**Use Case 3**
Nature of connectivity	**High-speed train**	**Traffic safety**		
Circuit switching / Packet switching	No matter	No matter	No matter, preferable packet, due to the nature of clients' formats	No matter, preferable packet, due to the nature of clients' formats
Connection-oriented communication / Connectionless communication	Connection oriented	Connection oriented	Connection oriented	Connection oriented
E-LAN	Yes	Yes	Yes	Yes
E-Tree	Yes	Yes	Yes	Yes
E-Line	Yes	Yes	Yes	Yes
BW variability	Yes	Yes	Yes	Yes
BW capacity	High	Not important	High	High (with high granularity)
Hierarchical containers/frames	Maybe a plus	Not important	Not strictly necessary	They may be a plus for managing huge number of connections
Possibility of implementing Quality of Service mechanisms	Yes	Yes	Yes, fundamental	Yes
Synchronization	Yes	Yes	Yes	Yes
Monitoring and control				

Max time for modifying connections	Short	Very short	Relatively short	Very short
SLA verification	Yes	Yes	Not essential	Yes, but not essential

	Use Case 1		**Use Case 2**	**Use Case 3**
Nature of connectivity	**High-speed train**	**Traffic safety**		
Failure localization	Yes	Yes	Yes	Yes
Performances				
Max latency	Low	Very low, comparable with propagation	Low	Low
Max jitter / Max Packet delay Variation	Low	Very low	Low	Low
Bit Error Rate	Low	Low	Low	Very low
Packet Loss Rate	Low	Low	Low	Very low
Resilience				
Time of recovery after failure	< 50 ms	< 50 ms	< 100 ms	< 100 ms
Mean availability	99.999%	99.999%	99.99%	99.99%
Carrier class devices	Yes	Yes	Not essential, provided that the mean availability and the time of recovery remain under limits	Not essential, provided that the mean availability and the time of recovery remain under limits
Support limitations				
UE density	≥ 1M terminal/km^2			
Guaranteed user data rate	> 50Mb/s			
Mobility support	Up to 500km/h			

2.3.2 Functional-oriented use cases

2.3.2.1 UC4 – Multi-tenancy

Background / Rationale

5G-Crosshaul technology will allow flexible sharing of backhaul/fronthaul physical resources across multiple network operators (multiple tenants). This is a key feature to maximize the degree of utilization of 5G-Crosshaul deployments and minimize the overhead due to the costs of roll-out and maintenance.

Scenario description

Multi-tenancy technology allows the owner of the 5G-Crosshaul infrastructure to provide virtual resources over its substrate infrastructure to multiple operators. The specific SLA and parameters to be exposed on the virtual view should be technology independent and should take into account the end user service parameters. A virtual network (VN) is a logical topology comprised of a set of virtual nodes (e.g., virtual routers and switches) interconnected by virtual links over the substrate network. The following entities (see Figure 7) are considered:

- 5G-Crosshaul Physical Infrastructure Provider (X-PIP), which owns and manages the substrate infrastructure.
- 5G-Crosshaul Virtual Network Provider (X-VNP), responsible for assembling virtual resources from one or multiple PIPs into a virtual topology.
- 5G-Crosshaul Virtual Network Operator (X-VNO), which maintains and configures a virtual network over the virtual topology provided by a VNP according to the needs of a Service Provider. One VNO can set up multiple virtual networks (VNs) for different services.

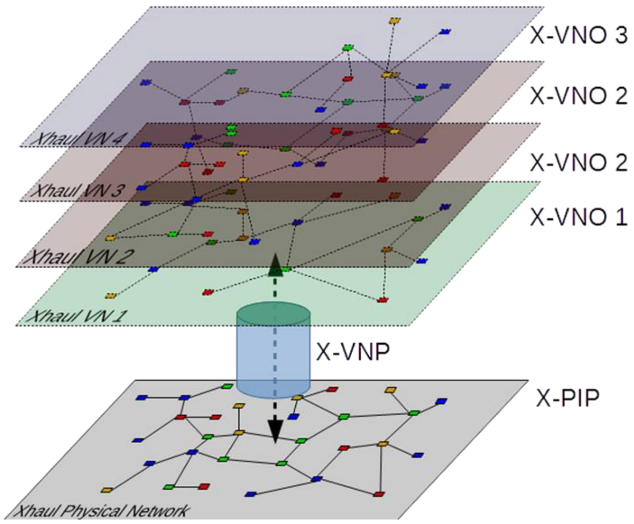

Figure 7: Multi-tenancy

To further increase the network efficiency, the sharing among the multiple tenants or multiple operators may require to some switching devices on certain network segments the support of tenant/operator awareness capabilities. The implications derived from multi-tenancy with respect to the unified data plane design and the optimization possibilities will be also investigated.

2.3.2.1.1 Addressed objectives and potential benefits

Table 6: Multi-tenancy objectives and benefits

Objectives addressed	**5G-Crosshaul Objectives** • Design of the 5G-Crosshaul Control Infrastructure (XCI)

	• Specify the XCI's northbound interface • Unify the 5G-Crosshaul data plane • Design scalable algorithms for efficient 5G-Crosshaul resource orchestration **<u>Other objectives</u>** Multi-tenancy support shall provide the following features: • Virtual resources are provided concurrently and seamlessly to the tenants • Virtual domains are isolated across tenants, i.e. each VNO shall use the complete addressing space, deploy their choice of network OS and set their own (virtual) topology • Virtual slices of resources are allocated dynamically, allowing the network to scale to multiple tenants without service disruption to existing VNOs • The Virtual slices can be required on-demand
Potential benefits of 5G-CROSSHAUL solution	5G-Crosshaul Multi-tenancy will allow increasing the usage efficiency of a physical deployment of backhaul/fronthaul infrastructure, e.g., by leasing spare physical resources to additional virtual operators. In this way, 5G-Crosshaul technology will reduce CAPEX and OPEX of the infrastructure owner and mobile network operators, fostering densification and thus higher availability to serve users. Besides that, both 5G-Crosshaul infrastructure provider and operators gain additional benefits: • The infrastructure provider gains the flexibility on provisioning virtual network slicing with different features to network operators to meet their individual requirements. • VNO's virtual network can achieve optimal utilization with dynamically scaling up/down feature to meet their dynamic requirements on load, coverage and topology.
Functions involved	• Network Function Virtualization • Service Function Chaining • Admission control • Joint BH/FH optimization (routing, scheduling, load balancing, etc.) • Virtual infrastructure planning
Stakeholders involved	Service Providers, (Virtual) Network Operators, Infrastructure Providers, Virtual Network Infrastructure Provider.
Pre-conditions	Physical infrastructure with virtualization capabilities, with enough computing resources in the cloud nodes supporting NFV. Support for multi-tenancy in the unified data and control plane.
Business model	Business-to-business

Physical IT and/or network elements participating in the solution	All physical IT and networking elements (nodes and links) are subject to be shared and partitioned.

2.3.2.1.2 Energy efficiency

Energy efficiency improvements can be achieved by an efficient utilization of physical resources, i.e. minimizing energy-consuming idle periods.

2.3.2.2 UC5 – Mobile Edge Computing

<u>Background / Rationale</u>

Dense network environments are characterized by a high number of users which simultaneously demand connectivity resources. In the radio access part such connectivity needs can be alleviated by the deployment of small cells in order to increase the radio capacity in that area. However, this increment on the population to be served impacts on the backhaul network deployed to cover such area.

This is due to the significant increase in the use of mobile broadband services, especially on-demand video content (basically affecting the volume of traffic to be delivered) and gaming (mainly impacting on the latency).

Mobile-Edge Computing (MEC) [2] proposes the deployment of IT and cloud-computing capabilities within the Radio Access Network (RAN), in close proximity to mobile subscribers (see Figure 8). Content, service and application providers can leverage on such distributed computing capabilities to serve the high-volume, latency-sensitive traffic on dense areas concentrating high number of users.

In consequence, the introduction of computing capabilities at the edge of the mobile network interconnected through 5G-Crosshaul can improve the service delivery to the end user on one hand, and allow to efficiently deliver the traffic minimizing transport resource consumption (through savings in the backhaul capacity) on the other hand. The idea of this use case is to illustrate how the integration of FH/BH can benefit MEC, by facilitating the optimization process of the (re-)allocation of computing resources in a network-aware fashion, thanks to flexible and programmable network architecture.

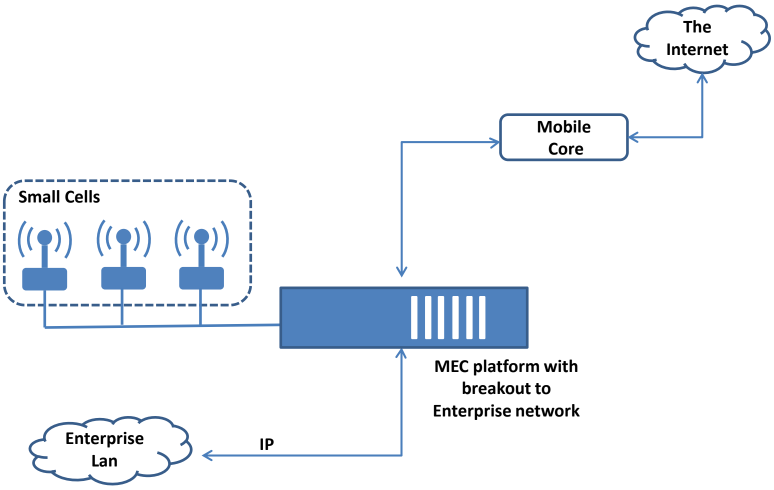

Figure 8: MEC. High level scheme

Three categories of services are benefited by MEC:

- Consumer-oriented services: these are innovative services that generally benefit directly the end-user, i.e. the user using the UE. This allows end-users to offload applications or data to the edge network nodes for battery-saving purposes or for accessing computing capacity beyond their resource-limited handset.
- Operator and third party services: these are innovative services that take advantage of computing and storage facilities close to the edge of the operator's network.
- Network performance and QoE improvements: these services are generally aimed at improving the performance of the network, either via application-specific or generic improvements. To this purpose, in-network analytics can be an example of efficient exploitation of these capabilities from the operator's point of view, by performing the computation at the network edge and only transmitting the significant set of results to more advanced computation platforms.

Scenario description

Figure 9 describes the MEC architecture where a user equipment is about to run an application. The offloading framework of the operating system at the device polls the 5G access point to which it is attached to check the availability of in-network pool of resources with computing capabilities able to execute this application with the required quality level. The access point forwards this request to a MEC server or entity in charge of the management of the edge computing resources (hosted at the XPUs), which calculates if the request can be satisfactorily handled according to the computing and network situation within the cluster. The information about the network situation relies on a simplified architecture provided by 5G-Crosshaul, which facilitates the overall operation of the MEC. This implies that the XCI provides monitoring information to the MEC server.

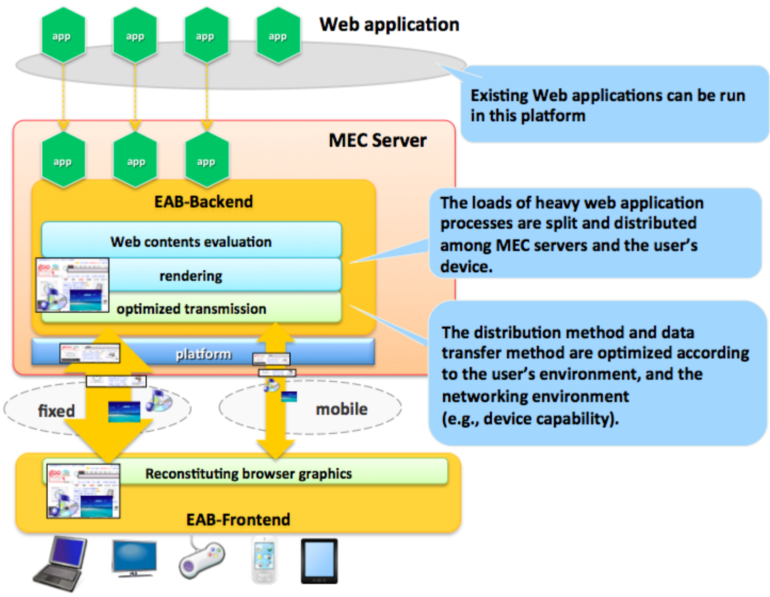

Figure 9: MEC architecture

Generally, MEC enables ultra-low latency requirements (e.g., for gaming or traffic control), the caching of content and data for multiple UEs (e.g., web browsing, augmented reality during events, adverts based on position) and offload high-performance data applications from the UEs to the MEC server.

Furthermore, MEC can provide access directly to some special content server or Enterprise LANs to reduce backhaul traffic or provide additional functionality like security.

As a further example, a MEC server can execute compute-intensive functionalities with high performance, by offloading the computation from the end-user to the MEC server. This reduces the energy consumption of the mobile end user (typically high computing intensive applications with little transmission needs, such as a chess game).

2.3.2.2.1 Addressed objectives and potential benefits

Table 7: MEC objectives and benefits

Objectives addressed	<u>**5G-Crosshaul Objectives**</u> • Deployment of mobile edge computing in the 5G-Crosshaul architecture • Requirements for 5G-Crosshaul on the NBI/SBI in order to support MEC • Optimization of computing resources management taking into account both network and computing resources utilization
Potential benefits of 5G-CROSSHAUL solution	For End-users: better QoE (lower latency, faster download) and preserved battery lifetime. For Operators: reduced capacity needed in the backhaul, competitor differentiation by offering specialized MEC applications, such as location-based services (adverts, traffic,..).

Functions involved	• Relocation of the applications and network functions on distributed MEC servers due to the network context (e.g., mobility of the end-users) • Both network and IT Control and resource management • Network reconfiguration functions • Joint BH/FH optimization (routing, load balancing, etc.)
Stakeholders involved	Service Providers, Network Operators, Infrastructure Providers, Application/Data Providers, Computing Facilities Providers.
Pre-conditions	RAN Access Distributed RAN (BB-functionality close to MEC server) or even higher Layer processing up to IP user data Distributed computing capabilities User equipment is offloading-capable (offloading framework available)
Business model	Business-to-business
Physical IT and/or network elements participating in the solution	MEC solutions are independent on the underlying physical technology • XCI: has to control the connectivity and status of the MEC nodes • XFE: controlled by XCI to establish traffic paths with MEC nodes. • MEC nodes

2.3.2.2.2 Energy efficiency

Content caching has the potential of reducing the backhaul capacity requirements up to 35%. Server consolidation can be applied to MEC for energy consumption reduction. Live Virtual Machine (VM) migration technology is often used to consolidate VMs residing on multiple under-utilized servers onto a single server, so that the remaining servers can be set to an energy-saving state. Functions and applications relocation can help optimize the consumption of network resources, including energy efficiency.

2.3.2.3 Mapping into network services

The network services that carry functional-oriented use cases data should present some characteristics, summarized in the following paragraph:

- Use case 4 - The main parameters are: virtualization, dynamic bandwidth allocation and management of QoS, even for huge capacity. The continuous verification of SLA completes the picture. Among the non-functional requirements, robustness and resilience are the most important ones.
- Use case 5 - The main parameters to be considered for choosing a network service for this use case are: virtualization, dynamic bandwidth allocation and QoS management. Due to the specific nature of the use case, the ability to support mobility and a high security level are essential. Among the non-functional requirements, usability and resilience are the most important ones.

Table 8: Use cases mapped into functional-oriented network services

	Use Case 4	Use Case 5
Nature of connectivity		
Circuit switching / Packet switching	No matter, preferable circuits since probably there will be the necessity of managing (relatively few) huge connections	No matter, preferable circuit, due to the short latency and security requirement
Connection-oriented communication / Connectionless communication	Connection oriented	Connection oriented
E-LAN	No	No
E-Tree	No	No
E-Line	Yes	Yes
BW variability	Not necessary	Yes
BW capacity	High (with high granularity)	High granularity, not huge traffic
Hierarchical containers/frames	They may be a plus for management huge number of connections	Not strictly necessary
Possibility of implementing Quality of Service mechanisms	Yes	Yes. In any case high quality is required
Synchronization	Yes	Yes
Monitoring and control		
Max time for modifying connections	Short	Very short
SLA verification	Yes, but not essential	Yes
Failure localization	Yes	Yes
Performance		
Max latency	Low	Very low
Max jitter / Max Packet delay Variation	Low	Very low
Bit Error Rate	Very low	Very low
Packet Loss Rate	Very low	Very low
Resilience	Resilience	
Time of recovery after failure	< 50 ms (not for all connections)	< 50 ms
Mean availability	99.999% (not for all connections)	99.999%
Nature of connectivity		
Carrier class devices	Yes	Yes

2.4 Requirement analysis of selected use cases

Based on the considered use cases, it is evident the necessity that the service could be virtualized, that is the abstraction and virtualization of physical resources. So, it is essential that 5G-Crosshaul provides a "virtualization layer" capable of showing to the customer (user or tenant) the resources not corresponding to the physical infrastructure.

From the analysis of the network services tailored for the 5G-Crosshaul, it is clear that the majority of use cases require (or prefer) packet switching. The reason under this choice is due to the nature of user data (terminals produce packets), to the necessity of point-to-multipoint services (E-LAN and E-Tree) and the implementation of Quality of Service mechanisms. In any case it is required a connection-oriented communication system. In certain cases, circuit might be preferable, even if not strictly necessary. That is the case of multi-tenancy, where it is expected that infrastructure owner will manage a few, huge bandwidth connections. In this case wavelengths or OTN connections are easier to be managed. A second case is represented by MEC, where security requirement may be better satisfied by circuits, guaranteeing isolation and physical segregation of traffic.

Furthermore it is important, in all cases, that it would be possible to monitor the network in order to both guarantee a better level of quality (e.g., a better failure localization allows greater availability figures). Regarding the data plane, it is important that the quality of certain connections (BER, packet loss, latency, jitter (packet delay variation)) should be very good, even in presence of QoS mechanisms.

On the control plane side, it is required that it is possible to manage connections in a very short lapse of time (that is set-up/tear-down or modify the endpoints of the connections).

Furthermore, 5G-Crosshaul has first elaborated a list of high-level functional and non-functional requirements, which are reported in Table 9 and Table 10. Then each of them has been analyzed in details with reference to the relevant layer(s) of the 5G-Crosshaul architecture.

Table 9: Functional Requirements description

ID	Requirement	Description
FT-01	Infrastructure virtualization	Abstraction and virtualization of physical resources.
FT-02	Dynamic (re-)allocation of virtual resources to physical resources	Reconfiguration of the mapping between logical resources and physical resources.
FT-03	Mapping of virtual to physical resources synchronization	Mechanisms to keep virtual resources consistent with the underlying physical resources.
FT-04	Resource discovery	Ability of discovering 5G-Crosshaul components.
FT-05	On-demand adaptation	Bandwidth re-allocation and Traffic Engineering.
FT-06	Monitoring and accounting	Metering and accounting of physical and/or virtual resources. Notification of asynchronous events.
FT-07	Physical requirements -	Delay.

ID	Requirement	Description
	Latency	
FT-08	Physical requirements – Jitter	Delay variation.
FT-09	Physical requirements – Data rate	Throughput / bandwidth requirements.
FT-10	Physical requirements – Packet loss	Amount of successfully delivered packets vs total sent packets in a given time.
FT-11	Clock synchronization	Clock distribution.
FT-12	Density of connections	Number of supported connections.
FT-13	Mobility	Mobility management for mobile devices in 5G-Crosshaul infrastructure.
FT-14	Transferred data replication	Data input replication on output ports in 5G-Crosshaul devices.
FT-15	Energy efficiency	Optimization of power consumption for physical and/or virtual infrastructure.
FT-16	Combined network and computing resource provisioning	Joint provisioning and deployment of network + IT resources.
FT-17	Management	Supervision of 5G-Crosshaul components.
FT-18	Security	Secure operations and data privacy.
FT-19	Backward compatibility	Adaptation or interaction of 5G-Crosshaul system with legacy systems.
FT-20	SLAs mapping	Validation of SLAs.

Table 10: Non-functional Requirements description

ID	Requirement	Description
NF-01	Programmability	Ability of 5G-Crosshaul infrastructures to be dynamically configured and provisioned in an automated way
NF-02	Scalability	Ability to handle growing amounts of work in a graceful manner.
NF-03	Usability	Efficiency and simplicity of the interaction between the user and the 5G-Crosshaul system.
NF-04	Consistency	Uniformity in the service offer.
NF-05	Robustness of resilience	Ability of 5G-Crosshaul system to cope with errors during the execution of its procedures and to operate in case of abnormal situations.
NF-06	Responsiveness	Ability and readiness of the 5G-Crosshaul system to react to a given input.
NF-07	Availability	Carrier grade availability of the 5G-Crosshaul system (99.999%).
NF-08	Planning, design and development	Maintenance and access to data repositories where structured information about different classes of resources and services can be queried.
NF-09	Isolation	Separation of logical infrastructures on 5G-Crosshaul physical resources.
NF-10	Resource efficiency	Optimal use of 5G-Crosshaul resources.
NF-11	Convergence	Support of different services on the same 5G-Crosshaul infrastructure.

2.4.1 5G-Crosshaul functional and non-Functional requirements

This section describes the 5G-Crosshaul requirements applied to the different layers of the 5G-Crosshaul architecture, i.e. the data plane, the control plane and the application plane. This analysis provides the foundations to identify:

- The characteristics and capabilities required at the network data plane of the 5G-Crosshaul physical infrastructure, as input to WP2 studies on unified data plane.
- The functionalities and features which must be offered by the 5G-Crosshaul control infrastructure (XCI) and 5G-Crosshaul applications, as input to WP3 and WP4 studies on control plane and applications, respectively.

A list of qualitative KPIs is also provided for the main requirements. As a further step (to be accomplished and fully reported in Deliverable 2.1), they will be quantified for the different use cases providing the criteria for the 5G-Crosshaul system evaluation in WP5.

Furthermore, Annex II provides a complete description of the functional and non-functional requirements analysis for 5G-Crosshaul.

2.4.2 Mapping of requirements to 5G-CROSSHAUL use cases

This section presents how the different requirements identified in previous sections can be mapped to each use case and what is their relative importance regarding the use case. In addition, this section presents a first overview of the impact that each requirement has on the technical Work Packages (WP2/3/4), regarding their functionality for each use case.

Each requirement has been evaluated for all use cases and given a relative weight. We have selected three levels of importance for each requirement:

i) High impact (H), indicating that this requirement is of upmost importance for the use case.

ii) Medium impact (M), indicating that the use case is impacted by this requirement in a moderate level.

iii) Low impact (L), indicating that the requirement does not have a substantial impact on the use case.

The methodology used to evaluate each requirement consists on different steps. First of all each partner involved in the use case has indicated its assessment for it. Then an averaging formula has been applied reaching the overall consideration for each requirement and its impact on the use case. In addition, this assessment has been fed back to the technical WPs, which have provided the fall out of each requirement on the functionality expected to be developed in the WPs.

In the following the summary tables for the overall evaluation are presented.

Table 11 summarizes the relative impact of each of the identified functional requirements for the different 5G-Crosshaul use cases (H= High, M=Medium, L=Low, '--' = Does not apply).

Table 11: Relative impact of functional requirements in 5G-Crosshaul use cases

Req. id	Req. Statement	UC1 - Vehicle Mobility	UC2 - Media Distribution	UC3 - Dense Urban Society	UC4 – Multi-tenancy	UC5 - MEC
FT-01	Infrastructure Virtualization	H	H	L	H	H
FT-02	Dynamic (re-)allocation of virtual resources to physical ones	H	H	L	H	H
FT-03	Mapping of virtual to physical resource synchronization	H	L	M	H	H
FT-04	Resource Discovery	M	M	M	H	L
FT-05	On-demand adaptation	H	H	H	H	H
FT-06	Monitoring and accounting	H	H	L	H	H
FT-07	Physical requirements – Latency	H	H	H	L	H
FT-08	Physical requirements – Jitter	H	H	H	L	H
FT-09	Physical requirements - Data Rate	L	M	M	L	M
FT-10	Physical requirements - Packet Loss	H	H	M	L	H
FT-11	Clock synchronization	L	H	L	--	H
FT-12	Density of connections	L	M	H	--	M
FT-13	Mobility	H	M	H	--	H
FT-14	Transferred Data Replication	H	H	--	--	L
FT-15	Energy Efficiency	M	L	L	H	M
FT-16	Combined network and computing resource provisioning	L	H	M	H	H
FT-17	Management	M	M	M	L	M
FT-18	Security	H	M	L	L	H
FT-19	Backward compatibility	L	L	L	--	L
FT-20	SLAs mapping	L	M	L	H	L

Table 12 summarize the relative impact of each of the identified non-functional requirements for the different 5G-Crosshaul use cases (H= High, M=Medium, L=Low, '-' = Does not apply).

Table 12: Relative impact of non-functional requirements in 5G-Crosshaul use cases

Req. id	Req. Statement	UC1 - Vehicle Mobility	UC2 - Media Distribution	UC3 - Dense Urban Society	UC4 – Multitenancy	UC5 - MEC
NF-01	Programmability	M	H	M	M	H
NF-02	Scalability	M	M	M	L	M

Req. id	Req. Statement	UC1 - Vehicle Mobility	UC2 - Media Distribution	UC3 - Dense Urban Society	UC4 – Multitenancy	UC5 - MEC
NF-03	Usability	L	H	L	H	H
NF-04	Consistency	L	M	H	L	M
NF-05	Robustness or resilience	M	H	H	L	H
NF-06	Responsiveness	M	H	M	M	M
NF-07	Availability	H	M	H	M	M
NF-08	Planning, Design and Development	M	M	M	L	M
NF-09	Isolation	H	L	L	H	H
NF-10	Resource efficiency	M	M	M	H	M
NF-11	Convergence	M	M	L	L	M

The final priority assigned to each requirement is summarized in Table 13, considering the scored impacts to different use cases selected in Table 11 and Table 12. The final priority was calculated as the arithmetic average of the priorities of each requirement for each of the use cases. The labels 'H' (High), 'M' (Medium), 'L' (Low), '-' (Does not apply), were given a weight (3, 2, 1, 0 respectively) and the average result was considered to be the final priority using a normal rounding method:

Table 13: Overall impact of requirements in 5G-Crosshaul

Req. id	Req. Statement	Priority
FT-01	Infrastructure Virtualization	H
FT-02	Dynamic (re-)allocation of virtual resources to physical ones	H
FT-03	Mapping of virtual to physical resource synchronization	M
FT-04	Resource discovery	M
FT-05	On-demand adaptation	H
FT-06	Monitoring and accounting	H
FT-07	Physical requirements - Latency	M
FT-08	Physical requirements - Jitter	M
FT-09	Physical requirements - Data Rate	L
FT-10	Physical requirements - Packet Loss	M
FT-11	Clock synchronization	L
FT-12	Density of connections	M
FT-13	Mobility	M
FT-14	Transferred Data Replication	M
FT-15	Energy Efficiency	M
FT-16	Combined network and computing resource provisioning	M

Req. id	Req. Statement	Priority
FT-17	Management	M
FT-18	Security	M
FT-19	Backward compatibility	L
FT-20	SLAs mapping	M
NF-01	Programmability	M
NF-02	Scalability	M
NF-03	Usability	M
NF-04	Consistency	M
NF-05	Robustness or resilience	M
NF-06	Responsiveness	M
NF-07	Availability	M
NF-08	Planning, Design and Development	M
NF-09	Isolation	M
NF-10	Resource efficiency	M
NF-11	Convergence	M

For more details, Annex III reports the complete analysis of the requirements referring each of the identified use cases. In particular, the impact on WP2 (data plane), WP3 (control plane) and WP4 (application plane).

3 System Architecture

This chapter presents an overall 5G-Crosshaul architecture for the implementation of 5G-Crosshaul key features, to build the envisioned adaptive, flexible and software-defined future 5G transport networks, integrating multi-technology fronthaul and backhaul segments.

In the control plane, it needs to include a group of key functional elements (e.g., topology discovery, network monitoring, technology abstraction, provisioning of virtual infrastructure, etc.) and their main interfaces towards the applications (northbound interface) and towards underlying technologies (southbound interface). For the design of the control plane we leverage on the SDN (Software Defined Networking) principles to have a unified control, management and configuration of the 5G multi-technology transport network, and apply NFV to the 5G-Crosshaul infrastructure enabling flexible function placement and cost-effective usage of the 5G-Crosshaul infrastructure resources. The SDN principle allows the separation of the data and control planes, fostering network and device programmability. NFV allows infrastructure and function virtualization (see also [1]), where the underlying physical infrastructure and network functions can be virtualized in such a way that they will be appropriately instantiated, connected and combined over the 5G-Crosshaul substrate.

In the design of the data plane architecture, it needs to reflect the integration of heterogeneous technologies for the fronthaul and backhaul links into a single SDN-based controlled network. The main challenge of the data plane is the need for extended flexibility, to adapt to the new fronthaul and backhaul technologies arising with 5G as well as to incorporate legacy technologies through abstraction interfaces.

To achieve such a design, our approach is to leverage the state-of-the-art SDN and NFV architectures to maximize the compatibility and integration of 5G-Crosshaul system design with the existing standard frameworks and reference specifications.

So far the most well-developed open source SDN controllers which provide carrier grade features and can be used for 5G networks are: Open Daylight (ODL) [5] and Open Network Operating System (ONOS) [6]. In the NFV case, ETSI NFV ISG is currently studying the ability to deploy instances of network functions running on VMs, providing network operators with the ability to dynamically instantiate, activate, and re-allocate resources and functions. Based on these open source initiatives and standards, our 5G-Crosshaul architecture keeps the architecture compatibility with the existing ODL/ONOS and ETSI NFV architecture frameworks. For the overall architecture design, we take a bottom-up approach to evolve from current Management Systems towards the integration of MANO concepts.

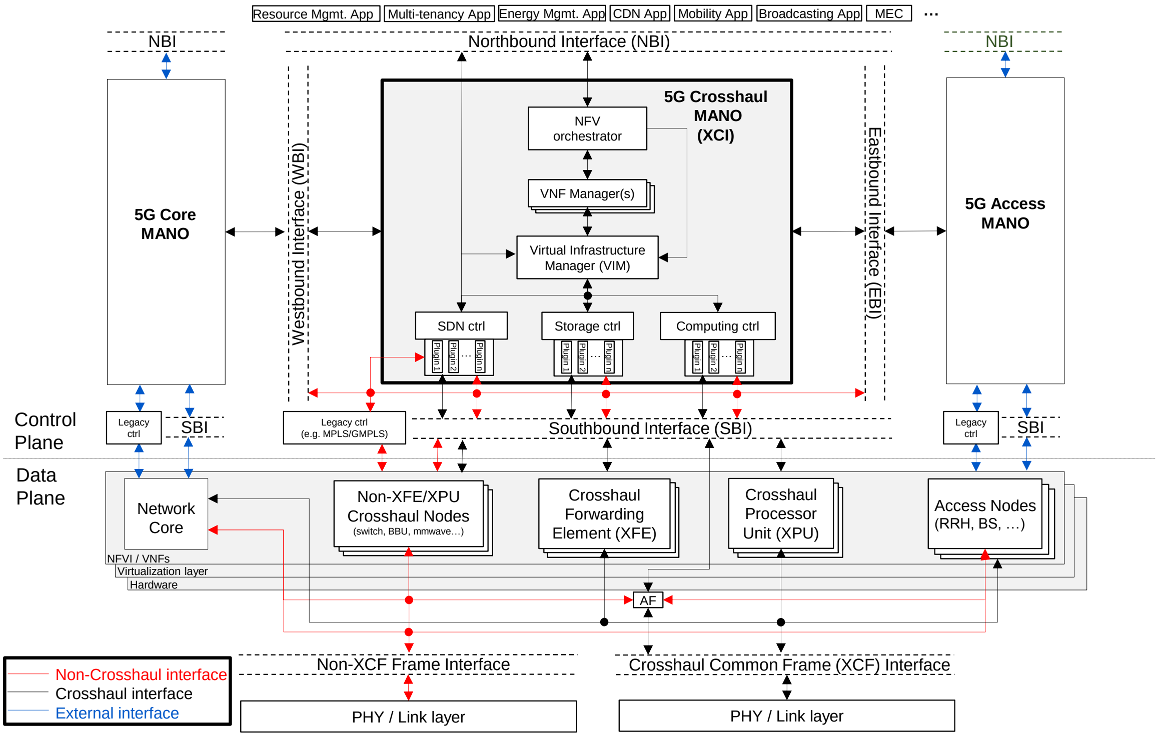

Figure 10: 5G-Crosshaul Architecture Illustration

3.1 Single MANO

Based on the design criteria exposed in the introduction above, we propose that the 5G-Crosshaul architecture devised in our design shares the same principles of the SDN reference architecture as defined by ONF in [7]:

1) Decoupled data plane and control plane.
2) Logically centralized control.
3) Exposure of abstract resources and state to external applications.

3.1.1 Control Plane

As illustrated in Figure 10 we divide the control plane into two clearly differentiated layers: a top layer for external applications and the XCI below. An ecosystem of applications at the topmost part of the system architecture exploits 5G-Crosshaul resource orchestration functions to support the most diverse functionalities such as planning, network and service monitoring/prediction, optimization of resources, energy management, multi-tenancy, media distribution such as content delivery networks and TV Broadcasting, etc. In turn, the XCI is our 5G transport Management and Orchestration (MANO) platform that provides control and management functions to operate all available types of resources (networking and cloud).

The XCI is based on the SDN/NFV principles and provides a unified platform which can be used by upper layer applications via a Northbound Interface (NBI) to program and monitor the underlying data plane by a common set of core services and primitives.

XCI interacts with the data plane entities via a Southbound Interface (SBI) in order to:

1) Control and manage the packet forwarding behavior performed by 5G-Crosshaul Forwarding Elements (XFEs) across the 5G-Crosshaul network.
2) Control and manage the PHY configuration of the different link technologies (e.g., transmission power on wireless links).
3) Control and manage the 5G-Crosshaul Processing Unit (XPU) computing operations (e.g., instantiation and management of VNFs via NFV).

3.1.2 Data plane

5G-Crosshaul integrates all communication links between Remote Radio Heads/Small Cells and core network entities in a unified transport network by designing a common data plane that enables the integration of heterogeneous technologies for the fronthaul and backhaul links into a single programmable, multi-tenant enabled packet-based network. To this aim, we use 5G-Crosshaul Forwarding Elements (XFEs). XFEs are switching units, based on packet or circuit technology, that interconnect a broad set of links and PHY technologies by means of a novel transport protocol which leverages the 5G Crosshaul Common Frame (XCF). The XCF is designed to simultaneously carry fronthaul and backhaul traffic, which might have very diverse requirements. Note that this entails the definition of fields for handling traffic prioritization and timing.

In turn, 5G-Crosshaul Processing Units (XPUs) carry out the bulk of the computing operations in 5G-Crosshaul. These operations shall support C-RAN, by hosting BBUs or MAC processors, but also those 5GPoA functionalities that can be virtualized (VNFs) and a heterogeneous set of other services (e.g., CDN-based services). In this manner, the NFVI comprises all data plane (software and hardware) components that build up the networking environment where VNFs are deployed and connected.

Of course, with backwards-compatibility in mind, XCI can communicate with non-5G-Crosshaul-specific entities, such as legacy switches, BBUs, mmWave switches, etc., using proper plugins. 5G-Crosshaul-specific data plane elements (XFEs, XPUs) can communicate with others non XCF-compliant elements by means of an Adaptation Function (AF) entity that acts as a translator between XCF and other protocols.

3.1.3 Interfaces

As mentioned above, an ecosystem of applications sits on top of the XCI to provide tools for optimization, prediction, energy management, multi-tenancy and others. The XCI is the means to achieve the application goals and the NBI (typically based on REST, NETCONF or RESTCONF APIs [4]) that interconnect both lands.

The configuration of network resources (e.g., routing), computing resources (e.g., instantiation of VNFs) and storage resources (e.g., CDN caches) is directly executed on each of the required data plane elements by the XCI by means of the SBI. Candidates for SBI are, e.g., OpenFlow, OF-Config, OVSDB (Open vSwitch, Database), SNMP, and/or an ecosystem of several of them.

The scope of operation of the XCI is limited to (physical/virtual networking/storage/computing) resources within the 5G-Crosshaul transport domain. However, given that a proper optimization of the data plane elements may require knowledge of the configuration and/or other information from the Core network and/or the Radio Access Network (RAN) domains, our system design contemplates a Westbound interface (WBI) to communicate with the 5G Core MANO and an Eastbound interface (EBI) to interact with the 5G Access MANO.

In both 5G Core and Access MANO cases, different architectural approaches could be preferred. Assuming a same hierarchy level relationship between the 5G MANO systems for 5G-Crosshaul, core and access, the WBI and EBI interfaces are used to transfer a subset of monitoring information across domains enabling a selected subset of the management and orchestration operations (abstracted level of operations and information available).

In the case of the 5G-Crosshaul MANO system being part of a hierarchical 5G MANO system spanning across 5G-Crosshaul and/or core and access, then the NBI interface is used and detailed monitoring information and low-level management and orchestration operations are enabled.

3.2 Multi-domain and multi-technology

While it is commonly recognized that the term domain may accept multiple definitions – depending, e.g., on administrative boundaries, topological visibility, etc., in the scope of this subsection, analogous to the IETF GMPLS definition of the data plane [6], we will refer to a domain as a collection of network elements within a common realm of address space, identified by a common technology and switching type, which is a collection of network resources capable of terminating and/or switching data traffic of a particular format. It is assumed that the network is deployed within a single administrative company performing a single instance of MANO.

Let us note that a single SDN controller with full topology visibility can be designed and conceived to control multiple data plane technologies, but such an approach may have important shortcomings, such as: while this controller can work for small to medium sized domains, large domains need to rely on the arrangement of multiple controllers, e.g., in a hierarchical setting, to overcome scalability issues. Additionally, having a single controller that can be deployed for multiple data plane technologies (by means of dedicated software extensions, plugins and an all-encompassing generalized protocol) is not straightforward. It may be the case that this is only possible provided that a common information model for all layers/technologies can be conceived within the controller, or that this only applies to well-known, mature technologies in specific combinations (e.g., combining a packet layer such Ethernet or IP/MPLS with an OTN circuit switching layer). In general, the diversity and heterogeneity of the relevant involved technologies in Crosshaul means that the single controller approach may not be applicable to emerging technologies such as mmWave while controlling a DWDM photonic mesh network.

Consequently, the approach taken by 5G-Crosshaul is to focus on a deployment model in which a (possibly redundant, high-available) SDN controller is deployed for a given technology domain, while the whole system is orchestrated by a "parent" controller, relying on the main concept of network abstraction (see Figure 11). For example, the parent controller may be responsible for the selection of domains to be traversed for a new provisioned service. Such domain selection is based on high-level, abstracted knowledge of intra- and inter-domain connectivity and topology. The topology abstraction, needed due to scalability and confidentiality reasons, is based on a selection of relevant TE attributes and represented usually as a directed graph or virtual links and nodes as allowed by the domain internal policy. Per domain controllers are responsible for segment expansion (i.e., computation) in their respective domains.

Let us note that a given Crosshaul network may be divided into different service layers, and connectivity across the highest service layer may be provided with support from successively lower service layers. Service layers are realized via a hierarchy of network layers and arranged based on the switching capabilities of network elements.

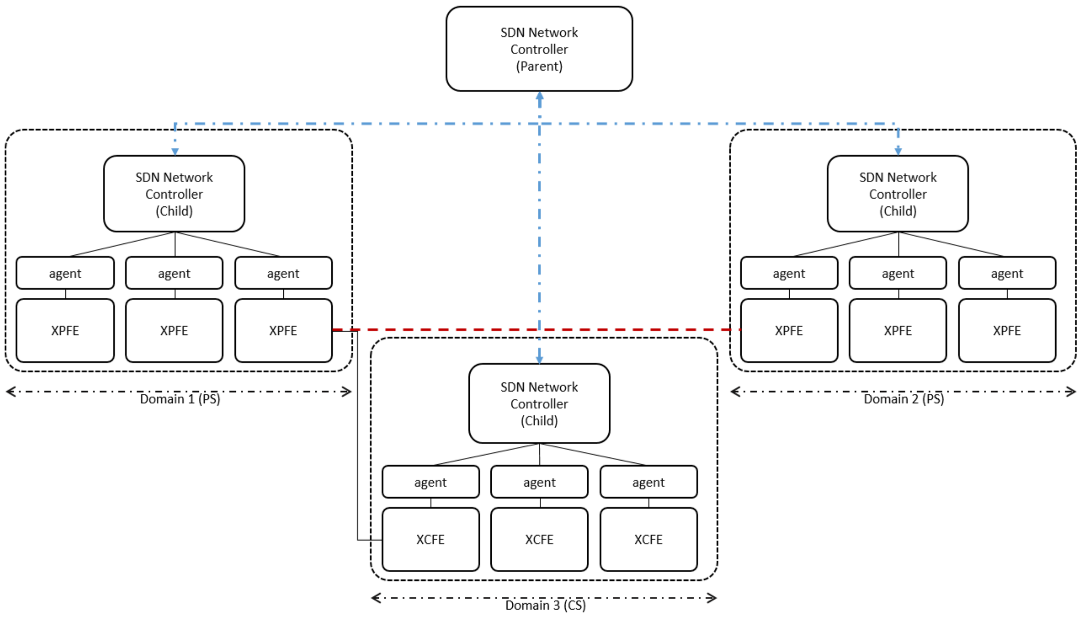

Figure 11: SDN-based hierarchical orchestration and control of multi-domain/multi-layer networks

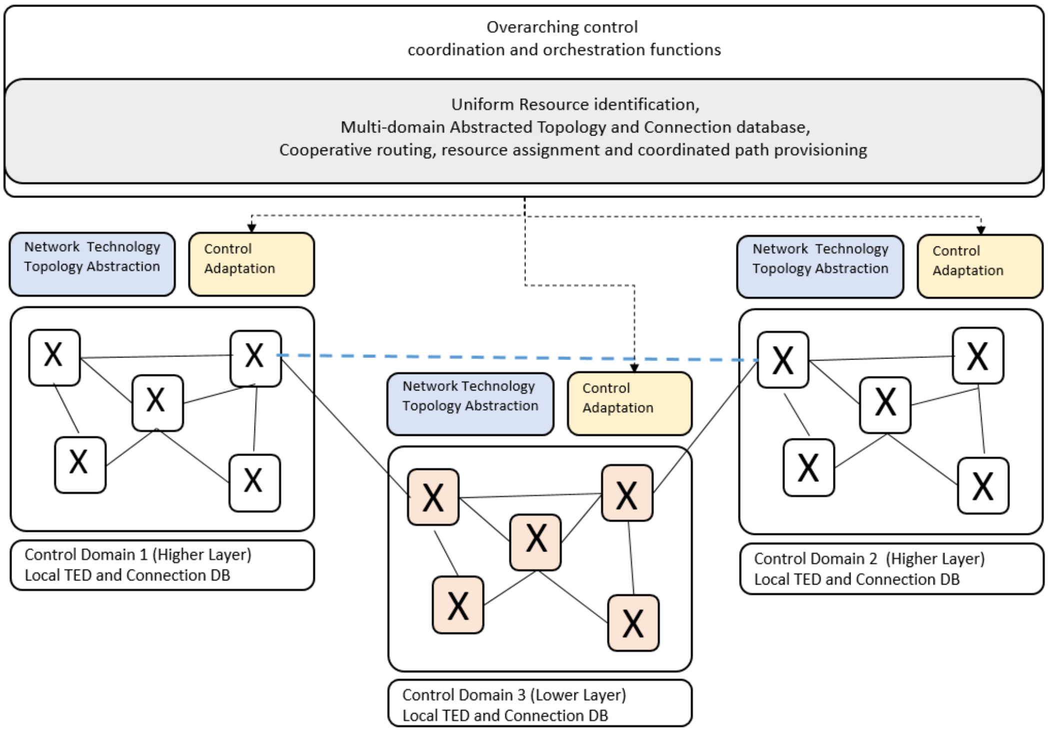

Figure 12: Over-arching control function mapping and adaptation

Specific per domain (child) controllers map the abstracted control plane functions into the underlying technology, implemented the specific technology extensions, while interacting with the parent controller in terms of the functions such as network topology abstraction, control adaptation, path computation and segment provisioning to support end-to-end services (see Figure 12).

3.3 Multi-MANO

The above section details the XCI architecture for the case where a single XCI instance runs the complete 5G-Crosshaul network. Multi-MANO concept covers the two following cases:

- A tenant requires complete control of its virtual infrastructure. In this case a recursive architecture of the XCI, where the tenant instantiates a complete XCI over the virtual infrastructure is proposed.
- Several 5G-Crosshaul providers are federated to build a Crosshaul network spanning multiple domains. In this case it is suitable to follow the architecture proposed by the 5GEx Project, to provide mechanisms for federation of 5G-Crosshaul infrastructures.

In the following, we list definitions that apply in the different activities within the project and, from the point of view of the XCI, where deployment and control models exist. The multiple entries for the term Tenant are defined, depending on the service and functional block that is considered. In control aspects section the different main services from the XCI are considered and, for such services, which kind of control is needed for each virtual infrastructure or tenant. Then the functional elements for MTA in the single MANO Crosshaul architecture and their functionalities are presented. Based on that, we also present how to enable the main services from the XCI control for multi-tenancy, namely the deployment of network services and the deployment of virtual infrastructures. Finally the ways for per tenant infrastructure control are discussed.

We consider two main services (groups of basic services): the allocation of Network Services (NS) as defined within the ETSI MANO architecture and the instantiation of Virtual Infrastructures with ultimate user control.
To some extent, this corresponds to having two models:

- <u>Overlay model</u> between Virtual Machines instantiated in XPUs and w.r.t. the external networks, based on tunnels, and
- <u>Partitioning model</u>, where some infrastructure is entirely provided to the tenant (e.g., XFE's cards & ports and the corresponding links) including resources in XPUs.

3.3.1 Terminology

The term Multi-Tenancy can be used in multiple contexts and can mean different concepts. As discussed within the ONF, the term *tenant* suggests occupancy, in some sense, of resources that are owned by a landlord. In general, the term should be used, e.g., when referring to hosting or ownership such as a customer application were hosted on a provider server. In other contexts, the occupancy implication may be irrelevant (e.g., in SDN provider-customer relations, where other terms are preferred).

In the scope of this section, we refer to multi-tenancy as either or one of the following, depending on factors such as the service offered by the Crosshaul XCI and the degree of control offered to operate and deploy a control layer to the allocated resources:

- When considering a specific functional element of component within the XCI and, more importantly, where existing projects or initiatives are targeting the implementation and deployment of such functional element, the definition of tenant is the one / accepted use. For example, the OpenStack cloud management software defines <u>a tenant as a group of users used to isolate access to resources</u> (also known as a "project").
- When considering the ETSI NFV architecture and, in particular, the deployment of multiple Network Services (NS) over the Crosshaul Infrastructure, <u>tenant refers to the entity that owns and drives the instantiation of one or more NS</u>. This is mostly in line with the ETSI use case #4 VNF forwarding Graphs [3] , and, to some extent also ETSI use case #1, "Network Functions Virtualization Infrastructure as a service".
- With ETSI use case #1, the notion of multi-tenancy is stated to refer to the same set of resources that supports multiple applications from different administrative

or trust domains, where a *service provider* (SP) runs NVF instances on the NFVI/cloud infrastructure of another service provider. A tenant is thus defined as the (administrative) entity within a trust domain that owns and runs VNF instances on a service provider.

- The capability of the Crosshaul XCI and related applications to support the slicing and partitioning of the underlying physical infrastructure, and to offer them as virtual infrastructures for, ultimately, their independent and isolated control. Herein, each entity or user that operates each of the *infrastructure slices* is referred to as a tenant. Likewise, to some extent, this is somehow related to ETSI Use case #3 Virtual Network Platform as a Service VNPaaS [3] .

It is important to note that the considered Crosshaul use cases refer to multiple Over-The-Top (OTT) operators, commonly referring to operators [8] offering the delivery of audio, video and other media over the Internet without the involvement of a multi-system operator in the control or distribution of the content, using for example an Internet service provider. The latter is not responsible for, nor able to control, the viewing abilities, copyrights and/or other redistribution of the content. Telco-OTT is a conceptual term that describes a scenario in which a telecommunications service provider delivers one or more of its services across all IP networks, predominantly the public internet or cloud services delivered via a corporation's existing IP-VPN from another provider.

An OTT operator can be a tenant in mainly two ways: a) by instantiating Network Services using the XCI MANO interface, where the OTT interacts with the VNF instances, e.g., by means of OSS/BSS systems once the instances are running or by b) owning (and ultimately controlling) an allocated virtual infrastructure including the ability to instantiate VNFs

As per the previous definitions, the concept of *tenant* mostly maps to the Crosshaul stakeholders Virtual Network Operators (VNOs) and Service Providers (SPs), as defined within the Crosshaul architecture.

The degree of support for multi-tenancy (including, notably, the finer level of control associated with each slice) varies depending on whether we assume a single MANO case (referring to instances of Crosshaul XCI) or a multiple MANO case (in which each slice can be controlled via an XCI instance, yielding a XCI/MANO form of recursion).

In view of this, for what it concerns the support for multi-tenancy, the Crosshaul XCI offers, as a control functional system, two main services:

- The deployment of *Network Services* (NS) as defined by the ETSI NFV architecture.
- The deployment of a coherent set of heterogeneous networks, compute and storage infrastructure, composed for example of virtual hosts interconnected by

network slices. This can be referred to as "Virtual Infrastructure", but the term is prompt to confusion.

3.3.2 Deployment of Network services

The deployment of Network Services (NS), in line with ETSI use case #4 VNF Forwarding Graphs (VNF-FGs) in section [3], is done through the XCI NBI. A single "tenant" can deploy multiple NSs over a XCI controlled physical or virtual infrastructure. For this, it uses the services and API offered by the XCI NFV MANO and, in particular of the NFV-O (Orchestrator).

Each network service is thus a set of endpoints connected through one or more VNF-FGs. The actual logic deployed within the network service (e.g., a CDN infrastructure, a database application, etc.) is out of scope of this document.

It is assumed that the deployment of network services does not require instantiation of multiple XCI systems or recursive instances. The operation, driven by each OTT, of Network Service is assumed to follow the MANO architecture, in which each OTT/tenant OSS/BSS interacts with the NFVO via the Os-Ma-Nfvo interface and with the EMS that configures / bound to the VNFs within the network service.

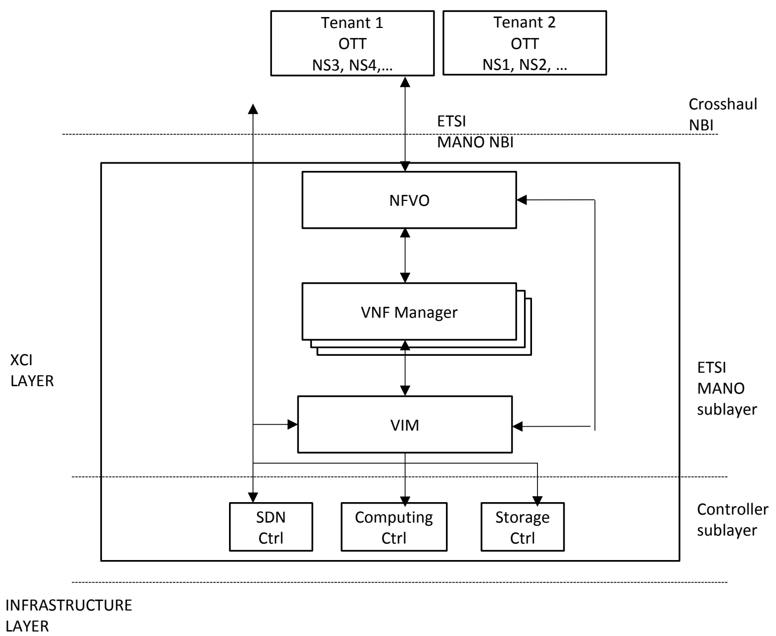

Figure 13: Multi-Tenancy support (as OTT) using Crosshaul MANO XCI NBI

As shown in Figure 13, the Crosshaul NBI XCI is a term for exported north bound interfaces including, but not limited to, the ETSI MANO NBI. For example, Crosshaul NBI can allow access directly to the underlying controllers using APIs not covered in the MANO framework. Depending on the actual tenant support within the ETSI MANO API (e.g., the separation of users), the separation of tenants and the allocation of resources per tenant is part of the actual MANO. The separation is logical – as an implementation within MANO – if MANO does not support this, the MTA needs to be deployed to keep track of the tenants, their NS and the allocated resources.

Let us note that, in this case, OTT tenants act as OSS/BSS in the ETSI MANO architecture by using, e.g., a NBI that is an analog to the Os-Ma-Nfvo ETSI interface. Thus, OTT control their network services _as if_ they were Crosshaul applications, in the sense that they can implement their business logic and application logic by using the Crosshaul XCI NBI that bundles the service.

3.3.3 Deployment of Virtual Infrastructures

The second service is the deployment of Virtual Infrastructures, encompassing a subset of resources. In this sense, a virtual infrastructure is composed of virtual links, virtual network nodes and virtual hosts (in other words, virtual hosts interconnected by network slices).

As shown in Figure 14, the allocation of a virtual infrastructure is started by the tenant (VNO), going through the Multi-Tenancy Application (a functional aspect of VNP), using the services of the VIMaP (Virtualized Infrastructure Manager and Planning) application and, ultimately, relying on the tenancy support of the XCI controllers (network, computing and storage) part of the PIP. Let us name, for example, the allocation of network slices, which does depend on the support of SDN controllers.

In this service, a functional element (referred as Multi-Tenancy application or MTA) allocates and provides resources where virtual infrastructures / slices are isolated per tenant, i.e. each VNO shall use the complete addressing space, with virtual slices of resources allocated dynamically, allowing the network to scale to multiple tenants without service disruption to existing VNOs.

The MTA thus offers to each tenant / VNO the possibility to allocate a virtual infrastructure, using a dedicated API that is part of the MTA NBI. Note that, as for one of the use cases of the ETSI NFV (i.e. NFVIaaS) the MANO of its provider is already capable of slicing and allocating/deallocating virtual infrastructures. The MTA then offers this as generic low level service, (enabling for example low level access to virtualized hosts) regardless of the NFV, even if at the end it ends up delegating to the MANO / VIM the actual instantiation. The MTA will also be the bridge for the actual control as detailed later.

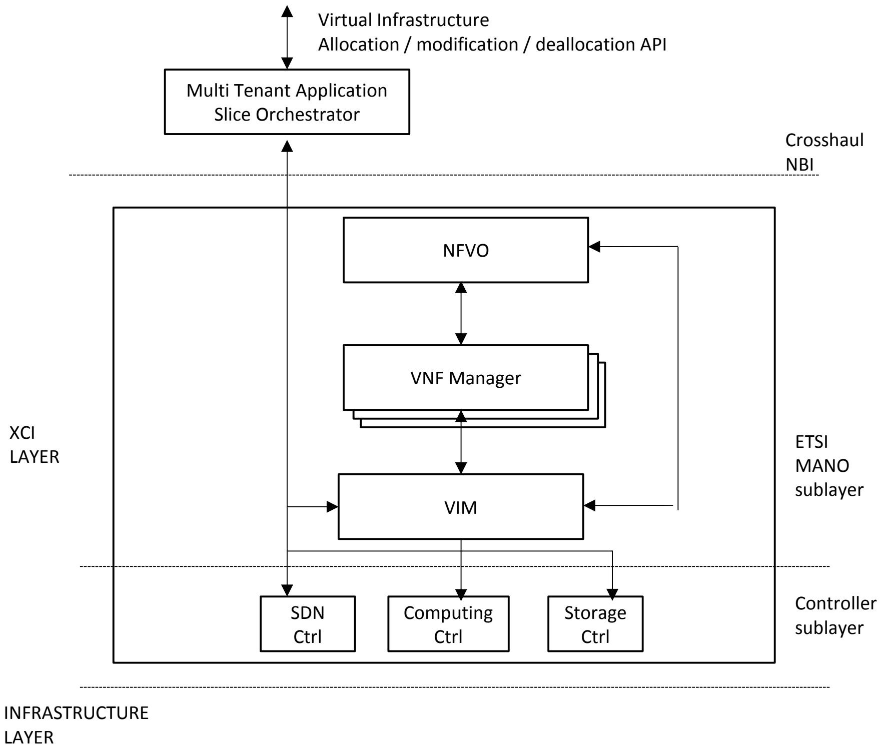

Figure 14: Use of a Slice Orchestrator/MTA for the allocation/modification / deallocation of virtual infrastructures, conveying network slices and virtual hosts.

3.3.4 Per-Tenant Infrastructure Control

Regarding the actual control of the allocated virtual infrastructures, there are different options, by design:

- The control that each tenant (owner or operator of the allocated network slice) exerts over the allocated infrastructure is limited, scoped to a set of defined operations over the allocated virtual infrastructure.
- Each allocated virtual infrastructure can be operated as a physical one, that is, each tenant is free to deploy its choice of infrastructure operating system / control. VNO is able to manage and optimize the resource usage of its own virtual resources. That means, we allow each tenant to manage their own virtual resources inside each tenant. So we will require a per-tenant controller or per-tenant MANO (XCI) approach. In case of one MANO (XCI) per tenant, this will result in multi-MANO (XCI) architecture.

It is important to state that network, computing and storage resources need to be able to be partitioned recursively. In particular, a network resource (link or node) could be partitioned regardless of whether it is physical or virtual and a given host / node should, in turn, allow the allocation of virtual nodes (guests) even if the host node is itself virtual.

The Multi-MANO concept requires to detail the concept of XCI recursion. In fact, in the Crosshaul System Architecture the concept of XCI recursion is of primal importance to support the multi-tenancy use case. As described in the previous chapter, this service use case corresponds to a tenant that has delegated a full degree of control of a slice of the physical infrastructure through some agreement with the physical infrastructure provider.

Figure 15 illustrates a two-level XCI recursion, where the infrastructure provider delegates a physical slice to a Network operator with full access. The low-layer XCI corresponds to the infrastructure provider, whereas the upper layer XCI corresponds to the Network operator with full degree of control of a physical slice. Such recursion of XCIs is enabled by the addition of the MTA/Slice Orchestrator (detailed in next section). The MTA/SO can be used to delegate full control of network/compute/storage controller to tenants. Several network operators with full access over a physical slice can coexist in the envisioned architecture. The resolution of potential slice conflicts between tenants corresponding to network operators full access is attained through the MTA/SO.

The MTA/SO requires direct interaction with the SDN, Compute and Storage controllers in order to have a full degree of control of a slice of the physical infrastructure, which is therefore delegated from the low-layer XCI to the upper layer XCI (see Figure 15). This is attained through the NBI that directly exports the proper functionalities and information data models from the SDN/compute/storage controller to the MTA/SO. The MTA/SO will, therefore, properly "commute" the NBI functionalities and information data model from a slice to the proper Network operator full access tenant.

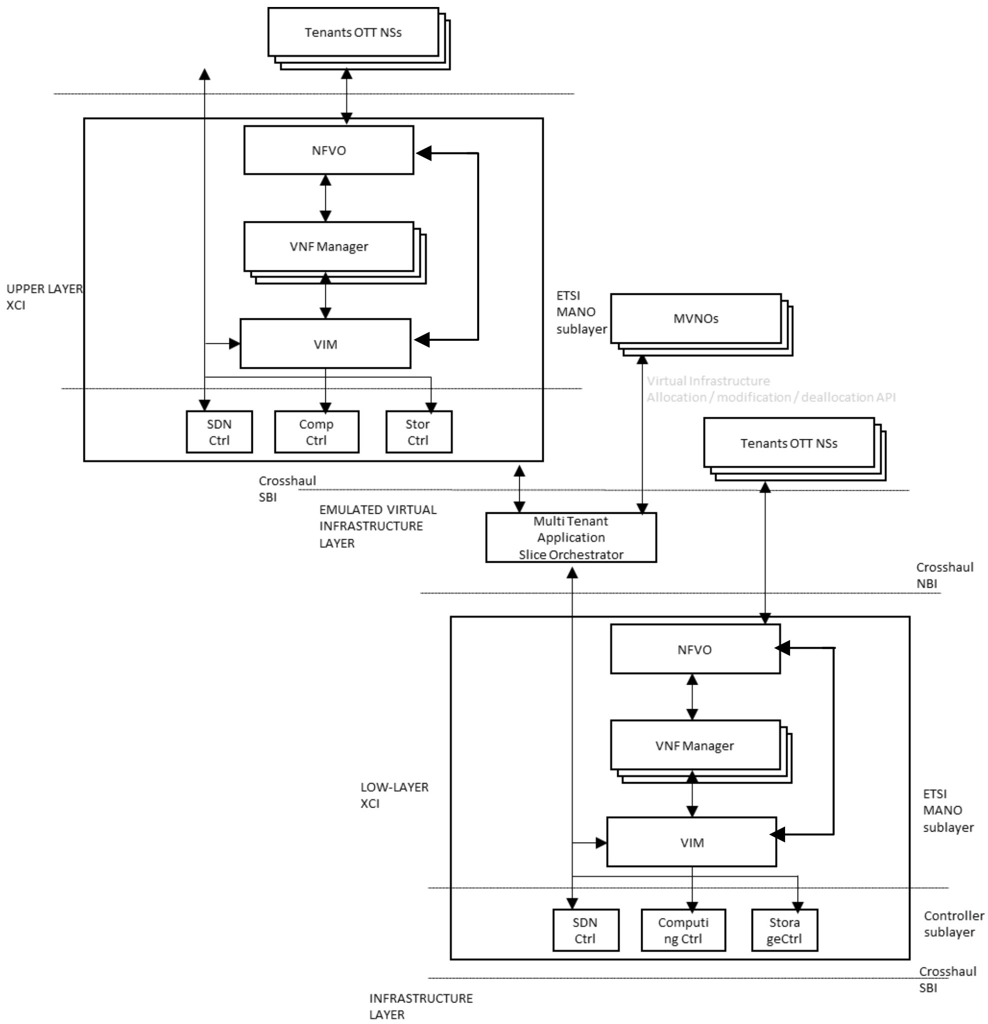

Figure 15: Recursive XCI architecture

In this sense, it is worth mentioning that the Crosshaul SBI shall handle the interaction not only with the data plane Crosshaul elements but also with the MTA/SO in order to support the concept of recursion. In turn, the Crosshaul architecture allows that the tenant encompasses an XCI (see Figure 15) and therefore can offer virtual or physical slices allocation/de-allocation to other tenants or OTT NS to other tenants.

On the other hand, note that the MTA/SO interacts with the VIM to handle the MVNO service use case, in which the tenant has a limited control over the allocated virtual slice. Though not represented in Figure 14, it is worth mentioning that, in turn, an MVNO tenant on top of a low-layer XCI could provide OTT NSs on top of its ETSI MANO orchestration layer.

3.3.4.1 Limited slice control

Once the virtual infrastructure has been allocated, the Slice Orchestrator/MTA offers an API that enables the tenant to have some limited forms of control over it. While the tenant can retrieve, for example, a limited or aggregated view of the virtual infrastructure topology and resource state and perform some operations, it is assumed that the tenant operates over an abstracted and simplified view.

In this case, all operations go through the Slice Orchestrator/MTA. As depicted in Figure 16, this slice control API, part of the orchestrator NBI, is used by different tenants. It is expected that this API is high-level, allowing a limited form of control, and different from controlling or operating a physical infrastructure. For example, the actual configuration and monitoring of individual flows at the nodes may not be allowed, and only high-level operations and definitions of policies are expected.

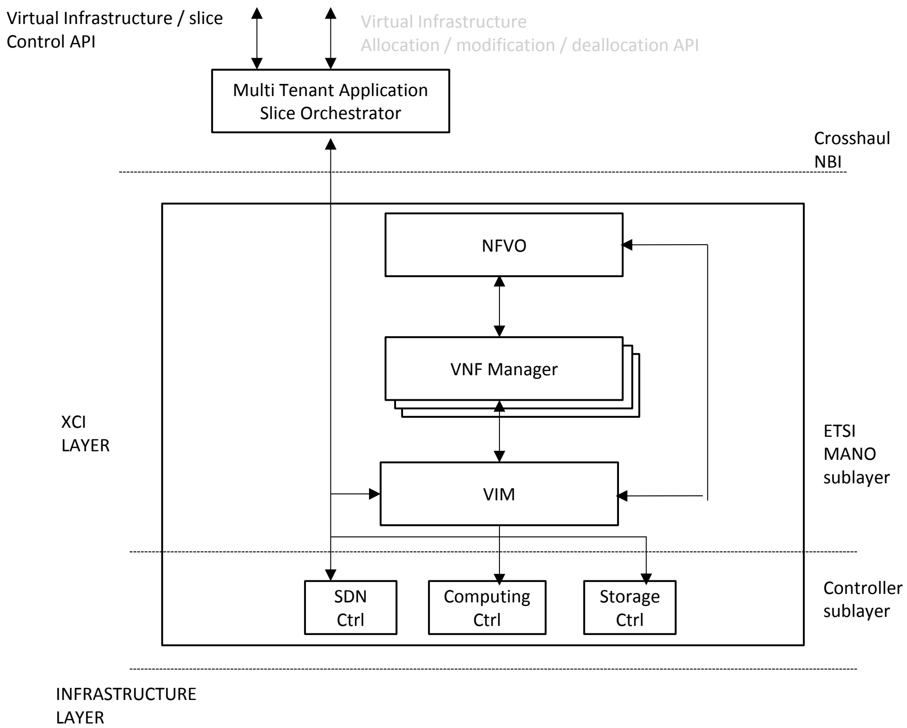

Figure 16: Use of a Slice Orchestrator/MTA API for the limited control of the allocated virtual infrastructure

3.3.4.2 Per tenant slice XCI based control

Alternatively, it may be desired that the different tenants / MNO operate their virtual slices in a very similar way to the way that a physical infrastructure operator operates a physical infrastructure, that is, via the deployment of a virtual infrastructure / slice-specific XCI /MANO instance.

This approach enables the ultimate control of the allocated slice, down to the low-level operation of the virtual slice, including for example the definition of flows and similar operations in the SDN controller, the allocation of virtual machines and, importantly, the ability to offer ETSI Network Services (NS) over its allocated virtual infrastructure.

An important issue to address is the mismatch between the SBI, defined in Crosshaul for the control of the hardware (notably, the XFE) and the NBI that the slice orchestrator/MTA offers.

The Slice Orchestrator/MTA (see Figure 17) must present itself (in one or multiple endpoints) for the control of the per-tenant allocated slice individual agents in the (virtual) data plane nodes, instead of having a dedicated agent. In other words, the Slice orchestrator/MTA proxies access to the virtual resources. As a simple example, if a SBI for the Crosshaul XCI is based on the OpenFlow protocol over a TCP connection between the controller and the agent in the node, when considering operations over the virtual infrastructure the SBI of the tenant XCI instance may need to multiplex different operations on different virtual hardware elements over the same TCP connection to the down Slice orchestrator / MTA.

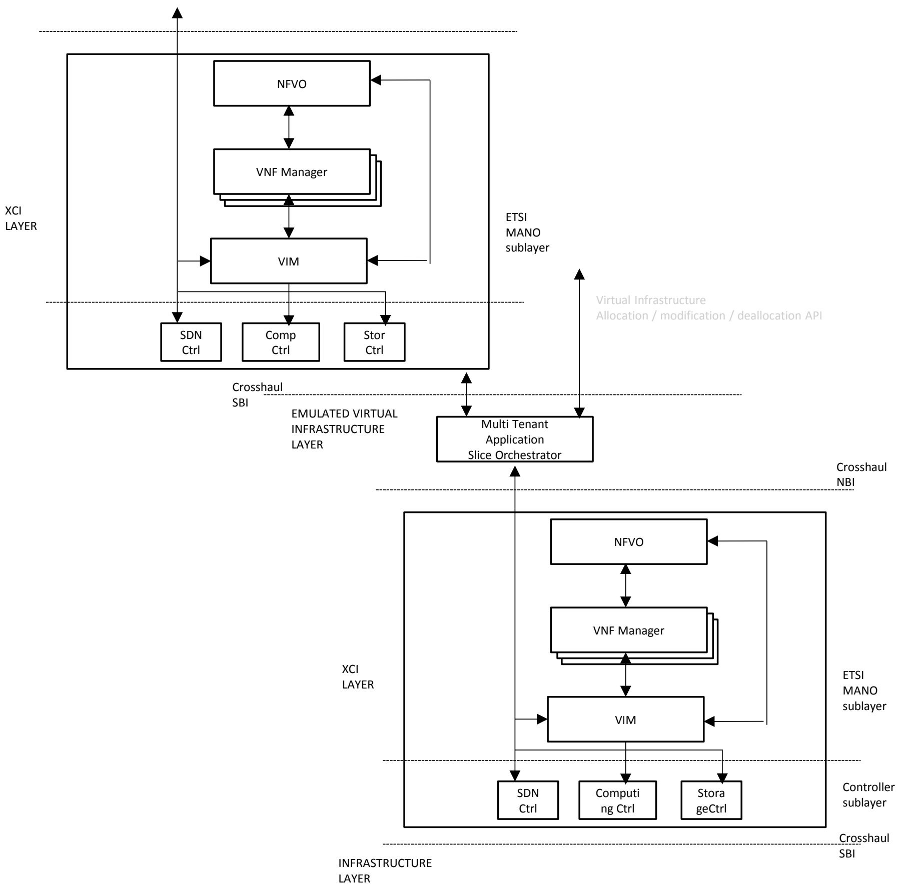

Figure 17: Use of a Slice Orchestrator/MTA API for per tenant slice XCI based control of the allocated virtual infrastructure

3.3.4.3 Network slicing and partitioning mechanisms

It is important to state that, for this approach to work, network, computing and storage resources need to be able to be partitioned recursively. In particular, a network resource (link or node) could be partitioned regardless of whether it is physical or virtual and a given host / node should, in turn, allow the allocation of virtual nodes (guests) even if the host node is itself virtual.

The actual mechanisms to carry out this resource partitioning are multiple, and there is no formal or standard mechanism to do so. Let us discuss a few common approaches.

- Storage resources. Storage resources, either in the form of object storage or block storage, can be easily partitioned and it is the storage controller that is responsible for this. Existing technology to partition and aggregate volumes, disks, etc. is sufficiently flexible to allow this from a virtual infrastructure perspective. In particular a given physical hard disk can be used to allocate volumes or partitions to multiple Virtual Machines, becoming their virtual hard disk. In turn, that virtual hard disk can also be divided.
- Computing resources. Supporting recursive partitioning of computing resources is, at least in theory, simple. A given compute node or unit (e.g., Crosshaul XPU) has a containment relationship with, e.g., Virtual Machines (VMs) or Containers depending on the type and use of hypervisor. A virtual machine can, in turn, become an XPU for a given tenant slice, as part of the physical infrastructure. This means that VMs or containers are instantiated within a VM itself. While this is possible, performance degrades and it becomes harder to have direct hardware access, offloading and other related mechanisms.
- Networking resources. Mechanisms for partitioning a network are several, including static or dynamic partitioning. Network resources include interface cards, link bandwidth, switching capabilities, ports and so on. Several of the partitioning approaches rely on the asynchronous multiplexing associated to packet switching: the link bandwidth is thus partitioned between different users although traffic is only isolated by, e.g., VLAN tags. This raises the problem of monitoring and enforcement of the partitioning.

Enabling recursive partitioning can be accomplished for specific scenarios: for example, a simple static partitioning approach is to allocate ports within a switch to specific tenant or group of tenants. This results in a virtual switch modelled as a switch with less ports for that tenant or group of tenants. Link bandwidth can be recursively partitioned by controlling the degree of statistical multiplexing. Network nodes can be partitioned assigning ports / interfaces (or sub-interfaces) to specific tenants.

While these are the simplest models, this is an active area of research. For example, in such network nodes there are other resources like forwarding capacity (what if forwarding tenant A’s packets is more expensive than tenant B’s, so tenant A is using a larger share of the forwarding capacity), flow table sizes (how to share the available entries in the flow tables among the tenants) or control capacity: an OpenFlow control switch has a limited capacity in terms of changes of the flow tables per second. So, it is important to define and control how this capacity is allocated to the tenants.

In general, this is a complex aspect of partitioning and hard to address. While some of them would seem (apparently) more straightforward (e.g., an OpenFlow switch supporting partitioning could rate limit control messages after classifying them on a per tenant basis, or Tenant virtual NICs/veths/taps should have rate limiting and traffic conditioning applied), other resources would need research or measurements to conclude something, especially if using existing mechanisms (adding quotas on CPU or memory for some processes supporting, e.g., a virtual switch, one cannot clearly deduce how this translates into forwarding performance drop).

3.4 Orchestration of Crosshaul Slices from Federated Administrative Domains

SDN and NFV together could not be enough to address future scenarios from a service provider perspective. The deployment of network infrastructure is a time consuming process, requiring careful business planning to support the necessary investments, in order to be ready for service delivery at the proper time when the demand arises. In addition to that, infrastructure ownership may be unsustainable in a revenue-decreasing scenario, driving to infrastructure sharing to reduce the total cost associated to the service provisioning.

In this situation, the idea of leasing virtualized networking and computing environments is gaining momentum. Thus, Infrastructure Providers (InP) can play the role of facilitators for service providers in order to lower the Total Cost of Ownership (TCO), simplify the network architecture and streamline the operation and their associated costs.

This can be significantly the case for access and aggregation networks. Uncertainty in the number of end users, their distribution and mobility patterns and heterogeneous service requirements (from data intensive residential-like service to flow-intensive machine-to-machine connections) make unpredictable and dynamic the demand of connectivity and network services.

Specifically, for the aggregation stages, close to the radio access (what is typically known as a conjunction of fronthaul and backhaul areas, or 5G-Crosshaul in the context of this project) it seems quite appealing to introduce flexibility to dynamically adapt the deployed resources to the concrete demand. The demand of dynamic resource allocation involves networking but also computing facilities, in order to flexibly deploy services and host content at the edge, thus saving core network capacity and decreasing service latency.

Furthermore, the capability of combining resources from different InPs can provide further flexibility and adaptation to diverse end user behaviors and performance requirements, thus overcoming current limitations imposed by tight coupling of service and infrastructure.

Then two possible multi-domain cases can be taken into consideration: *(i)* composition of administratively separated Crosshaul domains, and *(ii)* composition of end-to-end administratively separated domains (including Core Network, Crosshaul and Radio Access Network –RAN–). This section focuses on the first case.

There is yet a gap to reach the goal of hosting Crosshaul in a multi-domain federated infrastructure: a market place where networking and computing facilities are traded. An extension of the traditional concept of telco exchange is needed, covering new needs and capabilities, such as offering resource slices for deployment of the services requested by third party service providers.

This section proposes to further develop the concept of multi-domain Crosshaul (as introduced in Section 3.2) by presenting an architectural framework enabling the dynamic request of Crosshaul slices through a multi-provider exchange.

3.4.1 Enablement of Dynamic Network Service Deployments

5G-Crosshaul will make available slices of compound resources to different tenants for deploying services as composition of virtualized network functions. In addition to that, networking capabilities will be provided accordingly to connect the network functions among them, and to provide connectivity towards the Crosshaul border. A similar approach is described in [9] where the authors propose a dynamic virtualized environment for deploying services in telecom networks relying on own infrastructure, even with virtualization capabilities. The concepts of Service Graph (SG) and Forwarding Graph (FG) are introduced, separating service and resource problems at the time of service provision. However multi-domain scenarios are not considered, averting the problem of deploying services on slices leased from different InPs.

Management and control of resources and services in multi-domain scenarios is a fundamental challenge in 5G networks, especially for Crosshaul applications. Network sharing approaches [10] are becoming more and more common because of the potential TCO reduction, and then it is required to address this multi-domain environment in the context of SDN and NFV.

3.4.2 5G-Exchange as market place for Multi-Domain 5G services

Currently deployed solutions to steer and manage traffic will not be capable of supporting future 5G traffic. They lack the required flexibility and agility, leading to complex and rigid network policies, which are even worse if multiple domains are involved. Mechanisms such as SDX (Gupta & al, 2014) aim at tackling these issues, but they are not sufficient for the purposes of the scenarios targeted in this report. What is needed is a framework allowing relevant stakeholders to trade resources and service functions in order to flexibly deploy end-to-end services by involving the required providers. In particular, the need of enabling different 5G-Crosshaul providers to build services encompassing multiple technology and administrative domains. Here is where the concept of 5G-Exchange enters into the picture.

5G-Exchange (5GEx) project[1] is defining appropriate mechanisms for supporting multi-domain trading of resources and functions as space for bootstrapping collaboration and service delivery between telecommunications operators regarding 5G infrastructure services. Such services and associated resources will play a crucial role in making 5G happen, as they provide the foundation of all cloud and networking services apart from the radio interface itself. 5GEx is seen as a facilitator to enable operators to buy, sell and integrate infrastructure services, enabling one-stop shopping for their customers. It will

[1] http://www.5gex.eu/

provide the ability to automatically trade resources, verify requested services and it will lead to clear billing and charging.

5GEx is building a logical exchange or factory for globally reachable automated 5G services creation. For the sake of clarity: the exchange is implemented by APIs, not by statically (directly) connected physical appliances. The exchange will allow the resources such as access, connectivity, computing and storage in one network to support different verticals and applications such as e-Health, robotic communications, media, etc. Resources can be traded among federated providers using this exchange, thus enabling service provisioning on a globally reachable basis.

The 5G Exchange scope includes an automated service orchestration, as well as the management and trading of network, storage and cloud resources. The development of a novel technology framework is based on the architectural concepts hereby described.

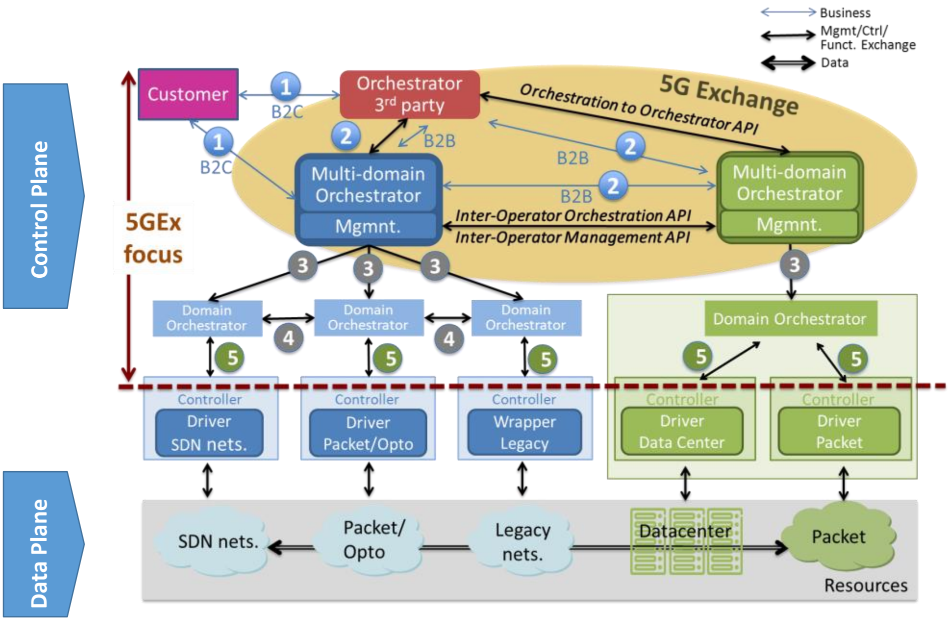

Figure 18: 5G-Exchange concept

Figure 18 highlights the scope of 5GEx by presenting a logical interworking architecture, showing not only functional entities but also the different APIs between them. The core of 5GEx system is composed of *(i)* the Multi-domain Orchestrator/Manager, *(ii)* various domain orchestrators and *(iii)* collaboration with domain orchestrators and controllers, which are in charge of enforcing the requested services on the underlying network, compute and storage components.

Co-operation between operators takes place at the higher level through the inter-operator orchestration API (2) that exchanges information, functions and control. This interface also serves for the Business-to-Business relation between operators in complement to the Business-to-Customer API (1), through which customers request service deployment. The *Multi-Domain Orchestrator* (MDO) maps service requests into own resource domains and/or dispatches them to other operators through interface (2). This interaction is performed at MDO level: each operator MDO can expose to other operators' MDOs an abstract view of its resource domains and available service functions. Using such an inter-working architecture for multi-domain orchestration will make it possible use cases that are nowadays hard to tackle due to the interactions of multiple heterogeneous actors and technologies.

The MDO enforces the decision through interface (3) as exposed by Domain Orchestrators, each one orchestrating and managing resource domains through the northbound interfaces (5) exposed by technology-specific controllers.

The Multi-domain orchestrator in 5GEx is considered to have three main components: *(i)* the Runtime Engine, which monitors, configures and runs connectivity and cloud resources across administrative domains, *(ii)* the Exchange of Functions, which monitors, configures and manages service components across administrative domains, and *(iii)* the Exchange of Information & Control, which deploys and runs autonomic management functions.

3.4.3 Multi-domain composition of 5G-Crosshaul infrastructures

The 5GEx multi-domain orchestration framework can be used to realize scenarios involving multiple Crosshaul domains, belonging to different network operators. 5G-Crosshaul XCIs can play the role of single-domain orchestrators coordinated by 5GEx multi-domain orchestrators. XCI orchestrates networking resources and compute plus storage within a single administrative domain. Those resources can be offered as dedicated slices in the multi-domain environment. Resource slicing is enabled by the 5G-Crosshaul Multi-Tenancy Application (MTA), which acts as a mediation layer between the tenants and the shared infrastructure. In a recursive way, the tenant can program the underlying network facilities and instantiate network functions on the processing units of Crosshaul, by using an XCI instance (then stacking XCI control elements) logically isolated from other tenant's XCIs.

Multi-domain Orchestration capabilities are partially supported by the MTA. However, either additional features in the MTA or in a fully new branded application are required in 5G-Crosshaul to fully support inter-operator orchestration and management, i.e. full 5GEx interface (2) support.

These additional features need to support a number of functionalities for service provisioning in multi-domain environments, like:

- SLA negotiation, in order to ensure a proper service delivery on the offered Crosshaul slice.
- Service mapping mechanisms, in order to assign proper sliced resources to the service request. In the case of 5G-Crosshaul this applies to networking (e.g., bandwidth, latency, etc) and compute plus storage (e.g., in terms of CPUs, memory size, type of drive, etc).
- Reporting of Crosshaul metrics, including both the compute and networking substrates, since there is a dependency of the networks function deployed in Crosshaul with regards the hosting facilities and the networking reachability.

- Proper control and management interfaces, to dictate actions in the offered Crosshaul slice, e.g., traffic steering, type of forwarding (packet vs circuit) or network function scale up or down.

The modular nature of the 5G-Crosshaul system architecture permits the introduction of these new functionalities, e.g., in the form of a new application for supporting multi-domain environments just implementing interface (2) of 5GEx, or even as an add-on to MTA. Figure 19 shows all of these new functionalities represented as a single box embedding also MTA. This could be an implementation option, where a tight binding among MTA and the entity in charge of terminating 5GEx interface (2) in Crosshaul are part of the same component. Other alternatives could be also possible, and this is a matter of further analysis.

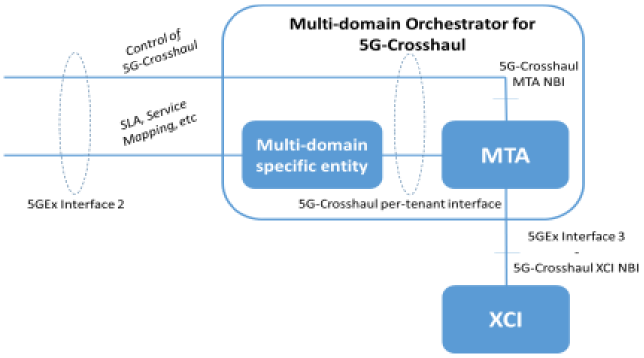

Figure 19: Multi-domain entity for 5G-Crosshaul

4 5G-Crosshaul applications (inputs from WP4)

This chapter introduces seven 5G-Crosshaul applications defined in WP4, which will support the 5G-Crosshaul use cases that are defined in Chapter 2. A brief description of the individual applications is given separately below. Furthermore a mapping of the applications to support the defined use cases is provided.

4.1 Multi-Tenancy Application (MTA)

Multi-Tenancy is a desired feature by 5G-Crosshaul to enable a generalized, flexible sharing of 5G-Crosshaul infrastructures among multiple network operators or service providers (i.e., multiple tenants). The target is to significantly reduce the CAPEX and OPEX by sharing the infrastructure resources and maximize their utilization in a cost-efficient manner. The 5G-Crosshaul XCI relies on the integration and alignment with existing initiatives and projects (e.g., SDN controllers such as OpenDaylight) supporting multi-tenancy to some degree. However, a coherent management of multi-tenancy is required horizontally, unifying the concepts of infrastructure virtualization and multi-tenancy in all involved segments and resources. For this purpose, the Multi-Tenancy Application (MTA) is needed to provide such management. The MTA is in charge of assembling these physical resources into a virtual network infrastructure and then allocate the virtual resources to the tenants. Each tenant is composed of a network subset with virtual nodes and links, referred to as a slice, owning a subset of the physical resources (including computing, storage and networking resources). The tenant is created making use of virtualization techniques. The MTA allows on-demand, dynamic allocation of virtual resources to the tenants, providing per-tenant monitoring of network QoS and resource usage. Moreover, the MTA also allows the tenants to control and manage their own virtual resources. The main challenge is to ensure a clean isolation across tenants.

4.2 Resource Management Application (RMA)

Considering the high degree of flexibility which is required to provide network resources to service providers, MVNOs and MNOs, it is necessary to leverage on efficient resource management. This is indeed crucial in a shared multi-tenant environment to dynamically (re)allocate resources among several tenants. The RMA takes care of optimizing 5G-Crosshaul resources in a centralized and automated fashion, in order to promptly react to network changes and to meet the requirements of different client applications. The RMA relies on the XCI controllers for the actual provision and allocation of resources. The RMA can operate over physical or virtual network resources, on a per-network or a per-tenant basis, respectively. Essentially, the RMA has two main functional pillars: (i) dynamic resource allocation and (re-) configuration (e.g., new routes or adaptation of physical parameters) as the demand and network state change, and (ii) dynamic NFV placement, e.g., enabling multiple Cloud-RAN functional splits flexibly allocated across the transport network.

4.3 Mobility Management Application (MMA)

The main goal of MMA is to provide mobility management for scenarios such as vehicle mobility use cases like high speed train, and also to optimize traffic offloading for media distribution like CDN, TV Broadcasting. The challenge for traffic offloading is to optimize the location and relocation procedures for services such as CDN in combination with resource management decisions. In this case, Crosshaul mobility will be based on a flat IP network, on which traffic is forwarded to the nearest point of connection to the Internet. The forwarding will be based on direct modification of flow tables at the data path elements, using, e.g., the OpenFlow protocol [6]. The MMA aims to provide traffic offload to the Internet and/or moving the applications to the edge as close as possible to the users. The MMA uses the services offered by the RMA to provide best paths between the different elements of the network, with the main goal to optimize the route or path followed by mobile users' traffic towards the Internet or to a core service provided in a datacenter. The assignment of Points of Connection (PoC) to the Internet and possible points of offloading to CDN networks or core nodes will depend on the criteria adopted by each tenant owning the network. After computing the best set of elements to provide a service to the user, the MMA will request the RMA to find the best path connecting these points based on the network status. The focus of the MMA is to exploit the context information as well as the load of some candidate target Base Stations (BSs), in determining the target BS and the corresponding resource allocation. This application will exploit the deterministic trajectory of the node for the proactive creation of paths in advance, placing cache nodes and even core nodes in the path of movement.

4.4 Energy Management and Monitoring Application (EMMA)

The Energy Management and Monitoring Application (EMMA) is an infrastructure-related application of the 5G-Crosshaul system. It aims at monitoring energy parameters of RAN, fronthaul and backhaul elements, estimate energy consumption and trigger reactions to optimize and minimize the energy footprint of the virtual network while maintaining the required QoS for each VNO or end user. Together with energy-specific parameters like power consumption and CPU loads, EMMA will also collect information about several network aspects: traffic routing paths, traffic load levels, user throughput and number of sessions, radio coverage, interference of radio resources and equipment activation intervals. All these data can be used to compute a virtual infrastructure energy budget for subsequent analysis and optimizations.

The application is designed to optimally schedule the power operational states and the levels of power consumption of 5G-Crosshaul network nodes, jointly performing load balancing and frequency bandwidth assignment, in a highly heterogeneous environment. Also the re-allocation of virtual functions across 5G-Crosshaul will be done as part of the optimization actions. This will allow moving fronthaul or backhaul VNFs to less power-consuming or less loaded servers, thus reducing the overall energy footprint of the network.

4.5 CDN Management Application (CDNMA)

The Content Delivery Network Management Application (CDNMA) is an OTT application of 5G-Crosshaul related to the distribution of media content over 5G networks. Content distribution, especially video traffic, is expected to be the dominant contributor to the mobile data traffic demand. Thus, providing efficient ways of delivering content to the end users is a must. A CDN is a combination of a content-delivery infrastructure (in charge of delivering copies of content to end-users), a request routing infrastructure (which directs client requests to appropriate replica servers) and a distribution infrastructure (responsible for keeping an up-to-date view of the content stored in the CDN replica servers). This application is designed to manage the transport resources for a CDN infrastructure, controlling load balancing over several replica servers, strategically placed at various locations, to deal with massive content requests while improving content delivery, based on efficient content routing across the 5G-Crosshaul fronthaul and backhaul network segments and the corresponding user demands.

4.6 TV Broadcast Application (TVBA)

The TV Broadcast Application (TVBA) aims to provide a solution for TV broadcasting & multicasting services utilizing the 5G-Crosshaul architecture, running as an OTT service. A TV broadcasting/multicasting service is offered starting from the content of a live-source (e.g., a football match), which is processed till be finally transcoded to the objective format and bit rate (e.g., image resolution, scan format, etc.) and injected into the 5G-Crosshaul network. The TVBA deploys media transmission, live video broadcast over the 5G-Crosshaul infrastructure with focus on minimizing both the cost and the spectrum consumption of the next generation TV. The TVBA offers broadcast as a service, taking the 5G-Crosshaul network as a facility for management of construction, deployment and provision of the involved resources. The target is to optimize the content delivery and assure a real-time delivery with the lowest possible delay offered to the users.

4.7 Applications and use cases mapping

The applications are designed to be able to support the use cases defined in chapter 2. The following table maps the applications for the different use cases according to their required functions.

Use Cases	Main functions required	Required applications

Use Cases	Main functions required	Required applications
1. Vehicle mobility	- Mobility management functions - FH/BH resource management functions - Multi-tenancy functions	**MMA**: to solve the frequent HandOver (HO) problem challenged by high mobility and high data rate requirements of this use case. The MMA exploits the routing information, including train location, speed, direction, etc. to maintain the routing path and reduce the handover time, keeping a high level of successful handover without degrading user performance. **RMA**: to compute the optimum routing path on request between two provided nodes from MMA. **MTA**: to create and manage virtual networks of multiple virtual network operators (VNOs) in the vehicles, and also provide per-tenant information on QoS and resources utilization for each of them.
2. Media Distribution: CDN	- Content distribution functions required for replicating the content - FH/BH resource management functions in terms of routing - Allows multiple CDN operators (tenants) for deployment of their network services	**CDNMA:** responsible for CDN infrastructure instantiation, control and management of the CDN service. **RMA**: to deal with the network resources to compute the optimal paths between the user and the CDN server assigned. **MTA**: to provide tenant identification and per-tenant monitoring information for each tenant. **MMA**: to provide the user network entry point to the CDNMA.

Use Cases	Main functions required	Required applications
2. Media Distribution: TV Broadcasting	- Content distribution functions required for replicating the content - FH/BH resource management functions in terms of routing - Allows multiple TV service operators (tenants) for deployment of their TV services	**TVBA**: responsible for TV service requirements establishment, control and management of the video play-out. **RMA**: to deal with the network resources to compute the optimal paths for the broadcast tree. **MTA**: to provide tenant identification and per-tenant monitoring information for each tenant.

Use Cases	Main functions required	Required applications
3. Dense urban society	- FH/BH resource resources management functions - Mobility management functions - Fault management functions - Energy and monitoring management functions - Allows multiple virtual operators (tenants) for deployment of their virtual networks	**EMMA**: to monitor the power consumption of the system and provide information to be used for dynamic control of the network topology for energy saving. **RMA:** to deal with the network resources to optimize the optimal paths for FH/BH traffic and the RAN functional split, taking into account the newly deployed end points and property of dynamic crowd. The RMA shall also solve the problem of function and service placement over computing nodes. **MMA:** to handle the mobility of users in terms of optimizing handover, monitoring the user location and traffic offloading by placement of mobility anchors and breakout points. If the network entry point changes due to the dynamic crowd, the MMA will notify the MTA, RMA and EMMA for efficient network reaction. **MTA:** in charge of creation of virtual networks for one or multiple VNOs to share the FH/BH resources while meeting their individual SLAs, also providing per-tenant information on QoS and resources utilization for each.
4. Multi-tenancy	- Create tenants for deployment of virtual networks or network services - FH/BH resources management functions - Energy management and monitoring functions	**MTA:** in charge of creation of virtual networks for one or multiple VNOs or network services to share the FH/BH resources while meeting their individual SLAs, providing per-tenant information on QoS and resources utilization. **RMA**: to compute the optimum routing path on request of MTA to decide on the mapping between a virtual link and a physical path. **EMMA**: to provide to the MTA the monitoring services for each

Use Cases	Main functions required	Required applications
		physical/virtual infrastructure or single physical/virtual elements, and provisioning of "energy-optimized" network paths or even "energy-optimized" virtual infrastructures.
5. Mobile edge computing	- (Re)location of the applications and network functions on distributed MEC servers due to mobility of the end users - Energy management and monitoring functions - FH/BH resource management functions	**RMA**: to deal with the network resources to compute the optimal paths to connect the VNFs in distributed MEC servers, as well as the location of the VNFs considering the computing resources. **MMA**: to compute the location and relocation of VNFs and services and the placement of MEC servers. **EMMA**: to monitor the power consumption of the MEC servers and provide information to be used for dynamic control of the VNFs for energy saving.

5 XCI design (inputs from WP3)

The 5G Crosshaul Control Infrastructure (XCI) architecture is designed in order to provide management and control among heterogeneous resources located in the Crosshaul physical infrastructure, e.g., network nodes like the XFEs or process units (XPUs). The XCI is a SDN/NFV-based platform that can be used by the upper level applications with the aim to manage and configure the network data-plane elements through a set of specific functionalities implemented as core services and primitives. In particular, these functionalities enable the on-demand provisioning of network slices, and, on top of them, the deployments of service chains according to the ETSI VNF paradigm [3].

In the 5G Crosshaul overall architecture, the XCI is placed at the control-plane level and, as depicted in Figure 20, it interacts with external layers through the following interfaces:

- South-Bound Interface (SBI): towards the 5G Crosshaul data-plane (i.e. XFEs and XPUs)
- orth-Bound Interface (NBI): towards the 5G Crosshaul applications
- East-West Interfaces (EBI and WBI): towards core network and RAN domains (out of scope for the 5G-Crosshaul project)

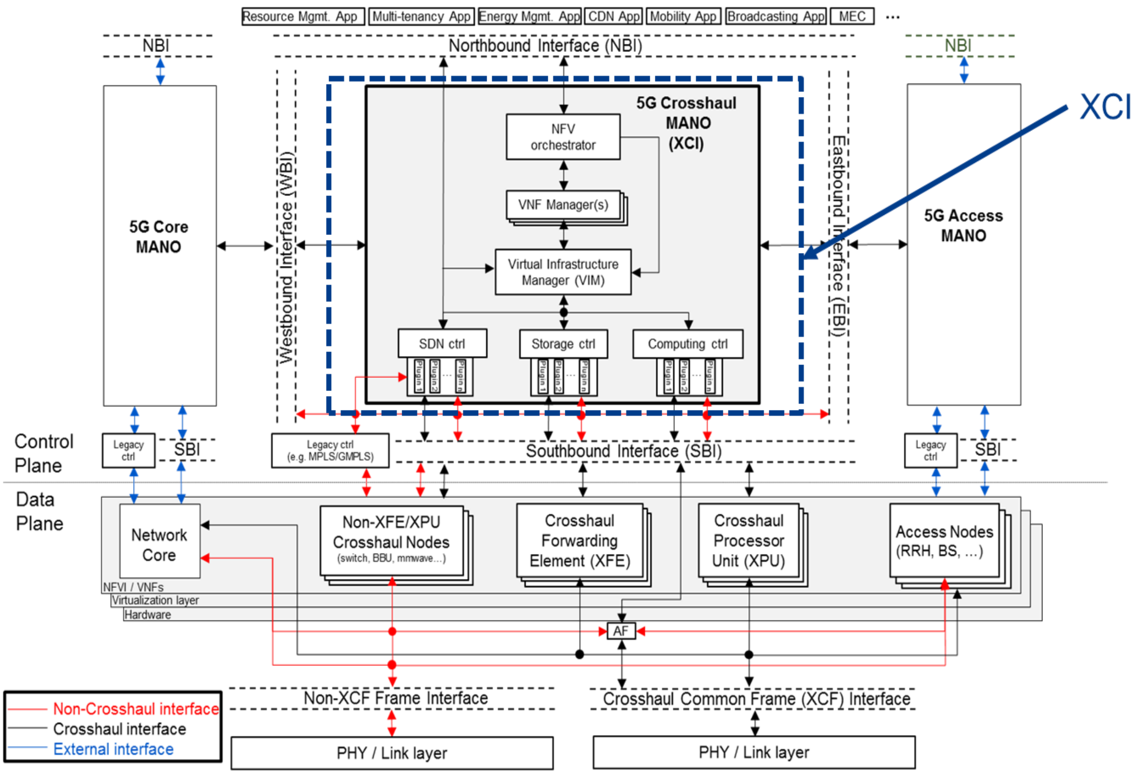

Figure 20: XCI in 5G-Crosshaul system architecture

The XCI, with the whole functionalities defined within its architecture, is designed in order to provide the following main services:

1) The provisioning of (multi-tenant enabled) connectivity in the converged fronthaul-backhaul network and the efficient operation of the whole Crosshaul network through the dynamic programmability of the heterogeneus XFE devices. These functionalities are implemented through SDN controllers which interact with the different data plane elements through standard SBI protocols, properly extended for each specific technology.
2) The provisioning and management of heterogeneous resources to build several isolated virtual infrastructures sharing the same physical substrate. This service is implemented through the Virtual Infrastructure Manager (VIM), in combination with controllers dedicated to different types of resources (network, storage, computing).
3) The provisioning and management of Virtual Network Functions (VNFs) instantiated on the top of the 5G Crosshaul virtual infrastructures. This kind of service is coordinated by the VNF Manager (VNFM) and the NFV Orchestrator (NFVO), in compliance with the ETSI NFV specification [3].

In particular, the interaction with the different types of resources in the data-plane is performed through the SBI in order to:

- Control and manage the packet forwarding behavior on 5G-Crosshaul XFEs.
- Control and manage the PHY configuration of the XFEs, depending on their specific technologies (e.g., regulate the transmission power on wireless links).
- Discover the XFE devices and the physical topology of the 5G-Crosshaul network.
- Monitor the status and the performance of XFEs and XPUs.
- Control and manage the 5G-Crosshaul Processing Units (XPU) computing operations (e.g., instantiation and management of Virtual Machines (VMs) to run the VNFs).

5.1 XCI high-level architecture

The 5G Crosshaul XCI, as depicted in Figure 20 is the intelligent core controlling the overall operation of the 5G Crosshaul network and processing elements. The functionalities needed in order to actuate the main services mentioned above are split between NFV MANO components, dealing with VNFs instantiation and orchestration, and specific controllers responsible for the operation and configuration of single resources in the Crosshaul infrastructure (i.e. SDN controllers for XFEs and storage and computing controllers for XPUs).

In compliance with the NFV MANO architecture defined by the ETSI NFV ISG [3], three main functional blocks have been introduced in the Crosshaul MANO segment:

- The Network Function Virtualization Orchestrator (NFVO), responsible for the instantiation of Network Services (i.e. sequences of VNFs) and management of their lifecycle.

- The Virtual Network Function Manager (VNFM), that covers the management of single VNFs.
- The Virtual Infrastructure Manager (VIM), in charge of controlling and managing the heterogeneous resources in the Crosshaul infrastructure, interacting with the dedicated controllers. In the 5G Crosshaul architecture the VIM is extended with planning algorithms specialized for the provisioning of virtual infrastructures tailored to the requirements of a Crosshaul environment and operating on top of XFE and XPU physical resources.

The SDN controller is in charge of configuring the network resources in the entire Crosshaul segment, according to the conventional SDN paradigm. One of the aims of 5G Crosshaul is to extend the SDN support to the multiple technologies used in Crosshaul transport network, in order to operate and reconfigure the physical/virtual network substrate, depending on tenants' specific request and needs.

It should be noted that in this section we are considering a single network domain, thus operated by a single SDN controller. In case of a network infrastructure structured in multiple domains (e.g., on a multi-vendor or a multi-technology basis) the network control plane can be deployed following a hierarchical model. Several “child” controllers operate single domains, abstracting the internal details of the local resources in order to allow an upper layer “parent” controller to compute and allocate end-to-end and inter-domain connections. This is implemented through the coordination of the lower level controllers’ actions, which are responsible for the configuration of resources in their own network domain (see section 3.3).

5.2 XCI interfaces

The 5G-Crosshaul network architecture is structured as an SDN network where the control plane (XCI) and the forwarding plane (XFE) are clearly separated and communicate through a South-Bound Interface (SBI). Applications located outside the control plane interact with the XCI and make use of the exposed capabilities using the North-Bound Interface (NBI), while the functions in the control layer can perform automated or on-demand reconfigurations of the network resources applying the necessary configuration and rules into the forwarding plane components through the SBI.

Several protocols can be used at the NBI and SBI. A deep investigation about protocol alternatives and their pros and cons have been performed in WP3. Relevant candidates at the SBI are the OpenFlow protocol, for the configuration of the forwarding behavior of the XFEs, and the NETCONF protocol or REST APIs for their management (even if this kind of API is usually based on proprietary information models). REST based APIs and RESTCONF protocol [4]. are quite common in the NBI area. Widely adopted SDN controllers, like OpenDaylight [5] and ONOS [6], are based on extensible architectures able to support several protocols at the SBI (e.g., OpenFlow, OVSDB, NETCONF, SNMP, etc.) and flexible information models at the NBI, usually based on REST or RESTCONF.

5.2.1 SDN controller North-Bound Interface

In a preliminary analysis, the transport paradigms identified to be possible adopted in the implementation of the XCI SDN controller NBI were namely: Representational State Transfer paradigm (REST), RESTCONF and the Network Configuration protocol (NETCONF). Subsequently, it was decided to base the implementation of the NBI mostly on REST, with the aim to develop a resource oriented interface and using RESTCONF only in that cases where the use of RPCs (Remote Procedure Call) or notification subscriptions is needed. In this last case, RESTCONF is a proper alternative to NETCONF in order to allow the transport of YANG data-model, using the NETCONF data-store definitions in a RESTful way over HTTP.

Several standardization activities, especially in IETF, are now focusing on the definition of YANG based information models for management and control of network domains. Relevant examples are the modeling of network topologies for L2 and L3 domains, as well as their extensions to support Traffic Engineering (TE) parameters. Other YANG models (e.g., for intent based network representation and virtual networks modeling) are under definition and development in open source initiatives, like the ones dedicated to the SDN controllers mentioned above. These YANG models constitute valid starting point which can be properly re-used and, where needed, extended for the NBI of the Crosshaul XCI controller services.

5.2.2 SDN controller South-Bound Interface

Concerning the SDN controller SBI, we have to distinguish between protocols to control the forwarding and protocols to manage and configure the nodes in the network substrate.

The OpenFlow Protocol (OF), standardized by the Open Networking Foundation (ONF) [7] and supported by all the major SDN controllers, is the protocol selected in order to program the forwarding plane in the XFEs. Suitable extensions will be needed for specific XFE technologies, e.g., to support the forwarding in optical devices.

In addition to network controller/switch communication interface, the OpenFlow protocol defines a generalized internal architecture of OpenFlow-enabled packet-based switches. In short, an OpenFlow switch is structured in a pipeline of flow tables which can be re-configured through the insertion of flow entries describing the forwarding behaviour for specific flows, identified through classifiers based on L2-L3 fields. In 5G Crosshaul the design of XPFEs (5G-Crosshaul Packet Forwarding Element) will follow the same approach, with the XCF (Common Frame), designed using the MAC-in-MAC as possible baseline (see chapter 6 for more details). The detailed analysis of the different versions of OpenFlow as well as the definition of the extensions required to configure XPFEs is addressed in WP3, while WP2 is focusing on OpenFlow extensions to operate the XCSEs (5G-Crosshaul Circuit Switching Elements, see chapter 6 for more details).

Regarding the monitoring and management of the switches in the data-plane, the choice does not fall on a specific standard protocol. Some alternatives could be for example: NETCONF, REST APIs and Simple Network Management Protocol (SNMP).

The SNMP protocol presents some limitations in performance and configuration management and is usually used to manage devices' fault in the network. NETCONF, which is a more recent protocol, provides an higher level of flexibility and capabilities and it was designed with the aim to provide mechanisms to install, modify and delete configurations in network devices. NETCONF operations are realized on top of a simple RPCs layer. The architecture will not mandate a single management protocol, but will be open to several solutions, through the adoption of dedicated SBI driver at the SDN controller.

5.2.3 Storage/computing controllers South-Bound and North-Bound Interfaces

Storage and computing controllers in 5G Crosshaul will be responsible for the operation and management of XPU elements. However, the project is not going to innovate in this area and existing solutions from open source initiatives like OpenStack [8] can be adopted in our architecture. For example, the OpenStack Cinder and Nova projects can be used as storage and computing controller and their APIs considered as reference APIs for the 5G Crosshaul architecture.

In particular, the Nova component provides a REST API, called OpenStack Compute API, which is based on the HTTP protocol and uses a JSON data serialization formats for the representation of its resources. Through this API, the computing controller provides scalable, on demand, self-service access to compute resources and exposes methods for CRUD (Create, Read, Update, Delete) and operational (e.g., start, stop, pause, create an image, resize, migrate) actions on VMs, diagnostics features or physical host management. In the same way, the Cinder project offers REST HTTP services to manage data through the Block Storage API.

5.2.4 XCI MANO APIs

As for computing and storage controllers, 5G Crosshaul can re-use most of the concepts currently available in the ETSI NFV MANO specification, adopting the interfaces defined for the MANO components for the orchestration, instantiation and lifecycle management of network services and VNFs. However, the NFV standardization in the API area is still at an early stage. Work is currently in progress around the definition of the NFV-related information models to be used at the major reference points identified in the ETSI MANO architecture (e.g., at the NBI of the NFVO, between NFVO and VNFM or VIM, between VNFM and VIM or VNFs). In particular, the focus is on descriptors and records for VNFs, virtual network services, Virtual Network Function Forwarding Graphs (VNFFG) and Virtual Links, making use of TOSCA or YANG models. On the other hand, no concrete proposals are currently available for the protocols specification. However, several open source initiatives (like Open Source MANO – OSM, OpenMANO or OpenBaton) are already proposing initial solutions based on REST APIs. A similar approach will be also adopted in 5G Crosshaul, re-using where possible the initial ETSI NFV outcomes in terms of information models and extending the models where needed (e.g., in support of multi-tenancy).

5.3 XCI components

This section provides an initial description of the XCI macro-components (i.e. XCI MANO components and SDN controller). More detailed designed activities are performed in WP3.

The following picture highlights the XCI MANO components and the XCI SDN controller, together with their expected interactions with the other elements of the architecture, currently under development in WP2 (XCFEs and XPFEs at the data plane) and WP4 (applications and VNFs places in the green boxes). An high-level description of the main XCI components and their functionalities is provided in the next subsections, while further details on their internal modules will be available in WP3 deliverables. A preliminary analysis of potential matching between XCI architecture and existing open source projects in the areas of SDN controllers and NFV management and orchestration is reported in Annex I – , as initial input for WP3 implementation activities.

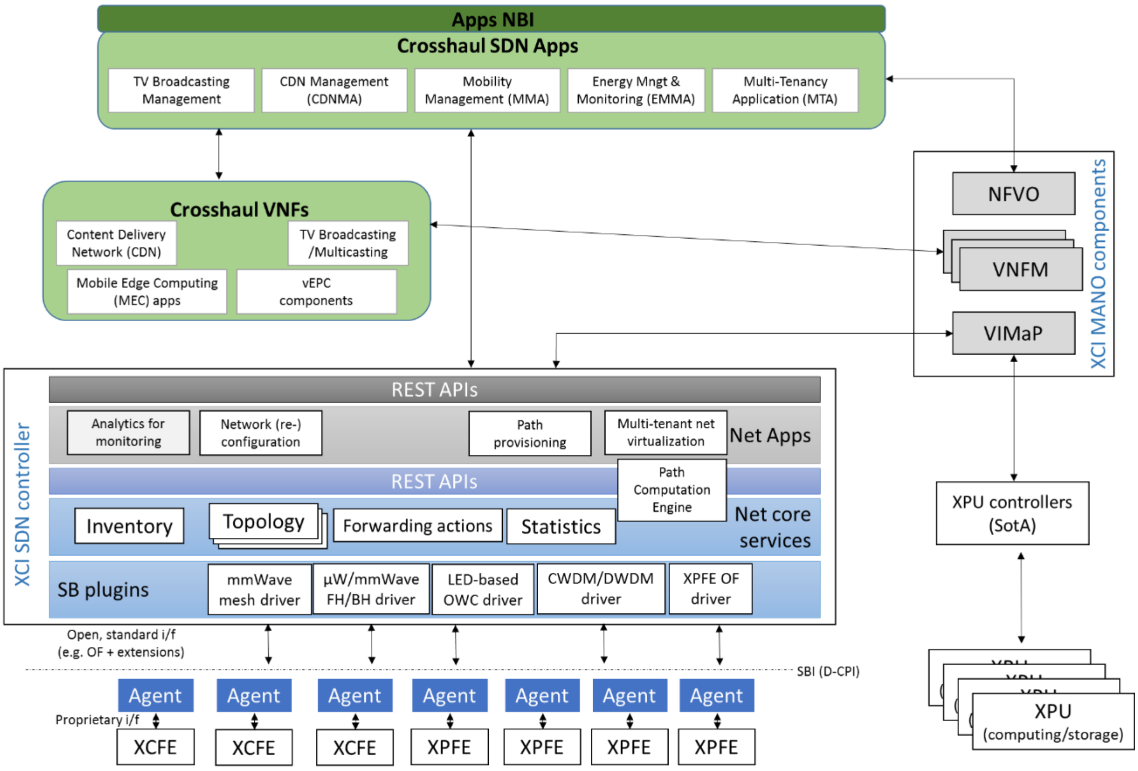

Figure 21: XCI design

5.3.1 XCI SDN controller

The SDN controller is responsible to manage and configure the different XFEs available in the 5G Crosshaul data plane, using specialized technology-dependent drivers at the controller's SBI (see Figure 21). In particular, this entity implements a set of unified network services to enable the smart programmability of the network infrastructure from upper layer network applications. The interaction between network applications and the core services implemented within the controller is enabled through REST APIs at the SDN controller NBI. Moreover, the SDN controller exposes NBIs which can be used by the VIMaP (Virtual Infrastructure Manager and Planner) to create dynamic instances of virtual networks over the 5G Crosshaul physical infrastructure.

The SDN controller implements most of the network-related features of the Crosshaul XCI, in terms of configuration, management, topology discovery, network monitoring and connection provisioning, hiding the details of the managed network domains from the upper layer entities (e.g., XCI MANO components and SDN applications).

In terms of macro-functionalities, we can distinguish three main layers within the XCI SDN controller. Using a bottom-up approach we have the following layers:

- Abstraction layer, with a set of southbound plugins (i.e. protocol drivers) dedicated to the interaction with the different data plane devices. This layer allows the network services implemented in the controller to interact with and operate on different data-plane technologies in the Crosshaul physical infrastructure, through unified information models which are independent on the SBI protocols. The plugins located at this level are technology dependent and implement the controller side of the protocol adopted at the SBI (e.g., OpenFlow, eventually extended, NETCONF, etc) and translate between the SBI messages and the common information model adopted in the core of the controller. In hierarchical and multi-domain deployments, a driver may interact with lower layer controllers (i.e. child controllers) operating on specific domains.
- XCI controller core services, which implement internal functions of the SDN controller and are used to virtualize, monitor and configure the entire set of XFEs as a whole. They interact with the different devices making use of the unified APIs provided by the SBI drivers and guarantee the coordination and consistency of the configuration across multiple network nodes (e.g., to configure flow entries in all the nodes along a path between two end-points). Other services are responsible for the collection of information from the whole network, for topology discovery and updated network inventory maintainance.
- XCI network control services, whichare related to internal network applications deployed at the SDN controller level and introduce a first level of automation and intelligent control in the physical infrastructure. They expose APIs which can be used by external services and components (e.g., the VIMaP) acting as client of the SDN controller and implements the logic to coordinate the setup of end-to-end connectivity in the multi-layer and multi-technology Crosshaul network, manage network virtualization over XPFEs and XCFEs, perform efficient allocation of resources in on-demand and automated re-optimization manner.

5.3.2 XCI MANO components

The XCI MANO components are the parts of the XCI responsible for NFV management and orchestration and, as initially explained in section 5.1, they consist of three main functional blocks cleary ispired by the ETSI NFV architecture, namely: the NFV Orchestrator (NFVO), the VNF Managers (VNFMs), associated to the different 5G-Crosshaul VNFs, and the Virtual Infrastructure Manager (VIM) extended with planning features (VIMaP):

- NFVO (NFV Orchestrator): functional block to orchestrate Network Service provisioning and manage its lifecycle. It coordinates the lifecycle of the different VNFs (supported by the VNFM) and manages the resources available at the NFV Infrastructure (NFVI), supported by the VIM. Its internal orchestration algorithms ensure an optimized allocation of the necessary resources, both at the computing and network level. It is also the entity responsible to coordinate the virtual connectivity setup between the VNFs.
- VNFMs (VNF Managers): responsible for creation, modification and termination of VNF instances, as well as for their configuration, monitoring and automated scaling during their entire lifecycle. VNFMs are usually specialized for single VNFs and in 5G Crosshaul will be adapted to the specific requirements of the VNFs targeted in the project (e.g., for CDN nodes).
- VIMaP (Virtual Infrastructure Manager and Planner): the entity responsible for the coordination of the controllers' actions and the allocation and configuration of the resources in the 5G Crosshaul segment, including both computing and networking entities, i.e. XPUs and XFEs. In 5G Crosshaul architecture, the VIM integrates also planning features towards an integrated VIMaP entity. In particular, the planning algorithms computes optimal VMs placement and network configuration in a joint manner.

6 Data plane design (inputs from WP2)

6.1 Data plane architecture

This section presents an overview of different architectural elements of the data plane developed within the project. In WP2 the mostly-suitable technologies for the deployment of a 5G-Crosshaul network are investigated, envisaging a unified data plane encompassing innovative high-capacity transmission technologies and novel deterministic-latency framing protocols (more details are available in specific WP2 deliverable).

Different Layer-1 and Layer-2 transport technologies, both wired and wireless, and their main metrics are investigated within the project. Regarding wireless technologies, a particular focus is on mmWave, *Visible Light Communications* (VLC), *Free Space Optics* (FSO). Concerning wired access media, both fiber-based and copper-based access standards are covered. These include all PON flavors such as GPON, XG-PON, TWDM-PON (NG-PON2), WDM-PON and copper-based technologies like DSL, DOCSIS, PLC, copper Ethernet and G.Fast. In particular, WDM is considered as enabler for high aggregate capacity, in line with the related 5G KPI, network convergence, protocol transparency (an important feature in 5G, where different protocol splits are being introduced), baseband processing centralization and flexible topology. Novel techniques exploiting sliceable bandwidth variable transponders are also investigated. All such technologies are analyzed taking into account both performance and cost aspects, namely: capacity, latency, synchronization, distance and link budget, energy efficiency, cost considerations and operational aspects. This will also facilitate the definitions of the parameters that will be abstracted to the SDN SBI.

As already mentioned in paragraph 5.2.2, it has also been provided a proposal towards the 5G-Crosshaul data plane architecture, describing the components of its fundamental block, namely the XFE. Essentially, the XFE is modeled as a modular multi-layer switch, that can support single or multiple link technologies (mmWave, microwave, Ethernet, copper, fiber, etc.). The XFE is mainly made up of a packet switch (*5G-Crosshaul Packet Forwarding Element*, XPFE) and a circuit switch (*5G-Crosshaul Circuit Switching Element*, XCSE).The packet switch is controlled by a unified Common Frame (XCF), identified as a requirement for 5G-Crosshaul and designed jointly by WP2-WP3 (see next paragraph for details). The circuit switch can have an optical cross-connection component (based on wavelength selective switches) and a TDM part, based on OTN, a new cost effective approach for deterministic delay switching. A detailed description of those elements is provided in specific deliverable of WP2. Different adaptation functions are used to adapt the frame format of RRH XPU and BBU to the one used by the XPFEs.

In WP2 they have also been overviewed the requirements for latency critical fronthaul transport, starting from CPRI analysis, and they have been envisaged solutions to multiplex and transport fronthaul and backhaul signals in the same optical or wireless physical channel. In more details, WP2 realized that fiber media technology like GPON is not suitable for transporting CPRI signals. In any case, the Project understood that not only DWDM or dark fiber can be the technologies able to carry CPRI, but also some solutions based on a CPRI over packet (or OTN) encapsulation or over wireless media might represent an efficient alternative to pure optics.

6.2 5G-Crosshaul Common Frame

One of the key architectural elements that have been defined during the first phase of the Project was the unified transport frame to be used across the 5G-Crosshaul network, the 5G-Crosshaul Common Frame (hereafter XCF).

WP2 and WP3 together identified a set of precise requirements for the packet technology to be elected as XCF.

Said requirements can be summarized as follows:

- *Support multiple functional splits simultaneously*
  - Including Backhaul and CPRI-like Fronthaul
- *Multi-tenancy*
  - Isolate traffic (guaranteed QoS)
  - Separate traffic (tenant privacy)
  - Differentiation of forwarding behavior
  - Multiplexing gain
  - Tenant ID (identification of tenants' traffic)
- *Coexistence, Compatibility*
  - Ethernet (same switching equipment, for example different ports, etc.)
  - Security support
  - Synchronization: IEEE1588, IEEE802.1AS
- *Transport efficiency*
  - Short overhead
  - Multi-path support
  - Flow differentiation
  - Class of Service Differentiation
- *Management*
  - In band control traffic (OAM info, …)
- *Energy efficiency*

  - Energy usage proportional to handled traffic (e.g., sleep mode, reduced rate)

- *Support of multiple data link technologies*

  - IEEE 802.3, 802.11 (including mmWave), etc.

- *No vendor lock-in*

The possibility of using the IEEE 802.1ah definition of frame, also known as Provider Backbone Bridge or MAC-in-MAC has been discussed, comparing it with other frames like the Multi-Protocol Label Switching-Transport Profile (MPLS-TP). After long comparison of characteristics, advantages and disadvantages in using one frame rather than another one, the Project finally reached consensus on the use of MAC-in-MAC for transporting backhaul and fronthaul traffic within 5G-Crosshaul. In the following we present some information regarding the MAC-in-MAC format and how it can be mapped to IEEE 802.11 (relevant since millimeter wave links use the standard IEEE 802.11ad) links.

Provider Backbone Bridges belongs to IEEE Std 802.1Q and is a set of architecture and protocols for switching over a provider's network, allowing interconnection of multiple Provider Bridge Networks without losing each customer's individually defined VLANs. Nowadays, MAC-in-MAC cannot be transparently carried over IEEE Std 802.11 links, because IEEE Std. 802.11 was originally designed as access network, with the assumption that connected devices would be leaf nodes of the network.

A set of IEEE task groups, namely IEEE 802.11ak, IEEE 802.1Qbz and IEEE 802.1AC, have been created to explore the use of IEEE 802.11 links as connections within bridged networks. Those amendments will optionally extend the 802.11 standard so that communication links can be established between devices that are usable as transit links inside a network conformant to IEEE Std 802.1Q. This means that IEEE 802.11 links shall carry 802.11Q tags like B-VID, I-SID, S-Tag, and C-Tag. Tagging makes use of high layer protocol discrimination procedure to signal the presence of the tag and its value. 802.2 LLC sub layer uses two methods to determine the high layer protocol: EtherType Protocol Discrimination (EPD) and LLC protocol discrimination (LPD). The former is used by MAC-in-MAC, while the latter is used by 802.11. The tag insertion and deletion on EPD and LPD is similar, but the format of the Tag Protocol Identifier (TPID) was different until 2014, when IEEE Std 802.1Q and IEEE 802.1AC finally harmonized the encoding. As a result, MAC-in-MAC can be transparently mapped onto 802.11 links thanks to the harmonized EPD/LPD encoding as depicted in Figure 22. Therefore, MAC-in-MAC template is a viable XCF baseline in 5G-Crosshaul.

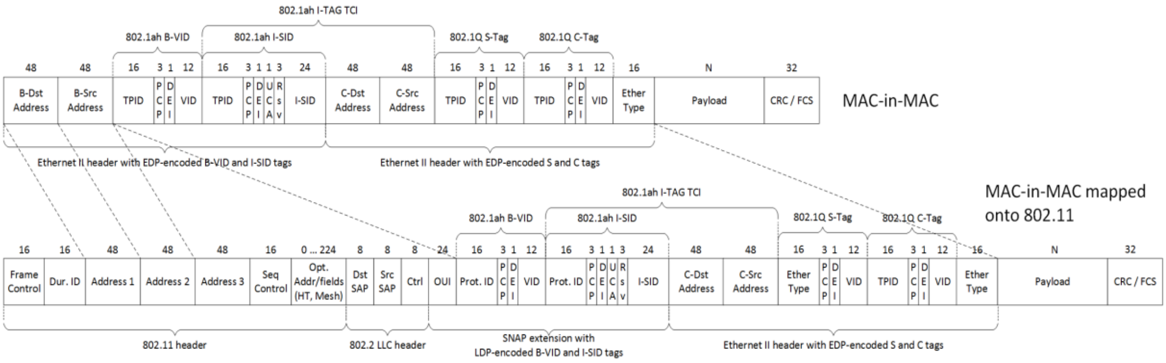

Figure 22: MAC-in-MAC mapping onto 802.11 frames

The Project also considered MPLS-TP as an important alternative for XCF. As well as MACinMAC, MPLS-TP is able to satisfy the identified requirements.

Stacked labels and QoS guarantee the multi-tenancy support, as shown in Figure 23.

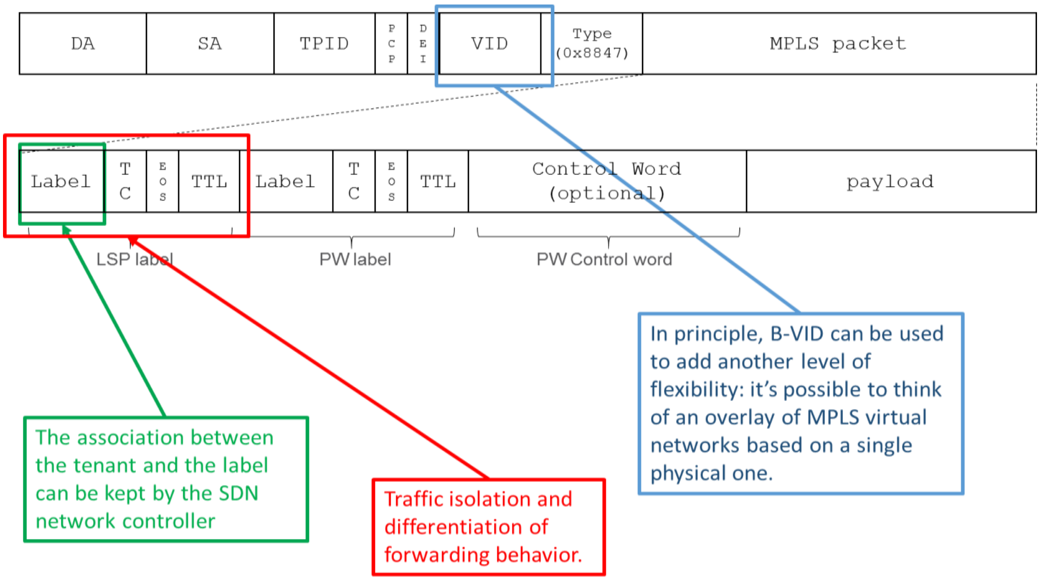

Figure 23: MPLS-TP frame and multi-tenancy compatibility

Finally, the project stated the equivalence of MAC-in-MAC and MPLS-TP, since both are able to satisfy the identified requirements. In any case, MAC-in-MAC has been elected as the best candidate for XCF for its simple layer 2 only characteristics.

7 Cost model

7.1 Objective

The objective #5 of the 5G-Crosshaul Description of Work (DoW) "Increase cost-effectiveness of transport technologies for ultra-dense access networks" imposes to take into account the 5G KPI of *reducing Total Cost of Ownership (TCO) by 30% by improved optical transmission and sharing mobile and fixed access equipment*. This can be enabled by *developing physical layer technologies with reduced cost per bit, as well as new energy saving schemes, which further reduce operational costs* as stated in the Project proposal.

In order to evaluate the accomplishment of this goal due to the 5G-Crosshaul network, it is fundamental to set-up a tool able to numerically calculate costs for the innovative network with respect to a legacy solution.

7.2 Cost evaluation

7.2.1 Comparison parameter

In the 5G KPIs the CAPital EXpenditures (CAPEX) and OPerating EXpenditures (OPEX) analysis is part of a more comprehensive Total Cost of Ownership (TCO) evaluation that gives, as comparison parameter between legacy and 5G Crosshaul networks, the Yearly Total Cost per bit/s (YTC):

$$YTC = \sum_{i=1}^{N} \frac{CAPEX_i}{AP_i} + \sum_{j=1}^{M} OPEX_j$$

$CAPEX_i$ and $OPEX_j$ are the i-th component and j-th component of CAPEX and OPEX respectively. In order to harmonize the sum, each CAPEX has to be annualized, splitting the investment by the appropriate *amortization period* (*AP*). This is the easiest way to calculate the Total Cost of a system taking into account both CAPEX and OPEX, neglecting inflation and cost of the money used for investment (for example interests on outstanding debts like bonds, bank loans, etc.).

7.2.2 Methodology

The idea of the methodology for cost evaluation is shown in Figure 24. It consists in dimensioning the legacy and 5G-Crosshaul networks considering the same traffic matrix, in order to better compare the costs. In the legacy situation the backhauling and fronthauling networks are separated and supported by different equipment, while in 5G-Crosshaul architecture the two networks involve the same pieces of equipment integrated in a single one, namely the 5G-Crosshaul Element (XFE).

Finally, in both situations the Yearly Total Cost per bit/s is calculated and it represents the comparison numerical figure, highlighting the cost savings obtained adopting the 5G-Crosshaul network concept.

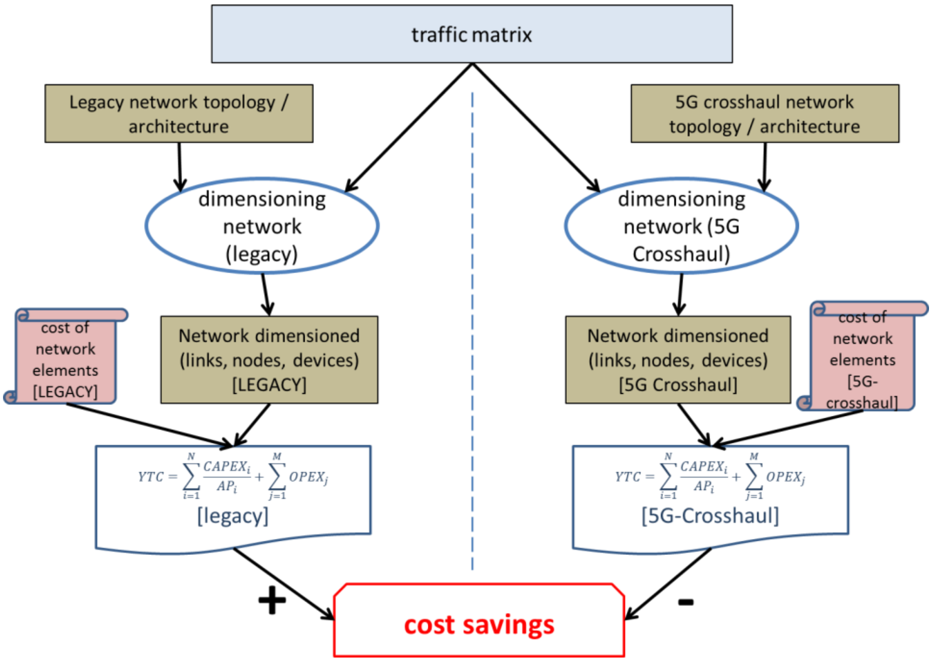

Figure 24: Proposed methodology for cost savings evaluation

The evaluation of cost savings can be done in two phases:

- A preliminary phase where a generic cost model is provided and can be applied to the legacy network as well as to the 5G Crosshaul network. This model is referred to the Gbit/s cost unit, but it is important to take into account that the cost per Gbit/s does not directly correspond to the cost of the service. In fact the cost should be calculated per real user flow, that depends on the fronthauling functional splitting between RRH and BBU both in 4G (legacy) and 5G (Crosshaul) cases.
- A second phase where, in a selected number of reference networks/use cases, there will be a dimensioning of the networks in terms of devices, systems and their equipment and an economic valorization of them. This second phase will be possible only when the 5G Crosshaul project will have clearly defined the network topology, the adopted technologies, the splitting functionality and the devices configurations.

In the following of the document, only the preliminary phase is considered.

7.2.3 Legacy network

The legacy network is composed by two separate networks:

- The fronthauling network, where solutions based on Metro ROADM can be used to connect the RRHs to the BBUs, presently carrying CPRI data over dark fiber. The equipment cost model, already developed in the FP7 EU IDEALIST project, has been adapted to a Metro DWDM network based on fixgrid Broadcast&Select ROADM having 2 line systems (ring archictecture), each carrying 24 channels at 100 Gbit/s and 2 colorless add/drop chains. These equipment elements are based on 1x4 WSSs (Wavelength Selective Switches) plus splitters/combiners. These CAPEX have been forecasted to the 2020 horizon considering a 9% of costs reduction every year.

- The backhauling network, connecting the BBUs to the Mobile Core network, is composed by aggregation/metro Packet Transport equipment based on the MAC-in-MAC (or PBB) framework. For this equipment CAPEX have been equalized to the costs of Packet Transport equipment based on MPLS-TP, that have been studied in the context of the FP7 EU STRONGEST project, and now are projected into 2020 with a 9% cost reduction per year. In particular, a 1.6 Tbit/s switching matrix has been considered, conveying traffic from tributary cards based on 20 x 1 Gbit/s or 10 x 10 Gbit/s grey transceivers to line cards with 10 x 40 Gbit/s or 4 x 100 Gbit/s grey transceivers.

As regards the CAPEX of RRH and BBU, these units have presently a centralized intelligence that requires the support of CPRI for data transmission, while in the future costs could vary depending on the functional split chosen for RRH and BBU. These new equipment configurations could be supported also by the legacy network.

Also the fiber infrastructure has been considered as CAPEX, with estimation for digging, trenching and fiber deployment. As regards wireless, the cost of the devices will be considered, divided by their amortization period. For copper its use will be considered as an OPEX item since operators do not forecast to deploy new copper infrastructures.

7.2.4 5G-Crosshaul network

The 5G Crosshaul Project has identified a high level data plane architecture (Figure 25) represented the 5G Crosshaul Packet Forwarding Elements (XFEs), that consists of packet forwarding elements (the XPFE) and circuit switching elements (the XCSE). The XPFE and XCSE forms a meshed network envisaged to support fronthauling as well as backhauling functionalities.

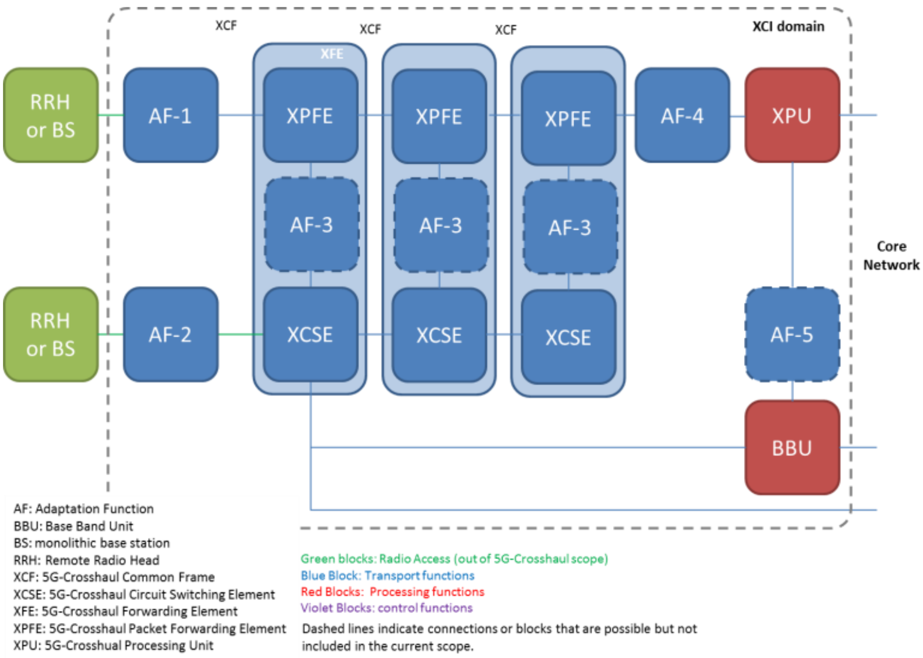

Figure 25: 5G-Crosshaul data plane architecture

The devices to be economically valorized as CAPEX should be the ones depicted inside the dashed rectangle of Figure 25:

- the XFEs, with its sub-elements
- the 5G Crosshaul Processing Units (XPUs)
- the adaptation functions AFs between the various equipment and also towards the RRHs and BBUs
- the types of connections among all previous mentioned devices (fiber, copper, microwaves, etc.)

In particular, as regards the integration in the XFE of the XPFE and XCSE components, there will be economic savings w.r.t. the legacy equipment due to:

- technology evolution of optical equipment like ROADM, that will be based on monolithically integrated silicon photonics chips
- the 5G Crosshaul Common Frame (XCF) choice, that is based on a simple Ethernet (MAC-in-MAC) equipment, whose cost could be lower w.r.t. the MPLS-TP one
- simpler equipment control due to the 5G Crosshaul Control Interface (XCI)
- L0/L2 integration leading to savings also at OPEX level, due to minor energy consumption and minor space occupation inside the rented buildings (see paragraph on OPEX model).

As regards the CAPEX of RRH and BBU, the same consideration done for the legacy network can be done for the 5G Crosshaul network, that will consider all cases, i.e. the costs for transmission over the optical layer of CPRI data, but also the important item of equipment virtualization for future 5G connections, that imply a different functional split between RRH and BBU, with all the possible costs variations.

For what it concerns the media costs, the considerations are the same presented in the previous section for legacy network.

7.3 Cost model

The cost model described in the following refers, for simplicity of description, to a legacy network where fronthauling corresponds to the optical network and backhauling corresponds to the packet network. Obviously, the model is indeed able to evaluate the cost of networks where fronthauling and backhualing consists of both L2 and optical devices. Finally, since the developed algorithms are tailored for 5G-Crosshual network, it is possible to evaluate the costs of a network where backhauling and fronthauling collapse in a unique network consisting of hybrid L2/optical devices.

7.3.1 CAPEX model

The CAPEX model is to calculate the cost of network segments (backhauling, fronthauling) per Gbit/s of user traffic. The input of the model is a set of CAPEX elements (RRH, BBU, fiber, fronthauling and backhauling network nodes,…):

- Cost of RRH and BBU: C_{RRH} , C_{BBU} [€/flow]
- Cost of fiber: C_f [€/Gbit/s km]
- Cost of optical device, i.e. ROADM: C_{ROADM} [€/Gbit/s]
- Cost of packet L2 device: C_{L2} [€/Gbit/s]

Starting from the cost per Gbit/s, calculated considering the total available capacity, the corrective parameters described in the following are applied.

A. An average percentage of usage is taken into account, since not the whole installed capacity is used. For this puropose, four parameters have been set:
    - an average percentage of usage of installed fiber capacity in the fronthauling (uff, “used fiber fronthauling”) and in the backhauling (ufb, “used fiber backhauling”)
    - an average percentage of usage of the devices capacity in the fronthauling (udf) and in the backhauling (udb)

    So, the costs per Gbit/s of fiber and devices increase taking into account these expressions:
    - $C_{ff} = C_f$ / uff
    - $C_{fb} = C_f$ / ufb
    - $C_{ROADM\_1} = C_{ROADM}$ / udf
    - $C_{L2\_1} = C_{L2}$ / udb
B. Some parameters taking into account the crossing of a network (multiple devices, length of fibers in km, ...) have been considered:

- the mean length (in kms) of crossed fiber (flf, flb, i.e. fiber length for fronthauling and backhauling respectively)
- the average number of devices traversed by the single flow (cdf, cdb, i.e crossed devices in fronthauling and backhauling respectively).

So, the fiber cost can be modified in the following way:

- $C_{fiber\_f} = C_{ff} * flf$ (fronthauling)
- $C_{fiber\_b} = C_{ff} * flb$ (backhauling)

While the cost of the Gbit/s traffic unit crossing several devices, i.e the cost for the optical devices (C_{od}) and the cost for the L2 devices (C_{L2d}) becomes:

- $C_{od} = C_{ROADM} * cdf$
- $C_{L2d} = C_{L2} * cdb$

C. A parameter taking into account the real traffic (i.e. the real number of transported bits) has been considered. This is due to different splitting functionality options (between RRH and BBU) that lead to completely different bandwidth occupation (in particular in the fronthauling segment). For this reason the cost per Gbit/s should be corrected by :

- the ratio between the real traffic and the user traffic in the fronthauling (FHfactor)
- the ratio between the real traffic and the user traffic in the backhauling (BHfactor)

The cost of fibers and devices should be rearranged by these factors:

- Cost Fronthauling Network Unit: $C_{FNU} = (C_{od} + C_{fiber\_f}) * FHfactor$
- Cost Backhauling Network Unit: $C_{BNU} = (C_{L2d} + C_{fiber\_b}) * BHfactor$

D. A parameter taking into account the surplus of resources required for the protection, with an additive percentage parameter. Two parameters have been set:

- resilience additional-capacity for the fronthauling (raf)
- resilience additional-capacity for the backhauling (rab).

Therefore, the cost for the protected networks will be:

- Cost Fronthauling Protected Network:$C_{FPN} = C_{FNU} * raf$
- Cost Backhauling Protected Network:$C_{BPN} = C_{BNU} * rab$

E. Finally, in order to be able to have a total cost of ownership the CAPEX is divided by the amortization period, to result in a yearly cost.

7.3.2 OPEX model

The considered items for OPEX evaluations are the following ones:

- the rented space for equipment allocation (also named “footprint”)
- the energy consumption for power suppply and cooling
- the maintenaince costs

- the renting of some media (e.g., copper,..)

The hosting costs of equipment can vary from nation to nation and also from urban, suburban or countryside sites. A reference rental offer from Telecom Italia (for co-location services to the wholesale customers) gives the costs for space rental of an ETSI N3 Rack Unit and for power supply and air conditioning facilities. The costs vary from about 2500 euro per year for a rack occupied with 1 shelf to a maximum of about 3000 euro for a rack fully occupied with 4 shelves.

The prices for power and air conditioning supply are considered apart in this study, in order to better evaluate the cost savings introduced by the 5G Crosshaul network architecture. The reference costs derived from the TI wholesale offer amount to 0.1647 euro per KWh for the power supply and to 0.1318 per KWh for the air conditioning.

The maintenance costs are considered as a percentage of the investments (CAPEX) done for the specific equipment or infrastructure, typically using a value between 3% and 5%. These items include the manpower for maintenance and repairs after failures, the spare parts and warehouse costs.

As already said in previous paragraphs, the fiber infrastructure has been considered as a CAPEX item even if, in some business context like for transnational operators, the fiber should be rented. In this case, as described in the IDEALIST project, it has been estimated a cost of about 117k euro per km for a 5 years rental of 100 fiber pairs.

7.4 Energy model

Beside the cost model, an energy model has been set up. The evaluation of energy consumption has a twofold utility:

- The cost for energy consumption of devices/components and the power cost for cooling are important items in the OPEX evaluation.
- It is a commitment of this research to reduce the energy consumption necessary for transporting information.

The energy evaluation is similar to the cost evaluation. In fact:

- The energy consumption is evaluated per user traffic flow.
- The energy consumption evaluation takes into account all the correction parameters considered for the costs (average usage, protections, average number of crossed devices).

Finally, besides the energy consumption for equipment functioning, it is important to consider a parameter that takes into account the energy consumption for cooling, that can vary the total energy needs for a relevant amount.

An example of typical energy consumption values for commercially available ROADM amount to 1.26 KWh per Gbit/s per year for each line system. This value will be surely reduced in the future 5G Crosshaul ROADM based on silicon photonics chip. The amount of this energy reduction will be evaluated in the next future, as well as the energy consumption of the L2 device and of the RRH and BBU with different functional splits.

8 Conclusions

After the first year, the 5G-Crosshaul project has gone ahead towards the developing of a 5G transport network solution integrating the fronthaul and backhaul segments of the network. It is expected that 5G-Crosshual can provide an adaptive, programmable and cost-efficient substrate for advanced services on top of it.

The workflow has reached its first ambitious goal to define five key use cases. Three of them are service-oriented use cases, meaning that they are related to specific applications or set of applications, in particular: (i) vehicle mobility, (ii) media distribution (CDN and TV broadcasting), and (iii) dense urban information society. In addition to them, two functional-oriented use cases have been considered: (iv) multi-tenancy, and (v) mobile edge computing. A common set of functional and non-functional requirements are identified and mapped to these use cases, including prioritization.

The second step has been to provide the system architectural design to facilitate the works in other WPs. WP1 provided the common agreement of the project regarding the architecture of the Crosshaul control plane (including the support for multi-tenancy), unified data plane and relevant 5G-Crosshaul applications.

Some important technical achievements have been reached, in particular about the control of the infrastructure in a multi-tenancy environment. Besides the definition of a classification of the different service use cases for the tenants, the Project defined a taxonomy of three categories: *Over-The-Top* (OTT), *Mobile Virtual Network Operator* (MVNO) and V*irtual Infrastructure Provider (VNP)*, each of them with different characteristics and requirements for the Crosshaul.

Furthermore the Project defined the 5G-Crosshaul architecture for the Single-*Management and Orchestration* (MANO) scenario, considering the case where different technologies must be orchestrated, and then it went ahead by applying this concept in order to envisage the definition of the Multi-MANO architecture, in which the *Multi-Tenancy Application* (MTA) plays a central role.

As an important technical work, WP1 provided an initial design of the Resource Manager Application, fundamental part of the XCI.

Another fundamental result has been the identification of the overall system architecture, which should be declined into applications, control and data plane. This work has been done by the technical WPs and WP1 has been the contact point among them.

In more details, the application layer, defined in WP4, is focused on the enabling of a multi-tenant usage of the physical infrastructure. Anyway, since the multi-tenancy is not the only 5G Croshaul use case, a mapping of the applications needed to support all the defined use cases is provided.

The control layer interacts with external layers through the following interfaces: the South-Bound Interface (SBI), towards the 5G Crosshaul data-plane, the North-Bound Interface (NBI), towards the 5G Crosshaul applications and the East-West Interfaces

(EBI and WBI), towards the core network and RAN domains (out of scope for the 5G-Crosshaul project).

The studies about data plane resulted in the definition of the mostly-suitable technologies for the deployment of a 5G-Crosshaul network. The final goal is to envisage a unified data plane encompassing innovative high-capacity transmission technologies and novel deterministic-latency framing protocols. The project also selects a Crosshaul Common Frame (derived from MAC-in-MAC Ethernet technology) as its framing protocol.

Finally, in order to evaluate the 5G-Crosshaul solutions in terms of costs and energy consumptions, WP1 has also developed a preliminary cost and energy methodology for modeling and analyzing the investiment and operational expendituresand the energy consumption. This latter is very important since it represents a significant part of yearly expenditures for a network operator and because the 5G network should give its contribution to reduce the carbon emissions.

9 Annex I – Relationship between XCI design and major open source projects

9.1 Matching between XCI SDN controller architecture and open source projects

The architecture of XCI is depicted in Figure 26.

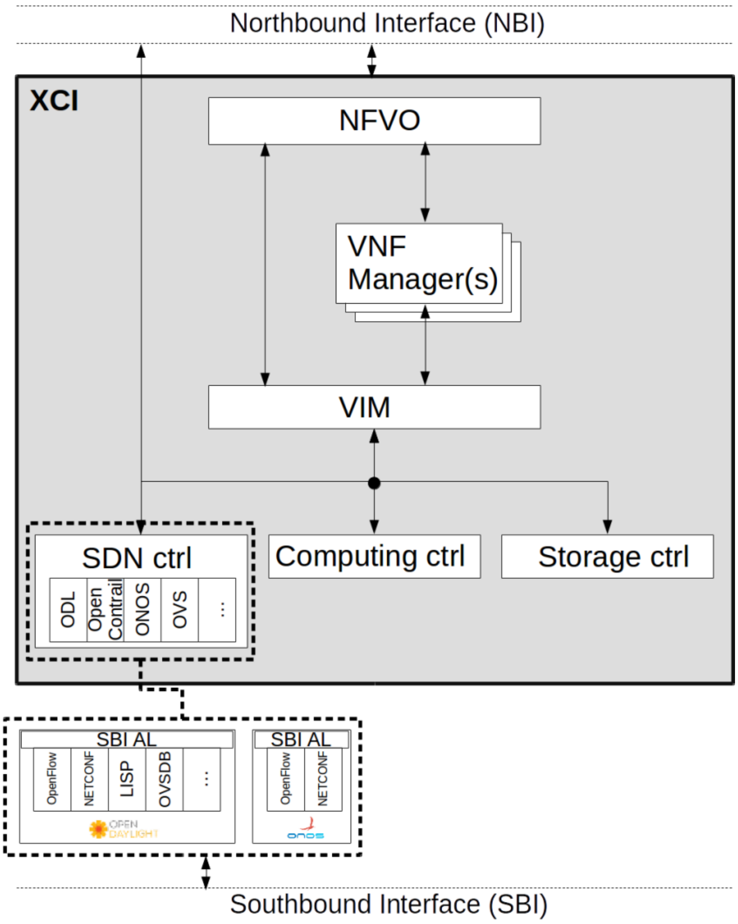

Figure 26: XCI architecture and SDN open source project

9.1.1 OpenDaylight (ODL)

At the time of writing a new version of OpenDayLight (Beryllium) have been recently issues. The text refers to the previous version of ODL, named “Lithium”. It was first released in June 2015 and the last Service Release made public in December 2015. ODL is a highly available, modular, extensible, scalable and multi-protocol controller infrastructure built for SDN deployments on modern heterogeneous multi-vendor networks. ODL provides a model-driven service abstraction platform that allows users to write apps that easily work across a wide variety of hardware and south-bound protocols. Moreover, its architecture is leveraged by a growing number of commercial products and solutions, as well as the *Open Platform for NFV* (OPNFV). 466

individuals contributed to the Lithium release making ODL one of the fastest-growing open source projects.

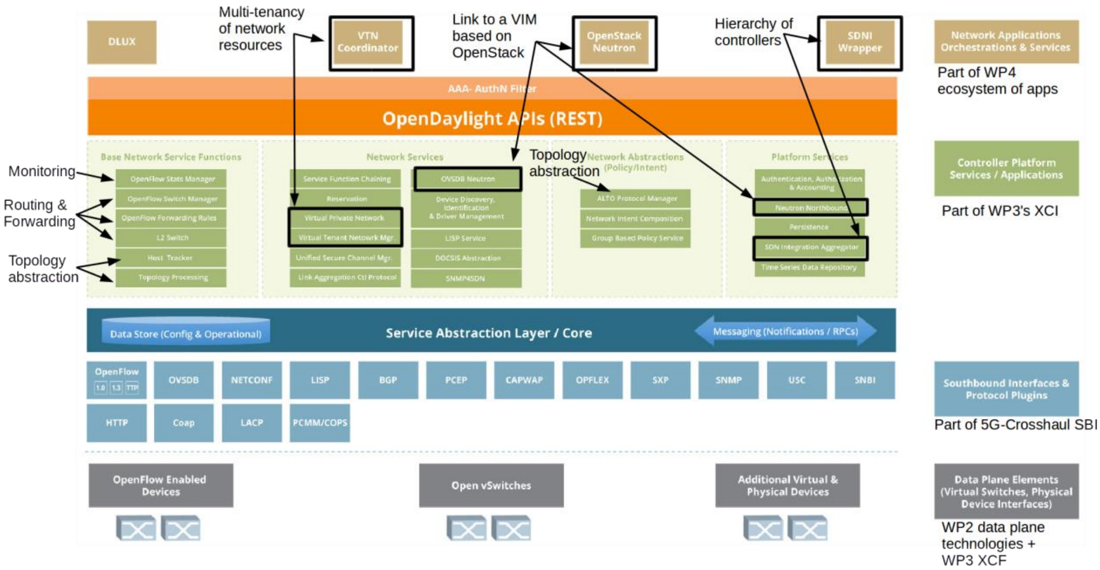

Figure 27: OpenDaylight architecture

The ODL platform (depicted in Figure 27) is composed of a number of different modules that can be combined as needed to meet the requirements of a given scenario. For instance, as shown in Figure 28, OpenStack cloud can be paired with ODL to offload network processing and provide enhanced services. This basic use case can be implemented after starting the core ODL controller by enabling the AAA, Neutron and OVSDB services. These services alone can support OpenStack by automating network virtualization and providing centralized control and management of distributed virtual switches and routers across the OpenStack cloud.

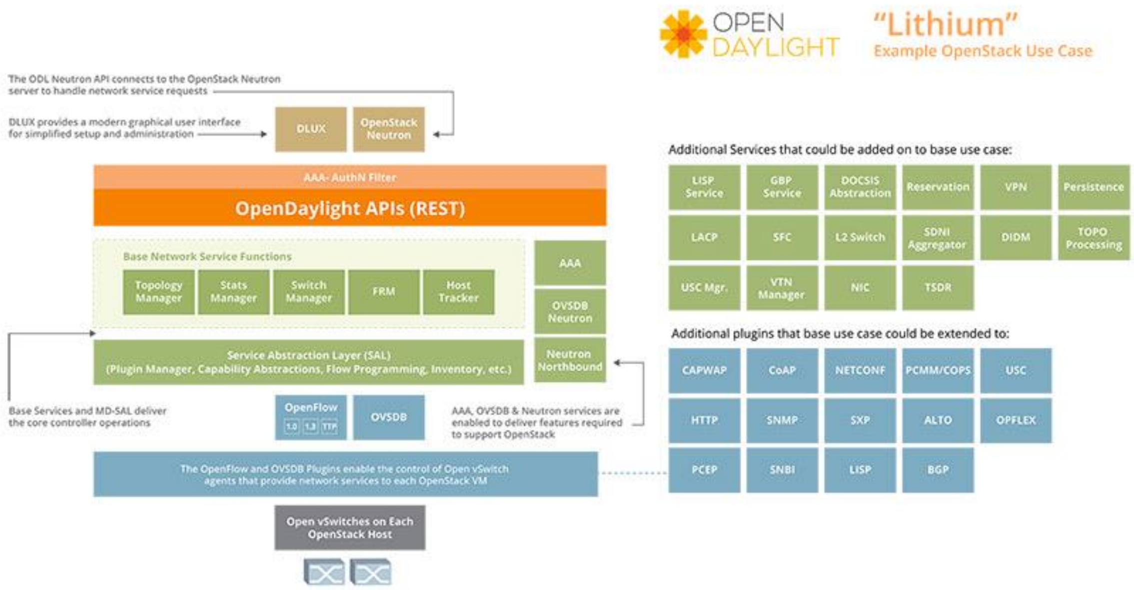

Figure 28: Integration of ODL and OpenStack

The core services in ODL are based on Java Virtual Machines using the OSGi framework and Karaf containers. This enables ODL to run a small lean set of core services and only run additional code as needed to enable features only when they are used. The OSGi framework and Karaf containers allow these additional features to be spun up and down as needed without reboots to enhance the stability of the system.

An additional key value of the ODL platform is in its ability to bring together a vast array of network types under a common control and management framework. For example, the base use case shown in Figure 28 is built using the OpenFlow plugin to control virtual switches on each OpenStack host. This could however be changed to control physical switches with OpenFlow, or could leverage other southbound plugins such as NETCONF, BGP/LS/PCEP or others to extend services across an array of different network device types. Additional features can be thought of as add-on that the can be turned on and configured to deliver additional value-added capabilities. For example additional security can be implemented and added on the Unified Secure Channel features to encrypt communications, or we can enable the group-based policy and secure group tagging services to automate policy enforcement across the infrastructure. If a use case requires virtual firewall, load balancing or other L4-7 services users can enable the Service Function Chaining features to stitch together.

An additional key value of the ODL platform is in its ability to bring together a vast array of network types under a common control and management framework. For example, the base use case shown in Figure 28 is built using the OpenFlow plugin to control virtual switches on each OpenStack host. However, this could however be changed to control physical switches with OpenFlow, or could leverage other southbound plugins such as NETCONF, BGP/LS/PCEP or others to extend services across an array of different network device types.

9.1.1.1 Mapping of 5G Crosshaul requirements to ODL

The selected SDN controller shall cover as many applications and support as many use cases defined for 5G-Crosshaul as possible. Figure 28 highlights some of the overlapping functionalities as requirements to support 5G-Crosshaul use cases and applications.

9.1.1.2 Multi-tenancy application (MTA)

WP3 specifies two key requirements to support MTA: Abstraction of Crosshaul Virtual Network Provider infrastructure and abstraction monitoring information. The first includes providing an abstraction of the physical and virtual infrastructure, information on data plane gear (XFEs, XPUs and legacy equipment) and their links, and location of physical elements. The second implies monitoring information on the underlying infrastructure such as capacity or link latencies. Moreover, MTA requires an SDN controller capable of performing routing, tunneling and traffic shaping functions.

ODL provides a suite of services to abstract the underlying infrastructure (either physical or virtual) and monitor the data plane equipment. Moreover ODL Lithium provides ODL Virtual Tenant Network (VTN). VTN allows the users to define the network with a look and feel of conventional L2/L3 network. Once the network is designed on VTN, it will automatically be mapped into underlying physical network, and then configured on the individual switch leveraging SDN control protocol. Users can design and deploy any desired network without knowing the physical network topology or bandwidth restrictions.

It is implemented as two major components: VTN Manager and VTN Coordinator. The VTN Manager is an ODL Controller (ODC) Plugin that interacts with other modules to implement the components of the VTN model. It also provides a REST interface to configure VTN components in ODL controller. VTN Manager is implemented as one plugin to the ODL controller. This provides a REST interface to create/update/delete VTN components. The user command in VTN Coordinator is translated as REST API to VTN Manager by the ODC Driver component. In addition to the above mentioned role, it also provides an implementation to the Openstack L2 Network Functions API.

The VTN Coordinator is an external application that provides a REST interface for a user to exploit the VTN Virtualization. It interacts with VTN Manager Plugin to implement the user configuration. It is also capable of multiple controller orchestration. It realizes Virtual Tenant Network (VTN) provisioning in ODL Controller. In the ODL architecture VTN Coordinator is part of the network application, orchestration and services layer. VTN Coordinator has been implemented as an external application to the ODL controller. This component is responsible for the VTN virtualization. VTN Coordinator will use the REST interface exposed by the VTN Manager to realize the virtual network using the ODL controller. It uses ODL APIs (REST) to construct the virtual network in ODC. It provides REST APIs for northbound VTN applications and supports virtual networks spanning across multiple ODCs by coordination across ODCs.

Moreover, ODL's VTN can be integrated with OpenStack. In the integration, VTN Manager works as network service provider for OpenStack. VTN manager featuresenable OpenStack to work in pure OpenFlow environment, in which all switches in data plane are OpenFlow switches.

Other requirements like traffic shaping can be satisfied using OVS.

9.1.1.3 Virtual Infrastructure Manager and Planner Application (VIMaP)

Similarly, VIMaP also requires abstractions of the underlying Crosshaul infrastructure which, as we showed before, ODL properly satisfies. Moreover, ODL can integrate with OpenStack via its Neutron service to support OpenStack, by automating network virtualization and providing centralized control and management of distributed virtual switches and routers. ODL's Neutron northbound project is focused on the communication from the ODL drivers in OpenStack to the ODL Neutron service and saves the Neutron models into ODL data store for other providers to be used. It does not include direct manipulation of low-level network/overlay elements - these are left to the providers that receive information from this Project.

9.1.1.4 Resource Management Application (RMA)

Besides the required abstraction and monitoring of infrastructure we discussed already above, RMA requires XCI to provide network adaption (e.g., re-routing) and network function placement. Routing is a primary functionality provided by any SDN controller, including ODL. Moreover, we showed above the integration of ODL with OpenStack to provide connectivity between VNFs across the network. In particular, ODL SFC provides the ability to define an ordered list of network services (e.g., firewalls, load balancers). These services are then "stitched" together into the network to create a service chain. This project provides the infrastructure (chaining logic, APIs) needed for ODL to provision a service chain in the network and an end-user application for defining such chains.

9.1.1.5 Energy Management and Monitoring Application (EMMA)

This is an application that concerns SDN and OpenFlow features. OpenFlow does not support the collection of energy consumptions stats, therefore the intention is to use other protocols, such as NETCONF, which does support it, to collect those stats.

9.1.1.6 Content Delivery Network Management Application (CDNMA)

This is an OTT application that will leverage infrastructure abstractions similarly as decribed above and will exploit other applications (e.g., RMA). Thus, all the functionalities required by this application have been analyzed for the previous applications.

9.1.1.7 Broadcast Application (BA)

This is an OTT application that will leverage infrastructure abstractions similarly as decribed above and will exploit other applications (e.g., RMA). Thus, all the functionality required by this application has been analyzed for the previous applications.

9.1.1.8 Mobility Management Application (MMA)

MMA works very closely with RMA. Monitoring, abstraction of infrastructure and routing support are functionalities already analyzed for RMA in the context of ODL.

9.1.2 ONOS (Open Network Operating System)

The Open Network Operating System (ONOS) is the first open source SDN network operating system targeted specifically at the Service Provider and mission critical networks. ONOS is purpose built to provide the high availability, scale-out and performance that these networks demand. In addition, ONOS has created useful northbound abstractions and APIs to enable easier application development and southbound abstractions and interfaces to allow the control of OpenFlow-ready and legacy devices.

ONOS has been developed in concert with leading service providers (AT&T, NTT Communications), with demanding network vendors (Ciena, Ericsson, Fujitsu, Huawei, Intel, NEC), R&E network operators (Internet2, CNIT, CREATE-NET), collaborators (SRI, Infoblox), and with ONF to validate its architecture through real world use cases.

The following are the defining features of ONOS:

- Distributed Core that provides scalability, high availability, and performance – bringing
- Carrier grade features to the SDN control plane.
- Northbound Abstraction/APIs that include network graph and application intents to ease development of control, management, and configuration services.
- Southbound Abstraction/APIs: enable pluggable protocols for controlling both OpenFLow and Legacy devices. The southbound abstraction insulates the core of ONOS from the details of different devices and protocols. The southbound is a key enabler for migration from legacy devices to OpenFlow-based white boxes.
- Software Modularity: makes it easy to develop, debug, maintain and upgrade ONOS by a community of developers and by the providers.

The following figure presents the ONOS architecture: the middle layer is the distributed core, on top of that is the NB core while the one below is SB core.

9.1.2.1 Distributed Core

ONOS is deployed as a service on a cluster of servers, and the same ONOS software runs on each server. Deployment symmetry is an important design consideration as it enables rapid failover in the event of an ONOS server failure. The network operator can add servers incrementally, without disruption, as needed for additional control plane capacity. The ONOS instances work together to create what appears to the rest of the network and applications as a single platform. Applications and network devices do not have to know if they are working with a single instance or with multiple instances of ONOS. This feature makes ONOS scalable i.e., the ONOS capacity can be scaled seamlessly. It is the Distributed Core that does the heavy lifting to realize these capabilities.

9.1.2.2 Northbound abstraction

There are two powerful northbound abstractions: Intent Framework and Global Network View.

The *Intent Framework* allows an application to request a service from the network without having to know details of how the service will be performed. This allows network operators as well as application developers to program the network at a high level. They can simply specify their intent: a policy statement or a connectivity requirement. The Intent Framework takes such requests from all applications, figures out which ones can and cannot be accommodated, resolves conflicts between applications, applies policies set by an administrator, programs the network to provide the requested functionality and delivers the requested services to the application.

The *Global Network View* provides the application with a view of the Network: the hosts, switches, links and any other state associated with the network such as utilization. An application can program this network view through APIs.

9.1.2.3 Southbound abstraction

ONOS and its SB abstraction allow plug-ins for various southbound protocols and devices, where a Plugin maps or translates generic network element description or operation on the device to the specific and vice-versa. Thus the southbound enables ONOS to control or manage multiple and diverse devices, even if they use different protocols (OpenFlow, NetConf, etc.).

As shown in Figure 29 at the bottom are the network devices or elements. ONOS interacts with devices through protocols. The protocol specifics are abstracted away by the network element plug-in or adapter. As a result, the core of the southbound can maintain its network element objects (devices, hosts and links) without having to know the specifics of the protocols and network elements. Through the adapter API, the distributed core is kept up to date on the status of the network element objects. The adapter API insulates the distributed core from having to know details about protocols and network elements (see Figure 30).

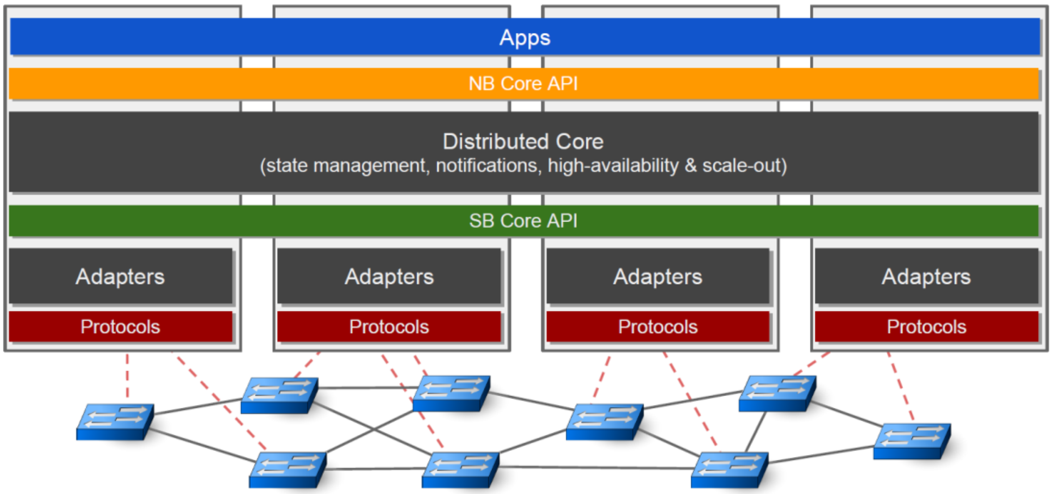

Figure 29: ONOS distributed architecture

The Figure 29 presents the ONOS subsystem from the latest release. A **service** is a unit of functionality that is comprised of multiple components creating a vertical slice through the tiers as a software stack. We refer to the collection of components making up the service as a **subsystem**.

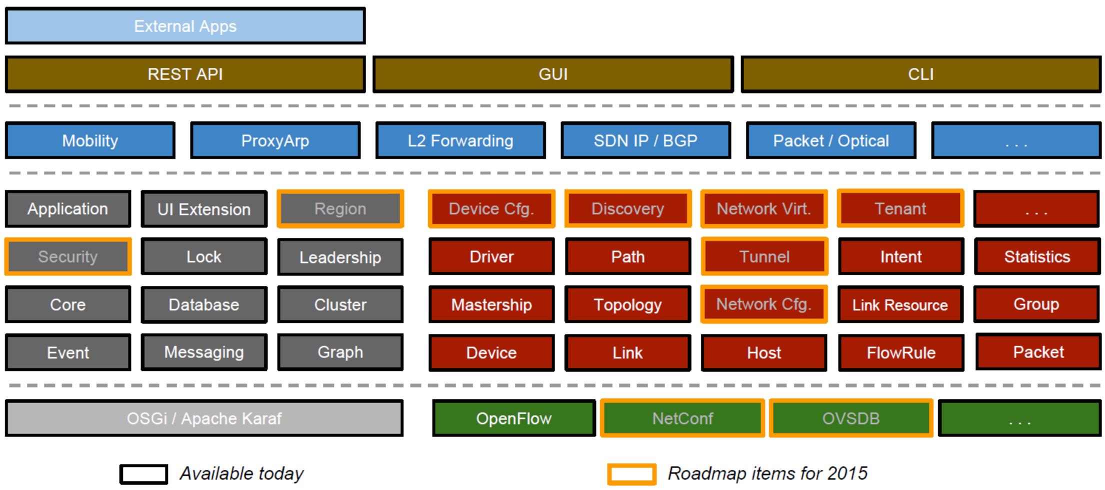

Figure 30: ONOS subsystems of latest release from 2015

ONOS defines a group of primary services (subsystems):

- *Device Subsystem* - Manages the inventory of infrastructure devices.
- *Link Subsystem* - Manages the inventory of infrastructure links.
- *Host Subsystem* - Manages the inventory of end-station hosts and their locations on the network.
- *Topology Subsystem* - Manages time-ordered snapshots of network graph views.

- *PathService* - Computes/finds paths between infrastructure devices or between end-station hosts using the most recent topology graph snapshot.
- *FlowRule Subsystem* - Manages inventory of the match/action flow rules installed on infrastructure devices and provides flow metrics.
- *Packet Subsystem* - Allows applications to listen for data packets received from network devices and to emit data packets out onto the network via one or more network devices.

9.2 Matching between XCI MANO components and open source projects

Several recent open-source initiatives are developing software solutions for the ETSI NFV architecture, addressing in particular the MANO (ETSI & GS, Network Functions Virtualisation (NFV): Management and Orchestration, 2014) components (see *Figure 31*).

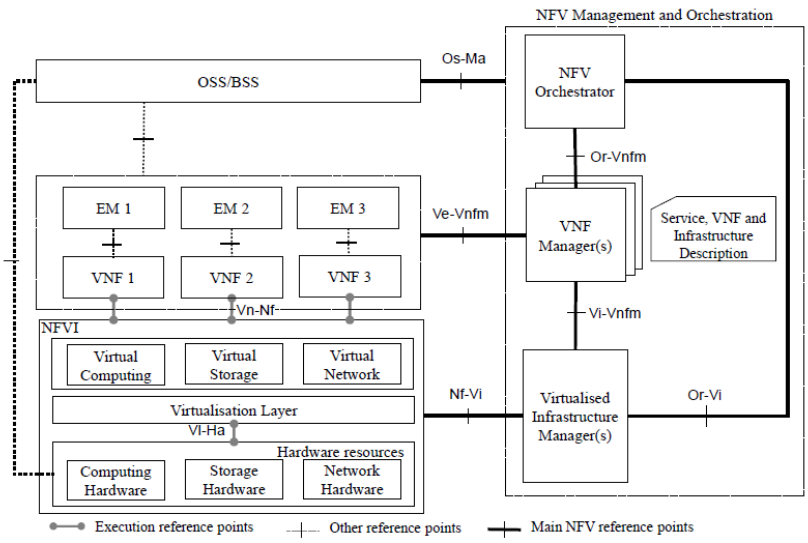

Figure 31: NFV Reference Architectural Framework (ETSI & GS, Network Functions Virtualisation (NFV): Architectural Framework, 2014)

This section provides a brief overview of these open-source projects, to provide the basis for the evaluation and selection of the reference platform to be adopted, deployedand (if needed) extended to the 5G-Crosshaul project.

The analysis is mostly focused on the architectural aspects. The objective is to identify the positioning of the tools in the whole NFV framework, the compliance with the current standards (even if, in large part, still under specification) and the flexibility of the solution. This is particularly important to support different infrastructures and virtualization technologies at the south-bound as well as several kinds of *Virtual*

Network Functions (VNFs) and *Network Services* (NSs) through extendable interfaces and the support of specialized VNF Managers.

An additional criterion considered in this analysis concerns the potential impact of the 5G-Crosshaul project in the NFV community, in relation to the adoption of a particular MANO solution. In this area we take into account the strength of the open-source community beyond each project, the involvement of key industrial partners and the adoption in other research or industrial projects.

9.2.1 OpenStack

OpenStack [8] is an open-source cloud computing software for public and private clouds, released under the Apache 2.0 license. It supports mainly the Infrastructure-as-a-Service cloud model, providing a modular software platform to control the whole set of a datacenter resources (computing, storage and networking resources). In the NFV architecture, the OpenStack core components can be mapped on the *Virtualized Infrastructure Manager* (VIM), while an additional project called Tacker (Tacker website) is building an *NFV Orchestrator* (NFVO) with a built-in general purpose VNF Manager.

OpenStack is a well established project that is very popular in the cloud community. It is used by several industrial companies[2] and constitutes the basis for OpenStack-powered products and cloud services or apps available from the OpenStack marketplace[3].

- OpenStack is based on a modular architecture with a set of core services to manage specific types of resources. In the 5G Crosshaul architecture, these OpenStack core services can be mapped over the controllers (i.e. the compute controller, the storage controller, the network controller). In order to implement a more flexible management of the network resources, OpenStack can operate in combination with an SDN controller (e.g., ODL, Ryu or ONOS) and it is able to operate over different devices through the Nova: responsible for the management of computing resources, it handles the lifecycle of the Virtual Machines (VMs), including their scheduling, provisioning and decommissioning in an on-demand manner.
- Cinder: responsible for the management of persistent block storage for running instances.
- Swift: it offers an object storage service, for storing and retrieving unstructured data objects, with features for fault tolerance, data replication and scalability.
- Glance: responsible for the storage of VM disk images.
- Neutron: implements networking services for other components, like Nova. Provides APIs to create networks and attach VMs, and it is based on a pluggable

[2] https://www.openstack.org/user-stories/
[3] https://www.openstack.org/marketplace/

architecture to support different underlying networking technologies and devices (including SDN controllers).

- Keystone: provides authentication and authorization mechanisms for all the other OpenStack services.

A simplified view of the architecture for the latest release of OpenStack (Liberty, October 2015) is reported in *Figure 32*. The OpenStack core services are the following:

Beyond these core services, a set of additional projects offer more enhanced features like orchestration of entire cloud stacks (Heat), monitoring and telemetry functions (Ceilometer), a web-based dashboard (Horizon), support for containers (Magnum) or bare-metal provisioning (Ironic) etc.

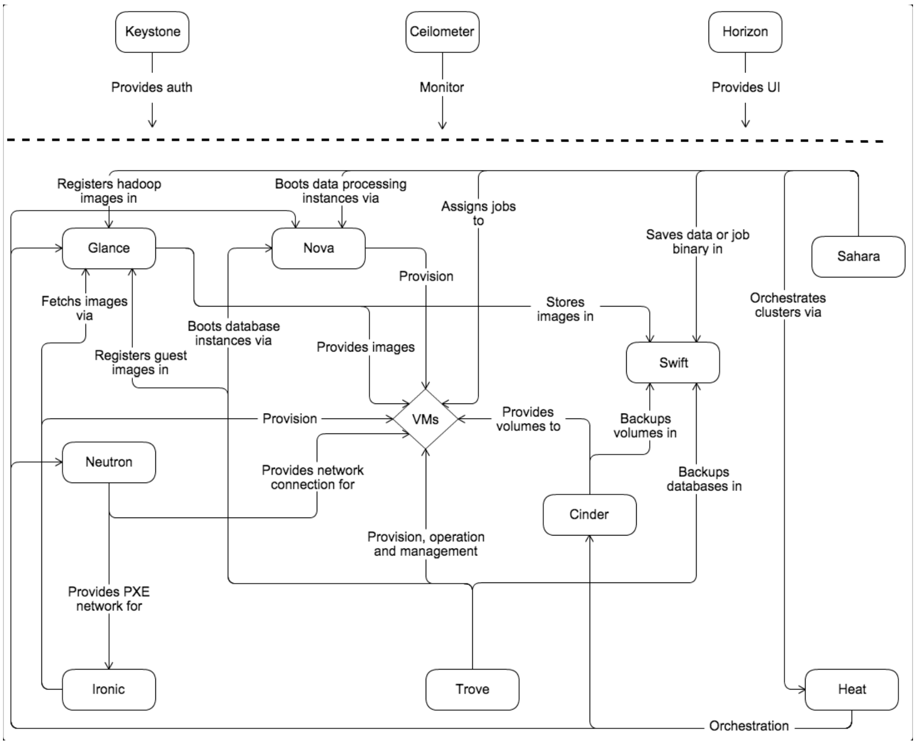

Figure 32: OpenStack Liberty components

The Tacker project, still in progress and not yet available in the official release, implements an NFVO with an integrated general purpose VNFM, operating over the other components of OpenStack used as VIM. The Tacker NFVO includes initial functions to provide an end-to-end orchestrated set of VNFs, interconnected through a SFC described in a *VNF Forwarding Graph* (VFNFFG) and possibly deployed across multiple VIMs. It also includes mechanisms for VIM resource check and allocation with VNF placement policies to guarantee an efficient positioning of the VFN over the available resources. At the generic VNFM level, it supports the basic VNF life-cycle (load descriptor, start, stop), its initial configuration and performance and health monitoring. The VNF catalogue uses descriptors compliant with the TOSCA NFV profile (Oasis, 2015).

9.2.2 OpenMANO

OpenMANO (OpenMANO) is an open source project, under the Apache 2.0 license, which provides an implementation of the ETSI MANO NFVO and VIM components, including also a web GUI to interact with the OpenMANO server. OpenMANO has still a small community, with Telefonica as main contributor.

OpenMANO architecture (see Figure 33) includes three main components, as follows:

- OpenVIM, which implements the NFV VIM component and interfaces with compute nodes to create and deploy VNFs and with an OpenFlow controller to configure the networking connections. The OpenVIM offers a CLI (Command Line Interface) and REST APIs for CRUD (Create, Read, Update, Delete) operations on VM instances, networks, disk images, etc. In the 5G Crosshaul architecture it can be mapped on the VIM features of the VIMaP application.
- OpenMANO, which implements the NFVO component. It interacts on its southbound side with the OpenVIM REST API to create virtual instances. On the other hand, it offers a CLI and REST APIs on its northbound side for CRUD operations on VNF and NS templates and instances.
- OpenMANO-gui, which provides the web-based GUI which allows the user to interact with the northbound REST APIs of the OpenMANO.

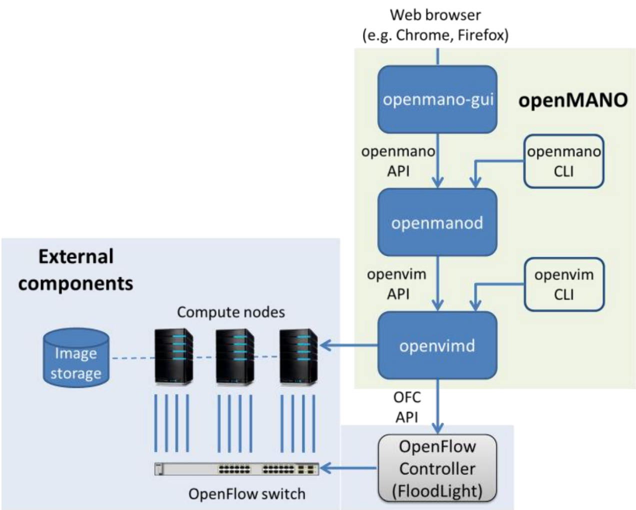

Figure 33: OpenMANO architecture

OpenMANO implements its own VIM (the openVIM) that indeed, in its latest stable version (v0.4), is also able to support OpenStack as VIM. In terms of OpenFlow controllers, both OpenDaylight and Floodlight are supported.

The VNF and NS descriptor templates follow a proprietary information model, expressed in YAML language. The information model includes a subset of the main concepts defined in the ETSI specification. For example, a VNF descriptor includes the list of the VNF components (VNFC), the internal and external connections, while additional parameters like flavors, monitoring parameters, scale-in/out policies are missing.

9.2.3 OpenBaton

OpenBaton (OpenBaton) is an open source project, led by Fraunhofer FOKUS and with the code available under the Apache 2.0 License, which implements an NFVO with an integrated, general-purpose VNFM.

OpenBaton is highly compliant with the ETSI NFV specification and it can be easily integrated in existing cloud environments and adapted to different kinds of VNFs and NSs. In particular, at VIM level, it natively supports the integration with (multi-site) OpenStack environments, but it also provides an SDK to implement VIM-specific drivers. On the VNF side, it implements a generic VNFM, but it can also interoperate with external VNF-specific VNFM via Json REST APIs or publish/subscribe mechanisms through a message queue. Finally, the interaction with the user is handled through REST APIs or a web-based dashboard.

OpenBaton architecture is based on two main components: the NFVO (see *Figure 34*) and the Generic VNFM (see *Figure 35*).

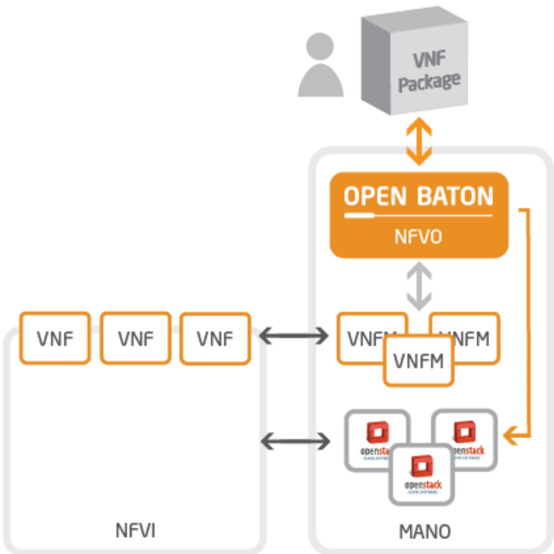

Figure 34: OpenBaton NFVO

The NFVO implements the main orchestrator features defined in the ETSI specification. In particular:

- It keeps an overview of the underlying multi-site infrastructure, offering mechanisms to dynamically register several NFV *Point of Presence* (PoP) VIMs (e.g., several OpenStack instances).
- It offers mechanisms for loading VNF packages (including VM images), VNF and NS descriptors (VNFD and NSD), maintaining the associated catalogues.

The VNFD and NSD templates are in JSON format and they are based on a detailed information model which includes most of the attributes defined in the ETSI MANO specification.

- It offers mechanisms for on-demand deployment of VNFs and NSs, based on the loaded descriptors, with the possibility to specify the VM placement and implement multi-tenancy, even though just in a limited scope.
- It implements basic resource reservation, depending on the capabilities offered by the underlying VIM. For example, when operating over OpenStack it makes use of the quota feature.

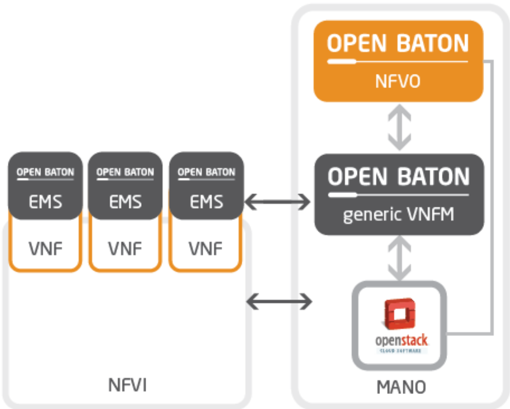

Figure 35: OpenBaton Generic VNFM

The Generic VNFM offers a basic support for the management of VNFs lifecycle and interacts with the NFVO or the VIM to request the instantiation, modification, starting and stopping of the virtual services where the VNFs are running. The interaction with a VNF is mediated through the generic OpenBaton EMS, a software module that runs on the VNF itself and enables a communication based on message queues. This interaction is mainly used for VNF configuration purposes or to trigger the execution of scripts on the VNF side.

9.2.4 OPNFV

OPNFV (OpNFV) is an open source project by Linux Foundation, announced in 2014, with the objective of providing a carrier-grade, integrated platform to accelerate the introduction of new NFV products and services. Therefore, OPNFV is a platform created as a community-led and industry-supported open source framework, that integrates both SDN and NFV to deliver a de facto standard open source NFV platform for the industry.

The main goals of OPNFV are:

- Provide consistency and interoperability between NFV capabilities.
- Define an environment for NFV with open standards and open source software.
- Contribute in open source project that will operate within OPNFV.

- Increase performance and power efficiency.
- Deliver comprehensive platform instrumentation to improve reliability, availability and serviceability.

The scope of OPNFV's initial release is focused on building NFV Infrastructure (NFVI) and Virtualized Infrastructure Management (VIM), by integrating components from upstream projects such as ODL, OpenStack, Ceph Storage, KVM, Open vSwitch and Linux. These elements, along with the APIs to other NFV elements, provide the basic infrastructure required for the NFVI and for the MANO support.

Technically OPNFV looks to realize the ETSI NFV architectural framework by bringing together upstream software components to implement an end-to-end platform for NFV. Therefore, activities within the project focus on integration of components and automated build and deployment of the integrated environment, where testing the platform for key NFV use cases is the way to meet NFV industry needs.

Arno, released in January 2015, is the first developer-focused release of the OPNFV project. It provides an initial build of the NFV Infrastructure (NFVI) and Virtual Infrastructure Manager (VIM) components of the ETSI NFV architecture (see *Figure 36*).

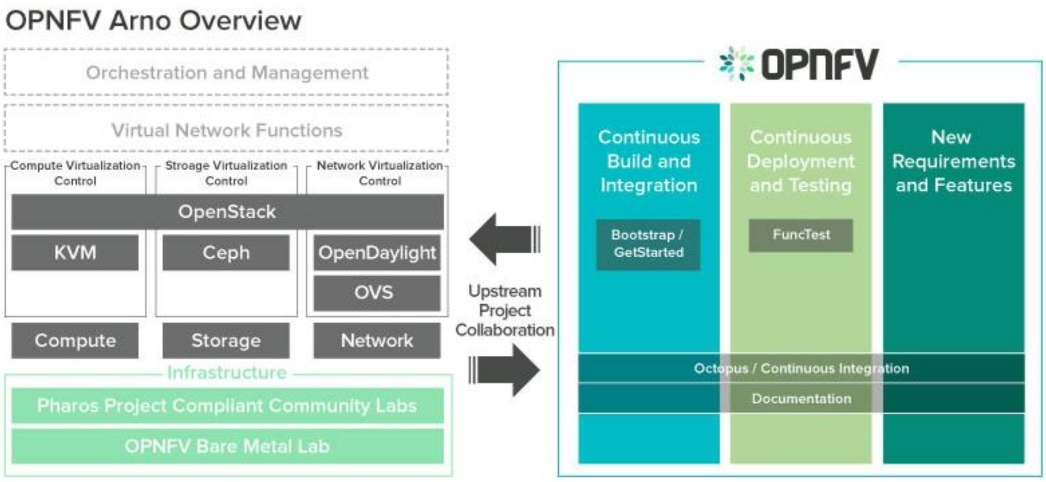

Figure 36: OPNFV Arno release

In particular, OpenStack Juno is used as the main VIM component. The request for NFVI management and CRUD operations of the stacks for VNF or NS deployment can be performed through the OpenStack interfaces, for example by using the REST APIs provided by the Heat component. In order to perform actions on the networking elements of the stack, the Arno release uses OpenDaylight Helium. ODL interfaces are available for checking topology and interacting with the SDN controller.

The main functionalities supported by OPNFV are related to the management of VNFs and NFVI resources. In particular, the following features are supported:

- Life-cycle management of VNFs, including deployment, instantiation, configuration, start and stop, upgrade/downgrade and final decommissioning.
- Specification and interconnection of VNFs, VNFCs and PNFs, following an approach which is agnostic to the underlying physical network infrastructure.
- Mechanisms for dynamic instantiation and decommission of VNF instances to meet performance, scaling and network bandwidth requirements.
- Mechanisms for fault detection and recovery at the NFVI or VIM level.
- Mechanisms for traffic steering among physical network functions and virtual network functions.

The Pharos Community Labs project (Pharos) provides a federated NFV test lab, geographically distributed and including different technologies. It allows the deployment and testing of OPNFV instances in different physical environments, over diverse labs and a wide range of hardware from different vendors.

9.2.5 NFV tools comparison

The following table summarizes the main features of the NFV tools analyzed in the previous sections.

Table 14: Survey of NFV tools

	OpenStack	**OpenMANO**	**OpenBaton**	**OPNFV**
Web-site	https://www.openstack.org/	https://github.com/nfvlabs/openmano	http://openbaton.github.io/	https://www.opnfv.org/
Software code	https://github.com/openstack	https://github.com/nfvlabs/openmano	https://github.com/openbaton	Sw code of single integrated projects
Latest release	Liberty, October 2015	V0.4, December 2015		Arno, January 2015
License	Apache 2.0	Apache 2.0	Apache 2.0	Depends on the licenses of the integrated projects. For new components Apache 2.0
Core Language	Python	Python	Java (Spring IO)	Depends on the integrated projects
Docs	http://docs.openstack.org/	https://github.com/nfvlabs/openmano/wiki/Getting-started	http://openbaton.github.io/documentation/#	https://wiki.opnfv.org/
VIM module	Yes	Yes	No. Provides a driver for OpenStack and an SDK to implement other VIM drivers	Yes
VNFM module	General purpose VNFM Integrated in Tacker project	No	Generic VNFM. SDK to develop Proprietary VNFM	No
NFVO module	Yes, Tacker project	Yes	Yes	No
NFVO NBI	Tacker REST API	REST API, CLI, web GUI	REST API, web GUI, SDK for integration in other apps	N.A.
VNF	Tosca NFV	Proprietary	JSON	OpenStack Heat template

Descriptor	profile schema			
NS Descriptor	Tosca NFV profile schema	Proprietary	JSON	OpenStack Heat template
Or-Vnfm interface	Internal	N.A.	REST API or message queue based	N.A.
Ve-Vnfm-em interface	N.A.	N.A.	Message queue based	N.A.
Ve-Vnfm-vnf interface	N.A.	N.A.	Message queue based	N.A.
Vi-vnfm interface	OpenStack REST APIs	REST API	OpenStack REST API	N.A.
Support for external VIMs	--	OpenStack support	OpenStack support. SDK to implement other VIM drivers	--
Support for proprietary VNFMs	--	--	Yes, REST API (for external VNFMs) or SDK (for proprietary VNFMs)	--

10 Annex II – Functional and non-functional requirements analysis

10.1 Functional requirements

The following functional requirements have been considered for 5G-Crosshaul.

Table 15: FT-01 – Infrastructure virtualization

<table>
<tr><th colspan="2">FT-01 – Infrastructure virtualization</th></tr>
<tr><td>Impact on data plane</td><td>Choice of physical technologies able to support virtualization.</td></tr>
<tr><td>Impact on control plane</td><td>Abstraction and virtualization of physical network resources:
Abstraction of the physical network nodes through uniform information models describing "logical" network resources (e.g., nodes, ports, links, etc.).
Virtualization of physical network resources through aggregation or splitting mechanisms (depending on the specific technology) in isolated virtual resources.
NB APIs to provide access to single virtual resources.
Server virtualization for the processing element, mostly based on the features already available in existing cloud platforms.
Capability to control the deployment of virtual storage and VMs, together with their network interconnectivity, characterized by bandwidth constraints.
Capability to coordinate the SDN-based network virtualization with NFV functionalities.</td></tr>
<tr><td>Impact on application plane</td><td>Application for composition and organization of elementary virtual resources created and exposed by the XCI in multiple isolated virtual infrastructures.
Application to create virtual infrastructures for each tenant, with the following features:
Multi-tenancy isolation.
Dynamic instantiation of VMs, according to traffic demands.
Selection of network resources to transport traffic to/from dense RANs.
Capability to orchestrate the virtualized services or applications running on the virtual infrastructures.</td></tr>
<tr><td>KPIs</td><td>Isolation of Virtual Infrastructures
Usage of the physical infrastructure
Time required to establish a virtual infrastructure</td></tr>
</table>

Table 16: FT-02 – Dynamic (re-)allocation of virtual resources to physical resources

<table>
<tr><th colspan="2">FT-02 – Dynamic (re-)allocation of virtual resources to physical resources</th></tr>
<tr><td>Impact on data plane</td><td>None</td></tr>
<tr><td>Impact on control plane</td><td>Virtual network resources can be dynamically re-allocated, triggered by and/or depending on:
Explicit requests from the multi-tenancy application.
Modification of the capabilities of the physical resources.
Changes in the status of the data plane (the failure of a physical port may trigger the re-mapping of the virtual port previously associated to the failed one to another, available, physical port).
On the computing side, the system should support dynamic VM migration, coordinated with mechanisms for SFC re-composition, changes in the traffic steering</td></tr>
</table>

	and in the bandwidth of the VMs interconnectivity (coordination between SDN and NFV functionalities).
Impact on application plane	Application for multi-tenancy virtual infrastructures: • Capability to take decisions about dynamic re-mapping of virtual network resources to physical links and nodes, e.g., as consequence of mobility. • Capability to take decisions about VMs and specific VNFs instantiation and migration depending on traffic demands. Application for the coordinated execution of the decisions about resource re-allocation.
KPIs	Time required to take decisions about resource re-allocation. Time required to execute the re-allocation of the virtual resources (at the network level, at the VM level, at the whole service level).

Table 17: FT-03 – Mapping of virtual to physical resource synchronization

FT-03 – Mapping of virtual to physical resource synchronization	
Impact on data plane	None
Impact on control plane	Changes in the status of the physical resources must be reflected in suitable events at the level of the corresponding virtual resources, triggering suitable notifications at the NBI.
Impact on application plane	None
KPIs	Time of propagation from the detection of an event related to a physical resource to the notification of the associated event as related to the corresponding virtual resource(s).

Table 18: FT-04 – Resource discovery

FT-04 – Resource discovery	
Impact on data plane	Capability of data plane network nodes to advertise their characteristics, capabilities and management configuration towards the XCI, possibly through the mediation of technology-specific agents.
Impact on control plane	The XCI has to be aware of all the network elements and all the XPUs available in the 5G-Crosshaul physical infrastructure, including information about their capabilities, status and configuration, physical interconnection and availability of their resources (e.g., bandwidth). This knowledge must be acquired from the data plane through suitable advertising procedures at the XCI southbound interface. New physical resources added at runtime in the physical infrastructure must be discovered as well following similar procedures. The XCI must be able to build the topology of the whole physical infrastructure starting from the information collected from the data plane and to expose the relevant data to the upper-layer SDN applications through the northbound interface.
Impact on application plane	Most of the upper-layer SDN applications (e.g., multitenant application, mobility management application) need to collect information about the network topology and the (abstract) capabilities of the physical infrastructure from the XCI northbound interface. Moreover, some applications need to receive notifications about new physical resources as input to elaborate and trigger new resource optimization actions.
KPIs	Time required to discover a new network device or a new XPU at the XCI. Time required to update the network topology at the XCI as a consequence of an additional network element. Time required to notify a new network device or a new XPU at the application layer.

Table 19: FT-05 – On-demand adaptation

FT-05 – On-demand adaptation	
Impact on data plane	Support for Class of Services and traffic marking.
Impact on control plane	The XCI must be able to support the reconfiguration of the network and IT resource allocation to ensure enough capacity to serve the required traffic with a given QoS. In particular, on the network side, the virtual resources (e.g., virtual nodes, virtual links) or network services (e.g., network connections) exposed at the northbound interface must be able to scale up and down on-demand, in compliance with the capabilities of the underlying physical resources (e.g., modifying the capacity of virtual links or network connections, the number of virtual ports on a virtual node, etc.) On the XPU side, the XCI must support mechanisms for VMs upscaling and downscaling, optionally triggering VM migration, on demand or automatically triggered by threshold-based events on measurable metrics. Upscaling and downscaling in network and computing domains must be properly coordinated.
Impact on application plane	In order to exploit on-demand adaptation capabilities, the applications must be able to receive notifications about changes in network and traffic demands which would require automated reactions. This kind of information at the 5G-Crosshaul infrastructure domain should be provided by the XCI. However, traffic conditions in external network domains (e.g. the RAN) should be also taken into account. In this case, the applications should be able to support interactions towards the RAN controller in order to receive information about traffic demands in the RAN and adapt the 5G-Crosshaul network configuration accordingly. Examples of triggers for adaptation decisions at the application layer

	should include interference issues, movement of mobile users, changes in traffic demands or physical infrastructure capabilities. Adaptation decisions may involve both network and computing resources (e.g., scaling in and out VMs or network connections) and should be regulated through the adoption of policies and constraints associated to the specific service.
KPIs	Time required to enforce an adaption action. Usage of resources before and after adaptation action.

Table 20: FT-06 – Monitoring and accounting

FT-06 – Monitoring and accounting	
Impact on data plane	Capability to provide monitoring information about physical resources (i.e. network nodes and servers), e.g., in terms of usage, performance and operational status. Support of different counters, logs and alarms.
Impact on control plane	The XCI must be able to collect, organize, store and elaborate monitoring information received from network elements and XPUs about status and performance of physical and virtual resources as well as QoS metrics (throughput, delay, loss, etc.). The XCI should be able to receive asynchronous event notifications from the data plane (e.g., to notify a failure or a change in the status of a physical resource). Monitoring information and notification events should be properly exposed through the NBI towards the application (e.g., to detect congestion or enable accounting procedures).
Impact on application plane	5G-Crosshaul application should be able to elaborate the basic monitoring information provided by the XCI in support of: • accounting functions • metering functions • monitoring of service requests and (virtual) network infrastructure(s) as base to take decisions about optimal delivery, network and SFCs' reconfiguration, energy management, SLA verification.
KPIs	Type of monitoring information collected at the different architectural layers.

Table 21: FT-07 – Physical requirements – Latency

FT-07 – Physical requirements - Latency	
Impact on data plane	The 5G-Crosshaul data plane must guarantee a maximum latency which depends on the QoS/QoE required by the services and applications of the different use cases.
Impact on control plane	The existence of the XCI controller must not degrade the final service due to additional overhead
Impact on application plane	The applications should consider the latency as one of the constraints in the creation of virtual infrastructures, in mobility management and in SLA verification.
KPIs	Maximum latency

Table 22: FT-08 – Physical requirements - Jitter

FT-08 – Physical requirements - Jitter	
Impact on data plane	The 5G-Crosshaul data plane must guarantee a maximum jitter which depends on the QoS/QoE required by the services and applications of the different use cases. 5G-Crosshaul data plane technologies may mitigate jitter issues through proper device buffers.
Impact on control plane	None.
Impact on application plane	The applications should consider the jitter as one of the constraints in the creation of virtual infrastructures and in SLA verification.

KPIs	Maximum jitter

Table 23: FT-09 – Physical requirements - Data Rate

FT-09 – Physical requirements - Data Rate	
Impact on data plane	The 5G-Crosshaul data plane must guarantee high data rates which depend on the QoS/QoE required by the services and applications of the different use cases.
Impact on control plane	Depending on the technologies, the XCI may be required to create queues or meters (e.g., on the OVS instances running in the servers) with a given rate.
Impact on application plane	The applications should consider the data rate as one of the constraints in the creation of virtual infrastructures and in SLA verification.
KPIs	Minimum guaranteed data rate

Table 24: FT-10 – Physical requirements - Packet Loss

FT-10 – Physical requirements - Packet Loss	
Impact on data plane	The data plane network nodes must be able to provide counters about packet loss through the XCI southbound interface.
Impact on control plane	The XCI must be able to receive and store information about the packet loss in the data plane network nodes.
Impact on application plane	The applications should consider the packet loss as one of the constraints in the creation of virtual infrastructures and in SLA verification.
KPIs	Maximum packet loss

Table 25: FT-11 – Clock synchronization

FT-11 – Clock synchronization	
Impact on data plane	The XFE should incorporate the ability to transport and/or regenerating clock signal in a precise way in order to have full synchronization in terms of time, frequency and phase.
Impact on control plane	The XCI must ensure prioritized delivery of clock signal across 5G-Crosshaul.
Impact on application plane	Some applications can be constrained by a lack of accuracy on the clock signal across the radio access (e.g., broadcast transmission in radio part).
KPIs	Clock accuracy across 5G-Crosshaul

Table 26: FT-12 – Density of connections

FT-12 – Density of connections	
Impact on data plane	Traffic isolation among the different users and support of multiple flows in a scalable way. Proper allocation of resources in XFEs to guarantee minimal QoS. Scalability in terms of number of forwarding rules supported by device.
Impact on control plane	Scalability in terms of number of simultaneous users being served in an area.
Impact on application plane	Scalability in terms of number of simultaneous users being served in an area.
KPIs	Maximum number of simultaneous flows that can be handled within 5G-Crosshaul

Table 27: FT-13 – Mobility

FT-13 – Mobility	
Impact on data plane	Fast adaptation of new paths including allocation of resources for flows. Capacity for reconfiguring the different virtual elements serving the users to the new location,

	e.g., reallocation of caches or rerouting to the most appropriate interconnection point to the internet
Impact on control plane	The XCI should dynamically populate convenient forwarding rules to different XFEs in 5G-Crosshaul accompanying the movement of the mobile users.
Impact on application plane	Mobility management can be required in some applications to maintain the service delivery while the users move.
KPIs	Time required to change a path in the network. Time required to reallocate services to the appropriate locations depending on new point of attachment of the user.

Table 28: FT-14 – Transferred Data Replication

FT-14 – Transferred Data Replication	
Impact on data plane	The XFE requires the ability of replicating the same input data on several output ports minimizing delay and jitter.
Impact on control plane	The XCI should keep state of the output ports requiring replication. In addition to that, XCI is responsible of building and maintaining the distribution trees across 5G-Crosshaul.
Impact on application plane	The application should be able to provide the proper format to the content data to be replicated. Membership management and subscription rights should be considered for an appropriate service delivery.
KPIs	Time to recover from failure thanks to replication paths.

Table 29: FT-15 – Energy efficiency

FT-15 – Energy efficiency	
Impact on data plane	Energy efficiency requires capacity to dynamically decommission parts of the network that are not used or to establish which used capacity can be reallocated to other parts of the network.
Impact on control plane	Control plane must support the dynamic switch -on and -off of elements, including not only network resources but also computing resources. Control plane must provide the required algorithms to detect optimization opportunities and the control interfaces for turning on and off elements of 5G-Crosshaul.
Impact on application plane	The Energy Efficient requirement can only be achieved by designing a smart application able to handle the above mentioned complexity. This application requires an overall and global view of the 5G-Crosshaul system.
KPIs	Energy savings compared between the peak and low hour.

Table 30: FT-16 – Combined network and computing resource provisioning

FT-16 – Combined network and computing resource provisioning	
Impact on data plane	Capacity of the data path must be configured according to the computing resources allocated. Reconfiguration of data path must be provided to accommodate changes in the allocation of computing resources such as the reallocation of virtual functions to different XPUs.
Impact on control plane	The Control Plane must be able to consider network and computing resources as a global optimization problem. The Control Plane must be able to reallocate computing resources to the places where more network capacity is available, while reducing the load in overloaded paths.
Impact on application plane	The intelligence of such optimization must reside on the application plane, providing smart applications able to carry this task. In addition, applications may be moved to the better place according to the network

	and computing resources available.
KPIs	Ratio between the average load achieved in the overall XPU systems and the average available network capacity.

Table 31: FT-17 – Management

FT-17 – Management	
Impact on data plane	All the 5G-Crosshaul data path elements must support a common SDN-like API for management.
Impact on control plane	The Control Plane elements should support a common SDN-like API for management, including computing, orchestration and MEC resources. Management plane must be distributed among the XCI.
Impact on application plane	Collection of notifications from the 5G-Crosshaul management capabilities. The applications should consider such notifications as one of the triggers for internal application events.
KPIs	None identified.

Table 32: FT-18 – Security

FT-18 – Security	
Impact on data plane	Data path elements must be authenticated. XFE's controller must be authenticated. Privileged administrative access must be granted with strong authentication. Traffic belonging to different tenants must be isolated and provided with privacy.
Impact on control plane	Multi-tenant control plane must be authenticated and provide private operations. Tenant operations require non-repudiation characteristics. Authentication, authorization and accounting required per tenant. All XCI operations must be authenticated and authorized.
Impact on application plane	Application must be provided with certificates of authenticity, so the XCI is able to validate their origin. All application operation must be authorized and authenticated, storing a record of operation for traceability.
KPIs	Security analysis.

Table 33: FT-19 – Backward compatibility

FT-19 – Backward compatibility	
Impact on data plane	The data plane must be able to interoperate through well-defined SAPs with legacy networks for the interconnection between 5G-Crosshaul and private operator aggregation networks. Adaptation layers between the XCF (5G-Crosshaul Common Frame) and the standard frame used in legacy networks must be provided.
Impact on control plane	The Control Plane must be able to communicate the needed information for interconnection and control the points of exchange with the legacy network.
Impact on application plane	None identified.
KPIs	None identified.

Table 34: FT-20 – SLA mapping

FT-20 – SLA mapping	
Impact on data plane	Distinction of flows already at the edge subject to SLA conforming.Queues and forwarding mechanism in XFE to support SLAs parameters. QoS support in the newly defined XCF (5G-Crosshaul Common Frame).
Impact on	The XCI must be able to transform SLAs parameters into policies and the capability

control plane	to apply and guarantee these policies. Configuration of the network to fulfill SLAs per tenant.
Impact on application plane	Application behavior must be conformant to the overall policies defined in the SLAs.
KPIs	QoS metrics and the evaluation of SLAs level of satisfaction.

10.2 Non-functional requirements

The following non-functional requirements have been considered for 5G-Crosshaul.

Table 35: NF-01 – Programmability

NF-01 – Programmability	
Impact on data plane	Dynamic programmability of unicast and multicast and differentiation in terms of QoS and buffering. Application of forwarding rules populated from central control elements external to the device. Fast adaptation to the status and property changes instructed from the controller.
Impact on control plane	Dynamic configuration of network resources to provide capacity for delivery such demand. Algorithms and logic for computing 5G-Crosshaul-wide rules. Population of computed rules to the 5G-Crosshaul elements.
Impact on application plane	For mobility, the handover trigger condition can be dynamically configured and provisioned automatically. Mandatory for energy management and resource management. Possibility to choose their (virtual) topology and have complete addressing space available. Dynamic instantiation of computing points according to traffic demand.
KPIs	Number of classes managed by QoS mechanism. Energy /resource management.

Table 36: NF-02 – Scalability

NF-02 – Scalability	
Impact on data plane	Very high number of flows. Scalability in indoor behavior. Different flows of the same content with different coding.
Impact on control plane	Capacity for controlling as many physical/virtual elements as possible. Methods to reduce the overhead by blade-to-blade or DC to DC communication. The virtual resources should expose some level of programmability (depending on their capabilities) to the associated tenant, via NBI. Dynamic instantiation of computing points according to traffic demand and dynamic configuration of network resources to provide capacity for delivery such demand. Capacity for controlling as many network elements as possible.
Impact on application plane	Capability to trigger changes in the virtual infrastructure to cope with increasing service requests. Low overhead and fine granularity in slicing of resources. Updating optimization results due to new network elements. End point re-distribution in the network. Change from unicast to multicast/broadcast (if supported).
KPIs	Number of supported flows. Multi/broadcast functionality.

Table 37: NF-03 – Usability

NF-03 – Usability	
Impact on data plane	Not applicable.
Impact on control plane	APIs for service invocation. Control VM lifecycle.
Impact on application plane	End point re-distribution in the network. Change from unicast to multicast/broadcast (if supported). User interfaces for resources request in order to create tenant. APIs for service invocation.
KPIs	Multi/broadcast functionality.

Table 38: NF-04 – Consistency

NF-04 – Consistency	
Impact on data plane	Different flows of the same content with different coding.
Impact on control plane	Control proper VM implementation together with their network connectivity. NBI interfaces for creation and manipulation of virtual resources should follow common information models and operate in CRUD mode (as for other services exposed by the SDN controller). Video quality adaptation. Change from unicast to multicast/broadcast transmission (if supported).
Impact on application plane	Request for dynamic instantiation of VMs according to service demand. Similar experience to fixed and mobile users. Multi-screen.
KPIs	Different coding compatibility.

Table 39: NF-05 – Robustness or resilience

NF-05 – Robustness or resilience	
Impact on data plane	The XFEs should provide robust mechanisms to prevent system failures (e.g., Non-Stop Routing, alarm/event generation, etc).
Impact on control plane	The SDN controller should include mechanisms for persistency (but nothing strictly related to multi-tenancy). The NBI must allow the app to abort requests for creation of virtual resources. Control available resources to ensure QoS. Automated reactions in case of VMs failures, at both network and IT level.
Impact on application plane	Dynamic instantiation of computing points and broadcast/multicast distribution tree re-configuration. Important to maintain Latency and Packet Loss requirements. Applications may need to reconfigure resources allocation when 5G-CROSSHAUL components fail. Fault tolerance mechanisms.
KPIs	Mean availability. Max Mean Time To Repair (MTTR).

Table 40: NF-06 – Responsiveness

NF-06 – Responsiveness	
Impact on data plane	Reaction capacity facing changes in the network, for example sending event notifications when applicable.
Impact on control plane	The XCI has to manage the events triggered by the data plane and the requests from the applications. Requests for changing the BW, QoS, etc. should be received from the applications

	and network reconfiguration should be handled automatically.
Impact on application plane	5G-Crosshaul applications will react according to network events or requests from the users or services. Possible dynamic (re)deployment of VMs according to user´s mobility, network status, computing elements status, policies and service requirements and handovers or massive requests will be managed.
KPIs	Response time, i.e. time of response from the detection of an event related to the network to the reaction facing this event.

Table 41: NF-07 – Availability

NF-07 – Availability	
Impact on data plane	Pre-computed forwarding rules used in case of losing the communication with the controller.
Impact on control plane	Support for High Availability (HA) deployment models. Monitor the network status and automatically provide new paths in case of link losses inside the requested QoS and control of bandwidth and computing resources to provide VMs serving as distribution end-points.
Impact on application plane	5G-Crosshaul applications have to manage mechanisms in order to avoid the downtime in the network and implement alternatives in case of failure. It will be mandatory for network slices to provide stable services. Also the admission control to be required to admit new services or new users based on the available resources.
KPIs	Service availability. Availability of services relative to the availability agreed in SLAs. Network availability. Availability of network infrastructure.

Table 42: NF-08 – Planning, Design and Development

NF-08 – Planning, Design and Development	
Impact on data plane	Differentiation of QoS and buffering.
Impact on control plane	Application of distribution schemas on application demand.
Impact on application plane	Decisions of optimal distribution schemas based on context information, user distribution and traffic statistics. These schemas are sent to the controller for execution purposes.
KPIs	None in particular (application dependent)

Table 43: NF-09 – Isolation

NF-09 – Isolation	
Impact on data plane	The data plane should implement mechanisms facilitating the separation of traffic (e.g., vlans).
Impact on control plane	Isolation of virtual resources, per-tenant access to virtual resources and isolating applications as much as possible. Isolation between Virtual Machines. Isolation of network resources inside one network element.
Impact on application plane	The application must support multi-tenancy.
KPIs	None.

Table 44: NF-10 – Resource efficiency

NF-10 – Resource efficiency	
Impact on data	Minimize overhead.

plane	Tradeoff between dimensioning due to peaks of bandwidth requests and efficiency to handle the demand of non-busy hours.
Impact on control plane	Distribution schema taking into account the different applications and different users distribution. The NBI must expose enough information about physical resources to enable the multi-tenancy app to run the dedicated algorithms responsible to take efficient decisions about resource utilization (i.e. optimal sharing of the physical infrastructure among multiple virtual network slices).
Impact on application plane	Optimal use of 5G-Crosshaul resources based on distribution schemas managed in a dynamic way.
KPIs	Consumed resources / assigned resources. Overhead in data plane.

Table 45: NF-11 – Convergence

NF-11 – Convergence	
Impact on data plane	Simultaneous delivery of different applications traffic (e.g., simultaneous delivery of multicast/broadcast and unicast traffic towards access points).
Impact on control plane	The XCI must regulate the access of applications to the different underlying physical resources. Handle different network segments across 5G-Crosshaul. Support of fixed and mobile customers (and stationary customers on mobile environments, e.g., high-speed train).
Impact on application plane	None
KPIs	None

11 Annex III – Requirements analysis for selected use cases

This annex reports the complete analysis of the requirements referring to each of the identified use cases. In particular, the impact on WP2 (data plane), WP3 (control plane) and WP4 (application plane).

11.1 UC1 – Vehicle mobility

Req. id	Req. Statement	Impact on WP2	Impact on WP3	Impact on WP4
FT-01	Infrastructure Virtualization	Not identified	Abstraction of physical resources	Multi-tenancy application: create virtual infrastructure for each tenant
FT-02	Dynamic (re-)allocation of virtual resources to physical ones	Not identified	Triggered by multi-tenancy application request or the changes in physical resource, such as due to mobility	Multi-tenancy application: dynamic (re-)mapping of virtual infrastructure to physical links and nodes, especially when the train is moving and the connecting BSs keep changing
FT-03	Mapping of virtual to physical resource synchronization	Not identified	Not identified	Not identified
FT-04	Resource discovery	Not identified	Discover new physical resources and expose them via the NBI to the related applications	Multi-tenancy application: needs topology information Mobility management application: needs topology information
FT-05	On-demand adaptation	Not identified	Network (re-) configuration	Multi-tenancy application: trigger re-optimization when network and demand change. Mobility management application: when handover happens, offload the original traffic of the target BS to other appropriate BSs for load balancing
FT-06	Monitoring and accounting	Provide physical information	Metering and accounting of physical resources (computing and network resources) and QoS metrics (throughput, delay, loss, etc.).	Multi-tenancy application: Metering and accounting of virtual resources and QoS metrics (throughput, delay, loss, etc.)

FT-07	Physical requirements - Latency	Not identified	Not identified	Multi-tenancy application: to accommodate requirement from (virtual) operator Mobility management application: to accommodate requirement from (virtual) operator
FT-08	Physical requirements - Jitter	Not identified	Not identified	Multi-tenancy application: to accommodate requirement from virtual operator
FT-09	Physical requirements - Data Rate	Not identified	Not identified	Multi-tenancy application: to accommodate requirement from virtual operator
FT-10	Physical requirements - Packet Loss	Not identified	Not identified	Multi-tenancy application: to accommodate requirement from virtual operator
FT-11	Clock synchronization	Not identified	Not identified	Not identified
FT-12	Density of connections	Not identified	Not identified	Not identified
FT-13	Mobility	Not identified	Provide relevant context information to mobility management application and execute the network reconfiguration issued by mobility management application	Mobility management application: support context-aware handover optimization by defining input (train speed, train direction, train location, BS loading, etc.) and output (target BS, handover initiation time, data forwarding path, etc.)
FT-14	Transferred Data Replication	Not identified	Not identified	Mobility management application: during handover, replicate the data for the source BS at the target BS
FT-15	Energy Efficiency	Nodes can be switched on/off remotely	Disable remote antenna unit (RAU) transmission when high speed train is not in the coverage	Not identified

FT-16	Combined network and computing resource provisioning	Not identified	Not identified	Not identified
FT-17	Management	Not identified	Not identified	Not identified
FT-18	Security	Not identified	Not identified	Multi-tenancy application: authentication, authorization, and accounting (AAA) functionality are required for each tenant
FT-19	Backward compatibility	Not identified	Not identified	Not identified
FT-20	SLAs mapping	Not identified	Not identified	Not identified
NF-01	Programmability	Not identified	Not identified	Mobility management application: the handover trigger condition can be dynamically configured and provisioned automatically
NF-02	Scalability	Not identified	Not identified	Multi-tenancy application: low overhead and fine granularity in slicing of resources to introduce new tenants
NF-03	Usability	Not identified	Not identified	Not identified
NF-04	Consistency	Not identified	Not identified	Not identified
NF-05	Robustness or resilience	Not identified	Not identified	Not identified
NF-06	Responsiveness	Not identified	Not identified	Mobility management application: handover can be triggered by pre-defined condition of the input.
NF-07	Availability	Not identified	Not identified	Mobility management application: handover initiation control and BS load balancing is required to avoid radio link failure and blocked

				handover
NF-08	Planning, Design and Development	Not identified	Not identified	Mobility management application: Context information is stored as data repo for access and query to assist handover operation
NF-09	Isolation	Not identified	Isolation of virtual resource access per tenant	Isolation between tenants
NF-10	Resource efficiency	Not identified	Optimal physical resource sharing by multiple tenants	Optimal use of XHAUL resources
NF-11	Convergence		Not identified	Not identified

11.2 UC2 - Media distribution: CDN and Broadcast

Req. id	Req. Statement	Impact on WP2	Impact on WP3	Impact on WP4
FT-01	Infrastructure Virtualization	Not identified	Control of computing resources to provide VMs to serve as distribution end-points	Dynamic instantiation of CDN end points according to traffic demand
FT-02	Dynamic (re-)allocation of virtual resources to physical ones	Not identified	Control of computing resources to provide VMs to serve as distribution end-points. VM migration.	Dynamic instantiation of CDN end points according to traffic demand
FT-03	Mapping of virtual to physical	Not identified	Not identified	Not identified

	resource synchronization			
FT-04	Resource discovery	Not identified	Availability of computing resources and computing facilities. The controller has to be aware of all network elements	Not identified.
FT-05	On-demand adaptation	Traffic marking	Control of network resources to ensure enough capacity	Scale-in and -out of computing resources for serving CDN end-points Policies and constraints according to requested content.
FT-06	Monitoring and accounting	Not identified	Usage of computing resources for accounting. Usage of network resources to detect congestion. Control and manage the information received from network elements	Monitoring of service requests and network status for optimal delivery
FT-07	Physical requirements - Latency	Not severe in XHAUL environments Transmission Media (wireless radio, optical fibers…)	Not severe in XHAUL environments Computing capability	Not severe in XHAUL environments Computing capability
FT-08	Physical requirements - Jitter	Mitigated by device buffer	Not identified	Not identified
FT-09	Physical requirements - Data Rate	Massive high definition services (4k video) Transmission Media (wireless radio, optical fibers…)	Not identified	Not identified
FT-10	Physical requirements - Packet Loss	Impact on video quality	Not identified Manage notifications, alarms…	Service re-planning
FT-11	Clock synchronization	Synchronization is needed for broadcasting content on RAN	Not identified	Not identified

FT-12	Density of connections	Reduction in the number of required flows	Not identified	Not identified Re-routing
FT-13	Mobility	Flow mobility for unicast transmission. Potential distribution tree reconfiguration for broadcast / multicast distribution.	Flow mobility	Not identified
FT-14	Transferred Data Replication	Replication required for multicast / broadcast scenario also unicast	Distribution tree control for broadcast / multicast distribution	Not identified
FT-15	Energy Efficiency	Reduction in the number of required flows	Not identified	Not identified
FT-16	Combined network and computing resource provisioning	Not identified	Provision of CDN caches on computing environments in XHAUL with proper network capacity for traffic delivery	Not identified
FT-17	Management	Not identified	Management of status for network and computing resources.	Not identified
FT-18	Security	Not identified	Not identified	Privileged access to contents (end user AAA)
FT-19	Backward compatibility	Not identified	Not identified	Not identified
FT-20	SLAs mapping	Not identified		
NF-01	Programmability	Dynamic programmability of unicast and multicast. Differentiate QoS and buffering.	Dynamic configuration of network resources to provide capacity for delivery such demand.	Dynamic instantiation of CDN end points according to traffic demand.

NF-02	Scalability	Different flows of the same content with different codings	Not identified Capacity for controlling as many network elements as possible	End point re-distribution in the network. Change from unicast to multicast/broadcast (if supported)
NF-03	Usability	Not identified	APIs for service invocation	APIs for service invocation
NF-04	Consistency	Different flows of the same content with different codings	Video quality adaptation. Change from unicast to multicast/broadcast transmission (if supported)	Similar experience to fixed and mobile users. Multi-screen.
NF-05	Robustness or resilience	Not identified	Not identified Control available resources to ensure QoS	Dynamic instantiation of CDN end points and broadcast/multicast distribution tree re-configuration
NF-06	Responsiveness	Not identified	Not identified	Avalanche effect when massive requests for a given content. Reconfiguration capability
NF-07	Availability	Pre-computed forwarding rules in case of losing communication with controller	Control of computing resources to provide VMs to serve as distribution end-points. VM migration.	Dynamic instantiation of CDN end points and broadcast/multicast distribution tree re-configuration
NF-08	Planning, Design and Development	Differentiate QoS and buffering.	Not identified	Optimal distribution schema
NF-09	Isolation	Unicast from multicast isolation can be needed	Not identified	Not identified
NF-10	Resource efficiency	Not identified	Not identified	Dynamic instantiation of CDN end points and broadcast/multicast distribution tree re-configuration

				Optimal distribution schema
NF-11	Convergence	Simultaneous delivery of multicast/broadcast and unicast traffic towards access points	Not identified	Dual use for broadcast and unicast video distribution (e.g., live and catch-up video)

11.3 UC3 - Dense urban society

Req. id	Req. Statement	Impact on WP2	Impact on WP3	Impact on WP4
FT-01	Infrastructure Virtualization	Choice of technologies, in particular for XCF, that should support virtualized traffic.	Control of bandwidth and computing resources to provide VMs to serve as distribution end-points	Choice of networks to transport traffics to/from dense RANs
FT-02	Dynamic (re-)allocation of virtual resources to physical ones	Not identified	Control of bandwidth and computing resources to provide VMs to serve as distribution end-points	[Stadium] Trigger BB location deployment due to movements of the masses of spectators
FT-03	Mapping of virtual to physical resource synchronization	Not identified	Not identified	Not identified
FT-04	Resource discovery	Not identified	Availability of bandwidth, computing resources and computing facilities.	Updating optimization results due to new NE elements
FT-05	On-demand adaptation	Class of Service considerations. For backhaul traffic, service classes relate to user applications but for fronthaul the differentiation may be between user data (e.g., IQ samples), fast ctrl, slow	Control of network resources to ensure enough capacity	[lamp post installation] Trigger reconfiguration of transport network due to temporary Interference [Stadium] Trigger reconfiguration of transport network due to movements of

		Ctrl, etc.		the masses of spectators
FT-06	Monitoring and accounting	Not identified	Usage of computing resources for accounting. Usage of network resources to detect congestion.	Monitoring and accounting functions are needed in Xhaul as an insensitive for reconfiguration
FT-07	Physical requirements - Latency	Depends on applications (QoS/QoE is required) XCF overhead for short packets should be considered since fronthaul may need short packets to limit latency.	Depends on applications	Request from RAN (or VNO) includes Latency in mission critical applications
FT-08	Physical requirements - Jitter	Depends on applications (QoS/QoE is required) . Some applications can benefit by buffers, some other ones need more stringent latency requirements. Features like pre-emption may be needed to reduce jitter if Ethernet is used. High-resolution time-stamping needed, especially for fronthaul.	Depends on applications	Requirement on Jitter might be considered as variance of Latency requirement
FT-09	Physical requirements - Data Rate	High data rate is required	Flow bundling might be required for high data rate	Request from RAN (or VNO) includes Data Rate in mobile broadband applications
FT-10	Physical requirements - Packet Loss	Depends on applications (QoS/QoE is required). Some applications can benefit by buffers, some needs more stringent latency requirements.	Not identified	Request from RAN (or VNO) includes Packet Loss in all types of applications
FT-11	Clock synchronization	Synchronization is needed for	Not identified	Not identified

		broadcasting content on RAN		
FT-12	Density of connections	Very high number of required flows	Not identified	Mandatory for dense urban information society
FT-13	Mobility	Important the concept of bandwidth crowd. Flow mobility for unicast transmission. Potential distribution tree reconfiguration for broadcast / multicast distribution.	Flow mobility	Optimizing the transport network due to high mobility of users (.e.g., cars or pedestrians)
FT-14	Transferred Data Replication	Depends on applications	Distribution tree control for broadcast / multicast distribution.	
FT-15	Energy Efficiency	Very important, in particular for indoor scenario	Not identified	Trigger reconfiguration of transport network due to efficiency based on monitoring functionality in WP2 and WP3
FT-16	Combined network and computing resource provisioning	Important to improve terminals performance (battery, computations,...)	Provision of CDN caches on computing environments in XHAUL with proper network capacity for traffic delivery	Reducing capacity requirement on Xhaul in high traffic areas
FT-17	Management	Not identified	Management of status for network and computing resources.	Managing energy efficiency of Xhaul network while maintaining requests from VNOs Managing network resources based on requests from RANs (or VNOs)
FT-18	Security	It might be important for business	Not identified	End-to-end security (of VNOs) should not be violated regardless of network reconfiguration
FT-19	Backward compatibility	Very important	Not identified	To be connected with legacy networks

FT-20	SLAs mapping	Not identified		
NF-01	Programmability	Differentiate QoS and buffering.	Dynamic instantiation of CDN end points according to traffic demand. Dynamic configuration of network resources to provide capacity for delivery such demand.	Mandatory for energy management and resource management
NF-02	Scalability	Very high number of flows. Scalability in indoor behavior	Not identified	Updating optimization results due to new NE elements
NF-03	Usability	Not identified	APIs for service invocation	Not identified
NF-04	Consistency	Not identified	Not identified	Not identified
NF-05	Robustness or resilience	Quite important. Due to the high data rate requirements, it is probably too costly to keep redundant paths. Fast path reselection needed in case of node or link failure.	Really important	Important to maintain Latency and Packet Loss requirements
NF-06	Responsiveness	Not identified	Not identified	Not identified
NF-07	Availability	Pre-computed forwarding rules in case of losing communication with controller	Control of bandwidth and computing resources to provide VMs to serve as distribution end-points	Mandatory for VNOs to provide stable services
NF-08	Planning, Design and Development	Differentiate QoS and buffering.	Distribution schema taking into account different applications and different users distribution	Deployment should be based on user distribution and traffic statistics
NF-09	Isolation	Isolation among different applications	Not identified	Preferable to realize physical security
NF-10	Resource efficiency	Important trade off between	Distribution schema taking into account	Optimize resource usage in HetNets

		dimensioning at peak for BW crowding and efficiency	different applications and different users distribution	
NF-11	Convergence	Simultaneous delivery of different applications traffic	Not identified	Convergence of different planes from different networks

11.4 UC4 – Multi-tenancy

Req. id	Req. Statement	Impact on WP2	Impact on WP3	Impact on WP4
FT-01	Infrastructure Virtualization	Not identified	Abstraction of physical resources	Multi-tenancy application: create virtual infrastructure for each tenant
FT-02	Dynamic (re-)allocation of virtual resources to physical ones	Not identified	Triggered by multi-tenancy application request or the changes in physical resource, such as the ones due to mobility	Multi-tenancy application: dynamic (re-)mapping of virtual infrastructure to physical links and nodes, especially when the train is moving and the connecting BSs keep changing
FT-03	Mapping of virtual to physical resource synchronization	Not identified	Not identified	Not identified
FT-04	Resource discovery	Not identified	Discover new physical resources and expose them via the NBI to the related applications	Multi-tenancy application: needs topology information Mobility management application: needs topology information
FT-05	On-demand adaptation	Not identified	Network (re-) configuration	Multi-tenancy application: trigger re-optimization when network and demand changes. Mobility management application: when handover happens, offload the original traffic of the target BS to other appropriate BSs for load balancing
FT-06	Monitoring and accounting	Provide physical information	Metering and accounting of physical resources (computing and network resources) and QoS metrics (throughput, delay, loss, etc.).	Multi-tenancy application: Metering and accounting of virtual resources and QoS metrics (throughput, delay, loss, etc.)

FT-07	Physical requirements - Latency	Not identified	Not identified	Multi-tenancy application: to accommodate requirement from (virtual) operator Mobility management application: to accommodate requirement from (virtual) operator
FT-08	Physical requirements - Jitter	Not identified	Not identified	Multi-tenancy application: to accommodate requirement from virtual operator
FT-09	Physical requirements - Data Rate	Not identified	Not identified	Multi-tenancy application: to accommodate requirement from virtual operator
FT-10	Physical requirements - Packet Loss	Not identified	Not identified	Multi-tenancy application: to accommodate requirement from virtual operator
FT-11	Clock synchronization	Not identified	Not identified	Not identified
FT-12	Density of connections	Not identified	Not identified	Not identified
FT-13	Mobility	Not identified	Provide relevant context information to mobility management application and execute the network reconfiguration issued by mobility management application	Mobility management application: support context-aware handover optimization by defining input (train speed, train direction, train location, BS loading, etc.) and output (target BS, handover initiation time, data forwarding path, etc.)
FT-14	Transferred Data Replication	Not identified	Not identified	Mobility management application: during handover, replicate the data for the source BS at the target BS
FT-15	Energy Efficiency	Nodes can be switched on/off remotely	Disable remote antenna unit (RAU) transmission when high speed train is not in the coverage	Not identified

FT-16	Combined network and computing resource provisioning	Not identified	Not identified	Not identified
FT-17	Management	Not identified	Not identified	Not identified
FT-18	Security	Not identified	Not identified	Multi-tenancy application: authentication, authorization, and accounting (AAA) functionality are required for each tenant
FT-19	Backward compatibility	Not identified	Not identified	Not identified
FT-20	SLAs mapping	Not identified	Not identified	Not identified
NF-01	Programmability	Not identified	Not identified	Mobility management application: the handover trigger condition can be dynamically configured and provisioned automatically
NF-02	Scalability	Not identified	Not identified	Multi-tenancy application: low overhead and fine granularity in slicing of resources to introduce new tenants
NF-03	Usability	Not identified	Not identified	Not identified
NF-04	Consistency	Not identified	Not identified	Not identified
NF-05	Robustness or resilience	Not identified	Not identified	Not identified
NF-06	Responsiveness	Not identified	Not identified	Mobility management application: handover can be triggered by pre-defined condition of the input.
NF-07	Availability	Not identified	Not identified	Mobility management application: handover initiation control and BS load balancing is required to avoid radio link failure and blocked

				handover
NF-08	Planning, Design and Development	Not identified	Not identified	Mobility management application: Context information is stored as data repo for access and query to assist handover operation
NF-09	Isolation	Not identified	Isolation of virtual resource access per tenant	Isolation between tenants
NF-10	Resource efficiency	Not identified	Optimal physical resource sharing by multiple tenants	Optimal use of XHAUL resources
NF-11	Convergence		Not identified	Not identified

11.5 UC5 – Mobile Edge Computing

Req. id	Req. Statement	Impact on WP2	Impact on WP3	Impact on WP4
FT-01	Infrastructure Virtualization	Not identified	Control and manage storage and computing resources. ??VMs. XCI has to provide the network configuration and control of the NEs. Coordination between SDN and NFV functionality	Orchestration of services/applications hosted on the MEC platform.
FT-02	Dynamic (re-)allocation of virtual resources to physical ones	Not identified	Control and manage storage and computing resources. VMs migration XCI has to provide the network configuration and control of the NEs. Coordination between SDN and NFV	Orchestration of services/applications hosted on the MEC platform. Trigger XCI to change the network topology

			functionality.	
FT-03	Mapping of virtual to physical resource synchronization	Not identified	Control VMs. Synchronization inside Xhaul is packet-based. As the "physical" location of the resource will change by mapping from physical to virtual functionality, the VM presenting functionality has to be able to synchronize. Additionally VM and its counterpart has to update to the new delay. **Inside Xhaul** trigger Xhaul NEs to use new delay in case of moving of functionality.	Not identified
FT-04	Resource discovery	Not identified	The controller has to be aware of all network elements and provide control and connectivity. The XCI needs to be aware of all the available XPUs, their capabilities and the resources currently available.	Discovery of deployed VMs running MEC services.
FT-05	On-demand adaptation	Not identified	Control available resources to ensure QoS inside Xhaul. VM migration and upscaling/downscaling. Dynamic modification of network connectivity. Coordination between up/downscaling in network and computing domains.	Policies and constraints according to requested service. Interface to RAN Controller to align the transport network with the demands by RAN.
FT-06	Monitoring and accounting	Provide the information for the nodes	Control and manage the information received from network elements (XFE, XCI and nodes) and the XPUs.	Monitoring of service requests and service delivery and network status.
FT-07	Physical requirements - Latency	Not identified	Detection of the flows serviced by the MEC at the edge (e.g., ultra low latency) and serviced in	Not identified

			the core	
FT-08	Physical requirements - Jitter	Not identified	Not identified	Not identified
FT-09	Physical requirements - Data Rate	Not identified	Not identified	Not identified
FT-10	Physical requirements - Packet Loss	Not identified	Not identified	Not identified
FT-11	Clock synchronization	Not identified	Not identified	Not identified
FT-12	Density of connections	Not identified	Control a large number of VMs. Support of Multiplexing.	Provide XCI with multiplexing options
FT-13	Mobility	Not identified	Flow mobility. VMs migration.	Possible dynamic (re)deployment of VMs according to user´s mobility, network status, computing elements status, policies and service requirements.
FT-14	Transferred Data Replication	Not identified	Not identified	Not identified
FT-15	Energy Efficiency	Support of control in case of "OFF"	Dynamic ON/OFF management of physical and/or virtual resources (dynamicity of resources)	Resource management to minimize the energy footprint of the virtual XHAUL network
FT-16	Combined network and computing resource provisioning	Not identified	Provision of storage and computing resources. VMs	Not identified
FT-17	Management	Not identified	Management of network status and computing resources.	Orchestrator for Network and IT resources, integrated with the management on MEC services.
FT-18	Security	Not identified	Isolating applications as much as possible. Isolation between Virtual Machines. Slices in the XFE (controlled by one master	Privileged access to resources, VMs (end user AAA)

			OSS). Security in case of mobility	
FT-19	Backward compatibility	Not identified	Not identified	Not identified
FT-20	SLAs mapping	Not identified	Distinction of flows already at the edge. Configuration of the network to fulfill SLAs. Queues and forwarding mechanism in XFE QoS in Common Frame protocol.	Not identified
NF-01	Programmability	Not identified	Dynamic configuration of network resources to provide capacity to deliver such demand.	NBI to request automated changes to the XCI
NF-02	Scalability	Not identified	Capacity for controlling as many physical/virtual elements as possible. Methods to reduce the overhead by blade-to-blade or DC to DC communication.	Capability to trigger changes in the virtual infrastructure to cope with increasing service requests.
NF-03	Usability	Not identified	Control VM lifecycle	APIs for service invocation
NF-04	Consistency	Not identified	Control proper VM implementation together with their network connectivity.	Dynamic instantiation of VMs according to requested service.
NF-05	Robustness or resilience	Not identified	Control available resources to ensure QoS. Automated reactions in case of VMs failures, both at network and IT level.	Fault tolerance mechanisms
NF-06	Responsiveness	Not identified	Requests for changing the BW or QoS should be received from WP4 and network reconfiguration should be handled automatically in 15 min	Possible dynamic (re)deployment of VMs according to user´s mobility, network status, computing elements status, policies and service requirements.
NF-07	Availability	Not identified	Monitor network status and automatically provide new paths in case of link losses inside	Monitor network status and automatically provide new paths in case of link losses, if XCI

			the requested QoS	can't provide new passes inside requested QoS
NF-08	Planning, Design and Development	Not identified	Not identified	Not identified
NF-09	Isolation	Not identified	Isolating applications as much as possible. Isolation between Virtual Machines. Isolation of network resources inside one NE	Service isolation in case of multi-tenancy
NF-10	Resource efficiency	Not identified	XCI will change network configuration based on Trigger from WP4	Optimal distribution schema
NF-11	Convergence	Not identified	Handle different network splits inside the network and the Xhaul NEs	Provide overall deployment to XCI

References

[1] G. Schaffrath et al. “Network Virtualization Architecture: Proposal and Initial Prototype” - ACM VISA, 2009

[2] ETSI GS MEC 002, “Mobile-Edge Computing (MEC); Technical Requirements”, v0.3.1 (draft), July 2015.

[3] ETSI GS NFV 003 V1.2.0 (2014-11), European Telecommunications Standard Institute.

[4] RESTCONF protocol. https://tools.ietf.org/html/draft-ietf-netconf-restconf-12

[5] OpenDaylight [Online]. Available: http://www.opendaylight.org

[6] ONOS [Online]. Available: http://onosproject.org

[7] Open Networking Foundation (ONF), "OpenFlow Switch Specification," March 2015. [Online] Available: https://www.opennetworking.org/images/stories/downloads/sdn-resources/onf-specifications/openflow/openflow-switch-v1.5.1.pdf

[8] OpenStack. Available: [Online] http://www.openstack.org

[9] I. Cerrato, A Palesandro, F. Risso, M. Suñé, V. Vercellone, H. Woesner “Toward dynamic virtualized network services in telecom operator networks” - Computer Networks 92, 380-395

[10] X. Costa-Perez, J. Swetina, T. Guo, R. Mahindra, S. Rangarajan “Radio Access Network Virtualization for Future Mobile Carrier Networks” - IEEE Communications Magazine 51