5G Crosshaul
the integrated fronthaul/backhaul

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

D1.2: Final 5G-Crosshaul system design and economic analysis

Abstract

This deliverable reports on the final architecture detailing all the subsystems and their dependencies, the details of their interfaces as well as their interactions. The document highlights also the interaction and collaboration hold with some other H2020 projects. It also includes an economic analysis of 5G-Crosshaul from different perspectives. First, analysis of three different deployment dimensions are considered: last mile access, topology impact and realistic metro/regional area. Second, the impact of two 5G-Crosshaul functional aspects are evaluated: energy efficiency and multi-tenancy.

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List of Acronyms

Acronym	Description
5GEx	5G-Exchange
5GPoA	5G Point of Access
API	Application Programming Interface
B2B	Business-to-Business
B2C	Business-to-Consumer
BBU	Baseband Unit
BH	Backhaul
CapEx	Capital Expenditures
CDN	Content Delivery Network
CoMP	Coordinated Multi Point
CPRI	Common Public Radio Interface
C-RAN	Cloud Radio Access Network
EBI	Eastbound Interface
EMMA	Energy Management and Monitoring Application
FG	Forwarding Graph
FH	Fronthaul
GMPLS	General Multiprotocol Label Switching
IaaS	Infrastructure as a Service
InP	Infrastructure Provider
ISD	Inter Site Distance
MAC	Medium Access Control
MAN	Metro Area Network
MANO	Management and Orchestration
MdO	Multi-domain Orchestrator
MIMO	Multiple-Input Multiple-Output
MNO	Mobile Network Operator
MPLS	Multiprotocol Label Switching
MPLS-TP	Multiprotocol Label Switching – Transport Profile
MTA	Multi-Tenancy application
MVNO	Mobile Virtual Network Operator
NBI	Northbound Interface
NETCONF	Network Configuration Protocol
NFV	Network Function Virtualization
NFVI	Network Function Virtualization Infrastructure
NFVO	Network Function Virtualization Orchestrator
NS	Network Service
ODL	Open Daylight
ONF	Open Networking Foundation

ONOS	Open Network Operating
OpEx	Operating Expenditures
OTT	Over the Top
OVSDB	Open Virtual Switch Database
P2MP	Point-to-Multipoint
P2P	Point-to-Point
PHY	Physical media
QoS	Quality of Service
RAN	Radio Access Network
REST	Representational State Transfer
RF	Radio Frequency
RRH	Radio Remote Head
RWA	Routing and Wavelength Assignment
SBI	Southbound Interface
SDN	Software Defined Networking
SDX	Software Defined eXchange
SDMC	Software-Defined Mobile network Control
SG	Service Graph
SiP	Silicon Photonics
SLA	Service Level Agreement
SNMP	Simple Network Management Protocol
TCO	Total Cost of Ownership
TE	Traffic Engineering
TED	Traffic Engineering Database
VI	Virtual Infrastructure
VIM	Virtual Infrastructure Manager
VM	Virtual Machine
VNF	Virtual Network Function
VNFM	Virtual Network Function Manager
VNO	Virtual Network Operator
VNP	Virtual Network Provider
VPN	Virtual Private Network
vRAN	Virtualized Radio Access Network
WBI	Westbound Interface
WSS	Wavelength Selective Switching
XCF	5G-Crosshaul Common Frame
XCI	5G-Crosshaul Control Infrastructure
XCSE	5G-Crosshaul Circuit Switching Element
XCU	5G-Crosshaul Cost Unit
XFE	5G-Crosshaul Forwarding Element
XPFE	5G-Crosshaul Packet Forwarding Element

XPU	5G-Crosshaul Processing Units
YTC	Yearly Total Cost

Executive Summary

5G-Crosshaul clearly defined objectives and KPIs also referring to the activity of Work Package 1 (WP1), i.e. the definition of the final architecture and the cost and energy consumption reduction enabled by project solutions.

This deliverable is divided in two parts, one focused on architecture topics and another one centered on techno-economic analysis.

Regarding the architecture, the deliverable defines in detail the system architecture, highlighting also the interaction and collaboration hold with other H2020 projects. Chapter 2 presents the final and consolidated architecture of the 5G-Crosshaul project. The baseline architecture represented by the single MANO case describes the three planes considered in line with ONF architecture, that is, Data, Control and Application planes. The interfaces used for these planes are also described.

Apart from the single MANO case, insights are provided for the multi-technology domain case, presenting hierarchical approach to the SDN control for comprehensively control the distinct technologies present in 5G-Crosshaul.

An in depth view of the multi-tenancy concept is also provided, as key enabler of the slicing concept in future 5G networks.

Finally, for the interaction with neighboring network domains (i.e., RAN and mobile core) we foresee both hierarchical and peer-to-peer structures. This is in line with the architectures of 5G-NORMA and 5G-Exchange projects.

With respect to the techno-economic analysis, the deliverable presents outstanding results according to the analysis produced. Regarding the commitment of reducing CAPEX and OPEX due to unified data plane (25%) and to multi-tenancy (80%), these requirements have been mostly satisfied. In fact the project demonstrated that in the metro segments the unified control plane introduce a CAPEX/OPEX savings of about 25 to 30 %. With respect to multi-tenancy, for the yearly CAPEX (i.e. the CAPEX / amortization time) savings of about 70% are obtained; the OPEX savings are about 72%. The savings on the total cost of ownership are about 70%.

In WP1 we also paid particular attention to the reduction of Total Cost of Ownership (TCO) and energy consumption. A TCO reduction 30% is achieved due to new optical transmission systems and by sharing mobile/fixed access. In more detail for the access network (i.e. last mile), the saving is about 65%, while for the metro segment the savings might be evaluated between 25% and 30%.

The unified control plane also introduces energy savings of about 35%. Moreover, the energy consumption takes advantage from multi-tenancy. In fact w.r.t. the sum of energy consumption of 4 independent operators, the saving is of more than 70%. Furthermore, EMMA algorithm, developed by the project in WP4, enables further 12%. The final result is 0.65 * 0. 3 * 0.88 = 17% (savings 83%, reduced by a factor 6). If we also consider the technological evaluation the savings is larger than 90% (1/10) w.r.t. W per bit/s.

Finally, a specific study has been provided on indoor solutions, demonstrating that indoor systems based on LTE backhauling guarantee a saving between 50% and 60 % with respect to WiFi based solutions.

1. Introduction

Architectural flatness and decentralization, pushing intelligence out to the edge, has traditionally been an axiomatic criterion to design 3G/4G systems with affordable topological flexibility and high capacity; we refer to this architecture as Distributed Radio Access Network (D-RAN). More recently, an opposing paradigm, termed Cloud RAN (C-RAN), has gained momentum and holds itself out as a promising solution for 5G. In its purest form, the functionality of a base station (BS) is fully decoupled from the radio unit (referred to as RU, RRU or RRH) and it is virtualized into a centralized cloud computing platform or central unit (referred to as BBU or CU). (Virtual) BSs/CUs are connected to the evolved packet core (EPC), e.g., charging, gateways to Internet, etc., via a backhaul (BH) network. On the other side, RRHs exchange digitized IQ radio samples with CUs through a high-capacity fronthaul (FH) network, typically using CPRI or OBSAI interfaces. This approach has been shown to improve spectrum efficiency and reduce costs (pooling gains) in certain setups. However, its benefits become questionable in many realistic large-scale deployments for 5G. This is due to the stringent requirements on the FH, which can only be met in practice by costly fiber point to point links. In addition, nowadays FH architectures have the following limitations: (i) Bandwidth usage is constant and independent of user load, i.e. no statistical multiplexing; (ii) Data rate demand grows linearly with the number of antennas, which disallows massive MIMO; (iii) Low (or none) path diversity between RUs and CUs (poor resilience, high inefficiency); (iv) No infrastructure reuse: FH and BH are incompatible in terms of interfaces, data or control planes.

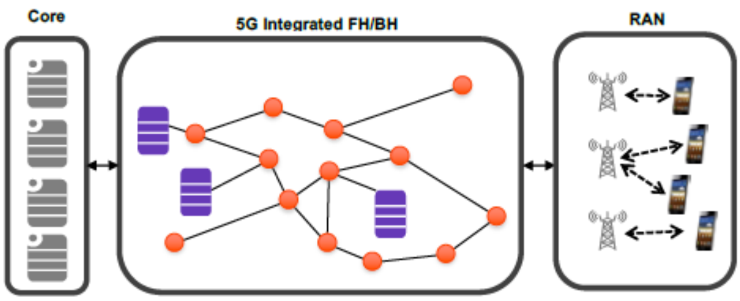


Figure 1: Integration of Fronthaul and Backhaul.

5G services will require the support of different kind of services with very distinct needs onto the same physical infrastructure. Types of services like enhanced Mobile Broadband (eMBB), massive Machine-Type Communications (mMTC) and ultra-Reliable and Low Latency Communications (uRLLC) impose the need of supporting greatly different capabilities at the same time on the same infrastructure to meet all the requirements in terms of bandwidth, latency, number of handled sessions, etc.

In parallel, a revolution is expected with regards of the service provisioning and end-user experience thanks to the positioning of 5G networks as technological enablers for several industries as it is the case of vertical customers. A number of sectors (i.e., areas like Media and Entertainment, eHealth, Energy, Automotive, and Manufacturing-

Factories of the Future) are advancing towards the definition of the requirements needed by 5G networks for playing such supportive role.

From the technology perspective a number of trends have been coming up, related to network virtualization and programmability, such as Network Function Virtualization (NFV) and Software Defined Networking (SDN). These technologies brought the ability of abstracting the network functionality from its physical configuration, paving the way to a less problematic sharing of resources and functional components, to their orchestration into composite services, and to service lifetime management.

One of the crucial network segments in future 5G networks will be the Crosshaul, which considers both current and future fronthaul and backhaul network segments in an integrated approach, not only from the networking perspective but also from the viewpoint of making available distributed computing capabilities closer to the end users. The Crosshaul is key since it provides the necessary capillarity and modularity to reach the end user for the different kind of services as observed before.

In light of the above, 5G-Crosshaul addresses this issue by integrating both backhaul and fronthaul segments into one single, flexible and SDN based transport network for data exchange between the RAN and its respective operator's core network in an adaptive, cost efficient and sharable manner, as shown in Figure 1. Two pivotal paradigms steer the design of 5G-Crosshaul. First, 5G-Crosshaul is designed based upon a simpler packet-based transport protocol that enables statistical multiplexing, infrastructure reuse and higher degrees of freedom for routing. Unfortunately, coexistence between FH and BH traffic in a common packet-based network faces an important challenge. That is, the tough requirements of full C-RAN centralization are now subject to more limited—and likely shared—transport resources. However, retaining as much centralization as possible, when full offloading is unfeasible due to transport constraints, would be desirable. This leads to 5G-Crosshaul's second driving concept: a flexible split of the RAN functionality. The idea is to divide a classic BS into a set of functions that can either be processed co-located with the RRH or offloaded into a CU, depending on the transport requirements and centralization needs. In this way, we can better balance cost/performance (the more aggressive the offloading, the higher the centralization gains) and requirements (the softer the offloading, the more relaxed the network constraints).

This deliverable addresses two very relevant aspects of the 5G-Crosshaul project. On one hand, this document presents the final 5G-Crosshaul architecture framework, presenting the enabling technology to reach the goal of a virtualized and programmable Crosshaul network segment. On the other, this report presents a structured techno-economical analysis of the solution through a number of scenarios (single access, theoretical layout coverage, and realistic metropolitan roll-out) and dimensions (multi-tenancy, small cell deployment, energy efficiency).

The first part of this document, represented by Chapter 2, presents the consolidated architectural design of 5G-Crosshaul. The information conveyed in this document collects all the architectural details of the different functional blocks of 5G-Crosshaul, including information spread through different deliverables in WP2, WP3 and WP4, as well as amendments to details provided in D1.1.

Going into detail, 5G-Crosshaul project has defined a network architecture at data plane and control plane level, envisaged to support fronthauling and backhauling functionalities through different transport technologies, namely active or passive fiber wirelines as well as high capacity wireless mmW connections.

The high-level data plane architecture reported in Figure 2 is focused on the 5G-Crosshaul Forwarding Elements (XFEs) that consist of pure L2 Packet Forwarding Elements (XPFEs) and L1 optical Circuit Switching Elements (XCSEs). The XPFEs and XCSEs can be connected through different network topologies and media technologies between them and towards the radio units (RRH), in order to support the fronthauling traffic to the Base Band Unit (BBU) as well as the backhauling traffic between the BBUs and the mobile Core network (EPC).

The XPFE is an Ethernet switch based on the MAC-in-MAC/PBB 802.1ah framework, supported by a protocol interface that is called 5G-Crosshaul Common Frame (XCF), as reported in Figure 2. The XCSE is an active WDM equipment based on Reconfigurable Optical Add Drop Multiplexer (ROADM). The packet switching equipment are involved in the transport of most delay-tolerant traffic, while the circuit switching equipment are devoted to extremely low-latency jitter-sensitive and bandwidth consuming traffic like legacy fronthauling CPRI. The XCSE is also involved in traffic offloading when high bandwidth demands must be transported, so that L2 devices are used only at the connection edges.

Usually, in present 3G and 4G environments the BBU functionality is distributed almost at all transport metro sites being part of monolithic eNB architectures. However, for the new 5G systems, it is expected that the BBU capabilities will be concentrated in a few nodes per metro area, by virtualizing their functionalities on server units. In 5G-Crosshaul network the server function is performed by the XPU (Processing Unit), which in general has the task of storage and computing activities and cloud functionalities. In particular, it performs the Network Function Virtualization (NFV) useful for mobile Cloud Radio Access (vBBU for Cloud RAN) and mobile Core virtualization (vEPC), for media distribution services (CDN and TV Broadcasting/Multicasting) as well as for Mobile Edge Computing (MEC) applications.

All nodes (RRH, XFE, XPU, etc.) are connected to each other by means of protocol Adaptation Functions (AFs), that perform media adaptation (e.g. from air to fiber) and protocol adaptation (e.g. from mmWave/802.1ad to Ethernet). Furthermore, they can support different split options of the radio access protocols, spanning from pure backhaul, based on Ethernet, to pure fronthaul, based on CPRI or CPRI-like interfaces.

All these network functions are controlled by the 5G-Crosshaul Control Infrastructure (XCI), represented by a server that plays the role of SDN controller, performing network provisioning and management, also in a multi-tenancy scenario.

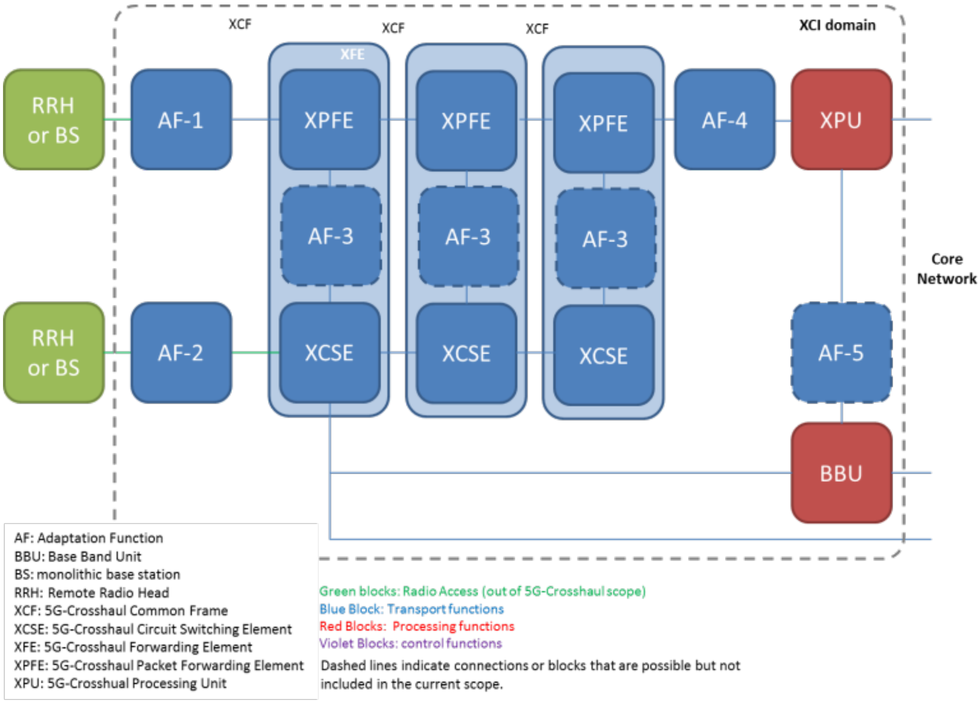


Figure 2 – 5G-Crosshaul data plane architecture

Besides the architectural studies, WP1 also provides the techno-economical analysis that demonstrated the affordability and sustainability (from the energy consumption point of view) of 5G-Crosshaul solutions.

In fact, 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 define tools and methodologies that numerically assist on the calculation of the costs for the innovative network with respect to a legacy solution.

According to 5G-Crosshaul architecture, a set of evaluations have been provided in order to understand both whether 5G-Crosshaul solutions are economically viable or not, and which technical solution is the most appropriate taking into account also the economic side and the energy consumption.

The main evaluation, reported in Chaper 3, have been:

- The last mile costs, i.e. between the antenna side and the closest node.
- The costs of a general architecture in greenfield and brownfield case, taking into account the topology between the antenna (RRH) and the BBU hotel and among BBU hotels, network strategies, used technologies and the status of the environment (e.g. geo-type, infrastructure, etc).
- The cost and energy consumption of a realistic metropolitan / regional network carrying both fronthauling and backhauling traffic, following 5G-Crosshaul ideas.
- The evaluation of cost and energy consumption due to the introduction of small cells both in outdoor and indoor behavior.
- The economic evaluation referred in a scenario of multi-tenancy
- The energy savings introduced by specific applications, like EMMA, also envisaged by the project.

2. Consolidated 5G-Crosshaul System Architecture Design

This chapter presents the consolidated design of the overall 5G-Crosshaul architecture. This design enables the implementation of 5G-Crosshaul's key features to build adaptive, flexible and software-defined future 5G transport networks that integrate multi-technology fronthaul and backhaul segments. Along the chapter, we present architectural details shown in D1.1 and the extensions carried out since then, particularly addressing multi-tenancy and network slicing (described in section 2.3), multiple administrative domains (section 2.4) and in the integration with neighbouring RAN and Core domains (section 2.5).

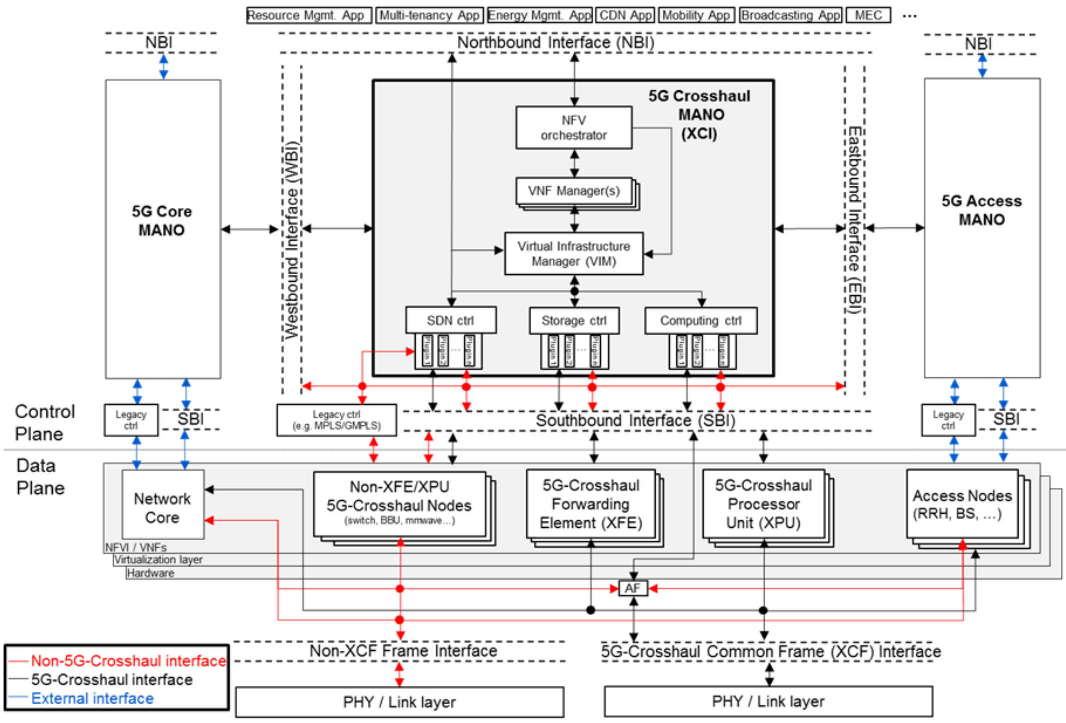


Figure 3 – 5G-Crosshaul Baseline Architecture

Figure 3 depicts the baseline architecture of 5G-Crosshaul. This architecture follows the SDN principles: *(i)* data and control plane are fully decoupled, *(ii)* control is logically centralized and *(iii)* applications have an abstracted view of resources and states.

In the **control plane**, it includes 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 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, 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.

The **data plane**, in turn, integrates 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-known open source SDN controllers which provide carrier grade features and can be used for 5G networks are: Open Daylight (ODL) [1] and Open Network Operating System (ONOS) [2]. 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 [3]. 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 Management and Orchestration (MANO) concepts. In the remaining of this chapter, we provided detailed information of the baseline architecture (single MANO), and then introduce extensions to particular scenarios, namely, *(i)* multi-domain/multi-technology scenarios, *(ii)* multi-tenancy and *(iii)* orchestration of federated Crosshaul domains.

2.1. Baseline Architecture (single MANO)

Based on the design criteria exposed in the introduction above, we proposed that the 5G-Crosshaul architecture devised in our design should share the same principles of the SDN reference architecture as defined by Open Networking Foundation (ONF) in [4]:

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

2.1.1. Control Plane

As illustrated in Figure 3 we divided the control plane into two clearly differentiated layers: a top layer for external applications and the 5G-Crosshaul Control Infrastructure (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 like content delivery networks and TV Broadcasting, etc. In turn, the XCI is our 5G transport MANO platform that provides control and management functions to operate all available types of resources (networking and cloud).

The XCI has been based on the SDN/NFV principles, providing 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 Virtual Network Functions (VNFs) via NFV).

The XCI controls the overall operation of the 5G-Crosshaul system. The XCI part dealing with NFV comprises three main functional blocks, namely: NFV orchestrator, VNF Manager(s) and Virtual Infrastructure Manager (VIM) (following the ETSI NFV architecture [3]):

- The **NFVO** (NFV Orchestrator) is a functional block that manages a Network Service (NS) lifecycle. It coordinates the VNF lifecycle (supported by the VNFM) and the resources available at the NFV Infrastructure (NFVI) to ensure an optimized allocation of the necessary resources and connectivity to provide the requested virtual network functionality.
- The **VNFMs** (VNF Managers) are functional blocks responsible for the lifecycle management of VNF instances (e.g. instance instantiation, modification and termination).
- The **VIM** (Virtualized Infrastructure Manager) is a functional block that is responsible for controlling and managing the NFVI computing, storage and network resources via a set of specialized controllers to deal with the control of the underlying network, storage and computation resources:
    - SDN Controller: This module is in charge of controlling the underlying network elements following the conventional SDN paradigm. 5G-Crosshaul extends current SDN support of multiple technologies used in transport networks (such as micro-wave links[1]), in order to have a common SDN controlled network substrate which can be reconfigured based on the needs of the network tenants.

[1] ONF is actively working towards the definition of a southbound interface for micro-wave links: http://5g-crosshaul.eu/wireless-transport-sdn-proof-of-concept/

- Computing/Storage Controllers: Storage and Computing controllers are included in what we call a Cloud Controller. A prominent example of this kind of software framework is OpenStack[2].

Note that the SDN/Computing/Storage controllers are functional blocks with one or multiple actual controllers (hierarchical or peer-to-peer structure) that centralize some or all of the control functionality of one or multiple network domains. We considered as well the utilization of legacy network controllers (e.g. MPLS/GMPLS) to ensure backward-compatibility for legacy equipment.

2.1.2. Data plane

5G-Crosshaul has integrated all communication links between Remote Radio Heads/Small Cells and core network entities within 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 and/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.

In turn, **5G-Crosshaul Processing Units** (XPUs) carry out the bulk of the computing operations in 5G-Crosshaul. These operations shall support Cloud RAN (C-RAN), by hosting BBUs or MAC processors, but also those 5G Point of Access (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 radios, etc., using proper plugins. 5G-Crosshaul-specific data plane elements (XFEs, XPUs) can communicate with others non XCF-compliant elements by means of Adaptation Function (AF) entities that act as a translator between XCF and other protocols.

2.1.2.1. 5G-Crosshaul Forwarding Elements (XFE)

XFEs are switching units that support single or multiple link technologies (e.g. mmWave, Ethernet, fiber, microwave, copper, etc.). A key part of the envisioned solution is a common switching layer in the XFEs for enabling a unified and harmonized transport traffic management. This common switching layer supports the

[2] https://www.openstack.org/

XCF format across the various traffic flows (of fronthaul and backhaul) and the various link technologies in the forwarding network. The common switching layer in the XFEs is controlled by the XCI which is foreseen to have a detailed (as per the abstraction level defined) view of the fronthaul and backhaul traffic and resources, and to expose this detailed view through a further abstraction to the orchestration layer to enable intelligent resource, network functions and topology management across the two domains.

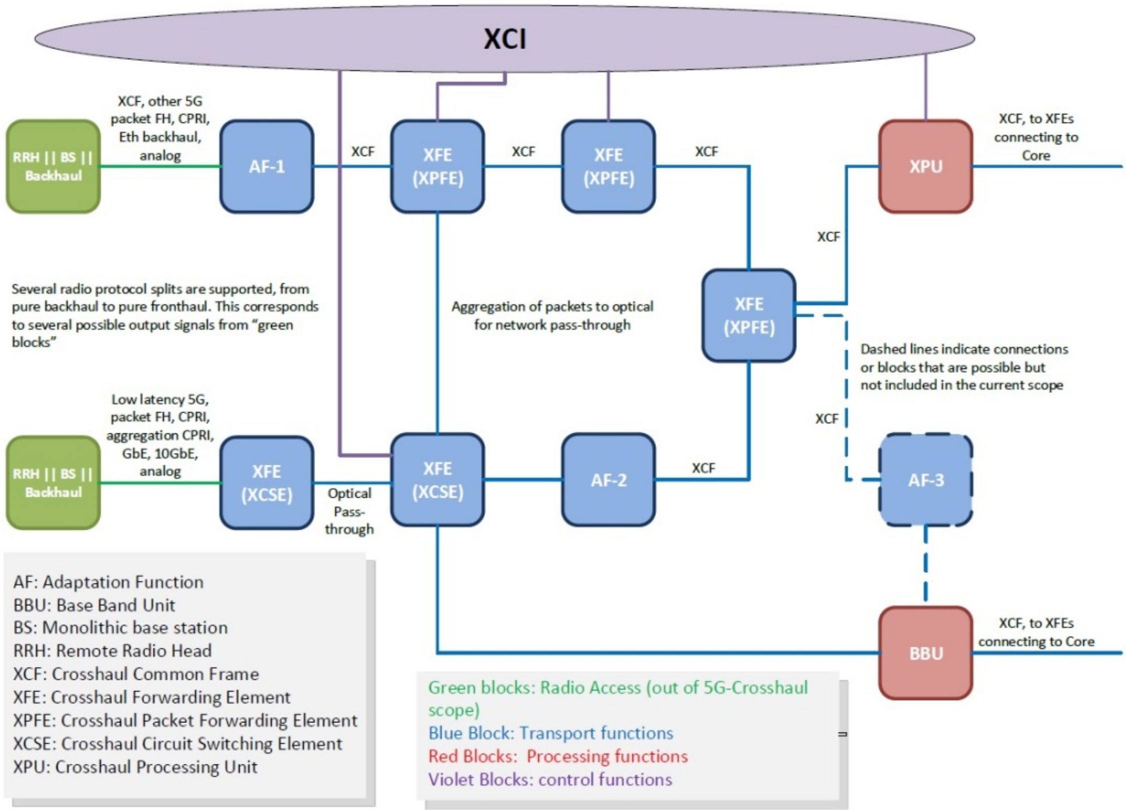


Figure 4 – 5G-Crosshaul Data Path Architecture

As depicted in Figure 4, XFEs include packet switching elements (**XPFE**) and circuit switching elements (**XCSE**). Two paths are defined in this framework, namely *(i)* a packet switching path (upper part), and *(ii)* an all-optical circuit-switching path (lower part). The packet switching path is the primary path for the transport of most delay-tolerant fronthaul and backhaul traffic, whereas the circuit-switching path is there to complement the packet switching path for those particular traffic profiles that are not suited for packet-based transporting (e.g. legacy CPRI or traffic with extremely low delay tolerance). This two-path switching architecture is able to combine bandwidth efficiency, through statistical multiplexing in the packet switch, with deterministic latency ensured by the circuit switch. The modular structure of the 5G-Crosshaul switch, where layers may be added and removed, enables various deployment scenarios with traffic segregation at multiple levels, from dedicated wavelengths to VPN, which is particularly desirable for multi-tenancy support.

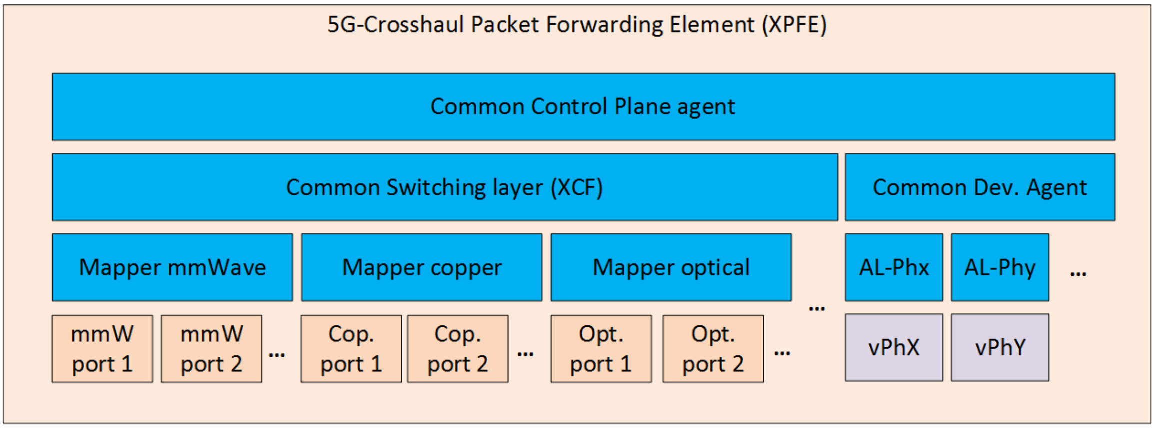


Figure 5 – XPFE Functional Architecture

Figure 5 depicts a baseline functional architecture for the 5G-Crosshaul Packet Forwarding Element (XPFE). It includes the following key functions:

- A common switching layer based on the common frame (XCF) to forward packets between technology-independent interfaces. The switching engine is technology-agnostic.
- A common device agent to talk with system peripheral. This agent exposes to the control infrastructure device-related information like CPU usage, RAM occupancy, battery status, GPS position, etc.
- Mappers for each physical interface.
- Physical interfaces to transmit the data on the link. Multiple physical interfaces of different technologies can coexist in the unit including different technologies.

The common control-plane and device agents are relevant for both packet and circuit switched forwarding element of the XFE. In the XPFE, the common abstraction of the heterogeneous data-plane provides a technology independent data-plane and allows dynamic reconfiguration of the transport resources. It also allows the interworking with transport legacy technology. That function is enabled by the SBI that allows exposing legacy domains to the XCI.

2.1.2.2. 5G-Crosshaul Common Frame (XCF)

The XCF is the frame format used by the XPFE. Ideally, the XCF is supported by all physical interfaces where packets are transported. Circuit switched forwarding is independent of the XCF. Where necessary, the frame format of the endpoints is mapped to the XCF for forwarding by the XPFEs. As an example, CPRI over Ethernet would have to be mapped to the XCF. Mapping functions are also used among XPFEs and legacy switches.

The XCF is based on Ethernet, utilizing MACinMAC (or Provider Backbone Bridge Network) [5]. MACinMAC, provides a more flexible separation of tenants compared to single VLANs. Networks of different tenants can be separated via the outer Backbone VLAN, nevertheless within one tenant there can be several virtual customer networks. The priority bits of the Ethernet header are used to indicate the priorities of the different traffic flows. Basing the XCF on Ethernet eases reuse of legacy switches and increases synergies with the development of more generic switches.

2.1.2.3. 5G-Crosshaul Processing Unit (XPU)

While the SDN control platform is responsible for the configuration of the network elements of the 5G-Crosshaul physical infrastructure (i.e. the XFEs), the Cloud and Storage control platform of the XCI handles the 5G-Crosshaul IT components (computing and storage resources) in the XPUs. Virtual infrastructure in XPUs is instantiated, configured and operated by XCI, where VNFs can be deployed to run the 5G-Crosshaul services in a proper and efficient manner.

2.1.3. Application plane

The 5G fronthaul and backhaul integration enables a new set of use cases that are summarized in Table 1.

Table 1 – 5G-Crosshaul Use Cases

Use Cases	Description
Dense urban society	This use case addresses the connectivity required at any place and at any time by humans in dense urban environments, considering both traffic between humans and the cloud, and direct information exchange between humans and/or environment.
Mobile edge computing	This use case is focused on the deployment of IT and cloud-computing capabilities towards the edge of the network. Content, service and application providers can leverage on such distributed computing capabilities to serve high-volume and latency-sensitive traffic on dense areas with a high number of users.
Media Distribution: CDN/TV broadcasting	This use case addresses the distribution over 5G networks of media contents, especially video traffic, and TV broadcasting, which are expected to be the dominant contributors to the mobile data traffic demand.
Vehicle Mobility	This use case addresses the support of 5G communication in vehicles during motion, e.g. passengers using 5G services as real-time video on a very high-speed train (500 km/h) and messages among vehicles for traffic control, emergency and safety.
Multi-Tenancy/ Network Slicing	This use case addresses the flexible sharing of backhaul/fronthaul resources across multiple tenants. It is a key enabler to maximize the utilization of 5G-Crosshaul infrastructure in a cost-efficient manner.

To support the above use cases, we developed a set of SDN/NFV applications to manage and optimize the 5G-Crosshaul network in order to achieve high cost-efficiency, scalability and flexibility. The applications focus on the resource management including both networking and IT resources, energy management, mobility management, media distribution to offer CDN and TV broadcasting services over Crosshaul network, multi-tenancy to provide network slicing for multiple tenants.

2.1.4. Interfaces

As mentioned above, an ecosystem of applications on top of the XCI provides tools for optimization, prediction, energy management, multi-tenancy and others. The XCI is the mean to achieve the application goals and the NBI (typically based on REST, NETCONF or RESTCONF APIs [9]) interconnects 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. OpenFlow has been the reference SBI for 5G-Crosshaul, however the system could permit the integration and usage of some other alternative if required.

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 the 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.

2.2. Multi- -technology domains

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, we will refer to a domain as a collection of network elements within a common realm of address space. Typically this relates to 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 organization performing a single instance of MANO.

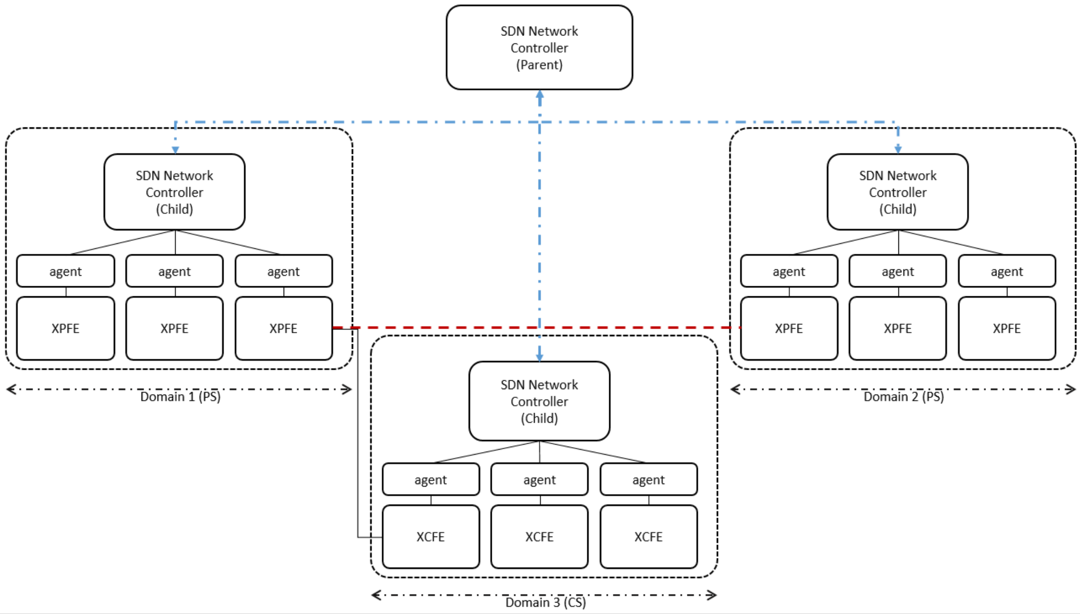


Figure 6 – SDN-based hierarchical orchestration and control of multi-domain/multi-layer networks

Let us note that a single SDN controller with full topology visibility can be designed and conceived to control multiple data plane technologies. However, an approach like this may have important shortcomings, for example scalability issues in a hierarchical settings, i.e., while this controller can work for small to medium sized domains, large domains need to rely on the arrangement of multiple controllers.. Additionally, having a single controller 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 implies 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, highly-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 6* and *Figure 7*). 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 Traffic Engineering (TE) attributes, represented usually as a directed graph or virtual links and nodes (stored in a TE Database, TED) 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.

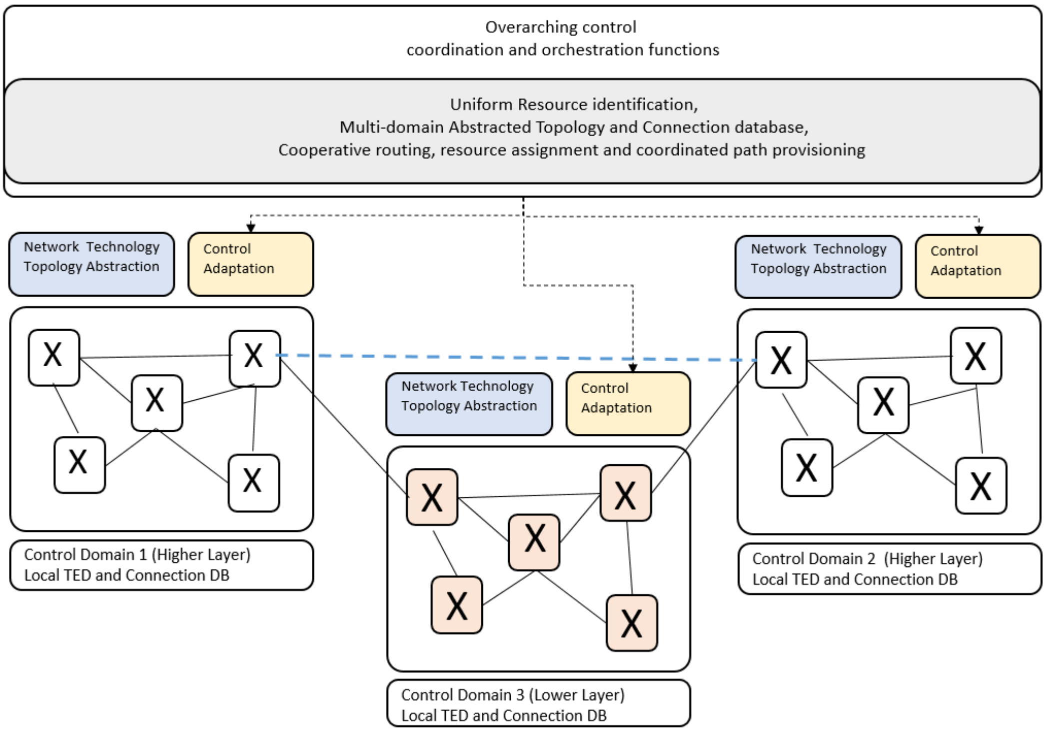


Figure 7 – Over-arching control function mapping and adaptation

2.3. Multi-Tenancy and Network Slicing

One of the most important features of 5G-Crosshaul is multi-tenancy, i.e., the ability to support multiple users or tenants while enabling flexible sharing of 5G-Crosshaul physical infrastructure, so that each tenant can operate, independently, a subset of such resources. The aim of multi-tenancy is to maximize the degree of utilization of infrastructure deployments and to minimize the costs of roll-out, operation and management (so reducing both the capital (CapEx) and operational (OpEx) expenditures), and to reduce energy consumption, which are essential goals of 5G. In our context, a tenant can be associated to an administrative entity or user of a given service and implies a notion of ownership of one or more service instances and isolation between these instances.

Multi-tenancy is enabled by technologies such as network virtualization and network slicing, both covering, to some extent, the processes by which an infrastructure is physically or logically partitioned, segmented and assigned to different users of such resources. More formally, we define **a network slice as a self-contained, coherent set**

of functions along with the infrastructure required to support such functions, offering one or more services for end-users.

Although multi-tenancy in its wide sense is a concept that has been developed since long time in many contexts, its applicability and benefits within transport networks has been addressed more recently, with specific research work regarding, e.g., network virtualization in projects such as GEYSERS[3] and STRAUSS[4]. In the scope of 5GPPP, projects like 5G-NORMA [5] have addressed multi-tenancy for the RAN, while CHARISMA[6] has targeted a multi-tenancy architecture for 5G access networks. The work in 5G-Crosshaul has complemented them by focusing on the aspects directly related to the combined fronthaul and backhaul, targeting per-tenant services, which combine computing, storage, switching and transmission resource management.

Our final target is to enable multi-tenancy , addressing the dynamic allocation of slices over a shared 5G-Crosshaul network, enabling economies of scale. The allocation of a slice involves the selection of the functions, their constrained placement, and the composition of the underlying infrastructures in fulfilling the services' requirements, in terms of, e.g., latency, bandwidth or processing capacity. The infrastructure to support the slice-defining functions and their interconnection can be either physical or virtual. We consider two main network slicing services that enable different degrees of explicit control and are characterized by different levels of automation of the network slices management: (i) the provisioning of **Virtual Infrastructures** (VI) under the control and operation of different tenants —in line with an Infrastructure-as-a-Service (IaaS) model—; and, (ii) the provisioning of tenant's owned **Network Services** (NS) as defined by the ETSI NFV architecture [3]. In the former service, 5G-Crosshaul deals with the allocation and deallocation of VIs. The logical entities within a VI, encompassing a set of compute and storage resources, are interconnected by a virtual, logical network (i.e. virtual nodes are interconnected by virtual links over the substrate network). The VIs can be operated by the tenant via different SDN control models. In the latter, NS are instantiated directly over a shared infrastructure, and as a set of interrelated Virtual Network Functions (VNFs). A NS corresponds to a set of endpoints connected through one or more VNF Forwarding Graphs (VNF-FGs). Note that, whether the allocation of a NS is implemented in terms of the allocation of an underlying VI and the subsequent instantiation of the VNFs over the containing Virtual Machines (VMs) is an implementation choice.

Multi-tenancy is an orthogonal characteristic that can be applied to both kinds of service, guaranteeing separation, isolation and independence between different slices coupled with the efficient sharing of the underlying resources for both VI and NS concepts. Consequently, 5G-Crosshaul defines the term tenant as a logical entity

[3] http://cordis.europa.eu/project/rcn/93786_en.html
[4] http://www.ict-strauss.eu/
[5] https://5gnorma.5g-ppp.eu/
[6] http://www.charisma5g.eu/

owning and operating either one or more Virtual Infrastructures or one or more Network Services, ultimately controlling their life-cycle.

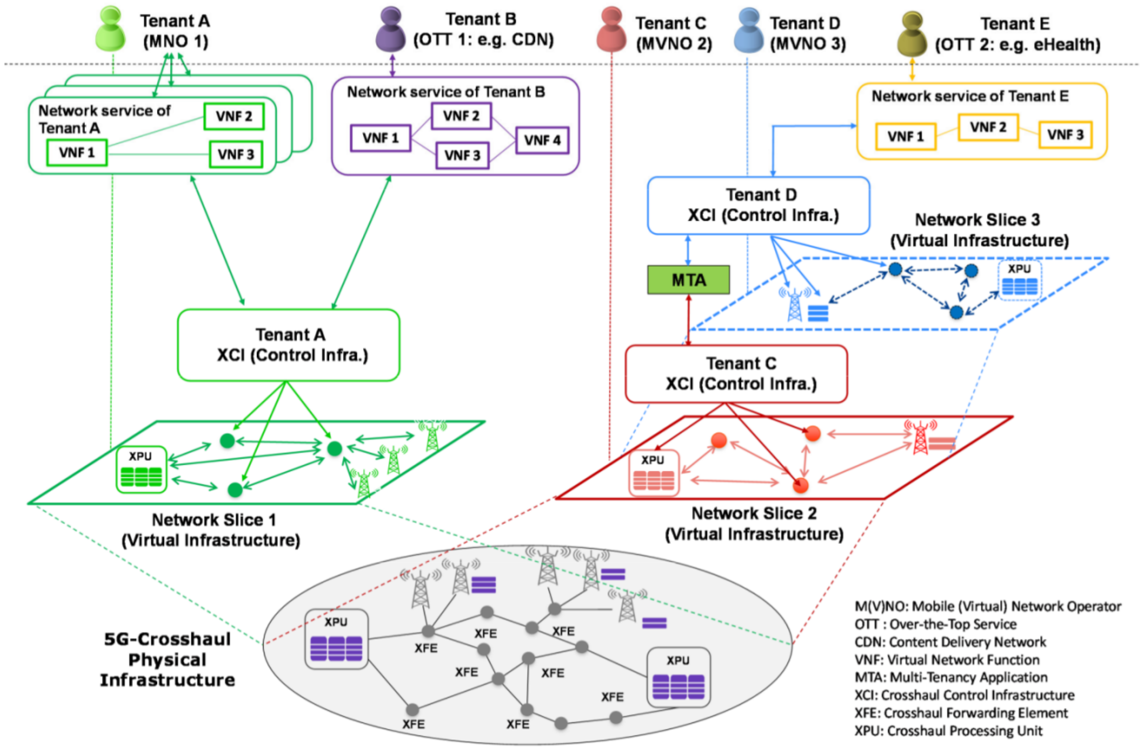


Figure 8 – Network slicing in 5G-Crosshaul for multi-tenancy support.

The concept of multi-tenancy is illustrated in Figure 8, where the owner of the physical infrastructure allocates virtual infrastructures over its substrate network, providing multiple network slices to be offered to different tenants. Each tenant, e.g., a Mobile (Virtual) Network Operator (MNO or MVNO), owns a network slice, operating the allocated virtual infrastructure. In this example, tenant A, C and D owns the network slice 1, 2, and 3, respectively. Moreover, tenant A itself is an MNO who also owns the physical infrastructure that can be shared by other MVNOs. The MVNO tenants can further deploy their own NS or allow multiple third-party tenants (e.g., OTTs) to instantiate their NS on top of the virtual infrastructure, e.g., tenant B deploying its NS over the VI of tenant A. It is possible to instantiate a VI on top of another one following a recursive approach, by applying the same principles and operational procedures, e.g., the VI of tenant D is instantiated over the one of tenant C.

From the point of view of business models, network slicing allows Mobile Network Operators (MNOs) to open their physical transport network infrastructure to the concurrent deployment of multiple logical self-contained networks. The availability of this vertical market multiplies the monetization opportunities of the network infrastructure as (i) new players may be involved (e.g. automotive industry, e-health, etc.), and (ii) a higher infrastructure capacity utilization can be achieved by exploiting multiplexing gains. For the particular 5G-Crosshaul services, VI deployments are oriented to the B2B market, targeting customers like MVNOs or cloud providers specialized in customizable IaaS services, since they need a deep control on the network segment between distributed data centers. VIs can also be deployed by network operators to create virtualized and highly controlled environments to test and validate services before their roll out. Conversely, NSs target customers operating in the B2C segment, like application or service providers that offer services to end users (e.g., content providers specialized in video streaming services).

2.3.1. 5G-Crosshaul Architecture for Multi-Tenancy Services

The architectural extensions of our baseline architecture are depicted in Figure 9, which can support several use cases of Multi-Tenancy. It extends the baseline architecture of 5G-Crosshaul presented in Figure 3. The extensions we developed on top of the baseline architecture are the Multi-Tenancy Application (MTA), and a set of APIs to support the various multi-tenancy services. These APIs are conceived for the control of a VI or NS lifetime, instantiation, modification and deletion (API classes *(a)* and *(d)* in Figure 9), and for the control of the VI in its limited or full-featured form (API classes *(b)* and *(c)* in Figure 9, respectively).

The Multi-Tenancy Application (MTA) is the application that implements the support for multi-tenancy, by coordinating and managing tenants' access to the shared infrastructure, driving resource allocation for instances assigned to different tenants, and delivering multi-tenancy related services by means of dedicated APIs[7]. A high-level requirement is resource isolation, understood as the function of partitioning, separating and book-keeping of resources such that a tenant has no visibility of / or access to the resources associated to another tenant. To perform this function, the MTA uniformly wraps and complements the infrastructure elements capabilities (e.g., SDN controllers, cloud management systems, network elements, etc.) to provide multi-user and resource isolation support, offering uniform and abstracted views to tenants. Regarding mechanisms for isolation, our approach is to rely on existing ones, with the MTA acting as middle-ware and hypervisor. Full resource isolation requires system/infrastructure support and it is not straightforward or cannot even be achieved, e.g., without hardware redundancy. 5G-Crosshaul provides soft-resource isolation including, notably, driving the SDN controller capabilities to create per-tenant networks, allocating software switches within XPUs dedicated to per-tenant traffic, defining security groups and per-tenant addressing, switching and routing within XPUs and logically separating traffic within XPEs. Similarly, from the ETSI NFV/MANO perspective, the MTA manages states regarding to allocation of network services mapping tenants to actual instances and relying on implementations support.

The MTA supports multi-tenancy by allowing the constrained allocation, operation and deallocation of virtual infrastructures (VIs) and/or of ETSI NS instances, in compliance with the desired degree of detail and control. The MTA acts as a front end between the

[7] In the considered model, a single tenant entity owns one or more instances of each service in a 1:N relationship.

tenants and the tenants' service instances, although it is a matter of operator's policy whether direct access to the XCI is allowed, which can be justified in specific scenarios for, e.g., efficiency reasons.

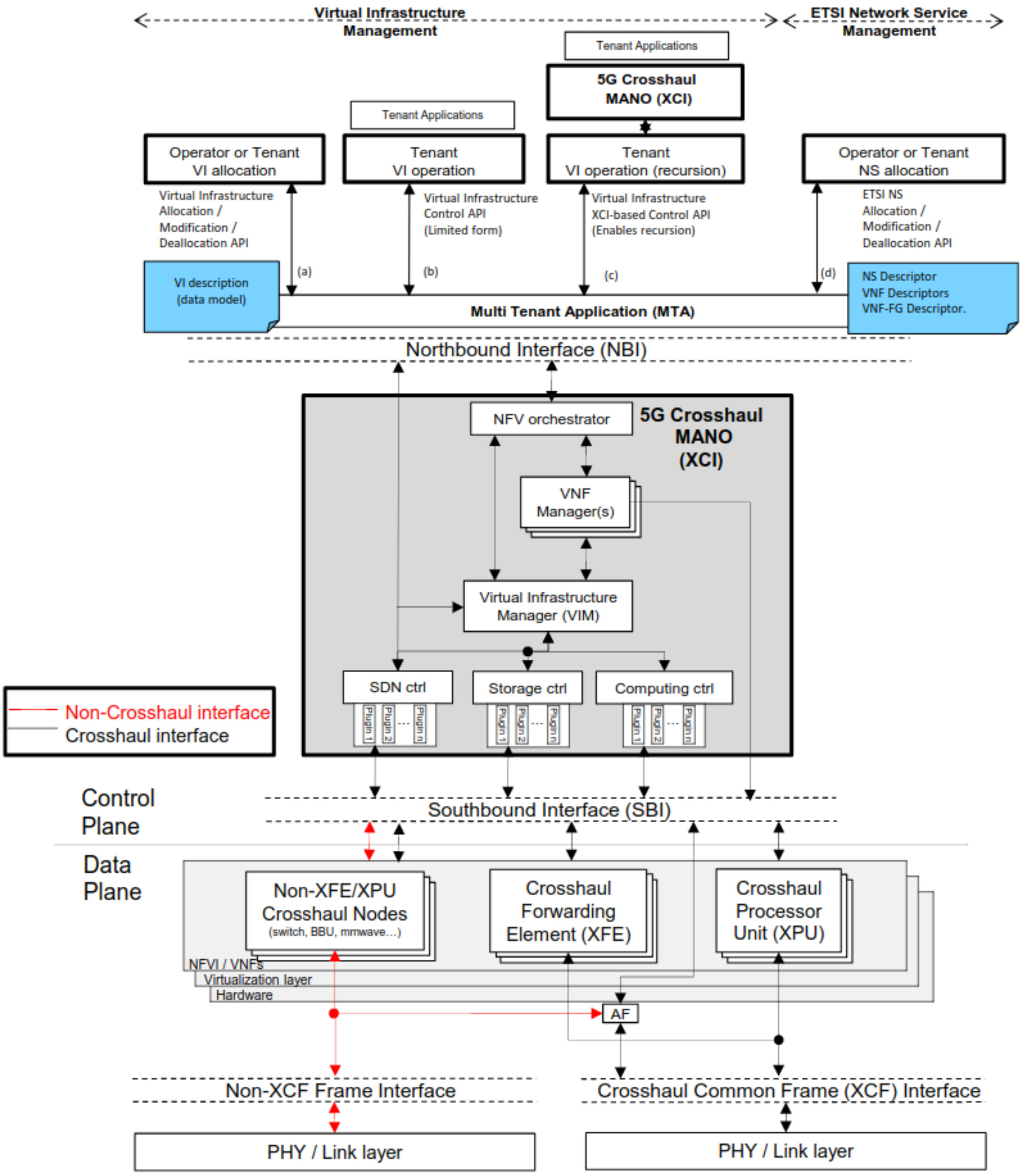


Figure 9 – 5G-Crosshaul architecture for multi-tenancy.

5G-Crosshaul targets two main service types, defined below.

- Virtual Infrastructure (VI) Deployment. As stated, a VI is a logical construct composed of virtual links, virtual XFE and virtual XPUs which, as a whole, "behaves as" and "can be operated as" a physical infrastructure, with different degrees of internal control. This service involves the dynamic allocation of a VI, its operation and, subsequently, deallocation. The actual realization of a VI combines, for example, aspects such as the partitioning and book-keeping of resources or the instantiation of connections supporting virtual links characterized in terms of, e.g., unreserved bandwidth or latency. The provisioning of a VI also commonly requires direct hardware elements support, or its emulation through software (e.g., software based hypervisors) for multiplexing over the shared infrastructure.

- Network Service (NS) Deployment. In this case, the MTA allocates a NS on behalf of a tenant, typically upon request. A NS corresponds to a set of VNFs connected through one or more VNF Forwarding Graphs (VNF-FGs). Following the ETSI MANO architecture, each tenant Operating and Business Support Systems (OSS/BSS) is able to interact with the Element Management System (EMS) that configures the VNFs allocated in the network service and, if allowed by operators' policy, with the NFV-O via the Os-Ma-Nfvo interface.

2.3.2. Deployment of Virtual Infrastructures

The allocation of a VI can be triggered by a tenant (such as a MVNO), either directly consuming the MTA API—Figure 9 API a)—or via the intervention of the infrastructure operator in a less dynamic environment, after an off-line Service Level Agreement (SLA). The VI concept is quite generic and could be extended to incorporate infrastructure elements beyond the ones considered herein. As part of the deployment of the VI, network, computing and storage resources need to be partitioned and aggregated, eventually recursively if a hierarchy is enabled. This partitioning can be committed in full at the time of instantiation (hard allocation) or reflected in terms of pre-defined quotas that are enforced at the time of use (soft allocation).

It is noteworthy that VI allocation follows an IaaS model, so the actual use of the VI (including the functions and related business logic) is defined by the tenant. The infrastructure owner is agnostic to the VI end use. Once a given VI has been allocated, the 5G-Crosshaul MTA empowers the tenants with different degrees of control to be exerted over it, with different operational models of control and management. In simple terms, this ranges between either: (i) the control and management is restricted to the operational management and integration with tenant OSS/BSS, so that the operation of VI is mostly autonomous, with limited involvement of the tenant, such as monitoring and SLA validation, or (ii) each tenant is free to deploy their choice of the infrastructure operating system and control plane, allowing the optimization of the resource usage within each VI.

The former model involves the MTA offering an API that enables the tenant to have a limited form of control over the (abstracted) elements that constitute the VI—Figure 9 API b), including a set of operations and policies that can be applied (e.g., retrieve an aggregated view of the virtual infrastructure topology and resource state and apply rules that affect element configuration and behaviour). In this model low level operations such as the actual configuration and monitoring of individual flows at the nodes may not be allowed. The latter model implies per-tenant controller—Figure 9 API c)—or per-tenant MANO (XCI) including, most importantly, the ability to offer network services over its allocated virtual infrastructure. This approach ultimately enables recursion (as detailed in Section 2.3.5).

2.3.3. Deployment of Network Services

The allocation of a Network Service (NS) extends and complements the concept of VI deployment—Figure 9 API d), to automatically deliver isolated chains of virtual services composed of specific VNFs, and to exploit the sharing of a common physical infrastructure with computing, storage and network resources. The tenant request usually specifies the type of VNFs (i.e., the desired virtual application components) in the NS descriptor, their capabilities and dimensions through one or more VNF descriptors and how they must be interconnected through a VNF-FG descriptor. Templates for the unified description of these information elements are currently under standardization process in the ETSI NFV ISG and in OASIS TOSCA standards [6].

As described in the previous section, in the pure VI case the tenant is responsible for the installation and configuration of its own applications over the allocated virtual infrastructure and it is interested in maintaining a certain level of control on the operation of the low-level virtual resources in its VI. When deploying a NS, instead, the tenant is interested in operating the applications that run in these virtual resources and expects that the needed level of resource capacity is seamlessly available in real-time without any further configuration effort. The deployment and continuous management of the whole service is completely automatized and totally delegated to the MTA and the NFVO within the XCI. The tenant has access to application-level interfaces only and the NS provisioning API follows an "intent-based" modelling approach, where the tenant just asks for the composition of some network functions, without caring about how they should be deployed and delivered.

In this scenario, the MTA is responsible for maintaining and coordinating the logical mapping between tenants and their assigned services, in terms of NS and VNFs instances and underlying virtual resources, in compliance with the established SLAs. Multi-tenancy can be handled at different levels: at lower level, a tenant has assigned physical and/or virtual resources in the domain of a VIM; at upper levels, tenants have assigned VNFs and NSs. These different kinds of tenant can overlap and be merged in a single entity or be mapped over separate entities. For example, a VNO can further virtualize the rented VI to serve different kinds of business customers, like CDN providers, delivering dedicated VNFs and NSs. The management of these tenants' relationships, together with the correlated authorization and SLA validation and assurance procedures, is under the responsibility of the MTA. Moreover, in these scenarios, NSs are not built directly on top of physical resources, but over Virtual Infrastructures through the allocation of VNFs and VNF-FGs in VMs and virtual network nodes, following a recursive approach. This involves the operation of multiple

MTA instances deployed at different levels and requires the mediation of XCI components deployed over the VI itself (further details are provided in Section 2.3.5).

At a lower level of service coordination, the NFVO in the XCI is responsible for the instantiation of the different NS components, based on the descriptors and metadata provided at the instantiation stage by the tenant. The NFVO, with the optional cooperation of the MTA, takes decisions about the most convenient usage of infrastructure resources and allocates the required VMs and network connections accordingly. Moreover, during the NS lifecycle, the NFVO is also responsible for the continuous monitoring of resource failures or infrastructure and application performances, coordinating the automated reactions for up/down-scaling and self-healing procedures at single VNF and global NS level.

2.3.4. Requirements and Enabling Technologies for Realizing Multi-Tenancy

Multi-tenancy support requires a coordinated, holistic approach from the hardware to the XCI controllers up to the application layer, where the MTA acts as a global orchestrating entity. In this section, we present the main requirements to support multi-tenancy at all these layers, analysing the approaches that can be adopted to meet them.

2.3.4.1. Data Plane

When carrying the data of several tenants through the network, several requirements have to be considered:

- Traffic separation. One tenant should not be able to listen to the traffic of other tenants or of the network provider.
- Traffic isolation. The network has to provide guaranteed QoS to traffic of different tenants. Traffic of one tenant should not impact the QoS of the traffic of other tenants.
- Traffic differentiation. The traffic of different tenants may be forwarded differently, even when entering or exiting the network at the same points of attachment.
- Statistical multiplexing. Multiplexing gains should be possible among the traffic of different tenants.

The technical solution for traffic separation and isolation depends on the specific data plane technology adopted for the XFE, circuit or packet switched forwarding. For circuit switched forwarding, traffic separation and isolation can be achieved by creating different circuits per tenant. Although this is beneficial to achieve low and deterministic latency for example, it does not provide statistical multiplexing gains among the traffic of different tenants. For packet switched forwarding, the requirements are supported by using a common frame format across the network and different transmission technologies i.e., the 5G-Crosshaul XCF. We use Provider Backbone Bridge Traffic Engineering (PBB-TE) [7] as common format to encapsulate the tenants' traffic. Note that other frame formats such as, e.g., MPLS-TP could be used alternatively. The XFEs can make use of the additional fields in the PBB-TE header (see Figure 10) to achieve the requirements.

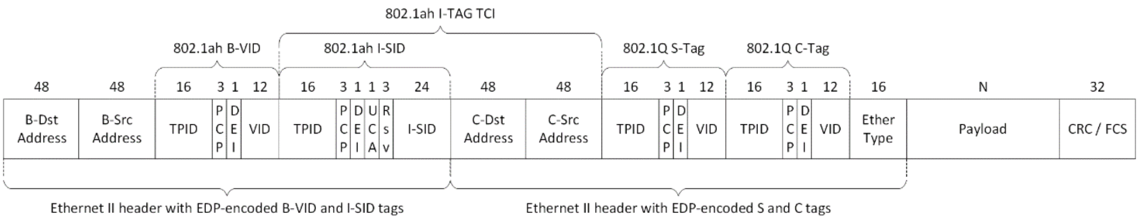


Figure 10 – Provider Backbone Bridge Traffic Engineering (PBB-TE) header

XCF forwarding is harmonized across the network thanks to the adoption of the XPFE as switch and a forwarding abstraction model common to all the XFEs, either circuit or packet based. Such models are defined by the southbound protocols that define the interaction between the data and control planes. We use OpenFlow as the southbound interface for controlling the forwarding of XCF frames. OpenFlow defines a rich set of operations that can be applied to incoming packets for differentiating the forwarding behaviour.

In our solution, the fields in the PBB-TE header are used to achieve the multi-tenancy requirements as follows. Traffic separation is based on the Backbone VLAN ID (B-VID) and the Service ID (I-SID), used to identify the traffic for different tenants by using unique identifiers per tenant or even per service of the tenants. This allows to create different virtual networks and to keep the traffic separate at the XFEs. Independent forwarding decisions are also taken at the level of these separate traffic flows, thus achieving traffic differentiation on a per-tenant basis. Traffic isolation regarding QoS is based on the three priority-code-point bits within the header, used to distinguish different types of service within the network and to schedule the packets forwarding based on this priority information. At the ingress of the network this priority has to be set appropriately and consistently across the different tenants to simplify the rules within the network.

Per-tenant XCF forwarding decisions are elaborated at the control plane and configured on the data plane following a forwarding abstraction model common to all the XFEs, either circuit or packet based. Such models are defined by the southbound protocols that define the interaction between the data and control planes.

2.3.4.2. Control Plane

Support of multi-tenancy has a strong impact on the XCI components, from the network controller to the VIM and MANO components for the orchestration and delivery of VNFs and NSs. At the SDN controller level, multi-tenancy requirements are related to the following aspects:

- Delivery of per-tenant virtual network infrastructures, providing the user with a uniform, abstract and data-plane independent view of its own logical elements, while hiding the visibility of other coexisting virtual networks.

- Logical partitioning of physical resources to allocate logical and isolated network elements handling per-tenant traffic.
- Configuration of traffic forwarding at the data plane level compliant with per-tenant traffic separation, isolation and differentiation in the data plane.

Tenant-based virtual networks delivery is handled through a dedicated SDN controller service. Its north-bound APIs allow authorized tenants to request and operate their own network instances following abstract specifications, e.g., based on intent-based network models. Access to virtual resources is wrapped by the SDN controller and it is regulated at the north bound APIs based on tenants' profiles. Physical resource partitioning is managed within the SDN controller service through resource allocation algorithms combined with procedures to map logical network concepts with their corresponding entities or traffic configurations at the physical level.

Traffic separation is achieved through the creation of tagged connections, exploiting the XCF multi-tenancy features as explained in Section 2.3.4.1. Forwarding rules for the resulting traffic flows are then installed across the physical network following the paths computed by the resource allocation algorithms on a per-tenant basis (traffic isolation), while QoS is handled through the creation of meters or queues (traffic differentiation).

An example of SDN application for provisioning of virtual network infrastructures with multi-tenancy support is the OpenDaylight Virtual Tenant Network (VTN) project [8].

The VTN application allows a tenant to request a virtual network composed of virtual bridges, routers, tunnels, tunnel end points, virtual interfaces and virtual links. The mapping between network packets exchanged between OpenFlow switches at data plane level and instances of virtual networks defined at logical level is based on ports and/or VLANs (see Figure 11). Each virtual network entity implements the typical functions of a corresponding physical element (e.g. virtual routers provide routing, ARP learning and DHCP relay agent functions). Moreover, the tenant has the possibility to control the network behaviour defining a set of actions per flows matching L2-L3 filters.

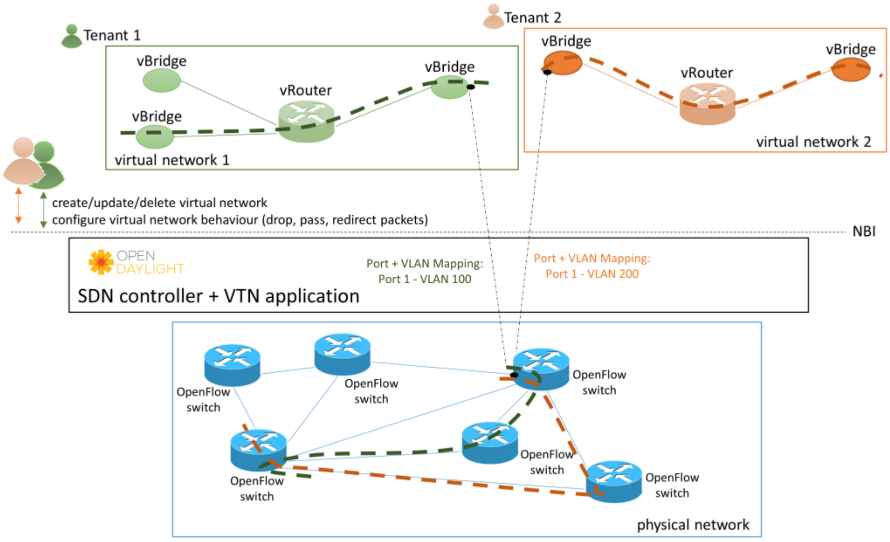


Figure 11 – Virtual networks mapping in OpenDaylight Virtual Tenant Network (VTN) application

At VIM and VNF MANO level, beyond similar considerations on virtual resource allocation and isolation extended to computing elements, a suitable modelling of the tenant and its capabilities needs to be supported. Resource allocation is handled through the creation of virtual machines and software switches assigned to specific tenants within the XPU, with isolation managed allocating specific addressing spaces and configuring proper routing rules and security groups. Tenant profiles are defined at VIM and at NFV Orchestrator. At VIM, each tenant has its own view of the VIM capacity, policies to regulate the access to the resources (e.g. a quota of dedicated resources) and, optionally, custom resource flavors and VM images. Requests for new VI must be authenticated and authorized, and they are evaluated considering the resources still available in the tenant’s quota. Finally, the access to the instantiated VI is strictly limited to the tenant owing the specific instance.

A similar approach, based on per-tenant profiles and policies, needs to be adopted at the NFV Orchestration level, extending the virtual resources concept to VNF and NS entities. Each tenant must have the view and the control on its own VNFs and NSs only. They must be maintained fully isolated from other entities belonging to different tenants, in order to guarantee their security and their desired KPI level, independently on the load of other VNFs. New service requests must be granted depending on the tenant’s profile, in combination with the tenant-related policies at VIM level, which may have an important role in the VIM selection. Currently, this implies extending the functions of the NFVOs to have the tenant separation and identify the mapping of a tenant to a NS.

In general, our MTA approach is based on virtualization and this usually involves refinements in the components architecture, enabling one-to-many and many-to-many relationships of software components and implementing the required mechanisms to guarantee security and isolation. From the point of view of performance, the overhead strongly depends on the underlying infrastructure and technology support (VLAN tagging, separate switching instances, compute resource quotas, etc.) and the need or not to purely emulate such features by software. In our considered use cases, it is largely within acceptable operational ranges.

2.3.4.3. Multi-Tenancy in the Application Plane

A coherent management of multi-tenancy is required horizontally for unifying the concepts of infrastructure virtualization and multi-tenancy in all involved segments and resources. The MTA at the application level provides such a management, becoming the logical decision entity and serving as an optimizer to decide the allocation/modification/deallocation of network, compute and storage resources. Essentially, the application is in charge of deciding an optimum subset of nodes (node mapping) and links (link mapping) in the substrate network to build a VI for a tenant which satisfies its resource demand and SLAs, by solving classical virtual network embedding (VNE) problems.

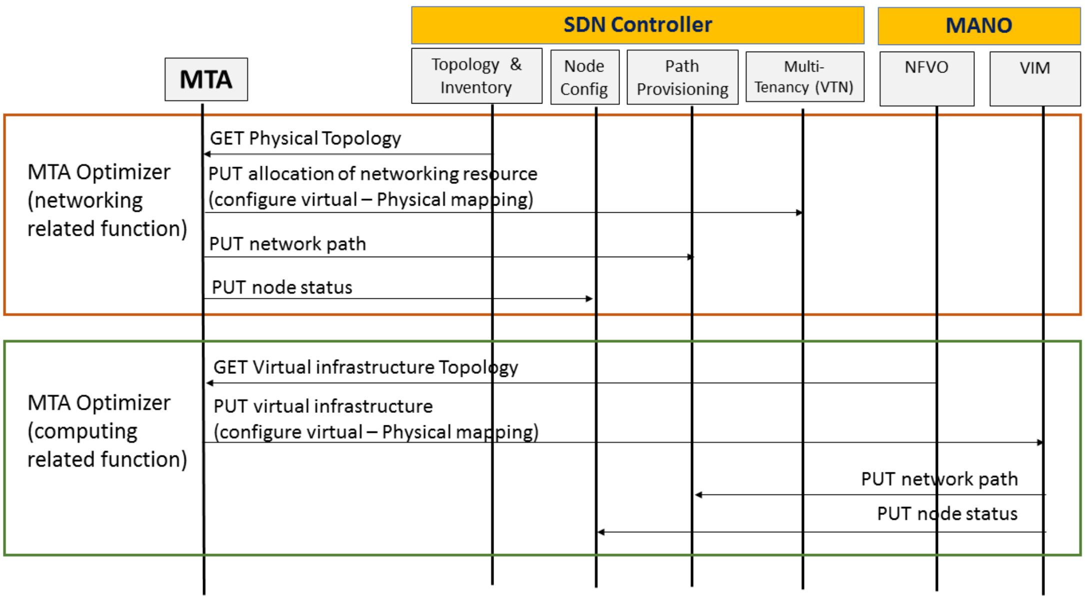


Figure 12 – Workflow of Multi-Tenancy Application: interaction with control plane

A VNE process consists of two coupled sub-problems: node mapping and link mapping problem. The node mapping problem consists of reserving, for each virtual node, enough computational resources of a substrate node without exceeding capacity. Analogously, the link mapping phase consists of finding, for each pair of virtual nodes, a path (i.e., a collection of substrate links) to connect them. The selected paths must satisfy the networking requirements of each virtual link, without exceeding network capacity on the physical links. The problem is recognized as NP-hard, which compromises optimality to find feasible solutions.

To deploy and enforce the computed mapping, the MTA needs to interact/coordinate with several functional entities inside the XCI, namely, the SDN controller, the NFVO and the VIM, either to collect information (GET command) or to provide commands (PUT command) (see Figure 12). The MTA covers both network- and computing-related functions. The actual workflows are strongly dependent on each use case. For the network-related services, the MTA firstly collects information on physical topology, traffic paths and link load through the XCI, then it computes the optimum allocation of networking resources and finally it commands the XCI to perform the required configuration. This may involve direct requests to the SDN controller (to provision network paths and/or to allocate virtual nodes providing the desired mapping between physical and virtual ports). For the computing-related services, the MTA may ask the NFVO to provide a virtual infrastructure topology specifying where the VNFs must be placed or instruct directly the VIM to enforce the mapping between virtual infrastructures and corresponding physical resources. The VIM itself will in turn request the SDN controller for the provisioning of required network paths and related nodes configurations.

2.3.5. Multi-Tenancy Recursion (Multi-MANO)

The 5G-Crosshaul architecture is designed in such a way that multiple providers, each owning its own MANO, can share a common transport infrastructure. We refer to this case as Multi-MANO. The Multi-MANO concept requires a XCI recursion to support multiple instances of the 5G-Crosshaul MANO operating on top of the set of services provided by the XCI instance below.

The 5G-Crosshaul architecture enables this functionality by, on the one hand, providing support and book-keeping of resources, maintaining a consolidated state of the virtual resources provided to each tenant and, on the other hand, by providing a homogeneous API for controlling the underlying virtual resources, which is transparent to the level of the hierarchy where the tenant is operating.

Figure 13 shows the 5G-Crosshaul layered recursive architecture. In the lower layer, the owner of the physical resources (MNO), instantiates its XCI. Different tenants request the provisioning of virtual infrastructures to the MTA. By means of a template, blueprint or SLA, each tenant specifies not only the slice characteristics (topology, QoS, etc.) but also some extended attributes, such as the level of desired resiliency. The provider must take care of meeting the requirements and managing the available resources. Through the use of the MTA application, the resources at the MNO are hidden to the MVNOs, providing a layer of abstraction that eases the management of each slice.

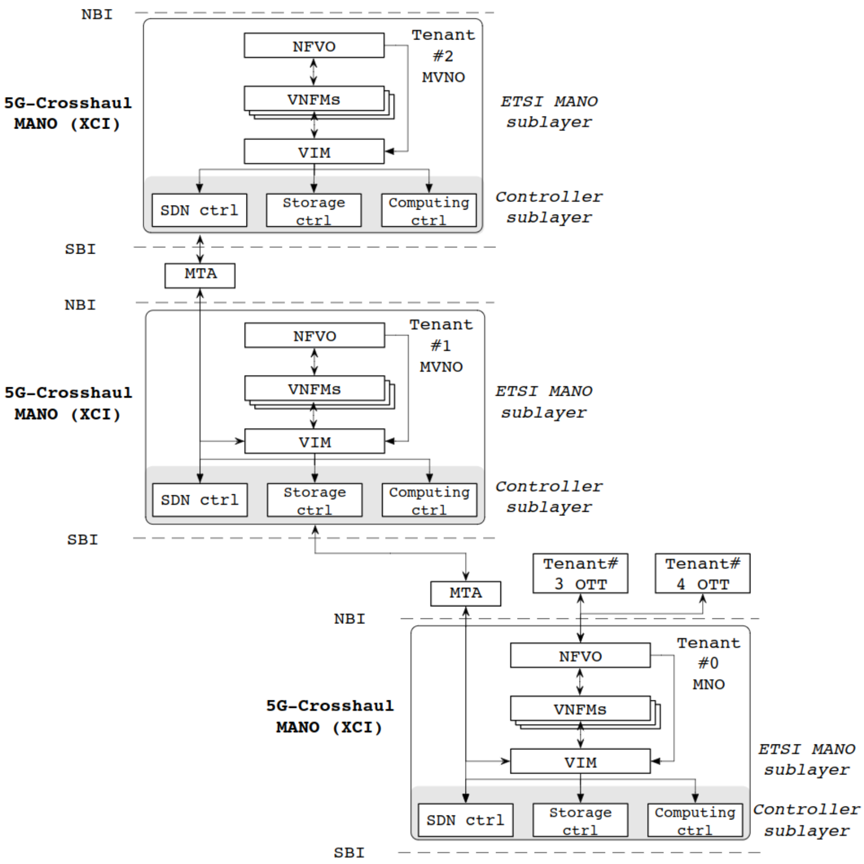


Figure 13 – Crosshaul Control Infrastructure (XCI) Recursion: Multi-MANO

In a recursive and hierarchical manner, each tenant can operate its VI as the MNO operates on the physical one, allocating and reselling part of the resources to other MVNOs. Figure 13 shows this practice between Tenant#1 and Tenant#2, the infrastructure of MVNO#2 operates over the virtual network offered by the MVNO#1 which operates on top of the MNO infrastructure (the physical one).

The multi-tenant architecture presented in this section is very challenging. In order to devise a feasible and flexible framework we have followed the recursion principles of the ONF architecture [3].

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 the resource partitioning are multiple, and there is no formal or standard mechanism to do so. Let us present 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. The 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., 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 a specific tenant or a 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. In some cases, however, some of them seem (apparently) more straightforward (e.g., an OpenFlow switch supporting partitioning could rate limit the control messages after classifying them on a per tenant basis, or Tenant virtual NICs/veths/taps should have rate limiting and traffic conditioning applied).

2.4. Orchestration of Crosshaul Slices from Different 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 investment, 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 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 (typically known as a conjunction of fronthaul and backhaul areas, or 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 also host contents 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 behaviours and performance requirements, thus overcoming current limitations imposed by tight coupling of service and infrastructure.

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). This section focuses on the first case.

As starting point we assume that the Crosshaul domains in a multi-domain infrastructure (e.g., in a federation) include a market place where networking and computing facilities are traded (being this out of the project’s scope). An extension of the traditional concept of telco exchange is needed, covering new needs and capabilities, such as offering resource slices for deployment of services requested by third party service providers.

This section develops the concept of multi-domain Crosshaul by presenting an architectural analysis of a framework to enable the dynamic request of Crosshaul slices through a multi-provider exchange.

2.4.1. Enablement of Dynamic Network Service Deployments

5G-Crosshaul makes available slices of compound resources to different tenants for deploying services as composition of virtualized network functions. In addition to that, networking capabilities can be provided accordingly to connect the network functions among them, and to provide connectivity towards the Crosshaul border. The generic concepts of Service Graph (SG) and Forwarding Graph (FG) can be handled separating service and resource problems at the time of service provision. Multi-domain scenarios introduce 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 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.

2.4.2. 5G-Exchange as market place for multi-domain 5G services

5G-Exchange (5GEx) project[8] 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 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.

5GEx defines an ecosystem for the trading of resources (with the slice as extreme case) in a multi-provider multi-domain environment. The high-level architecture framework of 5GEx, shown in Figure 14, identifies the main functional components and the interworking interfaces involved in multi-provider multi-domain orchestration, where each participating provider represents a distinct operator administrative domain.

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

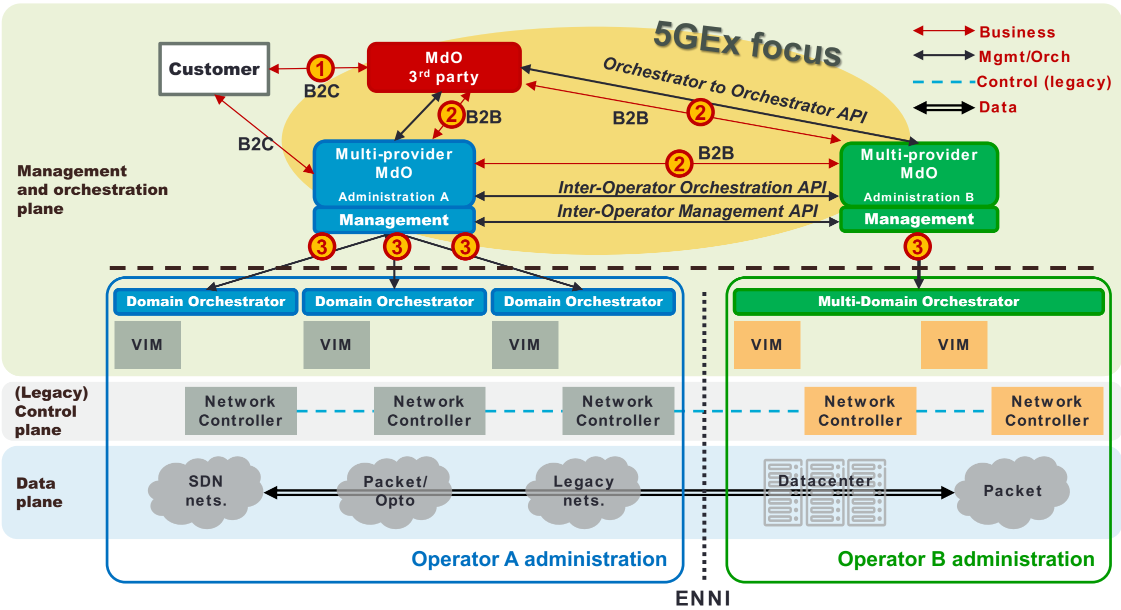


Figure 14 – 5G-Exchange concept

The core of 5GEx system is composed of *(i)* the multi-domain orchestrator, that is actually a Multi-provider multi-domain orchestrator (MP-MdO), *(ii)* various single domain orchestrators for the single provider 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 providers takes place at the higher level through the inter-operator orchestration API, I_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 I_1, through which customers request service deployment. The MP-MdO maps service requests into own resource domains and/or dispatches them to other operators through interface I_2. This interaction is performed at MP-MdO level: each operator MP-MdO can expose to other operators' MP-MdOs an abstract view of its resource domains and available service functions. Using such an inter-working architecture for multi-provider and 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 MP-MdO enforces the decision through interface I_3 as exposed by its Domain Orchestrators, each one orchestrating and managing resource domains exposed by technology-specific controllers.

Different steps are needed for service provisioning in a multi providers' domain environment. The following ones can be identified as basic stages in the service provision: *(i)* discovery; *(ii)* request; *(iii)* fulfilment; and *(iv)* assurance. Then, the aforementioned interfaces should incorporate capabilities for each of these steps. These means to consider different implementations for each of such stages. From the perspective of interfaces functional capabilities, the functional split considered on each of them is related to service management (*-S* functionality), VNF lifecycle management (*-F*), catalogues (*-C*), resource topology (*-RT*), resource control (*-RC*) and monitoring (*-Mon*).

The association of the stages with the described functional split is as follows:

- Discovery phase will be accomplished by I_x*-C* and I_x*-RT* interfaces
- Service request phase will be accomplished by I_x*-S* interface
- Fulfillment phase will be accomplished by I_x*-F* and I_x*-RC* interfaces
- Assurance phase will be accomplished by I_x*-Mon* interface (even fulfillment actions through I_x*-F* and I_x*-RC* interfaces are expected as well during this phase, as result of the data collected for monitoring and service assurance).

Figure 15 highlights three different administrative domains (A, B and C) involved in the multi-provider multi-domain service/resource orchestration process. All the providers in 5GEx are considered to contain the same components and modules (the Operator-Operator relationships are symmetrical in 5GEx), although in Figure 15 the complete view is only shown for the provider on the left (for illustration purposes), just showing exemplary consumer-provider roles with arrows from consumer to provider functional blocks. In the figure, Operator Domain A (left-hand) consumes virtualization services of Operator B (transit domain, in the middle) and Operator C (right-hand).

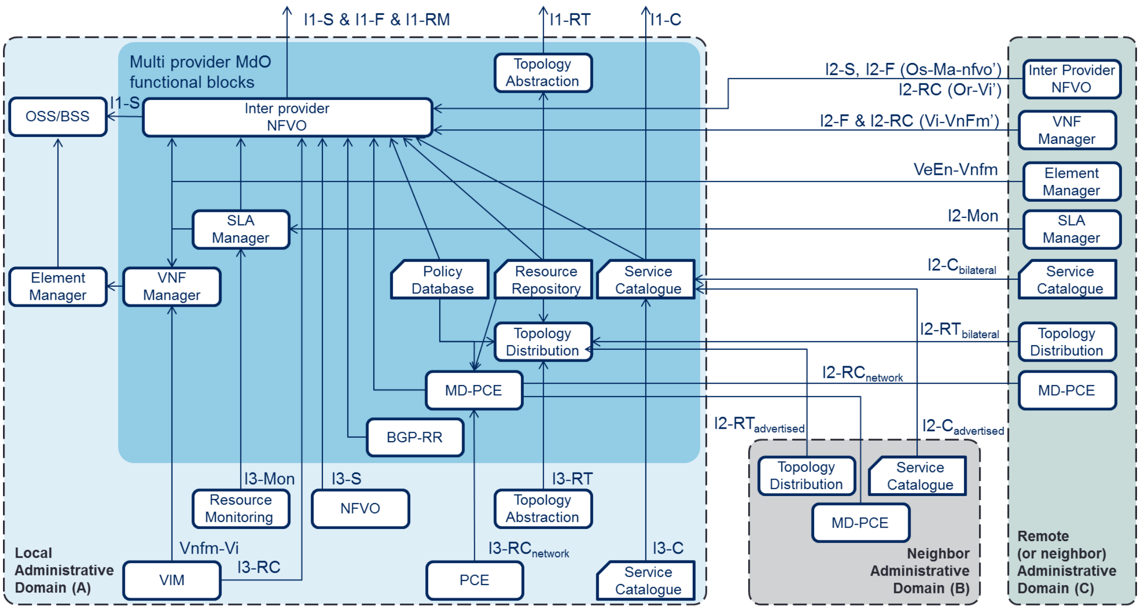


Figure 15 – 5GEx unctional model of multi domain orchestration

For multi-provider network service orchestration, the multi-provider multi-domain orchestrator (MP-MdO) offers Network Services by exposing an OSS/BSS-Inter Provider NFVO interface to other multi-domain Orchestrators from other providers. For multi-provider resource orchestration, the MP-MdO presents a VIM-like view and exposes an extended NFVO-VIM interface to other MP-MdOs. The multi-provider

MdO exposes a northbound interface (*I_1-S*) through which a customer (e.g., a vertical industry) sends the initial request for services and handles command and control functions to instantiate network services. Such functions can include the request for the instantiation and interconnection of Network Functions (NFs). Interface *I_2-S* is meant to perform similar operations between MdOs of different administrative (i.e. operator) domains.

Interfaces *I_3-RT* and *I_2-RT* are used to keep an updated global view of the underlying infrastructure topology exposed by domain orchestrators.

The service catalogue exposes available services to customers on interface *I_1-C* and to other service operators' MdOs on interface *I_2-C*.

Finally, resource orchestration related interfaces are broken up to *I_2-RC*, *I_2-Mon* to reflect resource control and resource monitoring respectively. Furthermore, the notation introduced before is generalized and also used for interfaces I_3 and I_1.

2.4.3. Integration analysis of 5G-Crosshaul and 5G-Exchange Architectures

After the review of both 5G-Crosshaul and 5GEx architectures, the integration analysis performed by both projects indicates that functional adaptation is feasible for allowing the trading of 5G-Crosshaul slices through 5G-Exchange. However, there are yet some gaps that would require certain extension in 5G-Crosshaul for full compliance with a 5GEx ecosystem. This section summarizes these aspects as follows.

- **Statistics and monitoring of Crosshaul resources.** The current 5G-Crosshaul architecture supports the collection of both IT and network statistics, as well as analytic reports elaborated on top of the previous mentioned monitoring information. All of this could be reported as part of the 5GEx *I_2-Mon* interface, providing operational information to other administrative domains requesting Crosshaul services.
- **Topology and Inventory.** The topology information is critical in a multi-domain environment in order to make the right decisions for placement of functions and connectivity. 5G-Crosshaul supports both network and IT topology and inventory reporting, and thus enables the dissemination of this information outside the Crosshaul domain borders. This topology and inventory information can be provided at the 5GEx *I_2-RT* interface, for feeding the resource and topology functional blocks of the MdOs of the other provider domains in the Exchange.
- **Provisioning and Control of resources.** The XCI in 5G-Crosshaul facilitates the control of the networking resources to fit the underlying forwarding elements to the needs of the flows to be transported in the Crosshaul area. This capability can be easily integrated in 5GEx by mapping it to the *I_2-RC* interface.
- **VNF management and orchestration.** 5G-Crosshaul permits to accomplish the full management of the VNF lifecycle via the XCI. The APIs offered by 5G-Crosshaul for this function can be homologated to the *I_2-F* interface in 5GEx.

With the integration in a multi-provider multi-domain environment, the 5G-Crosshaul XCI and the applications on top of it (as defined nowadays) become the 5GEx MP-MdO. Thanks to the recursive properties of XCI, also a dedicated XCI could be devoted to multi-provider/multi-domain aspects interacting as a client with a XCI instance below focused on the Crosshaul domain.

Interestingly, the VIMaP functional block in 5G-Crosshaul provides additional capabilities for planning as an extension of the usual VIM functionality. These planning capabilities can be quite useful on assisting the decisions for placement and connectivity in certain services, as the VNFaaS proposition in 5GEx. In this sense, the I_2-*F* interface from 5GEx could be augmented to support the interaction with the VIMaP module in 5G-Crosshaul in this direction.

There are instead some other functions not present in 5G-Crosshaul. The missing capabilities are the ones related to business support. Here there is a brief summarization of the findings:

- **Business support.** Specially, the population of the services supported in 5G-Crosshaul in terms of catalogue of services is not yet defined. This feature is necessary for advertising the capabilities of each Crosshaul environment in an area in terms of networking and computing resources, as well as some added value services that could complement the offer.
  In order to complement the 5G-Crosshaul architecture, a new functional module would be required on top of the XCI, in charge of disseminating to other domains the Crosshaul capabilities supported in such domain. This new block, the 5G-Crosshaul service catalogue would be placed at the same level as the other applications defined in 5G-Crosshaul (e.g., Resource Management, Energy Management, etc). In addition, this block is required to support 5GEx I_2-*C* interface for integration on 5GEx ecosystem.
- **Service specification and request**. In a multi-provider multi-domain environment such as 5GEx, it is necessary to have a common understanding on the services offered by each of the participants in the Exchange. To do that, the same semantics and abstractions have to be handled by the different administrative domains in order to ensure consistency. Such abstractions at technical level imply the utilization of common information and data models for the resources to be configured and used. In the case of integrating 5G-Crosshaul in a 5GEx environment, the former has to support the request of services through 5GEx I_2-*S* interface.

2.5. Eastbound/Westbound towards neighboring network domains (RAN and Core Network)

2.5.1. Architecture View

In 5G-Crosshaul 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, as shown in Figure 3, contemplates a WBI to communicate with the 5G Core MANO and an EBI to interact with the 5G Access MANO.

In both 5G Core and Access MANO cases, different architectural approaches could be preferred. Assuming the 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 management and orchestration operations (abstracted level of operations and information available) with a peer-to-peer structure.

In the case of 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 can be used and detailed monitoring information and low-level management and orchestration operations are enabled, thanks to such a hierarchical structure.

In the following, we review both types of relationship: hierarchical and peer-to-peer relationship.

2.5.1.1. Hierarchical Structure

A global orchestration engine controls the MANO of each domain (RAN, transport and Core) via northbound-southbound interfaces. Projects like 5G NORMA [9] define NBI/SBI to communicate with other network domains.

The objective of 5G NORMA mobile network architecture is to allow for integrating different technologies and enabling different use cases. Due to the partly conflicting requirements, it is necessary to use the right functionality at the right place and time within the network. In order to provide this flexibility, the NFV paradigm is adopted in the mobile access and core network domains, enabling mobile network functionality to be decomposed into smaller functional blocks, which are flexibly instantiated.

The 5G NORMA functional control and data layer incorporates the novel concept of software-defined mobile network control (SDMC). The interfaces of those novel centralized SDMC-enabled control functions run as applications on top of the SDM coordinator (SDM-X) or SDM controller (SDM-C). The interfaces enable the SDMC applications to control the “legacy” distributed control functions as well as the distributed data layer functions.

[9] https://5g-ppp.eu/5g-norma/

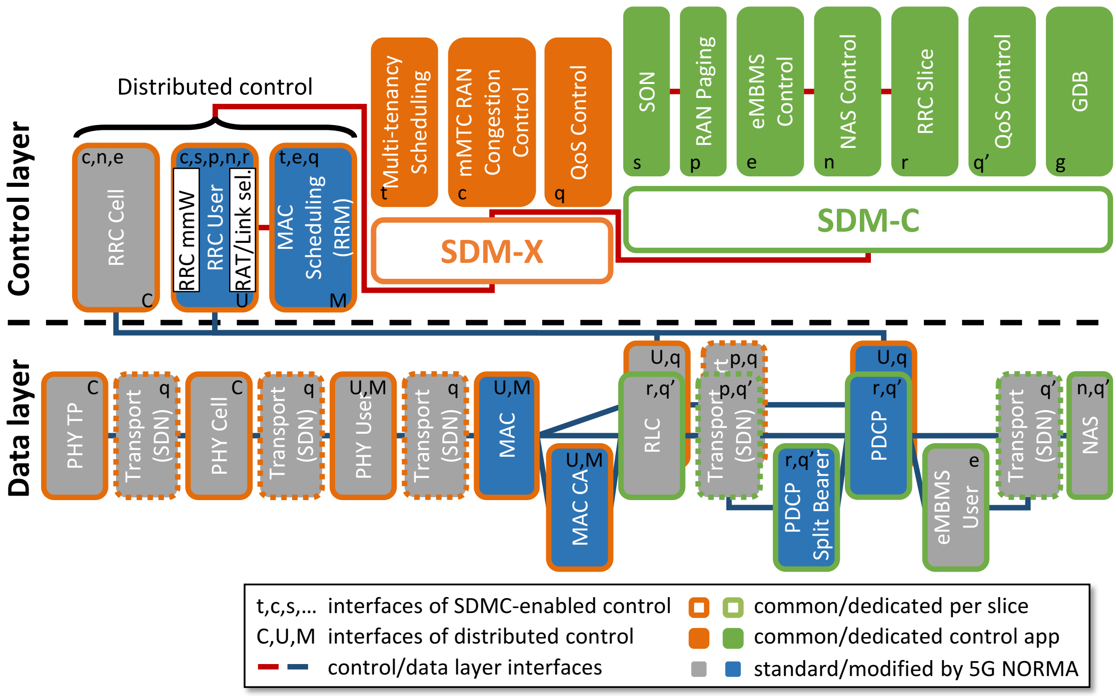


Figure 16 – 5G NORMA control and data layer functional architecture

The control/data-layer architecture is depicted in Figure 16, here for the case of RAN slicing i.e., with a common MAC layer. Functions are classified whether they belong to the control or data layer. The control layer functions are further classified into i) distributed, ii) common and iii) dedicated control. Distributed control functions are implemented as VNFs throughout the network, while common and dedicated control functions employ the SDMC concept and run as applications on top of SDM-X and SDM-C, respectively.

The SDM-C and SDM-X configure the 5G network architecture including NFs and SDN transport elements via their SBI. A SBI provides an abstraction of the NF to the SDM-C/X, enabling direct representation of the NF behaviour and requirements. The SDMC applications presented below require a specific set of information to operate. The SDM-C/X extracts such information from the distributed data and control layer NF via the SBI.

2.5.1.2. Integration of 5G-Crosshaul and 5G NORMA Architectures

5G NORMA and 5G-Crosshaul cover together the complete design of the operator network. Both network architectures design will be built on the network function virtualization and software defined networking paradigms and will support infrastructure sharing and multi-tenancy. While 5G NORMA is focused on the core and radio access network domains, 5G-Crosshaul controls and manages the transport domain, providing both architectures a complementary role and a complete design of the whole network, as shown in Figure 17.

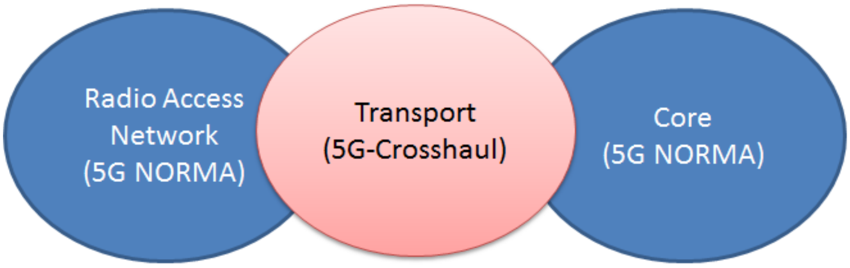


Figure 17 – Complementary project roles

2.6. Summary

This chapter has presented the final and consolidated architecture of 5G-Crosshaul project. The baseline architecture represented by the single MANO case describes the three planes considered in line with ONF architecture, that is, Data, Control and Application planes. The interfaces used for these planes are also described.

Apart of the single MANO case, insights are provided for the multi-technology domain case, presenting hierarchical approach to the SDN control for comprehensively control the distinct technologies present in 5G-Crosshaul.

An in depth view of multi-tenancy concept is also provided, as key enabler of the slicing concept in future 5G networks.

Finally, for the interaction with neighboring network domains (i.e., RAN and mobile core) the project has analyzed both hierarchical and peer-to-peer structures. This is in line with the architectures of 5G-NORMA and 5G-Exchange projects.

3. Cost and energy evaluations

This chapter performs the techno-economic analysis of 5G-Crosshaul from different dimensions. In one hand, deployment costs are taken into consideration for different scenarios and configurations, ranging from last mile to a complete regional network. Furthermore, such analysis is complemented with the economic impact evaluation of two functional capabilities as provided by 5G-Crosshaul: the efficient management of energy consumption, and the multi-tenancy of the underlying infrastructure.

3.1. Reference data for CapEx, OpEx and energy

This section summarizes the reference costs for the equipment used in the present legacy scenario and in the 5G-Crosshaul one.

The legacy network is a metro network where L1 and L2 equipment are not integrated as in the 5G-Crosshaul scenario, and are based on commercially available systems including proprietary control planes, whose costs are reported at the time this activity started, i.e. 2016, and for 2020, with a forecast obtained starting from different reference sources of present or past years.

For the 5G-Crosshaul network, besides the integration of L1 and L2 equipment into the XFE, there is also integration at chip level for some functions presently performed by different equipment boards.

All the costs reported in the following are expressed in 5G-Crosshaul Cost Unit (XCU), in other words they are normalized to the cost of a grey 10G SFP Short Reach transceiver as available at the beginning of 2016 [10].

3.1.1. Reference data for CapEx model

Reference data is elaborated for subsequent techno-economic analysis for both CapEx and OpEx. The Capex costs are provided for both legacy and 5G-Crosshaul solutions.

3.1.1.1. Legacy systems

The cost of legacy equipment has been derived from different sources. In most cases they are based on referenced public data, in particular from manufacturers data involved in the 5G-Crosshaul project, from European projects or OVUM Consulting[10] analysts estimation. In some cases, the prices have been derived from internal data of the Telco operators in the project (TIM, Orange, Telefonica). All these costs are reported in Table 2 and are expressed in XCU units together with the amortization period for the investment.

The costs of L1 and L2 access equipment used for fronthauling (see Section 3.2) have been assessed by Orange, that has evaluated the current prices of installed field equipment, supporting CPRI3, or equipment on which experimentation is on-going for higher layer functional splits fronthauling in the next future. For low layer split, passive

[10] https://ovum.informa.com/

CWDM at 16 channels (i.e. passive MUX/DEMUX 1:16) or access switch for CPRI over Ethernet have been considered, with prices of 2016 reported in Table 2. The related costs of transceivers are also reported, specifically SFP CPRI3 long reach for CWDM and SFP CPRI3 short reach together with SFP+ 25GEth long reach for CPRI over Ethernet. In the Table 2 they are also reported the costs of Mux/Demux at 4 or 8 wavelengths, used for Telefonica costs calculation (see section 3.3). For the higher layer functional split at PDCP/RLC level, an Ethernet access switch is considered (because it needs to manage a lower amount of traffic) together with short and long reach 1 GEth SFPs.

The cost of the packet L2 switch aggregation/metro network is mostly forecasted starting from the EU FP7 STRONGEST project [11], that published its costs estimation on MPLS-TP L2 switches also in a scientific paper dating 2013 [12]. For some equipment parts, the estimation derives from public costs on Cisco SR SFP modules available at the end of 2016 [13]. The economical values of the L2 switch fabric (or matrix), having a capacity from 320G to 19.2T, have been projected to 2020 assuming a cost reduction of 9% per year from the initial 2012 STRONGEST costs, therefore for a total amount of 8 years. The cost of the 100G matrix has been estimated using a re-parameterization factor depending on switch fabric capacity. As regards the grey transceivers, the yearly 9% cost reduction results are in line with Cisco prices for the 1G transceivers, while it has been noticed that for 10G and 40G transceivers the cost forecast to 2020 was even higher than today Cisco prices. For this reason, starting from real prices at the end of 2016, a further reduction of 36% has been considered that takes into account the 4 years until 2020. The cost of the 100G transceiver has been estimated to be 2.5 times the cost of the 40G transceiver, as done in the STRONGEST project. The costs of colored transceivers (that can be used together with passive CWDM also on RRHs and BBUs, as suggested by Telefonica in section 3.2), derive from the STRONGEST project, applying again the 9% per year of cost reduction from 2012 to 2020. The costs of tributary and line cards, where interfaces at 1G, 10G, 40G and 100G are inserted, have been estimated with the usual 9% per year of cost reduction till 2020.

The cost of the L1 Metro ROADM is based on TIM internal data provided by manufacturers for a case study activity performed in 2014. The alternatives of using the EU FP7 STRONGEST or IDEALIST project data [14] have been considered not viable because these costs refer to long haul equipment whose parts, line system, add/drop module and transponder, have prices much higher than the metro ones. All costs have been projected to 2020 using the 9% yearly price saving. As regards the 100G transponder, it has been used an OVUM Consulting estimation w.r.t. the 10G transponder cost, that attributes to the 100G transponders in 2016 and 2020 a cost that is respectively about 3 times and about 6 times the cost of the 10G transponder [15]. The price of the 40G transponder has been estimated to be 2.5 times less than the 100G one. Regarding the Muxponders considered in the Telefonica cost model, the only available reference is the STRONGEST project, used considering the yearly 9% of price reduction.

For the central office router used in Telefonica analysis, the prices for common parts and cards refer to an equipment with 2.24 Tbit/s of routing capacity and 16 slots at 140 Gbit/s, and derive from the routers analyzed in the STRONGEST project, with the 9% yearly cost reduction till 2020.

For the NG-PON2 WDM P2P connection, two OVUM estimations have been used for OLT and ONT ([16],). According to the first OVUM reference, the cost of the OLT for NG-PON2 can be estimated to be 50 times the cost of GPON. Therefore, starting from TIM internal data on GPON costs dating 2014, a cost projection to 2020 has been performed considering the usual 9% per year of cost reduction, and the final result has been multiplied by 50. Regarding the OLT port and the ONT, in the second reference document OVUM has reported some precise costs in dollars that have been simply converted into the XCU prices.

For microwave devices, data from the EBLink manufacturer have been used, specifically on a couple of FrontLink 58-60 equipment with CPRI transmission from 2.5 G to 7.5 G. As in the other cases, the 2016 costs have been projected to 2020 with a 9% yearly price reduction.

For mobile nodes (RRH and BBU) the costs derive from today TIM internal data. The prices refer to an RRH with two transmitters for one sector and to a BBU without expansion module, in both cases considering the usual 9% yearly saving.

Finally, if we consider the fibers deployed by the Telco Operator, we must include them in the CapEx items. Their price includes digging, trenching and deployment activities and the amortization period considered is 25 years. In this case the data source comes from Telefonica that gives a cost per fiber per Gbit/s per km.

Table 2 – Legacy CapEx in 2016 and 2020

Legacy CapEx	Cost 2016 [XCU]	Cost 2020 [XCU]	Amortization period [years]
L1 Access passive CWDM			
Mux/Demux 1:4	-	1.07	
Mux/Demux 1:8	-	3.21	
Mux/Demux 1:16	5.36	3.79	
SFP CPRI 3 CWDM long reach	1.25	-	
L2 Access Switch			
Access switch for CPRI over Ethernet	7.14	-	
Access switch for Eth high layer RAN split	1.79	-	
SFP 1GETh short reach	0.36	-	
SFP 1GETh long reach	0.71	-	
SFP CPRI3 short reach	0.54	-	
SFP+ 25GEth long reach	5.36	-	
L2 Metro / Aggregation Network			
L2 Matrix 100 G & CP	18.90	12.96	5

L2 Matrix 320 G & CP	60.49	41.48	5
L2 Matrix 640 G & CP	83.27	57.10	5
L2 Matrix 1,6 T & CP	244.91	167.95	5
L2 Matrix 3,2 T & CP	734.73	503.84	5
L2 Matrix 4,8 T & CP	1102.10	755.76	5
L2 Matrix 6,4 T & & CP	1469.46	1007.69	5
L2 Switch 12,8 T & CP	2351.14	1612.29	5
L2 Switch 19,2 T & CP	3526.71	2418.44	5
L2 card 10x10G	83.27	57.10	5
L2 card 10x40G	265.48	182.05	5
L2 card 4x100G	331.85	227.57	5
L2 10G SR grey transceiver	0.89	0.61	5
L2 40G SR grey transcv.	4.31	2.95	5
L2 100G SR grey transcv.	24.49	16.79	5
Colored 10G SFP transceiver	-	5.76	5
Colored 40G SFP transceiver	-	35.84	5
Colored 100G SFP transceiver	-	89.60	5
L1 Metro FOADM/ROADM			
Common parts	16.67	12.56	5
Line syst FOADM 4 deg.	14.53	8.25	5
Line syst. ROADM 9 deg.	45.69	25.95	5
Line syst. ROADM 20 deg.	71.80	40.77	5
Add/drop FOADM	14.53	8.25	5
Add/drop ROADM 9	45.69	25.95	5
Add/drop ROADM 20	71.80	40.77	5
Transponder 100G	241.77	137.29	5
Transponder 40 G	96.71	54.92	5
Transponder 10G	12.22	6.94	5
Muxponder 4 x 10G	-	32.00	5
Muxponder 2 x 40G	-	102.40	5
Muxponder 10 x 10G	-	83.20	5
Muxponder 10 x 40G	-	154.57	5
Muxponder 4 x 100G	-	139.11	5
Optical in Line Amplifier	14.29	8.11	7
Central Office Router			
2.24 Tbit/s Router	-	344.26	5
IP card 48 x 1G		182.72	5
IP card 14 x 10G	-	204.67	5
IP card 1 x 100G	-	230.40	5
NGPON2			
WDM PON 10G P2P	-	54.93	10
MOBILE nodes			
RRH	4.56	3.13	5
BBU	4.92	3.37	5
MicroWave			

FrontLink 58-60 CPRI Opt. 3 (2.5G)	34.54	23.68	5
FrontLink 58-60 2xCPRI Opt.3 (5G)	41.68	28.58	5
FrontLink 58-60 3xCPRI Opt.3 (7.5G)	48.82	33.48	5
Fiber deployment			
Digging, trenching & fiber deployment	4.25	4.25	25

3.1.1.2. 5G-Crosshaul systems

The costs of 5G-Crosshaul equipment are based from one side on Ericsson projects development of future L1 Silicon Photonics (SiP) ROADM and on the other side from TIM internal data on L2 switches based on single chip solution used in other SDN/NFV research projects. The costs of XCI and XPU are those of present servers used for controller and network function virtualization. All the prices are summarized in Table 3.

The 5G-Crosshaul Circuit Switching Element (XCSE) is the future Ericsson Silicon over Photonics ROADM, which comprises 12/24 WDM channels at 100G and two-line systems for ring interconnection. In case more line degrees are required, this XCSE integrates the add/drop functions and interfaces between the transponders and the classical Wavelength Selective Switching (WSS) used for line systems, obtaining an equipment with 48 wavelength channels and a capacity of tens of Terabit/s (see IRIS project, [17]). The 100G transponders are based on new economically viable modulation formats such as CAPS-3, that is suitable for the short haul systems of the 5G-Crosshaul project, leading to a price reduction (including DCF - Dispersion Compensation Fiber) of about 40% w.r.t. legacy DP-QPSK transponders. In general, the SiP solution together with these new optical interfaces reduces the price of the 12-channels system to about the 30% of the cost of a legacy ROADM in 2020.

The cost estimations of the XPFE are based on TIM internal data on equipment used in SDN/NFV research projects, in particular on switches operating at 720 Gbit/s based on the Broadcom single chip solution, integrating switch fabric, tributary and line cards. Solutions at higher rates are also available with the Broadcom chip BCM88650 [18], (a 200G packet processor, with traffic manager & fabric interface in a single chip device), that can be interconnected as stackable boxes allowing up to 1.6 Tbit/s of traffic capacity and furthermore, with the interconnection to BCM88750 switch fabrics, the throughput may achieve up to 25 Tbit/s. For the whole XPFE estimation, the costs of the grey transceivers have been considered the same as those forecasted for the legacy equipment. The final 2020 cost of these new SDN switches will be about 20-25% of the price of legacy L2 systems.

The cost of the XCI is that of two typical medium size servers (one server needed for redundancy purpose). A server as the one used in 5G-Crosshaul experimentation, based on an Intel Hexa-Core Xeon E5-2420, with 96 GB of RAM and 4 TB of hard disk, costs about 17,86 XCU. Concerning the XPU, we must consider that present high-end size servers, with 2 Xeon CPU (12 cores each) and 192 GB of RAM, can support traffic rates of 40 Gbit/s and up to 100 Gbit/s which is expected in the future, and cost about 25 XCU (including the storage functionality). Therefore, the number of servers needed to provide XPU functionalities in the 5G-Crosshaul architecture will depend on traffic estimation for 2020. From this data, it is possible to calculate the total XPU cost.

Table 3 – 5G-Crosshaul CapEx in 2020

Crosshaul CapEx	Cost 2020 [XCU]	Amortization period [years]
XPFE (L2 PBB SDN Switch)		
Basic node 1.6T	45.54	5
Basic node 3.2T	182.14	5
Basic node 6.4T	364.27	5
Basic node 12.8T	728.54	5
Basic node 19.2T	1092.82	5
L2 10G grey transcv.	0.61	5
L2 40G grey transcv.	2.95	5
L2 100G grey transcv.	7.39	5
XCSE (L1 SiP mini-ROADM)		
Common parts 2 nodal degree	7.14	5
Common parts IRIS 8 degree	117.86	5
Transponder 100G + DCF	8.93	5
Servers		
XCI	17.86	5
XPU	25.00	5

3.1.2. Reference data for OpEx model

The items considered for OpEx evaluations are the following ones:

- The rented space for equipment allocation (also named "footprint").
- The energy consumption for power supply and cooling.
- The renting of the transport media (e.g., fiber).
- The maintenance costs.

All the costs considered by the TIM cost model (section 3.4) are reported in, being the same for all network scenarios and for the two periods (2016 and 2020).

The equipment hosting prices may vary from one nation to another and also from urban, suburban or countryside sites. A reference rental offer, from Telecom Italia Wholesale for colocation services to Other Licensed Operator (OLO) customers [19], gives the costs for space rental of an ETSI N3 Rack Unit and for power supply and air conditioning facilities. In our model, we have considered a space occupancy price for typical equipment consuming more or less 800-900 W.

The hosting cost reported in Table 4 does not include the power consumption for equipment operation and air conditioning, that the TI Wholesale document offers to 0.00056 XCU per kWh for power supply and to 0.00045 XCU per KWh for air conditioning, thus giving the total result shown in Table 4.

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%, as already done in the IDEALIST project. These items include the manpower for maintenance and repairs after failures, the spare parts and warehouse costs. Therefore, the maintenance costs have been considered to be an average of 4% w.r.t. CapEx.

As already stated in previous paragraphs, the fiber infrastructure can be considered as a CapEx item or, in some business context like transnational operators, the fiber may be rented, thus becoming an OpEx item. The single fiber rental, derived from IDEALIST project, amounts to 0.83 XCU per Gbit/s per km per year.

Table 4 – OpEx for Legacy and 5G-Crosshaul scenarios

OpEx	Cost [XCU]
Fiber Rental	
Fiber rental per km per year	0.83
Equipment hosting per year	
1 Rack with 4 shelves	10.28
Power supply and conditioning	
Power per kWh	0.001
Maintenance	
Maintenance_cost_percentage	4%

The OpEx considered by the Telefonica cost model is reported in section 3.2, and includes also service provisioning and management.

3.1.3. Reference data for energy model

The reference data used to calculate the energy consumptions and costs of the different equipment derive from network operators' laboratory set-up and on-field installations or from manufacturers' data sheets and vendors forecast on future devices. Table 5 summarizes the power consumptions expected for legacy and 5G-Crosshaul systems, expressed in KWh per Gbit/s per year.

The energy of legacy DWDM equipment refers to a vendor data sheet for 8.8 Tbit/s ROADM [20], that declares a maximum required power of 1270 W, from which it derives a per year power consumption of 1.26 KWh per Gbit/s. The energy of legacy L2 equipment has been obtained starting from TIM information on MPLS-TP switches with 320 Gbit/s matrix, whose consumption amounts to about 816 W. From this value, we obtain 22.34 KWh of power consumption per Gbit/s per year.

For the 5G-Crosshaul XCSE developed inside the project, based on SiP ROADM with 12/24 channels at 100G and 2 line systems, TEI estimates a power consumption of 2 W for the chip module and 120 W for the PAM4 or DMT transponder at 100 Gbit/s. These data lead to a value of about 0.89 KWh per Gbit/s per year.

For the 5G-Crosshaul XPFE, we have considered TIM information on SDN/NFV switches at 720 Gbit/s with Broadcom single chip solution, whose typical power consumption is declared to be 282 W, and Cisco data on grey transceivers. In particular, the 1G and 10G modules should consume 1 W [21], while the 40G and 100G modules should consume 3.5 W [22] [23]. With these data, the calculation on a fully equipped XPFE has given a value of power consumption per year of 4.61 KWh per Gbit/s. The estimation of power dissipation for NG-PON2 WDM P2P connection was taken from a publication of the FP7 EU TREND (Towards Real Energy-efficient Network Design) project [24], and shows a total of 23.4 W for a 10G OLT port plus ONT, that corresponds to 20.5 KWh per Gbit/s per year.

Regarding microwave devices, EBLink has indicated a power consumption of 50 W for the FrontLink 58-60 equipment, from which they derive the data reported in Table 5 for transporting the different number CPRI3 flows.

For mobile nodes (RRH and BBU) the power consumptions information is from today's TIM internal data. In particular, we have considered that the power efficiency of the radio module presently amounts only to 15%, so that 20 W of power per sector requires 133 W for the RRH plus RF module. The total measured busy hours power, consumed by a system composed by the BBU, a three-sector antenna and the transport element, amounts to about 688W. This means that about 289 W can be attributed to the BBU and the transport equipment, that means about 250 W required by the BBU.

For what it concerns the XCI and XPU servers, a power consumption of 350 W for the XCI and 400 W for the XPU have been estimated considering today available servers. For the XCI, the management traffic should not overcome the 10 Gbit/s, while for the XPU the future capability to manage 100 Gbit/s of data traffic has been considered. From this information, the following values are derived in Table 5**.**

Table 5 – Energy consumption for Legacy and 5G-Crosshaul scenarios

Equipment Energy consumption	Power [kWh/Gbit/s/year]
NGPON2	
WDM PON 10G P2P	20.5
Legacy L2	
L2 Switch	22.34
Legacy L1	
FOADM/ROADM	1.26
Mobile	
RRH	116.51
BBU	18.25
MicroWave	
FrontLink 58-60 CPRI Opt. 3 (2.5G)	356.39
FrontLink 58-60 2xCPRI Opt.3 (5G)	178.19
FrontLink 58-60 3xCPRI Opt.3 (7.5G)	118.80
5G-Crosshaul L2	
XCFE (PBB SDN switch)	4.61
5G-Crosshaul L1	

XCSE (SiP ROADM)	0.89
5G Crosshaul Servers	
XCI	306.60
PU	35.04

3.2. Design and cost evaluation of fixed access network

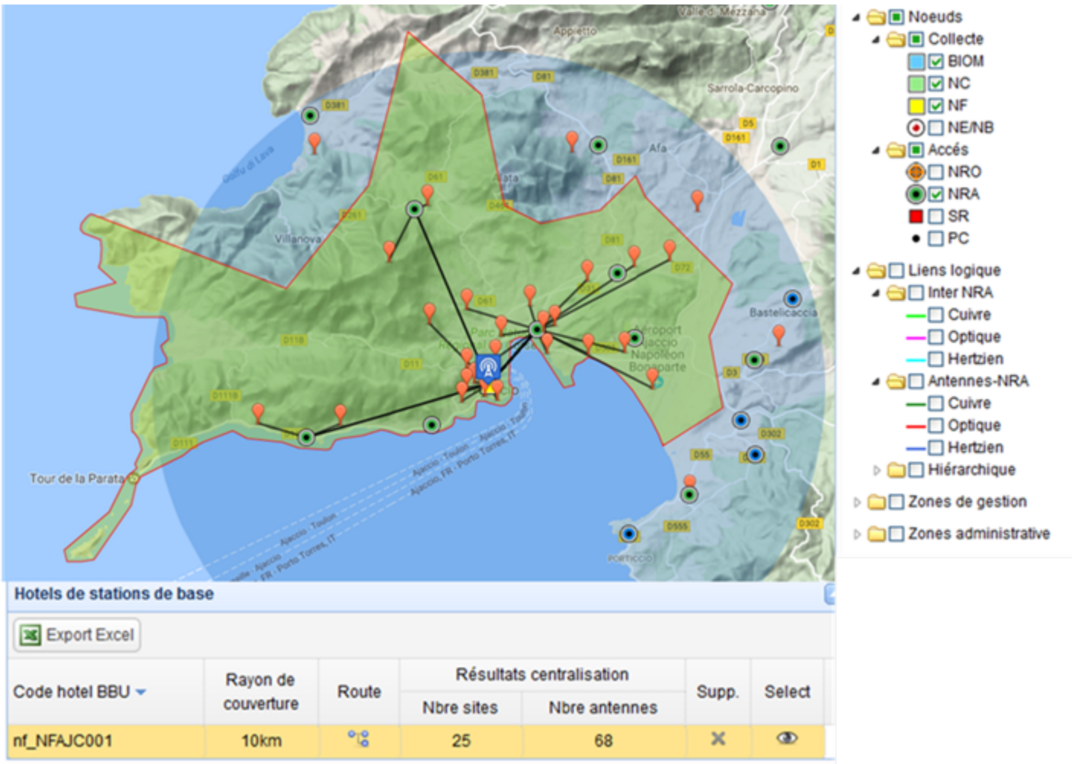
A major part of CapEx and OpEx for telecommunication network corresponds to the access segment. Due to its high capillarity, this final part of the network infrastructure incurs a considerable cost per km. In this section, there is a focus on the access segment with the help of a proprietary web-based cartographic tool that provides detailed information about geographical and telecommunication sites.

This web tool is able to present on a map the network entities of both fixed and mobile networks. It is based on a consolidated database provided by ARCEP, the French telecommunications agency[11]. The input parameters are the following ones:

- the list of fixed access nodes with their ID number, their name and their geographical coordinates (latitude and longitude): Central office for xDSL and FTTX, edge node, core nodes.
- the list of optical fiber, copper and microwave links, with their ID number, endpoints nodes and the length (in km). A coefficient can be used to take into account the real length of deployed fiber ducts instead of straight lines connecting two points.
- the list of antennas, with their ID number, number of radio access technologies and carriers as well as mobile operators (in case of antenna sharing scenarios).

This web tool can also compute the attachment ratio of the antenna sites to a fixed node in function of the maximum distance between them. The figure below shows a screen shot of the developed web tool.

[11] https://www.arcep.fr/



Code hotel BBU	Rayon de couverture	Route	Résultats centralisation		Supp.	Select
			Nbre sites	Nbre antennes		
nf_NFAJC001	10km		25	68		

Figure 18 – Screen shot of the tool used for the cost assessment of the access segment

3.2.1. Results of cost evaluations of fixed access network

3.2.1.1. Fiber to the antenna site (FTTA) deployment cost

The deployment costs of a fiber infrastructure to connect an antenna site to a central office could be shared with those of the deployment of a Fiber To The Premise (FTTP) structure. We consider in this deliverable, however, that such cost sharing is not effective. It is not effective due to a variety of reasons: the lack of supernumerary fiber in PON deployment in the trunk segment, the wholesale business case that required separate infrastructure, and regulation constraint. Thus, we propose to consider the deployment cost of a dedicated fiber infrastructure between central office and antenna sites for the Radio Access Network. This dedicated infrastructure deployment cost will be a function of the number of antenna sites and the distance between antenna sites (i.e., density of antennas per km^2). We use the term ISD for Inter Site Distance (km) to consider different scenarios with respect to the number of antennas per km^2 in C-RAN and functional split-based vRAN scenarios. We propose in this deliverable to focus on three ISD values: 500m, 750m and 1km. These could be considered as three different scenarios of an urban area with small cell, micro-cell and macro-cell coverage. Based on the ISD parameter, it is possible to achieve a calculation of the fiber infrastructure deployment CapEx cost including:

- Fiber cables (with 12, 36 , 48 , 72, 144, 288, 432 fibers) for ducts and poles.
- Civil engineering including cable laying, back-filling, permissions and traffic management.

- Splices and connectors.
- Closure equipment at the antennas and at each cable nodes.
- Labour of professionals for civil engineering and deployment with configuration studies and dashboards.

We consider that ducts and poles could be reused. We include in this study the fact that for each pole a cost per pole is required for assuring that it supports fiber cable. The following figure presents the maps for the proposed infrastructure deployment scenarios. We consider that each antenna site requires a single 12 fibers cable. The topology used for the cost estimation is based on a P2P topology. Thus, at the central office, we have also 12 fibers per antenna site. The cost difference between the three scenarios is mainly due to the amount of sharing of the cables and to civil engineering. In the figure below, different cable colors show the different types of cable.

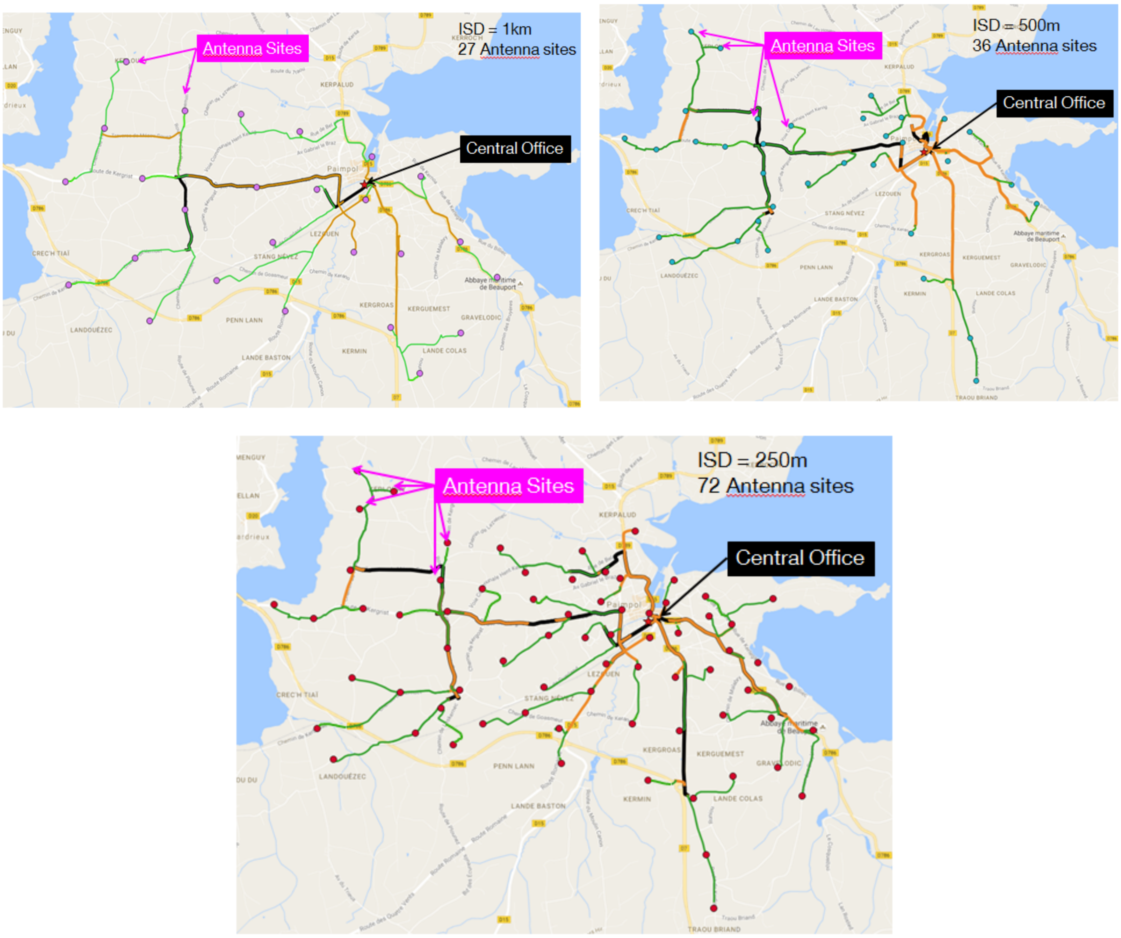


Figure 19 – Map of fiber infrastructure deployment plan in function of ISD: a) 1km/27 antenna sites, b) 500m/36 antenna sites, and c) 250m/72 antenna sites

Table 6 presents the relative CapEx cost analysis for the three scenarios considering the previous ISD values. The synthesis is that the cost per antenna site decrease with the density of antenna but the total cost increases. One interesting point is that the total fiber infrastructure cost does not increase linearly with the number of antenna sites. For instance, in scenario 2, the antenna site increases by 33% but we have only 16% of CapEx increase for the fiber infrastructure.

Table 6 – CapEx cost estimation of fiber infrastructure to reach antenna site for three scenarios

	Scenario 1	Scenario 2	Scenario 3
ISD (m)	1,000	750	500
Radio cell size (km²)	0.79	0.44	0.20
Number of antenna site	27	36	72
Number of antenna site	Ref. "A"	Ref. "A" + 33%	Ref. "A" + 178%
CapEx per Antenna site	Ref. "B"	Ref. "B" - 13%	Ref. "B" - 34%
Total CapEx	Ref. "C" = Ref. "B" x 27	Ref. "C" + 16%	Ref. "C" + 82%

3.2.1.2. Optical system deployment cost

Now that we have analyzed the cost of the deployment of an optical fiber infrastructure that reaches the antenna site, we need to include the costs of the optical system equipment between the pool of BBUs and RRHs. We consider here different optical access solution (cf. Figure 20) which are: *a)* low layer RAN split (CPRI) over WDM, *b)* Ethernet (or OTN) equipment which achieve encapsulation of the framing of low layer RAN split with or without compression, and *c)* Ethernet equipment which transport the high layer RAN split based on P2P or P2MP topologies.

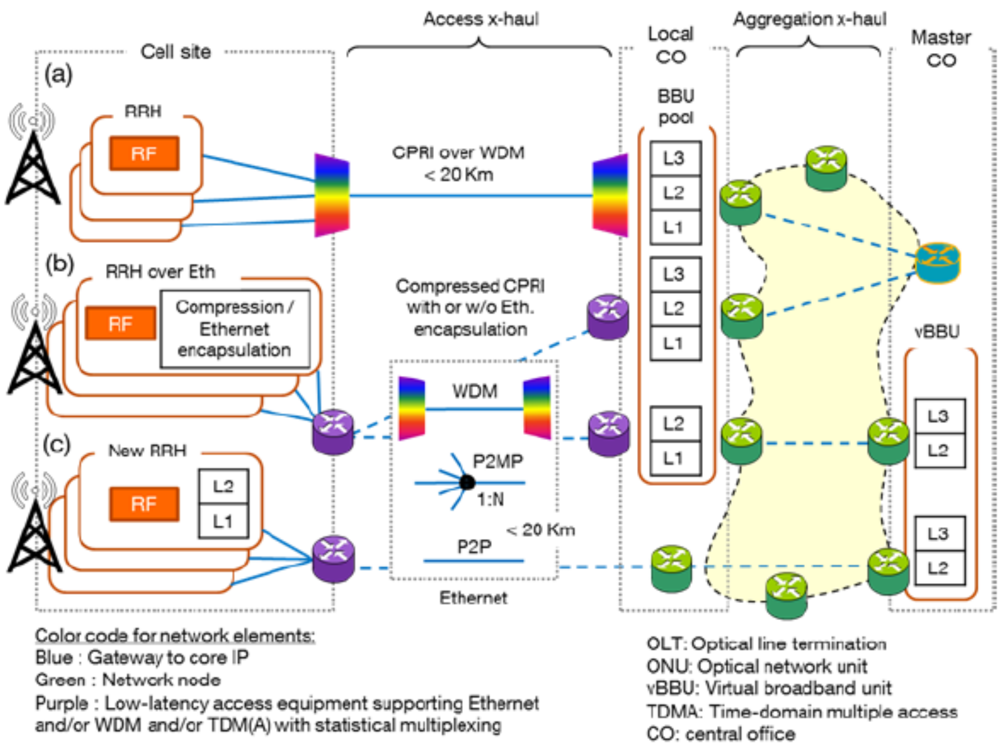


Figure 20 – Fiber deployment solutions

The costs of equipment and pluggable optoelectronic transceivers have been reported and discussed in Table 2 and in section 3.1.1.1. The transceivers are used in RRH, BBU and Ethernet equipment. The summation of their costs for a cell site configuration is not negligible.

We consider a configuration of the antenna cell site based on three LTE carriers with 20 MHz RF bandwidth with MIMO 2x2 and three cell sectors per site. This is a typical macro cell site configuration for full capacity 4G coverage. The low layer RAN split (CPRI) is working at 2.5Gbit/s (CPRI3) for each RRH.

The backhaul throughput of this configuration is about 3 times 150 Mbit/s (450 Mbit/s). We consider 20% additional traffic for high layer RAN split [25], but it remains below 1GEth. The following table makes a comparison of these three scenarios. For the first one, we consider 9 CPRI3 links with a couple of passive CWDM MUX/DeMUX.

For the second scenario, we consider 9 short reach CPRI3 links and one long reach link at 25Gbit/s and a couple of active switches for CPRI over Ethernet. For the last scenario, we consider 2 Ethernet switches for high layer RAN split equipped with GEth transceivers for 9 links in short reach mode and 2 links in long reach mode. The results of these calculations are reported in Table 7.

Table 7 – CapEx comparison of three optical system configurations for fronthauling in the access network

Scenario of 3 carriers 20MHz with MiMo 2x2 and three cell sectors	a) CPRI over passive CWDM [XCU]	b) Ethernet (or OTN) for low layer RAN split [XCU]	c) Ethernet for high layer RANsplit [XCU]
Transceiver	18 x 1.25	18 x 0.54 +2 x 5.36	18 x 0.36 + 2 x 0.71
Passive equipment	2x 5.36	-	-
Active equipment	-	2 x 7.14	2 x 1.79
TOTAL	**33.22 XCU**	**34.72 XCU**	**11.48 XCU**

To conclude this section, this table shows that high layer RAN split provides the cheapest configuration, about 33-34% w.r.t. low layer RAN split solutions (i.e. about 67% savings). It is an obvious conclusion due to the fact that this configuration requires low rate interfaces. On the other hand, low layer RAN split has the advantage of providing a reduced footprint for the antenna sites and enables an efficient implementation of Coordinated Multi Point (CoMP). In addition, it is worth noticing that both the passive solution has the benefit to also reduce the OpEx due to the absence of power consumption.

3.3. Dimensioning and technical-economic analysis of a theoretical 5G-Crosshaul scenario

In this section, we present a techno-economical cost-modeling tool used for theoretical analysis of several possible deployment network scenarios. The aim of this study, based on the development of a specific tool, is to permit the analysis of different options in terms of topology deployment, network strategy, underlying technologies in use and some other characteristics such us geo-type, infrastructure availability, etc.

The main objective in the evaluation is to assess and compare scenarios from both technical and economical perspectives. Through this comparison analysis, it is possible to obtain the pros and cons for the several considered scenarios.

3.3.1.1. Deployment layout

The baseline scenario over which we have calculated the total cost exercise is based on a hexagonal cell layout, with each cell representing the deployment of a macro-cell (located in the center of the hexagon). The distribution of the cells is uniform and all the hexagons share the same properties (same cell sizes, similar mean user traffic per cell, etc).

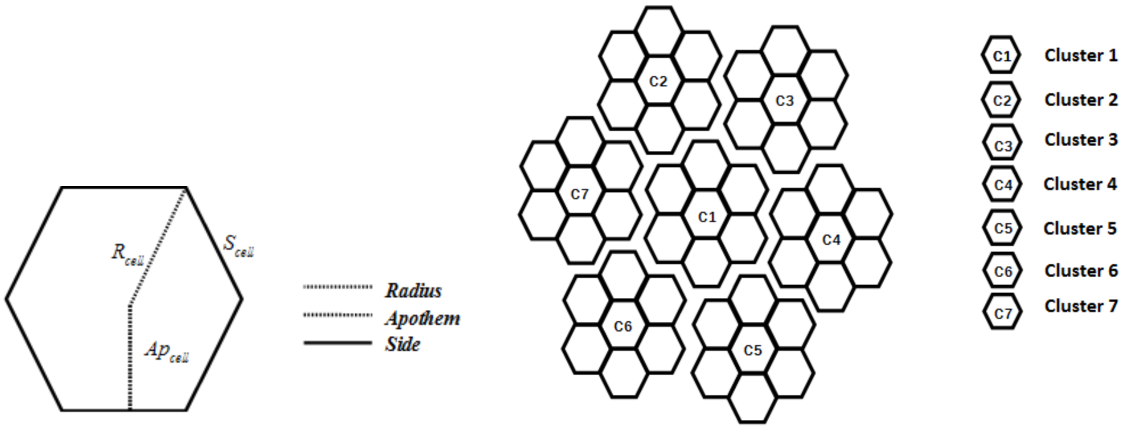


Figure 21 – Baseline network scenario

The complete reference scenario is dimensioned as a layout of 7x7 cells, arranged in seven clusters each with seven cells per cluster, as reflected in *Figure 21*. The initial scenario assumes one Radio Access Technology with three RRH elements forming a tri-sectorial coverage area (120° per sector) per cell.

The cell is assumed to have the theoretical hexagonal shape with radius (R) and different possible areas (in km^2) depending on the geo-type (namely Urban, Sub-Urban and Rural), being the apothem (A_p), see *Figure 21*, a key parameter for the definition of the cell area (A_{cell}).

The resulting values per geo-type for the cell-radius and area are shown in next Table 8. Here, we have assumed the same cell sizes considered in the COMBO project [26] which are realistic values.

Table 8 – Cell Radius/Area per Geo-type

	Urban	Sub-Urban	Rural
Cell Radius (*R*)	0.50 km	1.37 km	2.76 km
Cell Area (A_{cell})	0.65 km^2	4.90 km^2	19.85 km^2

The value of the apothem is given by

$$A_p = \sqrt{3}\frac{R}{2} \quad (1)$$

As it can be seen in this symmetric scenario, the distance between the cell center of two adjacent cells corresponds exactly to two times the value of the apothem, in other words, $\sqrt{3}\,R$.

Furthermore, the distance (D), between any two cells (with the same area size) follows the law of cosines:

$$D = \sqrt{\left(i\sqrt{3}R\right)^2 + \left(j\sqrt{3}R\right)^2 - 2\left(i\sqrt{3}R\right)\left(j\sqrt{3}R\right)\cos(120)} = R\sqrt{3(i^2 + ij + j^2)} \quad (2)$$

Figure 22 graphically represents the distance between any two cells.

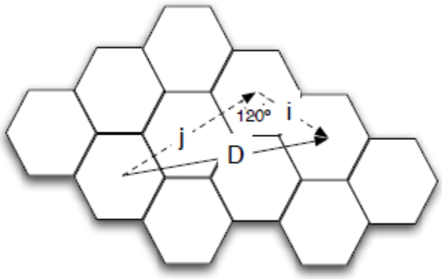


Figure 22 – Cell's geometry: distance between cells

With these geometric values, it is possible to establish the length of the fiber necessary in each scenario to be analyzed.

Another important issue to take in account in is the status of the infrastructure. We distinguish between three cases. The first one, called "greenfield", is based on the case where the network is built from scratch, including the deployment of the fiber. The second one, referred to as brownfield, assumes the existence of a pre-deployed fiber infrastructure. The final scenario, named leasing, is similar to the previous brownfield scenario but in this case the fiber infrastructure belongs to a third-party provider, and it has to be rented.

3.3.1.2. Analysis

This section introduces the different options analyzed with this cost model tool. Firstly, the different topologies to apply, then the three strategies followed in network deployment and finally the study of the possibilities in a technical view.

Topologies

One of the principal characteristics of the network deployment is relative to the physical topology that reflects the distinct way in which the nodes and network elements are deployed in a given area. In our study, we focused on some typical topologies (serial bus, ring, star). Furthermore, it could be feasible to have a mix of different topologies on the same scenario, by assuming a certain network design between the central point of the layout and the central point of the peripheral 7-cells sub-clusters.

The central cell of the complete layout is supposed to provide the connection with the Wide Area Network, then becoming the border of the fronthaul / backhaul aggregation environment (in other words, where the central office connecting to the backbone is located).

An example of a topology disposition over the baseline layout scenario is shown in Figure 23. It can be seen that the central cells of every sub-cluster act as the concentration point for each of those sub-clusters.

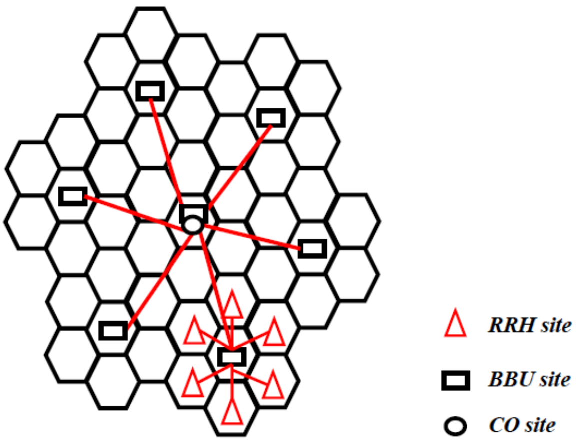


Figure 23 – Tree Topology distribution

In this example, in the outer (peripheral) 7-cell clusters, the distributed RRH connect to the BBU site in each central cell with a star connectivity. The traffic per cell is concentrated in the central cell of each cluster where the BBU site is located, with the necessary BBU elements to accomplish such a function. A BBU node can provide network functionality to various RRHs (up to six in our study).

The inner (central) 7-cell cluster supports the connection between the BBU distributed site and the central office (center cell of the full scenario). In this point, we need to provide connectivity to each cell in the network.

Following the same steps in the rest of topologies included in the tool, it is possible to identify the following options:

- Pure Star: All the cells directly connect to the layout central cell in a point-to-point manner. This scenario provides less delay transmission and best bandwidth capacity from the technical point of view, but the total fiber deployed (in kilometers) is the highest, thus generating the higher cost as well.
- Tree-Star: Corresponds with the previous topology described in Figure 23.
- Tree-Ring: Same as Tree-Star but with a passive ring in the outer clusters.
- Ring-Star: The opposite of the Tree-Ring, being point-to-point in the outer clusters and ring in the inner one.
- Double Ring: with ring configuration in both inner and outer clusters.

- Daisy Chain: with a serial bus connecting RRHs in the outer clusters (up to 3 cells) and point-to-point connections between central cells of outer and inner clusters.

Figure 24 presents some of these topologies.

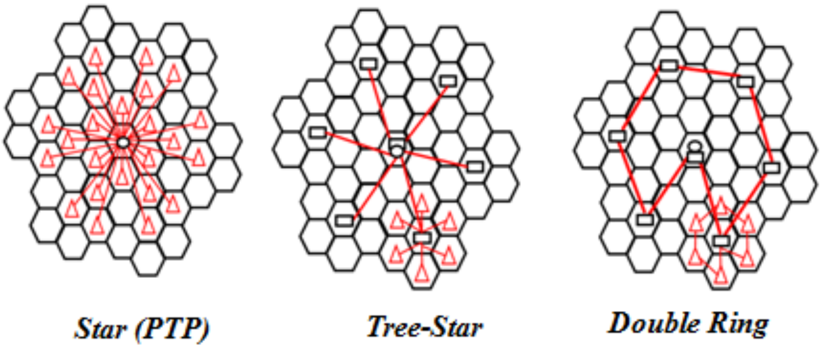


Figure 24 – Some topology examples

Strategies of deployment

In terms of network strategies, we have studied three different options. These cases are differentiated by the point of centralization of the BBU in the network.

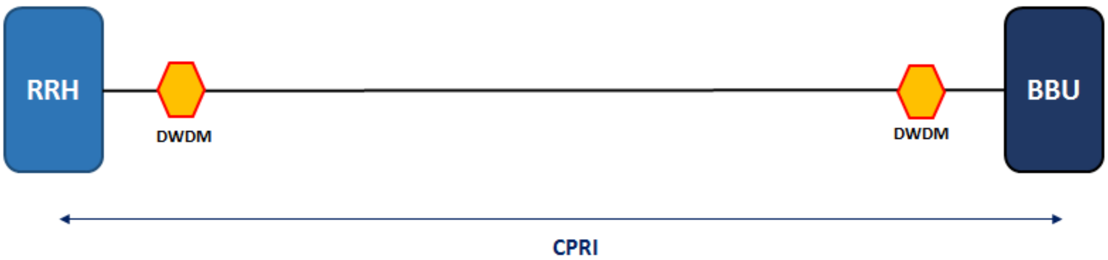


Figure 25 – Strategy (1) - All FH

The '*all fronthaul*' strategy (1) is shown in Figure 25, with DWDM as a possible example. This strategy presents a total fronthaul deployment up to the central site of the layout, where the CPRI signal is processed in the BBU. The delay requirement in the CPRI transmission makes this option as the most restrictive in technical terms, since all the path is limited by the stringent latency requirements of CPRI.

The second option - strategy (2) -, named '*FH+BH*' (i.e., Fronthaul plus Backhaul) presents a C-RAN configuration with CPRI processing in the BBU sites at the outer clusters plus an Ethernet transport up to the Central Office (CO), in the central point of the inner cluster. In this case the limitation of the distance to cover with the CPRI signal is less restrictive than the former case. Figure 26 shows this case, exemplified again with DWDM nodes in the outer clusters.

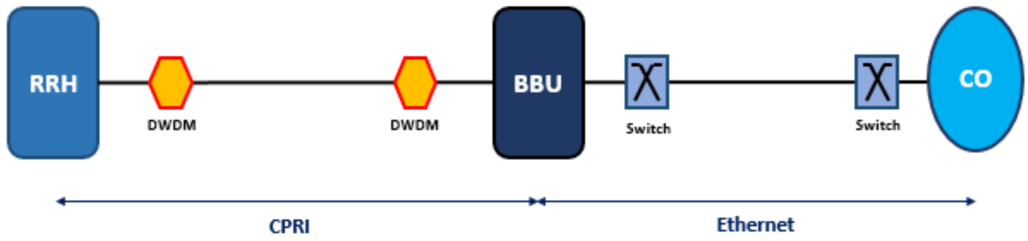


Figure 26 – Strategy (2) - FH + BH

The last strategy - strategy (3) - corresponds to the deployment of XFE nodes in line with 5G-Crosshaul. In this case the BBUs are placed in the same points as in the Fronthaul plus Backhaul strategy, allowing the coexistence with legacy technology. The switching elements are the new elements defined by 5G-Crosshaul, and the central cells in each cluster are equipped with the corresponding XFE/XPU to host virtualized BBUs.

Figure 27 shows this case.

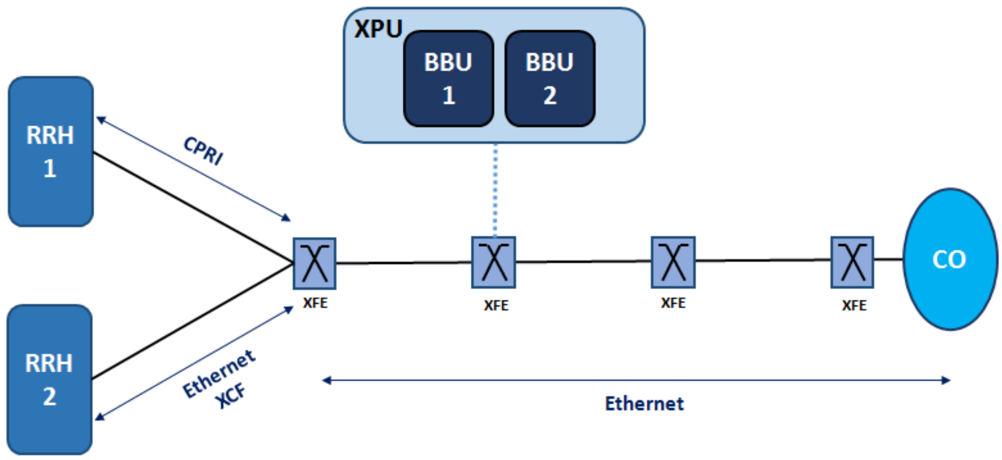


Figure 27 – Strategy (3) - 5G Crosshaul

Technology Selection

It is also possible to select, as an option in the tool, the technology or transport solution to be used in the network. Regarding this, we present the following cases:

- Passive Transport Solution: Consists in the deployment of passive transport elements between RRH and BBU. Hence, the SFPs used in the RRHs must be colored SFPs, with a specific work frequency (lambda) for each signal. This signals are concentrated on a passive optical multiplexer and delivered to the central site of the cluster to be processed by the BBU equipment.

Figure 28 depicts the passive solution.

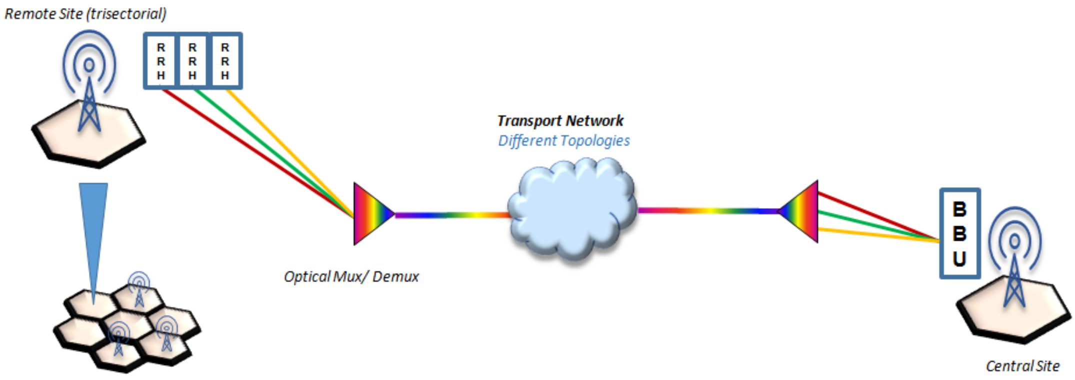


Figure 28 – Passive Solution

- Dark Fiber Solution: This scenario consists in a simplistic approach where it is considered one direct connection with a dedicated dark fiber between each RRH to its corresponding BBU. It is supposed to be the simplest scenario despite the clear overconsumption of fiber. Figure 29 illustrates this case.

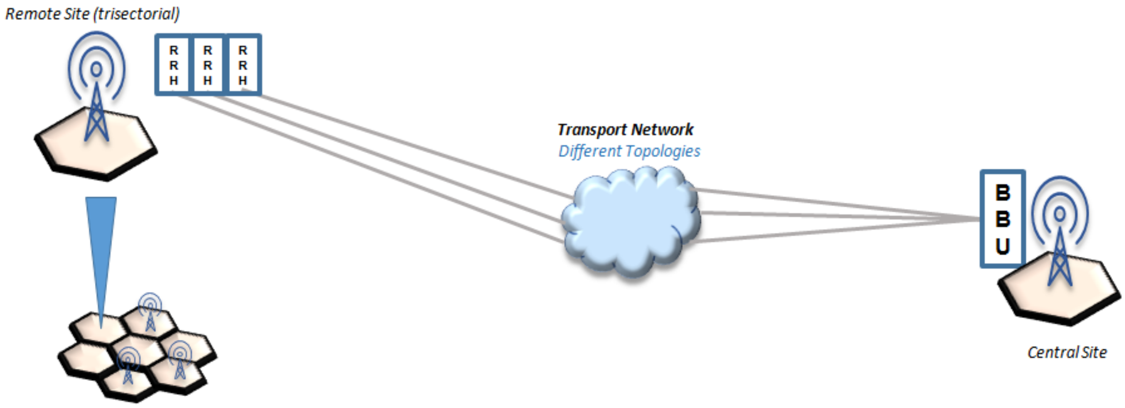


Figure 29 – Dark Fiber Solution

- Active Transport Solution with Transponder + Mux: In this case it is considered to have grey SFP interfaces on the RRH. For each RRH, the active transport equipment assigns a certain optical lambda through the utilization of a transponder element. Afterwards, the different frequencies are mixed with a passive optical multiplexer towards the BBU. Figure 30 represents this case.

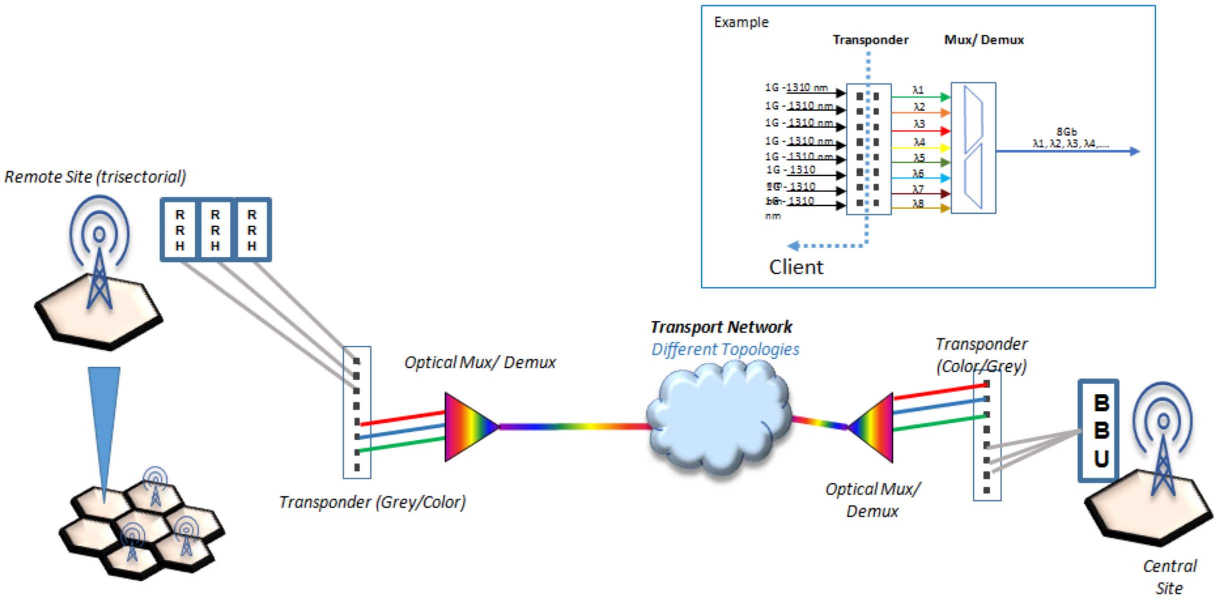


Figure 30 – Active – Transponder + Mux

- Active Transport Solution with Mux + Transponder (Muxponder): This solution is practically the same as the one before. However, this one considers an element that integrates both functionalities. Figure 31 illustrates the scenario.

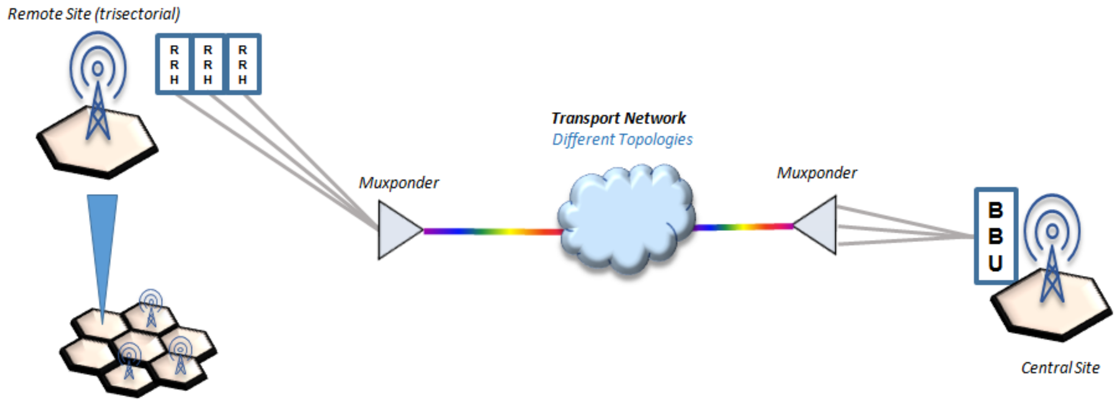


Figure 31 – Active – Muxponder

- 5G-Crosshaul (XFE) Solution: As commented before, this scenario considers the deployment of XFEs as aggregation elements. The Figure 32 shows the scenario.

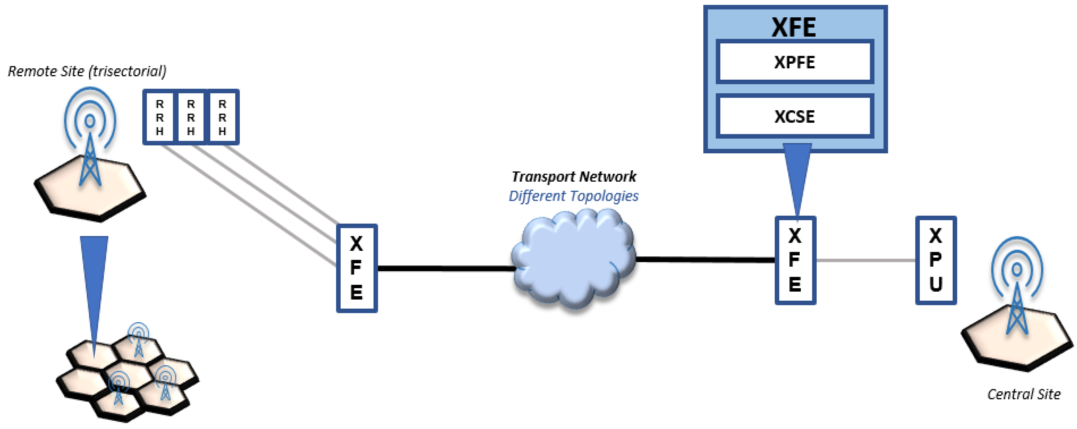


Figure 32 – XFE Solution

3.3.1.3. Tech-Cost Modeling Tool

Once the different possible scenarios have been presented, the cost-modeling tool is here described for illustrating the analysis capabilities and some exemplary results, in terms of CapEx and OpEx.

CapEx calculation

On one hand, from CapEx perspective, it is required to count the total needed infrastructure in each network deployment, including number of elements and fiber required, for the different alternatives available in the tool.

In order to illustrate the usage of the tool, let us consider an example for a certain scenario according to the next inputs:

- Topology: Tree-Star
- Strategy: (2) FH+BH
- Geo-Type: Urban
- Tech Solution: Transponder+Mux
- Infrastructure state: Greenfield
- RRH supported per BBU: 6
- RRH per cell: 3 (tri-sectorial)
- Traffic per cell: 0.15 Gbps

The total list of components required in the CapEx analysis is identified as:

- Distributed hardware: Related to the distributed elements in each cell, it includes the RRHs and the transceivers (SFPs), see Table 9.

Table 9 – Number of distributed hardware for strategy (2)

Distributed Hardware (RRH)		
Hardware Equipment	**Description**	**Value**
Grey SFP	Number of Grey SFP transceiver	147
Color SFP	Number of Color SFP transceiver	0
RRHs	Number of Total Radio Remote Head (RRH)	147

- Centralized hardware: Related to the elements in both outer and inner clusters. It includes BBUs, transceivers, switches, routers, etc. (see Table 10).

Table 10 – Number of centralized hardware for strategy (2)

Centralized Hardware (RRH-BBU)		
Hardware Equipment	**Description**	**Value**
Grey SFP	Number of Grey SFP transceiver	147
Color SFP	Number of Color SFP transceiver	0
BBUs	Number of Total Baseband Unit (BBU)	28
Ports of 1G	Number of 1G Ports required	14
Ports of 10G	Number of 10G Ports Required	0
Ports of 100G	Number of 100G Ports Required	0
Transport Cards of 1G	Number of 1G Transport Cards	7
Transport Cards of 10G	Number of 10G Transport Cards	21
Transport Cards of 100G	Number of 100G Transport Cards	0
Switch Slots	Number of slots required in Switch	28
Number of Switches	Number of Switches required	7

Centralized Hardware (BBU-CO)		
Hardware Equipment	**Description**	**Value**
Ports of 1G	Number of 1G Ports required	14
Ports of 10G	Number of 10G Ports Required	1
Ports of 100G	Number of 100G Ports Required	0
IP Cards of 1G	Number of 1G IP Cards	1
IP Cards of 10G	Number of 10G IP Cards	1
IP Cards of 100G	Number of 100G IP Cards	0
Router Slots	Number of slots required in Router	2
Number of Routers	Number of Router required	1

- Crosshaul hardware: Taken into account only when Crosshaul scenario is selected (not applying to this example), see Table 11.

Table 11 – Number of 5G-Crosshaul hardware for strategy (2)

Crosshaul Hardware		
Hardware Equipment	**Description**	**Value**
XPFE	Number of XPFE equipments	0
XCSE	Number of XCSE equipments	0
XPU	Number of XPU equipments	0

- Transport hardware: Related to the components of the technical transport solution (transponders, muxponders, multiplexers), see Table 12.

Table 12 – Transport hardware list and number

Transport Hardware		
Hardware Equipment	**Description**	**Value**
Mux/Demux in RRH sites	Number of Mux/Demux (1:4) in RRH sites	98
Transponders in RRH sites	Number of Transponders in RRH sites	294
Muxponders in RRH sites	Number of Muxponders in RRH sites	0
Aggregation Points	Number of Aggregation Points (mux/demux)	0

- Optical Fiber Deployment: In Table 13 is reported the total cost in XCU of the fiber deployment (depending on the distances, the situation of the infrastructure and the geo-type).

Table 13 – Optical fiber deployment cost (in XCU)

Fiber deployment		
Hardware Equipment	**Description**	**Value**
Fiber deployment	Total distance of fiber deployment	50,23

The reference CapEx (in XCU) of the items used by the tool are reported in section 3.1.

OpEx calculation

On the other hand, the applicable OpEx for network deployment follows the same assumptions of the work in reference [27], according to the following calculation.

$$
\begin{aligned}
&OpEx \\
&= number\ of\ devices \times rack\ space\ (m^2) \times \frac{yearly\ rent}{m^2} \\
&+ number\ of\ devices \times \frac{yearly\ consumption}{device (in\ kW)} \times \frac{cost_{kW}}{year} && \text{continuous cost of infrastructure} \\
&+ number\ of\ shifts \times \frac{\frac{hours}{shift}}{year} \times \frac{wage}{hour} \\
&+ number\ of\ hardware\ failures \\
&\times \Big[distance\ to\ failure\ (in\ km) \times \frac{cost}{km} \\
&+ time\ to\ reach\ the\ failure\ location\ (in\ hour) \times \frac{wage}{hour} && \text{maintenance and repair} \\
&+ time\ to\ fix\ the\ failure \times \frac{wage}{hour} + hardware\ replacement\ cost \Big] \\
&+ number\ of\ software\ failures \\
&\times \Big[average\ time\ to\ fix\ a\ software\ failure\ (in\ hour) \times \frac{wage}{hour} \Big] \\
&+ \frac{number\ of\ connections\ to\ be\ configured}{year} \\
&\times \Big[configuration\ time\ per\ connection\ (in\ hour) \times \frac{wage}{hour} && \text{service provisioning} \\
&+ documentation\ time\ per\ connection\ (in\ hour) \times \frac{wage}{hour} \Big] \\
&+ \frac{number\ of\ connections\ to\ be\ reconfigured}{year} \\
&\times \Big[configuration\ time\ per\ connection\ (in\ hour)\ x\ \frac{wage}{hour} && \text{service management} \\
&+ documentation\ time\ per\ connection\ (in\ hour)
\end{aligned}
\quad (3)
$$

The number of years considered for OpEx calculation have been 5 for the equipment and 25 for the fiber.

The parameterization used for OpEx calculation is exemplified in Table 14, with a specific parametrization for illustration purposes.

Table 14 – Parameterization of OpEx variables

OPERATING EXPENDITURE	
Continuous Cost of Infrastructure	
Element Description	**#**
Number of devices	928
Rack spaces ***(in m2)***	0,78
Yearly Rent per m2 ***(in XCU)***	0,61
Yearly Consumption per Device ***(in kW)***	0,59
kW cost per year ***(in XCU)***	9,64
Maintenance and Repair	
Element Description	**#**
Number of Shifts	5
Hours per shift per year	80
Wage per hour	0,18
Number of hardware failures	8
Distance to failure ***(in km)***	0,87
Cost per km	0,00
Time to reach the failure location ***(in hour)***	1
Time to fix the failure ***(in hour)***	3
Hardware replacement cost	200,64
Number of software failures	52
Average time to fix a software failure ***(in hour)***	2
Service Provisioning	
Element Description	**#**
Number of connections to be configured per year	20
Configuration time per connection ***(in hour)***	1,28
Documentation time per connection ***(in hour)***	1,28
Service Management	
Element Description	**#**
Number of connections to be reconfigured per year	5

The resultant OpEx in this specific case amounts to 7403.06 XCUs.

3.3.2. Results

We present one of the multiple examples available in our tool, through a complete deployment with the next inputs selected as shown in Table 15.

Table 15 – Input for the tool in a 5G-Crosshaul strategy

Network Parameters		
Element	**Description**	**Value**
Topology	**Select**Network Topology	**Tree-Star**
Strategy	**Select**Network Strategy	**(3) Crosshaul**
Geo-type	**Select**Scenario Geo-type	**Sub-urban**
Scenario	**Select**Scenario Fiber Deployment	**Already Deployed - Brownfield**
Solution	**Select**Infrastructure Solution	**Crosshaul (XCSE)**

As we can see in Table 16, the summary of the economic analysis shows that the principal costs correspond to the optical fiber deployment, as expected, following the

OpEx and the centralized hardware (equipment of centralization to processing, switching & routing).

Table 16 – Tool results for 5G-Crosshaul strategy

Economic Analysis		
Hardware Equipment	**Description**	**Cost (XCU)**
Distributed Hardware	Total Cost of distributed elements (RRH, SFPs)	532,14
Centralized Hardware	Total Cost of centralized elements (BBU, CO, SFPs)	1324,63
Transport Hardware	Total Cost of the Transponders/Mux-Demux/Muxponders	15,00
Crosshaul Hardware	Total Cost of the purely Crosshaul Elements (XFE,XPU)	463,19
Optical Fiber Deployment	Total Cost of the fiber deployment	6143,58
OPEX	Total Cost of the Operating Expenditure	5514,13
Total Network Cost	**Total Cost of the Deployment (XCU)**	**13992,67**

A graphical summarized representation (Figure 33) allows seeing the considerable differences among each sub-section in the network deployment.

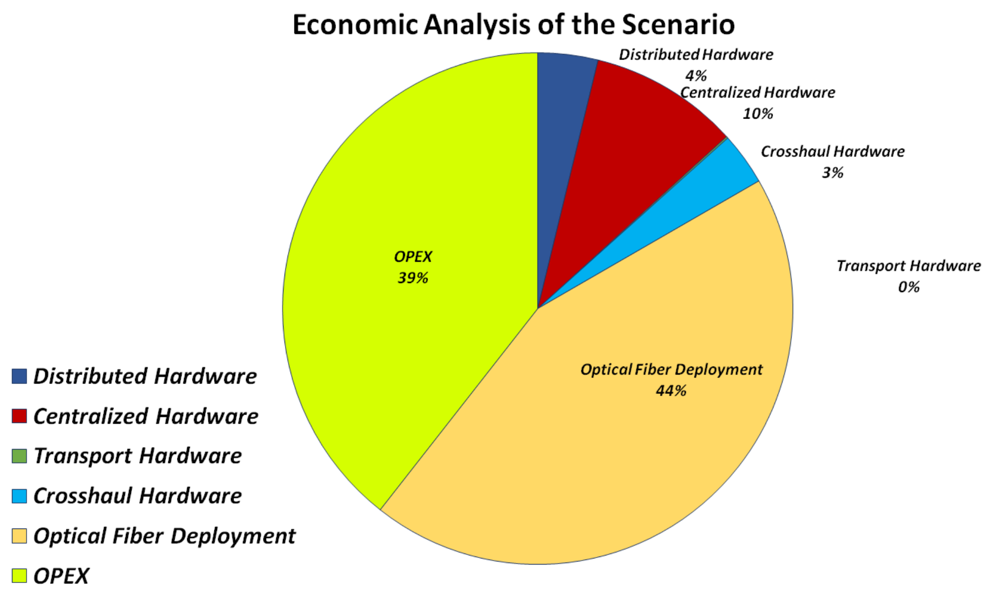


Figure 33 – Cost distribution for the topological analysis on the theoretical layout

Regarding the topology comparison, the principal difference remains in the distances to address in each case, i.e. the kilometers of optical fiber to deploy. In Figure 34 we can see the results obtained (costs in XCU) per each node disposition over the case of study. This comparison has also been done in a brownfield/sub-urban environment and with a passive technical solution.

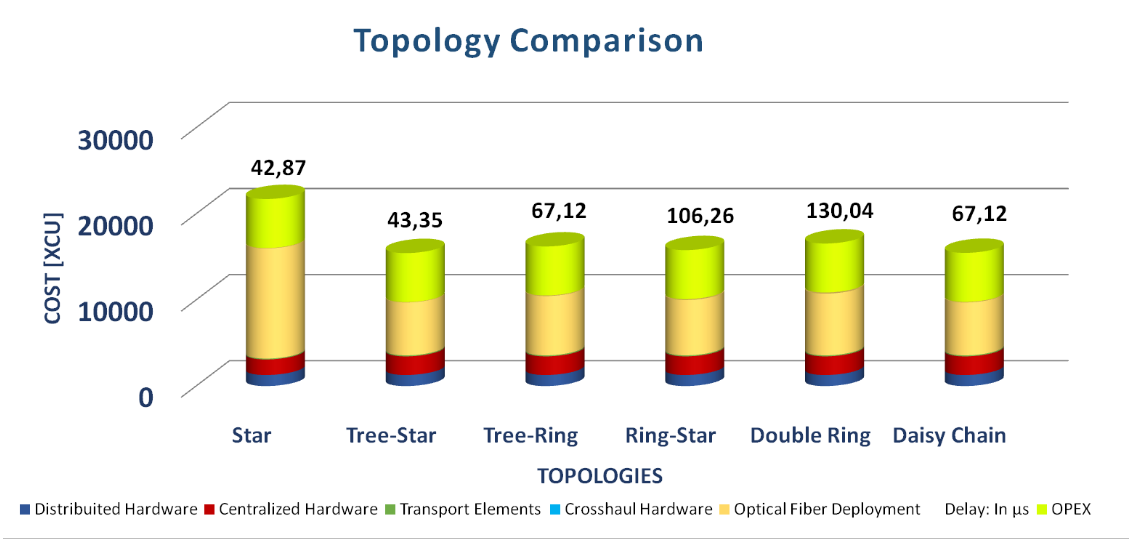


Figure 34 – Tech/Cost comparison in different topologies

As it is easily noticeable, most of the cost output parameters are unchanged by the topology switching with the exception of the fiber and lightly for the centralized hardware in the star topology, due to the single point of centralization disposed in this scenario. Another remarkable point is the delay of transmission (in bold above the bars, in microseconds), that presents the best case in the star topology, followed closely by tree-star, while the worst case is the double ring due to the great distances that the signal must travel through the network.

The modification of the scenario conditions (greenfield case or rural environment) presents relatively the same relation of the outputs, except in the rising or decreasing of the total cost of the network depending on the case.

Knowing this, the best option from the technical/economical point of view is the Tree-Star topology. For this reason, the following study is applied to it, having as main objective the comparison between a legacy scenario, with an C-RAN deployment, and a purely 5G-Crosshaul deployment. The results are shown in Figure 35 (costs expressed in XCU).

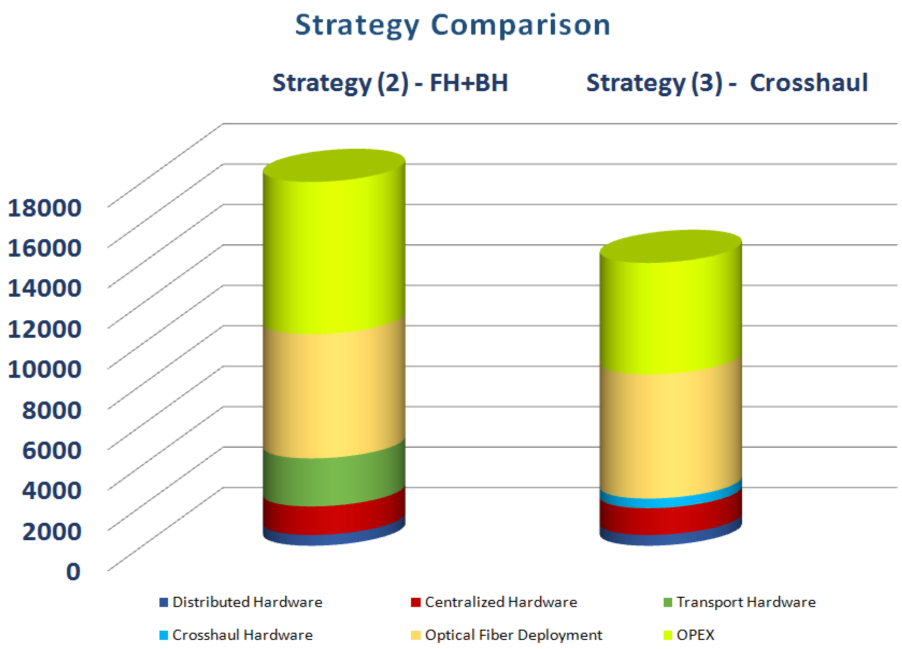


Figure 35 – Cost comparison in different strategies

The results show that the introduction of the new network paradigm (novel 5G-Crosshaul infrastructure and new elements in the stations and centrals, e.g. XPU or XPFE) brings several improvements in the network performance. In terms of costs, despite some necessary hardware investments (new equipment), greater OpEx savings are achieved, especially in the brownfield scenario. The final result is that the 5G-Crosshaul case presents savings in the range of 10-30% w.r.t. the legacy cases.

3.4. Tool for design and cost/energy evaluation of metropolitan network

Although the previous section considers the tree-star topology as the most cost-efficient choice, the adopted scenario used for the evaluation of a metropolitan network is a brownfield case, representing a real optical network based on interconnected rings topology, that has also the advantage to assure resiliency from failures.

The cost and energy 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 and optical network.

Obviously, the model is indeed able to evaluate the cost of networks where fronthauling and backhauling consists of both L2 and optical devices. Finally, since the developed algorithms are tailored for 5G-Crosshaul network, it is possible to evaluate the costs of a network where backhauling and fronthauling converge in a unique network consisting of hybrid L2/optical devices.

The tool is able to calculate the total cost and energy of a reference network by means of a network dimensioning based on a Dijkstra algorithm with weights based on link-length in km. As a consequence, the working path corresponds to the shortest path while the protection path is imposed to be the shortest path with links disjointed w.r.t. the working ones. The paths are the same for L1 and L2 connections, with a bandwidth threshold imposed for the off-loading of packet traffic over the optical paths.

The input parameters are the following ones:

- The list of nodes, with their ID number, their name and their geographical coordinates (latitude and longitude).
- The list of links, with their ID number, endpoint nodes and the length (in km).
- The list of antennas, with their ID number. For each antenna it is important to indicate:
  - The belonging node, i.e. the node directly attached to the antenna by a point to point connection.
  - The type of MIMO (2x2, 4x4).
  - The distance between the antenna and the belonging node (in km).
  - The type of media (optical fiber, WDM-PON or wireless).
  - The site hosting BBU connected to the RRH present in the antenna site.
  - The user traffic and the fronthauling traffic.

Some further parameters are to be set:

- **IPoverMobile**. The input traffic is related to antennas, so it is just mobile traffic. The ambition of telecommunication operators is to build an integrated network capable of carrying all traffic. The IPoverMobile parameter represents the ratio between the total traffic (IP+Mobile) and the mobile only. This parameter is uniformly applied to all the traffic demands.
- **Number of slot per fiber.** In the optical layer, WDM is considered. So it is necessary to indicate how many slots are to be considered per single fiber. All lightpaths occupy one slot, regardless of the bitrate.
- **Threshold for optical bypass.** For a two layers L2/L1 network, it is possible to establish a threshold, above which the traffic demand will be carried only at L1 level, that is called optical bypass.

3.4.1.1. Tool description

Figure 36 shows the general high-level data flow of the tool in order to provide the main required results:

- Yearly Total Cost
- Energy Consumption

As described above, the description of nodes and links allows the software to build the topology of the network. Each antenna (or better a site hosting one or more antennas) is connected point-to-point to a node, **the belonging node,** and provides a given traffic (peak user traffic), that we consider being the same as backhauling traffic, especially if the belonging node and the BBU site are the same node. Then the backhauling traffic is between BBU and the core network node. The fronthauling traffic, on the contrary, is between RRH and BBU including the local loop and a section of the network (if the belonging node, endpoint of the local loop is not BBU site) and the amount of this depends by the adopted splitting option, and so, it should be explicitly indicated in the input data.

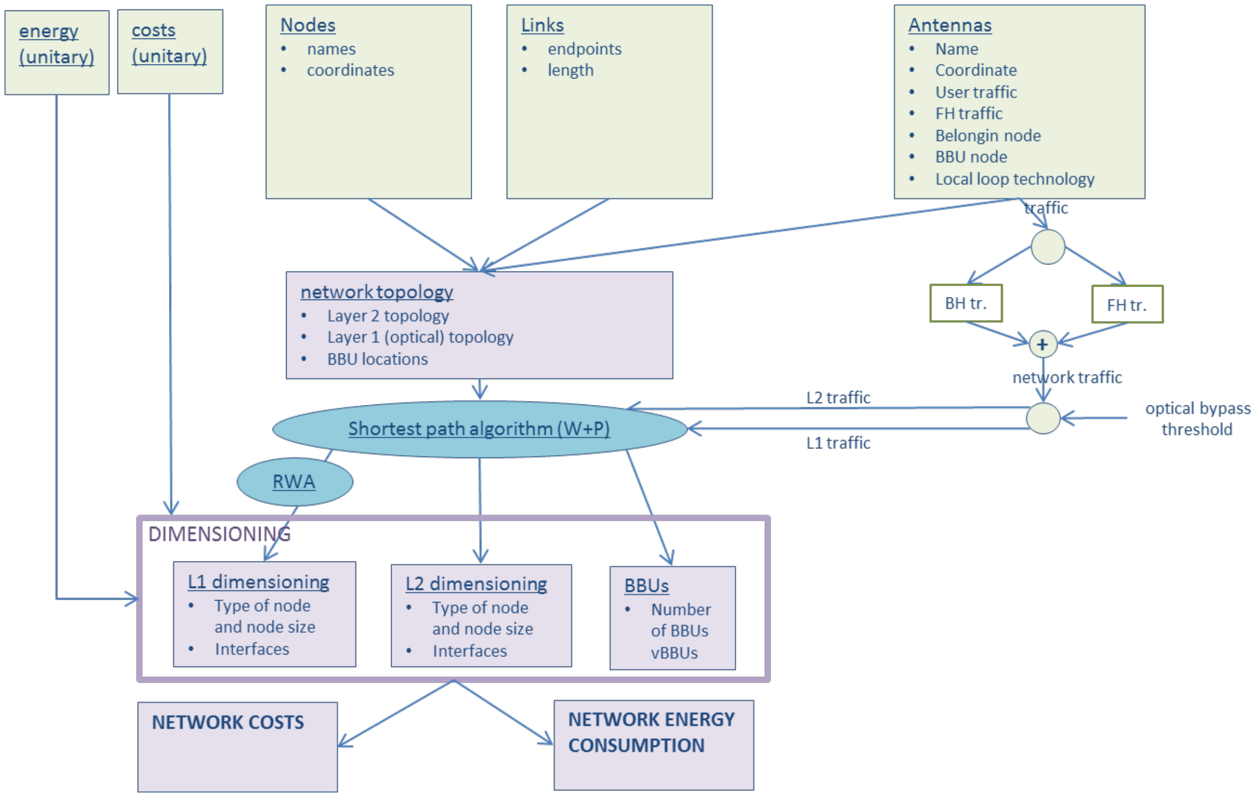


Figure 36 – High level scheme of the tool

The network that can be dimensioned and analyzed is schematically depicted in Figure 37. The local loop contribution might be roughly evaluated by the tool, but it is out of the scope of the current study, because the costs of this network segment are obtained from analysis of the network last mile (see chapter 3.2).

Each node at the edge of the network grooms (at layer 2) the traffic towards the same destination and split the traffic into L2 traffic demands and L1 traffic demands, if the traffic is below or above a certain threshold.

L2 demands are routed through the network and regenerated and aggregated with other traffic in each intermediated node, while L1 traffic is optical bypassed. Of course, the lightpaths load slots in DM system following a Routing and Wavelength Assignment (RWA) algorithm.

After the routing, it is possible to dimension links and nodes.

Figure 38 enlarges the vision of the node. Every node has the same functionalities (L1 and L2 switching), but different size. Each node is composed of two pieces of equipment: a L2 device and a L1 one.

The L2 device is a MPLS-TP or MAC-in-MAC device respectively for Legacy and 5G-Crosshaul scenarios. The main difference is placed in the size (for legacy the size range is between 100G and 19.2T of throughput, while for 5G-Crosshaul between 1.6T and 19.2T).

The L1 devices for legacy scenario are FOADM (if the nodal degree is below 4) or ROADM (1x9, 1x20) based on WSS for greater nodal degrees. The 5G-Crosshaul scenario adopts optical switches based on silicon photonics.

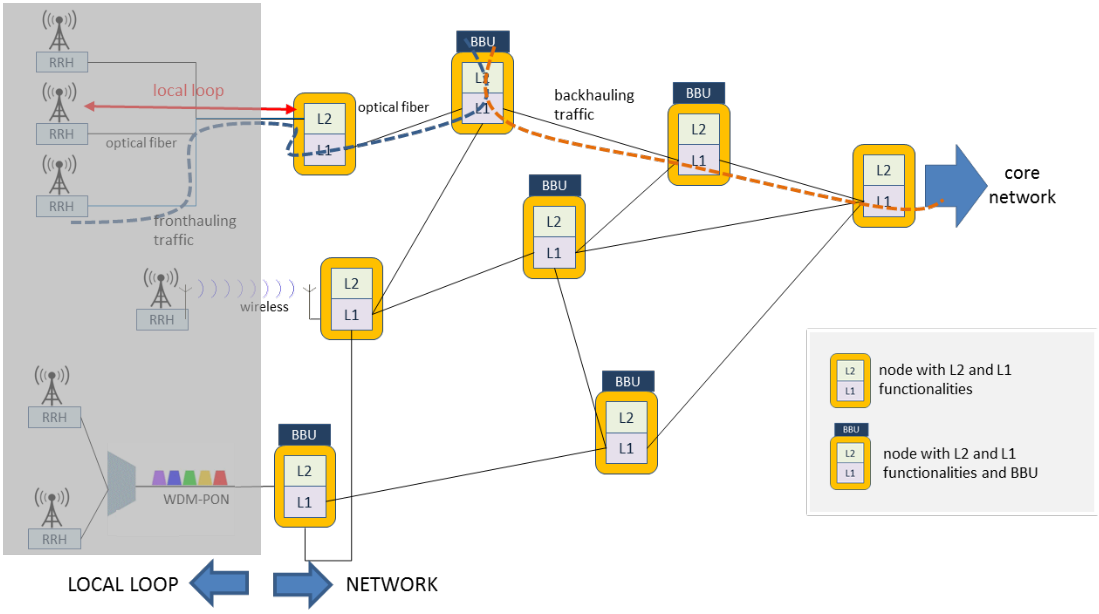


Figure 37 – Architecture of the network that can be analyzed by the tool

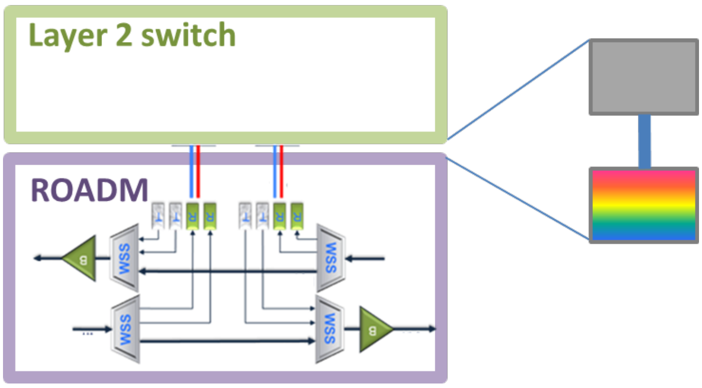


Figure 38 – Detail of the node

Routing algorithm

Given the traffic matrices (referring to Layer 1 and Layer 2), the tool calculates the paths of these demands, using the Dijkstra algorithm where the weights are the distance in kilometers. Working and protection paths are computed taking into account link-disjoint paths.

Both L1 and L2 demands are provisioned using the same algorithm. In addition to this, layer 1 demands (i.e. lightpaths that are routed on the L1 layer only in the intermediate nodes of the path) occupy slots according to heuristic RWA consisting by the following items:

- The path is calculated by a shortest path algorithm where the weights are represented by the length in km.
- Once calculated the path the wavelength occupies the first slot empty for every link of the path.
- The number of parallel used fiber pairs is the ceiling of the highest busy slot divided by the fiber capacity.

Cost calculation

In the 5G KPIs the Capital Expenditures (CapEx) and Operating Expenditures (OpEx) analysis is part of a more comprehensive 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.).

3.4.2. Results: cost and energy evaluation for a realistic network

3.4.2.1. Network topology

The network under analysis is a metro/regional network (MAN) placed in the northern area of Italy, with a very high user density distribution close to the core site and a large rural area along the edge of the whole MAN with a reduced amount of user traffic.

The network is composed of groups of two or three interconnected rings linked to a central star that interconnects the hub nodes of each group to the core site. Each ring is composed of a variable number of BBU sites and L1/L2 nodes, as shown in Figure 39.

One of the BBU sites directly linked to the core segment of the network is split in two different co-located components that are connected to each other both with a direct link and with a ring topology, that aggregates BBUs of a user crowded area. At the same time, each of those elements is independently connected to another ring that collects BBU sites from the edge of the MAN.

A large number of antennas, more than 1000 elements, are placed on the MAN with a non-uniform distribution on the region. Larger number of antennas are deployed in areas where it is necessary to provide higher mobile radio coverage and only few nodes are not provided of any link to antennas.

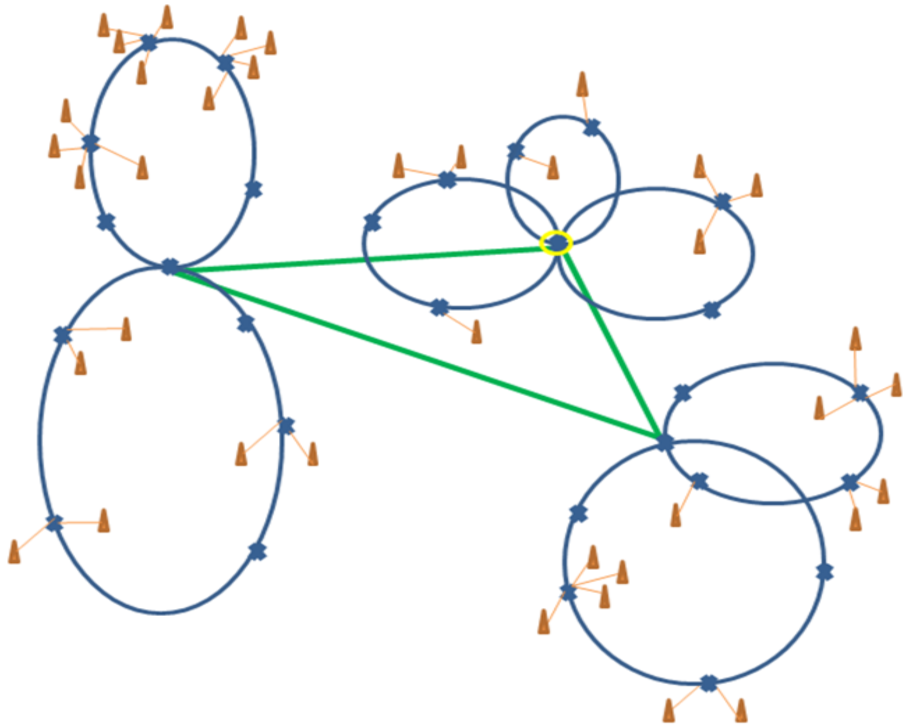


Figure 39 – Network architecture

This network is based on 51 nodes and 61 links; in the Table 17 are listed all links that compose the network and the real cable distance between each source and destination.

Table 17 – List of links

ID	MC-SOURCE-ID	MC-TARGET-ID	Cable distance
1	N28	N37	12.43
2	N34	N28	101.46
3	N22	N34	37.74
4	N42	N22	50.95
5	N31	N42	27.67
6	N23	N31	23.13
7	N37	N23	18.54
8	N26	N37	6.48
9	N20	N26	8.94
10	N13	N20	23.75
11	N43	N13	5.53
12	N5	N43	3.59
13	N37	N5	5.75
14	N48	N32	59.33
15	N32	N50	41.45

16	N50	N7	80.07
17	N7	N39	25.21
18	N39	N33	11.56
19	N33	N30	4.66
20	N30	N48	8.78
21	N48	N11	4.16
22	N11	N1	2.45
23	N1	N47	3.50
24	N47	N14	6.37
25	N14	N15	20.05
26	N15	N48	18.58
27	N48	N21	27.62
28	N21	N16	42.26
29	N16	N40	28.92
30	N40	N17	28.03
31	N17	N27	54.30
32	N27	N48	66.06
33	N2	N3	1.89
34	N3	N44	7.34
35	N44	N38	57.33
36	N38	N29	39.08
37	N29	N36	12.85
38	N36	N8	12.14
39	N8	N2	2.56
40	N2	N24	4.44
41	N24	N45	0.75
42	N45	N9	1.51
43	N9	N4	2.54
44	N4	N6	5.17
45	N6	N51	8.14
46	N51	N12	7.29
47	N12	N10	6.86
48	N10	N19	5.54
49	N19	N46	3.17
50	N46	N2	3.54
51	N51	N41	20.79
52	N41	N25	18.79
53	N25	N35	15.73
54	N35	N18	10.15
55	N18	N49	3.40
56	N49	N51	6.94
57	N2	N51	0.00
58	N37	N2	11.06
59	N37	N51	11.06

60	N48	N2	5.92
61	N48	N51	5.92

In Figure 40 it shows the real network topology: at the center of the MAN there is an area deeply covered by BBUs, that corresponds to the area densely populated with a huge traffic request. Far from the center there are several BBU sites that allow to provide mobile services to periphery or rural areas. The ring topology is clearly visible.

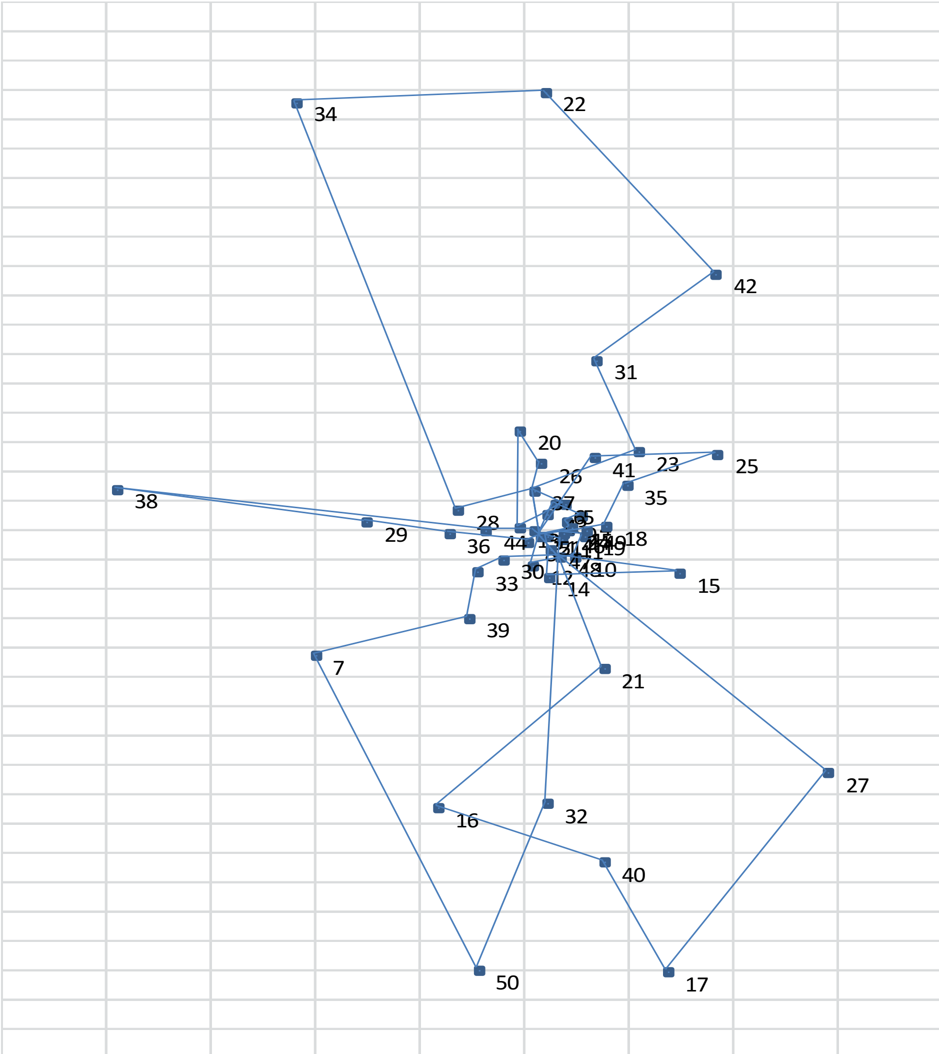


Figure 40 – Network topology

3.4.2.2. Evaluations

In the following section five different scenarios are shown: each of them is characterized by different amount of traffic, splitting option or type of equipment, while network topology is still the same for all evaluations.

All costs reported in the following are not expressed in Euros but in XCU (5G-Crosshaul Cost Unit), see section 3.1.

Legacy 2016

General architecture

- *Topology:*
  Shown in Figure 39, it is composed of 8 rings, 51 nodes and 61 links.
- *Splitting option:*
  All CPRI for fronthauling segment network.
- *Location of RRHs and BBUs:*
  Each node is BBU site, due to CPRI constraints.

Technology

- *Layer 2 technology:*
  MPLS-TP commercial devices, grey transceivers for L2 at 10 Gbit/s, 40 Gbit/s and 100 Gbit/s.
- *Layer 1 technology:*
  FOADM with maximum 4 line degrees, ROADM with WSS 1x9 (i.e. 9 line degrees) or WSS 1x20 (i.e. 20 line degrees). Transponders for L1 with coexistence of 10/40 Gbit/s non-coherent transponders and 100 Gbit/s coherent transponders, with the technical rule that the first ones should occupy separated fibers w.r.t. the last one.
- *Type of control:*
  Embedded on the equipment.
- *Radio details:*
  MIMO 2x2 for all antennas.

Settings

IPoverMobile	Yes
Number of slot per fiber	80
Threshold for optical bypass	9 Gbit/s

Results

This scenario represents the current situation deployed on field in the northern metropolitan area network in 2016. Traffic is extracted from real TIM internal statistics, based on more than 1000 antennas, and fronthauling is realized using CPRI.

As shown in Figure 41 the biggest contribution for CapEx is due to 10G interfaces: traffic processed by each device in this scenario is not so high to request interfaces with high capacity and it is also distributed along the whole network. It implies a massive use of 10G interfaces to carry all the traffic and then this justifies the reported cost results.

CAPEX	Total cost	amortment time	Yearly cost
WDMPON	0.00	10.0	0.00
RRH			
BBU	1322.90	5.0	264.58
L2 matrix	185.32	5.0	37.06
10G interfaces	4253.54	5.0	850.71
40G interfaces	0.00	5.0	0.00
100G interfaces	0.00	5.0	0.00
L1 devices	832.77	5.0	166.55
wireless	0.00	5.0	0.00
embedded control	0.00	5.0	0.00
Total CAPEX [XCU]	6594.54		1318.91

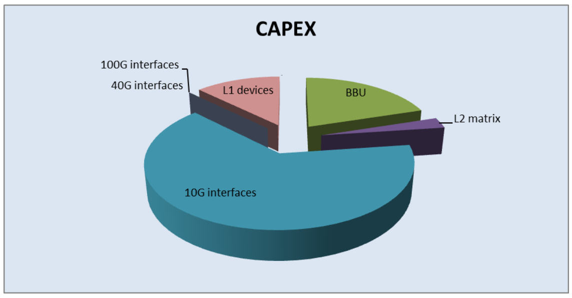


Figure 41 – CapEx items and pie-chart for legacy 2016

As shown in *Figure 42*, maintenance and energy is the biggest cost contributions for OpEx.

OPEX	Yearly cost
energy	319.23
fiber network	32.87
fiber local loop	
space (racks)	85.97
maintenance	536.88
Total OPEX [XCU]	974.94

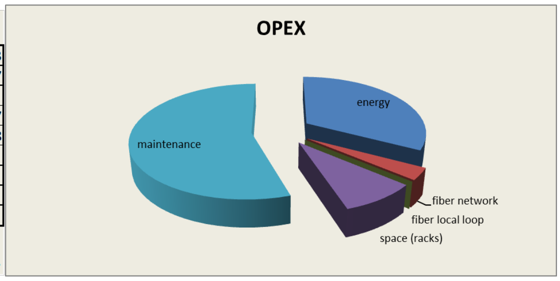


Figure 42 – OpEx items and pie-chart for legacy 2016

Analyzing energy consumption, as shown in Figure 43, it is possible to notice that BBU contribution is quite high although energy consumption for each single BBU is not so high. It is due to the huge number of BBUs installed on the field.

ENERGY	kWh/year
RRH	
WDMPON	0.00
wireless	0.00
L2 device	21900.52
L1 devices	2772.00
BBU	294555.00
Total (kWh/year)	319227.52

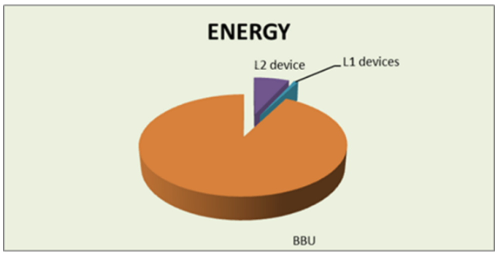


Figure 43 – Energy pie-chart for legacy 2016

<u>Legacy 2020 (all CPRI)</u>

<u>General architecture</u>

- *<u>Topology:</u>*
  Shown in Figure 39, it is composed of 8 rings, 51 nodes and 61 links.
- *<u>Splitting option:</u>*
  All CPRI for fronthauling segment network.
- *<u>Location of RRHs and BBUs:</u>*
  Each node is BBU site, due to CPRI constraints.

<u>Technology</u>

- *<u>Layer 2 technology:</u>*

MPLS-TP commercial devices, grey transceivers for L2 at 10 Gbit/s, 40 Gbit/s and 100 Gbit/s.

- *Layer 1 technology:*
  FOADM with maximum 4 line degrees, ROADM with WSS 1x9 (i.e. 9 line degrees) or WSS 1x20 (i.e. 20 line degrees). Transponders for L1 with coexistence of 10/40 Gbit/s non-coherent transponders and 100 Gbit/s coherent transponders, with the technical rule that the first ones should occupy separated fibers w.r.t. the last one.
- *Type of control:*
  Embedded on the equipment.
- *Radio details:*
  MIMO 2x2 for all antennas.

Settings

IPoverMobile	yes
Number of slot per fiber	80
Threshold for optical bypass	9 Gbit/s

Results

The case analyzed in the following is still a legacy scenario, with legacy equipment and CPRI used for fronthauling, but traffic data are defined considering the estimated growth expected for mobile traffic in 2020. Costs of this scenario, both CapEx (see Figure 44) and OpEx (see Figure 45) are almost the same as the previous ones, but there are very huge savings if Yearly Total Costs per Gbit/s are compared, in fact in 2016 this value is one order of magnitude higher than the value in 2020.

$$\mathrm{YTC}_{\mathrm{per}\frac{\mathrm{Gbit}}{\mathrm{s}}2016} = 102.1\ XCU$$

$$\mathrm{YTC}_{\mathrm{per}\frac{\mathrm{Gbit}}{\mathrm{s}}2020} = 12.6\ XCU$$

CAPEX	Total cost	amortment time	Yearly cost
WDMPON	0.00	10.0	0.00
RRH			
BBU	906.91	5.0	181.38
L2 matrix	539.88	5.0	107.98
10G interfaces	3792.46	5.0	758.49
40G interfaces	235.87	5.0	47.17
100G interfaces	1021.10	5.0	204.22
L1 devices	472.94	5.0	94.59
wireless	0.00	5.0	0.00
embedded control	0.00	5.0	0.00
Total CAPEX [XCU]	6969.16		1393.83

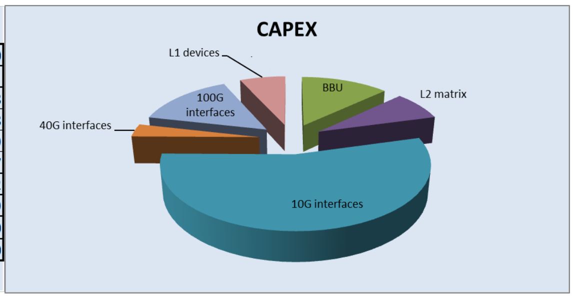


Figure 44 – CapEx items and pie-chart for legacy 2020

The first reason that contributes to increased savings is the yearly price reduction of all legacy devices used in the network, but the most significant cause for this gain is the mobile traffic transported by the network in 2020, that is more than 8 times the 2016 mobile traffic.

OPEX	Yearly cost
energy	390.31
fiber network	32.87
fiber local loop	
space (racks)	89.34
maintenance	466.11
Total OPEX [XCU]	978.63

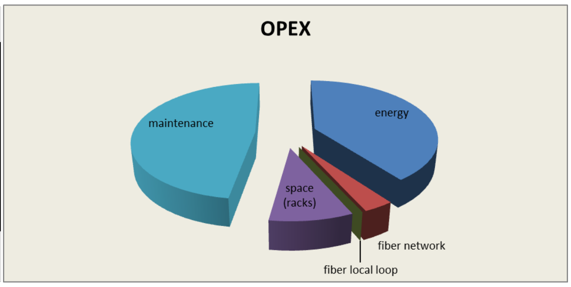


Figure 45 – OpEx items and pie-chart for legacy 2020

As reported in Figure 46, BBUs contribution to energy consumption is prevalent, but the power needed for L1 and L2 devices increases due to the use of 100G interfaces.

ENERGY	kWh/year
RRH	
WDMPON	0.00
wireless	0.00
L2 device	90238.95
L1 devices	5518.80
BBU	294555.00
Total (kWh/year)	390312.75

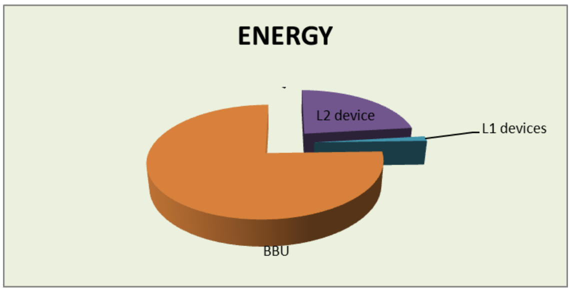


Figure 46 – Energy items and pie-chart for legacy 2020

5G-Crosshaul (all CPRI)

General architecture

- *Topology:*
  Shown in Figure 39, it is composed of 8 rings, 51 nodes and 61 links.
- *Splitting option:*
  All CPRI for fronthauling segment network.
- *Location of RRHs and BBUs:*
  Each node is BBU site, due to CPRI constraints.

Technology

- *Layer 2 technology:*
  XPFE (MAC-in-MAC device), grey transceivers for L2 at 100 Gbit/s.
- *Layer 1 technology:*
  XCSE (SiP ROADM), transponders for L1 are 100 Gbit/s coherent.
- *Type of control:*
  SDN.
- *Radio details:*
  MIMO 2x2 for all antennas.

Settings

IPoverMobile	Yes

Number of slot per fiber	40
Threshold for optical bypass	9 Gbit/s

Results

This case is really meaningful for the analysis because it shows the impacts of the new 5G-Crosshaul network, above all compared with legacy scenario at 2020. In fact, the following case evaluates costs for a network with no legacy devices, traffic forecast in 2020 and CPRI for fronthauling segment network.

CAPEX	Total cost	amortment time	Yearly cost
WDMPON	0.00	10.0	0.00
RRH			
XPU (vBBU)	1200.00	5.0	240.00
L2 matrix	425.50	5.0	85.10
10G interfaces	0.00	5.0	0.00
40G interfaces	0.00	5.0	0.00
100G interfaces	3654.40	5.0	730.88
L1 devices	132.32	5.0	26.46
wireless	0.00	5.0	0.00
XCI	0.05	5.0	0.01
Total CAPEX [XCU]	5412.27		1082.45

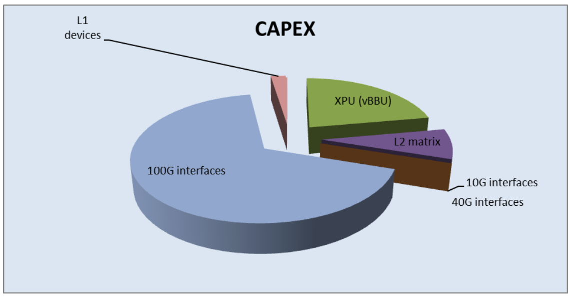


Figure 47 – CapEx items and pie-chart for 5G-Crosshaul "all CPRI"

Comparing the YTCs in 2020 for legacy and 5G-Crosshaul network:

$$\mathrm{YTC}_{\mathrm{per}\frac{\mathrm{Gbit}}{\mathrm{s}}\mathrm{legacy2020}} = 12.6\ XCU$$

$$\mathrm{YTC}_{\mathrm{per}\frac{\mathrm{Gbit}}{\mathrm{s}}\mathrm{5Gcrosshaul2020}} = 9.9\ XCU$$

CapEx (Figure 47) and OpEx (Figure 48) contribute to about 21% of cost savings, because of the introduction of new L1 and L2 equipment and less expensive 100G transponders, although the 100G interfaces are also in this scenario the biggest cost share.

OPEX	Yearly cost
energy	258.41
fiber network	32.87
fiber local loop	
space (racks)	89.34
maintenance	403.83
Total OPEX [XCU]	784.45

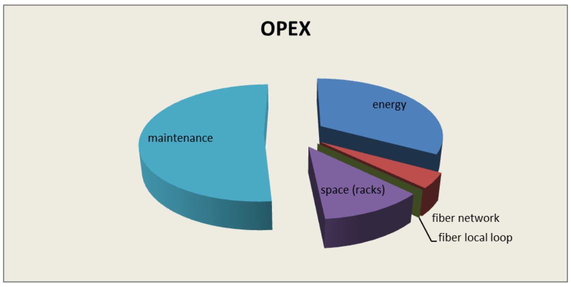


Figure 48 – OpEx items and pie-chart for 5G-Crosshaul "all CPRI"

Another important point to underline is the use of virtualized BBUs: the idea is to implement all BBUs functionalities in general purpose servers. This solution increases costs for BBUs deployment but drastically reduces energy consumption, as shown in Figure 49.

ENERGY	kWh/year
RRH	
WDMPON	0.00
wireless	0.00
L2 devices	64136.60
L1 devices	19949.44
XPU (vBBU)+ XCI	174324.00
Total (kWh/year)	258410.04

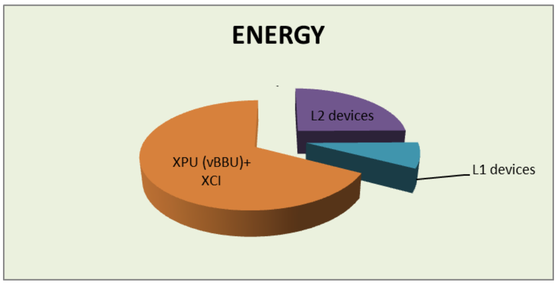


Figure 49 – Energy items and pie-chart for 5G-Crosshaul "all CPRI"

5G-Crosshaul (hybrid)

General architecture

- *Topology:*
  Shown in Figure 39, it is composed of 8 rings, 51 nodes and 61 links.
- *Splitting option:*
  Coexistence of CPRI and PDCP/RLC for fronthauling segment network.
- *Location of RRHs and BBUs:*
  BBU sites are spread at the edge of the network, while in the center there is a concentration of BBU sites and, as consequence, a reduced number of them.

Technology

- *Layer 2 technology:*
  XPFE (MAC-in-MAC device), grey transceivers for L2 at 100 Gbit/s.
- *Layer 1 technology:*
  XCSE (SiP ROADM), transponders .Transponders for L1 are 100 Gbit/s coherent.
- *Type of control:*
  SDN.
- *Radio details:*
  MIMO 2x2 for all antennas.

Settings

IPoverMobile	yes
Number of slot per fiber	40
Threshold for optical bypass	9 Gbit/s

Results

In this scenario, the splitting option is changed with respect to the scenarios previously described: CPRI is not used in the whole network but only at the edge of the MAN to transport traffic from rural areas. In areas with high user density, the splitting option used is different from CPRI. This allows aggregation of traffic towards a reduced number of BBU sites that means a reduction also in terms of costs for BBUs deployment, as shown in Figure 50.

CAPEX	Total cost	amortment time	Yearly cost
WDMPON	0.00	10.0	0.00
RRH			
XPU (vBBU)	850.00	5.0	170.00
L2 matrix	425.50	5.0	85.10
10G interfaces	0.00	5.0	0.00
40G interfaces	0.00	5.0	0.00
100G interfaces	3687.03	5.0	737.41
L1 devices	132.32	5.0	26.46
wireless	0.00	5.0	0.00
XCI	0.05	5.0	0.01
Total CAPEX [XCU]	5094.90		1018.98

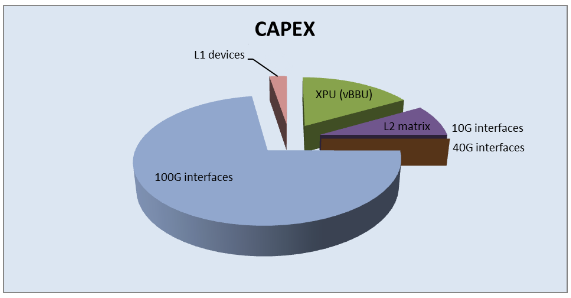


Figure 50 – CapEx items and pie-chart for 5G-Crosshaul "hybrid"

The 100G interfaces cost still remains the highest contribution to CapEx, while OpEx contributions (see Figure 51) are still distributed as in previous cases. Servers used to implement virtualized BBU and controller, although they are less than in "all CPRI" case, constitute the significant segment for energy consumption (see Figure 52).

OPEX	Yearly cost
energy	209.53
fiber network	32.87
fiber local loop	
space (racks)	89.34
maintenance	391.13
Total OPEX [XCU]	722.88

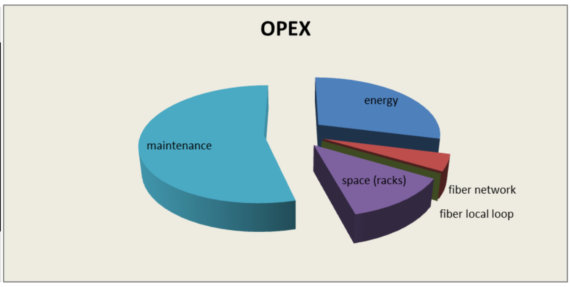


Figure 51 – OpEx items and pie-chart for 5G-Crosshaul "hybrid"

In any case, comparing YTC result of this scenario with the previous one it is possible to obtain an additional saving of 7%.

ENERGY	kWh/year
RRH	
WDMPON	0.00
wireless	0.00
L2 devices	64136.60
L1 devices	20127.56
XPU (vBBU)+ XCI	125268.00
Total (kWh/year)	209532.16

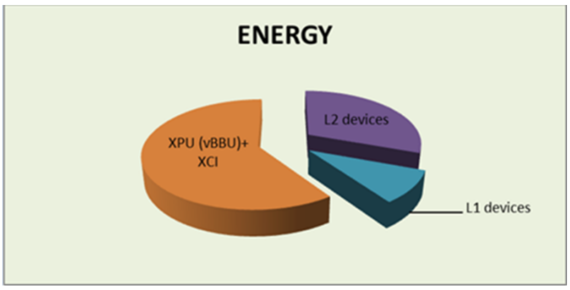


Figure 52 – Energy items and pie-chart for 5G-Crosshaul "hybrid"

5G-Crosshaul (4 virtual BBUs)

General architecture

- *Topology:*
  Shown in Figure 39, it is composed of 8 rings, 51 nodes and 61 links.
- *Splitting option:*
  PDCP/RLC.
- *Location of RRHs and BBUs:*
  4 centralized BBUs (Virtual BBUs).

Technology

- *Layer 2 technology:*
  XPFE (MAC-in-MAC device), grey transceivers for L2 at 100 Gbit/s.
- *Layer 1 technology:*
  XCSE (SiP ROADM), transponders. Transponders for L1 are 100 Gbit/s coherent.
- *Type of control:*
  SDN.
- *Radio details:*
  MIMO 2x2 for all antennas.
- *Transport technology in the local loop:*
  All P2P fiber connections.

Settings

IPoverMobile	yes
Number of slot per fiber	40
Threshold for optical bypass	9 Gbit/s

Results

For the last scenario, the implemented solution is deeply focused on the deployment of virtualized and remote BBU sites. On the whole MAN only four BBU sites are set up and each of them is composed of several servers, that process traffic (not CPRI) coming from the periphery or from the center of the MAN. These four sites are placed far from the periphery and near the core of the network: this choice is due to the geographical BBUs distribution, to efficiently collect mobile traffic.

Costs in this case are split as in the previous one: 100G interfaces introduce the largest contribution, L1 and L2 devices costs are the same as in all 5G scenarios because of the unchanged network topology and mobile traffic data. A strong reduction for virtualized BBU costs is remarkable using this solution (see Figure 53).

Analogously to previous cases, the most important share for OpEx (see Figure 54) is maintenance followed by energy consumption.

The same consideration is observed having a look at Figure 55: substituting legacy BBUs hardware with virtualized ones and aggregating them in only few sites, both costs and energy savings are obtained.

CAPEX	Total cost	amortment time	Yearly cost
WDMPON	0.00	10.0	0.00
RRH			
XPU (vBBU)	675.00	5.0	135.00
L2 matrix	425.50	5.0	85.10
10G interfaces	0.00	5.0	0.00
40G interfaces	0.00	5.0	0.00
100G interfaces	3556.51	5.0	711.30
L1 devices	132.32	5.0	26.46
wireless	0.00	5.0	0.00
XCI	0.05	5.0	0.01
Total CAPEX [XCU]	4789.38		957.88

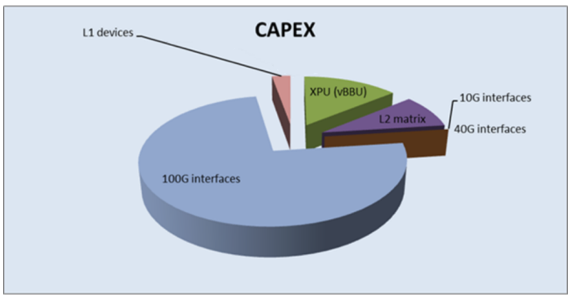


Figure 53 – CapEx items and pie-chart for 5G-Crosshaul "4 BBUs"

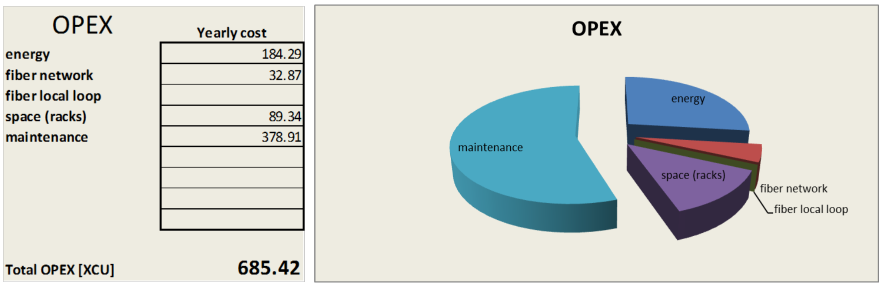


Figure 54 – OpEx items and pie-chart for 5G-Crosshaul "4 BBUs"

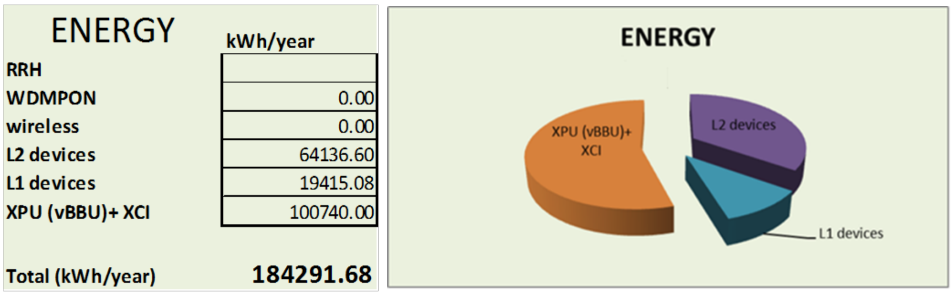


Figure 55 – Energy items and pie-chart for 5G-Crosshaul "4 BBUs"

3.4.2.3. Conclusions

In Table 18 the costs of the different scenarios and the savings with respect to scenario 1 (legacy 2016) and w.r.t. scenario 2 (legacy 2020) are highlighted in the columns at the right of the table.

The column denominated YTC shows the Yearly Total Cost of Ownership for the solution, limited to the transport network (L1/L2 nodes, fibers, BBUs), including the investment mortgage and the OpEx, comprehensive also of maintenance and power consumption.

The column denominated "w.r.t. 1" represents the cost savings of each scenario versus scenario 1, in terms of YTC per Gbit/s. This impressive savings amount leverages on different reasons:

- the increase of total traffic makes a better usage of network resources.
- the cost of telecommunications equipment respects a learning curve, decreasing by a factor per year, due to technology maturity.

These cost-reducing factors are independent from 5G-Crosshaul researches.

Table 18 – Summary of cost savings among different simulation scenarios

	Scenario	YTC [XCU] per Gbit/s	w.r.t 1	w.r.t 2
1	legacy 2016	102.1	0.0%	
2	legacy 2020	12.6	-87.7%	0.0%
3	5G all CPRI	9.9	-90.3%	-21.4%
4	5G hybrid	9.2	-91.0%	-27.0%
5	5G 4 BBUs	8.7	-91.5%	-31.0%

The cost savings due to 5G-Crosshaul are highlighted in the last column. These savings are between 21% and 31%, essentially due to the cheaper technology for L2, based on XCF and L1, based on silicon photonics. Also, the cost of BBUs decreases. In particular, due to a more concentration in fewer BBU hotels, a hybrid solution (where there is the coexistence of CPRI and another splitting, e.g. PDCP/RLC) and a scenario where only 4 BBUs are present in a wide metropolitan area allow further cost savings respectively of about 5% and 10%, due to a better usage of BBUs.

Table 19 – Summary of energy consumption savings among different simulation scenarios

	Scenario	kWh/Gbit/s year	w.r.t 1	w.r.t 2
1	legacy 2016	14210	0.0%	
2	legacy 2020	2068	-85.4%	0.0%
3	5G all CPRI	1366	-90.4%	-33.8%
4	5G hybrid	1109	-92.2%	-46.4%
5	5G 4 BBUs	983	-93.1%	-52.7%

Concerning energy consumption, the considerations are similar. A big decrease of energy consumption per Gbit/s between legacy 2016 and legacy 2020 scenarios (not directly connected to 5G-Crosshaul studies) are due to a better use of resources for the increase of the total traffic.

The energy savings due to 5G-Crosshaul solutions reaches more than 50%. This study does not take into account the applications envisaged by the project (e.g. EMMA, which is considered later in 3.7), that would allow further energy savings.

3.5. Multi-tenancy cost and energy evaluation

The goal of this study is to empirically evaluate the advantages in terms of cost and energy savings obtained thanks to the introduction of multi-tenancy and network slicing.

In order to evaluate the cost savings due to multi-tenancy approach the idea is to consider two scenarios:

- Scenario 1) The whole traffic is splitted and carried by several (four) independent physical infrastructures. Each infrastructure is owned and managed by a different carriers (operators). The traffic of said operator is carried only on this infrastructure.
- Scenario 2) The whole traffic is carried by several slices of the same physical infrastructure, owned by a single carrier, but managed by different operators (tenants).

The method followed to obtain the evaluation is composed by the following steps:

- Calculate whole network costs (multi-tenancy).
- Calculate separate tenant network costs.

The evaluation has been performed using the tool provide by TIM for 5G-Crosshaul project. The parameters used for the simulations are:

- Costs include fiber in the network and they do not include local loop fiber and RRH.
- 40 lambdas per fiber.
- 80 Gbit/s is the threshold for optical bypass.
- Only mobile traffic is considered (no IP traffic).

In this study, a region of northern Italy is considered, consisting of 51 nodes and 61 links. The topology is depicted in Figure 56. The network is inspired by a regional TIM network.

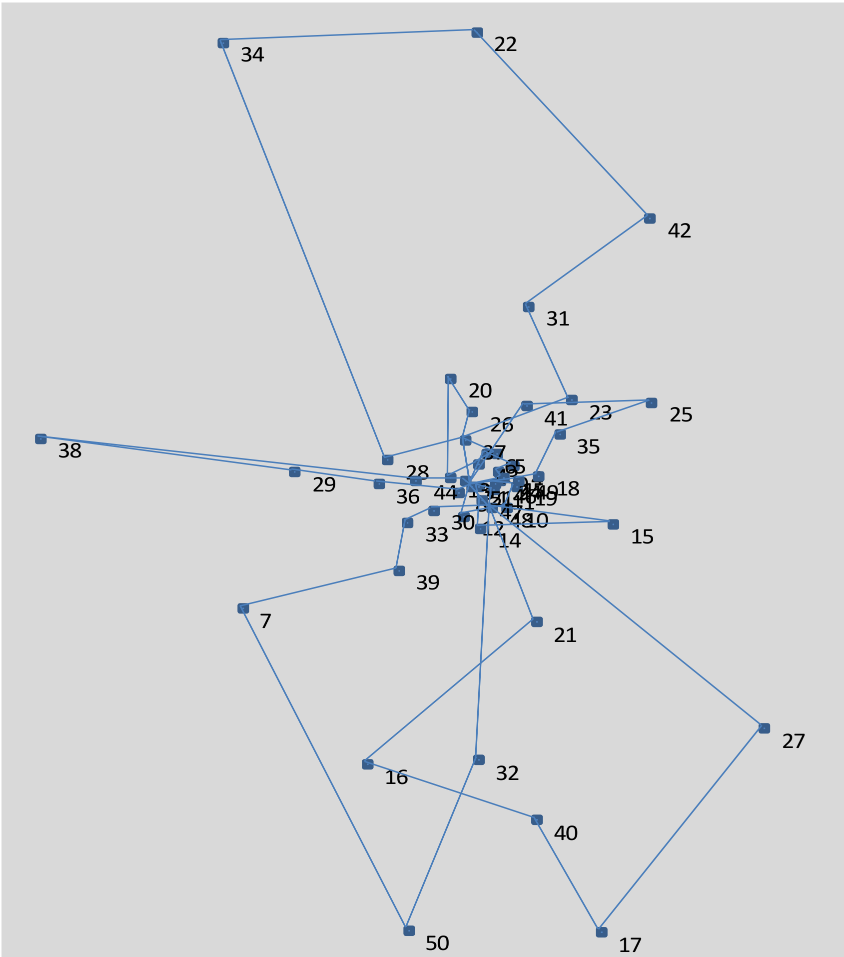


Figure 56 – Network graph

Furthermore, connected to the core nodes there are more than 1400 antennas, all connected via optical fiber to the nodes.

The whole traffic is about 188 Gbit/s. The adopted splitting option is that the traffic is carried towards 4 nodes and the "fronthauling traffic" is similar w.r.t. the user traffic, with a few overhead.

3.5.1. Scenario 1 – no Multi-tenancy

The whole traffic is split and carried by several (four) independent physical infrastructures. Each infrastructure is owned and managed by a different carriers (operators). Each of these operators has a share of the total traffic of the region.

The four tenants are, respectively, 12%, 24%, 30% and 34% of the whole traffic. Each tenant operates in all the nodes of the network.

The traffic is carried over the network infrastructure depicted in Figure 56 adopting link-disjoint 1+1 protection. The links consist of optical fiber and each fiber can accommodate within 40 wavelengths, 100G coherent. Each node is composed by L2 (e.g. MPLS-TP) and L1 (RAODM) capabilities. The traffic demand undergoes optical bypass (no L2 switching in intermediate nodes) if the bandwidth is above 80 Gbit/s.

CAPEX	Total cost	amortment time	Yearly cost
WDMPON	0.00	10.0	0.00
RRH			
XPU (vBBU)	675.00	5.0	135.00
L2 matrix	2458.92	5.0	491.78
10G interfaces	0.00	5.0	0.00
40G interfaces	0.00	5.0	0.00
100G interfaces	3882.80	5.0	776.56
L1 devices	807.14	5.0	161.43
wireless	0.00	5.0	0.00
XCI	0.05	5.0	0.01
Total CAPEX [XCU]	7823.92		1564.78

OPEX	Yearly cost
energy	505.79
fiber network	200.52
fiber local loop	
space (racks)	534.67
maintenance	500.30
Total OPEX [XCU]	1741.28

Figure 57 – CapEx/OpEx evaluations for scenario 1 (multi-tenancy, tenant 1, 12% of the whole traffic)

ENERGY	kWh/year
RRH	
WDMPON	0.00
wireless	0.00
L2 devices	383851.52
L1 devices	21200.52
XPU (vBBU)+ XCI	100740.00
Total (kWh/year)	505792.04

Figure 58 – Energy consumption evaluations for scenario 1 (multi-tenancy, tenant 1, 12% of the whole traffic)

CAPEX	Total cost	amortment time	Yearly cost
WDMPON	0.00	10.0	0.00
RRH			
XPU (vBBU)	675.00	5.0	135.00
L2 matrix	2595.52	5.0	519.10
10G interfaces	0.00	5.0	0.00
40G interfaces	0.00	5.0	0.00
100G interfaces	4698.51	5.0	939.70
L1 devices	807.14	5.0	161.43
wireless	0.00	5.0	0.00
XCI	0.05	5.0	0.01
Total CAPEX [XCU]	8776.23		1755.25

OPEX	Yearly cost
energy	517.63
fiber network	200.52
fiber local loop	
space (racks)	544.95
maintenance	538.39
Total OPEX [XCU]	1801.49

Figure 59 – CapEx/OpEx evaluations for scenario 1 (multi-tenancy, tenant 2, 24% of the whole traffic)

ENERGY	kWh/year
RRH	
WDMPON	0.00
wireless	0.00
L2 devices	391233.28
L1 devices	25654.41
XPU (vBBU)+ XCI	100740.00
Total (kWh/year)	517627.69

Figure 60 – Energy consumption evaluations for scenario 1 (multi-tenancy, tenant 2,24, 2% of the whole traffic)

CAPEX	Total cost	amortment time	Yearly cost
WDMPON	0.00	10.0	0.00
RRH			
XPU (vBBU)	675.00	5.0	135.00
L2 matrix	2777.66	5.0	555.53
10G interfaces	0.00	5.0	0.00
40G interfaces	0.00	5.0	0.00
100G interfaces	5448.97	5.0	1089.79
L1 devices	807.14	5.0	161.43
wireless	0.00	5.0	0.00
XCI	0.05	5.0	0.01
Total CAPEX [XCU]	9708.83		1941.77

OPEX	Yearly cost
energy	536.49
fiber network	200.52
fiber local loop	
space (racks)	544.95
maintenance	575.69
Total OPEX [XCU]	1857.66

Figure 61 – CapEx/OpEx evaluations for scenario 1 (multi-tenancy, tenant 3, 30% of the whole traffic)

ENERGY	kWh/year
RRH	
WDMPON	0.00
wireless	0.00
L2 devices	405996.80
L1 devices	29751.99
XPU (vBBU)+ XCI	100740.00
Total (kWh/year)	536488.79

Figure 62 – Energy consumption evaluations for scenario 1 (multi-tenancy, tenant 3, 30% of the whole traffic)

CAPEX	Total cost	amortment time	Yearly cost
WDMPON	0.00	10.0	0.00
RRH			
XPU (vBBU)	675.00	5.0	135.00
L2 matrix	2777.66	5.0	555.53
10G interfaces	0.00	5.0	0.00
40G interfaces	0.00	5.0	0.00
100G interfaces	4829.03	5.0	965.81
L1 devices	807.14	5.0	161.43
wireless	0.00	5.0	0.00
XCI	0.05	5.0	0.01
Total CAPEX [XCU]	9088.88		1817.78

OPEX	Yearly cost
energy	533.10
fiber network	200.52
fiber local loop	
space (racks)	544.95
maintenance	550.89
Total OPEX [XCU]	1829.47

Figure 63 – CapEx/OpEx evaluations for scenario 1 (multi-tenancy, tenant 4, 34% of the whole traffic)

ENERGY	kWh/year
RRH	
WDMPON	0.00
wireless	0.00
L2 devices	405996.80
L1 devices	26367.03
XPU (vBBU)+ XCI	100740.00
Total (kWh/year)	533103.83

Figure 64 – Energy comsumption evaluations for scenario 1 (multi-tenancy, tenant 4, 34% of the whole traffic)

Figure 57 - Figure 64 report costs and energy consumption for each of the 4 separate networks owned and managed by the 4 operators.

3.5.2. Scenario 2 –Multi-tenancy

Each operator carries its traffic (the same amount w.r.t. scenario 1) but on the same physical infrastructure. In other terms, the four operators do not own a physical infrastructure, but they share the one owned by another actor.

The infrastructure consists of duct, fibers, nodes, sites and BBU hotels. The network structure is the same as in scenario 1 and the same L2 and L1 transport technologies.

CAPEX	Total cost	amortment time	Yearly cost
WDMPON	0.00	10.0	0.00
RRH			
XPU (vBBU)	675.00	5.0	135.00
L2 matrix	3870.46	5.0	774.09
10G interfaces	0.00	5.0	0.00
40G interfaces	0.00	5.0	0.00
100G interfaces	5612.11	5.0	1122.42
L1 devices	1042.86	5.0	208.57
wireless	0.00	5.0	0.00
XCI	0.05	5.0	0.01
Total CAPEX [XCU]	11200.49		**2240.10**

OPEX	Yearly cost
energy	611.20
fiber network	201.56
fiber local loop	
space (racks)	586.08
maintenance	635.36
Total OPEX [XCU]	**2034.19**

Figure 65 – CapEx/OpEx evaluations for scenario 2 (no multi-tenancy)

ENERGY	kWh/year
RRH	
WDMPON	0.00
wireless	0.00
L2 devices	479814.40
L1 devices	30642.77
XPU (vBBU)+ XCI	100740.00
Total (kWh/year)	**611197.17**

Figure 66 – Energy consumption evaluations for scenario 2 (no multi-tenancy)

In Figure 65 and in Figure 66, costs and energy consumption evaluation for scenario 2 (multi-tenancy) are reported. The costs are comprehensive of the whole network, able to carry the traffic of the 4 operators. The cost does not include local loop (the link between antenna and the most external node).

3.5.3. *Evaluations*

The conclusion of this study is that, for a realistic network, carrying realistic traffic projected to 2025 forecasts is summarizing in Table 20. Considering the yearly CapEx (i.e. the CapEx / amortization time) the saving is about 70%, while the OpEx saving is about 72%. The savings on the total cost of ownership is about 40%.

Table 20 – Costs and energy comparison in a multi-tenancy environment

	w.r.t whole	CAPEX/year	OPEX	Energy
Tenant 1	12%	1564.78	1741.28	505792.6
Tenant 2	24%	1755.25	1801.49	515627.7
Tenant 3	30%	1941.77	1857.66	536488.8
Tenant 4	34%	1817.78	1829.47	533103.8
Total		**7079.58**	**7229.9**	**2091013**
whole	**100%**	**2240**	**2034**	**611197**

The (apparently) strange figure is the CapEx for tenant 4 is lower than the one for tenant 3 despite a higher level of traffic. This is due to the optical bypass.

Also, the energy consumption takes advantages from multi-tenancy. In fact, w.r.t. the sum of energy consumption of 4 independent operators, the saving is more than 70%

3.6. Small cell cost and energy evaluations

The current evolution of mobile networks is strictly linked to the increased traffic loads due to proliferation of smart mobile devices, applications and users. To face the massive increment in capacity of the mobile networks, small-cell deployment seems to be a good solution: cell size is greatly reduced, spectral resources can be easily reused among cells with limited interference and coverage and mobility support is enhanced.

Integration between small cells and new 5G general architecture is still under investigation. The challenge is to create a unique mobile network that can include different radio access technologies and to develop a solid and efficient backhaul network in order to transport radio signal not only in a legacy scenario but also in a cloud-RAN architecture. What is expected is to improve technical performance of the network supporting high-speed data transmission and higher coverage, with a significant cost and energy reduction per bit/s w.r.t macro cell installation.

3.6.1. Comparison of Small-Cells solutions

The small-cells strategy is focused on cutting costs of legacy networks and increasing traditional profits. Another driver from the operator point of view is to find new revenue opportunities improving customer experience. A massive deployment of macro cells is not enough to satisfy all the customers' demand, and it would require a very huge investment. A different perspective is given by introducing small-cells in critical zones: as reported in [28], for the long-term period, it can be economically advantageous to add new small-cell sites instead of macro sites. In fact, it has been estimated that the TCO of a three-sector LTE small cell is from 16% to 23% less than the TCO of a macro cell. Several elements contribute to define this result, but the backhaul mainly impacts on the overall system because of higher costs of RAN solutions for macro cells.

Considering that macro and small cells solve different mobile coverage aspects; these two different technologies are not easily interchangeable and consequently not directly comparable in terms of costs. Then, in the following, two different analysis are proposed: the first one evaluates costs of small-cells installed in the current network architecture with distributed mobile components and the second one considers a cloud-RAN architecture with a BBU pooling.

Wireline and wireless small-cells backhauling solutions will be compared, highlighting TCO and energy efficiency aspects in order to evaluate benefits of the small-cell deployment.

3.6.2. Small-cells and legacy network

In this paragraph, the scenario showed in Figure 67 –is analyzed. Three-sectorial antennas provide connectivity for macro areas, while several small-cells are installed to extend coverage in denser traffic area. The BBU is at the bottom of the antenna site, each Remote Radio Head (RRH) is connected to the BBU of the corresponding macro cell and a link between BBUs and transport network is established.

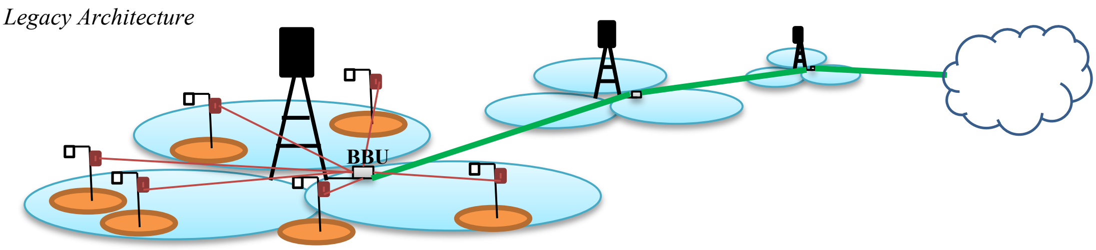


Figure 67 – Architecture with BBU at the bottom of each RRH

This is the deployment case where, for the last mile, each small cell is directly connected to the macro cell site using the existing network: FTTx is the main backhauling technology, but depending on their availability on the network near small cell sites, also PON or xDSL could be used to create a wired connectivity. For sure these are suitable methods for the network owner that already deployed fibers and that can guarantee high backhaul performances relying on massive fiber deployment.

The real challenge is to install new small-cells where there is no wired connectivity, because digging is the most costly part of the work. Similar to this scenario, it is quite expensive also to lease fibers from a third party provider.

An alternative solution is to implement a wireless backhauling, above all using Wi-Fi, that provides some advantages in term of time and costs savings.

For wireless backhauling solution three main aspects affect costs:

- Site rental and equipment installation. A good planning of mobile resources is important in order to provide a good coverage and avoid also interferences, minimizing the number of sites and then costs.
- Bandwidth acquisition. The use of unlicensed or lightly licensed spectrum could be possible to find new way out to save money in small cells deployment.
- Backhauling transport. Different topologies can be discussed and compared, the main ones are the Point-To-Point (P2P) and Point-to-Multi-Point (P2MP) that can combine Line-of-Site (LoS) and Non-Line-of-Site (NLoS) technologies in order to guarantee mobile coverage.

Generally speaking, it is clear that small-cells solutions have to be defined considering requirements and available resources, differentiating each case and optimizing costs after having ensured high mobile coverage and throughput. In fact, although fiber is ideal to guarantee the best performances, it is not available everywhere or cost effective. Sometimes, when a wireless backhaul option is taken into account, some considerations are required such as if licensed spectrum is available, if it can satisfy the traffic demand or whether interference becomes critical.

In Table 21 and Table 22 costs for outdoor and indoor sites are shown. They are extracted from [28] and expressed in XCU at the year 2020. In the document [28] they are expressed as current costs for year 2012, while in the tables below data are defined considering 9% of price decreasing per each year from 2012 to 2020.

Table 21 – Costs for outdoor sites [28]

	Macro	LTE Three sectors
CAPEX		
Equipment - Base Station	46,19	11,76
Equipment - Wireless backhaul	12,60	5,88
Equipment - Wireline backhaul	3,36	2,35
Planning, Installation, Commissioning	67,18	11,76
OPEX		
Site Lease - Base station	53,57	5,14
Backhaul – wireless	21,43	7,07
Backhaul – wireline	85,71	42,86
Power, maintenance, …	35,71	5,86
CAPACITY		
Gbit/s	0,162	0,162

Each CapEx item is described:

- *Equipment - base station*: it includes costs to buy devices such as antenna, RRH and link between antenna and RRH as shown in Figure 68.

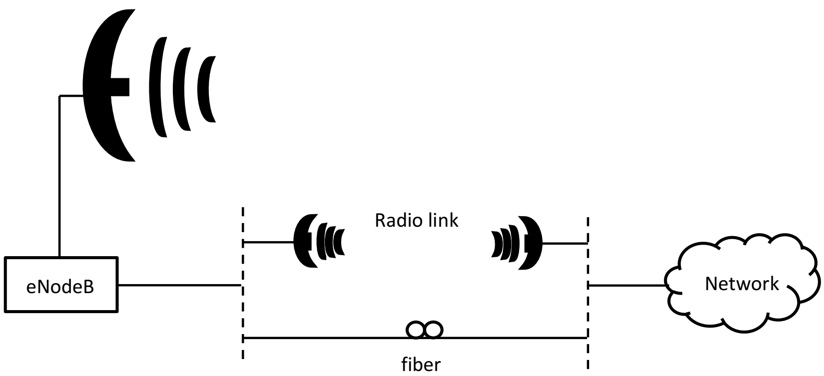


Figure 68 – Scheme of backhauling

- *Equipment - Wireless backhaul*: costs for transport segment realized using wireless radio link (Tx and Rx device).
- *Equipment - Wireline backhaul*: costs for transport segment that includes L2 switches and transceivers.
- *Planning, Installation and commissioning*: they consist of all costs related to installation of hardware or creation of a new site.

Table 22 – Costs for indoor sites [28]

	LTE Three sectors	Wi-Fi
CAPEX		
Base Station	9,99	2,50
Wireless backhaul	3,78	3,36
Wireline backhaul	0,81	0,67

Planning, Installation, Commissioning	9,49	5,19
OPEX		
Site Lease: Base station	3,09	1,93
Backhaul – wireless	3,86	3,54
Backhaul – wireline	21,43	14,29
Power, maintenance, …	3,53	2,13
CAPACITY		
Gbit/s	0.162	0.048

Regarding OpEx:

- *Site lease – Base station*: leasing costs for the site that physically hosts BBU and RRH hardware.
- *Backhaul - Wireless*: costs for licenses of spectrum portion.
- *Backhaul - Wireline*: costs for fiber renting.
- *Power, maintenance, etc.*: they consist of all costs related to power consumption, maintenance and management of the site.

The figures regarding OpEx consider 5 years expenditures. Taking into account that the average mortgage time of hardware is 5 years, the graphs report the total cost of ownership for 5 years.

In the following we show some graphs that compare different cost solutions of small-cell installation. First of all, we compare between a macro and a small-cell deployment with different backhauling technologies, i.e. wireless and wireline as in Figure 69.

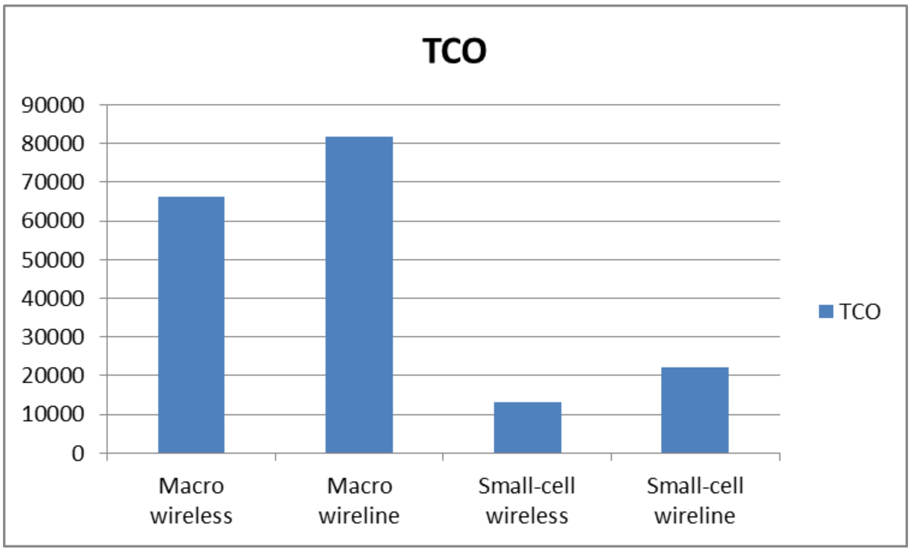


Figure 69 – Comparison of costs deployment for macro and small cell

It is evident that wireline solutions are more expensive than wireless ones, considering that OpEx are significantly higher because of fiber renting. This is the main reason, together with geographical wiring constraints, for the growing interest on wireless backhauling solutions.

Next graphs show again costs of macro and small-cell deployment splitting CapEx and OpEx parts (Figure 70) and considering also the normalized value per Gbit/s (Figure 71).

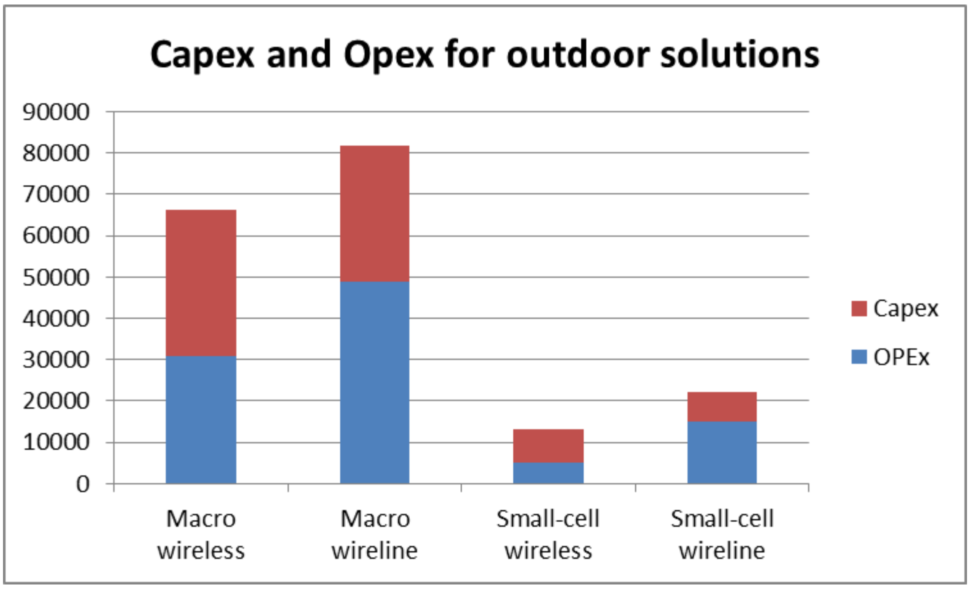


Figure 70 – CapEx and OpEx for outdoor solutions

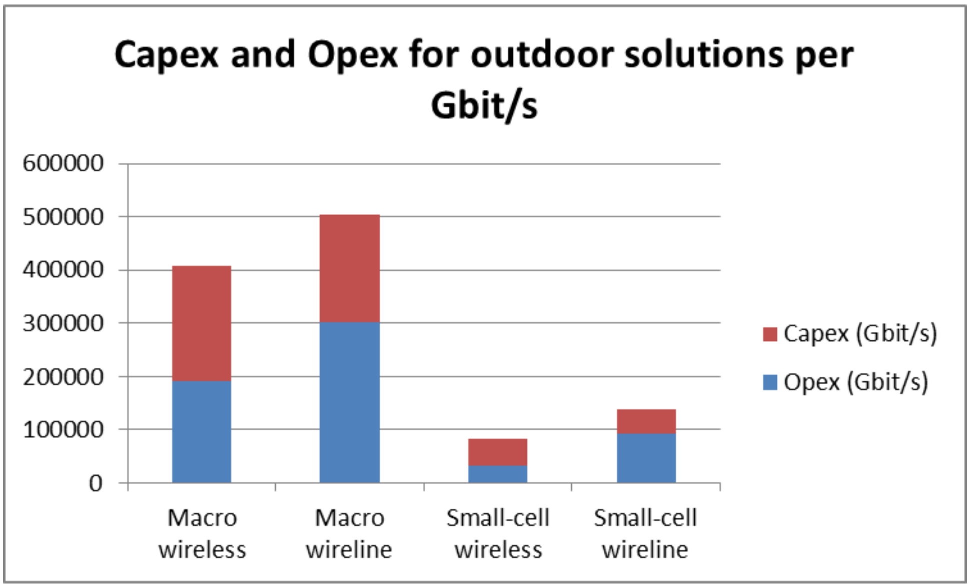


Figure 71 – CapEx and OpEx per Gbit/s for outdoor solutions

It is interesting to analyze the results in Figure 72 to underline the effectiveness of wireless outdoor backhauling. It has been supposed that the three different proposed solutions will guarantee additional coverage for the same geographical area, where a macro cell is already installed, increasing the available bandwidth for 3.4 Gbit/s.

The first solution considers the deployment of 18 small-cells with a wireline backhaul and 2 small-cells with a wireless backhaul, the second one considers the installation of the same number of wireline and wireless small-cells (i.e. 10) and for the last one the wireless backhaul dominates with 18 wireless small-cells installed and 2 wireline ones. Wireless and wireline small-cells can provide the same bandwidth capacity (162

Mbit/s), equal to macro cell capacity. As previously discussed, the high potential of the wireless solution is clearly shown in Figure 72. Being equal the advantage introduced in terms of coverage, the solution with prevalent wireless backhaul is preferable in terms of costs.

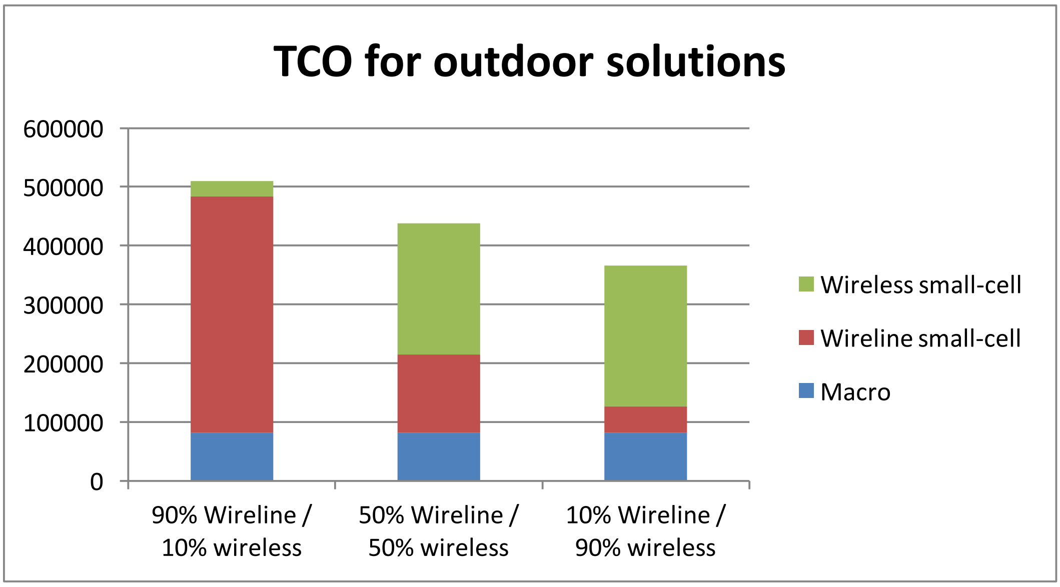


Figure 72 – Comparison of costs for different backhauling deployment considering 20 installed small-cells

For the indoor case, the proposed analysis is similar to the outdoor case. In Figure 73 the cost of one small-cell is shown for two different indoor technologies. Wi-Fi requires lower costs w.r.t. LTE, but provides also low bandwidth capacity, i.e. 48 Mbit/s.

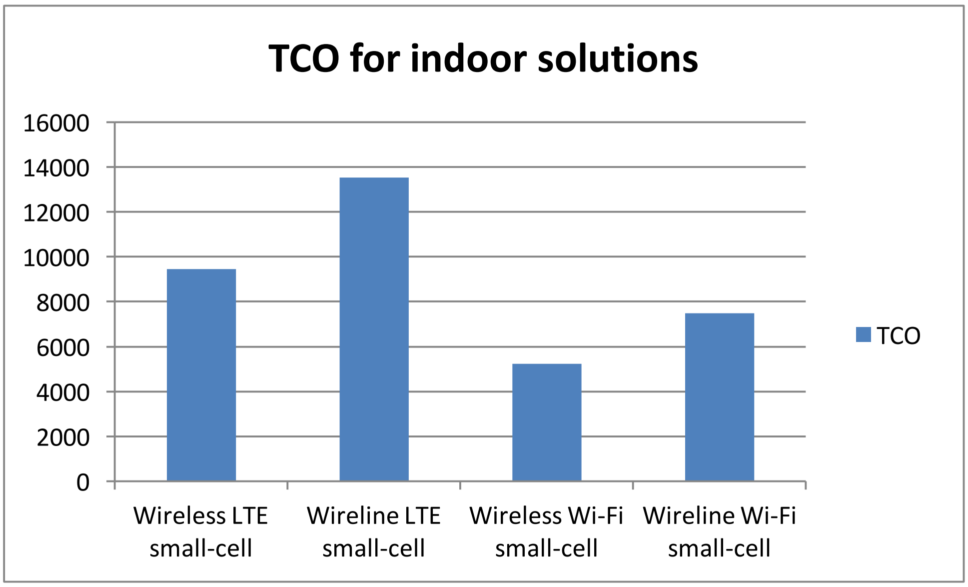


Figure 73 – Comparison of costs deployment for LTE and Wi-Fi small cell

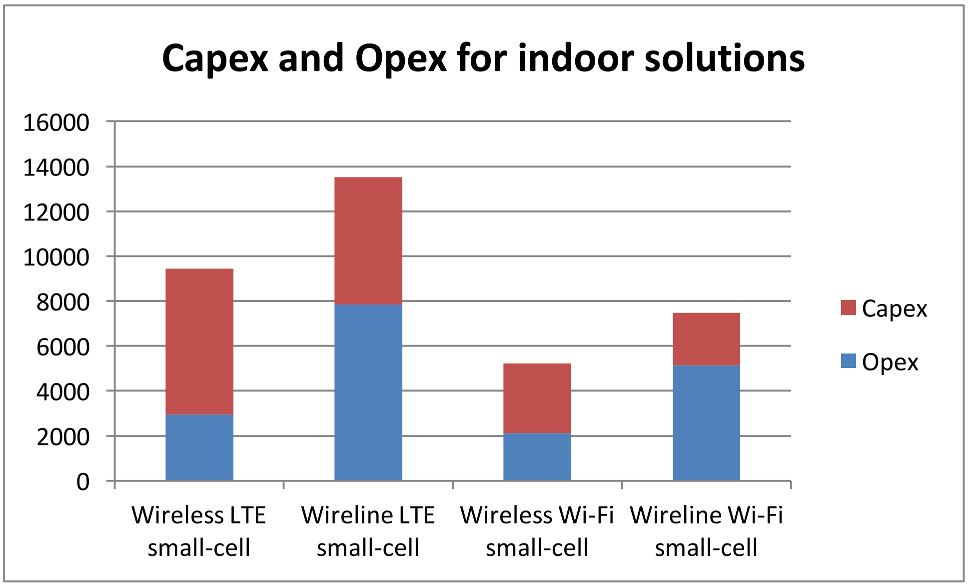


Figure 74 – CapEx and OpEx for indoor solutions

In Figure 74 it is clearly visible that CapEx is the greater contribution to total costs independently of which technology is used. The only exception might be for Wi-Fi solutions where the hotspots are wireline connected. In this case the wireline backhauling is comparable w.r.t. 5 years OpEx.

In Figure 75 it is possible to appreciate the costs per Gbit/s. The Wi-Fi is for sure the most affordable technology for a single small-cell site, but because of its lower bandwidth capacity it is the most costly.

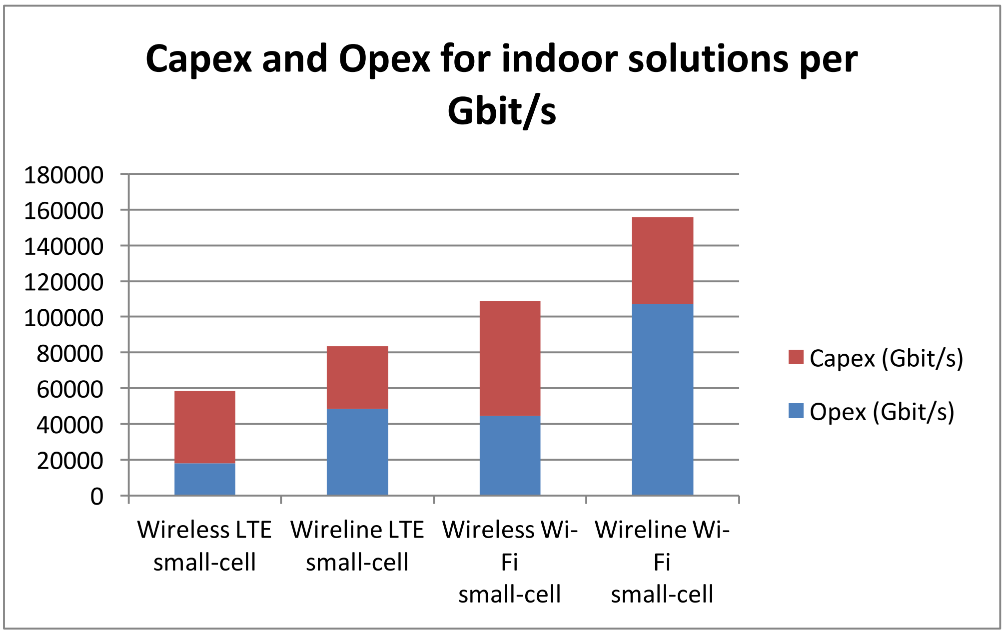


Figure 75 – CapEx and OpEx per Gbit/s for indoor solutions

In fact, considering to extend indoor bandwidth capacity at 3.4 Gbit/s, it is possible to deploy different solutions: in Figure 76 it is shown a comparison between the use of

LTE small-cells and Wi-Fi small-cells. Four scenarios are considered: the first is an indoor area installing 2 small-cells with wireline and 19 with wireless backhaul, the second has 19 wireless small-cells and 2 wireline small-cells. According to observations already discussed in previous paragraph, wireless backhauling reduces costs.

Third and fourth scenarios consider installation of only Wi-Fi small-cells mixing wireless and wireline backhaul. In order to satisfy additional bandwidth, 71 sites are necessary. In the scenario with wireless backhaul, predominance 64 wireless backhaul small-cells are installed and 7 wireline ones, in the other scenario 64 wireline and 7 wireless small-cells are supposed to be deployed.

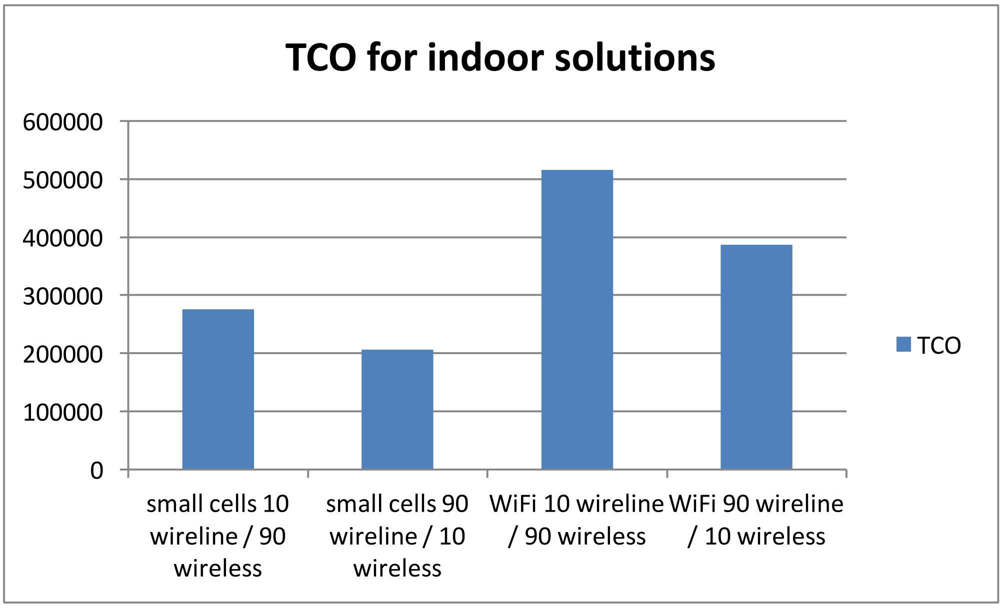


Figure 76 – Comparison of costs for different technology for indoor small-cells

In this case the most affordable solution in terms of cost saving is the deployment of 90-10% of wireline/wireless backhaul due to the higher costs of Wi-Fi equipment.

Having a look to Figure 76 it is clear that Wi-Fi is not the best solution for the indoor coverage when high bandwidth capacity is required.

3.6.3. BBU Pooling

Distributed architecture with C-RAN development centralizes the processes in the BBU site, improving coordination of radio capabilities and system performances. Cloud and NFV solutions introduce a big advantage allowing the resource sharing inside the network and providing the needed radio capacity where and when it is required. Other benefit due to SDN technology is the possibility to easily configure and reconfigure networks taking into account traffic demand and spectrum availability. Furthermore, BBU pooling is the starting point to implement high performances features such as CoMP.

In the following the scenario refers to three-sectorial antennas that provide connectivity for macro areas and several small-cells installed to extend coverage in denser user area. BBUs are pulled far from RRH, as shown in Figure 77. Fronthauling signals coming from antennas are collected in an aggregator and then sent to an Ethernet switch before reaching the BBU site.

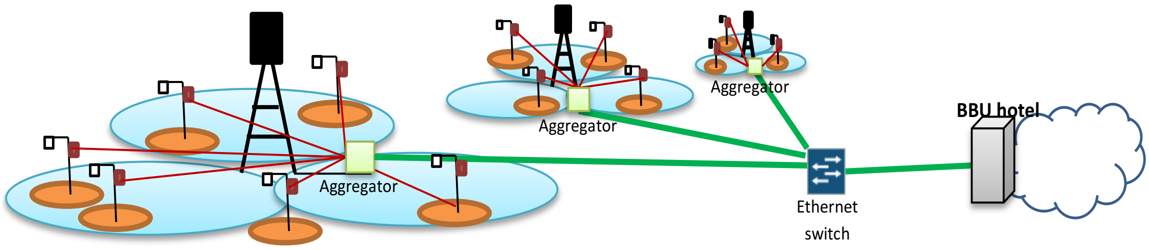


Figure 77 – Architecture with BBU pooling

In this case it has been supposed that aggregator is placed close to macro cell site. It has the ability to collect fronthauling (i.e. CPRI) but also Ethernet signal from several antennas, it can also compress CPRI signal reaching output bandwidth capacity up to 2.5Gbit/s. Fronthauling connections can be wireless or wireline, as shown in Figure 68, depending on geographical constraints or fiber availability.

The Ethernet switch, placed closer to the BBU site, is present in this architecture to collect backhauling flows from aggregators and to send them to the BBU hotel. This link is mainly made by a wireline connection because of high bandwidth (>10Gbit/s).

In Table 23 network costs of this scenario are shown end expressed in XCU. Sources are different, not only public documents (i.e. [28]), but also TIM internal data complete the list. Each of them will be deeply explained in the following.

Table 23 – Costs for BBU pooling scenario

	Common Network Parts	Macro	LTE Three sectors
CAPEX			
Equipment – Antennas		12,34	10,65
Equipment – vBBU	27,68		
Equipment – RRH		3,64	3,39
Equipment - Aggregator	9,54		
Equipment – Ethernet switch	168,78		
Equipment - Wireless transport		12,60	5,88
Equipment - Wireline transport		3,36	2,35
Planning, Installation, Commissioning		67,18	11,76
OPEX			
Site Lease - Antennas		53,57	5,14
Site Lease – vBBU	63,46		
Fronthaul – wireless		21,43	7,07
Fronthaul – wireline		17,14	8,57
Backhaul – wireline		68,57	34,29
Power, maintenance, …	14,09	35,71	5,86
CAPACITY			
Gbit/s		0,162	0,162

Each CapEx item is described:

- *Equipment – Antennas:* costs of RF module (TIM internal data).

- *Equipment – vBBU:* costs of server that hosts BBU software application in the BBU hotel (TIM internal data).

- *Equipment – RRH:* costs of RRH module (TIM internal data).

- *Equipment – Aggregator:* costs of switch hardware (40 Gbit/s switching capacity) plus four interfaces at 2.5 Gbit/s that receives fronthauling incoming flows and only a 10 Gbit/s interface that outputs an aggregated flow towards the BBU site (projected from STRONGEST data).

- *Equipment – Ethernet switch:* cost of switch hardware that aggregates and forwards flows up to 100 Gbit/s of traffic capacity. This cost includes also cost of ten inputs 10 Gbit/s interfaces, cards at 100 Gbit/s and one card at 100 Gbit/s in the output direction (projected from STRONGEST data).

- *Equipment - Wireless transport:* for transport segment realized using wireless radio link (Tx and Rx device). [28]

- *Equipment - Wireline transport:* for transport segment that includes L2 switches and transceivers. [28]

- *Planning, Installation and commissioning:* they consist of all costs related to installation of hardware or creation of a new site. [28]

Each OpEx item is described:

- *Site Lease – Antennas:* leasing costs for the site that physically hosts Radio Frequency module. [28]

- *Site Lease – vBBU:* leasing costs for the site that physically hosts servers that implement virtualized BBU. [28]

- *Fronthaul – wireless:* costs for licensed spectrum portion. Wireless segment, as in legacy case, provides coverage for the last mile segment between RRH and Aggregator, as shown in Figure 78. [28]

- *Fronthaul – wireline:* costs for fiber renting that transport traffic from the RRH site to the aggregator, as depicted in segment B in Figure 78. The value indicated in Table 23 is 1/5 of value reported in [28] because this segment is 1/5 of the whole path between RRH and BBU hotel.

- *Backhaul – wireline:* costs for fiber renting that transport traffic from aggregator to the BBU hotel, as depicted in segment B in Figure 78. It has been supposed that this segment carries traffic only over fiber because of high bandwidth capacities. The value indicated in Table 23 is 4/5 of value reported in [28]. In fact, it has been considered that the distance between eNodeB and Network in Figure 68 is the same as the distance between RRH and Network in Figure 78.

- *Power, maintenance, etc.:* they consist of all costs related to power consumption, maintenance and management of the site. [28]

Common Network Part OpEx contribution is 15% (3% per year) related to CapEx costs (TIM internal data).

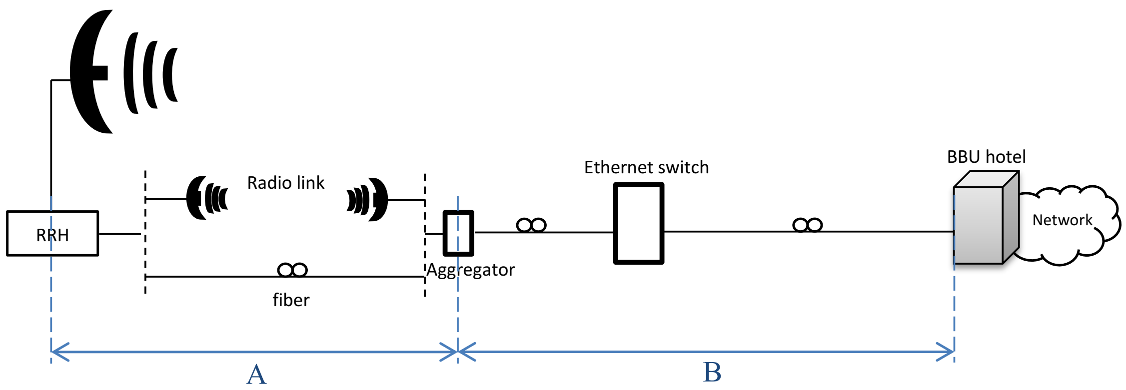


Figure 78 – Scheme of fronthauling backhauling

In the following, in Figure 79, the trend of CapEx and OpEx for three different BBU pooling small cells scenarios are shown. It has been supposed that one macro cell and 20 small cells are installed in the same geographical area. Backhauling technology varies in each proposed solution, in fact the first result shows costs for the installation of 18 wireless backhauling small cells and 2 wired backhauling small cells, the second result depicts costs for the deployment of the same number (10) of wireless and wireline small cells and the last one is the result due to the installation of 18 wireline small cells and 2 wireless small cells.

CapEx costs are higher than OpEx for all solutions because of high prices of hardware equipment. In any case costs for these three different solutions are comparable and there is not an economically convenient solution. Unique point to underline is that predominant BBU pooling wireline solution is less expensive than in the legacy case (see Figure 72).

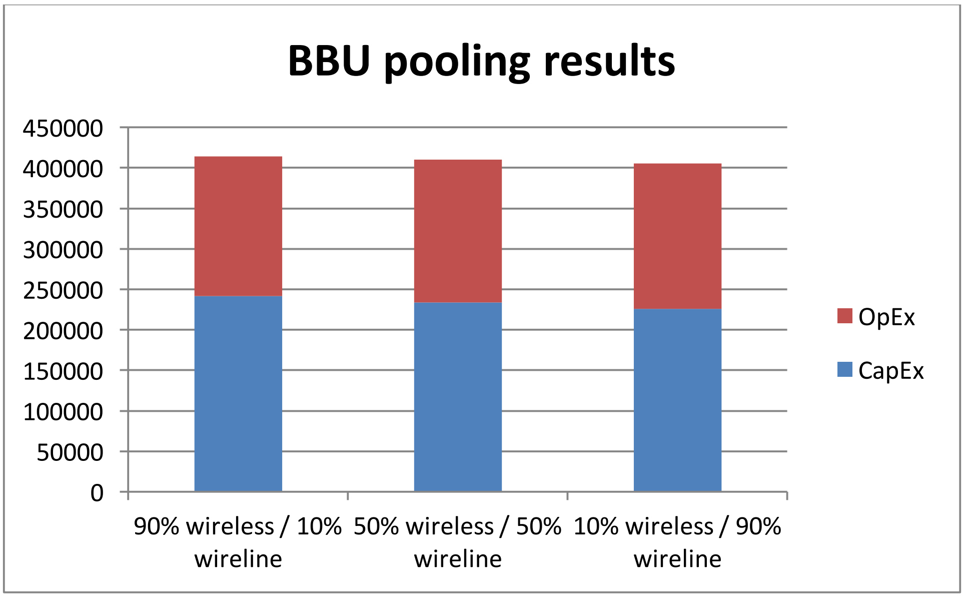


Figure 79 – CapEx and OpEx for BBU pooling (outdoor) solutions

3.7. Energy saving enabled by EMMA application

The implementation of resource allocation algorithms for energy savings in Crosshaul applications or XCI components allows to further reduce the global power consumption of the physical infrastructure through appropriate strategies to switch on and off the devices (or to change their power state) according to the current traffic. The reduction of power consumption has been evaluated with emulations in WP4 (see the results in D4.2 [29]) and with experimental activities in real test-beds in WP5. In particular, the technical feasibility of the EMMA solution has been validated in the 5G-Crosshaul test-bed, with XCI and EMMA prototypes running over physical networks based on RoF, XPFEs and mmWave technologies. The related results are presented in D5.2 [30].

As reported in [31] the actual reduction depends on the traffic type and on the level of redundancy of the network. For example, in the high-speed train scenario where the physical RoF nodes in a given area are activated only when a train is approaching, the traffic is discontinued and we can reach high levels of power consumption saving, around 90%. This saving is reduced when we consider scenarios with more homogeneous and continuous traffic, as in networks based on mmWave technologies or XPFEs software switches with network traffic distributed in a uniform manner among the network edges.

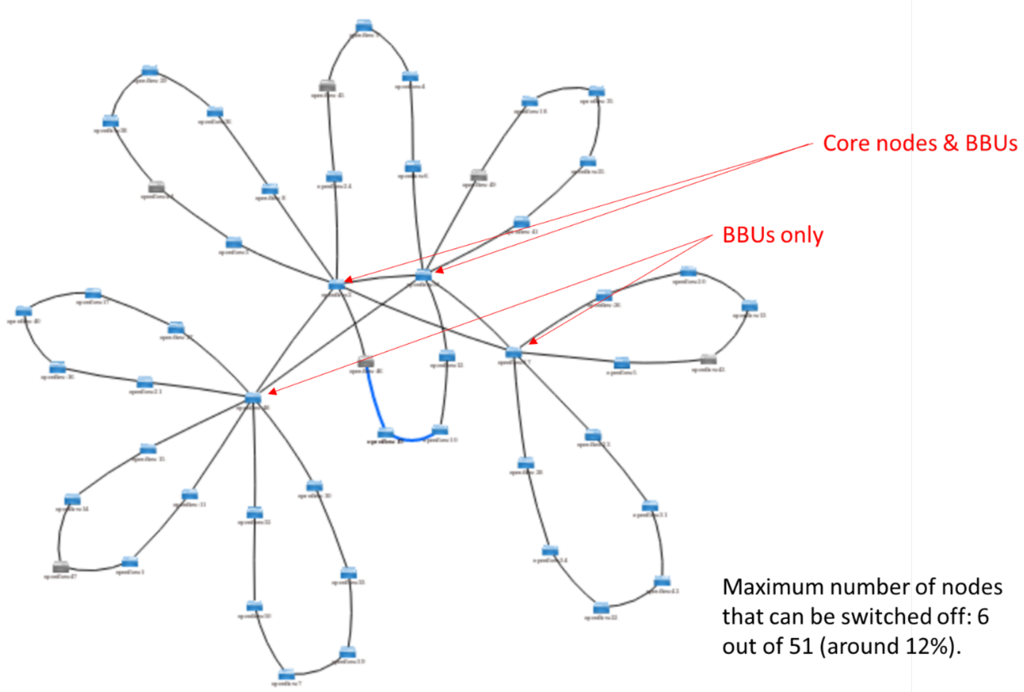


Figure 80 – Active (blue) vs. idle (grey) networks nodes in a realistic regional network with full traffic matrix active

In the context of WP1, the EMMA solutions for XPFE networks have been evaluated over an emulated network that implements the reference topology provided by TIM. It reflects the characteristics of regional network deployed in the North-West of Italy and includes 51 nodes (4 BBUs and 2 gateways) and 61 links organized in several rings. The XCI with EMMA has been used to establish bi-directional network paths between each edge nodes and the gateways and we have evaluated the total number of nodes that can be maintained in idle mode when all the flows of the expected traffic matrix are active. The result is depicted in Figure 80: a total of 6 nodes, represented as grey switches, can be maintained in idle mode thus bringing an additional energy saving of 12%.

4. Conclusions

Since the beginning of the project, and even in the proposal, 5G-Crosshaul clearly defined objectives and KPIs. Some of them refer to the activity of WP1, i.e. the definition of the final architecture and the demonstration that the project solutions enable significant cost and energy savings.

Chapter 2 of this document covers the first point, defining in detail the system architecture and specifying also the interactions and the collaborations with some other projects, like 5GEx and 5G-NORMA. A consolidated overview of the final 5G-Crosshaul architecture is provided, analyzing in detail aspects like multi-tenancy or multi-domain (from two perspectives: interworking of multiple technology domains, and interconnection of multiple administrative domains).

Specific KPIs on cost and energy savings have been defined. In more details, the commitment of reducing CAPEX and OPEX due to unified data plane (25%) and to multi-tenancy (80%) have been in the majority satisfied.

The project at its beginning clearly defined three important items as KPIs to be satisfied:

- The reduction of Total Cost of Ownership (TCO) by 30% due to new optical transmission systems and by sharing mobile/fixed access. In chapter 3 of this document we clearly reported studies about the access network (i.e. last mile), where we demonstrated that the saving might be about 65%. In the metro segment, the savings might be evaluated between 25% and 30%.
- Energy reduction by a factor 10. The unified control plane introduces an energy saving of about 35%. The energy consumption takes advantages from multi-tenancy. In fact, w.r.t. the sum of energy consumption of 4 independent operators, the saving is more than 70%. Furthermore, EMMA algorithm, developed by the project in WP4, enables a further 12% reduction. The final result is 0.65 * 0. 3 * 0.88 = 17% (i.e. 83% savings, energy reduced by a factor 6). If we also consider the technological evaluation the savings is more than 90% (1/10 of energy consumption) w.r.t. Watts per bit/s.
- Reduce TCO of indoor systems. A specific study has been provided and the results are summarized in Chapter 3. It demonstrates that indoor solutions based on LTE backhauling guarantee a saving between 50% and 60 % w.r.t. WiFi based solution.

Furthermore, about yearly CAPEX for multi-tenancy (i.e. the CAPEX / amortization time), the saving is about 70%, while the OPEX is reduced of about 72%. Therefore, the savings on the total cost of ownership is about 70%.

References

[1] OpenDaylight [Online]. Available: http://www.opendaylight.org
[2] ONOS [Online]. Available: http://onosproject.org
[3] ETSI GS NFV 003 V1.2.0 (2014-11), Network Functions Virtualisation (NFV); Terminology for Main Concepts in NFV, European Telecommunications Standard Institute.
[4] Open Networking Foundation (ONF) report TR-521 "SDN Architecture – Issue 1.1," January 2016. [Online] https://www.opennetworking.org/images/stories/downloads/sdn-resources/technical-reports/TR-521_SDN_Architecture_issue_1.1.pdf
[5] IEEE Std 802.1Q™-2014, Bridges and Bridged Networks. IEEE.
[6] OASIS, Organization for the Advancement of Structured InformationStandards,TOSCA Simple Profile for Network Functions Virtualization(NFV) Version 1.0, March 2016. [Online]. Available: http://docs.oasis-open.org/tosca/tosca-nfv/v1.0/tosca-nfv-v1.0.pdf
[7] IEEE 802.1 Task Group,IEEE 802.1ah-2008 - IEEE Standard for Localand metropolitan area networks – Virtual Bridged Local Area Networks Amendment 7: Provider Backbone Bridges
[8] OpenDaylight Virtual Tenant Network (VNT)." [Online]. Available:https://wiki.opendaylight.org/view/VTN:Main
[9] RESTCONF protocol. https://tools.ietf.org/html/draft-ietf-netconf-12.
[10] "Cisco Global Price List 2016," [Online]. Available: http://www.scan25.com/index.php?search=SFP-10G-SR.
[11] "Strongest," FP7 EU Project /2007-2013 under grant agreement n° 247674, [Online]. Available: www.ict-strongest.eu
[12] F. Rambach, et al., "A Multilayer Cost Model for Metro/Core Networks," J.Opt. Commun. Netw., vol. 5, no. 3, March 2013.
[13] "Google searches on Cisco prices for SFP at 1G, 10G and 40G," Amazon, Cisco GPL, Router-Switch.com. [Online].
[14] "EU ICT IDEALIST Project," 2013-2015. [Online]. Available: http://www.ict-idealist.eu.
[15] Daryl Inniss, OVUM, "Service Provider Optical Transmission; 100G for metro Networks," [Online]. Available: http://www.ecocexhibition.com/sites/default/files/files/2014%20MF%20presentations/ECOC2014_Dinniss_market_focus%20092214%20presentation_to_post.pdf.
[16] OVUM, "TWDM PON Is on the Horizon," [Online]. Available: http://info.ovum.com/uploads/files/TWDM_PON_white_paper.pdf.
[17] IRIS project, Deliverable D8.1: First Scientific Report," 2015. [Online]. Available: http://www.ict-iris.eu/dissemination/.

[18] "BCM88650 serie -Broadcom," [Online]. Available: https://www.broadcom.com/products/ethernet-connectivity/switch-fabric/bcm88650-series.
[19] "Offerta di riferimento di Telecom Italia 2017 - Servizi di colocazione," 28 Luglio 2016. [Online]. Available at: https://www.wholesale.telecomitalia.com/offerte/-/proposal_store/proposal/72043591.
[20] "Nokia 1830 PSS-4, PSS-16, PSS-32, PSS-64," [Online]. Available: resources.nokia.com/asset/194066.
[21] "Cisco 10GBASE SFP+ Modules Data Sheet - Cisco," 2015. [Online]. Available: http://www.cisco.com/c/en/us/products/collateral/interfaces-modules/transceiver-modules/data_sheet_c78-455693.html.
[22] "Cisco 40GBASE QSFP Modules Data Sheet - Cisco," [Online]. Available: http://www.cisco.com/c/en/us/products/collateral/interfaces-modules/transceiver-modules/data_sheet_c78-660083.html.
[23] Cisco, "Cisco 100GBASE QSFP Modules Data Sheet," [Online]. Available: http://www.cisco.com/c/en/us/products/collateral/interfaces-modules/transceiver-modules/datasheet-c78-736282.html.
[24] "Power consumption of Next-Generation Passive Optical Networks," [Online]. Available: http://www.fp7-trend.eu/system/files/content-public/502-final-trend-workshop-brussels-24-october-2013-presentations/powerconsumptionevaluationfor-next-generationpassiveop.
[25] P. Chanclou. et al., "Real Time Demonstration of the Transport of Ethernet Fronthaul based on vRAN in Optical Accesss Networks," in OFC, 2017.
[26] COMBO project, "D3.3 - Analysis of transport network architectures for structural convergence," [Online]. Available: http://www.ict-combo.eu/data/uploads/deliverables/combo_d3.3_pu.pdf.
[27] B. Naudts, et al., " How can a mobile service provider reduce costs with softwaredefined networking?," Int. J. Network Mgmt 2016, vol. 26, p. 56–72, December 2015.
[28] M. Paolini, "The economics of small cells and Wi-Fi offload", Senza fili Consulting [Online]. Available at: http://www.senzafiliconsulting.com/Portals/0/docs/Reports/SenzaFili_SmallCellWiFiTCO.pdf.
[29] 5G-Crosshaul project D4.2 "Final design of 5G-Crosshaul Applications and Algorithms"
[30] 5G-Crosshaul D5.2 "Report on validation and demonstration results"
[31] O.I. Abdullaziz, et al., "Energy Monitoring and Management in 5G Integrated Fronthaul and Backhaul", EuCNC 2017, 12-15 June, Oulu, Finland.