5G Crosshaul
the integrated fronthaul/backhaul

FINAL REPORT

(Corresponds to the technical part of the Second period)

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Disclaimer:

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List of Acronyms

Acronym	Description
ABNO	Applications Based network Operation
API	Application Programming Interface
AS-PCE	Active Stateful PCE
BBU	Base-Band Unit
BH	Backhaul
BP	Blocking Probability
C&M	Control and Management
CDF	Cumulative Distribution Function
CDN	Content Delivery Network
CDNMA	Content Delivery Network Management application
COP	Control Orchestration Protocol
CPE	Customer Premises Equipment
CPFH	Compressed and Packetized Fronthaul
CPRI	Common Radio Public Interface
DML	Directly Modulated Laser
DMM	Distributed Mobility Management
EMAN	Energy MANagement
EMMA	Energy Monitoring and Management Application
eNB	eNodeB
EPC	Evolved Packet Core
EVM	Error Vector Magnitude
FF	Fast Forwarding
FH	Fronthaul
FHU	Fronthaul Unit
GMPLS	Generalized Multi-Protocol Label Switching
GPON	Gigabit Passive Optical Network
GUI	Graphical User Interface
HD	High Definition
HL	Higher-Layer split

IPC	Industrial Personal Computer
I/Q	In-phase and Quadrature
IT	Information Technology
KPI	Key Performance Indicator
LL	Lower-Layer split
LSP	Label Switched Path
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MIB	Management Information Block
MMA	Mobility Management Application
MME	Mobility Management Entity
MW	Microwave
NFV	Network Functions Virtualization
NFVO	NFV Orchestrator
NS	Network Service
NSD	Network Service Descriptor
NTP	Network Time Protocol
OAI	OpenAirInterface
OAM	Operations, Administration, and Maintenance
ODL	OpenDaylight
OF	OpenFlow
OIF	Optical Interworking Forum
OVS	Open Virtual Switch
OWC	Optical Wireless Communication
OXC	Optical Cross-connect
PCE	Path Computation Element
PCI	Physical Cell Identifier
PDCP	Packet Data Convergence Protocol
PDU	Power Distribution Unit
P-GW	Packet Data Network Gateway
PHY	Physical layer

PM	Provisioning Manager
PoC	Proof-of-Concept
PON	Passive Optical Network
PSTN	Public Switched Telephone Network
PTP	Precision Time Protocol
QoS	Quality of Service
QoE	Quality of Experience
RH	Radio Head
RLC	Radio Link Control
RoF	Radio over Fibre
RMA	Resource Management Application
ROADM	Reconfigurable Optical Add Drop Multiplexer.
RRU	Remote Radio Unit
RTMP	Real-Time Messaging Protocol
RTT	Round-Trip Time
SAP	Service Access Point
SBI	Southbound Interface
SDN	Software Defined Network
S-GW	Serving Gateway
SNMP	Simple Network Management Protocol
SOTA	State of the Art
SPF	Shortest Path First
TCO	Total Cost of Ownership
TDM	Time-Domain Multiplexing
TVBA	TV Broadcasting application
TE	Traffic Engineering
TED	TE database
TM	Topology Manager
UE	User Equipment
vCDN	Virtual Content Delivery Network
vEPC	Virtual Evolved Packet Core

VIM	Virtual Infrastructure Manager
VM	Virtual Machine
VNF	Virtual Network Function
VNFM	Virtual Network Function Manager
VNTM	Virtual Network Topology Manager
VoD	Video on Demand
WSON	Wavelength Switched Optical Networks
WS-WDM	Wavelength Selected Wavelength Division Multiplexing
WS-WDM-PON	WS-WDM Passive Optical Network
WS-WDM-OLT	WS-WDM Optical Line Termination
WS-WDM-ONU	WS-WDM Optical Network Unit
XCI	5G-Crosshaul Control Infrastructure
XCF	5G-Crosshaul Common Frame
XCSE	5G-Crosshaul Circuit Switching Element
xDPd	OpenFlow eXtensible DataPath daemon
XFE	5G-Crosshaul Forwarding Element
XPFE	5G-Crosshaul Packet Forwarding Element
XPU	5G-Crosshaul Processing Unit

Executive Summary

This deliverable presents the technical advances performed during the second and last reporting period of the project. Although titled "Final Project Report" initially, after discussion with the Project Officer we decided to report only on the second period in this deliverable, which will be followed up with the official Final Periodic Report at the end of February 2018.

It is important to highlight that the deadline of D7.3 is the 31st of December, the final data for use of resources is still not available at the end of December. The full financial information will be included in the Final Periodic Report in February 2018.

This document includes the Publishable Summary, patents and dissemination activities that will be completed in the IT Tool too, a description of the technical work carried out by beneficiaries and overview of the progress in the first year of the project, including the objectives, the work performed by work package, the deliverables and milestones, the impact and finally the deviations of the project.

1. Publishable Summary

1.1.Summary of the context and overall objectives of the Project

5G-Crosshaul: The Integrated fronthaul/backhaul is a 30-month collaborative project running under H2020, addressing the topic "ICT 14 – 2014: Advanced 5G Network Infrastructure for the Future Internet" of the Horizon 2020 Work Programme 2014 – 2015. The aim of the project is to develop an adaptive, sharable, cost-efficient 5G transport network solution integrating the fronthaul and backhaul segments of the network whilst supporting existing and new radio access protocol functional splits envisioned in 5G. This transport network will flexibly interconnect distributed 5G radio access and core network functions, hosted on in-network cloud nodes, through the implementation of two novel building blocks: i) a unified data plane encompassing innovative high-capacity transmission technologies and novel deterministic-latency switch architectures (5G-Crosshaul Forwarding Element, XFE); ii) a control infrastructure using a unified, abstract network model for control plane integration (5G-Crosshaul Control Infrastructure, XCI) enabling the operators to easily set up end-to-end services, transparently to all the underlying technologies in the data plane.

Main innovations delivered by the project are:

- Integration of fronthaul and backhaul traffic through a common encapsulation (the Crosshaul Common Frame) a common data path based on a specifically desgned OpenFlow pipeline.
- Design of a packet/circuit hybrid switch (Crosshaul Forwarding Element), able to forward packet-based fronthaul and backhaul jointly with stringent non-packet based traffic such as CPRI.
- Design of an SDN-/NFV-based control infrastructure, which extends SDN/NFV concepts to the WAN network, enabling novel smart applications to take benefit of the transport network and multi-tenant by design.
- Design of a set of novel applications able to optimise the network (energy, traffic routes), enable new functionalities (caching, mobility, broadcasting) and providing multi-tenancy support.

The 5G-Crosshaul project has been active in disseminating its work into relevant standardization bodies. This dissemination activity has taken two forms: (1) A first form of informative nature which included reports, presentations, and white papers for information purpose; and (2) A second form more of a normative nature which focused on technical contributions backed by technology pieces intended for acceptance into standard specifications. The activity covered all the various aspects of the integrated fronthaul and backhaul solution developed in 5G-Crosshaul. These included: use cases, requirements, architecture, network softwarization, network management and orchestration, network slicing, wireline and wireless networking interfaces and their interworking.

Success in standardization dissemination has been achieved throughout the project noticeably with:

- More than 35 normative contributions feeding into key standardization specifications such as: eCPRI, G.metro, IETF CCAMP, IETF DETNET, and ONF.
- More than 25 contributions for information purpose in several standardization bodies and forums such as NGMN, ITU-T, FSAN, ETSI, IEEE, BBF, ONF.

The 5G-Crosshaul consortium includes the following partners: (Coordinator) University Carlos III of Madrid, (Technical Manager) NEC Europe LTD, (Innovation Manager) Ericsson Telecomunicazioni SpA, Ericsson AB, Atos Spain SA, Nokia Solutions and Networks GMBH & CO KG, InterDigital Europe LTD, Telefónica Investigación y Desarrollo SA, Telecom Italia SpA, Orange SA, Visiona IP, Nextworks, Core Network Dynamics, TELNET Redes Inteligentes, Fraunhofer-Gesellschaft zur Foerderung der angewandten Forschung e.V., Centre Tecnològic de Telecomunicacions de Catalunya, Center for research and telecommunication experimentation for networked communities, Politecnico di Torino, Lunds Universitet and Industrial Technology Research Institute (ITRI).

1.1.1. Project context

Current trends and traffic expectation on the upcoming 5G predict a steady increase of the mobile data traffic (increase 11-fold between 2013 and 2018) while expecting a reduction on the delay to accommodate new applications under the 5G scenario known as Ultra Reliable Low Latency Communications (URLLC). These two factors are shaping the design of the 5G network which will be characterized by an ultra-dense Radio Access Network (RAN), with extensive use of novel air interface technologies such as Cooperative Multipoint (CoMP), Carrier Aggregation (CA) and Massive MIMO, to support the data rates promised in 5G. In addition, to reduce the latency, traffic will be processed in Edge data centres, located near the final user, and traffic will be kept as local as possible, within the own metropolitan network. This yields to a centralization of the network operator premises including the central offices, which are subject to a major redesign, reducing their numbers and softwarizing them.

Since 2014, a paradigm known as Centralised-RAN (C-RAN) has been used in deployed networks. This concept is based on splitting eNB on radio specific functionalities, which are located in a remote radio head at the cell site, from the base band processing, which is located in a centralized location. Although C-RAN was initially thought as a mechanism for decreasing the OPEX and CAPEX of network by centralizing operations and reducing the cost of the cell sites, it has been realized that C-RAN application enables the use of multi-cell cooperation techniques that can be used to get extra performance out of the wireless interface. The problem faced in 5G is that the state of the art fronthaul solutions (the connection between the remote radio head and the base band unit) required to huge amounts of bandwidth and very stringent delay requirements which scale with the number of antennas and channel bandwidth. Considering 5G air interface solutions will most likely use massive MIMO and channel bandwidths of hundreds of MHzs, the legacy fronthaul solutions are ruled out of possible 5G deployments.

The 3GPP during these last years has realized the importance of the functional split of the eNB and the benefits that its usage can provide to the network. In addition, the centralization of parts of the RAN in the Edge data centres provides a unique opportunity to reduce the latency observed by the end users. Therefore, the 3GPP has worked on defining possible functional splits within the LTE and 5G New Radio (5GNR) with more relaxed requirements in terms of bandwidth and delay while keeping some of the benefits of the current fronthaul technology.

This is the context faced by 5G-Crosshaul during its execution. During the last 30 months, the 5G-Crosshaul project has become a reference for the industry, setting the basis of the transport network to be used in 5G. The project has been present and leading the international efforts in this area, from IEEE 802.1CM (dealing with the time sensitive transmission of fronthaul packets), the eCPRI initiative (next generation CPRI interface), the ETSI Crosshaul research group and many other industrial activities. 5G-Crosshaul has developed the next generation of 5G integrated backhaul and fronthaul in a common packet-based network, namely the Crosshaul, enabling a flexible and software-defined reconfiguration of all networking elements in a multi-tenant and service-oriented unified management environment. The 5G-Crosshaul transport network designed and demonstrated consists of high-capacity switches and heterogeneous transmission links (e.g., fibre or wireless optics, high-capacity copper, mmWave) interconnecting Remote Radio Heads, 5GPoAs (e.g., macro and Small Cells), cloud-processing units (mini data centres), and points-of-presence of the core networks of one or multiple service providers.

1.1.2. Project Objectives

The 5G-Crosshaul project is a very ambitious initiative aiming at designing the transport network that will serve the 5G deployments. The next generation transport network needs to unify the way it manages the different traffic sources, with really diverse, and potentially extreme, requirements in terms of bandwidth, latency or number of users. Specifically, the project pursues the following eight key objectives:

- Design of the 5G-Crosshaul Control Infrastructure (XCI): Develop XCI by extending existing Software Defined Network (SDN) controllers to provide the services for novel Northbound (NBI) and Southbound (SBI) Interfaces and enable multi-tenancy support in trusted environments.
- Specification of the XCI's northbound (NBI) and southbound (SBI) interfaces: Define interfaces to accelerate the integration of new data plane technologies (SBI) and the introduction of new services (NBI) via novel or extended interfaces.
- Unification of the 5G-Crosshaul data plane: Develop a flexible frame format to allow carrying fronthaul and backhaul on the same physical link to replace different technologies with a uniform transport technology for both fronthaul and backhaul.
- Development of physical and link-layer technologies to support 5G requirements: Exploit advanced physical layer technologies, not currently used in the 5G-Crosshaul network segment, as well as novel technologies, such as wireless optics, flexi-PON, etc. to increase coverage and aggregated capacity of

integrated backhaul and fronthaul networks. Increase cost-effectiveness of transport technologies for ultra-dense access networks

- Design of scalable algorithms for efficient 5G-Crosshaul resource orchestration: Develop and evaluate management and control algorithms on top of the XCI NBI that ensure top-notch service delivery and optimal 5G-Crosshaul resource utilization.
- Design of essential 5G-Crosshaul-integrated (control/planning) applications: Develop an ecosystem of most essential XCI NBI applications, both to support (prediction, planning, monitoring) and to exploit (media distribution, energy management) the 5G-Crosshaul resource orchestration functions.
- 5G-Crosshaul key concept validation and proof of concept: Demonstration and validation of 5G-Crosshaul technology components which will be integrated into a set of 5G testbeds in Madrid, Berlin, Barcelona and Taiwan.

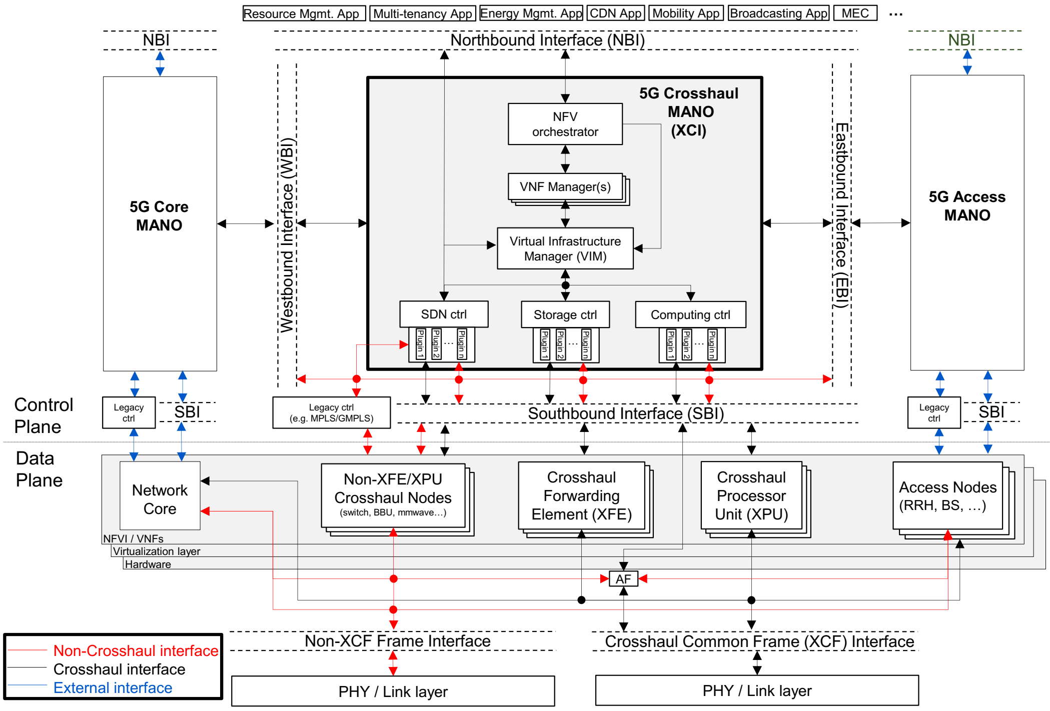

Figure 1: 5G-Crosshaul System Architecture

1.2.Work performed from the beginning of the project to the end of the period covered by the report and main results achieved so far

The time covered by this second report corresponds to the period between 1st of July 2016 to 31st of December 2017, a total duration of 18 Months. During this time, the project has focused on building and developing the key concepts behind a critical network segment required to make 5G possible. 5G promises an increase on end user available bandwidth without precedents, but in order to make available such a bandwidth at the air interface it is required to transport all of it inside the operator network, this is the aim of Crosshaul, build the 5G transport network. The work of the project has been divided in 5 technical Work Packages (WPs), a WP on dissemination, exploitation and standardization and another on management. WP1 is in charge of defining the set of use cases and scenarios to be used to challenge the architecture of the system. WP1 is also in charge of designing the baseline architecture of the 5G-Crosshaul, which has been subject to multiple design cycles based on the input from the implementation activities. From a data plane perspective, WP2 evaluates to what extent each of the optical, copper-based, and wireless technologies can fulfil the requirements of 5G traffic flows and identifies what is needed to ensure all requirements are met. This not only includes the design of the links, but also of the nodes from a forwarding point of view. Such data plane is under the control of the 5G-Crosshaul Control Infrastructure (XCI), which brings the software-defined networking (SDN) and Network Functions Virtualization (NFV) paradigms to the project as part of the WP3 work. In turn, WP4 designs the network management applications that will orchestrate the resources required by the use cases by exploiting the services offered by the XCI through its Application Programming Interfaces (APIs). The goal of each of these WPs is to focus mostly on the specific architectural components that are their subject of study as well as the definition of interfaces towards architectural components dealt with in other WPs. The main goal of WP5 is to integrate the components designed in WP2, WP3 and WP4 and to validate experimentally that all the conceived building blocks can work together to fulfil the heterogeneous 5G traffic flow requirements.

During this period WP1 (System Requirements, Scenarios and Economic Analysis) has continue its work towards the definition of an architecture that glues together the key project pillars (Innovations for data-plane integration across the heterogeneous transmission technologies, innovations for a unified programmable control and novel network applications running on top for optimizing the overall system performance). The innovative architecture framework has been designed taking into account both technical and techno-economical requirements from the stakeholders of the value chain, namely operators, vendors and service operators. A simple but complete architecture admits the possibility of obtaining a concrete overall system, able to satisfy the challenging requirements that the WP elaborated and defined since the beginning of the work. WP1 also developed a TCO model, demonstrating impressive cost savings both in CAPEX and OPEX and energy consumption reduction. These results lead directly to important socio-economic impact to all the stakeholders. A low industrial cost of the solution can wider the umbrella of users that can have a high-bandwidth connectivity, permitting to them the use of innovative applications like mega-events distribution, safety in driving, mobile edge computing. The reducing of energy consumption is important to reduce the footprint of telecom operators that nowadays is still too high and, when requiring more and more bandwidth, is a high risk of exploding in unsustainable energy consumption, both for the behaviour and the wallet.

In this line, the work of WP1 has focused on two main activities:

- Design of the 5G-Crosshaul architecture. The project has developed an ETSI NFV compliant architecture for the control (e.g., XCI) and a data plane reference architecture. Regarding the XCI, we have provided two complementary architecture designs. The first one focuses on the Single-Management and Orchestration (MANO) scenario, considering a network supporting multiple technologies through a multi-domain control. This design has been extended to the Multi-MANO architecture, in which the Multi-Tenancy Application (MTA) plays a central role to support recursive instantiation of XCIs. In addition, although the work has been mostly done by WP2/3/4, a data plane reference architecture, including the model for a multi-layer switch (Crosshaul Forwarding Element, XFE) and its components (the Crosshaul Packet Forwarding Element, XPFE, and Crosshaul Circuit Switching Element, XCSE). Finally, the project has studied how a Crosshaul network could be deployed in current operator networks and defined a clear path of migration with the operators of the consortium.

- Definition of a Total Cost of Ownership (TCO) cost model. The project has analysed how the Crosshaul key innovative technologies, in particular a layer 1 based on silicon photonics and layer 2 switching centered on 5G-Crosshaul common frame and the idea of merging together fronthauling and backhauling traffic, as well as Software Defined Network (SDN) control and Network Function Virtualization (NFV), can be used to provide significant cost savings. Main results of the model are i) recommendations for the usage of the upper layer and lower layer functional splits in terms of cost savings, ii) a theoretical study comparing techno-economic parameters for different scenarios taking into account the topology of deployment, showing that the 5G-Crosshaul strategy enables a cost saving (including both CapEx and OpEx) about 30%, in particular in a brownfield scenario where fibers are partially deployed, iii) a cost analysis regarding the cost savings of deploying a Crosshaul network, showing that the yearly total cost per Gbit/s decreases by more than 90% from 2016 legacy solution to 2020 5G-Crosshaul solutions, and finally iv) an study of energy efficiency, showing that the energy savings due to 5G-Crosshaul solutions in the metropolitan transport network reaches more than 50%.

WP2 (Physical and link layer of 5G-Crosshaul) has focused on the engineering of the transport technologies in order to move different fronthaul based on the multiple functional splits together with backhaul traffic. In order to do so, WP2 has worked in the following areas:

- Identification of the technologies that are most suitable for the deployment of a 5G-Crosshaul network, envisaging a unified data plane encompassing innovative high-capacity transmission technologies and novel deterministic-latency framing protocols. Different data transmission technologies (wireless, fixed access based on both fiber and copper, optical technologies) are considered and their performance is discussed. Furthermore, we focus on understanding how these technologies are combined in the 5G-Crosshaul network. In some cases, it is required to broaden the application domain of existing technologies out of their current scope. The performance parameters of the identified technologies are analyzed in comparison with the requirements of the use cases identified in WP1.
- Applicability study of the technologies identified to 5G reference scenarios. Four key 5G reference network scenarios have been considered, namely i) very dense deployment of indoor and outdoor small cells, ii) WDMPON-based

network, iii) multi-layer packet-optical networks, and iv) virtualized RAN based network. Each scenario has been analyzed considering four relevant use cases of WP1, namely i) high-speed train and vehicle safety, ii) media distribution, iii) dense urban society, and iv) mobile edge computing which require up to 10 Gbit/s peak rates. In addition to the end user service type or use case, the requirements on transport also depend on the radio split options utilized. The transport requirements for each use case in terms of bandwidth and latency have been derived considering the radio functional split options, ranging from option 8 (i.e. CPRI) to option 1 (i.e. backhaul).

- Development of Southbound Interfaces for the control of transport technologies. As the 5G-Crosshaul control plane is based on SDN and NFV, WP2 have focused on providing guidelines for the development of a southbound interface (SBI) able to deal with the variety of technologies encompassed by the 5G-Crosshaul data plane. To do so, we defined a novel approach based on a protocol agnostic set of parameters to model network nodes and transmission technologies, in order to enable applications, such as optimization of resource allocation and energy, running over the whole network infrastructure. Then, we selected a careful choice of the parameters sets, neither too small to inhibit some applications nor too wide to negatively affect solution cost and scalability, and defined the protocol extensions required, taking as baseline the latest version of the Open Flow specification.
- Finally, to meet the requirements imposed by the Crosshaul system, some novel technologies have been developed. Worth mention are: i) Prototype of silicon photonic integrated reconfigurable optical add drop multiplexer, providing optical 5G-Crosshaul networks with enhanced flexibility, at dramatically reduced cost compared to current solutions, ii) advanced compression schemes for fronthaul, allowing the reuse of the copper access infrastructure, as enabler for massive deployment of indoor small cell, iii) SDN enabled mesh mmWave networks, as an enabler for indoor small cells and frequency reuse with wireless transport technologies, iv) prototype of time-deterministic multi-layer switch based on a protocol agnostic framing protocol, capable to arbitrarily multiplex backhaul and fronthaul client signals on the same optical channel and finally v) highly spectrally efficient fronthaul schemes, based on Hybrid Analogue-Digital Radio over Fibre over WDM optical networks.

The work of WP3 (5G-Crosshaul Control and Data planes) focuses on designing the 5G-Crosshaul Control Infrastructure (XCI) and the 5G-Crosshaul Forwarding Element (XFE), with special focus on the interfaces connecting both. For the dataplane, WP3 defined the XCF, based on PBB, as a means to carry traffic with very diverse characteristics over the same network. WP3 defined a novel OpenFlow pipeline for encapsulation/decapsulation to/from the XCF and for forwarding XCF frames. WP3 defined new procedures for bootstrapping XPFEs and handling OAM locally at the XPFEs. WP3 developed solutions to achieve RU synchronisation in the presence of high packet delay variation and without support of PTP in intermediate nodes. These developments allow to carry both fronthaul and backhaul traffic over the same physical network while satisfying the requirements for the different traffic flows. The use of a common, packet based, network reduces CAPEX and OPEX for the operators, the methods for bootstrapping and local OAM support provide further OPEX reductions. A more efficient use of infrastructure does not only reduce OPEX and CAPEX for the operators, it also means a reduction of the energy consumption.

In the control plane, WP3 developed new algorithms and application for SDN controllers. These algorithms and applications allow the automated control of the compute and storage resources and the transport network. Especially, the applications allow to turn off unneeded links and nodes. WP3 developed mathematical models for energy consumption in virtualization environments and for network optimization to be used in the algorithms and controller applications. WP3 developed means to control networks consisting of heterogeneous technological domains by a hierarchy of controllers. The controller algorithms and applications allow a higher degree of automated control of the network, thereby reducing OPEX for the operators. The controller applications enable a more efficient use of the infrastructure, again reducing CAPEX and OPEX for the operators. The applications to reduce energy consumption, together with the more efficient use of the infrastructure, reduce the energy consumption of the network.

WP3 key areas of work during this period are the following:

- Continuation on the design of the Crosshaul Control Infrastructure (XCI). Based on the architecture provided by WP1, WP3 has designed the services exposed within the XCI towards the application-plane, and the set of software components that are part of proof-of-concept prototypes developed by 5G-Crosshaul partners. The XCI provide multi-tenancy support through the MTA application (WP4). WP3 has provided the integration between Software Defined Network (SDN) controllers and Management and Network Orchestrator (MANO) components in the XCI to establish paths in the 5G-Crosshaul network and to connect the Virtual Network Functions (VNFs) in the data centers to deliver the Network Services (NSs). Also, the XCI design includes the interaction between child and parent controllers in a hierarchical setup, in order to support multi-technology networks. In addition, the XCI design includes the Description of the information model, workflow and design of Application Programming Interfaces (APIs) exposed by XCI services towards the application-plane through a NBI. The services include Topology and Inventory, Provisioning and Flow actions, Information Technology (IT) infrastructure and Inventory, Statistics, Network Function Virtualization Orchestration (VNF-O), Virtual Network Function Management (VNFM), Analytics for Monitoring, Local Management Service (LMS) and Multi-tenancy.
- Continuation on the design of the 5G-Crosshaul data plane. The design of the data plane architecture, including the concept of 5G-Crosshaul Common Frame (XCF) and its use across the data path, was done in collaboration with WP2. The data plane design includes the specification of the 5G-Crosshaul Forwarding Element (XFE). To accommodate the Crosshaul requirements, the XFE is composed a packet forwarding element (XPFE) and a circuit switch all optical element (XCSE). This design enables the use of packet based technologies while having the possibility of offloading to a pass-through all

optical path for traffic with extreme delay and jitter requirements such as traditional fronthaul (e.g., CPRI). WP3 has also designed an OpenFlow pipeline to provide XCF encapsulation and forwarding within the XPFEs. The bootstrapping interaction between XFEs and SDN controllers for the initialization of the network has also been provided.

- Data plane related functionalities. Under this item, we group the innovations performed in WP3 which do not clearly belong to the data plane or control plane, but have a rather transversal application. First, it has been studied the implementation of enhanced Nodes b (eNbs) with different fronthaul splits. This allows to test the 5G-Crosshaul data plane with traffic streams having real latency and jitter requirements. An implementation of a PDCP/RLC (upper layer split) and PHY/MAC split (lower layer split) have been performed in this WP and used in the demonstrations on WP5. Second, besides the actual transport of data, the network has to provide synchronization to remote radio heads and baseband units. We describe packet-based synchronization and related synchronization technologies to be used for 5G-Crosshaul and how its accuracy depends on the existence of other traffic and its priority. We also describe Operation and Maintainance (OAM) functionality to manage the network. Finally, in order to provide a model of energy consumption for WP4 EMMA application, WP3 has developed a model for the power consumption of hypervisor- and container-based virtualization.

WP4 (Enabled innovations through 5G-Crosshaul) main focus is the application ecosystem running on top of the Crosshaul network, which can be used to provide intelligence and novel end services. The key innovations/areas of work of WP4 are listed in the following:

- Definition and design of the applications that can provide optimization and reconfiguration of 5G-Crosshaul resources through the NBI. WP4 has selected seven applications to become the first wave of novel applications on top of Crosshaul. These applications are: i) Multi-tenancy Application (MTA), ii) Mobility Management Application (MMA), iii) Energy Management and Monitoring Application (EMMA), iv) Resource Management Application (RMA), v) Virtual Infrastructure Manager and Planner Application (VIMaP), vi) Content Delivery Network Management Application (CDNMA), and vii) TV Broadcasting Application (TVBA).
- Definition and design of the Northbound Interface (NBI) connecting each application to the XCI and the different communication needed between each application to provide an end-to-end service. The interaction between the different applications and the main workflows and interfaces to other applications to be taken into account is a key point to harmonize the whole system performance.
- Crosshaul applications provide, in general, end-to-end services. As such, applications need to interact with the RAN and Core orchestrators. In WP4, and in collaboration with H2020 5G-PPP 5G-NORMA and 5G-Exchange, an outline of the interfaces to interwork with controllers of the neighbouring network domains, i.e., the RAN controller and the Core Network controller, detailing the

potential Crosshaul application requirements for such interfaces has been provided.

- For each application, WP4 has provided a design, interfaces, algorithms and proof of concept implementation. In the following a summary of each application is provided:
- The Multi-Tenancy Application (MTA) is the application on top of the 5G-Crosshaul XCI, which aims to enable flexible sharing of 5G-Crosshaul physical resources (networking, computing, and storage) among different tenants. The main objective of MTA is to reduce the costs (i.e., CAPEX and OPEX) by sharing the infrastructure resources and maximize their utilization in a cost-efficient manner, while at the same maximizing the energy efficiency. The MTA requires the support from the XCI components to configure the mapping of virtual infrastructure to the physical one and allocate the corresponding computing, networking and storage resources; as well as requires the support from the data plane to identify the tenants.
- Resource Management Application (RMA) is developed with the goal of optimizing the 5G-Crosshaul resources, motivated by the base requirements: (i) to manage Crosshaul resources including networking, computing and storage resources in a flexible and dynamic way, (ii) to cope with the level and variation of demand expected from 5G Points of Attachment (5G PoA), (iii) to optimize the resource utilization and maximize the cost-efficiency while meeting various service requirements.
- The Energy Management and Monitoring (EMMA) application implements two main functionalities: monitoring of power consumption and energy efficient management of resource allocation in infrastructures composed of software-based XPFEs and XPUs. The energy efficient management of resource allocation can operate in three different modes: (i) at the network level only, (ii) at the computing level only, and (iii) jointly for both network and computing resources. In all the cases, the EMMA adjusts dynamically the power state of the target devices based on the current traffic and processing requests, reducing the number of nodes in active states through a suitable resource allocation strategy.
- The Virtual Infrastructure Manager and Planning application (VIMaP) is logically part of the 5G-Crosshaul XCI and stays at the lowest level of the application hierarchy. The VIMaP enables other applications (such as the Multi-Tenant Application, MTA) to request the constrained allocation of physical and virtual Crosshaul resources (i.e., computing and networking resources) represented as an abstracted construct and proceeds to instantiate, deploy and provision them over the Crosshaul infrastructure. VIMaP consists of two components: the planner and the Virtual Infrastructure Manager (VIM). The planner component is in charge of running the required resource allocation algorithms for the planning and (re-) optimization of Crosshaul resources. The VIM is the component responsible for the dynamic provisioning and instantiation of Crosshaul resources. The planner runs the resource allocation algorithms with the aim of (re-)optimizing the Crosshaul resources. It is able to perform the constrained allocation of interconnected endpoints (including VMs, VNFs, etc) and network connectivity services.

- The Mobility Management Application (MMA) is one of the Over-The-Top (OTT) applications of the 5G-Crosshaul system. The main goal of the MMA is the reduction of the traffic to/from the core network by selective offload of traffic as near as possible to the RAN reducing the cost of the core network and improving the experience of the user reducing the latency and delay in end-to-end communications. Therefore, the MMA is in charge of the user detection and mobility management in the 5G-Crosshaul domain to optimize the traffic offload for media distribution. Then, the MMA requires some information to provide this service, the tenant's constraints, detailing the SLAs, PoC and XPUs available and the CDN nodes placement for the traffic offloading.
- The Content Delivery Network Management Application (CDNMA) is an application related to the distribution of media content that uses the services and APIs offered by the XCI NBI, and other applications like the RMA and MMA, to deploy and manage a vCDN service in which the CDN functions (CDN nodes –origin and replica servers- and load balancer) are dynamically allocated across the 5G-Crosshaul network.
- TV Broadcast Application (TVBA) aims at providing a solution for TV broadcasting and multicasting services making use of the 5G-Crosshaul architecture, running as an OTT service. This is the case in which service providers share the 5G-Crosshaul network to reach their remote customers so that different tenants operate in an agnostic manner over the underlying infrastructure which they do not require to control directly. The TVBA benefits from XCI services (i.e., SDN Controller and MANO) to deploy media transmission over the 5G-Crosshaul infrastructure. It communicates with the XCI manager (typically through a REST API) and provides the information needed for the service establishment and operation.

WP5 (Validation and proof of concept) has been the WP in charge of defining the demonstration and required integration activities to perform proof-of-concept demonstrations of key Crosshaul technologies. During the first year of the project a major effort on designing de demonstration and identifying technologies and modules required to implement them was performed. In the second period, WP5 has been driving the four envisioned demonstrations that are summarized as follows:

- Demo 1 focuses on demonstrating the applicability of the **5G-Crosshaul energy efficiency** concepts through different types of network technologies. Furthermore, it has demonstrated the feasibility of **power consumption monitoring** not only for physical infrastructure elements (XPFEs, XPUs), but also virtual or service-level entities like network paths, VNFs or tenants. It has also been demonstrated the **on-demand provisioning of energy-efficient network connections** over the 5G-Crosshaul Packet Forwarding Engine (XPFE) and Radio over Fibre (RoF) domains, with automated regulation of device´s power states (i.e., sleeping mode, active mode – low traffic, active mode – high traffic). In both domains, the results achieved have provided measurable energy savings. For instance, in the XPFE scenario, without connections, we reach a power saving of 60W when compared with the 210W of the "always on" approach (around 29%), while with a single path established, the power saving is of 20W (around 10% reduction).

- In demo 2, we have shown that the TV broadcasting and Video on Demand (VoD) services can be easily deployed on the 5G-Crosshaul network using the 5G-Crosshaull Control Infrastructure (XCI) and the 5G-Crosshaul applications. The results obtained prove the feasibility of deploying a vCDN infrastructure through the Management and Orchestration (MANO) components as well as building a multicast-tree through the SDN controller. Finally, a new unified experiment was defined to combine the resource efficiency provided by CDNMA and TVBA to manage the distribution of both live and on-demand content. Main results of this demonstration show average provision times of the involved services in the range of tens of seconds as higher bound.
- Demo 3 shows that a complex multi-domain and multi-technology transport network can be controlled through a hierarchy of SDN controllers that expose the appropriate APIs to the resource management application (RMA). These transport networks consist of heterogeneous technologies that need end-to-end orchestration. In the project, we evaluate a hierarchical controller for wireless/optical resources as seen from a resource management application (RMA). More specifically, we deploy a hierarchical XCI where child controllers deal with the specificities of each technology whilst the parent controller offers to the RMA the appropriate abstraction level and an end-to-end view (see Figure 3).
- Demo 4 combines a variety of data plane technologies and evaluates the suitability of different RAN splits transport over each combination of technologies. In this way, it is clearer for operators how to build the integrated fronthaul and backhaul at the data plane level to comply with given transport requirements. We have integrated both BH and FH traffic support over the same integrated infrastructure combining WS-WDM-PON and XPFE technology. Furthermore, the evaluation of the mixed digital/analogue radio over fibre implementation allows sending up to 11.05 Gb/s (9 x CPRI 2) CPRI-equivalent bit-rate using less than 200 MHz bandwidth of an off-the-shelf optical transponder, which represents a remarkable spectral efficiency improvement compared to conventional CPRI. Additionally, demo 4 also shows the integration of the different data plane technologies developed within Crosshaul, combining in a single data plane mmWave, XCSE, XPFE, different functional splits (CPRI, MAC/PHY, eCPRI and PDCP/RLC) and small cells (see Figure 4).

Figure 2: Exemplary equipment used for demonstration 3

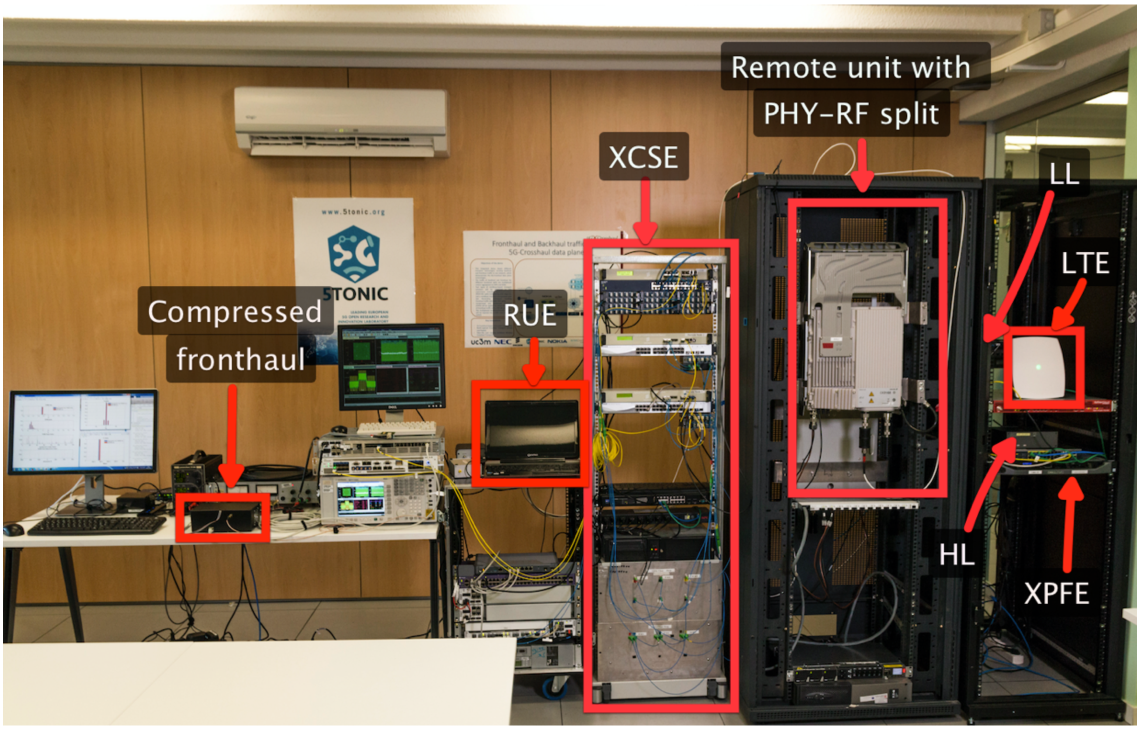

Figure 3: Exemplary equipment used for demonstration 4

As part of our commitment to the development of the 5G technologies in Europe, the 5G Crosshaul project has performed several activities in cooperation with other 5G PPP H2020 projects. The following activities have been performed in addition to the 5G IA WGs participation, which are declared in section 4.2.7.3:

- A key activity has been the development of the ETSI WP on Crosshauling, with the collaboration of the 5G-Xhaul and iCirrus projects.
- Several papers have been performed in collaboration with other projects:
    - Casellas, Ramon; Vilalta, Ricard; Mayoral, Arturo; Martínez, Ricardo; Muñoz, Raül; Contreras, Luis M.; "Control Plane Architectures Enabling

    - Transport Network Adaptive and Autonomic Operation" In Proc. ICTON 2017 (Joint work between H2020 5G-Crosshaul and H2020 Metrohaul)
    - R. Muñoz "5G-Crosshaul: An SDN/NFV based control plane for the integrated fronthaul/backhaul 5G transport network" in Proceedings of Networld2020 Annual Event and General Assembly 2016, 19 April 2016, Brussels (Belgium).
    - “Distributed multi-tenant cloud/fog and heterogeneous SDN/NFV orchestration for 5G services,” by Ricard Vilalta et al. Catalan Pavilion, Mobile World Congress 2016, Barcelona, Spain (Joint work between FP7 COMBO, FP7 STRAUSS and H2020 5G-Crosshaul)
    - "SDN/NFV Orchestration of Multi-technology and Multi-domain Networks in Cloud/Fog Architectures for 5G Services" by Ricard Vilalta etl al. in Proc. OECC/PS 2016 (Joint work between FP7 COMBO and H2020 5G-Crosshaul)
    - “The CTTC 5G end-to-end experimental platform: Integrating heterogeneous wireless/optical networks, distributed cloud, and IoT devices”, R. Muñoz et al., IEEE Vehicular Technology Magazine. (Joint work between FP7 STRAUSS, H2020 Flex5GWare and H2020 5G-Crosshaul)
    - R. Vilalta et al. "A Research Perspective for SDN Orchestration" Invited talk at IRR Network Virtualization Forum, Madrid (spain), 2015. (Joint work between FP7 STRAUSS and H2020 5G-Crosshaul)
    - G. Carrozzo, "Energy efficient service orchestration in converged fronthaul/backhaul"", WWRF 39 Ready ‘n’ Go – 5G trials and testbeds, 18-20 October 2017, Castelldefels (Barcelona), Spain" (joint session 5G-Crosshaul, 5Gex and 5G-Transformer)
    - “Orchestration of Crosshaul Slices From Federated Administrative Domains”, by LM. Contreras, CJ. Bernardos, A. de la Oliva, X. Costa, R. Guerzoni, at EUCNC 2016, Athens, Greece.
    - “Sharing of Crosshaul Networks via a Multi-Domain Exchange Environment for 5G Services”, by L. M. Contreras Murillo, C. J. Bernardos Cano, A. Oliva, and X. Costa-Pérez, to appear in Proc. MPNSV workshop, 3rd IEEE Conf. on Network Softwarization (NetSoft’17), Jul. 2017, Bologna, Italy.
- In addition, and most important, several demonstrations of 5G-Crosshaul technologies working in parallel with other projects developments, have been performed in:
    - “Flex5Gware - Joint demo with 5G-Crosshaul project: Network split with integrated fronthaul and backhaul”, at CLEEN’17 Workshop (Joint work between H2020 Flex5GWare and H2020 5G-Crosshaul)
    - Flexibility of 5G-Crosshaul Technologies”, at 5G-Crosshaul booth of EuCNC’17
    - Demonstration of 5G-Crosshaul research on orchestration at the 5G-PPP booth during ICT2015, Lisbon, Portugal.

1.3. Progress beyond the state of the art and expected potential impact (including the socio-economic impact and the wider societal implications of the project so far)

The 5G-Crosshaul Project targets innovations around three pillars of the future 5G transport network. These include: (1) Innovations for data-plane integration across the heterogeneous transmission technologies; (2) Innovations for a unified programmable control; and (3) Novel network applications running on top for optimizing the overall system performance. All these innovations are glued together into an innovative architecture framework that takes into account both technical and techno-economical requirements from the stakeholders of the value chain, namely operators, vendors and service operators.

On the basis of the activity carried out in the first part of the project, a high level of innovations has been reached both in each of the single components and in the global architecture where they are combined in relevant network scenario and analysed by simulation and experimentation.

These are presented briefly below:

1.3.1. Data-plane

A novel data plane, based on multi-layer architecture where packet, TDM and optical switches are combined in order to meet the tight requirements of 5G services. Relevant elements of the node have been: i) prototype of time-deterministic multi-layer switch based on a protocol agnostic framing protocol, capable to arbitrarily multiplex backhaul and fronthaul client signals on the same optical channel; ii) integrated silicon photonic reconfigurable optical add drop multiplexer to reduce cost and size (about 100x) with respect current technology based on WSS.

With respect to specific technologies Crosshaul has provided the following innovations:

- Advanced compression schemes for fronthaul, allowing the reuse of the copper access infrastructure, as enabler for massive deployment of indoor small cell has been defined and tested;

- Highly spectrally efficient fronthaul schemes, based on Hybrid Analogue-Digital Radio over Fibre over WDM optical networks.

- SDN enabled mesh mmWave networks, as an enabler for indoor small cells and frequency reuse with wireless transport technologies;

All the data-plane technology has been analysed according to the relevant 5G use cases and combined in realistic scenarios such as indoor, outdoor rural, outdoor high density integrated in demonstrations in the framework of WP5.

1.3.2. XCI

A new method was developed to combine the networks among virtual machines within a datacentre with the software defined network among the datacentres. An application has been developed to exchange the relevant information among the VIM for datacentre control and the SDN controller. Automated control has been extended from one technological domain to several ones by using hierarchical SDN control approach. Technology-specific 'child' controllers are connected by a technology independent 'parent' controller establishing paths across several technological domains. New NFVOs have been developed that allow to integrate resource allocation algorithms. Existing NFVOs neither have been ETSI NFV compliant nor did they allow to exchange or modify the resource allocation. A new bootstrapping procedure for safely integrating wired and wireless nodes via in-band management into an existing network has been developed. This ensures that only authorized XPFEs are connected to the network.

A set of novel SDN/NFV applications were developed to optimize the overall system performance and to manage the 5G-Crosshaul resources including networking, computing and storage resources providing context-aware resource orchestration. As an example, the EMMA - Energy Management and Monitoring Application has been designed to consistently monitor and optimize the use of the energy consumption of the 5G-Crosshaul infrastructures over different kinds of network technology domains including (1) networks composed of software-based switches (XPFEs) and cloud nodes (XPUs), (2) mmWave links, and (3) analogue Radio over Fibre (RoF) technologies. This enables a sustainable approach to dynamically determine an optimal resource allocation for both network connections and cloud-based services and hence save costs. Specifically, energy-based optimization is achieved through routing (and re-routing) of traffic flows, Virtual Network Functions (VNFs) placement, and regulation of network node power states (including their On/Off switching) depending on the network resource demand. Such optimization is either performed upon on-demand instantiation or automatically triggered by the monitoring application when re-planning is needed. Another example is 5G-Crosshaul Resource Manager Application (RMA), which has been designed to support flexible Cloud RAN deployment. The RMA was proposed to jointly route traffic across fronthaul/backhaul (i.e., 5G-Crosshaul) transport networks and select proper functional splits for each BS to maximize the degree of centralization while meeting next generation fronthaul network constraints on parameters such as capacity and latency. The different applications carried out performance evaluation via individual means (simulation, emulation, or test-bed implementation) to validate the application functionalities as well as to verify the desired target performance KPIs. For the evaluation, benchmark methods were selected among the state-of-the-art approaches for comparing against the proposed solutions.

All the above innovations are driven primarily by the need to make the future 5G transport network more flexible in order to ease and hence accelerate the deployment of new services, whilst guaranteeing cost-efficient use of all the resources in play. This obviously results into a direct socio-economic impact, through lower cost and higher efficiency for the networking infrastructure stakeholders (operators, vendors, and service providers), and the end user customer in terms of better service in terms of quality and ubiquitous access, and lower bills. The overall society will also see the benefit of driving the future transport network towards more flexibility and cost-efficiency, whilst supporting effectively the various services envisioned in future 5G system. In addition, the innovations from 5G-Crosshaul project are expected to give the industrial companies (large, medium and small) in 5G-Crosshhaul and the extended European 5G-PPP community a privileged position and competitive advantage in the European and global markets through new generations of flexible and innovative access and core networks solutions. An exploitation plan is being defined to assess the possible impact on the product roadmaps of the main vendors involved in the project.

In order to ensure wide-reach of the innovations developed in the project, the consortium members have been very active in disseminating the project concept and early results to the European (inside and outside the 5G-PPP community) and wide international research and industrial community. The consortium has promoted the envisioned concepts and R&D achievements through various types of dissemination activities, including (1) scientific publications (journal and conference papers), (2) talks/panels/webinars, (3) demonstrations, (4) sponsored/organized workshops, and (5) standardization. The topics covered by these dissemination activities range from architecture, use cases, data plane technologies, control plane solutions, and field trial results. In particular, the project has successfully delivered:

- 91 papers – in several prestigious journals such as IEEE transactions and flagship conferences
- 74 presentations/panels/webinars , and 14 (Co-)organized workshops – in key events
- 28 demonstrations including at flagship events such as MWC'16 and MWC'17
- 35 normative contributions feeding into key standardization specifications such as: eCPRI, G.metro, IETF CCAMP, IETF DETNET, and ONF.
- 25 contributions for information purpose in several standardization bodies and forums such as NGMN, ITU-T, FSAN, ETSI, IEEE, BBF, ONF.

The above results demonstrate the depth and breadth of the activities undertaken towards a strong impact of the project innovations paving the way for their exploitation intellectually and commercially by the various stakeholders.

2. Patents

The project has registered four patent applications below during the reporting period. An additional three invention disclosures with references NC104517, NC104518, NC104519 have also been reported by NOK-N, pending approval for filings.

- WO2017088902: Ethernet frames encapsulation within CPRI basic frames, by NEC and UC3M
- WO2017142862: Open flow functionality in a software-defined network by IDCC
- WO2017147076: Methods, apparatuses and systems directed to common transport of backhaul and fronthaul traffic, by IDCC
- WO2017204704: Method, decoder, and encoder for handling a bit stream for transmission over a transmission link between a remote unit and a base unit of a base station system, by EAB

3. Dissemination & Communication Activities

Table 1, lists all Journal/Magazine Papers published during the second period. Published or accepted for publication materials are reported. As reported, the project has published over 18 peer-reviewed journal/magazine articles in the second period. This gives an average of approx. 1 papers published or accepted a month.

It is worth highlighting that all publications of the project are available through the Zenodo [1] in the Green Access modality. In addition, all publications involving the academic partners are also published in their own institutional repository. In this way, we are committed to the Open Access rules as requested by the EC.

Table 1: Journal/Magazine Papers Publications in period 2.

#	**Type**	**Month**	**Description**	**Leading Partner**
1	MAG	Jul'16	"5G-Crosshaul: An SDN/NFV Integrated Fronthaul/Backhaul Transport Network Architecture", by X. Costa-Pérez, A. Garcia-Saavedra, X. Li, A. de la Oliva, P. Iovanna, T. Deiß, A, di Giglio, and A. Mourad, *IEEE Wireless Communications Magazine*, Vol. 24, No. 1, Feb. 2017.	NEC, UC3M, TEI, NOKIA, TI, IDCC
2	JRN	Sep'16	"5G-Crosshaul: An SDN/NFV Control and Data Plane Architecture for the 5G Integrated Fronthaul/Backhaul", by S. González, A. de la Oliva, X. Costa, A. Di Giglioz, F. Cavalierex, T. Deiss, X. Li, A. Mourad, *Transactions on Emerging Telecommunications Technologies*, Vol. 27, No. 9, Sept. 2016	NEC, UC3M, IDCC, NOKIA
3	JRN	Nov'16	"An LPC-Based Fronthaul Compression Scheme," L. Ramalho, M. N. Fonseca, A. Klautau, C. Lu, M. Berg, E. Trojer, and S. Höst, *IEEE Communications Letters*, November 2016.	EAB
4	JRN	Dec'16	"Future Proof Optical Network Infrastructure for 5G Transport", by P. Iovanna et al., *Journal of Optical Communications and Networking*, Vol. 8, Issue 12, pp. B80-B92 (2016)	TEI
5	JRN	Dec'16	"Quasi-Passive Optical Infrastructure for Future 5G Wireless Networks: Pros and Cons", by A.S. Gowda, L.G. Kazovsky, K. Wang, and D. Larrabeiti, *Journal of Optical Communications and Networking*, Vol. 8, Issue 12, pp. B111-B123 (2016)	UC3M
6	JRN	Dec'16	The Impact of Vehicular Traffic Demand on 5G Caching Architectures: a Data-Driven Study, by F. Malandrino, C.-F. Chiasserini, and S. Kirkpatrick, *Elsevier Vehicular Communications Journal*, Dec. 2016	POLITO
7	JRN	Dec'16	Trade-off between Power and Bandwidth Consumption in a Reconfigurable Xhaul Network Architecture, by V. Eramo, M. Listanti, F. G. Lavacca, P. Iovanna, G. Bottari, and F. Ponzini, *IEEE Access*, Vol. 4, pp. 9053-9065, Dec. 2016.	TEI

8	JRN	Jan'17	"The Need of a Transport API in 5G for Global Orchestration of Cloud and Networks through a Virtualised Infrastructure Manager and Planner (Invited)" by A. Mayoral, R. Muñoz, R. Vilalta, R. Casellas, R. Martínez, and V. López, *Journal of Optical Communications and Networking (JOCN*), vol 9, pp: A55-A62 (2017), special OFC2016 issue;	CTTC, TID
9	JRN	Mar'17	"Towards a unified fronthaul-backhaul data plane for 5G, The 5G-Crosshaul project approach," F. Cavaliere, P. Iovanna, J. Mangues, J. Baranda, J. Núñez, K. Lin, H. Chang, P. Chanclou, P. Farkas, J. Gomes, L. Cominardi, A. Mourad, A. de La Oliva, J. Alberto Hernández, D. Larrabeiti, A. Di Giglio, A. Paolicelli, P. Ödling, *Elsevier Computer Standards & Interfaces*, Vol. 51, pp. 56-62, March 2017.	TEI, CTTC, ITRI, ORANGE, HHI, IDCC, UC3M, TI
10	JRN	Mar'17	"Low Delay Random Linear Coding and Scheduling Over Multiple Interfaces", by A. Garcia-Saavedra, M. Karzand, and D. J. Leith, in *IEEE Trans. on Mobile Computing*, Mar. 2017	NEC
11	JRN	Mar'17	"Delay analysis of mixed fronthaul and backhaul traffic under strict priority queueing discipline in a 5G packet transport network", by A. Gowda, J. A. Hernández, D. Larrabeiti, and L. Kazovsky, in *Transactions on Emerging Telecommunications Technologies*, Vol. 28, No. 6, June 2017	UC3M
12	JRN	Apr'17	"Distributed Mobility Management solutions for next mobile network architectures", by L. Cominardi, F. Giustc, C. J. Bernardos, A. De La Oliva, *Elsevier Computer Networks*, Vol. 121, July 2017.	UC3M
13	MAG	Jun'17	"Advertisement Delivery and Display in Vehicular Networks", by F. Malandrino, C.-F. Chiasserini, and M. Sereno, accepted by *IEEE Magazine on Vehicular Technology*	POLITO
14	MAG	Jul'17	"Enabling Multi-Tenancy in 5G Transport Networks through Network Slicing", by X. Li, R. Casellas, G. Landi, A. de la Oliva, X. Costa, A. Garcia-Saavedra, T. Deiß, L. Cominardi, R. Vilalta, accepted by *IEEE Communications Magazine*, series May 2017/5G Network Slicing	NEC, CTTC, NXW, UC3M, NOKIA, IDCC
15	JRN	Aug'17	Distributed Downlink Power Control for Dense Networks with Carrier Aggregation, by Z. Limani Fazliu, C. F. Chiasserini, G. M. Dell'Aera and E. Hamiti, *IEEE Transactions on Wireless Communications*	POLITO
16	MAG	Sep'17	Advertisement Delivery and Display in Vehicular Networks: Using V2V Communications for Targeted Ads, by C. F. Chiasserini, F. Malandrino and M. Sereno, *IEEE Vehicular Technology Magazine*, vol. 12, no. 3, pp. 65-72.	POLITO
17	JRN	Sep'17	Cellular Network Traces Towards 5G: Usage, Analysis	POLITO

			and Generation, by F. Malandrino, C. F. Chiasserini and S. Kirkpatrick, *IEEE Transactions on Mobile Computing*	
18	JRN	Oct’17	Area formation and content assignment for LTE broadcasting, by C. Casetti, C. F. Chiasserini, F. Malandrino, C. Borgiattino, *Computer Networks, Vol. 126, 2017, pp. 174-186.*	POLITO

Table 2 shows all conference papers published during the second period, with a total count of 39, implying an average slightly above 2 publications per month.

Table 2: Conference Papers Publications in period 2.

#	**Month**	**Description**	**Leading Partner**
1	Jul’16	“SDN/NFV Orchestration of Multi-technology and Multi-domain Networks in Cloud/Fog Architectures for 5G Services“, by Ricard Vilalta, Arturo Mayoral, Ramon Casellas, Ricardo Martínez, Raul Muñoz, in Proc. *OECC/PS-2016*, Niigata, Japan	CTTC
2	Jul’16	“The Price of Fog: a Data-Driven Study on Caching Architectures in Vehicular Networks”, by F. Malandrino, CF. Chiasserini, S. Kirkpatrick, in Proc. *ACM MobiHoc Workshop on Internet of Vehicles and Vehicles of Internet (IoV-VoI),* July 2016, Paderborn, Germany.	POLITO
3	Aug’16	“FPGA-Based Testbed for Synchronization on Ethernet Fronthaul with Phase Noise Measurement,” by I. Freire, I. Sousa, I. Almeida, C. Lu, M. Berg and A. Klautau, in Proc. *1st International Symposium on Instrumentation Systems, Circuits and Transducers (INSCIT)*, August 2016, Brazil. (Best paper award)	EAB
4	Sep’16	“On-Demand Allocation of Control Plane Functions via SDN/NFV for Monitoring-enabled Flexi-grid Optical Networks with Programmable BVTs“, by R. Casellas, J. M. Fàbrega, R. Muñoz, L. Nadal, R. Vilalta, M. S. Moreolo, and R. Martínez, in Proc. *ECOC 2016*, Dusseldorf, Germany.	CTTC
5	Sep’16	“Experimental Investigation of Compression with Fixed-length Code Quantization for Convergent Access-Mobile Networks”, by L. Anet Neto, P. Chanclou, Z. Tayq, B. C. Zabada, F. Saliou, G. Simon, in Proc. *ECOC 2016*, Dusseldorf, Germany.	ORANGE
6	Sep’16	“Experimental Real Time AMCC Implementation for Fronthaul in PtP WDM-PON“, by Z. Tayq, L. Anet Neto, P. Chanclou, C. Aupetit-Berthelemo, in Proc. *ECOC 2016*, Dusseldorf, Germany.	ORANGE
7	Sep’16	“Performance Demonstration of Real Time Compressed CPRI Transport“, Z. Tayq, A. Quere, L. Anet Neto, P. Chanclou, F. Saliou, K. Grzybowski, C. Aupetit-Berthemelot, S. K. Yoo, S. E. Hong, in Proc. *ECOC 2016*, Dusseldorf, Germany.	ORANGE

8	Sep’16	“Efficient Multimedia Broadcast for Heterogeneous Users in Cellular Networks”, by C. Singhal, CF. Chiasserini, CE. Casetti, in Proc. *12th IEEE International Wireless Communications & Mobile Computing (IWCMC 2016),* Paphos, Cyprus.	POLITO
9	Oct’16	“Experimental Evaluation of an SDN-based Distributed Mobility Management Solution“, by M. I. Sanchez, A. de la Oliva and V. Mancuso, in Proc. *MobiArch 2016*, October 2016, New York, USA.	UC3M
10	Nov’16	“Innovative TV Broadcasting-related Media Use Case in 5G-Crosshaul H2020 Project”, by D. Jiménez, F. Álvarez, N. Sánchez, in Proc. *New European Media Summit*, Porto, 23-24 November, 2016.	VISIONA
11	Dec’16	“Analysis and Evaluation of End-to-End PTP Synchronization for Ethernet-based Fronthaul“, by Igor Freire, Ilan Sousa, Igor Almeida, Chenguang Lu, Miguel Berg and Aldebaro Klautau, in Proc. *GLOBECOM’16*, Dec. 2016, Washington DC, USA.	EAB
12	Dec’16	“How close to the edge? Delay/utilization trends in MEC”, by F. Malandrino, C.F. Chiasserini, S. Kirkpatrick, in Proc. *ACM Cloud-Assisted Networking 2016 co-located with ACM CoNEXT 2016*, USA.	POLITO
13	Mar’17	"Switch-On/Off Policies for Energy Harvesting Small Cells through Distributed Q-Learning", by M. Miozzo, L. Giupponi, M. Rossi and P. Dini, in Proc. *IEEE Wireless Communications and Networking Conference (WCNC) 2nd Workshop on Green and Sustainable 5G Wireless Networks (GRASNET 2)*, 19-22 March, 2017, San Francisco (CA), USA	CTTC
14	Mar’17	“A network sharing mechanism based on multi-operator core network”, by Chia-Lin Lai, Shahzoob Bilal Chundrigar, Samer T. Talat, and Hsien-Wen Chang, in Proc. *38th WWRF Meeting*, Hsinchu, Taiwan.	ITRI
15	Mar’17	“Real Time Demonstration of the Transport of Ethernet Fronthaul based on vRAN in Optical Access Networks”, by Z. Tayq, L. Anet Neto, B. Le Guyader, A. De Lannoy, M. Chouaref, C. Aupetit-Berthelemot, M. N. Anjanappa, S. Nguyen, K. Chowdhury, and P. Chanclou, in Proc. *Optical Fiber Communication Conference (OFC)*, Los Angeles, USA, Mar. 2017.	ORANGE
16	Mar’17	“Mobile Fronthaul Architecture and Technologies: a RAN Equipment Assessment”, by P. Chanclou, L. Anet Neto, K. Grzybowski, Z. Tayq, F. Saliou, and N. Genay, in Proc. *Optical Fiber Communication Conference (OFC)*, Los Angeles, USA, Mar. 2017.	ORANGE
17	May’17	“An FPGA-based Design of a Packetized Fronthaul Testbed with IEEE 1588 Clock Synchronization”, by I. Freire, C. Lu, M. Berg, and A. Klautau, in Proc. *European Wireless 2017*, Dresden, Germany, May 2017.	EAB
18	May’17	“Enabling 5G network slicing over heterogeneous optical	CTTC

		networks", by R. Casellas, R. Vilalta, R. Martínez, and R. Muñoz, in Proc. *Workshop Optical networks for data centres in the 5G era, within the 21st International Conference on Optical Networks Design and Modelling (ONDM2017),* Budapest, Hungary, May, 2017.	
19	May'17	"Novel Resource and Energy Management for 5G Integrated Backhaul/Fronthaul (5G-Crosshaul)", by X. Li, R. Ferdous, C. F. Chiasserini, C. E. Casetti, F. Moscatelli, G. Landi, R. Casellas, K. Sakaguchi, S. B. Chundrigar, R. Vilalta, J. Mangues, A. Garcia-Saavedra, X. Costa-Pérez, L. Goratti, D. Siracusa, in Proc. *IEEE International Conference on Communications (ICC)- 3rd International Workshop on 5G RAN design*, May 2017, Paris, France	NEC, NXW, CTTC, CREATE-NET
20	May'17	Traffic adaptive formation of mmWave meshed backhaul networks, by H. Ogawa, G. K. Tran, K. Sakaguchi, and T. Haustein (IEEE Conf. on Communications ICC Workshop)	HHI
21	Jun'17	"Energy Monitoring and Management in 5G Integrated Fronthaul and Backhaul", by O. I. Abdullaziz1, M. Capitani, C. E. Casetti, C. F. Chiasserini, S. B. Chundrigar, G. Landi, X. Li, F. Moscatelli, K. Sakaguchi, and S. T. Talat, in Proc. *European Conference on Networks and Communications (EuCNC'17),* June 2017, Oulu, Finland	HHI, ITRI, NEC, NXW, POLITO
22	Jun'17	"Experimental Evaluation of Hierarchical Control over Multi-Domain Wireless/Optical Networks", by J. Mangues-Bafalluy, J. Núñez-Martínez, R. Casellas, A. Mayoral, J. Baranda, J. X. Salvat, A. Garcia-Saavedra, R. Vilalta, I. Pascual, X. Li, R. Martinez and R. Muñoz, in Proc. *European Conference on Networks and Communications (EuCNC'17),* June 2017, Oulu, Finland	CTTC NEC
23	Jun'17	"Millimeter Wave for 5G Mobile Fronthaul and Backhaul", by P.-H. Kuo and A. Mourad, in Proc. *European Conference on Networks and Communications (EuCNC'17),* June 2017, Oulu, Finland	IDCC
24	Jun'17	"Energy-Efficient 5G Networks: Optimization Meets SDN", by G. Avino, C. Casetti, C. F. Chiasserini, F. Malandrino, M. Malinverno, Poster presentation at *CLEEN 2017*, June 2017, Turin. Italy.	POLITO
25	Jun'17	"Dataplane measurements on a Fronthaul and Backhaul integrated network", by T. Deiß et al., Poster presentation at *CLEEN 2017*, June 2017, Turin. Italy.	NOK-N
26	Jun'17	"The 5G-Crosshaul Packet Forwarding Element pipeline: measurements and analysis", by N. Molner, S. González, T. Deiß, and A. de la Oliva, in Proc. *CLEEN 2017*, June 2017, Turin. Italy	UC3M
27	Jun'17	"Understanding the Present and Future of Cellular Networks through Crowdsourced Traces", by F. Malandrino, C.-F. Chiasserini, and S. Kirkpatrick, in Proc. *IEEE WoWMoM*, June 2017, Macao, China	POLITO
28	Jul'17	"Energy Consumption Measurements in Docker", by S. Semu Tadesse, C.-F. Chiasserini, and F. Malandrino, to	POLITO

		appear in Proc. *IEEE COMPSAC*, July 2017, Turin, Italy	
29	Jul'17	"Sharing of Crosshaul Networks via a Multi-Domain Exchange Environment for 5G Services", by L. M. Contreras Murillo, C. J. Bernardos Cano, A. Oliva, and X. Costa-Pérez, to appear in *Proc. MPNSV workshop, 3rd IEEE Conf. on Network Softwarization (NetSoft'17)*, Jul. 2017, Bologna, Italy.	TID, UC3M, NEC
30	Jul'17	"Real Time Demonstration of Fronthaul Transport over a Mix of Analog & Digital RoF", by Z. Tayq, L. Anet Neto, F. Saliou, C. Aupetit-Berthelemot, J. Gomes, T. Haustein, M. Lacouche, J. Plumecoq, L. Bellot, and P. Chanclou, to appear in Proc. *International Conference on Transparent Optical Networks (ICTON)*, July 2017, Girona, Spain.	ORANGE
31	Jul'17	"Mobile Front-/Back-Haul Delivery in Elastic Metro/Access Networks with Sliceable Transceivers based on OFDM Transmission and Direct Detection" by J.M. Fabrega, M. Svaluto Moreolo, L. Nadal, F.J. Vílchez, J.P. Fernández-Palacios, and L.M. Contreras, to appear in Proc. *International Conference on Transparent Optical Networks (ICTON)*, July 2017, Girona, Spain.	CTTC, TID
32	Jul'17	Control Plane Architectures Enabling Transport Network Adaptive and Autonomic Operation by R. Casellas, R. Vilalta, A. Mayoral, R. Martínez, R. Muñoz and L.M. Contreras (International Conference on Transparent Optical Networks, ICTON 2017)	CTTC, TID
33	Aug'17	"Characterizing Docker Overhead in Mobile Edge Computing Scenarios", by G. Avino, M. Malinverno, F. Malandrino, C. Casetti, C.F. Chiasserini, to appear in Proc. *ACM SIGCOMM HotConNet*, Aug. 2017, Los Angeles, USA.	POLITO
34	Sept'17	"Transport Network Design for FrontHaul", by P. Sehier, A. Bouillard, F. Mathieu and T. Deiß, to appear in Proc. *3rd IEEE Workshop on Next Generation Backhaul/Fronthaul Networks (BackNets)*, Sept. 2017, Toronto, Canada.	NOK-N
35	Sep'17	Experimental Validation of a Converged Metro Architecture for Transparent Mobile Front-/Back-Haul Traffic Delivery using SDN-enabled Sliceable Bitrate Variable Transceivers, by J. M. Fabrega, M. Svaluto Moreolo, L. Nadal, F. J. Vílchez, R. Casellas, R. Vilalta, R. Martínez, R. Muñoz, J. P. Fernández-Palacios, L. M. Contreras (European Conference on Optical Communications, ECOC 2017)	CTTC, TID
36	Sep'17	Delay Analysis of Fronthaul Traffic in 5G Transport Networks, by G. O. Perez, J. A. Hernandez, and D. L. Lopez (IEEE International Conference on Ubiquitous Wireless Broadband ICUWB'2017)	UC3M
37	Nov'17	Quality Probe for Testing Multimedia Content in 5G Networks, by J.P. López, D. Jiménez, C. Navarro, J.A. Rodrigo, J.M. Menéndez, and N. Sánchez (NEM Summit 2017)	VISIONA
38	Nov'17	Hybrid SDN: Evaluation of the impact of an unreliable	CTTC

		control channel, by M. Osman, J. Nunez-Martınezy and J. Mangues-Bafalluyz (IEEE NFV-SDN'17 NFVPN Workshop)	
39	Nov'17	Resource Management in a Hierarchically Controlled Multi-domain Wireless/Optical Integrated Fronthaul and Backhaul Network, by J. Baranda, J. Nunez-Martınez, Inaki Pascual, J. Mangues-Bafalluy, A. Mayoral, R. Casellas, R. Vilalta, R. Martınez, R. Munoz, J. X. Salvat, A. Garcia-Saavedra, X. Li, J. Kocur (IEEE NFV-SDN conference, Demo Paper)	CTTC NEC CND

Table 3, shows the contributions to industrial white papers by 5G-Crosshaul partners during the second period.

Table 3: White Papers published in period 2.

#	**Month**	**Description**	**Leading Partner**
1	Jul'16	5G PPP Architecture Working Group White paper "View on 5G Architecture"	NEC
2	Jan'17	5G-PPP vision white paper at MWC 2017 "5G innovations for new business opportunities"	TEI
3	Mar'17	5GPPP Network Management & Quality of Service Working Group – Cognitive Network Management for 5G	POLITO
4	Apr'17	ETSI White Paper "Crosshauling - The convergence of fronthaul and backhaul through softwarization and virtualization", submitted for ETSI internal review	UC3M, IDCC
5	Jun'17	ONF mobile networks WG White Paper - "SDN-Based Network Architecture for 3GPP 5G" (expected for release in December 2017)	UC3M
6	Dec'17	5G-PPP Architecture Working Group White paper V2.0	NEC, IDCC, UC3M

5G-Crosshaul has been very active in the dissemination of its technical innovations in the industry. Table 4, shows all talks and panels contributed during the second period. Note that 38 talks have been done during this period, showing the reach and interest of the industry on the technology developed by the project.

Table 4: Talks and panels delivered in period 2.

#	**Month**	**Description**	**Leading Partner**
1	Sep'16	"Industrial perspective in 5G optical transport", by T. Deiss, at Tyrrhenian International Workshop on Digital Communication 2016, Livorno, Italy	NOK-N
2	Oct'16	"Fronthaul and Backhaul for 5G and Beyond", by A. Mourad at the 2nd COST IRACON meeting, Durham, UK	IDCC
3	Oct'16	"SDN in the H2020 5G-Crosshaul project", by Antonio de la Oliva at Workshop on OpenDayLight and NFV/SDN Orchestration	UC3M
4	Oct'16	"SDN for Microwaves PoCs Overview and Demo", by Luis	TID

		Miguel Contreras Murillo at Workshop on OpenDayLight and NFV/SDN Orchestration	
5	Oct'16	"European 5G scientific mission to South Korea", by Arturo Azcorra	UC3M
6	Nov'16	"5G-Crosshaul: mmW Transport Trial at 5G-Berlin Testbed", by A. Mourad and R. Gazda at 5G-Summit in Berlin	IDCC
7	Nov'16	"5G Crosshaul Media Use Case" by D. Jiménez, 5G Networks for Media and Entertainment Session, NEM Summit, 23-25 November 2016, Porto	VISIONA
8	Nov'16	"NFV & SDN innovations for 5G and Telco business", by G. Carrozzo, 87th TechDay@AlticeLabs – "ICT Industry Evolution Lines", 30 Nov 2016, Aveiro, Portugal	NXW
9	Dec'16	"Energy efficient orchestration of virtual services in 5G integrated fronthaul/backhaul infrastructures", by G. Landi presented at "End-to-end service orchestration for 5G and beyond" workshop, co-located with the 15th International Conference on Ubiquitous Computing and Communications (IUCC-2016), Granada, December 14th-16th, 2016	NXW
10	Dec'16	"Generalized Orchestration of IT/Cloud and Networks for SDN/NFV 5G Services", by R. Casellas, R. Vilalta, R. Muñoz, R. Martínez, at "End-to-end service orchestration for 5G and beyond" workshop, co-located with the 15th International Conference on Ubiquitous Computing and Communications (IUCC-2016), Granada, Spain, December 14th-16th, 2016	CTTC
11	Feb'17	"Network Slicing in Transport - Definition and implementation", by A. Garcia-Saavedra at 5GPPP Workshop, Athens, Greece	NEC
12	Feb'17	Crosshaul (Xhaul) Panel – The fusion of Fronthaul and Backhaul in 5G, Mobile World Congress (MWC) 2017, Barcelona, Spain	IDCC
13	Feb'17	NFV: A Re-Examination, Mobile World Congress (MWC) 2017, Barcelona, Spain	IDCC
14	Feb'17	5G Impact, Mobile World Congress (MWC) 2017, Barcelona, Spain	IDCC
15	Mar'17	"5G-Crosshaul Architecture Overview", by X. Costa-Pérez at 5GPPP Architecture Workshop	NEC
16	Mar'17	"Mobile Internet on Taiwan High Speed Rail", by H.-W. Chang at 38th WWRF Meeting, Hsinchu, Taiwan	ITRI
17	Mar'17	"On the Slicing of Crosshaul Transport Network", by P.-H. Kuo at 5G PPP Workshop on 5G Architecture and RAN Integration, Chertsey, UK	IDCC
18	Mar'17	"ETSI White Paper on Crosshauling", by A. de la Oliva at 5G PPP Workshop on 5G Architecture and RAN Integration, Chertsey, UK	UC3M
19	Mar'17	SDN and NFV for mobile networks, Scavenge ETN Marie Curie action school - "5G cellular networks and Internet of Things"	CTTC

20	May'17	IEEE ComSoc Webinar: SDN/NFV – Time for Real Innovations. http://event.lvl3.on24.com//event/14/16/84/1/rt/1/documents/resourceList1495556524256/webinarpowerpoint.pdf	IDCC, UC3M
21	Jun'17	"Hierarchical multi-domain fronthaul/backhaul orchestration in the 5G-Crosshaul Control Infrastructure", by J. Mangues-Bafalluy at EuCNC'17 Workshop - Software Networks and 5G: from network programmability to SDN/NFV combination for effective network slicing, Oulu, Finland	CTTC
22	Jun'17	"Packet network virtualization in 5G-Crosshaul", by T. Deiß, at EuCNC'17 Workshop - New x-haul solutions for the 5G transport challenge, Oulu, Finland	NOK-N
23	Jun'17	"5G-Crosshaul applications: Resource orchestration for the integrated fronthaul and backhaul", by X. Li at EuCNC'17 Workshop - New x-haul solutions for the 5G transport challenge, Oulu, Finland	NEC
24	Jun'17	"The 5G-Crosshaul testbed: Experimental validation of an integrated fronthaul and backhaul", by J. Mangues-Bafalluy at EuCNC'17 Workshop - New x-haul solutions for the 5G transport challenge, Oulu, Finland	CTTC
25	Jun'17	5G-Crosshaul Project overview and Demo Activity, by C. Casetti, 5G Focus Day, at Flex5Gware workshop, Turin, Italy	POLITO
26	Jun'17	"Key technologies for a 5G ready metro network", by J.P. Fernández-Palacios at Next Generation Optical Networking, Nice, France	TID
27	Jun'17	"The ingredients of the new networks - SDN, NFV and Slicing in the evolution towards 5G", by Luis M. Contreras at the University of Tokyo, Tokyo, Japan	TID
28	Jun'17	"Architecture and next steps", by A. De La Oliva Delgado at EU-Taiwan 5G Workshop, Brussels, Belgium	UC3M
29	Jul'17	"Sharing of Crosshaul Networks via a Multi-Domain Exchange Environment for 5G Services", by Luis M. Contreras, Carlos J. Bernardos, Antonio de la Oliva, Xavier Costa-Pérez at IEEE NetSoft 2017, Bologna, Italy.	UC3M
30	Jul'17	"5G-Crosshaul Project overview and Demo Activity", by C. F. Chiasserini at IEEE 5G Summit, Thessaloniki, Greece.	POLITO
31	Sep'17	"EU Project 5G-Crosshaul - 5G Transport Systems", by A. Mourad and C. Turyagyenda at European Conference on Optical Communication (ECOC 2017), Gothenburg, Sweden.	IDCC
32	Sep'17	"5G-Crosshaul Architecture Implementation", by A. Azcorra, at The 4th Taipei 5G Summit, Taipei, Taiwan.	UC3M
33	Sep'17	"Towards 5G Mobile Transport Platforms for Industry Verticals", by A. Bouillard and X. Costa-Pérez, at 3rd IEEE Workshop on Next Generation Backhaul/Fronthaul Networks - BackNets 2017, Toronto, Canada.	NOK-N, NEC
34	Oct'17	"Data-plane Integration for 5G Fronthaul and Backhaul – A proof-of-concept from 5G-Crosshaul", by C. Turyagyenda, at Special Session of WWRF 39th Meeting - 5G Mobile	IDCC

		Transport Networks, Barcelona, Spain.	
35	Oct'17	"Multi-Domain Hierarchical 5G-Crosshaul Control Infrastructure", by J. Mangues-Bafalluyz, at Special Session of WWRF 39th Meeting - 5G Mobile Transport Networks, Barcelona, Spain.	CTTC
36	Oct'17	"Energy Efficient Services Orchestration in Converged Fronthaul/Backhaul", by G. Carrozzo, at Special Session of WWRF 39th Meeting - 5G Mobile Transport Networks, Barcelona, Spain.	NXW
37	Oct'17	"Slicing Across Multiple Administrative Domains", by L. M. Contreras, at Special Session of WWRF 39th Meeting - 5G Mobile Transport Networks, Barcelona, Spain.	TID
38	Oct'17	"Cellular Access Multi-Tenancy through Small-Cell Virtualization and Common RF Front-End Sharing", by J. Mendes, X. Jiao, A. Garcia-Saavedra, F. Huici, I. Moerman at ACM WiNTECH 2017 Workshop, Snowbird, Utah, USA.	NEC

As contractually agreed on the DoA, 5G-Crosshaul has worked towards the organization of workshops in order to disseminate the technology developed. Table 5, presents the different workshops organized during the second period. Considering the final count, the project has been present in the organization of a workshop around every 3 months.

Table 5: Workshops organized.

#	Month	Workshop	Country
1	Jul'16	On-the-fly services in on-the-fly mobile infrastructures (OSOMI)	Germany
2	Dec'16	End-to-end service orchestration for 5G and beyond within the 15th International Conference on Ubiquitous Computing and Communications (IUCC-2016).	Spain
3	Dec'16	5G RAN design workshop at IEEE Globecom 2016.	USA
4	Mar'17	5G PPP Workshop on 5G Architecture and RAN Integration (A joint workshop co-organised by mmMAGIC, METIS-II, 5G-Crosshaul, 5G NORMA)	UK
5	Jun'17	EuCNC'17 Workshop: New x-haul solutions for the 5G transport challenge (A joint workshop of the iCIRRUS, 5G-Crosshaul and 5G-XHaul projects)	Finland
6	Oct'17	5G Mobile Transport Networks (Special Session of WWRF 39th Meeting)	Spain
7	Dec'17	5G for "dummies" in Media Sector seminar (Technical University of Madrid) (A joint workshop with 5G-MEDIA project)	Spain

Demonstrating the developed technologies is key in order to show the progress of the project and forces researchers to perform Proof-of concept of their ideas, showing their feasibility. 5G-Crosshaul has been present in 12 events during this last period. As shown in Table 6, some of the demonstration activities have been done in conjunction with other H2020 5GPPP projects.

Table 6: Demonstrations exhibited.

#	Month	Description	Leading Partners
1	Sep'16	mmWave integrated FH/BH – Live demo from Berlin to Brussels (at the project review meeting)	IDCC, HHI, CND
2	Nov'16	5G Crosshaul: mmW Integrated Fronthaul and Backhaul (for 5G Global Event)	IDCC, HHI, CND
3	Nov'16	Energy monitoring and management for network paths (for 5G Global Event)	NXW, POLITO
4	Nov'16	SDN-based TV Broadcasting Service (for 5G Global Event)	VISIONA
5	Nov'16	Silicon Photonic Reconfigurable Add Drop Multiplexer for Crosshaul networks (for 5G Global Event)	TEI
6	Nov'16	Next Generation Frounthaul Interface over LED-based Optical Wireless Link	HHI, CND
7	Feb'17	5G Impact (MWC'17) – Demonstration of 5G-Crosshaul solution with a remote surgery application	IDCC
8	Feb'17	MWC'17 Demonstration at InterDigital Stand - 5G-Crosshaul solution over InterDigital's EDGELINK platform, featuring demanding low-latency traffic from a remote surgery application.	IDCC
9	Feb'17	MWC'17 Demonstration at CTTC Stand - Demonstration by CTTC of an SDN- based management of a heterogeneous wireless Crosshaul, featuring automated technology and link selection over 802.11ac/ad links.	CTCC
10	Jun'17	"Flex5Gware - Joint demo with 5G-Crosshaul project: Network split with integrated fronthaul and backhaul", at CLEEN'17 Workshop	CTTC, UC3M, NXW, Nokia
11	Jun'17	"Flexibility of 5G-Crosshaul Technologies", at 5G-Crosshaul booth of EuCNC'17	VISIONA, NXW, CTTC, HHI, NEC
12	Oct'17	Resource management of the 5G-Crosshaul network at WWRF 39th Meeting, Barcelona, Spain	CTTC
13	Nov'17	"Resource Management in a Hierchically Controlled Multi-domain Wireless/Optical Integrated Fronthaul and Backhaul Network", proposed for demo at 3rd IEEE Conference on Network Function Virtualization and Software Defined Networks (NFV-SDN'17)	CTTC

In an industrial leadership project as 5G-Crosshaul, participating in standards and gaining leadership positions on them is key to improve the market penetration of European companies. 5G-Crosshaul consortium, includes the biggest European players in the area, hence its presence has been key in a set of different standards. Table 7 and Table 8 present the different standardization activities, respectively for dissemination (informative nature) and technical (normative nature) contributions, performed by the different partners of the project. Key aspect is the different contributions to the eCPRI standard, which key contributors are members of the project, and which development has been driven by the results of the project.

Table 7: Standardization dissemination in period 2.

#	**Month**	**SDO**	**Description**	**Leading Partner**
1	Jul'16	IETF	Presentation on "Microwave radio link - Problem Statement" in IETF meeting in Berlin	NEC, TEI, TID
2	Aug'16	IEEE	Presentation on "Towards a Unified BH/FH Data-Plane: 5G-Crosshaul", IEEE 1914.1 meeting	NEC, IDCC, NOK-N
3	Aug'16	NGMN	Impacts on network and service management and orchestration for 5G.	TID
4	Sep'16	ONF	Cross Stratum Optimization (CSO) on-line presentation during ONF Member Workdays on CSO Gap Analysis.	CTTC
5	Oct'16	ITU-T 2020FG	Key Challenges of the 5G-Crosshaul project	IDCC, TEI
6	Nov'16	ITU-T 2020FG	Application of network softwarization to IMT-2020 (IMT-O-036-updated)	CTTC
7	Dec'16	ETSI	White Paper: The convergence of fronthaul and backhaul through softwarization and virtualization	UC3M, IDCC
8	Dec'16	ONF	Third Wireless Transport SDN Proof of Concept White Paper	TID
9	Jan'17	ONF	Position Paper of Mobile Networks Working Group	UC3M

Table 8: Standardization contributions in period 2.

#	**Month**	**SDO**	**Description**	**Leading Partner**
1	Aug'16	IEEE	"Proposed options for functional splits for CRAN and fronthaul" submitted to IEEE P1914.1 TF August 2016 Meeting	NEC, IDCC, NOK-N
2	Oct'16	IRTF NFV	"VNF Pool Orchestration for Automated Resiliency in Service Chains"	NXW, TID
3	Nov'16	IETF DETNET	DETNET crosshauling requirements, IETF 97 meeting in Seoul, South Korea in November 2016.	UC3M, IDCC, TID
4	Nov'16	IETF SFC	Service Function Chaining Use Cases in Fog RAN, IETF 97 meeting in Seoul, South Korea in November 2016.	UC3M, IDCC
5	Nov'16	IEEE	Contribution to SDN Chapter of IEEE 802.1CF	UC3M
6	Nov'16	IETF CCAMP	"A framework for Management and Control of microwave and millimeter wave interface parameters", IETF 96 meeting in Berlin, Germany in July as well as in the IETF 97 meeting in Seoul, South Korea in November 2016.	NEC, EAB, TID
7	Nov'16	IEEE	"SDN Functional Decomposition" (omniran-16-	UC3M

			0089-00-CF00), IEEE 802.1 OmniRAN TG Conference call	
8	Dec'16	ONF	Microwave Information Model	TID
9	Dec'16	ONF	Contribution (onf2016.179) to draft "Gap Analysis for Application-Driven Cross Stratum Orchestration"	CTTC
10	Dec'16	IETF CCAMP	"A YANG Data Model for Microwave Radio Link", presented in IETF 97 meeting in Seoul, South Korea in November 2016b (to be updated in Dec. 2016).	NEC, EAB, UC3M
11	Feb'17	ONF	Use cases for T-API PoC (document onf2017.048)	TID
12	Feb'17	ONF	Requirements for compliance of TR-532 model (document onf2017.047)	TID
13	Feb'17	eCPRI	"Alignment to IETF RFC 2360" (Tdoc 1430)	NOK-N
14	Mar'17	IETF	"Service Function Chaining Use Cases in Fog RAN", IETF Meeting 98, Chicago, USA	UC3M, IDCC
15	Mar'17	IETF	"DetNet Data Plane", IETF Meeting 98, Chicago, USA	UC3M, IDCC
16	Mar'17	eCPRI	"eCPRI over Ethernet and eCPRI over IP sections text proposal" (Tdoc 1457)	NOK-N
17	Apr'17	eCPRI	"eCPRI requirements to the Transport network layer: work document" (Tdoc 1508)	NOK-N
18	Apr'17	eCPRI	"eCPRI network QoS definition" (Tdoc 1509)	NOK-N
19	Jun'17	eCPRI	"eCommon Public Radio Interface (eCPRI); Transport Network Services Specification" (Tdoc 1541)	NOK-N

Finally, Table 9, Table 10 and Table 11 present Communication events such as Press releases, Interviews and Videos that the project has participated in and are available in our web page.

Table 9: Press releases.

#	Month	Description	Lead partners
1	Sep'16	**InterDigital Demonstrates Integrated Fronthaul and Backhaul Over Millimeter Wave System** H2020 5GPPP 5G-Crosshaul Project uses InterDigital's EdgeLink™ in first proof-of-concept demonstration http://ir.interdigital.com/file/Index?KeyFile=36022570	IDCC
2	Nov'16	**5G-Crosshaul Partners Announce Successful Result of 5G Integrated Fronthaul-Backhaul Extended Outdoor Trial** Month-plus trial in real-world conditions, a first of its kind, delivers sub-millisecond latency, Gbps throughput; integrated fronthaul/backhaul sets stage for cost saving, flexibility in real-world deployable 5G architecture http://ir.interdigital.com/file/Index?KeyFile=36613495	IDCC, HHI, CND
3	Feb'17	**InterDigital Headlines GSMA 5G Showcase Alongside Industry Leaders at Mobile World Congress**	IDCC

		Company's Crosshaul project featured on mainstage alongside 5G demos by Ericsson, Qualcomm, Intel http://ir.interdigital.com/file/Index?KeyFile=38231311	

Table 10: Interviews.

#	Month	Description	Lead partners
1	Sep'16	Interview in Radio Exterior de España (15 minutes). https://www.youtube.com/watch?v=rlN4et8VnpY&feature=youtu.be	UC3M
2	Sep'16	Interview in SER Madrid Sur (14 minutes). http://play.cadenaser.com/audio/1473327004_983007/	UC3M
3	Mar'17	Interview at the program "World Ecommerce" in Radio Internacional de España. https://www.youtube.com/watch?v=LhwOyG2It2M&feature=youtu.be	UC3M
4	Jun'17	Interview on the project demonstrations at the EuCNC 2017 (link not available at the time of writing of this deliverable)	UC3M
5	Sep'17	Interview on the project demonstrations at the EuCNC 2017: Demo 1: SDN-based TV Broadcasting Service https://youtu.be/s7TSL5g6480	VISIONA
6	Sep'17	Interview on the project demonstrations at the EuCNC 2017: Demo 2: Energy Monitoring and Management for Network Paths **https://youtu.be/35TB9dHCagA**	NXW, NOKIA, POLITO
7	Sep'17	Interview on the project demonstrations at the EuCNC 2017: Demo 3: Resource management of the 5G-Crosshaul **https://youtu.be/QJs7lNB9OG0**	CTTC, NEC
8	Sep'17	Interview on the project demonstrations at the EuCNC 2017: Demo 4: Next Generation fronthaul/backhaul over hybrid Optical Wireless and mmWave Link **https://youtu.be/pCvwelbqELY**	HHI
9	Oct'17	Video interview provided by Project Coordinator to 5G Public Private Partnership (5G PPP), 2017: **https://www.youtube.com/watch?v=78wiM3KH210**	UC3M
10	Oct'17	Video interview provided by SME to 5G Public Private Partnership (5G PPP), 2017: **https://www.youtube.com/watch?v=gZ-UNflObdA**	VISIONA

Table 11 Videos.

#	Month	Description	Lead partners
1	Sept'16	**Video demonstration on the Berlin trial** was taken and published on YouTube, the project portal (http://5g-crosshaul.eu/5g-crosshaul-demonstrates-integrated-fronthaul-and-backhaul-over-millimeter-wave-system/), and partners' portals (e.g. http://www.interdigital.com/videos/5g-crosshaul). This	IDCC, HHI, CND

		video demonstration was also shown at the 5G-Global Event in Rome, November 2016.	
2	Feb'17	**MWC17: 5G-Crosshaul with EdgeLink™ Platform** (http://www.interdigital.com/videos/mwc17-)	IDCC
3	Mar'17	**Video on the MWC 2017 panel: Crosshaul – The Fusion of Fronthaul and Backhaul in 5G** (http://5g-crosshaul.eu/watch-crosshaul-panel-at-mwc17/)	IDCC

4. Explanation of the work carried out by the beneficiaries and Overview of the progress

4.1. Objectives

This section is devoted to present the progress towards the fulfilment of the project objectives. For each of the objectives identified in the Description of Action (DoA), we present the details on how are they being tackled technically and by which WP.

Obj.1	**Design of the 5G-Crosshaul Control Infrastructure (XCI)**	
Description	Develop XCI by extending existing Software Defined Network (SDN) controllers to provide the services for novel Northbound (NBI) and Southbound (SBI) Interfaces and enable multi-tenancy support in trusted environments. Introduce new mechanisms to abstract the mobile transport network and aggregate measured contextual information.	
R&D Topics	**WP**	**Details**
• Study of network partitioning techniques (= multi-tenancy support).	WP3	Support of multi-tenancy by XCF is described in D3.2 [2].
	WP4/ WP1	Definition and the scope of multi-tenancy within 5G-Crosshaul, and proposed design extensions of 5G-Crosshaul architecture to support multi-tenancy were described in D4.2 [3] and D1.2 [4].
• Multi-level, multi-criteria abstraction and network clustering for hierarchical SDN control under real-world transport network constraints.	WP3	The hierarchical SDN control design was given in IR3.2. XCI recursion to allow for multi-level abstraction for multi-tenant case was described in IR3.1. Final design of both hierarchical SDN control

		and XCI recursion are described in D3.2 [2].
• Dynamic (de-)centralization of network element functions such as radio link adaptation, monitoring, Operations Administration and Management (OAM), etc. (in line with current ONF OT-WG "Autonomous Functions" concept).	WP4	Develop a resource management application (RMA) which decides dynamic (de-)centralization of base station functions in 5G-Crosshaul. The design of this application and the algorithms was described in IR4.1, IR4.2, the evaluation results were reported in D4.2 [3].
• Design an SDN architecture that can cope with multiple types of agents (e.g., wireless agents, packet system, optical agents). •	WP1	The final 5G-Crosshaul system architecture including the SDN architecture has been designed, which was described in D1.2 [4].
• Contribute to relevant SDOs (such as ONF OT-WG, ONF WMWG and IRTF SDNRG).	WP6	Initial standardization activity roadmaps for 5G-Crosshaul data, control and application planes were reported in IR6.1. Refinement of the roadmaps accounting for latest developments in 5G-Crosshaul and in the relevant SDOs identified was reported in D6.1 [5] . First standardization activities were reported in IR6.2, with both types: dissemination and input contributions. Further dissemination and contribution activities into the various SDOs were reported in D6.1 [5]. Year 2 achievements and a plan for Year 3 were reported in D6.2 [6]. Year 3 achievements and future plans will be reported in D6.3 [7].
Verification	**WP**	**Details**

- Report on pros and cons of different hierarchical SDN architectures.	WP3	Investigation of different hierarchical SDN controllers was described in D3.2 [2].
- Develop a proof-of-concept XCI prototype (TRL 3) and demo of a hierarchical SDN system using the example of a parent umbrella controller integrating a wireless, packet and optical SDN controller.	WP5	Development of MANO for media distribution, energy and infrastructure management scenarios. Development of technology-specific SDN controllers. Selection of features to be exchanged through the child-parent SDN controller API. Demonstration at ICT and Mobile World Congress. Experimental results provided in D5.2 [8].

Obj.2	**Specify the XCI's northbound (NBI) and southbound (SBI) interfaces**	
Description	Define interfaces to accelerate the integration of new physical technologies (SBI) and the introduction of new services (NBI) via novel or extended interfaces.	
R&D Topics	**WP**	**Details**
- Specify an abstract network information model for 5G-Crosshaul technologies, including abstracted control parameters and system status metrics.	WP3	Definition of the abstraction information models for traffic, congestion, interference of radio resources, and energy savings are reported in D3.2 [2].
- Specify the set of southbound XCI actions (e.g., control the forwarding behavior, configure radio parameters, deploy/migrate 5G-Crosshaul functions).	WP3	OpenFlow is chosen as the southbound protocol to control the forwarding behaviour and configure the required network parameters. OpenStack is selected as XPU controller control, which is used to manage the migration of Virtual Machines to place 5G-Crosshaul functions. Description of migration path is given in D1.2 [4].
- Specify the set of northbound XCI actions (e.g., provisioning of new VPNs) to enable Service Level Agreement (SLA)-level reports, create new virtual	WP3	Defined a set of XCI services for the northbound XCI actions, e.g. for topology and inventory, IT infrastructure and inventory, path and flow provisioning, SLA and support multi-tenancy, etc. in D3.2 [2].

5G-Crosshaul slices for multi-tenancy support.		
Verification	**WP**	**Details**
• Prototype of the XCI SBI including multiple technologies (CPRI over WDM, packet over mmWave) and the XCI NBI (capacity reconfiguration).	WP5	Final prototype of SBI for packet over mmWave, packet over Ethernet, and optical nodes. Deployment of optical WDM equipment, BBU and RRH to generate CPRI traffic. Simple NBI to set-up e2e paths. Final NBI developments: • Development of energy-management functionality for switch ON/OFF XPFEs for energy saving at XCI to be exposed to EMMA application through NBI. • Development of RMA application for FH/BH traffic reconfiguration exploiting NBI exposed by available SDN controllers • Development of TVBA application and the required XCI functionality to set up broadcast tree • Development of CDNMA application and interaction with XCI. Final SBI development: • Selection of features to be exposed through SBI in the PoC • Development of SNMP SBI plug-in for controlling Analogue RoF equipment • Mixed A/D RoF solution through fiber in Sept. • Development of SNMP SBI plug-in for collecting energy-related information. All developments have been experimentally validated and demonstrated in D5.2 [8].

Obj.3	**Unify the 5G-Crosshaul data plane**
Description	Develop a flexible frame format to allow the usage of fronthaul and backhaul on the same physical link to replace different technologies by a uniform

	transport technology for both fronthaul and backhaul.	
R&D Topics	**WP**	**Details**
• Unified but versatile cross-technology frame format supporting all types of fronthaul (e.g., CPRI) and backhaul and their different demands on the type of payload, but also bandwidth, latency and synchronization.	WP2	Frame format has been defined for packet interfaces (Mac-in-Mac main option, MPLS-TP possible alternative). TDM frame has been defined to deal with CPRI and ultra-low latency links. The details were reported in D3.2 [2]
• Support for multi-tenancy in the unified data plane. •	WP3	A detailed analysis on multi-tenancy support by chosen XCF is described in D3.2 [2].
• Design the 5G-Crosshaul Packet Forwarding Element (XFE).	WP3	Final design of XFE is described in D3.2 [2]
Verification	**WP**	**Details**
• Prototype including XFE supporting a unified frame format.	WP5	Identification of software switch flavours for XPFE development to be able to support the XCF (Lagopus and OpenvSwitch). Final prototype of XCE with XCF support over Lagopus is reported in D5.2 [8]

Obj.4	**Develop physical and link-layer technologies to support 5G requirements**	
Description	Exploit advanced physical layer technologies, not currently used in the 5G-Crosshaul network segment, as well as novel technologies, such as wireless optics, flexi-PON, etc. to increase coverage and aggregated capacity of integrated backhaul and fronthaul networks. Develop novel data plane solutions, capable of meeting the stringent latency, synchronization, and jitter requirements in all heterogeneous 5G-Crosshaul scenarios.	
R&D Topics	**WP**	**Details**

• Advanced high capacity mmWave, and disruptive wireless optical transmission.	WP2	Techniques to enable mesh BH networks and high-speed FH. Description and simulation/experimental results were described in D2.2 [9].
• Programmable optical transceivers for flexible bandwidth allocation.	WP2	The programmable optical transceivers for flexible bandwidth allocation is designed based on OFDM. Details and simulation results are included in D2.2 [9]
• Multi-building baseband pooling, dynamic cell splitting and combining, copper-based reconfigurable indoor fronthaul	WP2	Copper based-reconfigurable indoor fronthaul was identified in IR2.1. D2.2 [9] further explains how copper technologies can be used to support multi-building baseband pooling, dynamic cell splitting and combining.
• Common framing structure for radio over packet. •	WP2	A common frame format has been defined for packet interfaces (Mac-in-Mac main option, MPLS-TP possible alternative). The details were reported in D3.2 [2].
• L1 switching techniques cooperating with L2 switching to guarantee upper bounds on latency.	WP2	Multi-layer architecture has been described in D1.2 [4]. Cooperation mechanism details will be defined during the second half of the project, after the forwarding mechanisms will be specified.
• Clock recovery at edge site for packetized fronthaul.	WP2	The related techniques were addressed in D2.2 [9]
Verification	**WP**	**Details**
• Proof-of-concept prototype, testing and measurement of each individual technology.	WP5	Final experimental evaluations of technologies (wireless, fixed access, and optical) were reported in D2.2 [9] Deployment of nodes embedding the technologies studied in 5G-Crosshaul in the testbeds (mmwave and microwave). Finish evaluation of technologies and presentation of results were reported in D2.2 [9]

Obj.5	**Increase cost-effectiveness of transport technologies for ultra-dense access**

	networks	
Description	Develop techniques to enable massive and cost-effective deployment of outdoor and indoor Small Cells, facing challenges such as hostile Radio Frequency (RF) propagation environment. Develop physical layer technologies with reduced cost per bit, as well as new energy saving schemes, which further reduce operational costs.	
R&D Topics	**WP**	**Details**
• Colorless transmitters.	WP2	The colourless transmitters were mentioned in IR2.1. Technology scouting output is included in D2.1 [10].
• Silicon photonics.	WP2	Experiments on a Silicon Photonics ROADM prototype are included in IR2.3 and D2.1 [10].
• Evolve high-capacity wireless technologies (including mmWave).	WP2	The technology solutions were described in IR2.1.
• Share technology with fixed access, e.g., Next Generation Passive Optical Network (PON).	WP2	The share technology was described in IR2.1. Coexistence mechanisms will be detailed in D2.1 [10].
• Common adaptation layer for control-plane integration of heterogeneous optical, copper and wireless fronthaul/backhaul.	WP2	The common adaptation layers were described in IR2.1.
• Indoor fronthaul solutions utilizing copper cable infrastructures.	WP2	The proposed fronthaul solutions were described in IR2.1.
Verification	**WP**	**Details**

• Techno-economic study.	WP1	The final version of a cost model for CAPEX and OPEX in order to numerically evaluate the Total Cost of Ownership (TCO) of the solutions envisaged by the Project was proposed in D1.2 [4].
• Energy-consumption measurements on prototypes.	WP5	Development of energy monitoring functions in mmwave mesh nodes. Lab tests for energy monitoring functions at XCI. Energy measurements in Analogue RoF. All experimental results have been presented in D5.2 [8].

Obj.6	**Design scalable algorithms for efficient 5G-Crosshaul resource orchestration**	
Description	Develop and evaluate management and control algorithms on top of the XCI NBI that ensure top-notch service delivery and optimal 5G-Crosshaul resource utilization, despite dynamically changing traffic loads, wireless link fluctuations, flexible functional RAN splits and both diverse and strict QoS requirements. The algorithms should be scalable in order to handle ultra-dense RAN requirements.	
R&D Topics	**WP**	**Details**
• Scalable orchestration algorithms for dynamic joint optimization of RAN policies (e.g., scheduling/shaping scheme, handover policies), routing and RAN/5G-Crosshaul function placement.	WP4	The Resource Management Application (RMA) and the Energy Management and Monitoring Application (EMMA), are designed for a joint optimization of routing, function placement and even suggesting the RAN parameters. The design of these applications and final evaluation results are described in D4.2 [3].
• Novel 5G-capable routing and traffic engineering algorithms considering inputs such as latency and jitter	WP4	The RMA, EMMA, and Mobility Management Application (MMA), focus on routing and traffic engineering algorithms considering inputs such as latency and jitter (across heterogeneous links),

(across heterogeneous links), RAN and wireless transport interference, user mobility, or RAN measurements.		RAN and wireless transport interference, user mobility, or RAN measurements. The design of these applications, detailed algorithms and final evaluation was reported in D4.2 [3]
• Techniques for path provisioning and handover for multi-Gbps multi-operator ultra-mobile (up to 300 km/h) hotspots backhauled via multiple base stations concurrently.	WP4	MMA is designed for optimizing mobility for high-speed train scenario while the RMA takes care of path provisioning. The definition of MMA and RMA, their algorithms and evaluation results were presented in D4.2 [3].
Verification	**WP**	**Details**
• Simulative proof of scalability and throughput performance of resource management algorithms based on real operator's backhaul network data.	WP4	Evaluation of resource management algorithms has been done via simulations in D4.2 [3]
• Prototype of at least one algorithm on top of real XFE test network.	WP5	Development of energy management functionality at XCI and EMMA application is finalized, as well as the energy management policies have been integrated in the EMMA application. Development of RMA application for FH/BH traffic reconfiguration is finalized. Development of TVBA application and required XCI functionality to set up broadcast tree. Development of CDNMA application and interaction with XCI. Lab tests of vCDN node deployment on top of which CDNMA algorithms is used. All experimental and validation results are reported in D5.2 [8].

<table>
<tr><th>Obj.7</th><th colspan="2">Design essential 5G-Crosshaul-integrated (control/planning) applications</th></tr>
<tr><td>Description</td><td colspan="2">Develop an ecosystem of most essential XCI NBI applications, both to support (prediction, planning, monitoring) and to exploit (media distribution, energy management) the 5G-Crosshaul resource orchestration functions.</td></tr>
<tr><th>R&D Topics</th><th>WP</th><th>Details</th></tr>
<tr><td>• Novel capacity-minimization and Quality of Experience (QoE) optimization techniques for wide-area media broadcast and multicast such as adaptive (in-network) video transcoding, optimization of Single Frequency Networks and congestion-aware caching.</td><td>WP4</td><td>The TV Broadcasting Application (TVBA) and the Content Delivery Network Management Application (CDNMA) are designed for broadcast and deliver video content focusing on optimizing the capacity usage and QoE. The definition of TVBA and CDNMA, their algorithms and their evaluation has been reported in D4.2 [3].</td></tr>
<tr><td>• Energy Manager (controlling optimal scheduling of equipment sleep cycles, routing parameters and function placement, and energy harvesting).</td><td>WP4</td><td>The definition of EMMA, its algorithms and its evaluation has been reported in D4.2 [3]</td></tr>
<tr><td>• Techniques for end-to-end monitoring, prediction and enforcement of QoS parameters (such as latency, loss, jitter, bitrate) across heterogeneous 5G-Crosshaul technologies.</td><td>WP4</td><td>EMMA also takes care of monitoring of energy related parameters. MTA takes care of monitoring of network QoS per tenant. The low-level monitoring of network statistics is taken care by the XCI, described in D3.2 [2].</td></tr>
<tr><td>• Algorithms for planning and dimensioning the overall 5G-Crosshaul hardware infrastructure (split RAN, cloud nodes, switches, routers, links) based on</td><td>WP4</td><td>RMA can be also used as an offline planning tool to plan base station function placement options at RRH/BBUs, as well as to dimension required cloud and networking resources for different regions of heterogonous traffic demand and different services. The definition of RMA, its</td></tr>
</table>

realistic performance and cost KPIs.		algorithms and evaluation via simulations is reported in D4.2 [3]
Verification	**WP**	**Details**
• Prototype of software for 5G-Crosshaul infrastructure planning.	WP5	Development of RMA application is finalized. For given resources (topology, RRHs, BBUs), it chooses the most appropriate functional splits and RRHs and BBUs out of all available in the network to fulfil requirements.
• Simulative analysis of the Energy Manager.	WP4	EMMA has been evaluated via simulations in D4.2 [3]
• Demonstrator for "Broadcast as a Service" system.	WP5	Development of TVBA application and required modifications at XCI is finalized. Final lab test of network control system supported by OpenVSwitch.

Obj.8	**5G-Crosshaul key concept validation and proof of concept**	
Description	Demonstration and validation of 5G-Crosshaul technology components developed in WP2, WP3 and WP4, which will be integrated into a software-defined flexible and reconfigurable 5G testbed in Berlin. Mobility related 5G-Crosshaul experiments will be performed by ITRI using Taiwan's high-speed trains.	
Verification	**WP**	**Details**

• Experiments in a cellular setup with up to 9 macro Evolved NodeBs (eNBs) and 20 Small Cells located in an urban macro environment in the center of Berlin operating in available IMT bands below 6 GHz. It will serve as demonstration platform for 5G-Crosshaul technologies including optical fiber, Free Space Optical (FSO), mmWave and microwave links.	WP5	Final setup of experimental frameworks, including 5GBerlin, was presented in D5.2 [8].
• Experiments with mobile backhaul for moving Small Cells in 12-coach trains along a 400 km high speed (300 km/h) rail track.	WP5	Final setup of the high-speed train experimental framework was presented in D5.2 [8]

4.2.Explanation of the work carried per WP

4.2.1. WP1: System Requirements, Scenarios and Economic Analysis

WP1 contributed to the satisfaction of the following objectives:

- Objective 1: design of an SDN architecture that can cope with multiple types of agents. In particular WP1 designed the system Architecture Design Task

- Objective 3: CAPEX and OPEX savings. WP1 demonstrated that CAPEX and OPEX savings due to unified data plane are about 25% and to multi-tenancy up to 80%. The studies furthermore demonstrated that in the metro segments the unified control plane introduce a CAPEX/OPEX savings of from 25 to 30 %. Finally, about the multi-tenancy, the yearly CAPEX (i.e. the CAPEX / amortment time) the saving is about 70%, while the OPEX saving is about 72

- Objective 5: TCO and energy. The reduction of the Total Cost of Ownership (TCO) due to the optical transmission and the sharing of mobile/fixed access is about 65% in the access segment, while in the metro one from 25 to 30%.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 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 more than 90% (1/10) w.r.t. W per bit/s.

Finally, WP1 demonstrated that indoor solutions based on LTE backhauling guarantees a saving between 505 and 60 % w.r.t. WiFi based.

The main activities carried out in the second part (last 18 months) of the Project lifetime have been:

- Consolidation of the overall system design (mainly developed by IDCC and UC3M), providening an anrchitecture following the SDN principles
    - data and control plane are fully decoupled;
    - control is logically centralized
    - applications have an abstracted view of resources and states.

Completion of the economic analysis, including studies about energy consumption (mainly developed by the network operators: TIM, TID and ORANGE) with the contribution of NOK and TEI as input data for the cost model. In particular Orange took care of last-mile analysis, TID provided an economical comparison of different topologies and TIM provided a study on a realistic metropolitan network.

In the following we present the main achievements in the second period of the project lifetime.

4.2.1.1.Task 1.1 - Use cases and Requirements

Task 1.1 finished after 7 months since the beginning of the project (31st January 2016). Its work and achievements are out of scope of this document that describes the project progresses from 1st July 2016 to 31st December 2017.

Involved Partners: UC3M, NEC, EAB, ATOS, NOK-N, TI, ORANGE, VISIONA, EBlink, NXW, TELNET, FhG-HHI, CTTC, ULUND, ITRI

4.2.1.2.Task 1.2 - 5G-Crosshaul System Design

In the second reporting period T1.2 updated and completed all the work about the system design reported in D1.1 [11] (delivered at the end of the first reporting period), and all subsequent extensions and amendments performed as a response to the feedback received from other Work Packages, namely WP2, WP3 and WP4, and as a result of the experience gained when developing the prototypes and proof-of-concept systems are reflected in this consolidated design.

The key technical achievements are summarized as follows:

- A consolidated design of the overall system, spanning data, control and applications plane, and including all interfaces across planes and between 5G-Crosshaul and neighbouring domains (5G Core and 5G Radio Access Network);
- Amendments and extensions to the system architecture to support multi-tenancy through network slicing, multi-domain and multi-technology, and orchestration of Crosshaul slices from federated administrative domains;
- Detailed analysis of key building blocks conforming 5G-Croshaul:

- **Data Plane**. The consolidated design of 5G-Crosshaul's multi-layer switch, the Crosshaul Forwarding Element or XFE, including the packet-based forwarding elements or XPFEs and circuit-based switchting elements or XCSEs is presented. In addition, the design of the 5G-Crosshaul Common Frame (XCF), a key enabler of the fronthaul/backhaul convergence targeted within this project is shown;
- **Control Plane**. 5G-Crosshaul Control Infractucture (XCI), including the interfaces towards the data plane (Southbound Interface) and the applications plane (Northbound Interface). The consolidated design of XCI's MANagement and Orchestration (MANO) components and APIs are also shown;
- **Applications Plane**. It includes Multi-Tenancy Application (MTA), Mobility Management Application (MMA), Resource Management Application (RMA), Energy Management and Monitoring Application (EMMA), CDN Management Application (CDNMA), and TV Broadcast Application (TVBA).

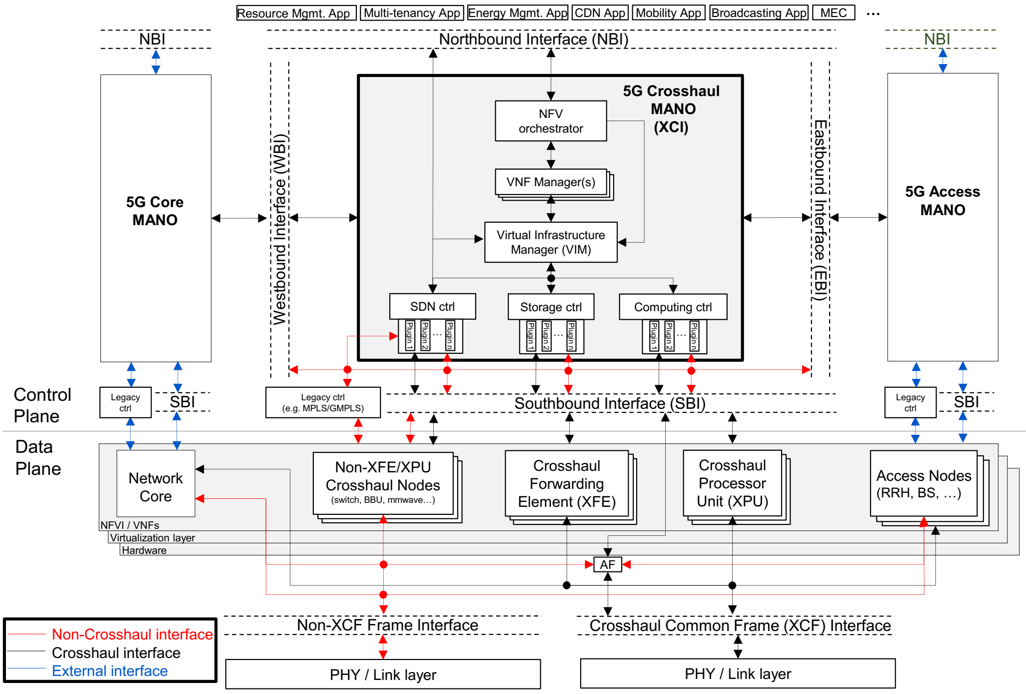

Figure 4: 5G-Crosshaul Baseline Architecture

Figure 4 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.

The **data plane** 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.

The **control plane**, in turn, 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), leveraging on the SDN principles to have a unified control, management and configuration of the 5G multi-technology transport network, and applying NFV to the 5G-Crosshaul infrastructure to enable 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.

To achieve such a design, our approach is to leverage the state-of-the-art SDN and NFV architectures to maximize the compatibility and integration of 5G-Crosshaul system design with the existing standard frameworks and reference specifications. So far, the most well-developed open source SDN controllers which provide carrier grade features and can be used for 5G networks are: Open Daylight (ODL) and Open Network Operating System (ONOS). 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. Furthermore, the task 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 5G-Crosshaul domains.

Control Plane

As illustrated in Figure 4 we divide the control plane into two clearly differentiated layers: a top layer for external applications and the XCI below. An ecosystem of applications at the topmost part of the system architecture exploits 5G-Crosshaul resource orchestration functions to support the most diverse functionalities such as planning, network and service monitoring/prediction, optimization of resources, energy management, multi-tenancy, media distribution such as content delivery networks and TV Broadcasting, etc. In turn, the XCI is our 5G transport Management and Orchestration (MANO) platform that provides control and management functions to operate all available types of resources (networking and cloud).

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

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

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

The XCI is the brain controlling the overall operation of the 5G-Crosshaul. 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):

- 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 (via Computing *ctrl*), storage (via Storage *ctrl*) and network resources (via SDN *ctrl*).

In addition to these modules, which are in charge of managing the different VNFs running on top of the 5G-Crosshaul, the XCI includes 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 aims at extending 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.
- 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.

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 consider the utilization of legacy network controllers (e.g. MPLS/GMPLS) to ensure backward-compatibility for legacy equipment

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[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/

Data plane

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

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

A complete view of the architecture of 5G-Crosshaul data path is reported in Figure 5.

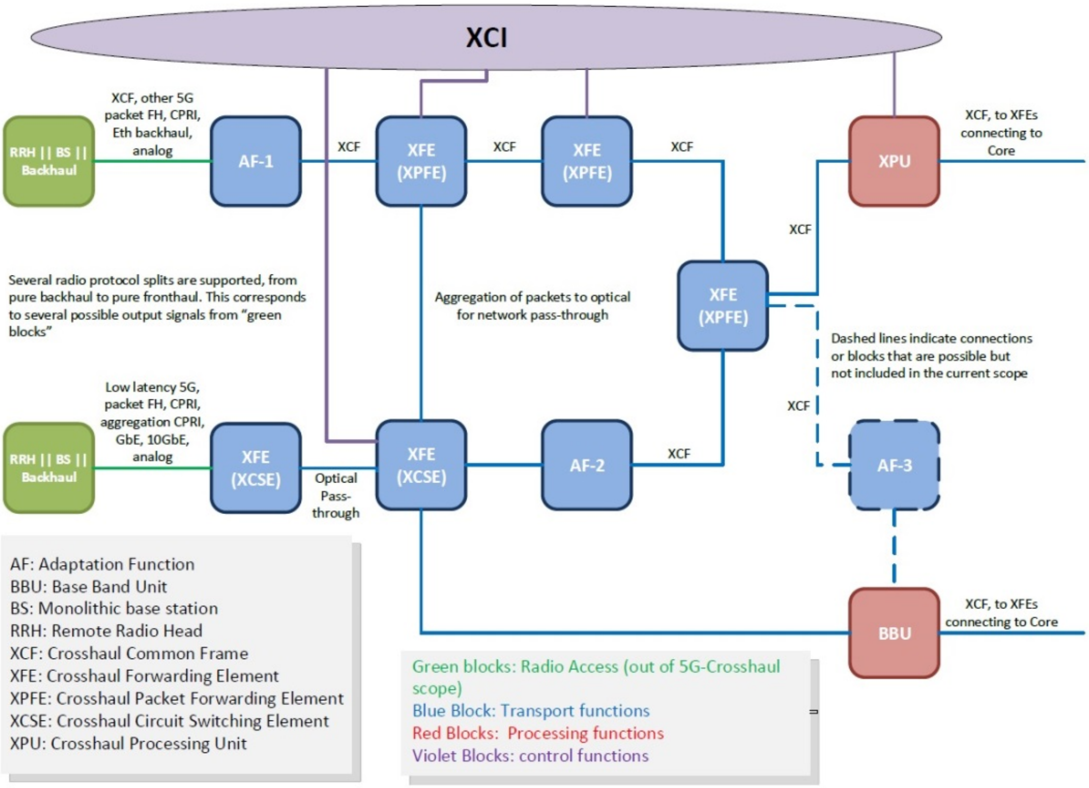


Figure 5: 5G-Crosshaul Data Path Architecture

Interfaces

As mentioned above, an ecosystem of applications sits on top of the XCI to provide tools for optimization, prediction, energy management, multi-tenancy and others. The XCI is the means to achieve the application goals and the NBI (typically based on REST, NETCONF or RESTCONF APIs) that interconnect both lands. The configuration of network resources (e.g., routing), computing resources (e.g., instantiation of VNFs) and storage resources (e.g., CDN caches) is directly executed on each of the required data plane elements by the XCI by means of the SBI. Candidates for SBI are, e.g., OpenFlow, OF-Config, OVSDB (Open vSwitch, Database), SNMP, and/or an ecosystem of several of them.

Multi-domain and multi-technology

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

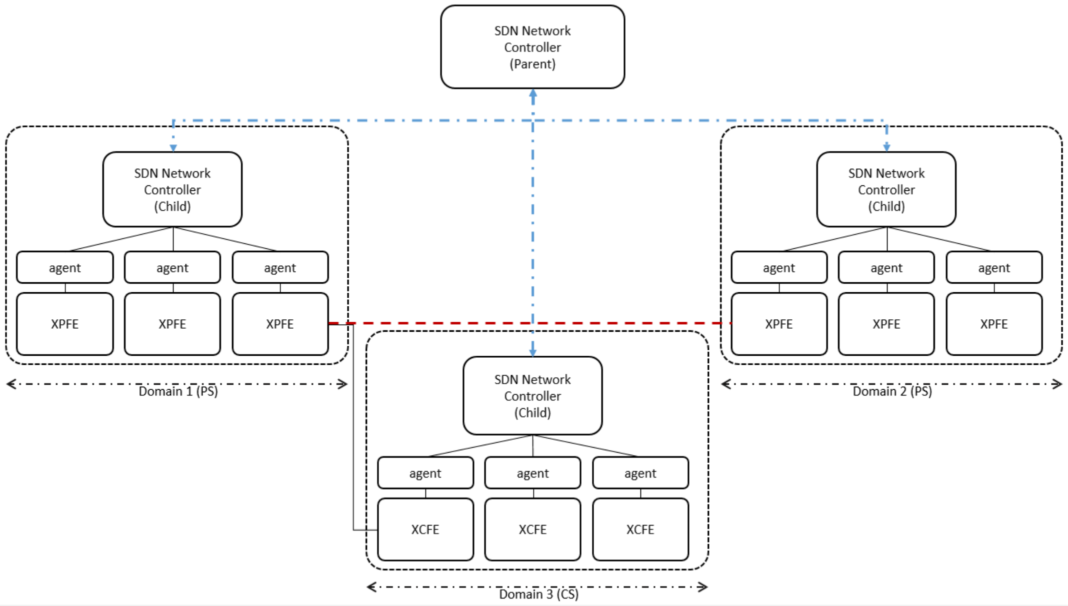


Figure 6: SDN-based hierarchical orchestration and control of multi-domain/multi-layer networks

The approach taken by 5G-Crosshaul is to focus on a deployment model in which a (possibly redundant, high-available) SDN controller is deployed for a given technology domain, while the whole system is orchestrated by a "parent" controller, relying on the main concept of network abstraction (see Figure 6). For example, the parent controller may be responsible for the selection of domains to be traversed for a new provisioned service.

It is essential to note that a given 5G-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. In other terms, service layers are realized via a hierarchy of network layers and arranged based on the switching capabilities of network elements, as depicted in Figure 7.

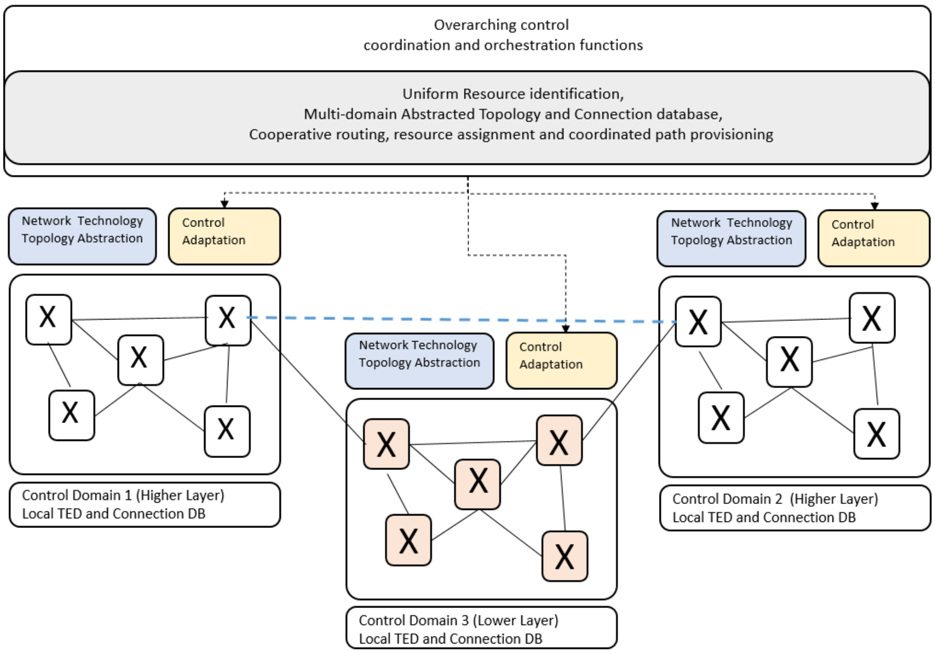


Figure 7: Over-arching control function mapping and adaptation

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—reducing both the capital (CAPEX) and operational (OPEX) expenditures—and to reduce energy consumption, which are essential goals of 5G. 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.**

The final target is to enable “Slicing as a Service” addressing the dynamic allocation of slices over a shared 5G-Crosshaul, 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.

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

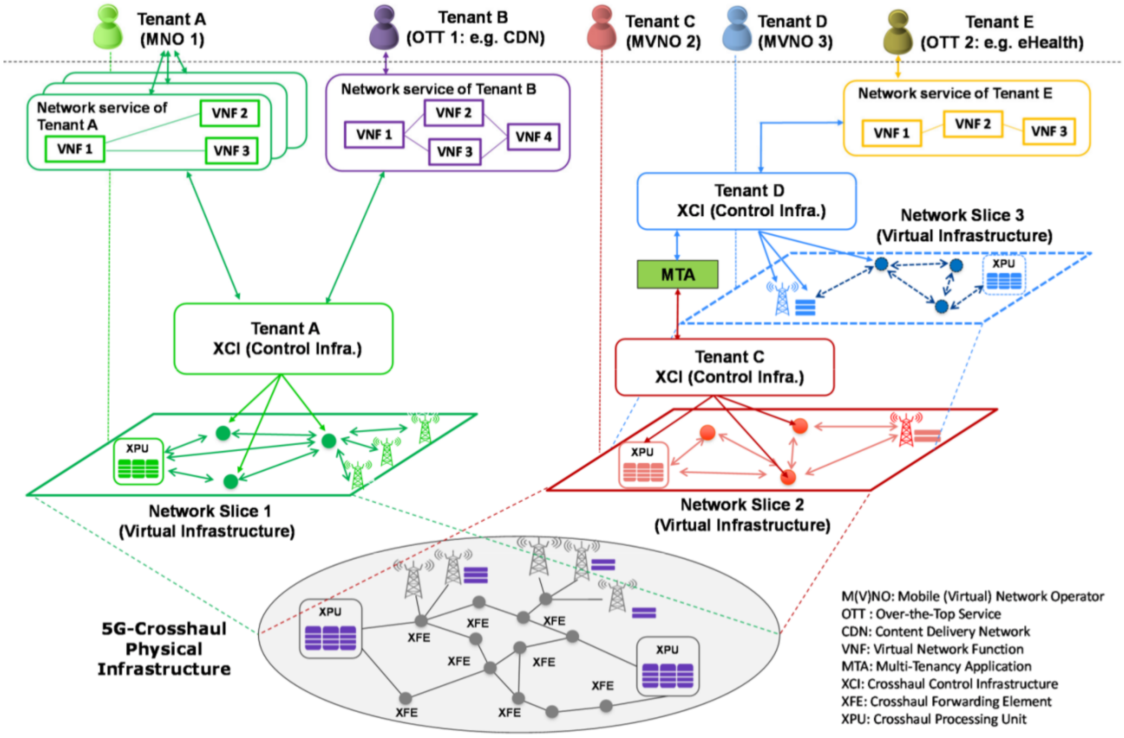


Figure 8: Network slicing in 5G-Crosshaul for multi-tenancy support.

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 offer 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.

Orchestration of 5G-Crosshaul Slices from Federated Administrative Domains

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

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

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.

Then two possible multi-domain cases can be taken into consideration: (i) composition of administratively separated 5G-Crosshaul domains, and (ii) composition of end-to-end administratively separated domains (including Core Network, 5G-Crosshaul and Radio Access Network –RAN–).

In any case, there is yet a gap to reach the goal of hosting 5G-Crosshaul in a multi-domain federated infrastructure: a market place where networking and computing facilities are traded. An extension of the traditional concept of telco exchange is needed, covering new needs and capabilities, such as offering resource slices for deployment of the services requested by third party service providers.

Involved Partners: UC3M, EAB, TEI, ATOS, TID, TI, ORANGE, VISIONA, EBlink, NXW, FhG-HHI, CTTC, ITRI

4.2.1.3.Task 1.3 -Techno-Economic Analysis

Task 1.3 provided evaluations in terms of the overall cost of the solutions (TCO, Total cost of ownership, comprehensive of CAPEX and OPEX) and the network energy consumption.

In order to provide final results, necessary to demonstrate the affordability and the sustainability of 5G-crosshaul solutions, it has been necessary a long jointly work among the network Operators inside the Consortium for defining the reference cost of single elements (switches, ROADM, fibre…) both 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 of writing this document, 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.

After defining these figures, an evaluation process in order to calculate the total cost of ownership and the energy consumption begun.

Three levels of evaluations have been provided:

- cost evaluation of fixed access network
- dimensioning and technical-economic analysis of a theoretical 5G-Crosshaul scenario
- design and cost/energy evaluation of metropolitan network

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.

Fiber to the antenna site (FTTA) deployment cost

The deployment costs of a fibre 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. 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 fibre 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 fibre cable. The following figure presents the maps for the proposed infrastructure deployment scenarios. We consider that each antenna site required a single 12 fibres cable. The topology used for the cost estimation is based on a P2P topology, as depicted in Figure 9.

Figure 9: Map of fibre infrastructure deployment plan in function of ISD: a) 1km/27 antenna sites, b) 500m/36 antenna sites, and c) 250m/72 antenna sites

Table 12 presents the 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 fibre 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 fibre infrastructure.

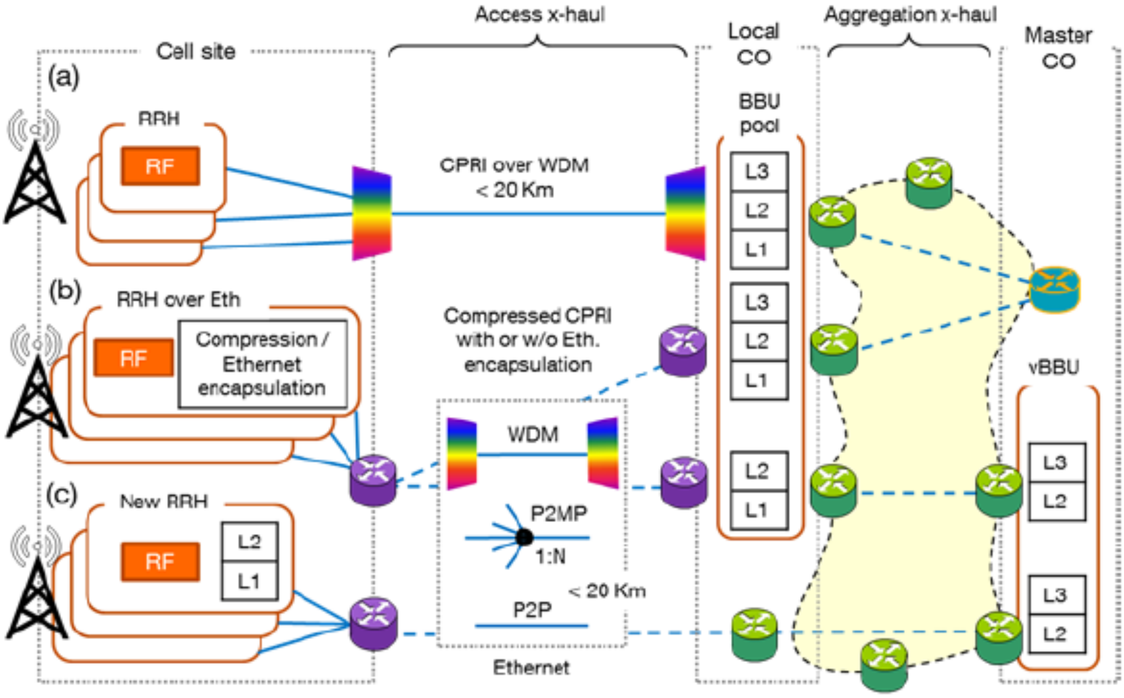
Table 12: CapEx cost estimation of fibre infrastructure to reach antenna site for three scenarios

	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%

Optical system deployment cost

Now that we have analysed the cost of the deployment of an optical fibre 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 below) which are: a) low layer RAN split (CPRI) over

WDM, b) Ethernet (or OTN) equipment which achieve encapsulation 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 10).



Color code for network elements:
Blue : Gateway to core IP
Green : Network node
Purple : Low-latency access equipment supporting Ethernet and/or WDM and/or TDM(A) with statistical multiplexing

OLT: Optical line termination
ONU: Optical network unit
vBBU: Virtual broadband unit
TDMA: Time-domain multiple access
CO: central office

Figure 10: Fiber deployment solutions

We propose to focus on 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). 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 13.

Table 13: Cost 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**

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). In addition, it is worth noticing that both the passive and active solution are very similar in CapEx costs. Nevertheless, a passive solution has the benefit to also reduce the OpEx due to the absence of power consumption.

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

The aim of this work 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 study is to evaluate 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.

CapEx and Opex 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 fibre 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

On the other hand, the applicable OpEx for network deployment is evaluated according to the following calculation.

$$\boldsymbol{OpEx}$$

$$\left.\begin{aligned}
&= number\ of\ devices\ \times rack\ space\ (m^2) \times \frac{yearly\ rent}{m^2}\\
&+ number\ of\ devices \times \frac{yearly\ consumption}{device(in\ kW)} \times \frac{cost_{kW}}{year}
\end{aligned}\right\}\ \text{continuous cost of infrastructure}$$

$$\left.\begin{aligned}
&+ number\ of\ shifts \times \frac{\frac{hours}{shift}}{year} \times \frac{wage}{hour}\\
&+ number\ of\ hardware\ failures\\
&\times \left[distance\ to\ failure\ (in\ km)\ \times \frac{cost}{km}\right.\\
&+ time\ to\ reach\ the\ failure\ location\ (in\ hour) \times \frac{wage}{hour}\\
&\left.+ time\ to\ fix\ the\ failure \times \frac{wage}{hour} + hardware\ replacement\ cost\right]\\
&+ number\ of\ software\ failures\\
&\times \left[average\ time\ to\ fix\ a\ software\ failure\ (in\ hour) \times \frac{wage}{hour}\right]
\end{aligned}\right\}\ \text{maintenance and repair}$$

$$\left.\begin{aligned}
&+ \frac{number\ of\ connections\ to\ be\ configured}{year}\\
&\times \left[configuration\ time\ per\ connection\ (in\ hour) \times \frac{wage}{hour}\right.\\
&\left.+ documentation\ time\ per\ connection\ (in\ hour) \times \frac{wage}{hour}\right]
\end{aligned}\right\}\ \text{service provisioning}$$

$$\left.\begin{aligned}
&+ \frac{number\ of\ connections\ to\ be\ reconfigured}{year}\\
&\times \left[configuration\ time\ per\ connection\ (in\ hour)\ x \frac{wage}{hour}\right.\\
&+ documentation\ time\ per\ connection\ (in\ hour)
\end{aligned}\right\}\ \text{service management}$$

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 14.

Table 14: 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 15, the summary of the economic analysis shows that the principal costs correspond to the optical fibre deployment, as expected, following the OpEx and the centralized hardware (equipment of centralization to processing, switching & routing).

Table 15: 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 11) allows seeing the considerable differences among each sub-section in the network deployment.

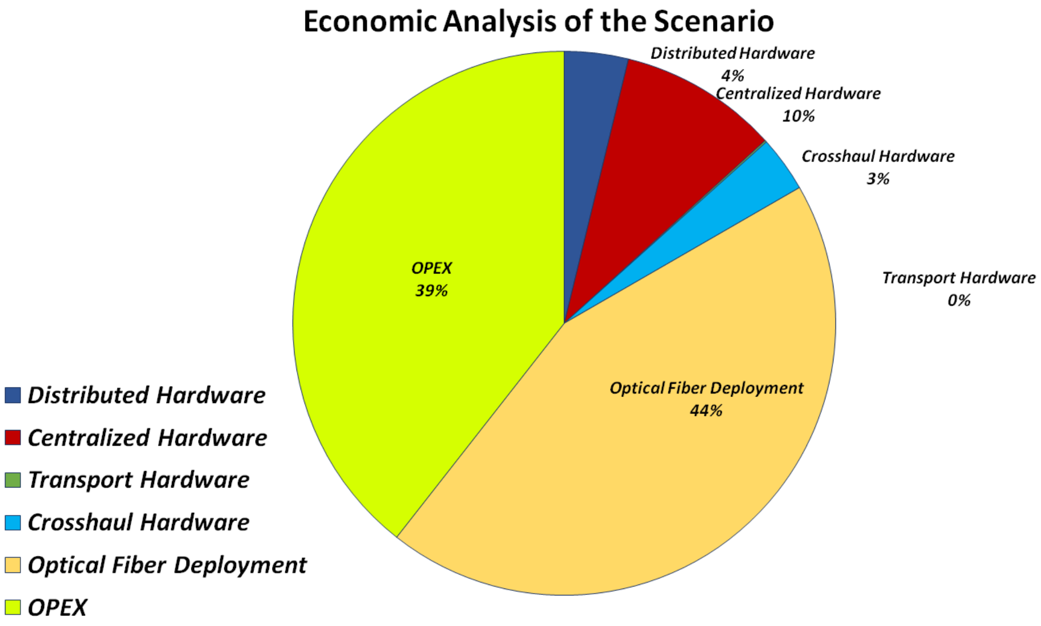


Figure 11: Cost distribution

Regarding the topology comparison, the principal difference remains in the distances to address in each case, i.e. the kilometres of optical fibre to deploy. In

Figure *12* shows 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.

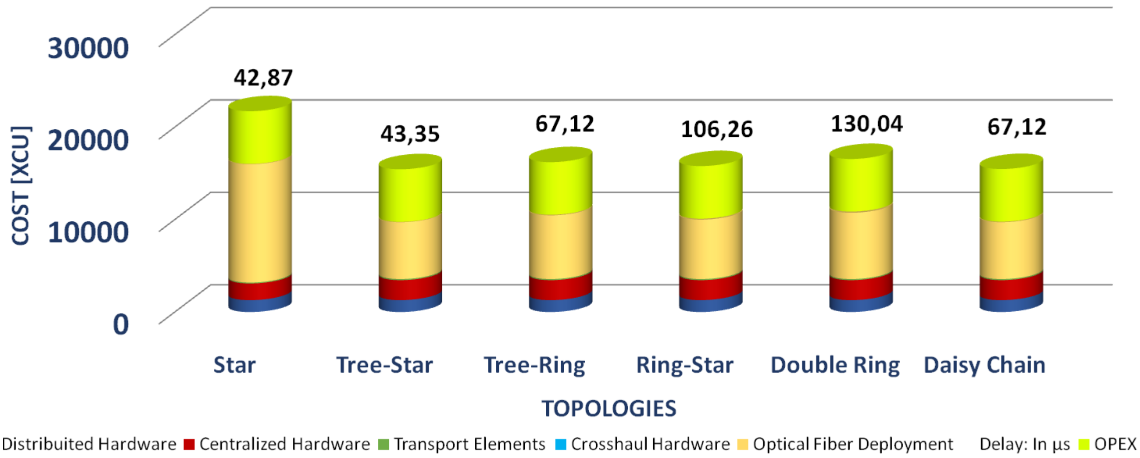


Figure 12: Tech/Cost comparison in different topologies

As it is easily appreciable, the most of cost output parameters are unalterable by the topology switching with the exception of the fibre 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), 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.

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.

Cost/energy evaluation of metropolitan network

Although the previous studies consider 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.

Legacy – 5G-Crosshaul comparison

In Table 16 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, fibres, 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 16: 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 17: 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 that would allow further energy savings.

Evaluations for multi-tenancy

The conclusion of this study is that, for a realistic network, carrying realistic traffic projected to 2025 forecasts is summarizing in Table 18. Considering the yearly CapEx (i.e. the CapEx / amortment 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 18 : 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**

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%.

Small cells

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: 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.

Small-cells and legacy network

In this paragraph, the scenario showed in Figure 13 is analysed. 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.

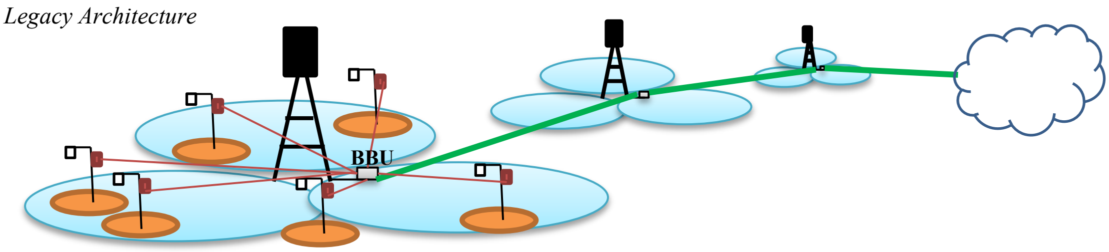


Figure 13: Architecture with BBU at the bottom of each RRH

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 fibres and that can guarantee high backhaul performances relying on massive fibre deployment.

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

In the following they are shown some graphs that compare different costs solutions of small-cell installation. First of all, it is proposed a comparison between a macro and a small-cell deployment with different backhauling technologies, i.e. wireless and wireline as in Figure 14.

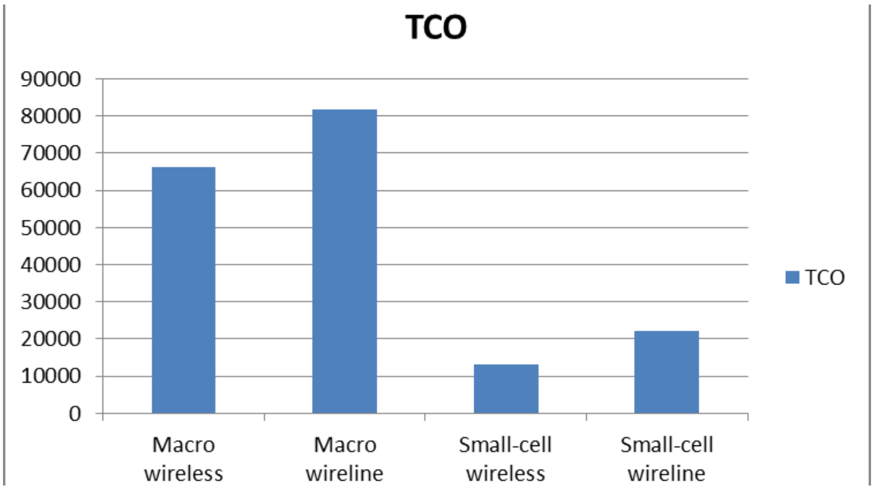


Figure 14: Comparison of costs deployment for macro and small cell

It is evident that wireline solutions are more expensive than wireless ones, considering that OpEx are significantly higher because of fibre 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 15) and considering also the normalized value per Gbit/s (Figure 16).

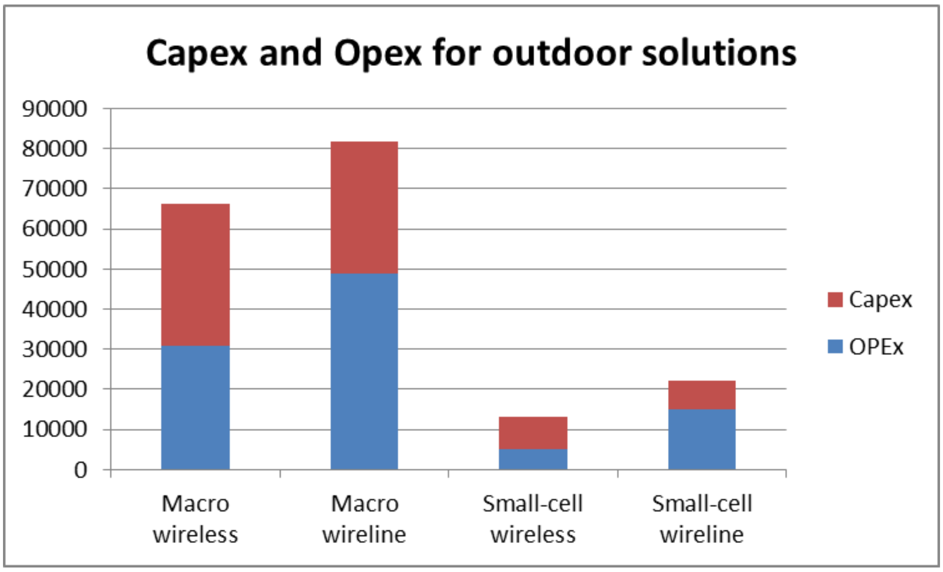


Figure 15: CapEx and OpEx for outdoor solutions

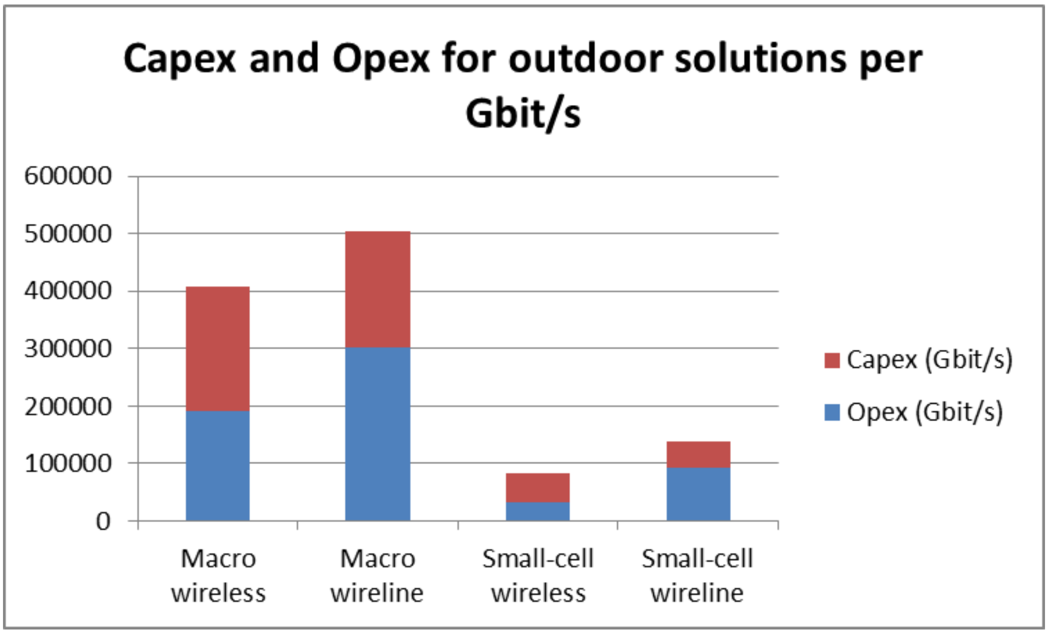


Figure 16: CapEx and OpEx per Gbit/s for outdoor solutions

It is interesting to analyse the results in Figure 17 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 it is already installed a macro cell, 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 17. Being equal the advantage introduced in terms of coverage, the solution with prevalent wireless backhaul is preferable in terms of costs.

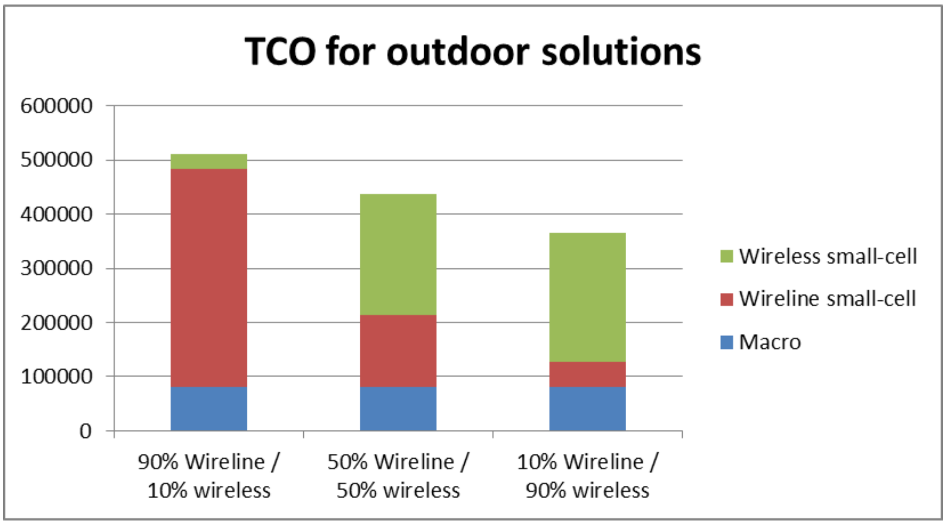


Figure 17: Comparison of costs for different backhauling deployment considering 20 installed small-cells

For the indoor case, the proposed analysis is similar to the outdoor case.

In Figure 18 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.

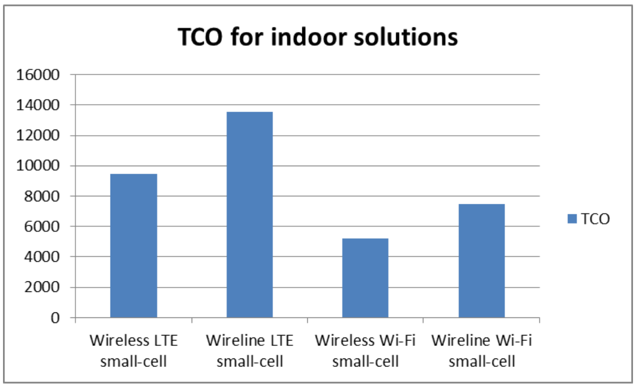


Figure 18: Comparison of costs deployment for LTE and Wi-Fi small cell

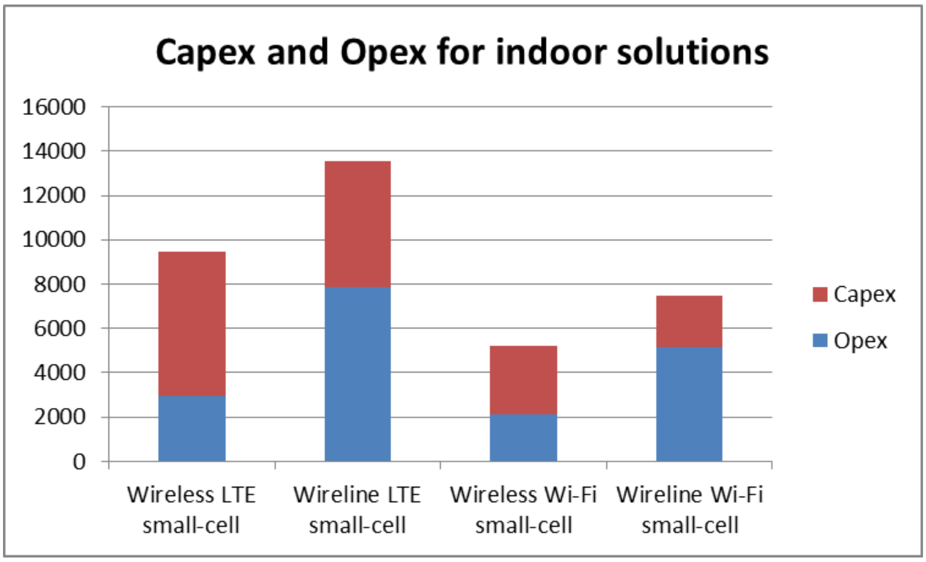


Figure 19: CapEx and OpEx for indoor solutions

In Figure 19 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 20 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 costliest.

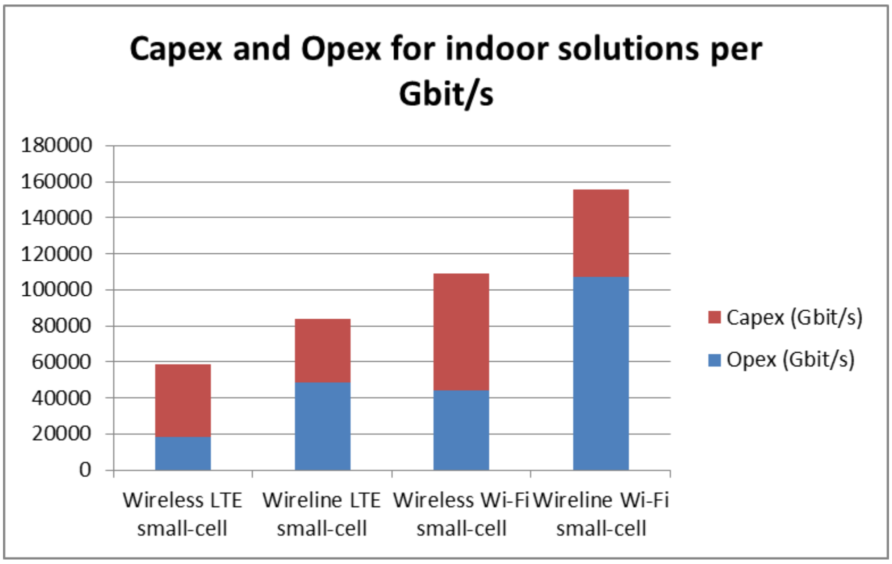


Figure 20: CapEx and OpEx per Gbit/s for indoor solutions

In fact, considering extending indoor bandwidth capacity at 3.4 Gbit/s, it is possible to deploy different solutions: in Figure 21 it is shown a comparison between the use of

LTE small-cells and Wi-Fi small-cells. The considered scenarios are four: 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.

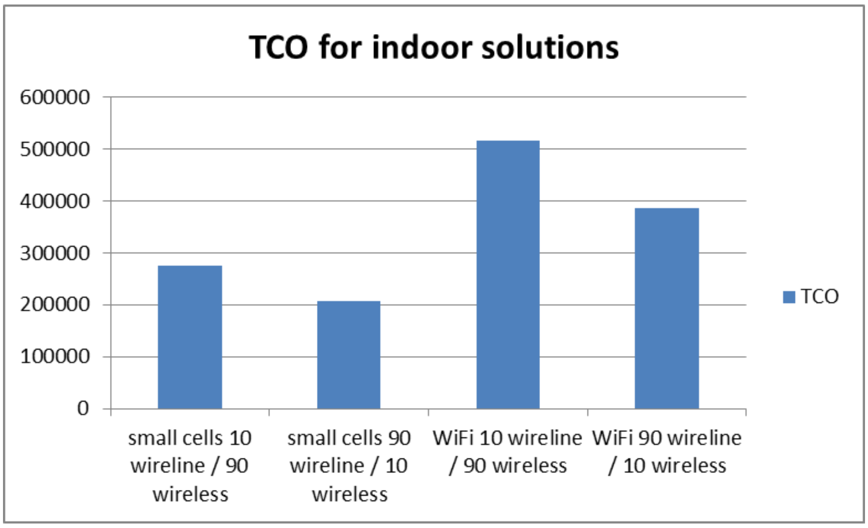


Figure 21: Comparison of costs for different technology for indoor small-cells

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 21 it is clear that Wi-Fi is not the best solution for the indoor coverage when high bandwidth capacity is required.

Small cells and 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 22. Fronthauling signals coming from antennas are collected in an aggregator and then sent to an Ethernet switch before to reach the BBU site.

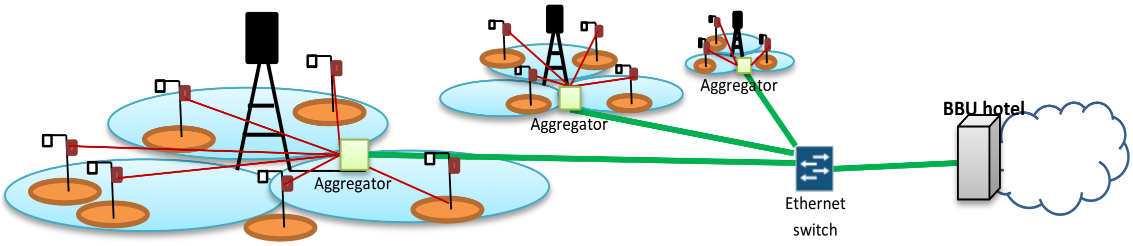


Figure 22: Architecture with BBU pooling

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.

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 the following, in Figure 23, 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 17).

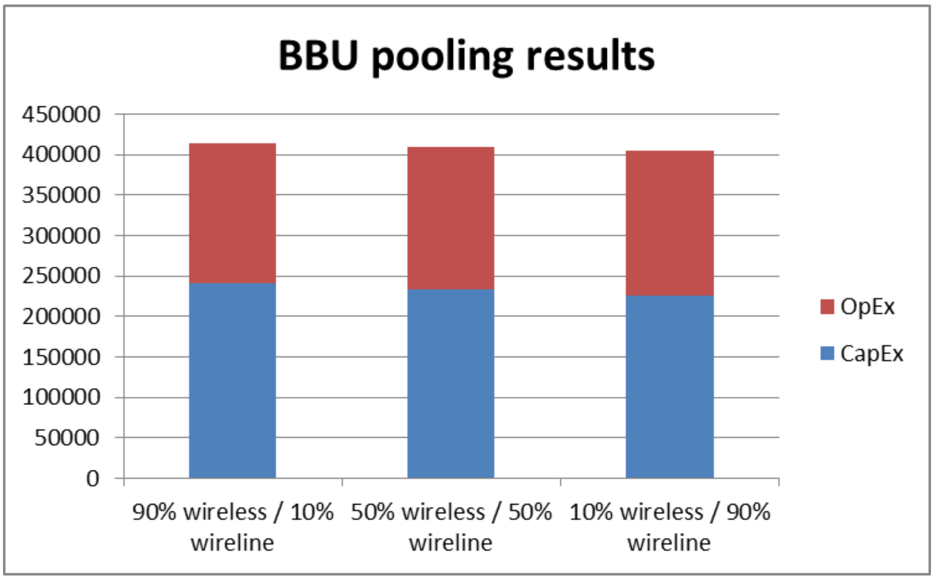


Figure 23: CapEx and OpEx for BBU pooling (outdoor) solutions

Involved Partners: UC3M, TEI, TID, FhG-HHI, ITRI

4.2.1.4.Deviations

None detected

4.2.1.5.Corrective actions

None required.

4.2.2. WP2: Physical and link layer of 5G-Crosshaul

WP2 contributed to the following key objective defined for the project.

- Objective 2: Specify the XCI's northbound (NBI) and southbound (SBI) interfaces. Define interfaces to accelerate the integration of new physical technologies (SBI) and the introduction of new services (NBI) via novel or extended interfaces.
- Objective 3: Unify the Xhaul data plane. Develop a flexible frame format to allow the usage of fronthaul and backhaul on the same physical link to replace different technologies by a uniform transport technology for both fronthaul and backhaul.
- Objective 4: Develop physical and link-layer technologies to support 5G requirements. Exploit advanced physical layer technologies, not currently used in the Xhaul network segment, as well as novel technologies, such as wireless optics, flexi-PON, etc. to increase coverage and aggregated capacity of integrated backhaul and fronthaul networks. Develop novel data plane solutions, capable of meeting the stringent latency, synchronization, and jitter requirements in all heterogeneous Xhaul scenarios.
- Objective 5: Increase cost-effectiveness of transport technologies for ultra-dense access networks. Develop techniques to enable massive and cost-effective

deployment of outdoor and indoor Small Cells, facing challenges such as hostile Radio Frequency (RF) propagation environment. Develop physical layer technologies with reduced cost per bit, as well as new energy saving schemes, which further reduce operational costs.

Throughout the reporting period WP2 worked primarily in the following topics.

- Define the transport requirements in terms of bandwidth and latency for the relevant use cases defined in WP1 corresponding to all the radio split options [UC3M, EAB,TEI, IDCC, TI, ORANGE, TELNET, FhG-HHI, CTTC, ULUND, EBLINK, ITRI]
- Provide a network analysis by simulation and/or experiments of the data-plane technology assessed in the WP2 for the relevant use cases and corresponding radio split options in order to understand which technology can meet the 5G requirements. [UC3M, EAB,TEI, IDCC, TI, ORANGE, TELNET, FhG-HHI, CTTC, ULUND, EBLINK, ITRI]
- Analyse the statistical multiplexing feasibility and gain of the multilayer node for XCSE and XPFE for low latency radio split functions.[UC3M, TEI]
- Advanced compression schemes for fronthaul, allowing the reuse of the copper access infrastructure, as enabler for massive deployment of indoor small cell; [EAB]
- Prototype of silicon photonic integrated reconfigurable optical add drop multiplexer, providing optical 5G-Crosshaul networks with enhanced flexibility, at dramatically reduced cost compared to current solutions; [TEI]
- SDN enabled mesh mmWave networks, as an enabler for indoor small cells and frequency reuse with wireless transport technologies [CTTC, IDCC];
- Prototype of time-deterministic multi-layer switch based on a protocol agnostic framing protocol, capable to arbitrarily multiplex backhaul and fronthaul client signals on the same optical channel; [TEI]
- Highly spectrally efficient fronthaul schemes, based on Hybrid Analogue-Digital Radio over Fibre over WDM optical networks.[EBLINK, ITRI]
- Work on the node and network analysis has been done in collaboration with WP1 the provided the relevant use cases and requirements for 5G, while the work related to the XFE and SBI has been carried out in tight collaboration with WP3. Most of the relevant results have been verified in the demo of WP5.

In the following we report on the different tasks composing this WP:

4.2.2.1.Task 2.1 – Technology Assessment and Evolution toward 5G-Crosshaul

This task ended in June of 2016 and is out of the scope of this reporting period.

4.2.2.2.Task 2.2 -- Technology integration and network architecture

The work has been carried out in tight collaboration with WP1, WP3, WP5. This task is mainly concern on the analysis if key technologies and how do they integrate in the overall architecture. The task, during the reporting period, has been focused on two elements:

- Network scenarios analysis for 5G use case support
- Multi-layer node analysis: 5G Crosshaul multiplexing and switching

In the following we Deep dive on each of these elements.

Network scenarios analysis for 5G use case support.

The main objective of this activity is to combine the technology analysed in the first period of the activity in a network context that represent the relevant scenarios. Four relevant scenarios have been considered namely i) very dense deployment of indoor and outdoor small cells (EAB, IDCC, Orange, EB-LINK, HHI, CTCC, ULUND, ITRI), ii) WDMPON-based network (UC3M, TELNET, ORANGE, CTCC) , iii) multi-layer packet-optical networks (TEI, UC3M, Nokia, TI, TID), and iv) virtualized RAN based network (ORANGE). Such scenarios have been analysed for the relevant use cases defined in WP1, namely i) high-speed train and vehicle safety, ii) media distribution, iii) dense urban society, and iv) mobile edge computing which require up to 10 Gbit/s peak rates. Initially all partners involved in the WP2 (UC3M, EAB,TEI, IDCC, TI, ORANGE, TELNET, FhG-HHI, CTTC, ULUND, EBLINK, ITRI)) worked to identify transport requirements for the relevant use cases. Actually, the transport requirements for each use case in terms of bandwidth and latency have been derived considering the radio functional split options, ranging from option 8 (i.e. CPRI) to option 1 (i.e. backhaul). For simplification, the functional split options have been organized in three main groups: 1) CPRI (i.e. option 8), 2) NR with centralized HARQ procedure (option 5-7) and 3) NR with distributed HARQ procedure (option 1-4). The higher the option number is, the more transport bandwidth is required. Basically, the transport requirements are derived such that the required bandwidths for NR option 1-4 are considered the same as the required service rate and the required CPRI option 8 bandwidths are given as reference values for comparison.

Actually, the discussion about the radio options is not fixed yet having each of them pro and cons in terms of bandwidth and latency at disadvantage of better radio performance. Moreover, there are situations where the geographical location poses the constraints in terms of transport technology that impact the amount of bandwidth and latency that can be offered. For example, in the rural scenario the availability of fibre could be a problem, hence it more reasonable utilize radio split options that limit the bandwidth requirements; while in dense area it could be more useful to take advantages of centralization at disadvantage of more bandwidth.

In the following table a summary of the results is reported:

Table 19: Summary of the evaluation results for different scenarios

Scenario	Functional split and technologies evaluated/analysed	Use Case supported/fulfilled	Comments
Packet optical - layer optical network	NR option 7A with packet-optical networks.	UC 1.a: high-speed train UC 1.b: vehicle safety UC 2: Media distribution	

		UC 3: Dense urban society UC4: Mobile edge computing	
Indoor Small Cell	FH compression of option 8 with copper based Ethernet technologies.	UC 1.a: high-speed train UC 3: dense urban society	Up to 10G Ethernet (i.e. 10GBase-T) is assumed for cost-effectiveness.
Outdoor Small Cell (mmWave and OWC)	NR option 1-4 and option 6, possibly also option 7 with mmWave-based solution.	UC 3: dense urban society	1 Gbit/s per sector transmission at 200 meters is going to be presented in D5.2 for option 2. Latency improvement techniques for supporting option 6 are included in D2.2 [9] in Section 5.1.3 and have been further investigated in D5.2 [8]. Option 7 may be possible.
WDM-PON based	NR option 1-4 with PtP WS WDM-PON and DD-OFDM S-BVT.	UC 1.a: High-speed train UC 1.b: Vehicle safety UC 2: Media distribution UC 3: Dense urban society UC 4: Mobile edge computing	Telnet SDN WS-WDM-PON achieves 10Gbit/s per DL and per UL. Option 5 and 6 may be possible.
Virtualized RAN	NR option 2 with P2P switch and PON systems	UC 1.a: high-speed train UC 1.b: vehicle safety UC 2: Media distribution UC 3: Dense urban society UC4: Mobile edge computing	The experimental results are based on Gigabit P2P switch and G-PON system. However, it indicates the feasibility to support all use cases with higher speed optical networks using NR option 2 interface.

Thanks to the high capacity transmission capability by optical technologies, the optical solutions with high speed WDMPON and multi-layer packet-optical networks can manage to meet the requirements of all use cases. More particularly, WDMPON only supports NR option 1-4 functional split (possibly up to option 6) while multi-layer packet-optical networks can support option 7 and up. For the indoor and outdoor small cell scenario, the cost-effective solutions based on copper Ethernet (up to 10Gbit/s) and mmWave technologies can fit with dense urban society use case. The indoor solution can also be used for high speed train use case. In the vRAN scenario, option 2 of PDCP/RLC functional split is evaluated experimentally. It shows how bandwidth and latency requirements can be relaxed down to the backhaul level and even good tolerance to packet losses.

It is further worth noticing that if a lower layer split is evaluated such that a use case can be supported, it also indicates that the based transport technologies/solutions can also be used to support any higher layer split than the functional split evaluated. This is because that the higher layer split has less stringent requirements in bandwidth, latency and jitter.

Multi-layer node analysis: 5G Crosshaul multiplexing and switching

On the basis of the multilayer architecture defined in the first period of the activity, a detailed analysis by means of simulation has been carried out to evaluate performance. Actually, the XFEs may include all layers or only one of them according the different requirements of the services to be supported. First an analysis of XCSE and XPFE has been carried out separately, then an algorithm for the coordination of the two switching granularities has been defined. The analysis and simulation results has been also demonstrated in WP5 experiments (demo 4).

No matter which switching technology is used (i.e. circuit or packet), the simulation results show that the multi-layer scenario is able to support all use cases for any radio split options. Detailed analysis and simulation have been done about the support of packet based traffic in case of low layer FH radio split where the requirements of latency are very challenges. For the XPFE and XCSE respectively a correspondent modelling has been defied and analysed. In case of XCSE, moreover the dependence of the radio requirements (e.g. Time Transmission Interval) has been done in order to highlight which are the dependency of radio and transport.

Moreover, the use of high speed optical transmission allows to use high amount of bandwidth and, the use of DWDM allows logical all-optical point-to-point connectivity between the edge nodes without any intermediated processing, thus greatly reducing latency when necessary (i.e. single hop link). Clearly the critical points could be the cost and the availability of the fibres. Regarding the cost, novel technologies (i.e. silicon photonics) is proposed to realize optical switches at low cost and size, while regarding the fibre availability it is necessary to consider alternative technology than the optical DWDM for covering scenarios with scarce fibre availability.

In addition, helper tools required to administer and run the 5G-Crosshaul network have also been looked at, specifically WP2 has worked on the supervision and monitoring of the network:

Supervision functions at XCSE

- Monitoring of WDM links
  1) Loss Of Signal (LOS): The optical signal is under the RX sensitivity threshold.
  2) Loss Of Frame (LOF): The receiver cannot lock to the TDM frame.
  3) Received Bit Error Rate (BER): Measured by FEC decoder.
  4) Excessive BER: The received BER is above the acceptable (programmable) threshold.
  5) Received Optical power on WDM links: Measured by optical transceiver module.
- Monitoring of CPRI clients
  1) Loss Of Signal (LOS): The optical signal is under the RX sensitivity threshold.
  2) Parity and out-of-table error rate: Rate of received symbol that violate 8B/10B or 64B/66B line coding rules.

Monitoring of Ethernet clients

1) Loss Of Signal (LOS): The optical signal is under the RX sensitivity threshold. Not applicable for copper clients where electrical SFP module is plugged.
2) Link Status: According to IEEE 802.3 specification for 1000BASE-X.
3) Parity and out-of-table error rate: Rate of received symbol that violate 8B/10B line coding rules.

Monitoring of Synchronization

1) Loss of Synchronization reference on Hub node: The source of synchronization on Hub node (chosen among one of the CPRI clients) is faulty.
2) Loss of Synchronization reference on Remote node: The Remote node has lost its synchronization reference (chosen among one of the WDM links).

The main challenges and solutions to implement packet-based Operations, Administration & Maintenance (OAM) mechanisms in SDN have been covered in the WP3 activity.

4.2.2.3. Task 2.3 -- Interface towards control layer

In order to realize SDN enabled mesh mmWave networks, current developments of different SBI concepts/agents have been reviewed. A PoC has been realized using ONF selected NETCONF over OpenFlow as a protocol for configuration and management of the microwave devices instead of OpenFLow used in the first PoC previously realized. Finally, some adapters, what ONF calls *mediators*, are used for translating the NETCONF/YANG information model to/from the existing proprietary management methods of each vendor's device, allowing this approach (unified YANG information model + NETCONF) to be more flexible than an OpenFlow extension, thus, saving time in the development, the debugging and the model adoption phase. CTTC IDCC

4.2.2.4. T2.4 -- Novel technologies for 5G-Crosshaul

The assessment of technology carried out in the first period has been completed with experiments and simulation analysis for the three alternatives, namely wireless, fixed access and optical technologies.

Wireless technology

The deployment of mmWave and OWC (optical wireless communication) technology in an outdoor small cell scenario has been carried on aiming to address three main aspects: i) reduce the latency to enable the multi-hop scenarios, ii) aggregate the capacity to meet 5G requirements, and iii) support energy harvesting capabilities. In order to reduce the latency in each hop, fast forwarding scheme has been devised in D2.2 [9]. Laboratory results acquired from both measurements and simulations shows that incorporating fast-forwarding techniques into the mmWave transport, the latency can be further reduced to below 100 µs, that is the latency in case of PtP configurations without mesh topology. Related the capacity aggregation, performance evaluation has been provided about the first-time study measuring real-time throughput results in a real outdoor deployment focused on the dependence on various weather parameters of an aggregated OWC/mmWave link developed within 5GCrosshaul project. Result demonstrated that optical wireless technology can also be expanded for 10Gbit/s over 1 km links. Moreover, the support energy harvesting capabilities has been carried out in collaboration with WP4 and WP3. In WP2 the develop of the SBI agent for energy consumption has been carried out and from the analysis of the Q-learning algorithm carried out in this WP, it is expected that EE also increases by a similar order of magnitude according to network densification reported in WP4. The activities have been carried out by CTTC and IDDC.

Fixed access (EAB, IDCC, Orange, EB-LINK, HHI, CTCC, ULUND, ITRI)

- *NG-PON2 and WDM-PON:* Two novel optical-based solutions for 5G access-metro networking have been presented. Firstly a PtP DWDM solution represents an important improvement regarding efficient utilization of the network resources that allows the convergence between fixed and mobile services over the same fiber access infrastructure. The evaluation results based on lab tests shows the feasibility to support different functional split options to C-RAN and vRAN deployment.
- Finally, a transparent delivery of mobile front-/back-haul for converged metro/access elastic networking has been experimentally demonstrated by DD-OFDM S-BVTs. Results show successful connections running at beyond 50 Gbit/s per flow from BBUs to the RRUs, when serving different paths and covering distances up to 60 km. Thus, it is a promising solution for serving the multiple endpoints employing S-BVT(s) at the 5G-edge nodes. This solution is aligned with use cases media distribution and dense urban society in terms of throughput and post-FEC BER. Nevertheless, the distances covered (up to 60 km) need a relaxation on the transport latency, from 100 µs up to 1ms.

- *New bandwidth-efficient fronthaul solution on copper cables, for massive and easy deployment of indoor Small Cell.* High efficiency fronthaul compression schemes based on the elimination of redundancy sources (oversampling and over-quantization) and entropy coding in digital fronthaul are also numerically have been investigated, showing that compression factors between 4x and 5x are achievable. Much higher compression factors (e.g. 30) are possible with more complex but still practical linear prediction and Huffman coding techniques, also investigated by simulations. Finally, a demo has been realized (demo4) to showcase the compressed FH scenario.

Optical Technology (TEI)

- *Low cost high rate transmission:* A study to understand what kind of modulation format could be used for the 5G Crosshaul distance (about 20 Km) at the cost of that ones used for data-center applications has been done. Based on simulation and lab test analysis the CAPS (Combined Amplitude Phase Shift) modulation format allows to reach such distance without any chromatic dispersion compensation.
- *Cost-effective ROADMs based on Silicon Photonics:* A ROADM based on integrated silicon photonics has been realized and tested. This node allows to reduce power consumption, cost and size about 100x with respect to the ROADM realized with traditional technology (WSS) typically utilized in the aggregation and metro networks. Such characteristics enable the utilization of optical switch in Crosshaul network segment where the utilization of traditional technology was prohibited by too much high cost and size (see Figure 24).

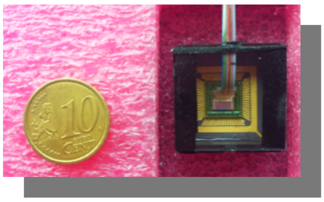


Figure 24: ROADM in integrated silicon photonics technology

- *DWDM trials in a real network setting:* A field trial has been performed with the goal of testing a realistic DWDM system configuration with 200 Gbit/s coherent. The field trial focused on two different solutions provided by two vendors (Vendor 1 and Vendor 2), based on integrated photonic technology. Results show that a common performance specification for coherent transmission solutions provided by different vendors is possible, allowing the adoption of standardized solutions suitable to be deployed in large volumes.

- *Analogue radio over fibre technologies for 5G-Crosshaul:* The hybrid Analogue/Digital RoF fronthaul solution, backward-compatible with installed CPRI solutions, has been demonstrated. The experiments performed in the downlink direction show that up to 90 km and 52.5 km are achievable with 6 and 36 carriers, respectively.

4.2.2.5. Deviations

None detected.

4.2.2.6. Corrective actions

None required.

4.2.3. WP3: 5G-Crosshaul Control and Data planes

WP3 contributed to the following key objectives defined for the project.

- Objective 1: Design of the 5G-Crosshaul Control Infrastructure (XCI); Develop XCI by extending existing Software Defined Network (SDN) controllers to provide the services for novel Northbound (NBI) and Southbound (SBI) Interfaces and enable multi-tenancy support in trusted environments. Introduce new mechanisms to abstract the mobile transport network and aggregate measured contextual information.
- Objective 2: Specify the XCI's northbound (NBI) and southbound (SBI) interfaces; Define interfaces to accelerate the integration of new physical technologies (SBI) and the introduction of new services (NBI) via novel or extended interfaces.
- Objective 3: Unify the 5G-Crosshaul data plane; develop a flexible frame format to allow the usage of fronthaul and backhaul on the same physical link to replace different technologies by a uniform transport technology for both fronthaul and backhaul.
- Objective 5: Increase cost-effectiveness of transport technologies for ultra-dense access networks; Develop techniques to enable massive and cost effective deployment of outdoor and indoor Small Cells, facing challenges such as hostile Radio Frequency (RF) propagation environment. Develop physical layer technologies with reduced cost per bit, as well as new energy saving schemes, which further reduce operational costs.
- Objective 6: Design scalable algorithms for efficient 5G-Crosshaul resource orchestration; Develop and evaluate management and control algorithms on top of the XCI NBI that ensure top-notch service delivery and optimal 5G-Crosshaul resource utilization, despite dynamically changing traffic loads, wireless link fluctuations, flexible functional RAN splits and both diverse and strict QoS requirements. The algorithms should be scalable in order to handle ultra-dense RAN requirements.

Throughout the reporting period, WP3 worked primarily on the following topics.

- 5G-Crosshaul data plane design. The initial design of the 5G-Crosshaul data plane and the 5G-Crosshaul Forwarding Element (XFE) proved to be mature enough to be used without changes. The analysis of data plane proposals was continued with an investigation of IEEE DetNet (IDCC).
- An OpenFlow 1.3 compliant pipeline for the 5G-Crosshaul Packet Forwarding Element (XPFE). The pipeline provides encapsulation and decapsulation of

tenant traffic to/from the 5G-Crosshaul Common Frame (XCF) format and forwarding of XCF encapsulated traffic. (UC3M, NOK-N, IDCC).

- Extending an OpenFlow 1.3 compliant software switch (lagopus) with queueing and scheduling at the egress and at internal processing stages (NOK-N).
- Inband procedures to integrate new XPFEs into existing 5G-Crosshaul networks. The procedures target both the general case as well as XPFEs with wireless links only. (NOK-N, IDCC).
- Definition and implementation for operation and maintenance (OAM) procedures executed on the XPFEs. The OAM procedures are defined in IEEE 802.1ag (UC3M, IDCC).
- Synchronization in packet base networks with packet delay variation. The behavior of a field programmable gate array (FPGA)-based precise timing protocol (PTP) implementation was investigated and improved in a testbed without PTP support in intermediate nodes. (EAB).
- Functional splits of a protocol stack. Two different splits of an LTE protocol stack, have been implemented and evaluated. The lower split was betweend the media access control (MAC) and physical (PHY) layer. The higher split was between the radio link control (RCL) and packet data convergence protocol (PDCP) layer. (CND)
- XCI design. Overall, the initial 5G-Crosshaul Control Infrastructure (XCI) design proved mature enough to be used in the implementation phase of the project. The design has been refined in the area of hierarchical control as a way to integrate specific controller for different technological domains. (NEC, CTTC).
- Link-related models. Information models for microwave and mmWave link were provided as well as cost and information models for microwave and Ethernet links. (TID, CREATE-NET)
- Models for network optimization and to support energy management algorithms. The network optimization determines optimal placement of central units (CU) and their connectivity to remote units (RU) and distributed units (CU). The models to support energy management algorithms provide the empirical data and formulae for network functions in virtualized environments and for powering on/off of dedicated links. (UC3M, POLITO, ITRI).
- Development of Controller components: Being the core part of T3.2, a large variety of components for SDN controllers was developed. The components include a flow configuration component as a low layer functionality in an SDN controller. The developed network application inside SDN controllers include a provisioning manager for flow rules in XPFEs including support for queues, a state manager to control power states and the corresponding component for energy monitoring, an analytics component, a resource management application (RMA), and the virtual infrastructure management and planning (VIMAP) component (IDCC, TID, NXW, CREATE-NET).
- Orchestration and placement algorithms. A virtualized network function (VNF) placement algorithm was developed. The VNFs deployed in data centers need to be connected among each other and with RUs. A procedure was defined and

implemented in the components to establish this connectivity via the SDN controllers and the virtual infrastructure manager (VIM), (TID, NXW).

- Hierarchical Control: hierarchical SDN controllers can be used to integrate different technological domains. The common orchestration protocol (COP) was developed further. An application based network operation (ABNO) controller was developed further as parent controller. Child controllers were developed or integrated for two different mmWave technologies. A resource management application was developed to control the parent SDN controller. (NEC, IDCC, CTTC)
- Orchestration Tools: Existing orchestration tools (VNFM, NFVO) have been analyzed. ETSI NFV compliant orchestration tools were developed. (ATOS, NXW)

Work on the XCI implementations has been performed in close collaboration with WP4.

4.2.3.1. Task 3.1 - 5G-Crosshaul Data Plane

The design of the 5G-Crosshaul data plane – initially developed by UC3M, TEI, ATOS, NOK-N, IDCC – consists of 3 major building blocks, as depicted in Figure 25: *i)* The XFEs as the actual forwarding plane, *ii)* the XCF as the frame format used among XFEs across the 5G-Crosshaul network, and *iii)* the AFs to adapt the frame formats used by the hosts to the XCF.

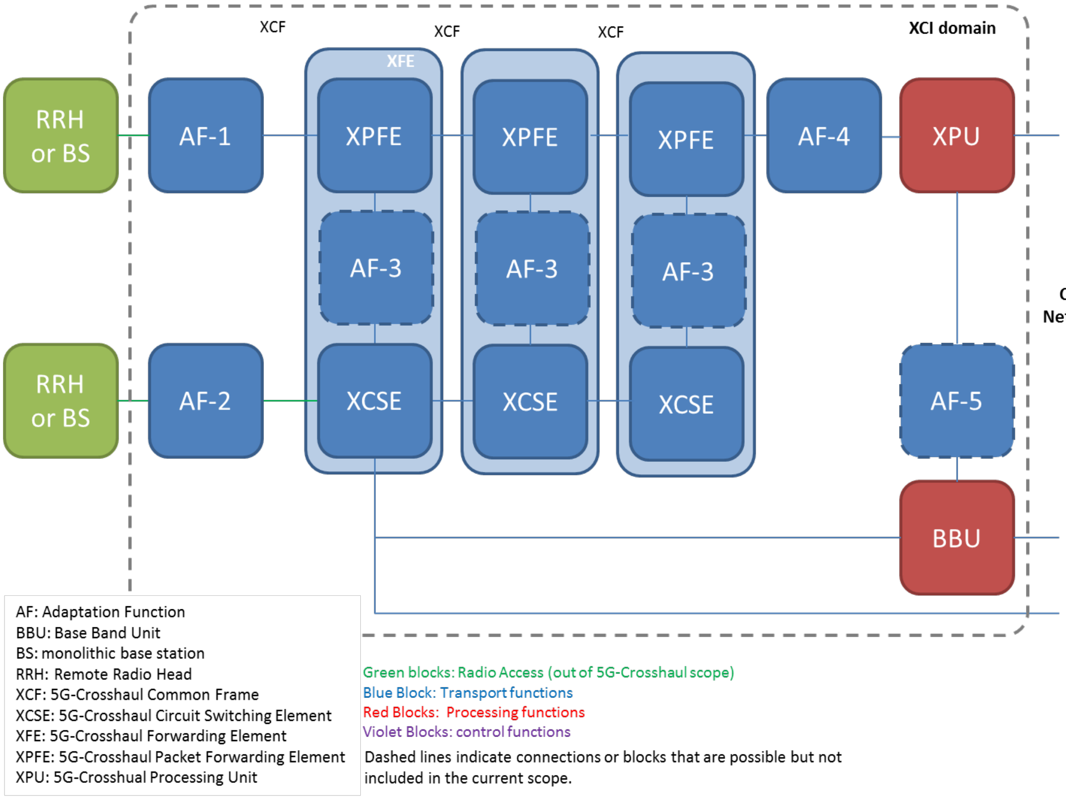


Figure 25: 5G-Crosshaul data plane architecture

The AF1, AF2, AF4, and AF5 perform frame format adaptation to and from the XCF. In the diagram above, these AFs have been drawn as independent functional blocks, but they might be included as well into the XFEs. AF3 is an internal adaptation function in the XFEs, adapting the XCF frames to the needs of the circuit-switched or purely optical transport.

The XCF is the frame format used among the XFEs, actually among the packet switched part of the XFEs, the XPFE. It is used as well among the AFs and the XPFEs.

Various proposals, especially MAC-in-MAC and MPLS-TP, have been evaluated against this list of requirements and a gap analysis was performed. No major gap was identified. On a technical level, no major advantage or disadvantage was identified for MAC-in-MAC or MPLS-TP. To keep focus within the project MAC-in-MAC was chosen as the XCF within this project, it is expected that the achieved results will hold as well for the frame format of MPLS-TP.

OpenFlow was decided as the protocol at the SBI of the XCI to control the XFEs. UC3M, NOK-N, and IDCC defined an OpenFlow compliant pipeline for forwarding of XCF encapsulated frames and for encapsulation to and decapsulation from the XCF format. This pipeline provides both XPFE and AF functionality, see Figure 26.

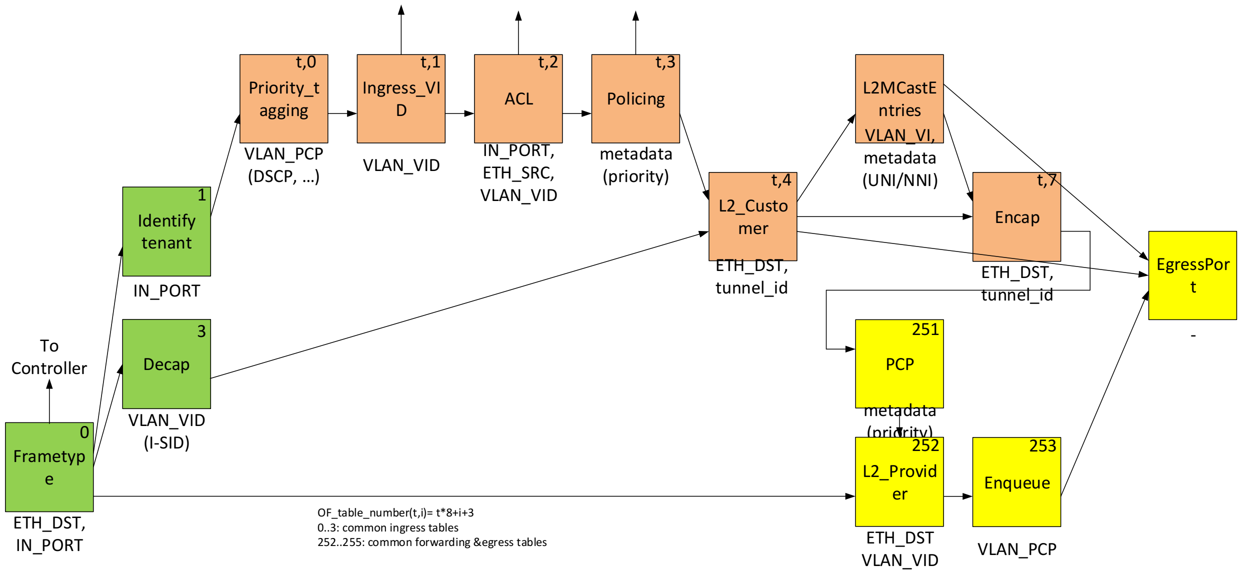


Figure 26: XPFE Open Flow Pipeline

In this pipeline definition, separate functionalities such as forwarding, tenant identification, access control, and encapsulation/decapsulation have been handled in separate tables. The tables could be kept small and functionality could be reused among the three paths through the pipeline, i.e. forwarding, encapsulation including access control, and decapsulation. The pipeline allows to handle both unicast and multicast traffic and considers priority of packets, such that FH traffic can be prioritized over BH traffic.

The corresponding flow actions are generated by the SDN controller of NXW and the pipeline was used and evaluated in the XPFEs in experiments in WP5. For further information on the pipeline see Section 6.3 of D3.2 [2].

An OpenFlow software switch (lagopus) provided already the support for MAC-in-MAC and thereby for the XCF format. This switch was modified by NOK-N to support egress queues corresponding to the OpenFlow pipeline shown before. The internal processing stages – receiving packets, OpenFlow processing of packets, transmitting packets – have been coupled with prioritized ring buffers. This allows to prioritize packets of FH traffic also in case the internal processing stages of this software switch get overloaded. This modified switch was used in experiments in WP5, further details on this modification are described in Section 5.2.2.3 of D3.2 [2].

All mobile systems require synchronization between RUs to support handover and to minimize interference. Also, the CU and RU need to share a precise clock to fulfil stringent regulatory requirements. With traditional time division multiplexing (TDM) based transport like CPRI FH, frequency synchronization in RUs could be derived from the physical layer of the FH transport technology between CU and RU. However, with the move towards packet-based transport or higher layer functional splits in general, other synchronization distribution methods are needed, e.g. PTP can be used. If other traffic (e.g. time-sensitive FH traffic) has higher priority than PTP through the XFEs, there may be significant jitter in the clock offset and propagation time estimation due to high packet delay variation (PDV) during the PTP message exchange. Even if PTP has the same or higher priority than interfering traffic, PDV may be high unless pre-emption is implemented.

The problem with high PDV during sync message exchange can be mitigated, at least to some extent, by proper strategies in the clock offset and propagation delay estimation process. To identify the most significant problems for synchronization in 5G-Crosshaul, an FPGA-based testbed was built, and phase noise measurements were performed on the recovered clock for a use case where PTP is only implemented in endpoints. Further work highlighted practical difficulties and potential solutions of selection and filtering techniques to achieve low time error in the presence of PDV. Results for the simplified topologies studied so far, show that it is possible to fulfil relevant 3GPP radio requirements even when PTP is only implemented in the endpoints. These results could be relevant for a case where legacy equipment is connected to 5G-Crosshaul XFEs via adaptation functions. For further details on synchronization see Section 5.5 of D3.2 [2].

Two different splits of the 4G radio protocol stack were implemented by CND. A low layer split between PHY and MAC and a high layer split between RLC and PDCP. The low layer split is based on the nFAPI interface of the small cell forum. The PHY software implements an interface to a software defined radio board, providing the actual air interface. The MAC and upper layers where implemented as a process on a bare metal server. The code was optimized to achieve 100Mbps throughput. For the high-layer split, the PDCP layer was implemented in a virtual machine, also achieving 100Mbps throughput. The implementations of both split options provide a portable possibility to generate realistic FH traffic. The implementation is also more cost-efficient compared to the deployment of complete eNbs for test purposes- Both split options were used in the experiments in WP5. For further information see Section 7 of D3.2 [2].

4.2.3.2. Task 3.2 - 5G-Crosshaul Control Plane

Based on the system architecture described in WP1, WP3 developed a design of the XCI. The design has been done initially by UC3M, NEC, NXW, CTTC, CREATE-NET, ITRI. The first design focused on the single-domain case. Multiple domains can be handled in different ways: different technological domains can be abstracted by different plugins to an SDN controller, as shown in Figure 27. Different technological domains as well as different administrative domains can be handled as well by a hierarchy of SDN controllers, where child controllers provide abstractions of their domain to a parent controller. Such hierarchical approaches have been investigated and implemented as well.

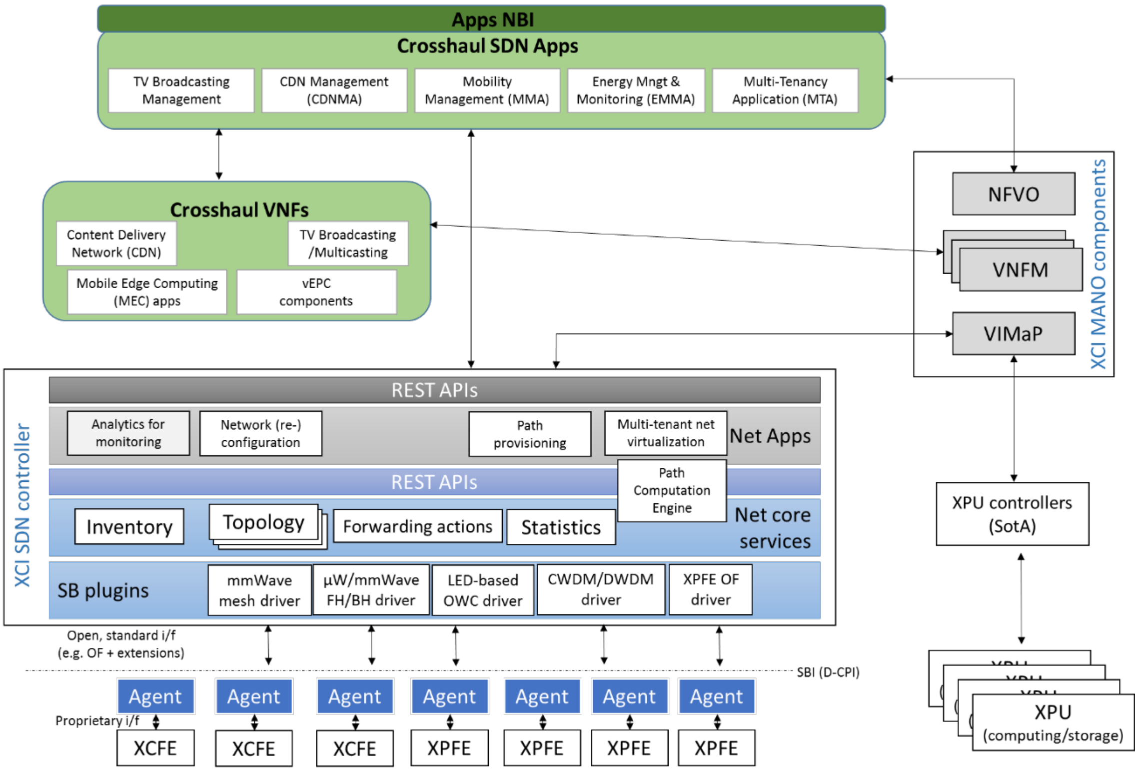


Figure 27: XCI design

Figure 27 shows the major parts of the XCI: The XCI MANO components, responsible for the instantiation, orchestration and management of Virtual Network Functions and Network Services and the XCI SDN controller, responsible for the configuration and management of the network infrastructure. The XCI MANO components include the NFV Orchestrator (NFVO), the VNF Managers (VNFM), and the Virtual Infrastructure Manager (VIM), in line with the ETSI NFV architecture. In 5G-Crosshaul, the VIM concept is extended with planning algorithms, which take efficient decisions about VMs placement and network configuration, towards integrated Virtual Infrastructure Management and Planning (VIMaP) functions.

To integrate an XPFE it needs to connect to an SDN control. In a 5G-Crosshaul it is expected that many switches are deployed in the field and do not have a dedicated control connection. The connection to an SDN controller needs to be established inband. NOK-N and IDCC developed procedures to integrate XPFEs into a network without requiring XPFE specific configuration. Still, only XPFEs authenticated by a vendor certificate can establish a connection to an SDN controller, preventing that a 5G-Crosshaul network can be extended in an unauthorized way. In the general case, the bootstrapping procedure consists of four phases:

1. Establish connectivity to the control network and retrieve connection identifiers (e.g. IP address) of an SDN controller and of elements of a Public Key Infrastructure.
2. Optionally authenticate to the Certificate Authority and create, sign and download an operator specific certificate.
3. Establish secure connection to the SDN controller (e.g. through Transport Layer Security (TLS)).
4. Register at the SDN controller by instantiating an OpenFlow session.

After these phases, the SDN controller can reconfigure the new XPFE for inband control and extend the 5G-Crosshaul network to include the new XPFE. In the specific case of XPFEs with wireless links only, e.g. nodes in a wireless mesh network, the authentication information is also used to establish the wireless links. The establishment of the wireless links can already be used for topology discovery. After these links are established, the general four phase procedure can be used to integrate the XPFE in a 5G-Crosshaul network. For a detailed description of the procedure see Section 5.4.1 of D3.2 [2].

The links and paths in a 5G-Crosshaul network have to be monitored for the occurrence of failures. UC3M and IDCC defined and implemented a solution for connectivity check, loopback, and linktrace locally on the XPFEs. This solution prevents that test packets have to be sent from SDN controller to an XPFE before and after it is exchanged on the monitored link(s). This solution reduces significantly the load on the SDN controllers and avoids the impact of the connection between SDN controller and XPFEs on the measurements. For further detail see Section 5.4 of D3.2 [2].

The applications and the MANO components rely on various models of the 5G-Crosshaul network. Information models for µWave and mmWave links have been developed by TID and to support energy management on dedicated links by ITRI. CREATE-NET developed a cost model for Ethernet and mmWave links as basis for a resource management application.

Given a 5G-Crosshaul network with a number of RUs, the placement of DUs and the corresponding functional splits of the BTSs can be seen as an optimization problem. UC3M formulated this optimization problem as a mixed integer linear program problem and implemented it. The algorithm determines an optimal placement of the DUs, optimal with respect to cost. The solution provides connectivity of all Rus and satisfy the bandwidth constraints within the network and the latency constraints of the selected functional splits. This optimization problem is described in more detail in Section 4.2 of D3.2 [2].

Energy management algorithms trying to place virtual network functions (VNFs) such that energy consumption is reduced, need to know the impact of their decisions. Based on empirical data, POLITO developed energy consumptions models for processing in virtual environments. Virtual-machine and container based virtualization were evaluated regarding the following aspects:

- Virtualization overhead
- Power consumption versus CPU utilization
- Power consumption versus data rate
- Power consumption versus memory usage
- Power consumption versus disk I/O blocksize

The results of these measurements were mapped to corresponding models, for details see Section 4.1 of D3.2 [2].

Many of the components for SDN controllers shown in Figure 27 were developed by IDCC, TID, NXW, and CREATE-NET. and used in the experiments in WP5. The components include a flow configuration component as a low layer functionality in an SDN controller. The developed network application inside SDN controllers include a provisioning manager for flow rules in XPFEs including mapping of packets to egress queues. The usage of egress queues corresponds to the queues defined in the XPFE. A component for an SDN controller to monitor energy consumption was developed together with a corresponding component to control power states via SNMP commands. E.g. the power states of XPFEs could be controlled, where power states are mapped to different processor frequencies, Additionally, an analytics component, a resource management application (RMA), and the virtual infrastructure management and planning (VIMAP) component were developed.

Multiple technological domains such as optical and wireless links can be controlled by using dedicated controllers per technological domain. NEC, IDCC and CTTC developed or enhanced a hierarchical controller solution. Child controller per technological domains are controlled themselves by a technology independent parent controller. This parent controller drives the provisioning (and recovery) of connectivity across heterogeneous transport networks, dynamically, and in real time. The interface and corresponding protocol among child and parent controllers allows to abstract the particular control plane technology of a given domain. The common orchestration protocol (COP) provides this abstraction. For an overview, how child and parent controllers are connected via client and server plugins to SDN controllers, see Figure 28. For further details see Section 3.3 of D3.2 [2].

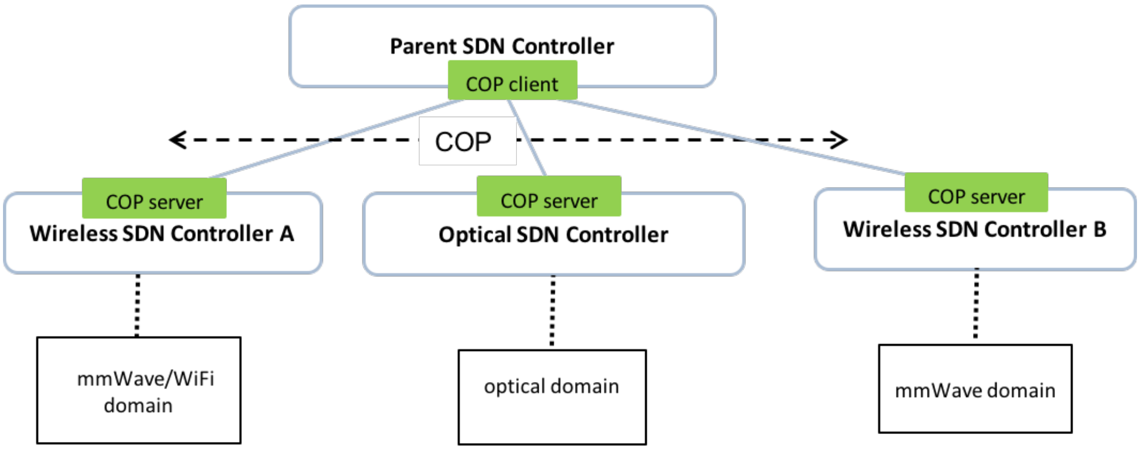


Figure 28: Integration of per technology child controllers with a centralized parent SDN controller

COP provides the following services for the interaction amongst parent and child SDN controllers:

- *Topology Services*: Upon request through the COP client, the parent SDN controller can retrieve a child SDN network topology. The COP definition covers the topological information about the network, which includes a common and homogeneous definition of the network topologies (based on of nodes and edges).
- *Path Computation Services:* The path computation service provides an interface to request (by the COP client in the parent SDN controller) a Path objects, which contains the information about the route between two service endpoints. Path computation is highly related to the call services. Note that in the call object, the connection object has been designed to have the possibility of containing explicit information about the flow match/action rules along the traversed path.
- *Call Services:* Using Call objects, the parent SDN controller can request the provisoning of end-to-end connectivity services across multiple transport domains. A Call object must describe the type of end-to-end connection service to be requested or served (e.g., Ethernet, MPLS). The Call object is formed by a list of connection objects, including the service endpoints. A connection object is used for a single per-technology transport network node domain. By design, the routes across one technological domain may be fully described (explicit) or abstracted (delegated to the child SDN controller) depending on the orchestration/control schemes used amongst parent and child SDN controller.

SDN controllers focus on establishing network connections. Corresponding functionality is needed to control the compute and storage resources. TID and NXW developed a virtualized network function (VNF) placement algorithm and a procedure to connect the VNFs to the 5G-Crosshaul data plane by the SDN controllers and the virtual infrastructure manager (VIM). After creating virtual machines (VM) an application requests the network related information from the VIM, especially the VLAN IDs and the MAC addresses of the VIM. This application determines the needed traffic flows, considering the placement of VMs in different data centres and then requests the provisioning manager in the SDN controller to establish the corresponding connections. The provisioning manager creates the necessary flow rules for the XPFEs, using the VLAN IDs and MAC addresses determined by the VIM for traffic classification. In the 5G-Crosshaul network this traffic is encapsulated according to the XCF, using a different outer VLAN-ID for tenant separation in the 5G-Crosshaul network. See Figure 29 for an example topology after applying this procedure and Section 3.2.4 of D3.2 [2] for further details.

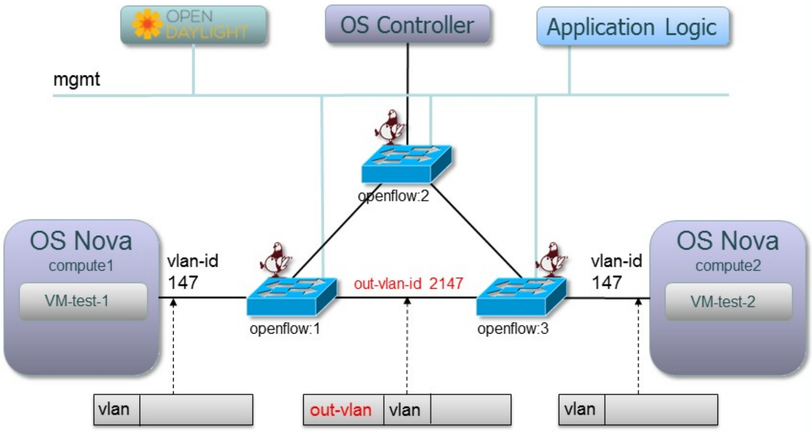


Figure 29: Configuration of underlying network connectivity at the XPFE data plane

NFVO and VNFM components were evaluated by ATOS and NXW. Available components were not compliant to ETSI NFV standards. Therefore, ETSI compliant NFVO and VNFM components were implemented and used in the experiments in WP5.

4.2.3.3.Deviations

None detected.

4.2.3.4.Corrective actions

None required.

4.2.4. WP4: Enabled innovations through 5G-Crosshaul

WP4 is focused on designing and developing essential SDN/NFV applications for managing the 5G-Crosshaul network including both networking and IT resources, providing context-aware system-wide resource orchestration. In total, 12 SDN/NFV applications have been developed within WP4 during the project: 5G-Crosshaul Resource Manager Application (RMA) was designed to manage different types of 5G-Crosshaul resources including networking, computing and storage, dealing with path computation, placement of VNFs, and configuration of different RAN functional splits. Energy management and monitoring Application (EMMA) was designed to minimize energy consumption of the 5G-Crosshaul network. Virtual Infrastructure Manager and Planner (VIMaP) was used for other applications to request the constrained allocation of physical and virtual 5G-Crosshaul resources, and to instantiate, deploy and provision them over the 5G-Crosshaul infrastructure. Multi-Tenancy Application (MTA) was developed to allow multiple tenants (e.g. network operators) to share the 5G-Crosshaul infrastructure resources in a high-speed train scenario. Mobility Management Application (MMA), Content Delivery Network Management Application (CDNMA) and TV Broadcasting Application (TVBA) are the Over-The-Top (OTT) applications on top of the 5G-Crosshaul network to provide different network services. MMA was developed to provide mobility services for high-speed train scenarios and to improve the traffic offloading with distributed mobility management solutions. CDNMA and TVBA were designed to provide efficient media distribution services over the 5G-Crosshaul network.

WP4 contributed to the following key objectives defined for the project.

- Objective 1: Design of the 5G-Crosshaul Control Infrastructure (XCI)
    - Designed the Virtual Infrastructure Manager and Planner (VIMaP) as a key MANO component of the XCI.
    - R&D Topics: Study of network partitioning techniques (= multi-tenancy support). WP4 explored multi-tenancy feature inside the XCI to support multi-tenancy (e.g. EMMA to provide per tenant monitoring) or deployment of virtual infrastructures for multiple tenants (MTA application for the high speed train scenario).
- Objective 2: Specify the XCI's northbound (NBI) and southbound (SBI) interfaces.
    - Specify the requirements for the NBI for the needs of applications. WP4 applications specified the requriemetns for the NBI in the scope of WP4.
    - Specify the requirements for the SBI for the needs of applications. WP4 applications helped to specify the requriemetns for the SBI, jointly with WP2 and WP3.
    - Specify abstraction information model, WP4 specified the abstaration on NBI jointly with WP3.
    - 5GPPP KPI impact: Enable the introduction/provisioning of new Crosshaul services in the order of magnitude of hours. Within WP4, EMMA, VIMaP, CDNMA, TVBA have successfully addressed the 5GPPP KPI impact: enable the introduction/provisioning of new 5G-Crosshaul services in the order of magnitude of hours.
- Objective 5: Increase cost-effectiveness of transport technologies for ultra-dense access networks
    - 5GPPP KPI impact: Reduce Total Cost of Ownership (TCO) by 30% by improved optical transmission and sharing mobile and fixed access equipment (MTA has addressed this KPI successfully).
    - 5GPPP KPI impact: Reduce energy cost per bit by a factor of 10 (EMMA has addressed this KPI successfully).
- Objective 6: Design scalable algorithms for efficient 5G-Crosshaul resource orchestration
    - R&D Topics: Scalable orchestration algorithms for dynamic joint optimization RAN, routing and function placement (RMA, EMMA,

  VIMaP, MMA for traffic offloading investigated the scalability of the algorithms).
  - R&D Topics: Novel 5G-capable routing and traffic engineering algorithms, jointly considering cloud and network resources (RMA, EMMA).
  - R&D Topics: Techniques for path provisioning and handover for multi-Gbps multi-operator ultra-mobile (up to 300 km/h) hotspots backhauled via multiple base stations concurrently (MMA).
  - 5GPPP KPI impact: Scalable management framework: algorithms that can support 10 times increased node densities (RMA, EMMA, VIMaP, MMA for traffic offloading).
  - 5GPPP KPI impact: Enable deployment of novel applications reducing the network management Operational Expenditure (OPEX) by 10% in terms of provisioning (MTA).
  - 5GPPP KPI impact: Increase of total 5G-Crosshaul network throughput by > 20% (RMA, MMA).
  - Verification: simulative proof of scalability and throughput performance of resource management algorithms based on real operator's backhaul network data (RMA, EMMA, MTA, MMA for high speed train scenario).
  - Verification: prototype of some application algorithms on top of real test network (RMA, VIMaP, MMA for traffic offloading, EMMA, CDNMA, TVBA).
- Objective 7: Design essential 5G-Crosshaul (control/planning) applications
  - R&D Topics: Novel capacity-minimization and Quality of Experience (QoE) optimization techniques for wide-area media broadcast and multicast such as adaptive (in-network) video transcoding, optimization of Single Frequency Networks and congestion-aware caching (TVBA).
  - R&D Topics: Energy Manager (controlling optimal scheduling of equipment sleep cycles, routing parameters and function placement, and energy harvesting) (EMMA).
  - R&D Topics: Techniques for end-to-end monitoring, prediction and enforcement of QoS parameters (such as latency, loss, jitter, bitrate) across heterogeneous Crosshaul technologies (EMMA).
  - R&D Topics: Algorithms for planning and dimensioning the overall Crosshaul hardware infrastructure (split RAN, cloud nodes, switches, routers, links) based on realistic performance and cost KPIs (RMA, VIMaP).
  - 5GPPP KPI impact: Reduce energy consumption in the Crosshaul by 30% through energy management (EMMA).
  - 5GPPP KPI impact: Reduction of Crosshaul infrastructure Capital Expenditure (CAPEX) by 20% due to automated planning (MTA).
  - Verfication: Prototype of software for Crosshaul infrastructure planning (VIMaP).
  - Verfication: Simulative analysis and software prototype of the Energy Manager (EMMA).

    - Verfication: Demonstrator for media distribution systems (TVBA, CDNMA).
- Objective 8: key concept validation and proof of concept
    - 5GPP KPI Impact: Self-healing mechanisms for unexpected 5G-Crosshaul link failures through alternative path routing in mesh topologies (TVBA).

Throughout the second year, WP4 worked primarily on the following tasks.

- In total 12 5G-Crosshaul applications were implemented and developpped in this project, according to the initial design from the first year. Each application carried out performance evaluation via individual means (simulation, emulation, or test-bed implementation) to validate the application functionalities as well as to verify the desired target performance KPIs. For the evaluation of the applications, benchmark methods were selected among the state-of-the-art approaches for comparing against the proposed solutions.
    - 5G-Crosshaul RMA on joint Path Computation and Virtual Network Function Placement (CREATE-NET)
    - 5G-Crosshaul RMA on joint Routing and C-RAN Functional Splits (NEC)
    - EMMA for XPFE/XPUs (NXW, POLITO)
    - EMMA for mmWave Mesh Networks (FhG-HHI)
    - EMMA for High Speed Train Scenario (ITRI)
    - EMMA for multi-tier networks (CTTC)
    - Virtual Infrastructure Manager and Planner (VIMaP) (CTTC, TID)
    - MMA for Traffic Offloading (UC3M).
    - MMA for High-Speed Train Scenario (ITRI)
    - MTA for High-Speed Train Scenario (ITRI)
    - CDNMA (ATOS)
    - TVBA (VISONA)

- The follwoing applications were also integrated into the different WP5 demonstrators and contributed to the experiments conducted in WP5.
    - EMMA for XPFE/XPU, EMMA for High Speed Train, EMMA for mmWave Mesh Networks were used in Demo 1 (NXW, ITRI, FhG-HHI)
    - RMA, MMA for Traffic Offloading, CDNMA and TVBA were used in Demo 2 (CREATE-NET, UC3M, ATOS, VISONA)
    - RMA was used in Demo 3 (NEC)
- To improve energy management, techniques for end-to-end monitoring and prediction were developped in EMMA.
    - For the XPFE domain, EMMA was designed to estimate the power consumption associated with virtual Network Services, i.e. collections of Virtual Network Functions which are interconnected through forwarding graphs established through dedicated network connections on the XPFE domain. (POLITO)
    - For multi-tier networks, a distributed Q-learning (QL) was proposed to dynamically learn when to switch ON and OFF both the backhaul and

the access according to the available harvested energy budget, the user traffic demand and the energy consumption of the node. QL was designed to learn a policy for optimizing the system performance in terms of throughput and energy efficiency by directly interacting with the observed environment. (CTTC)

- The following applications specified their requirements on the interfaces to the RAN and mobile core, to define their need of interaction with neighbouring domains.
    - RMA on joint Routing and C-RAN Functional Splits (NEC)
    - EMMA for mmWave (FhG-HHI)
    - EMMA for High Speed Train Scenario (ITRI)
    - EMMA for multi-tier networks (CTTC)
    - MMA for Traffic Offloading (UC3M)
    - MMA for High-Speed Train Scenario (ITRI)
    - CDNMA (ATOS)
    - TVBA (VISONA)

- We investgiated hierarchical and peer-to-peer structures for the interaction with the neighboring network domains (i.e., RAN and mobile core), highlighting the relationship of 5G-Crosshaul with other PPP Phase I projects: 5G-NORMA and 5G-Exchange projects. In terms of interfaces, we studied the design from the 5G-Ex project on the external interfaces and APIs towards other networks or administrative domains. The interfaces can be not only used for EBI/WBI, but can also be applied to the NBI/SBI of the 5G-Crosshaul MANO to interact with RAN and core network domain controllers. In this way, both hierarchical and peer-to-peer structures can be implemented. (TID, NEC, ATOS).

In the following, the implementation and evaluation of the developped 12 Crosshaul applications in WP4 are described individually, their related KPIs and results are summarized , while the details have been reported in D4.2 [3]. Note that we have decided to organise this WP based on the different applications instead of the traditional task based ordering since, in our opinion, makes more sense.

4.2.4.1. 5G-Crosshaul Resource Manager Application (RMA) on joint Path Computation and Virtual Network Function Placement – CREATE-NET

This RMA provides an efficient allocation and management of 5G-Crosshaul resources in infrastructures composed of XPFEs and XPUs through two types of services: *Path Computation (PC) service*, and *Path Computation-Virtual Network Functions Placement (PC-VNFP) service.*

The initial implementation of the RMA algorithms for PC and PC-VNFP services was implemented relying on the formulation of an equivalent ILP problem. The advantage of solving the ILP formulation consists in determining the best possible solution, if it exists. The main disadvantage incurred is a potentially long execution time to solve the ILP which makes it almost impractical to deploy in real time scenario. To this end, a heuristic algorithm for the PC-VNFP service was developed during the second year of the project to obtain a sub-optimal allocation of flows within an acceptable execution time ensuring the optimized use of network and compute resources.

The RMA application was designed to operate on physical infrastructures including software-based XPFEs and XPUs and it is developed as a python application. The application exposes a REST API towards other applications (e.g., CDNMA, TVBA) for sending path computation requests following different service constraints. The RMA relies on the XCI controllers for the actual provision and allocation of resources and can operate over physical or virtual network resources, on a per-network or a per-tenant basis. The RMA applications interacts with the XCI components, in particular the SDN controller, the VIM and the NFVO.

An analytical and simulative approach was chosen as main methodology for the evaluation of the RMA algorithms. Matlab simulation environment was used for this evaluation. Furthermore, the functional validation for RMA in a real test-bed was performed in WP5 under demo 2 and reported in D5.2 [8].

The heuristic solution for RMA PC-VNFP service was compared with the state-of-the-art solution that is done in practice where traffic/flow steering among the end points is performed following K-shortest path solution and a greedy approach is adopted for allocating the VNFs in the XPUs. Simulations results reported in D4.2 [3] have shown that with the RMA PC-VNFP solution the average link capacity utilization is below 10% which addressed the KPI on the increase of total 5G-Crosshaul network throughput. In addition, the RMA PC-VNFP solution reduces the resource management cost significantly compared to the state-of-the-art approaches. The cost saving increases with the increase of the network size, for example, in case of a network with 30 nodes (40% XPUs and 60% XPFE nodes) RMA reduces the cost up to 90%.

4.2.4.2. 5G-Crosshaul Resource Manager Application (RMA) on joint Routing and C-RAN Functional Splits - NEC

Different than the above RMA, this application is designed to support flexible Cloud RAN functional split deployment. The aim is retaining as much centralization degree as possible when full offloading of BS functionality is unfeasible due to transport constraints. For this purpose, a new metric “degree of centralization” is defined as our objective. The higher the centralization degree, the higher are the gains as well as higher spectrum efficiency. To solve this problem, we develop this application to jointly route traffic across fronthaul/backhaul (i.e., 5G-Crosshaul) transport networks and select proper functional splits for each BS to maximize the degree of centralization while meeting next generation fronthaul network constraints on parameters such as capacity, latency, and jitter.

This RMA was implemented on top of an SDN controller in the XCI through a REST-based NBI. Through the XCI, the RMA can gather topological information from the data plane (using the inventory service and the analytics for monitoring service) and can enforce the computed configuration via the network re-configuration and path provisioning services.

In the initialization phase, the RMA retrieves (through the XCI) a graph abstraction of the physical topology. Then, our application uses the algorithm described in D4.2 [3] to jointly compute the optimal paths between radio access points, vEPC and CU (when needed) and the functional split of capable Base Stations. Upon topology changes, e.g. a link failure or a change on the modulation of a wireless link, the RMA receives a notification from the SDN controller (which in turn receives a notification from the hardware components via SNMP) and a new configuration is computed (and enforced by the SDN controller via SNMP and OpenFlow for path setup).

In the scope of WP4, we demonstrated the RMA in a small-scale test-bed with a fault-tolerance use case to validate the RMA functionality of changing functional split jointly with routing. Besides, we accessed the performance of RMA via simulations with large-scale synthetic networks taking real topologies from major operators in Europe. For the evaluation, we defined a metric to measure the degree of centralization and proposed three algorithms to maximize it while meeting next generation fronthaul network constraints: BBB, GA-GR and GA-RR. BBB provides us with a near-optimal solution which yields a performance upper bound. GA-GR and GA-RR are greedy heuristic solutions where GA-GR achieves the best trade-off between computational load reduction and distance to the optimal solution. They were compared to the state-of-the-art approaches for routing based on shortest path, max-flow and max-min solutions. The resutls showed that these state-of-the-art approaches fail to trade off the centralization degree of some flows to benefit larger clusters of Base Stations. The RMA can be used both at network planning and operational runtime phases to achieve the maximum centralization degree, which properly addressed the KPI on increasing 5G-Crosshaul network throughput. GA-GR has been implemented in a proof-of-concept with commercial hardware and its properties at operational runtime have been analyzed.

In addition, this RMA was also provided as an application component to compute an end-to-end path over multiple technical domains in WP5 under demo 3 (hierarchical multi-domain resource management of 5G-Crosshaul) and reported in D5.2.

4.2.4.3. Energy Management and Monitoring Applications

Several Energy Management and Monitoring Applications (EMMAs) were developed for monitoring and management of power consumption of 5G-Crosshaul infrastructures over different kinds of network technology domains including (1) networks composed of software-based switches named Crosshaul Packet Forwarding Elements (XPFEs), (2) mmWave links, and (3) analogue Radio over Fibre (RoF) technologies.

The implementation of EMMAs is illustrated in Figure 30. A monitoring layer, developed on top of an SDN controller, collects, aggregates and elaborates energy-related measurements for different network domains. Importantly, energy consumption information can be collected not only for network paths, but also for virtual network slices, network services and tenants. This is accomplished through an extension module for the SDN controller which collects in real time the power consumption data provided through an SNMP agent by a power meter built into the server's power supply and combining it with per-flow processing data. Energy management is then implemented above the monitoring application to determine an optimal resource allocation for both network connections and cloud-based services. Specifically, energy-based optimization is achieved through several modules, each implementing a different task: routing (and re-routing) of traffic flows, Virtual Network Functions (VNFs) placement, and regulation of network node power states (including their On/Off switching) depending on the network resource demand. We remark that such optimization is either performed upon on-demand instantiation or automatically triggered by the monitoring application when re-planning is needed. EMMAs indeed include management interfaces that can put in place, through the southbound interface, the decisions made by the aforementioned modules, within each domain. This is achieved through signaling across the XCI, i.e., the 5G-Crosshaul Control Infrastructure, composed of a hierarchy of network and cloud controllers, together with orchestration and management entities. At the north-bound interface, the EMMA applications offer a set of REST APIs for monitoring, operation and management actions. Moreover, the operator can interact with the EMMA application using its Graphical User Interface.

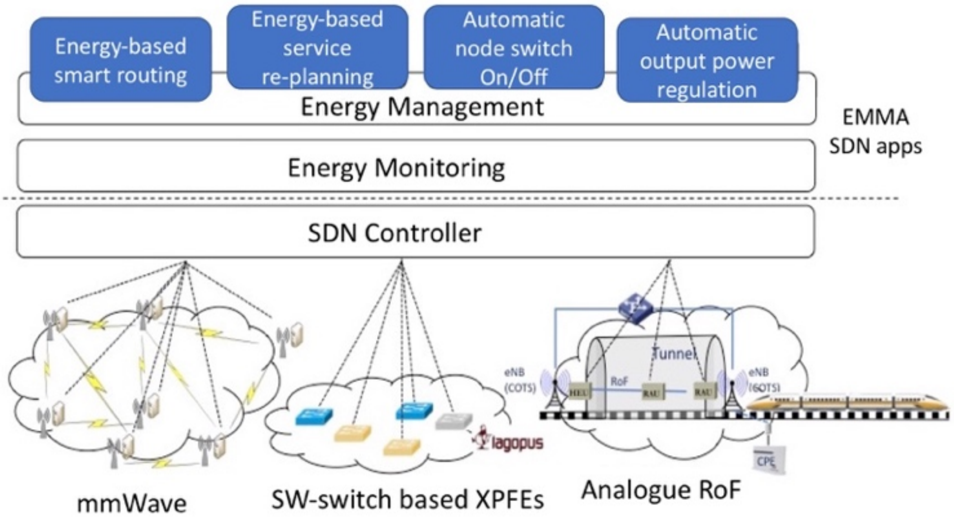


Figure 30: EMMAs operate over different domains and effectively monitors energy consumption

4.2.4.4. EMMA for XPFE/XPUs – NXW and POLITO

This EMMA application implemented two main functionalities: monitoring of power consumption and energy efficient management of resource allocation in infrastructures composed of software-based XPFEs and XPUs.

The monitoring of power consumption is performed for different kinds of physical and virtual entities. In particular, the application manages physical infrastructures composed of software based XPFEs and XPUs, computing both total consumption and contribution of single devices, i.e. XPU servers and XPFE network nodes, based on their computing or traffic load. At the virtual level, EMMA can estimate the power consumption for single network connections or all the network connections associated to a given tenant. This estimation is based on an analytical model that takes as input the flow statistics collected from the XPFEs. Moreover, EMMA is also able to estimate the power consumption associated with virtual Network Services, i.e. collections of Virtual Network Functions which are interconnected through forwarding graphs established through dedicated network connections on the XPFE domain. The EMMA offers a single graphical interface to visualize the current power state and power consumption of XPFEs and XPUs, as well as historical data on power consumption trends through graphs.

The energy efficient management of resource allocation implemented three different modes: (i) at the network level only, (ii) at the computing level only, and (iii) jointly for both network and computing resources. In all the cases, the EMMA adjusts dynamically the power state of the target devices based on the current traffic and processing requests, reducing the number of nodes in active states through a suitable resource allocation strategy.

The implemented EMMA software includes the EMMA application and the XCI. The EMMA application interacts with the XCI components, in particular the VIM, the NFVO and the SDN controller. The evaluation scenario is based on an emulated environment, using the Mininet tool to emulate a network with a representative 5G-Crosshaul topology including both network nodes (XPFEs) and hosts (XPUs).

The related Project KPIs are listed below:

- Obj.7: Design essential 5G-Crosshaul-integrated (control/planning) applications
- (5GPP KPI) Reduce energy consumption in the 5G-Crosshaul by 30% through energy management
- Obj.2: Specify the XCI's northbound (NBI) and southbound (SBI) interfaces
- (5GPP KPI) Enable the introduction/provisioning of new 5G-Crosshaul services in the order of magnitude of hours
- Obj.6: Design scalable algorithms for efficient 5G-Crosshaul resource orchestration
- (5GPP KPI) Reducing the network management Operational Expenditure (OPEX) by 10%

For the evaluation of the power saving gain of the EMMA, three states of the art approaches were considered as benchmark: (1) Provisioning of network connections based on shortest path algorithms; (2) Manual management of service provisioning, without energy efficient resource allocation algorithms; and (3) Provisioning of VNFs with static deployment.

Comparisons with state of the art results (as reported in D4.2 [3]) showed up to 35% improvement with EMMA in energy efficiency compared to always on approaches and up to 20% improvement if compared with other energy saving approaches. These results also demonstrated that the above these KPIs were successfully achieved.

In addition, the scalability of the EMMA was tested through emulation. The gain of EMMA compared to the No Power Saving scheme was investigated as the network size varies. The results confirm the steady performance of EMMA: it reduces the power consumption per flow by a factor ranging from 2 (for 10 core switches) to 8 (for 40 core switches), with the average power consumption/flow linearly increasing.

Time for path provisioning and time for vEPC service instance provisioning were also measured. The related measurement was performed in the context of WP5, through experiments on the 5TONIC testbed where EMMA was integrated with real hardware. The path provisioning time, if compared with the approach where all the XPFEs are always on, increases of a few seconds, due to the time needed to change the XPFEs' power state. Time for vEPC service provisioning also only increases of few seconds, which is negligible if compared with the total provisioning time (in the order of minutes and mainly bounded to the VNFs instantiation time).

4.2.4.5. EMMA for mmWave Mesh Networks – FhG-HHI

The design of the EMMA for mmWave mesh aims at the dense urban scenario where the user distribution is time-variant and spatially non-uniform. The considered Network topology is an mmWave mesh, overlaid by a LTE-macro BS. This forms a heterogeneous network (HetNet) while the user has access via LTE and mmWave at the same time (Multi-RAT). The focus is the mmWave mesh acting as wireless backhaul serving infrastructure with a mmWave gateway in the network for connecting to remote services. The goal for EMMA here is maintaining all the service while reducing the energy consumption of the whole network. Disabling and enabling various mmWave small cell base stations as the users are moving is key for satisfying the user's traffic demand. EMMA solves an optimization problem that determines mmWave mesh backhaul paths and ON/OFF status of each node.

The validation and evaluation of the EMMA mmWave mesh algorithm is a two-stage process. The first stage is a simulation evaluation within WP4, where the simulation is stand-alone and implemented in MATLAB; the second stage is an experimental demonstration of the core EMMA functionalities and integration within a real architecture in WP5, where the algorithm is tested within a real mmWave mesh network.

Two state of the art approaches were considered as benchmark: (1) Always on: this is the usual approach for dense networks where all available nodes are on all the time. The energy consumption is at a high base level and does not change much if traffic is send or received. (2) User based on: this approach takes into account the nodes that do not serve any user. These idle nodes can then be turned off to reduce the energy consumption of the network. Here, the traffic demand is not considered. Hence even an idle user in the cell will result in turning on the node.

The results show that even with very high traffic demand and dense user distribution the EMMA algorithm keeps user satisfaction to 100% while reducing energy consumption significantly. Comparing to the always ON and user-centric ON approach the EMMA algorithm outperforms both. The results show that the energy consumption is reduced by over 39% with EMMA. The KPI on reducing energy consumption in the 5G-Crosshaul by 30% was achieved.

4.2.4.6. EMMA for High Speed Train Scenario - ITRI

In high-speed train deployment, among the transceiving nodes deployed along high-speed rail track, Radio-over-Fibre (RoF) technology is deployed inside tunnels to provide constant coverage. RoF is integrated as the fronthaul technology for ground-to-train radio access to overcome Doppler effects. In the current deployment of high speed train system, the deployed RoF nodes are active all the time regardless of the presence of the trains within the tunnel. This leads to a waste of energy. If all or part of them can be turned on only when needed, system energy efficiency and OPEX can be improved Thus the goal of this EMMA is to develop a software-defined energy-efficient RoF management system in an attempt to move toward greener communication. EMMA controls the power state of RoF according to the presence of a high-speed train in close proximity of the nodes reported by cloud database. The application signals to the XCI that idle RoF nodes should be switched off when unused. The goal is to minimize the energy footprint of the deployed distributed RoF nodes in the 5G-Crosshaul network without degrading the QoS of ground-to-train communication.

The EMMA application for the high-speed train scenario was developed as a Python application implemented from scratch and operating on top of the 5G-Crosshaul XCI services, utilizing the XCI service by REST APIs. The correlation of mobility-related information of the High-Speed Train and energy-related information of RoF is exposed by the XCI to provide an overall view to the EMMA application. Based on the received information, EMMA will adjust the status of the connected RoF nodes (e.g., switching ON the set of connected nodes if a High-Speed Train is predicted in the coverage area of those connected RoF nodes). There modules were implemented: the context information module collects the information from the surrounding eNBs and predicts the current location of the train, which later is posted to the Statistics Module which analyses the information and triggers the Management module. The management module decides whether to switch ON/OFF the connected RoF nodes based on the received information.

For the evaluation, emulation was carried out, which consists of:

- ODL (XCI) integrating SNMP Driver;
- EMMA application consisting of Management, Statistics and Context information module, sitting on top of ODL (XCI) and using the REST APIs;
- RoF nodes.

With the EMMA-integrated solution, RoF nodes will be switched on only to serve the high-speed train when it is approaching, thus saving significant energy. Energy consumption for RoF nodes can save up to 90% compared to the current deployment of Analogue Radio-over-fibre, with all nodes always on. The results proved the target KPI on reducing energy consumption by 30% through energy management was achieved with the EMMA.

4.2.4.7. EMMA for multi-tier networks (EMMA-EH) - CTTC

This EMMA application implemented a two-tier architecture for the energy and radio resource management (RRM) of cellular networks with mmWave backhaul and energy harvesting capabilities. In this wo-tier architecture, macro BS are supported by small BS (SBSs). SBS network is modelled as a multi-agent system where each local agent (SBS) makes autonomous decisions, according to a Decentralized Self Organized Network (D-SON) paradigm. SBSs equipped with solar energy and batteries constitute an overlay layer in a two-tier network where macro BSs are powered by the electricity grid. The goal of this application is to improve the system energy harvesting (EH) and reduce its drop rate by assisting the SBS local agents in their learning process.

EMMA-EH was evaluated by simulation in order to reproduce scenarios with multiple SBS operating simultaneously with realistic traffic conditions over large time ranges (e.g., one simulated year) for collecting the behaviour of the system and of the algorithm when varying the energy harvesting conditions. More in detail, the evaluation environment is an octave based simulator which carefully models the channel condition, the LTE system and the energy harvesting phenomena.

Three state of the art approaches are studied as benchmark solutions: (1) grid; (2) greedy; and (3) Q-Learning (QL). The results reported in D4.2 [3] show that the throughput gain of EMMA-EH outperforms both QL and greedy. The QL solution already halves the drop error rate respect to the greedy which reaches 25% in winter and 15% in summer. However, EMMA-EH is able to further reduce the traffic drop rate of QL by reaching the 5% in winter and the 1% in summer.

Regarding the energy savings, the EMMA-EH outperforms both greedy and QL in winter. Moreover, EMMA-EH well scales with the number of SBSs, while standard QL solution experiences degradation till performing even worst respect to the greedy one. As expected in summer period, the amount of the energy in excess during the day is higher for all the solutions. However, greedy has always less abundant energy. While EMMA-EH, despite guaranteeing better system performance, has less abundant energy respect to the greedy solution. In all cases, the average energy efficiency improvement with EMMA-EH is 30% and up to 55%. The results demonstrated the EMMA-EH can meet the energy-related KPIs: (1) Reduce energy cost per bit by a factor of 10; (2) Reduce energy consumption in the 5G-Crosshaul by 30% through energy management.

4.2.4.8. Virtual Infrastructure Manager and Planner (VIMaP) – CTTC and TID

The Virtual Infrastructure Manager and Planning application (VIMaP) is logically part of the 5G-Crosshaul XCI and stays at the lowest level of the application hierarchy. The goal of this application is to plan and optimize the physical and virtual Crosshaul resources (i.e., computing and networking resources) and to instantiate over the Crosshaul infrastructure the decisions taken. VIMaP consists of two components: the planner and the Virtual Infrastructure Manager (VIM). The planner component is in charge of running the required resource allocation algorithms for the planning and (re-) optimization of Crosshaul resources. The VIM is the component responsible for the dynamic provisioning and instantiation of Crosshaul resources (handling jointly the different IT and Network resources). The planner runs the resource allocation algorithms for the planning and (re-)optimization needed to perform the placement of virtual machines within, and may also include the optimization of the network paths that provide connectivity. The VIM-P interface is between VIM and Planner component, which is internal.

The VIMaP algorithms consist of a baseline algorithm and Net2Plan-based algorithms. The net2plan software includes algorithms able to produce designs handling service chains like in NFV scenarios. Specifically, it includes a novel version of the k-minimum cost service chain algorithm, which computes the minimum cost paths that satisfy a service chain request. The tool developed to perform the implementation of the P-component functionalities has been denominated as Comp2Plan.

The VIMaP API was implemented to provide a virtual infrastructure slice to a dedicated tenant or user. The API involves a request including a set of virtual instances interconnected forming a Virtual Machine Graph (VMG). The VIMaP architecture (including resource manager, cloud infrastructure manager, network manager, and virtualized infrastructure controller) allows the VIMaP logic component to select the preferred algorithm depending on the desired resource allocation policy and delegate it to the P-component.

The performance of VIMaP was demonstrated with an implementation and proof-of-concept experimental deployment. The VIMaP was evaluated in two main scenarios: (1) integration with the Transport Network SDN Controller; (2) Integration with the P-Component. In both cases, the storage & computing controller is implemented in terms of a single OpenStack deployment, which controls several compute nodes (i.e. XPUs) distributed in different geographical locations within a single 5G-Crosshaul domain (NFVI administrative domain).

The target KPI of VIMaP is under Ojective 2 to enable the introduction/provisioning of new 5G-Crosshaul services in the order of magnitude of hours. Here the considered VIMaP service is the automated provisioning of a graph of Virtual Machines, and their interconnection, as received in a request from the operator by the VIMaP NBI. The service is deployed when the VMs are instantiated and flows are provisioned ensuring connectivity. And the VIMaP orchestrates the service and resources from an underlying SDN and cloud controller with optional third-party placement computation (P-component). The measured performance demonstrated that by means of SDN/NFV automation and the 5G-Crosshaul XCI, VIMaP services can be provisioned in orders of magnitude of minutes, thus meeting the target KPI value. The measurements have been obtained by means of experimental assessment processing the traces captured by Wireshark software taking as reference key events such as service provisioning trigger from the involved functional components. Besides, the P-component of the VIMaP was proven to be scalable, which supports max 1000 nodes, max 10000 demands for path computation and max 8000 links among those nodes.

4.2.4.9. Mobility Management Application (MMA) for Traffic Offloading – UC3M

The main goal of the MMA is the reduction of the traffic to/from the core network by selective offload of traffic as near as possible to the RAN reducing the cost of the core network and improving the experience of the user reducing the latency and delay in end-to-end communications. Therefore, the MMA is in charge of the **user detection** and **mobility management** in the 5G-Crosshaul domain to optimize the traffic offload for media distribution.

First, the MMA is in charge of detecting the presence of new users in the 5G-Crosshaul domain. This is possible through REST-based core and RAN interfaces. Once the MMA collects all the available and useful information of the new user it notifies the CDNMA and TVBA, after this notification the MMA receives the CDN node assigned to the user from the CDNMA and makes use of the RMA API to provide the best paths between the different elements of the network.

Second, the MMA mobility solution is based on Distributed Mobility Management (DMM), avoiding the bottlenecks and scalability problems of the centralized MIPv6 and PMIPv6 legacy solutions. DMM improves the scalability by flattening the network, distributing mobility anchors by placing multiple ones closer to the user. In this project, two DMM approaches were implemented for MMA: a DMM PMIPv6-based solution and an SDN-based solution. The 5G-Crosshaul mobility will be based on a flat IPv6 network, on which traffic is forwarded to the nearest Point of Connection (PoC) to the Internet. To make it possible the MMA will handle the association of the Gateways (GW) to the users in addition to the Neighbour Discovery mechanisms. The assignment of the PoC to the GW will be made based on heuristic and proximity.

The tests related to the User Monitoring Manager and the Notification Manager were focused on the validation of the correct operation of the application. The user detection and notification procedure worked as expected, which validated the correct operation of the MMA. For the tests of mobility, the results presented in D4.2 have shown that DMM introduces a lot of benefits compared to PMIPv6, avoiding bottlenecks and the single point of failure of the Local Mobility Anchor (LMA). DMM suffers performance degradation with long-lived IP flows. The experiment results showed that the SDN-based implementations have a better performance in handover signalling cost and flow recovery than the PMIPv6-based. The solution can be implemented easily and provides a lot of flexibility due to the softwarization of the SDN paradigm. In short flow scenarios DMM allows a higher throughput by reducing the overhead and in large deployments DMM decreases the packet delivery cost allowing more traffic thus increasing the node density. Thus, the KPIs to support increased node densities and the increase of total network throughput were addressed in this application.

4.2.4.10. Mobility Management Application (MMA) for High-Speed Train Scenario – ITRI

This MMA is to deal with mobility management for the high-speed train scenario. Traditionally, passengers use on-board point-of-access points which are then backhauled by ground-to-train communications; the outbound gateway(s) providing ground-to-train moving backhaul perform handover frequently to maintain the availability and quality of moving backhaul. Current LTE systems adopt break-and-make handover, which inevitably causes interruption and throughput degradation during handover. To solve this issue, this MMA is designed to act as a proxy between eNBs and MME and it will send the HO control signal on behalf of them. By doing so, the HO completion stage can be performed in parallel with HO execution stage, and the path switch doesn't need to wait until HO execution is done.

For the evaluation, simulation was carried out using MATLAB. The results demonstrated the benefit of 5% throughput gain with the design MMA compared to the LTE legacy handover mechanism, which improves the throughput KPI. In terms of handover processing time, the MMA shows the reduction of average delay by 20ms compared to the legacy HO process.

4.2.4.11. Multi-Tenancy Application (MTA) for High-Speed Train Scenario - ITRI

MTA for high-speed train scenario implemented two parts: On-board MTA and On-land MTA. **On-board MTA** was implemented in HST and is composed of Radio Access Network (RAN) for users (i.e., User Equipment (UE)) and outbound gateways (i.e., CPEs) for connection to outdoor wireless backhaul network (i.e., Macro Base Stations (MBSs). **On-land MTA** was implemented in a transport network which is shared among different network operators. Traffic of different network operators transmitted on the high-speed trains can be forwarded to their respective Core Networks (CNs) according to the configuration/pre-configuration by On-land MTA applied to the shared transport network.

The MTA was developed as a Python application implemented and operating on top of the 5G-Crosshaul XCI, utilizing the XCI services through the REST APIs. It has implemented the following functionalities:

- Onboard controller inspects the packet to analyse the information of the network operator and tags the packet w.r.t network operator. It also performs the load balancing to distribute the traffic load to make efficient use of the bandwidth of outbound gateways on-board.
- On Land controller manages the shared network w.r.t tagged packets and re-routes the packet to their appropriate core network. It also provides a web based GUI to the network operators allowing them to maintain and manage their own network topology in the shared infrastructure, where tenants can also initiate multiple services utilizing their allocated topology and resources.

The MTA was evaluated by means of simulation/emulation. The MTA was implemented over a Ryu SDN controller as the XCI and used Mininet to model the data plane composed of multiple XPFEs which are controlled by Ryu controller together with On-land MTA. Two costs models were investigated to evaluate the costs on the required CAPEX and OPEX. The results showed the gain of MTA on reducing both CAPEX and OPEX compared to the legacy solution of static sharing, meeting the cost related KPIs on reducing the total cost of ownership (TCO) by 30% and reducing the OPEX by 10%. The results also demonstrated the designed MTA had no impact on the throughput and latency, which can be ignored (3%). The slight differences were only due to the packet header overhead by the On-board MTA.

4.2.4.12. Content Delivery Network Management Application (CDNMA) - ATOS

The Content Delivery Network Management Application (CDNMA) is an application related to the distribution of media content that uses the services and APIs offered by the XCI NBI, and other applications like the RMA and MMA, to deploy and manage a vCDN service in which the CDN functions (CDN nodes –origin and replica servers- and load balancer) are dynamically allocated across the 5G-Crosshaul network.

A typical content delivery network is an infrastructure composed of replica servers located at the edge of the network to which the end-users are connected. In this infrastructure, the content based on the user request is obtained from the origin server and a user is served with the content from the closest replicated server. In this sense, the end users are communicated with a replicated CDN server close to them and receive the content from that server.

The CDNMA has implemented the following main functionalities:

- Request the vCDN infrastructure instantiation to XCI NBI, providing a complete descriptor file with detailed information about the CDN elements and how they have to be configured and connected.
- Management and storage of specific monitoring information got from the CDN nodes.
- Management and treatment of the information exchanged with the MMA and RMA applications.
- Management and update of the content delivery rules over the CDN nodes placed in the network (CDN node assignments), based on the monitoring information received and the logic defined by the CDN operator.

The CDNMA was designed as a Web application implemented in Python and Django Framework for Python and developed from scratch. It has implemtented two basic algorithms that allow the CDN service management and implementation over the 5G-Crosshaul network. The first algorithm is in charge of the CDN infrastructure instantiation, and the second one is oriented towards the control and management of the service during the lifetime. The control and management of the vCDN service took into account the monitoring information received from the CDN nodes, the point of attachment of the user to the network and the content delivery rules provided by the CDN operator. The CDNMA application uses the services and APIs offered by other applications (e.g. RMA for path compuatation and MMA for retrieving information about the Point of Attachment of the user) and the XCI NBI, SDN controller and NFV MANO, in particular the NFVO (Orchestrator), to manage the CDN infrastructure configuration and the content delivery rules on the 5G-Crosshaul network.

For the evaluaiton, a test-bed for CDNMA was set up in the 5TONIC-Madrid testbed. In the application plane the CDNMA interacts with the MMA and RMA applications. The XCI, comprised of an SDN controller and a specific NFV architecture, interacts with the application plane through its NBI. OpenDaylight (ODL) (Beryllium-SR3 release) was chosen as the SDN controller to manage the OpenFlow elements in the data plane. Openstack, Mitaka version, was used as VIM, and it is in charge of controlling the virtual infrastructure. Besides, a proprietary version of the NFVO and VNF Manager was developped in the second year for the orchestration of the CDN nodes and the VNFs lifecycle, which overcame the limitation of TeNOR to interact with VIMaP to provision the orign and replica servicers. The data plane was composed of six switches (XFEs) based on Lagopus software, which forms the data packet plane used to exchange traffic between all the infrastructure components under an Ethernet-based domain, and three servers (XPUs) for the deployment of VMs with the CDN nodes. The connection between the user terminal (laptop) and the network entry point will be done through a Wi-Fi connection.

The main objective of the tests was to prove that the CDNMA application is able to instantiate upon client (CDN operator) request, a vCDN infrastructure based on the CDN operator criteria and the network infrastructure available. The results reported in D4.2 showed that a vCDN can be instantiated and ready to provide the CDN service in a magnitude of minutes, which meets the KPI under ojective 2 to enable the introduction/provisioning of new 5G-Crosshaul services in the order of magnitude of hours.

4.2.4.13. TV Broadcasting Application (TVBA) - VISONA

The TVBA offers Broadcast-as-a-Service, providing solutions for TV broadcasting and multicasting services making use of the 5G-Crosshaul network as a facility for management of the instantiation, deployment and provision of the involved resources.

TVBA implemented a set of functions for content media management such as headend injection, routing by means of the selection of the most suitable physical or virtual nodes for very low-latency delivery, and media quality monitoring near the user in terms of QoS and QoE. In order to select the optimal path from the headend to the users, the TVBA makes use of RMA and MMA applications. For the quality monitoring it deploys Quality Probes (TVBAQPs) in the closest XPUs to the users. TVBAQPs are Virtual Network Functions (VNFs) managed by the NFV Orchestrator (NFVO), part of the XCI MANO, that analyze the media received through the same user's multicast group and send the results to the TVBA in terms of QoS (packet loss, media reception) and QoE (freezing frames, color alteration).

The TVBA was evaluated in a test-bed over a topology based on a mesh of 6 XPFEs (switches using Lagopus) and 3 XPUs (bare metal servers controlled by OpenStack) attached to different XPFEs. Such a scenario guarantee that multicast paths can be established, and QoS or QoE issues can be faced reconfiguring paths or changing quality in the source. In addition, 3 Virtual Machines were set up which are controlled by an Hypervisor in a server: one for NFVO (OpenBaton) for orchetration, one for the OpenDaylight SDN controller to manage the network, and one for TVBA includimg REST server, Web GUI and other TVBA components. Although part of the initial development has been done using several Virtual Machines in a local Hypervisor, the final evaluation environment has been moved to 5TONIC Testbed in Madrid.

Different test cases were performed for the functional validation and experimental assessment of TVBA and its interacation with cloud controller (OpenStack), with the SDN controller (OpenDaylight) and TVBA-TVBAQP interface, and TV headend injection. TVBA is focused on the following KPIs:

- Enable the introduction/provisioning of new 5G-Crosshaul services in the order of magnitude of hours.
- Self-healing mechanisms for unexpected 5G-Crosshaul link failures through alternative path routing in mesh topologies

Extensive experiments evidenced that the provisioning of a multicast TV service is in the order of magnitude of minutes which satisfied the first KPI target. Besides the TVBAQP-performed analysis of QoE and QoS received by Users demonstrated that the TVBA can heal the system by two mechanisms: modifying the service path or reconfiguring the source of media, which fulfilled the second KPI target.

4.2.4.14. Deviations

None detected.

4.2.4.15. Corrective actions

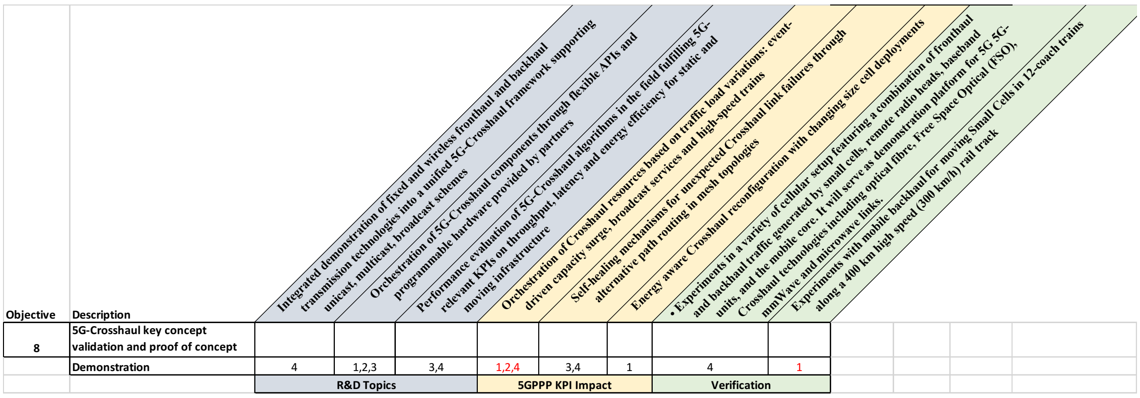
None required.

4.2.5. WP5: Validation and proof of concept

WP5 contributes mainly to objective 8 defined in the project:

- Objective 8. 5G-Crosshaul key concept validation and proof of concept. Demonstration and validation of 5G-Crosshaul technology components developed in WP2, WP3 and WP4, which are integrated into the software-defined flexible and reconfigurable 5G-Crosshaul testbed, which has multiple sites (Berlin, Madrid, Barcelona, Taiwan). Four integrated demonstrations (see below, Figure 33, for more detailed explanations) were defined that are thematically grouped to show the operation of the architectural components of the project.

More specifically, Figure 31 explains what demo covers each of the R&D topics, 5G PPP KPIs, and how different key aspects are verified.



Objective	Description	Integrated demonstration of fixed and wireless fronthaul and backhaul transmission technologies into a unified 5G-Crosshaul framework supporting unicast, multicast, broadcast schemes	Orchestration of 5G-Crosshaul components through flexible APIs and programmable hardware provided by partners	Performance evaluation of 5G-Crosshaul algorithms in the field fulfilling 5G-relevant KPIs on throughput, latency and energy efficiency for static and moving infrastructure	Orchestration of Crosshaul resources based on traffic load variations: event-driven capacity surge, broadcast services and high-speed trains	Self-healing mechanisms for unexpected Crosshaul link failures through alternative path routing in mesh topologies	Energy aware Crosshaul reconfiguration with changing size cell deployments	• Experiments in a variety of cellular setup featuring a combination of fronthaul and backhaul traffic generated by small cells, remote radio heads, baseband units, and the mobile core. It will serve as demonstration platform for 5G 5G-Crosshaul technologies including optical fibre, Free Space Optical (FSO), mmWave and microwave links.	Experiments with mobile backhaul for moving Small Cells in 12-coach trains along a 400 km high speed (300 km/h) rail track
8	5G-Crosshaul key concept validation and proof of concept								
	Demonstration	4	1,2,3	3,4	1,2,4	3,4	1	4	1
		R&D Topics			5GPPP KPI Impact			Verification	

Figure 31: Demonstrations that cover each of the R&D topics, 5G PPP KPIs, and verification of objective 8.

Given the scope of the work package, demonstrations and evaluations in the framework of WP5 also contribute to the following objectives, which are mostly related to technical work packages, which concepts are verified through demonstrations in WP5. For each objective, the demo covering it is listed below:

- Objective 1. Design of the Crosshaul Control Infrastructure (XCI)
    - Develop a proof-of-concept XCI prototype (TRL 3) and demo of a hierarchical SDN system using the example of a parent umbrella controller integrating a wireless, packet and optical SDN controller. Demo 3
- Objective 2. Specify the XCI's NBI and SBI interfaces
    - Prototype of the XCI SBI including multiple technologies (CPRI over WDM, packet over mmWave) and the XCI NBI (capacity reconfiguration). Demo 3
- Objective 3. Unify the 5G-Crosshaul data plane
    - Prototype including XFE supporting a unified frame format. Demo 4
- Objective 4. Develop physical and link-layer technologies to support 5G requirements
    - Proof-of-concept prototype, testing and measurement of each individual technology. Demo 1, Demo 3, Demo 4
- Objective 5. Increase cost-effectiveness of transport technologies for ultra-dense access networks
    - Energy-consumption measurements on prototypes. Demo 1
- Objective 6. Design scalable algorithms for efficient Crosshaul resource orchestration
    - Prototype of at least one algorithm on top of real XFE test network. Demo 1
- Objective 7. Design essential Crosshaul-integrated (control/planning) applications
    - Demonstrator for "Broadcast as a Service" system. Demo 2

Additionally, many of the concepts developed in each of the technical work packages are also covered in WP5 through the integrated demonstrations.

As for the tasks carried out in WP5, the first reporting period started and ended with Task 5.1 (Testbed definition and setup), during which the experimental components provided by partners were identified, based on which the experimental framework for the whole project was prepared. We focus below on the work done during the second reporting period.

4.2.5.1. Task 5.2 - Integration and proof-of concept

The goal of the 5G-Crosshaul project is to design an integrated fronthaul and backhaul transport network able to handle 5G traffic flows with a wide variety of requirements under the same infrastructure. This includes CPRI-like traffic with high bandwidth and low delay and jitter requirements, traffic generated by novel Radio Access Network functional splits, as well as regular backhaul traffic going from eNodeBs (eNBs) to the core network and vice versa. The volume and characteristics of these traffic flows are tightly linked with the use cases under consideration in the project, as defined in work package 1 (WP1).

Designing such a single infrastructure requires rethinking all architectural aspects of the transport network conceived in 5G-Crosshaul. From a data plane perspective, WP2 evaluates to what extent each of the optical, copper-based, and wireless technologies can fulfil the requirements of 5G traffic flows. This not only includes the design of the links, but also of the nodes from a forwarding point of view. Such data plane is under the control of the 5G-Crosshaul Control Infrastructure (XCI) conceived in WP3, which brings the software-defined networking (SDN) and Network Functions Virtualisation (NFV) paradigms to the project. In turn, WP4 designs the network management applications that will handle the resources required by the use cases by exploiting the services offered by the XCI through its Application Programming Interfaces (APIs). However, the goal of each of these WPs is to focus mostly on the specific architectural components that are their object of study as well as the definition of interfaces towards architectural components dealt with in other WPs, but not putting into practice the global system design done in WP1. Additionally, there are some components needed in the testbed to generate the variety of traffic flows served by the crosshaul (i.e., the integrated fronthaul and backhaul). They correspond to the access and core mobile network as well as computing resources. These are provided by WP5. Figure 32 presents the scope of WP5 and the WPs from which it receives inputs and to which it provides feedback after the evaluations.

Therefore, the main goal of WP5 is to integrate the components developed in the other WPs and to experimentally validate that all the conceived building blocks can work together to fulfil the heterogeneous 5G traffic flow requirements. This is done by building proofs-of-concept[2] over the 5G-Crosshaul testbed, which is deployed in four sites (5G-Berlin, 5TONIC-Madrid, CTTC-Barcelona, and ITRI-Taiwan).

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[2] Proof-of-concept and integrated demonstration are used interchangeably throughout this document.

Once the experimental setup required in 5G-Crosshaul was deployed, WP5 focused on the definition of how the identified building blocks were integrated. In this sense, four main groups of building blocks spanning the application, control, and data planes were defined. Each of these groups was defined to illustrate their joint operation towards a common 5G-Crosshaul goal.

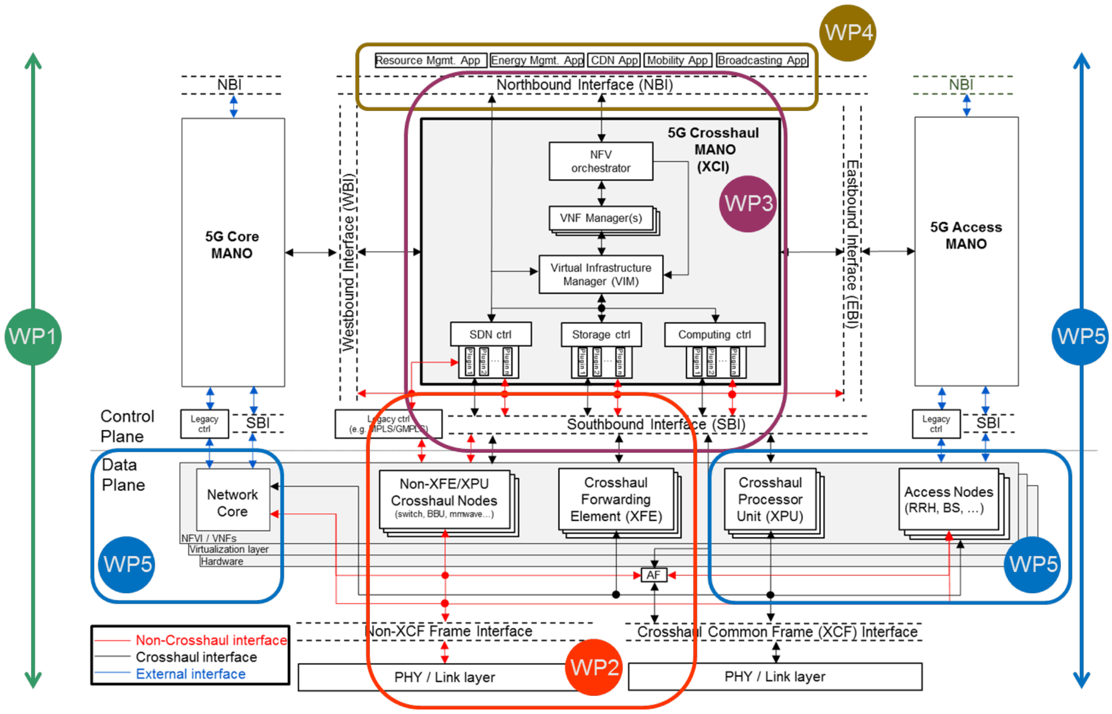


Figure 32: Representation of the scope of work package 5 (WP5) over the 5G-Crosshaul system architecture and WPs from which it receives inputs (coloured rectangles). Blue rectangles represent building blocks added by WP5

The initial part of the second reporting period served to define the goal, setup, and integration plan for each of the four integrated demonstrations (or proofs-of-concept) to illustrate the joint operation of the building blocks composing the 5G-Crosshaul system architecture. More specifically, these were the main tasks carried out:

- Thematic grouping of multiple heterogeneous technologies and building blocks belonging to all planes (application, control, and data) into four proofs-of-concept. Summary tables on use case coverage were also provided;
- Description of the relation of each proof-of-concept with the objectives and use cases of the project;
- Identification of the building blocks to be integrated in each proof-of-concept;
- Definition of the integration plan for each of the proofs-of-concept.

The four demonstrations of the 5G-Crosshaul network show:

- How fronthaul (FH) and backhaul (BH) traffic can coexist through integration of several transport technologies such as those present in the networks of mobile operators today and foreseen for 5G (Demo 4) (HHI, NOK-N, TELNET, ITRI, ORANGE, UC3M, IDCC, TEI, EAB, CND, NEC, ULUND);
- That the 5G-Crosshaul network can be controlled through SDN techniques despite its complexity and extension (Demo 3) (CTTC, NEC, CND, IDCC);
- That such network is capable of coping with the needs of the most demanding use cases associated with video transmission (Demo 2) (ATOS, VISIONA, UC3M, CREATE-NET); and
- That efficient energy management of the complex and heterogeneous 5G-Crosshaul network is possible (Demo 1) (NXW, ITRI, HHI, POLITO, UC3M, CND).

Figure 33 represents the building blocks involved in each of the integrated demonstrations.

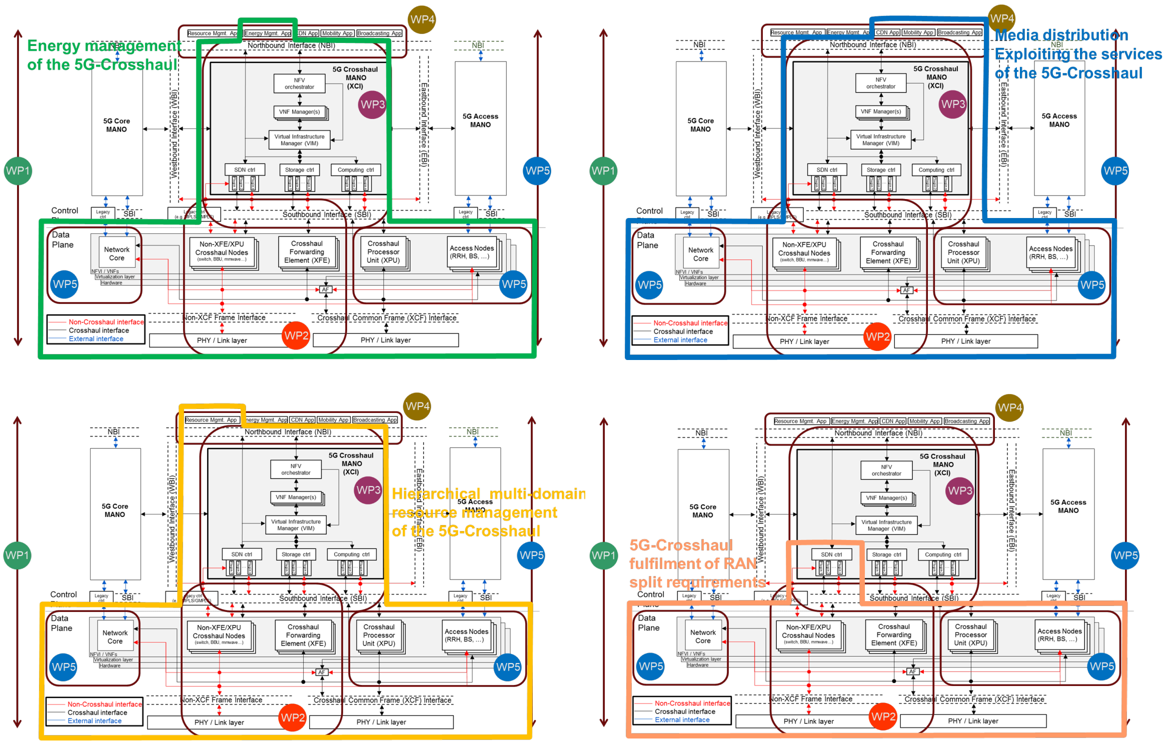


Figure 33. Representation of the four integrated demonstrations of the project and the 5G-Crosshaul architectural building blocks involved in each of them.

As a result, deliverable D5.1 presented the 5G-Crosshaul testbed (section 3), early integration efforts (section 4), and the four integrated proofs-of-concept (sections 5, 6, and 7), including their description, R&D objectives, Key Performance Indicators (KPIs) and use case coverage, building blocks involved, and integration plan. Additionally, Annex 1 presented an exhaustive list of the components provided by each partner and Annex 2 presented a description of the various RAN splits under study in the research community and their requirements.

4.2.5.2. Task 5.3 – Evaluation and Experimentation

As part of this task, specific experiments were designed for each of the demonstrations to validate and quantitatively evaluate the integrated operation of the 5G-Crosshaul architectural building blocks. A catalogue of experiments was defined for the four demonstrations in the project. A big effort was put on the definition of experiments towards integration of as much conceptually-related technologies as possible in a single experiment setup. This definition was done by always bearing in mind the practical constraints imposed by the physical deployments in place.

The catalogue of experiments run in the 5G-Crosshaul testbed across different locations integrating diverse technologies and functions and serve as proof that the concepts proposed in the project meet the 5G Key Performance Indicators (KPIs) and the objectives of the project. All experiments have been defined to provide quantifiable measurements aligned with those KPIs and objectives. As such, the results of this experimentation are the basis for dissemination and exploitation activities done in the project.

Notice also that various experimental setups covering some aspects of the four demonstrations have been presented in multiple events, including Mobile World Congress 2016 and 2017, EUCNC 2016 and 2017, the second Global 5G event (2016), WWRF39, IEEE NFV-SDN 2017, and various papers including experimental evaluations of technologies of the technical WPs have been presented in international conferences (e.g., EUCNC'17) or are under revision.

Key Achievements

Demo 1 focuses on demonstrating the applicability of the **5G-Crosshaul energy efficiency** concepts through different types of network technologies. Furthermore, it has demonstrated the feasibility of **power consumption monitoring** not only for physical infrastructure elements (XPFEs, XPUs), but also virtual or service-level entities like network paths, virtual network functions (VNFs) or tenants. The results have shown that the power consumption of a node can be decomposed into a constant baseline component and a traffic load dependent component. For the system under evaluation, the constant component is around 21 W in sleeping mode and 35 W in active mode, while the variable component due to the traffic load is very low, in the order of hundreds of mW (e.g., around 500mW for 1Gbps traffic for the devices under test). It has also been demonstrated the **on-demand provisioning of energy-efficient network connections** over the 5G-Crosshaul Packet Forwarding Engine (XPFE) and Radio over Fibre (RoF) domains, with automated regulation of device´s power states (i.e., sleeping mode, active mode with low traffic, active mode with high traffic). In both domains, the results achieved have provided measurable energy savings. For instance, in the XPFE scenario, without connections, we reach a power saving of 84 W when compared with the 210W of the "always on" approach (around 40%), while with a single path established, the power saving is of 42 W (around 20% reduction). **Scalability** of the energy saving algorithms was evaluated by emulating in mininet realistic topologies (including a 51-node regional network in the North-West of Italy and networks of up to

250 nodes). Under worst case traffic conditions (i.e., maximum traffic load) a global energy saving of 12% can be achieved (due to switching off 6 nodes). This saving must be added to those studied in WP1 (of up to 70%). Additionally, energy savings of 78.6%, which is equivalent to energy savings of approx. 17257 KJ per day, are achieved for the RoF system in the high-speed train site by appropriately switching on and off the RoF nodes. In the same way, substantial energy savings were obtained in the mmWave mesh topology under evaluation. These savings increase around 20% for each additional node that can be switched off as a function of traffic demand.

One additional key aspect to consider is that of service provisioning time, including the switching between different energy management states (when applicable). For the scenario under evaluation, connection setup time for network paths crossing three nodes is in the order of 3 seconds when an XPFE power state change is required. It is less than 1 second otherwise. Scalability tests were run with realistic topologies ranging from 50 to 250 nodes, the average connection setup time remains under 1s (i.e., 0.78s), though it may reach up to 7 seconds for the 250-node network if many nodes must change power state.

Additionally, when **IT resources** are involved (i.e., with automatic activation of the servers where vEPC virtual network functions are deployed), the average network service provisioning time is nearly 5 minutes, out of which the main component is virtual network function (VNF) configuration triggered and orchestrated at the network function virtualisation (NFV) Orchestrator and executed within each VNF followed by the virtual VNF virtual machine (VM) creation. Notice that the deployed VNFs result in fronthaul and backhaul traffic handled by the 5G-Crosshaul Control Infrastructure (XCI). These measurements demonstrate how network function virtualization and smart resource orchestration can effectively reduce the delivery time up to just a few minutes, even for complex end-to-end services, while guaranteeing an energy-efficient sharing of the infrastructure.

In summary, these results contribute in fulfilling the project and 5G PPP KPIs and objectives of reducing the energy consumption by 30% (and more) through energy management, and enabling the provisioning of 5G-Crosshaul services in the order of magnitude of minutes (instead of current values in the order of hours or days).

In the experiments of ***demo 2***, we have shown that the TV broadcasting and Video on Demand (VoD) services can be easily deployed on the 5G-Crosshaul network using the 5G-Crosshaul Control Infrastructure (XCI) and the 5G-Crosshaul applications. The results obtained prove the feasibility of deploying virtual media (vCDN and TV broadcasting) infrastructure by exploiting the services offered by the XCI. From the XCI services perspective, the provisioning time and the self-healing capabilities have been evaluated. For Virtual Content Distribution Network (vCDN) services, the provisioning time varies from 157 s for a vCDN with one replica server to 217 s for a vCDN with four replica servers. The biggest contributor to this process is the time needed by the virtual machines to boot and complete the network configurations, ranging from 118 s to 135 s for vCDNs with 1 to 4 replica servers. The self-healing worst case scenario would require a new replica server due to a detected network failure. This new instantiation takes 45.641 s where 30 s of them correspond to the time needed by the VM to boot and apply network configurations. Regarding the load balancing offered by the vCDN, the results have shown that the values obtained for latency and throughput are better when the user is assigned to a replica server closer to the user's location (0.771 ms for latency and 749 Kbits/s for throughput) than when the user is assigned to a server located in different subnetworks (20.888 ms for latency and 354 Kbits/s for throughput).

In the same way, for the TV Broadcasting Application (TVBA), the average and standard deviation of the multicast provisioning time when the TVBA quality probe (TVBAQP) was not previously deployed are 92.72 s ± 4.54 s (8.58 s ± 0.37 s when it was pre-deployed) and it consist of: 1) average user's provisioning time of 1.47 s ± 0.41 s, 2) average Quality Probe's deployment time of 83.62 s ± 4.47 s, 3) average Quality Probe's starting time of 0.33 s ± 0.13 s, and 4) average Quality Probe's analysing time of 5.72 s ± 0.46 s. On the other hand, the TVBA can self-heal the system in an average time of 41.67 s ± 7.28 s consisting of: 1) average reaction time of 15.88 s ± 9.10 s, 2) average TVBA's decision time of 0.16 s ± 0 s, 3) average solution time of 1.72 s ± 0.39 s and 4) same Quality Probe's times as before.

Finally, the measures obtained for the Live Content Distribution through a vCDN are populated from the two previous set of results. The total provisioning service time is composed of the instantiation time of a vCDN plus the TV Multicast service deployment time. For a vCDN initially configured with 2 replica servers, the total provisioning time is 249.72 s. Additionally, the self-healing time depends on whether a new replica server needs to be instantiated due to monitoring alerts detected by the CDNMA. If the CDNMA has to deploy a new CDN node the total self-healing time is 87.27 s. However, if only the TVBA needs to configure a new path, this time is set to 41.67 s.

In summary, this demo contributed in fulfilling the project and 5G PPP KPIs and objectives on service deployment time of hours (minutes in this case, for media services) and orchestration of 5G-Crosshaul resources based on traffic load variations.

In ***demo 3***, we have shown that a complex multi-domain and multi-technology transport network can be controlled through a hierarchy of SDN controllers that expose the appropriate application programming interfaces (APIs) to the resource management application (RMA). These transport networks consist of heterogeneous technologies that need end-to-end orchestration. In the project, we evaluate a hierarchical controller for wireless/optical resources as seen from an RMA. More specifically, we deploy a hierarchical XCI for which a parent-child relationship is established between contiguous layers. At the top of the hierarchy, the parent controller is based on the IETF Application-Based Network operations (ABNO) architecture. It offers to the RMA the appropriate abstraction level (end-to-end view) and orchestrates the different child controllers, which deal with the specificities of each underlying technology. To eventually understand the end-to-end behaviour related with service setup, we evaluate each network segment (wireless and optical), each plane (application and control planes), and each layer of the hierarchy inside the XCI. The results confirm the benefits of a hierarchy of controllers in which some technology-specific local decisions can be taken by the closest controller in the hierarchy, hence saving processing and propagation time. In our case, and depending on the domain, there may be differences in path setup/restoration values observed at child vs. parent controller ranging from around 500ms to one order of magnitude (up to units of seconds). For instance, the path restoration time values in the wireless domain (hundreds of ms) and the path setup time at the child controllers (around 2.5s.) is smaller than that observed by the parent ABNO (3.349s.) and RMA (3.971s.). For the scenario under study, the main components of the path setup delay are: 1) RMA processing, 2) RMA-to-parent ABNO latency (about 60ms of RTT) for each message exchange, 3) bidirectional multilayer connection setup in the optical network (around 2.5s.), and 4) wireless domain (tens of ms) assuming a wireless control channel. Overall, experimental results provided show an average of 3.971 seconds for end-to-end (E2E) path setup delay, hence contributing to the 5G target KPI of lowering the service deployment time, in this case, multi-domain path setup, from months to minutes. In fact, these setup times are much lower than those obtained with current (manual) practice, in which values in the order of hours (or even days) are obtained.

From a service management perspective, demo 3 also evaluates the time it takes to deploy all the network resources required to deploy an LTE mobile network service featuring both fronthaul and backhaul (10.5s on average). A total of 16 unidirectional flows were set up through the multi-domain transport network between eNodeBs, remote radio units (RRU), and baseband units (BBU) at the radio access network, and with the serving/PDN gateway (SPGW) and mobility management entity (MME) at the core network.

The flexibility provided by the hierarchical XCI in the processing of a service recovery triggered by a link down event was also evaluated. This recovery process can be done either locally at the child SDN controller level (the lowest level of the control hierarchy) or centralized at the RMA level (the uppermost level of the control hierarchy). The former allows much lower recovery times (0.299s on average) at the cost of potentially suboptimal resulting paths, unlike the latter, which takes 6.652s on average for re-establishing an optimal multi-domain path.

For the sake of completeness, the deployed setup of demo3 has been also analysed from the data plane perspective. The assessed transport setup offers around 153 Mbps end-to-end (E2E), which is mainly limited by a virtual private network (VPN) connection between remote sites, and where emulated users using the previously mentioned LTE mobile network service and placed at both edges of the setup achieve up to 140 Mbps.

In summary, the work carried out in demo 3 contributes in fulfilling the project and 5GPP KPIs objectives of enabling the introduction/provisioning of new 5G-Crosshaul services in the order of magnitude of minutes (seconds in this case). It offers a scalable management framework through its hierarchical deployment, and enables the deployment of novel applications and the orchestration of 5G-Crosshaul resources reducing the network management Operational Expenditure (OPEX) due to the flexibility and programmability offered by the XCI in a multi-domain multi-technology setup, which will be the norm in 5G network deployments.

Finally, ***demo 4*** combines a variety of data plane technologies and evaluates what radio access network (RAN) split options can be supported by each combination of technologies. The split options range between option 8 – split PHY – and option 1 – RLC-RRC. In this way, it is clearer for operators how to build the integrated fronthaul and backhaul at the data plane level to comply with given transport requirements.

We have integrated both backhaul and fronthaul traffic support over the same integrated infrastructure combining wavelength-selected wavelength division multiplexing passive optical network (WS-WDM-PON) that multiplexes traffic coming from 5G-Crosshaul Packet Forwarding Elements (XPFEs) and Radio-over-Fibre (RoF) technology. Data rates and latency measurements of WS-WDM-PON guarantee up to RAN split option 6 (symmetric 10Gbps per point-to-point dense WDM link). The data rates and latencies requirements up to RAN split option 6 are also supported in combination with an XPFE. In addition, Error Vector Magnitude (EVM) results with/without RoF integration are included, which are always below 2.5%. Therefore, it was experimentally validated that WS-WDM-PON+XPFE and RoF can coexist without any performance degradation. To support lower-layer splits in an efficient manner, innovative techniques were also evaluated. In fact, the mixed digital/analogue radio over fibre implementation allows sending up to 11.05 Gb/s (9 x CPRI 2) CPRI-equivalent bit-rate using less than 200 MHz bandwidth of an off-the-shelf optical transponder, which represents a remarkable spectral efficiency improvement compared to conventional CPRI. The system also allows reaching 36 km distance while still complying with the 3GPP EVM requirements.

We have integrated several transport technologies to a network transporting simultaneously backhaul and fronthaul traffic for both upper (option 2) and lower layer functional splits (options 6 and 8). They include mmWave, 5G-Crosshaul Circuit Switching Element (XCSE), and XPFE. In this setup, we demonstrated that the XCSE guarantees the required rates for all flows, independently of the functional split used (including the most demanding option 8 split). The compressed and packetized fronthaul traffic was also tested and transported over the XCSE, which generated fronthaul traffic of 262.4 Mbps. We also observed that the Fast Forward mmWave together with the XCSE can satisfy the one-way delay constraints imposed by the MAC-PHY split (the average round trip time (RTT) is 0.26 ms). This is also the case with high-load UDP traffic, where the RTT average value is 0.44 ms. The maximum RTT obtained with background traffic suggests that constraints are also satisfied if we take as reference the documents of the small cell forum, because the average of the maximum results is 1.27 ms, with a maximum of 1.5 ms. Other more stringent implementations and recommendations may not be fulfilled in all cases. In that case, prioritization of the fronthaul traffic over the backhaul traffic would reduce its impact, and so, lower layer splits would also be supported, as explained above for the WS-WDM-PON+XPFE setup.

Other functional tests done between the UE all the way through the mobile network (and the underlying 5G-Crosshaul transport) and up to an Iperf server resulted in the following measurements. The rates of the higher layer split under evaluation (option 2) is 18.28 Mbps in the downlink and 25.73 Mbps in the uplink; in other lower layer splits under evaluation (option 6), the rate is 67.65 Mbps in the downlink and 17.46 Mbps in the uplink; for the backhaul traffic, the resulting rate is 8.71 Mbps in the downlink and 10.37 Mbps in the uplink. The user equipment (UE) connected to the option 8 split remote radio unit (RRU) results in 45.504 Mbps in the downlink. These rates are achieved independently from whether there is simultaneous traffic of other UEs in the setup and show that the different functional splits are actually supported.

In a more focused setup, we demonstrated for a combination of mmWave and optical links (hybrid link) the feasibility to support higher-layer functional splits (option 2). The average latency values, depending on link technology of 0.5 ms to 1.5 ms are not suitable for lower layer splits, i.e., split options 5 to 8. These splits are within the hybrid automated repeat request (HARQ) loop and require shorter latencies. The split of the RLC, i.e., split option 4, is possible from a latency perspective, but requires higher bandwidth. Although the hybrid link provides more bandwidth than the individual ones, this is traded off by a latency increase. Therefore, these technologies can be used for splits between RLC and PDCP and for BH traffic only, i.e., split options 1 to 3 are supported.

In summary, the results confirm that the variety of technologies combined with their specific characteristics allow serving the needs of all RAN split options and contribute to fulfil the project and 5GPPP KPIs and objectives. More specifically, they contribute to increase the number of devices handled by the network, to reduce its CAPEX and OPEX, to find the appropriate settings in the quest to reduce latencies below 1ms and to increase the global throughput of the network.

4.2.5.3.Deviations

None detected.

4.2.5.4.Corrective actions

None required.

4.2.6. WP6: Dissemination and Communication Activities

4.2.6.1.Progress and achievements in this period

In this second period, WP6 continued its communications and dissemination activities to ensure maximum impact of the technological innovations output of the project. The activities undertaken are reported in two deliverables, namely D6.2 for the Year 2 (from 01 July 2016 to 30 June 2017) and D6.3 for the Year 3 (from 01 July 2017 to 31 December 2017).

In Year 2, WP6 deployed a range of activities to accompany the accelerated technology development in the technical work packages. These activities resulted in key achievements highlighted below:

- A noticeable presence at Mobile World Congress 2017, with a full programme including demonstrations, panel, invited talks, videos, leaflet, and press release.
- An active communication and dissemination through 25 talks and panels, and 5 organized workshops, in addition to press releases, videos, and interviews.
- A significant record of scientific peer-reviewed publications with 46 articles published or accepted for publication (and several others submitted) in reputed IEEE and ACM journals/magazines and conferences proceedings.
- A significant boost in the number of contributions submitted to standardization forums, with 19 contributions submitted in various groups, such as IEEE, ONF, IETF, and eCPRI.
- A proactive identification of key innovations from the project together with pre-commercial proof-of-concepts, and a new product (AnyHaul) from 5G-Crossaul partner Nokia, which all bear a good potential for further exploitation.

In Year 3, WP6 continued its full range of activities and added further achievements to this period noticeably:

- Release of eCPRI standard specification including contributions from 5G-Crosshaul partners.
- Addition of 17 more publications, 10 talks, and 2 workshops organized.
- Delivery of videos and video interviews on various demonstrations showcasing the technological innovations developed within the project.

In addition, WP6 planned for further activities going beyond the project lifetime noticeably in terms of communication for the shorter term for example to accompany MWC'18, and in terms of standardization and exploitation activities in the medium and longer terms. Partners within the consortium will also make use of the EU free services for disseminating project results provided by the Common Dissemination Booster (CDB). Up to five services will be available for 5G-Crosshaul members during 2018 to maximize the reach and impact of the innovations developed in the project.

Cumulatively over the project lifetime from 01 July 2015 to 31 December 2017, the project exceeded on all metrics set for the targeted objectives. An impressive record of activities has been achieved as highlighted below:

- Over 35 normative contributions feeding into key standardization specifications such as: eCPRI, G.metro, IETF CCAMP, IETF DETNET, and ONF. This is in addition to some 25 (informative) dissemination activities in standardization bodies and forums such as NGMN, ITU-T, FSAN, ETSI, IEEE, BBF, ONF.
- Nearly 100 peer-reviewed publications in IEEE and ACM proceedings, journals and magazines, over 75 talks and panels delivered at key events, and nearly 15 workshops and special sessions (co-) organized.

- Over 25 demonstrations exhibited at various events including at the flagship Mobile World Congress both in 2016 and 2017 and at the EC conference EuCNC in 2016 and 2017.
- Some 5 patent applications developed and reported by the project consortium.
- Proactive communication through blogs, press releases, video interviews, and leaflets, all actively promoted through various channels.

4.2.6.2.Deviations

None detected.

4.2.6.3.Corrective actions

None required.

4.2.7. WP7: Project Management

The management of the project, dedicated WP in the DoA, is led by UC3M. The main activities of this WP are related to ensure that the project runs successfully, that the partners collaborates each other and the technical objectives are achieved taking care of the time and the costs of the project. The project coordinator (PC) administered the financial contribution, allocating it between the beneficiaries, and activities in accordance to the Grant Agreement. The payments have been done with no delay. The PC kept the records and financial accounting, and informed the Commission of the distribution of the financial contribution of the Union. The PC verified consistency between the reports and the project tasks and monitors the compliance of beneficiaries with their obligations.

One deliverable has been delivered in time: i) D7.3 Final project report (December 30th 2017, this deliverable). Deliverable D7.3: Final project report, includes a description of the overall advances, progress and results of the project during its whole lifetime.

Two amendments have been done during the second reporting period:

Amendment 2, approved 1st of March 2017:

- Termination of participation in the project of EBlink. The reason for this termination was that the company entered into bankruptcy procedure.
- Change of legal name of CREATE-NET and Transfer of Rights and Obligation to Fondazione Bruno Kessler.

Amendment 3, approved 28th of April 2017:

- Reallocation of E-Blink remaining budget: The final remaining budget of E-Blink has been allocated to the partners that will carry out the EBlink pending tasks.
- Taking into account the total remaining budget of direct costs and the EBlink pending tasks were:

    - WP1: 1.18 PMs
    - WP2: 2.87PMs
    - WP3: 1.7PMs
    - WP5: 8.63PMs
    - WP6: 1.58PMs
- The budget has been reallocated between the following partners:
    - Transfer of 12,5 PMs to IDCC. In the following work packages WP3: 2PMs, WP5: 8.5 PMs and WP6: 2PMs.
    - Transfer of 3,73 PMs to EAB. That budget is allocated in in WP2 (2.73PMs in T2.4) and WP5 (1PM in T5.3).
    - Transfer of 1,32PMs to WP5 TEI.
    - WP1 is going to be finish without any reallocation of budget.
- Redistribution of UC3M budget: The UC3M budget has been redistributed in order to reach all the objectives of the project.
    - Transfer of 20,000 euros of direct costs from the cost category of personnel to the cost category of external services, for U. Carlos III. The motivation for this is that we will use this funding to pay for 1/3 of the membership fee of 5TONIC testbed, in order to demonstrate the projects results in it.
    - Transfer of 3PMs to CREATE-NET (WP5)
    - Transfer of 1,95PMs to WP5 CTTC.
- WP2 Leader change: Paola Iovanna from TEI becomes the new WP2 leader and she will continue to be the Innovation Manager of the project too.
- WP3 Leader change: Thomas Deiß from NOKIA has become the new WP3 Leader instead of Dirk Tiegelbekkers from the same organization.
- Reallocation of VISIONA PMs: During first period great effort has been made by members of VISIONA Team to progress in the development tasks linked to the 5G-Crosshaul aware media distribution service. Thus, until month M12, a total effort of 10PM up to the 15PM initially planned for Task 4.3 (M1-M28) were required to progress on the development of TVBA application; meaning a remanent of 5PM until the end of this task.
    - Taking into account the current status of developments, it is estimated that at least 8PM will be required to finalize development of TVBA Panel Control components and its complete integration for M24, when consolidated design for the enabled innovations through 5G-Crosshaul will be really achieved. VISIONA reaches the conclusion that tasks related to routing and adaptation to SDN controller were underestimated at the beginning of the project. A deviation from planned effort for QMR5, QMR6, QMR7 and QMR8 is therefore expected (in average, 2PM will be reported per QMR in the next 12 months for WP4). Furthermore, during QMR9 (M25-M27) final feedback from WP5 experiments running in parallel will be received so it is estimated that at least 0.5PM for final adjustment of the developments would be required. This means a total effort for finalizing WP4 tasks of 8.5PM instead of the 5PM initially planned (increment 3.5PM).

    - At the same time, VISIONA currently counts on 4PM of remaining effort in T2.2 (M1-M26) Technology integration and network architecture. It is their intention to continue participating in the call conferences and face to face meetings organized by WP2 leader ensuring TVBA requirements in terms of bandwidth and bounded latency are taken into account (estimated in 0.5PM). However, given the nature of our TVBA application, it is neither expected a hard redefinition of their specifications nor an impact on the underlying technologies at lower level layers. As a conclusion, VISIONA could take advantage of a total effort of 3.5PM from this WP2 to ensure success in other workpackages like WP4.
- Third party ATOS: Atos IT Solutions and Services Iberia SL is the Linked Third Party of ATOS Spain. Atos IT Solutions and Services is a company of Atos group that offers business and IT services consulting as well as vertical solutions in financial, utilities and telecom services. There was a reassignment of some members of Atos R&D team that belong to Atos IT Solutions and Services and were appointed to 5G CROSSHAUL. This was originally foreseen but their knowledge will help to improve the 5G CROSSHAUL demonstration activities.
    - Atos IT Solutions and Services will participate in the project providing the expertise with regards to Network Virtualization and Content Delivery Networks. In WP3 Atos IT Solutions and Services will work in T3.2 in order to develop the MANO components (Orchestrator and VNF manager) for the CDN application. In WP5 (Validation and proof-of-concept), Atos IT Solutions and Services will collaborate in T5.2 and T5.3 working on the vCDN demo, media distribution exploiting the services of Crosshaul.
- Reallocation of TELNET PMs: Extra adjustment in TELNET figures is required due to resources already consumed in Period 1 before reallocation of resources in Amendment 1 (AMD-671598-9). As a result, WP3 increase in 0.84 PMs and WP4 in 1.45 PMs. The total figures of PMs of TELNET remain the same (WP1, WP5 and WP6 decrease to compensate it).
- Reallocation of HHI PMs: Extra adjustment in HHI figures is required due to resources already consumed in Period 1 before reallocation of resources in Amendment 1 (AMD-671598-9). As a result, WP7 increase in 0.60 PMs. The total figures of PMs of HHI remain the same because T2.2 decrease in 0.60 PMs.
- Change in NOKIA PMs value: Due to an error made by Nokia in the project proposal phase, the Person month cost declared in Annex I was a lower cost than the one declared in the Periodic Report I.
    - Nokia has committed to deliver the planned resources to the project and accepts that no additional funding is available.
    - Part of the person months are refunded with the certified cost for Nokia and part of the person months will be provided by Nokia without refunding by the EU.

- Redistribution of ORANGE PMs: During the last year, Orange activities have been mostly focused on the evaluation of different radio access network (RAN) architectures at a data plane level.
    - Indeed, in view of Eblink's current situation and their need to seek bankruptcy protection under French law, Orange's been leading the research activities related to the mixed Analog/Digital Radio over Fibre (A/D-RoF) experiments. At a first moment, those were related to the WP 2 in the sense that they deal with the experimental characterization of Eblink's system and the analysis of their proposed architecture. Such work will be crucial on a second moment, for the WP 5 since Orange will lead the A/D-RoF experiment on Demo 4 test bench.
    - Furthermore, Orange's been participating on other evaluation activities on different RAN interfaces other that the Analog Radio over Fibre. Orange experience has shown them that such work will be very important on the proposal of different experiments that will be taking place on WP 5 with different RAN functional splits.
    - The demanded redistribution of efforts should be the following, WP1 decrease the amount of PMs from 8 to 4.5, the WP2 PMs increase from 8 to 13 and the WP5 PMs fall from 7 to 5.5. The total person months over all work packages, remains unchanged.
- Redistribution of EAB PMs: EAB will move 2 PMs from T2.3 to T2.4. The reason of the change is that Task 2.3 is specified to define the adaptation layer for controlling different BH/FH technologies. We have designed our packetized FH based on OpenFlow compliant Ethernet switches. An OpenFlow compliant controller which will be used in 5G-Crosshaul is supported. So there is no need for such an adaptation layer for our part of work in WP2. By moving the efforts to T2.4, we will be able to concentrate more the contributions in the compressed FH work, especially in prototyping.
- Reallocation of CREATE-NET PMs: In order to finalize the work on algorithms CREATE-NET will allocate 4 PMs from WP3 to WP4.
- Addition of risks in the project: In order to take into account additional project risks, in case of withdrawal of a partner or underperforming of a partner, the following items and countermeasures have been added.

Risk item	Probability	Impact	Countermeasure
Withdrawal of critical partner	Very Low	Strong	The Project Board (PB) will decide if either other partner(s) take over activities, or to initiate the process for replacement as soon as possible. Maintain contacts with possible alternative partners that can take up the role. Create open atmosphere between partners and management to get early indication of withdrawal.
Withdrawal of non-critical,	Low	Weak	Create open atmosphere between partners and management to get early indication of withdrawal

project partners			Prioritise remaining work and re-allocate resources.
A partner becomes deficient or entirely remiss in the execution of assigned obligations	Medium	Strong	Most of the organisations comprising the consortium have long experience in EU projects and large-scale projects, whereas several of them have worked together in various EU projects. In case that a partner becomes deficient, the Coordinator and Project Board will accord 1 month for corrective action and if negative, the workload and budget will be redistributed between partners or a substitute partner will be introduced.
Loss of critical competencies or of key people in the project	Medium	Strong	Get early indication of possible withdrawal of key persons from partner if not internally replaceable. Contact all partners on the availability of comparable competencies amongst other partners of the project (budget will be shifted from the “defaulting” partner to the partner that provides the competencies.) In the case that competencies are not available within the project, the Project Coordinator will initiate adding a new partner to the consortium and the shift of budget from the defaulting partner.

4.2.7.1.Task 7.1 - Project, administrative, financial, and legal management

In this period (M12-M30) 6 plenary meeting were held:

- 5th plenary meeting on 30th of June and 1st of July 2016 in Athens.
- 6th plenary meeting on 22nd – 24th of November 2017 in Madrid, at UC3M.
- 7th plenary meeting on 7th – 9th of March 2017 in Turin, at TIM.
- 8th plenary meeting on 30th – 31st of May 2017 in Stockholm, at EAB.
- 9th plenary meeting on 18th–19th of September 2017 in Madrid, UC3M.
- 10th plenary meeting on 14th and 15th of December 2017 in Madrid, UC3M.

Every plenary meeting has been organized according to the premise of cost effectiveness, trying to collocate the plenary meetings with any activity requiring strong presence from the consortium partners.

Bi-weekly technical remote meetings (per WP) were held to allow synchronization between the different partners using a collaborative tool for audioconferences (Join.Me and WebEx). During the conference calls several topics are discussed related to activities which illustrated the WPs update in the period. In a shared calendar, the remote meetings were planned in order to inform all the partners of the date and hour.

A report of the project progress in terms of technical activities and resources allocation is planned each three months by means the Quarterly Management Reports. A final report is presented at the end of this document.

The Consortium used the following tools for the management of the project:

- Redmine: a web based tool for the description of the activities and the coordination between the partners. A dedicated section has been created as repository of the meeting minutes. This includes a shared calendar for meetings bookkeeping.
- SVN repository: the repository where documentation and software have been stored and shared among the partners.
- Twelve mailing list has been created in order to communicate with the partners: xhaul-all, xhaul-admin, xhaul-netmaster, xhaul-dissemination, xhaul-legal, xhaul-wp1, xhaul-wp2, xhaul-wp3, xhaul-wp4, xhaul-wp5, xhaul-wp6 and xhaul-wp7.

The 5G-Crosshaul website is available from the beginning of the project (www.5g-crosshaul.eu). Moreover a twitter account has been created and available at @Crosshaul.eu and also a linkedin account https://www.linkedin.com/in/5g-crosshaul-project-221178101 and a linkedin account with 168 contacts linkedin.com/in/5g-crosshaul-project-221178101 and a linkedin group https://www.linkedin.com/groups/8344554 with 118 members (numbers taken at 24/11/2017).

4.2.7.2. Task 7.2 - Technical coordination, Innovation and Quality management

This task is led by NEC as technical manager and UC3M and TEI participate as project coordinator and innovation manager. NEC as the project technical manager, leads the technical innovations for the project and coordinating the work of all WPs. UC3M as project coordinator ensures the project progresses towards its objectives. TEI as the innovation manager has monitored the innovation and exploitation activities. As part of this task, the three managers have worked closely with the companies and SMEs of the consortium to fill the different questionnaires regarding innovation provided by the EC.

4.2.7.3. Task 7.3 - Interaction with other projects of the H2020 5G Infrastructure PPP

5G-Crosshaul has been active in 5G-PPP cross-projects collaboration activities, including the CSA working groups, METIS-II initiative on use cases and performance evaluation, and joint workshops.

CSA Working group	Description	Lead partner
Vision & Societal Perspective	Regular participation in the conference calls Inputs for 5G PPP Work Programme: • Comments on 2016-2017 WP text. Feedback on Phase1 portfolio and to recommendations and budget for WP2. • Definition of experimentation strategies and Phase 3 scoping paper	TI
Architecture	Regular participation in the conference calls and f2f meetings Participation on Golden Nuggets, Euro 5G Journal, Project	NEC/NOKIA

	cartography and other requests from the 5G IA. Contribution to the 5G PPP Revised Architecture paper for Public consultation – (White Paper) July 2017. Available: https://5g-ppp.eu/wp-content/uploads/2017/07/5G-PPP-5G-Architecture-White-Paper-2-Summer-2017_For-Public-Consultation.pdf	/UC3M/IDCC
Pre-standards	Regular participation in the conference calls. 5G-Crosshaul supported the WG proposal for EUCNC workshop and serving in the TPC	IDCC
Spectrum	Regular participation in the conference calls. Authors of paper presenting the WG vision on mmWave: Kuo, Ping-Heng, and Alain Mourad. "Millimeter wave for 5G mobile fronthaul and backhaul." *Networks and Communications (EuCNC), 2017 European Conference on*. IEEE, 2017. Available: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7980750	UC3M/IDCC
Net management, QoS and Security	Co-Authors of White Paper "5G-PPP Cognitive Network Management for 5G" (March 2017) by the NETMGMT Working Group. The paper is available here: https://5g-ppp.eu/white-papers/	POLITO
Software Networks	Submission of proposal for a full-day workshop at EuCNC Participation in regular telcos every 3-4 weeks Participation on the White Paper: Vision on Software Networks and 5G SN WG – January 2017. Available: https://5g-ppp.eu/wp-content/uploads/2014/02/5G-PPP_SoftNets_WG_whitepaper_v20.pdf UC3M has been co-chairing the Software Networks WG for the reporting period.	NOKIA/UC3M
KPIs	Participation in audioconferences to define the common metrics to measure the KPI performance improvements. 5G-Crosshaul has also participated by delivering several documents regarding the KPI measurements used within the project.	UC3M
Trials	Participation on the 5G-PPP Trials WG to define the Phase 3 pre-structuring model, as well as other activities of the Trial	VISIONA
SME	Participation in order to find new collaboration opportunities within the SME ecosystem. Participation at the 5G PPP SME WG booth at EUCNC 2017 (https://5g-ppp.eu/sme-booth-eucnc-2017-approved/) with interview (https://www.youtube.com/watch?v=tx_5iyDZPM4) and videos about demonstration of research activities in 5G-Crosshaul and SELFNET projects.	VISIONA/NXW

5G PPP Community Building Group	Participation on the audioconferences of this newly created group	UC3M
5G Common Dissemination Cluster	5G-Crosshaul has defined a cluster with 5G-CORAL and 5G-Transformer projects. It has requested the support for all 5 services and has been granted them.	UC3M

4.2.7.4. Deviations

The deviation in PMs is related to an upper effort in the management activities in WP7 mainly from UC3M.

The reason for this deviation is that the effort required to manage a project of this magnitude, including the participation in the different 5G-PPP bodies is much higher than expected. In addition, the management of the departure of EBlink from the project has required a considerable effort that was not planned.

Due to all these reasons, the amount of PMs devoted in this WP is higher than the ones planned.

4.2.7.5.Corrective actions

None required.

4.3.Deliverables

Table 20: Deliverables

#	Deliverable	Delivery date	On Schedule	Delayed	Completed
D1.1	5G-Crosshaul initial system design, use cases and requirements	2016-06-30			X
D1.2	Final 5G-Crosshaul system design and economic analysis	2017-12-31			X
D2.1	Study and assessment of physical and link layer technologies for 5G-Crosshaul	2016-06-30			X
D2.2	Integration of physical and link layer technologies in 5G-Crosshaul network nodes	2017-10-31			X
D3.1	XFE/XCI design at year 1, specification of southbound and northbound interface	2016-10-31			X
D3.2	Final XFE/XCI design and specification of southbound and northbound interfaces	2017-10-31			X
D4.1	Initial design of 5G-Crosshaul Applications and Algorithms	2016-10-31			X
D4.2	Final design of 5G-Crosshaul Applications and Algorithms	2017-10-31			X
D5.1	Report on validation and demonstration	2016-10-31			X

	plans				
D5.2	Report on validation and demonstration results	2017-12-31			X
D6.1	Year 1 achievements and plan for Year 2	2016-06-30			X
D6.2	Year 2 achievements and plan for Year 3 X	2017-06-30			X
D6.3	Year 3 achievements and future plans	2017-12-31			X
D7.1	Project handbook	2015-07-31			X
D7.2	First periodic report of the project	2016-06-30			X
D7.3	Final Project Report	2017-12-31			X

4.4.Milestones

Table 21: Milestones

#	Milestone	Delivery date	On Schedule	Delayed	Completed
MS1	Initial set of use cases and requirements available.	2015-10-30		One month	X
MS2	Initial specification of the 5G-Crosshaul System Design available.	2016-02-29			X
MS3	Initial XFE/XCI design, including southbound and northbound APIs available. Testbed setup completed. Integration task started.	2016-06-30			X
MS4	List of applications running on top of the XCI completed. Initial application implementation. Experimental validation task starts.	2016-10-31			X
MS5	Economic Analysis complete. Initial experimental evaluation results.	2017-03-31			X
MS6	Consolidated system design. Results from experimental evaluation available.	2017-08-31			X
MS7	Final System Design. XFE/XCI and applications design complete. PoC available.	2017-12-31			X

4.5. Exploitable Results

One of the relevant aspects of the project is the activity carried out for exploitation of the main innovation results. Actually, it has been defined a well-defined exploitation plan that allowed to identify relevant exploitable results that have been obtained as outputs of the multitude of activities carried out over the last two and half years. In particular exploitable results can be identified in terms of key innovations, proof of concepts, commercial grade products, and patents.

4.5.1. Exploitation of commercial products or PoC developed internally to the Company

Relevant part of the exploitation plan has been the definition of a strategy to identify and favour the exploitation of main output of the project on commercial products. Actually, some of the outputs directly map in product family already in commercial, while in some cases, internal PoC in the Company have been realized as initial step toward the realization of novel features and products. The exploitation strategy has been envisioned to:

- Identify products and services which might bear a potential impact from/to the innovations targeted by the Project;
- Identify innovations as the emerge from the technology development undertaken by the technical work packages (WP1/2/3/4/5);
- Map these innovations onto identified products and services of industrial stakeholders;
- Promote the exploitation of these innovations by the various stakeholders

Table 23 lists the key innovations that have been identified depending on the associated building blocks, namely XFE, XCI, and applications.

Table 22: Key innovations pertaining to 5G-Crosshaul building blocks.

#	**Building block**	**Innovation**	**Leading Partners**
1	XFE	Novel optical ROADM based on integrated silicon photonics to reduce cost and size of 100 times with respect current nodes.	TEI
2	XFE	A latency reduction solution for mmWave-based backhaul/fronthaul dubbed fast-forwarding was developed, in order to support wireless transport for scenarios with stringent latency requirements (e.g. lower-layer split).	IDCC
3	XFE	Novel optical access solution for crosshaul services (Packetized FH) based on WS-WDM-PON technology is evaluated in a PoC where C-RAN schemes with different functional split options and SDN support are demonstrated in terms of 5G network requirements.	Telnet
4	XFE	Extension and evaluation of a Radio Resource Management algorithm for a dense deployment of small cells with mmWave transport capabilities powered with renewable energies based on distributed Q-learning. The agents placed at each small cell running this distributed algorithm will be able to improve the energy efficiency of the system by learning from the local environment. Moreover, thanks to the activities in WP4, the agents can collaborate with EMMA application in order to include a system wide view which allows to guide the learning	CTTC

		process towards a more energy efficient solution (e.g., by avoiding conflicts among the small cells agents in multi cells scenarios).	
5	XFE	Development of a SBI agent to provide a common abstraction of wireless data-plane resources. The proposed approach decouples control operations from management operations. Thanks to this decoupling, the solution offers the required flexibility to evolve with the evolution and the integration of multiple technologies in 5G-Crosshaul networks.	All WP2 partners
6	XFE	Network solution to use multi-layer nodes (packet and optical) to support tight requirements of latency and bandwidth.	All WP2 partners
7	XFE	Local OAM was added to the data plane to support its operation. Packets for connectivity checks or latency measurements cannot be injected into the network from the SDN controllers. Local OAM allows the XPFEs themselves to generate and receive the corresponding packets. The invention provides a corresponding state machine on the XPFEs, which is under control of the SDN controllers. This allows to get accurate information on the status of the network without placing a computational burden on the SDN controllers.	UC3M, IDCC
8	XFE	Procedures were defined to integrate safely new XPFEs into existing 5G-Crosshaul networks for cases where no out-of-band management network was available. The procedures are applicable to the general case as well as to XPFEs with wireless links only.	NOK-N, IDCC
9	XFE	Compressed packetized Fronthaul to reduce bandwidth requirements for CPRI.	EAB
10	XFE	Several fronthaul splits (MAC/PHY, PDCP/RLC) have been implemented on virtual machines and dedicated processor boards. The traffic according to different fronthaul splits can be generated without changing the underlying hardware and without having to apply for spectrum at the air interface. This eases considerable test setups to evaluate network configurations.	CND
11	XFE	Central energy management application on mmWave mesh network for traffic optimization leading to significant power saving while maintaining user satisfaction based on traffic demands	HHI
12	XCI	In the control plane the VIM and the SDN controllers have been integrated to connect Virtual Machines in a Data Centre with other nodes in the Crosshaul network. The corresponding application allows the VIM to establish overlay virtual networks among Virtual Machines in Data	NOK-N, NXW

		Centres according to its own rules, e.g. using VLANs for traffic segregation. Thereafter the SDN controllers establish the network paths across the Crosshaul network, using the information provided by the VIM about the classifiers of the traffic among the VMs, in order to guarantee the required interconnectivity at the underlying transport level.	
13	XCI	An ETSI NFV-compliant MANO stack, including an NFVO and a VNFM for vEPC VNFs, has been developed introducing novel mechanisms for customized orchestration of network and computing resources, energy efficiency and integrated allocation of dedicated, QoS-enabled network connections. This NFVO allows to experiment with different optimization strategies to deploy VNFs in distributed environments and configure the transport network connectivity to guarantee QoS for VNFs' traffic.	NXW
14	XCI	The hierarchical SDN control component of the XCI of different technological domains was shown in a PoC, covering three different transport domains (one optical and two wireless domains of different partners). The hierarchical SDN model allows through network abstraction to control multiple transport network domains and at the same time to encapsulate per-domain specific technological details in the corresponding child controllers. The developed XCI hierarchical control model decreases the e2e service provision time while increasing the XCI scalability in terms of number of managed domains transporting both fronthaul and backhaul traffic, hence easing the integration of different technological transport domains.	CTTC, IDCC
15	Applications	An SDN application featuring graphical interface and the logic to manage requests for energy efficient paths and monitor power consumption for different physical (XPUs, XPFEs, entire infrastructure) or virtual (virtual paths, tenants) entities.	NXW
16	Applications	TV Broadcasting application (TVBA) – An application running as an OTT service whose purpose is to provide TV broadcasting and multicasting services through the 5G-Crosshaul network maintaining optimal QoS and QoE at user's reception.	VISONA
17	Applications	Content Delivery Network Management application (CDNMA) – A Web application comprising algorithms for management and implementation of CDN in 5G-Crosshaul network, including vCDN infrastructure instantiation, and control and management of the service during its lifetime.	ATOS

18	Applications	Resource Management application (RMA) – An application featuring algorithms for providing a centralized and automated management of 5G-Crosshaul resources, to promptly provision transport services with an adequate quality while ensuring that resources are effectively utilized. The application provides support to the VoD and live streaming services (provided by the CDNMA and TVBA applications) by provisioning the optimal path for mobile users' traffic.	NEC CREATE-NET
19	Applications	Mobility Management application (MMA) – An application based on Distributed Mobility Management (DMM) for traffic offloading optimization for media distribution like CDN and TV Broadcasting.	ITRI UC3M

Table 23 reports a map of the key innovation outputs that can have a potential impact on some area of commercials products or PoC internally developed in the Company.

Table 23: Mapping of key innovation outputs

Innovation	PoC / Product / Service	Partner
XFE **Packet**	eNB with flexible functional split PoC	CND
	Radio Dot System	Ericsson
	Router 6000 family	
	EdgeLink mmWave nodes	InterDigital
	Fast-Forward mmWave nodes	
	iPASOLINK converged packet radio	NEC
	Flexi Multiradio 10 Base Station	Nokia
	Ethernet VLAN switch	
	AnyHaul	
XFE **Circuit**	Fronthaul 6000	Ericsson
	Optical forwarding elements	
	AnyHaul	Nokia
XCI	OpenEPC	CND
	Wireless SDN Transport PoC	Ericsson

		NEC Telefonica
	Services SDN	Ericsson
	Cloud System	
	Network Manager	
	EdgeHaul SDN-based controller	InterDigital
	vEPC	NEC
	ProgrammableFlow controller	
	SDN/NFV PoC	Nextworks
	HetNet solution	Nokia
Network Apps	CDN	ATOS
	TV Broadcasting application (TVBA)	Visiona
	Energy efficiency management and monitoring	Nextworks / Polito
	Mobility management	UC3M / ITRI

Moreover, experiments and demonstration of the key innovations outputs of the Project have been implemented in test bed in the framework of WP5, allowing the creation of very fruitful environment where vendors, operators and SME cooperated to assess the new features in complex and integrated network scenarios. Such way of working creating the condition for fruitful joint work, enabling the possibility to share requirements, features and constraints and test innovative scenarios and solutions for 5G.

4.5.2. Exploitation on the realization of common platform among 5G-Crosshaul partners by means of testbed and demo developed in the WP5

Demo	Innovation	Partner
1	EMMA module for energy efficient network and IT resource management	NXW, POLITO
1	MANO extensions for energy-efficient management	NXW
1	OpenDaylight extensions for energy-efficient path setup	NXW
1	EMMA module for mmWave node energy management	HHI
1	EMMA module for energy-efficient RoF system for high-speed train	ITRI

	system	
1	ODL extensions for RoF system	ITRI
2	CDNMA application for vCDN instantiation and service management	ATOS
2	TVBA application for deploying quality probes and QoS/QoE-based service management	VISIONA
3	Hierarchical SDN control for multi-technology transport networks	CTTC
3	Hybrid mmWave/WiFi SDN controller with local recovery capabilities	CTTC
3	RMA application for QoS-based network resource management	NEC
4	XCSE multi-layer switch	TEI
4	mmWave mesh nodes (incl. fast forward capability)	IDCC
4	OpenvSwitch-based OLT	TELNET
4	XPFE switch	NOK-N
4	PDCP/RLC and MAC/PHY RAN splits	CND
4	Mixed Digital/Analog RoF	ORANGE
4	Compressed CPRI	EAB

4.5.3. Exploitation on standard

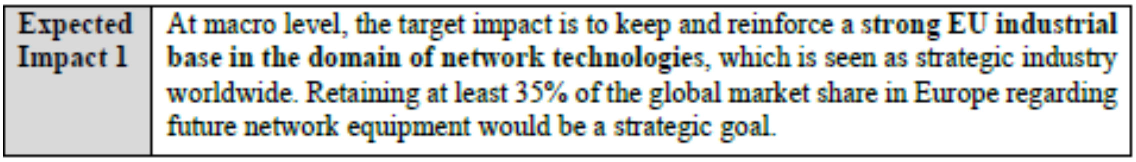
The 5G-Crosshaul project has been active in disseminating its work into relevant standardization bodies. This dissemination activity has taken two forms: (1) A first form of informative nature which included reports, presentations, and white papers for information purpose; and (2) A second form more of a normative nature which focused on technical contributions backed by technology pieces intended for acceptance into standard specifications. The activity covered all the various aspects of the integrated fronthaul and backhaul solution developed in 5G-Crosshaul. These included: use cases, requirements, architecture, network softwarization, network management and orchestration, network slicing, wireline and wireless networking interfaces and their interworking.

Success in standardization dissemination has been achieved throughout the project noticeably with:

- More than 35 normative contributions feeding into key standardization specifications such as: eCPRI, G.metro, IETF CCAMP, IETF DETNET, and ONF.
- More than 25 contributions for information purpose in several standardization bodies and forums such as NGMN, ITU-T, FSAN, ETSI, IEEE, BBF, ONF.

4.6. Impact

The 5G-Crosshaul contributions towards the expected impact reported in the section 2.1. of the DoA have been in line with the results of the Project as presented hereafter.



Expected Impact 1	At macro level, the target impact is to keep and reinforce a **strong EU industrial base in the domain of network technologies**, which is seen as strategic industry worldwide. Retaining at least 35% of the global market share in Europe regarding future network equipment would be a strategic goal.

Towards “Expected Impact 1”, the Project designed, implemented and assessed by demonstration and experiments concrete innovation outputs with high potential impact in relevant products area of the main vendors participating the Project. A list of the key innovations is provided in Table 23 above. Hereafter we present some examples these key innovations:

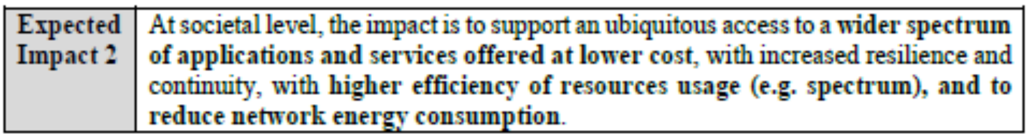
- XFE that combines both packet and circuit technology including innovative framing to support any type of traffic enabling the evolution towards 5G. In order to reduce cost, size and power consumption, novel technology for optical layer based on silicon photonics and novel modulation format have been designed.

- Fronthaul compression technique that allows to reduce the amount of bandwidth for indoor scenarios in case of use of Ethernet transport technology. Finally, the combined use of mmWave and OWC to deal with the scenarios where the fibre is not available.

- XCI that allowed to design and experiments a common control infrastructure for any technology enabling the realization of relevant application and test the technology in relevant network scenarios defined by operators.

All such technological outputs have been combined and tested through experimentations in the framework of WP5 activity providing concrete outputs for future development of related products.

Such results have been defined in continuous interworking and cooperation of the 5G-Crosshaul partners that includes relevant Mobile Network Operators (MNOs) , which have business in 14 countries in Europe (e.g. France, UK, Germany, Italy, Spain, Poland, etc.) and account for about 25% of the EU market share (84M orange, 84M Telefonica, 32M Telecom Italia), and manufactures, namely Ericsson, Nokia Networks, NEC, and InterDigital that are leading providers of fronthaul and backhaul equipment and solutions for Telecon Operators in Europe and Worldwide.



Expected Impact 2	At societal level, the impact is to support an ubiquitous access to a **wider spectrum of applications and services offered at lower cost**, with increased resilience and continuity, with **higher efficiency of resources usage (e.g. spectrum), and to reduce network energy consumption**.

For the “Expected Impact 2”, in the last one year and half, the 5G-Crosshaul provided relevant innovation outputs in line with the planned results and detailed in the following:

- Increase resources and energy efficiency by:
  - Design and verification by experiments and simulation of a novel data-plane to provide an agnostic transport where back haul and any split option of fronthaul can be combined in optimized way to better exploit the transport

resource. This includes: i) novel multi-layer nodes, where packet and circuit technology switch can be combined according the service requirements and network status; ii) innovative transmission technique such as compressed fronthaul technique to enable a consistent reduction of bandwidth in case of CPRI traffic. These outputs, demonstrated in the demo 4 of Work package 5, have been combined and assessed in a network infrastructure that included relevant network scenarios with different level of capillarity and traffic density (e.g. rural where fibre cannot be used, dense urban where there is availability of fibre, indoor and outdoor small cells) in order to provide an example of network deployment where each technology is used in the more efficient way from optimization and cost point of view.

  - XCI: also in the second period of activity the design of the common infrastructure for the control has been carried out, completed and tested in relevant experimentation carried out in WP5. In particular also the South Bound Interface (SBI) for mmWave has been completed in order to enable the dynamic selection of the right technology for energy efficiency. Extension and evaluation of a Radio Resource Management algorithm for a dense deployment of small cells with mmWave transport capabilities powered with renewable energies based on distributed Q-learning. The agents placed at each small cell running this distributed algorithm will be able to improve the energy efficiency of the system by learning from the local environment. Moreover, thanks to the activities in WP4, the agents can collaborate with EMMA application in order to include a system wide view which allows to guide the learning process towards a more energy efficient solution (e.g., by avoiding conflicts among the small cells agents in multi cells scenarios). In addition, a NFVO was developed, which is compliant to the ETSI NFV specifications and which allows using different resource orchestration mechanisms. This NFVO allows to experiment with different optimization strategies to deploy VNFs in a data centre.

- Increase the spectrum of applications and services that can be offered at low cost
  - Definition of an open API that enables the common control infrastructure (XCI) for heterogeneous data plane. In the second period of the project the development of a SBI agent to provide a common abstraction of wireless data-plane resources has been done. The proposed approach decouples control operations from management operations. Thanks to this decoupling, the solution offers the required flexibility to evolve with the evolution and the integration of multiple technologies in 5G-Crosshaul networks. Actually, a suitable North Bound Interface enable the implementation of applications and services whatever technology of data-plane is used. This approach allows to use the more suitable data-plane technology according the network scenario. In particular 12 applications have been designed and implemented in the scope of WP4 (see Section 4.2.4)

- Facilitate the network densification

  - An agnostic transport infrastructure able to concurrently support any type of traffic for fronthaul and back haul has been defined and demonstrated that includes the main following components: i) agnostic framing based on packet and circuit technology that can transport any type of traffic; multi-layer switch that combine packet and deterministic switch in order to guarantee the support of differentiated services including the case of tight requirements in latency required from 5G ;iii) suitable transmission technique such as the novel modulation format such as CAPS3 that allows to include high speed transmission at low cost, and packet compression method for indoor that allows to support high bandwidth radio interface (i.e. CPRI) also in case of plain Ethernet installed base; iv) mmWave technology combined with OWC that enables the support of 5G use case also in rural scenarios where the fibre could be scarce or too expensive; v) novel miniroadm switch based on silicon photonic technology that allows to reduce size, and cost with respect the traditional technology used in metro aggregation network (e.g. WSS) to target the cost of the 5G-Crosshaul network; vi) a dynamic control that allows the operators to dynamic configure and re-arrange the agnostic network infrastructure according his needs whatever the network scenarios is and data-plane technology is available.

- Reduce operational and investment cost
  - The agnostic transport infrastructure allows to use the more suitable technology to the network scenario, while the unique control plane allows to increase the automation and homogeneity of operational activity whatever the technology for data-plane is used. This practically means limiting the number of skilled people on the filed for operational activity.
  - Moreover, the agnostic transport network guarantees the operator to smooth evolve to future radio splits and services whatever it will be the needs without any detailed plan at the investment phase. Actually, the operator can evolve the networks when it needs without any initial over plan of the transport infrastructure.

4.6.1. Progress towards the 5GPPP Key Performance Indicators

In addition to the two main expected impacts highlighted above, the 1st year results already provide key **performance or operational indicators.** Table 24 presents the progress towards each KPI and the relation with the objectives of the project.

Table 24: KPI progress and Objectives relation

Obj	Objective description	KPI	WP	Details

1	Design of the 5G-Crosshaul Control Infrastructure (XCI)	Increase the number of connected devices per area by at least a factor of 10.	WP3	The KPI impact on the number of connected devices was achieved indirectly by the designed XCI. The XCI uses standard APIs to automatically control the network nodes, this automation allows to deploy nodes at a higher density. This allows deploying denser access networks in a cost-efficient manner. Besides, controlling multiple technological domains allows this densification even if different data link technologies are used. In turn, the denser access network allows more devices to connect to the network. Hierarchical control in the XCI, as detailed in D5.2, measured path setup times in both wireless and optical domains confirmed the advantage of a hierarchical orchestration model to cope with the higher densification of deployed data plane nodes.
		Energy-efficiency improvement by at least a factor of 3	WP3 & WP4	The implemented XCI offers the NBI services to monitor power consumption of physical/virtual network nodes (XPFEs and XPUs) as well as to configure the nodes (e.g. to switch ON/OFF nodes) for energy saving. In WP4, EMMA application was designed for serving this KPI. The EMMA evaluation results presented in D4.2 showed that the EMMA designed for different technologies can increase the energy efficiency by a factor of 3, thus reduce the energy consumption by 30%.
2	Specify the XCI's northbound (NBI) and southbound (SBI)	Enable the introduction/provisioning of new 5G-Crosshaul services in the order of magnitude of hours (e.g., VPNs, network	WP2 & WP3 &	The consecution of this KPI is a global project effort involving work of WP2, WP3 and WP4 and was demonstrated in WP5 Demo 3. WP2 contributed with the developed SBI agent to control, manage and configure a

	interfaces	slices).	WP4 & WP5	transport node including mmWave technology of Section 5.1.3 of D2.2. WP3 defined interfaces to accelerate the integration of new physical technologies (SBI) and the introduction of new services (NBI). Instead of deploying new services manually, they can be deployed automatically and their deployment can be greatly reduced. In WP4, EMMA, VIMaP, CDNMA, TVBA applications were developed to reduce the 5G-Crosshaul service provisioning time. The evaluation results of these applications (as reported in D4.2) verified that their provided services can be provisioned in the order of magnitude of minutes, which satisfied this KPI target. The experimental activities in WP5 have evaluated the provisioning time for network connections and Network Services with instantiation and configuration of VNFs over real test-beds deploying 5G-Crosshaul data plane technologies and software prototypes, including the XCI components. These experiments, detailed in D5.2, showed a provisioning time of few seconds for intra- and inter-domain network connections and few minutes for vEPC NSs with up to 4 VNFs (mostly caused by the time required by VM instantiation and booting).
3	Unify the 5G-Crosshaul data plane	CAPEX and OPEX savings due to unified data plane (25%) and multi-tenancy (>80%, depending on the number of tenants)	WP1 & WP2 & WP3	WP3 jointly with WP2 developed the XFE and XCF as a common and flexible frame format to carry both fronthaul and backhaul traffic through the network. The measurements of throughput, latency/jitter (detailed in D5.2) indicated that the flexible design of switches and frame format are able to satisfy the requirements of fronthaul and backhaul traffic.

				CAPEX and OPEX savings are determined indirectly via the more efficient use of the network devices. The CAPEX and OPEX of XFEs were analysed in the cost model developed in WP1 (described in IR1.3 and D1.2) against the costs of existing hardware switches. This cost model covers energy savings as well. Multiple tenants are supported by the developed XCI and the XFEs.
		80% increased energy efficiency due to consolidation of equipment.	WP3	Power consumption is determined by a tool evaluating power consumption on a network wide level.
4	Develop physical and link-layer technologies to support 5G requirements	10Gb/s over 1000m distance with hybrid wireless optical/mmWave	WP2	Technology investigation in WP2. Contribution to this KPI with hybrid mmWave/visible optical links.
		Latency of < 1ms between 5G Point of Attachment (PoA) and mobile core	WP2 & WP3	Link layer technologies have been investigated in WP2. L2 switching technologies were investigated in WP3. The measurements of data plane throughput, latency/jitter indicated the more flexible devices are able to satisfy the requirements of fronthaul and backhaul traffic.
5	Increase cost-effectiveness of transport technologies for ultra-dense access	Reduce TCO by 30% by improved optical transmission and sharing mobile and fixed access equipment	WP1 & WP4	MTA application results (presented in D4.2) verified this KPI has been achieved by sharing the 5G-Corsshaul infrastructure for multiple tenant operator networks.

	networks	Reduce energy cost per bit by a factor of 10.	WP4	EMMA for multi-tier networks (EMMA-EH) has evaluated this KPI and the evaluation results shown in D4.2 demonstrated that this KPI is satisfied with the EMMA.
		Reduce TCO of indoor systems by 50% compared to Distributed Antenna Systems.	WP1	WP1 has provided Techno-Economic Analysis (Task 1.3) providing evaluations in terms of TCO. D1.2 evaluated the cost of small-cell for different indoor technologies.
6	Design scalable algorithms for efficient 5G-Crosshaul resource orchestration	Scalable management framework: algorithms that can support 10 times increased node densities.	WP3 & WP4	WP3 has developed the XCI, including an algorithm for network optimization. The relevant aspect here is the scalability of the algorithms, being able to handle networks with 10 times more nodes. In addition, resource consumption, especially CPU usage, was measured to demonstrate that the XCI scales up. Topology and size of reference configurations are based on the topologies described in D1.2. WP4 developed RMA, EMMA, VIMaP, MMA applications, which have demonstrated the designed algorithms are scalable. The results presented in D4.2 showed that they all can support varying network size.
		Enable deployment of novel applications reducing the network management Operational Expenditure (OPEX) by 10% in terms of provisioning.	WP4	The MTA application developed in WP4 addressed this KPI. The results presented in D4.2 have demonstrated the reduction on CAPEX and OPEX using the MTA over different sharing percentages.
		Increase of total 5G-Crosshaul network throughput by > 20% by means of resource optimization alone compared to current operators' practice.	WP4	The RMA and MMA applications developed in WP4 have addressed this KPI. The results presented in D4.2 verified the network throughput can be improved with the designed applications.

7	Design essential 5G-Crosshaul-integrated (control/planning) applications	Reduce energy consumption in the 5G-Crosshaul by 30% through energy management.	WP3 & WP4	WP4 jointly with WP3, have developed applications to reduce energy consumption in the 5G Crosshaul by 30% through energy management application - EMMA. WP3: In the XCI, the control of optimal scheduling of equipment sleep cycles, routing and function placement is the key functional enabler for the Energy Monitoring and Management Application. WP4: The different EMMA applications developed for different technologies (see section 4.2.4.4 - 4.2.4.7) addressed this KPI. The EMMA results reported in D4.2 verified that the EMMA designed for different technologies can reduce the energy consumption by 30%.
		Reduction of 5G-Crosshaul infrastructure Capital Expenditure (CAPEX) by 20% due to automated planning.	WP4	The MTA application developed in WP4 addressed this KPI. The evaluation results presented in D4.2 showed the gain of MTA on reducing both CAPEX and OPEX compared to the legacy solution of static sharing, meeting the KPI target.
8	5G-Crosshaul key concept validation and proof of concept	Orchestration of 5G-Crosshaul resources based on traffic load variations: event-driven capacity surge, broadcast services and high-speed trains.	WP5	In WP5, the integrated demo 1, 2 and 4 (see section 4.2.5) demonstrated this KPI, the detailed test results were reported in D5.2.
		Self-healing mechanisms for unexpected 5G-Crosshaul link failures through alternative path routing in mesh topologies.	WP3 & WP4 & WP5	In WP5, the integrated demo 3 and 4 (see section 4.2.5) demonstrated this KPI, the detailed test results were reported in D5.2. WP3 contributed to the integrated demo in the testbed providing XCI and XFE components. Specifically, WP3 developed self-healing mechanisms. Our findings (reported in D5.2) reveal that, due to the self-healing mechanisms embedded in the control logic of the XCI and regardless of

				the control plane medium used, the designed XCI can restore data plane paths that have been affected by failures. In particular, the exhibited distribution of data plane restoration times is within the order of hundreds of ms (i.e., less than 300ms) whereas results with a wired control plane (i.e., a separate out-of-band control plane) were below 10ms. The results were obtained by evaluating different data plane failure events (e.g., a mmWave data plane node failure or a WiFi data plane node failure). Algorithms for resource orchestration based on traffic load and energy-aware optimization and reconfiguration are part of the applications in WP4, e.g. TVBA. The TVBA results reported in D4.2 demonstrated that TVBA application can heal the system by two mechanisms: modifying the service path or reconfiguring the source of media, which fulfilled this KPI target.
		Energy-aware 5G-Crosshaul reconfiguration with changing size cell Deployments.	WP5	In WP5, demo 1 (see section 4.2.5) focused on demonstrating the applicability of the energy efficiency concepts over the 5G-Crosshaul Packet Forwarding Engine (XPFE) and Radio over Fibre (RoF) domains, with automated regulation of device´s power states (i.e., sleeping mode, active mode – low traffic, active mode – high traffic). In both domains, the results achieved have provided measurable energy savings. The detailed evaluation results were reported in D5.2.
Obj	**Objective description**	**KPI**	**WP**	**Details**

1	Design of the 5G-Crosshaul Control Infrastructure (XCI)	Energy-efficiency improvement by at least a factor of 3	WP4	EMMA is designed for serving this KPI though the objective evaluation is still ongoing. A preliminary evaluation is shown in IR4.3 and a more thorough evaluation will appear in D4.1.
3	Unify the 5G-Crosshaul data plane	CAPEX and OPEX savings due to unified data plane (25%) and multi-tenancy (>80%, depending on the number of tenants)	WP1	CAPEX/OPEX savings are estimated in D1.1 and will be demonstrated at the end of the Project.
		80% increased energy-efficiency due to consolidation of equipment	WP4	This is considered by EMMA application – an initial evaluation is shown in IR4.3 – and in the design of XCF presented in IR3.2 (though no objective evaluation has been presented yet).
4	Develop physical and link-layer technologies to support 5G requirements	10Gb/s over 1000m distance with hybrid wireless optical/mmWave	WP2	Technology discuss in IR2.1 and D2.1.
		Latency of < 1ms between 5G Point of Attachment (PoA) and mobile core	WP2	Technology discuss in IR2.1 and D2.1.
5	Increase cost-effectiveness of transport technologies for ultra-dense access networks	Reduce TCO by 30% by improved optical transmission and sharing mobile and fixed access equipment	WP1	TCO is estimated in D1.1 and will be demonstrated at the end of the Project.

6	Design scalable algorithms for efficient 5G-Crosshaul resource orchestration	Enable deployment of novel applications reducing the network management Operational Expenditure (OPEX) by 10% in terms of provisioning.	WP4	MTA and RMA (shown in IR4.3) increase the utilization of the physical infrastructure with the goal of reducing the OPEX, though an objective evaluation has not been completed yet.
		Increase of total 5G-Crosshaul network throughput by > 20% by means of resource optimization alone compared to current operators' practice.	WP4	RMA (shown in IR4.3) optimizes the amount of RAN centralization that enables interference coordination techniques that boost user throughput, though an objective evaluation has not been completed yet.
7	Design essential 5G-Crosshaul-integrated (control/planning) applications	Reduce energy consumption in the 5G-Crosshaul by 30% through energy management.	WP4	EMMA is designed for serving this KPI though the objective evaluation is still ongoing. A preliminary evaluation is shown in IR4.3 and a more thorough evaluation will appear in D4.1.
		Reduction of 5G-Crosshaul infrastructure Capital Expenditure (CAPEX) by 20% due to automated planning.	WP4	RMA (shown in IR4.3) serves as a tool to optimally place BS of different functional split that help in reducing CAPEX, though an objective evaluation has not been completed yet.
8	5G-Crosshaul key concept validation and proof of concept	Orchestration of 5G-Crosshaul resources based on traffic load variations: event-driven capacity surge, broadcast services and high-speed trains.	WP5	Deployment of initial experimental frameworks for the orchestration PoCs Started development of CDNMA and EMMA applications and related functionality at XCI
		Energy-aware 5G-Crosshaul reconfiguration with changing size cell Deployments.	WP5	Development of EMMA application is Ongoing.

5. Update of the plan for exploitation and dissemination of result

This part is fully described in D6.3, delivered at the same time as this deliverable, on 31st of December 2017.

6. Deviations from Annex 1

6.1.Tasks

During the second period, there has been no deviations from the workplan.

6.2. Use of resources

As the project close the 31st of December, the final information of PMs used in the last 18 months will not be available until the 15th of January 2018 at least.

The Final Project Report process, which will start shortly after the end of the project, will include the complete information on the use of resources.

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