5G Crosshaul
the integrated fronthaul/backhaul

FIRST PERIODIC REPORT

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Table of Contents

List of Tables

List of Figures

1 Executive Summary

The present deliverable called D7.2 presents the Part B of the First Periodic Report that will be delivered before 28th of August. It mainly includes the information of the scientific work carried out between 1st of July 2015 and 30th of June 2016.

It is important to highlight that the deadline of D7.2 is the 30th of June, the final data for use of resources is still not available at the end of June. The full financial information will be included in the First Periodic Report in August.

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.

2 Publishable Summary

2.1 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.

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, EBlink, 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).

2.1.1 Project context

According to the latest predictions, mobile data traffic will increase 11-fold between 2013 and 2018. 5G radio access network (RAN) technologies serving this mobile data tsunami will require fronthaul and backhaul solutions inside the RAN and between the RAN and the packet core capable of dealing with this increased traffic load. Further, there will be a sizable growth in the capillarity of the network since data rate increase in the 5G RAN is expected to stem to a large extent from increasing the number of base stations and reducing their coverage, i.e., mobile network densification.

To support the increased capillarity of mobile networks (e.g., in terms of interference coordination), and in order to achieve the required 5G data rates, extensive support for novel air interface technologies such as Cooperative Multipoint (CoMP), Carrier Aggregation (CA) and Massive MIMO will be needed. Such technologies require processing of information from multiple base stations simultaneously at a common centralized entity and also tight synchronization of different radio sites. Hence, backhaul and fronthaul will have to meet the most stringent requirements not only in terms of data rates but also in terms of latency, jitter and bit error rates.

Given that the aforementioned challenges will need to be addressed by service providers in a business environment where a revenue increase proportional to the data volume increase is unrealistic, a cost-efficient network deployment, operation and evolution strategy is required. The preferred approach to address the cost-efficiency challenge by the industry, as can be observed in major standardization bodies, e.g., ETSI Network Functions Virtualization (NFV), is virtualization, which exploits multiplexing gains of softwarized network functions on top of commoditized hardware. On the RAN side, this has led to the Cloud RAN concept where cellular base station functions are hosted in cloud computing centers. Once virtualized, base station functions can be flexibly distributed and moved across data centers, providing another degree of freedom for load balancing.

Besides, base station functions can be decomposed in multiple different ways, giving rise to the so-called flexible functional split, where the split between centralized and remote base station functions can be adjusted on a case-by-case basis. In this context, the division between fronthaul and backhaul transport networks will blur as varying portions of functionality of 5G Points of Attachment (5GPoA) might be moved towards the cloud network as required for cost-efficiency reasons. Also for cost reasons, the heterogeneity of transport network equipment must be tackled by unifying the data, control, and management planes across all technologies as much as possible.

To address the aforementioned challenges, the 5G-Crosshaul project aims at developing 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 envisioned will consist of high-capacity switches and heterogeneous transmission links (e.g., fiber or wireless optics, high-capacity copper, mmWave) interconnecting Remote Radio Heads, 5GPoAs (e.g., macro and Small Cells), cloud-processing units (mini data centers), and points-of-presence of the core networks of one or multiple service providers.

2.1.2 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

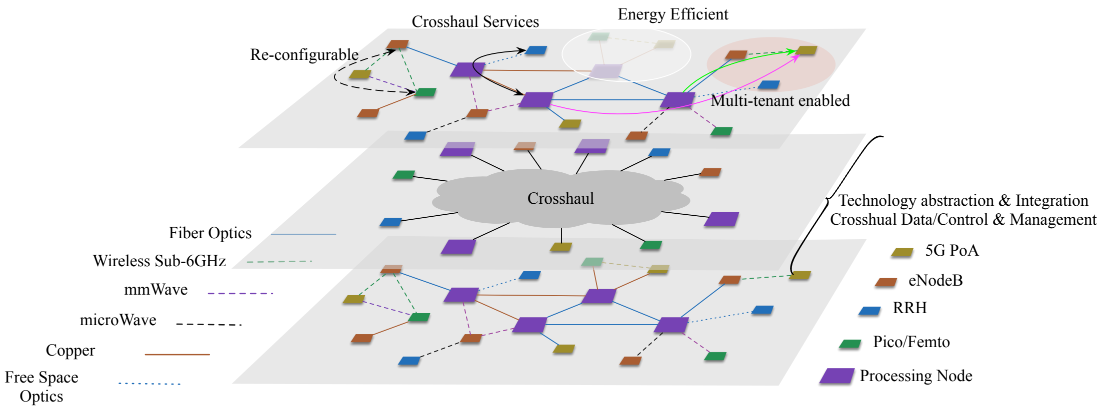

Figure 1 - 5G-Crosshaul System

2.2 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 first year of the project has been devoted mainly to the initial design and specification of the overall system that will become the integrated 5G transport infrastructure. Designing such a single infrastructure requires rethinking of all architectural aspects of the transport network conceived in 5G-Crosshaul. Work Package (WP) 1 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 will be refined in the second year based on the implementation experience gained. 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 fulfill the heterogeneous 5G traffic flow requirements. This will be done by building proof-of-concepts over the various testbeds that are available in the project (5G-Berlin, 5TONIC-Madrid, CTTC, and ITRI).

In WP1 (**System Requirements, Scenarios and Economic Analysis**) five use cases have been finally selected considering the potential benefits of the 5G-Crosshaul usage for the use cases, the compatibility with other 5G projects and the demonstrability through experimentation. Three of the five use cases are service-oriented, meaning that the use cases are related to specific applications. The service-oriented use cases are: (i) vehicle mobility, (ii) media distribution (CDN and TV broadcasting), and (iii) dense urban information society. In addition to them, two more functional-oriented use cases have been considered: (iv) multi-tenancy, and (v) mobile edge computing.

Due to the multi-tenancy nature of the 5G-Crosshaul, we have defined a classification of the different service use cases for the tenants. We have defined a taxonomy of three categories; *i)* Over-The-Top (OTT), *ii)* Mobile Virtual Network Operator (MVNO) and *iii)* virtual infrastructure provider. Each of them imposes different characteristics and requirements to the 5G-Crosshaul design. Regarding the architecture, in the first year of the project we have worked towards the definition of the 5G-Crosshaul architecture for 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. During this initial stage of the project we have also worked in defining a clear path of migration with the operators of the consortium. It is worth highlighting that we have also worked actively with the 5G-Exchange project to define mechanisms in order to include our transport network in their architecture and with the 5GPPP Architecture Working Group to push our architecture into the common architectural framework.

Finally, a preliminary version of a cost model in order to numerically evaluated the Total Cost of Ownership (TCO) of the solutions envisaged by the Project.

In WP2 (**Physical and link layer of 5G-Crosshaul**) the work has been focused first on identifying 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. As the 5G-Crosshaul control plane is based on SDN and NFV, in a second stage, we 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.

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). During the first 6 months of the project we have focused on understanding the different requirements for each of these elements and sketching a first design of the architecture of each element. The initial 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. First we have worked towards the initial design of the 5G-Crosshaul Forwarding Element (XFE). Its design has been refined to consider 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).

At this stage, we have also defined the 5G-Crosshaul Common Frame (XCF). This frame will serve as a common transport encapsulation for different technologies, enabling several desired characteristics, such as multi-tenancy and isolation of traffic flowing through the transport network. We have adopted as XCF the MAC-in-MAC encapsulation (Provider Backbone Bridges), and adaptation functions (AFs) for the different media considered. To also support networks already deployed, we also consider a secondary profile for the XCF, based on MPLS-TE. The selection of the technology of choice for the XCF was done after a gap analysis based on the requirements established in WP1.

The work on the XCI has been focused on the initial description of the information model and APIs exposed by a set of XCI services towards the application-plane through a Northbound Interface (NBI). Such services include Topology and Inventory, Provisioning and Flow actions, IT infrastructure and Inventory, Statistics, NFV Orchestration, VNF Management, Analytics for Monitoring, Local Management Service, and Multi-tenancy.

WP4 (**Enabled innovations through 5G-Crosshaul**) work during this period has focused on determining initial set of requirements for the Northbound Interface (NBI) of the 5G-Crosshaul Control Infrastructure (XCI) and the design of the applications that can provide optimization and reconfiguration of 5G-Crosshaul resources through the NBI. A set of applications have been defined: Multi-tenancy Application (MTA), Mobility Management Application (MMA), Energy Management and Monitoring Application (EMMA), Resource Management Application (RMA), Virtual Infrastructure Manager and Planner Application (VIMaP), Content Delivery Network Management Application (CDNMA), and TV Broadcasting Application (TVBA). Following this analysis, WP4 has provided an in-depth description of the applications in a clear and schematic way of the main algorithms that the applications will implement as well as the main modules involved for the application design and the scenarios considered. The interaction between the different applications and the main workflows and interfaces to other applications to be taken into account has been a major piece of work during this time, this is a key point that will allow harmonizing the whole system performance. In addition, an initial high-level software design of the applications and their implementation roadmap are defined to provide guidelines for the implementation.

Finally, the work performed in WP5 (**Validation and proof of concept**) has been devoted to identify all the components provided by partners that will be integrated. This includes components already available that enable the construction of the experimental frameworks as well as components that will be developed during the project according to the design decisions taken at the application, control infrastructure, and data plane levels. In addition to preparing the experimental frameworks required by the project, the above analysis already enabled some early integration efforts among a reduced number of components, which have already been demonstrated at various events (e.g., preliminary multi-domain wireless and optical control plane). We have also defined an initial list of the demonstrations that are planned to be carried out over each of the testbeds. These demonstrations are tightly linked with the use cases defined by the project as well as the key performance indicators (KPIs) that the project targets. In this way, we try to clearly state the purpose of each of the validations undertaken towards meeting the project goal. In any case, it is expected that the demonstrations will be adapted during the project as a function of project decisions to adequately tackle the R&D objectives of the project.

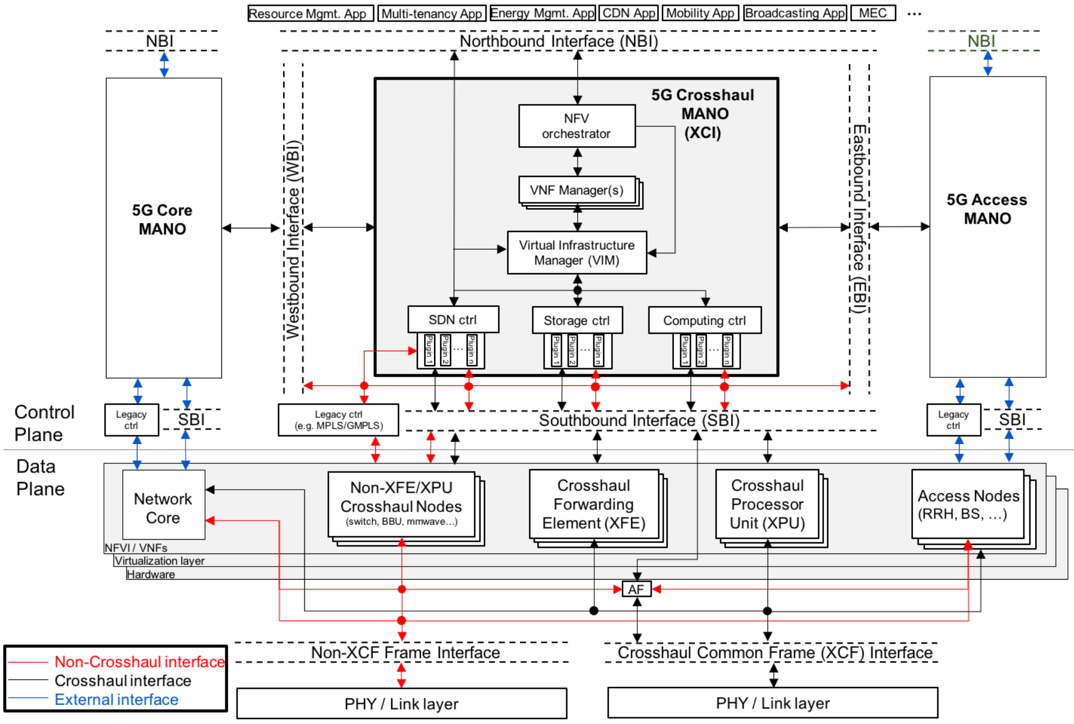

Figure 2 - Architecture of 5G-Crosshaul

2.3 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.

In the first year, significant progress has been made to bring in early innovations that the project can build on and nurture further in the following years. These are presented briefly below:

1. An innovative design for the data plane that allows for the multiplexing of various 5G backhaul and fronthaul data across heterogeneous transmission and switching technologies. The innovative design featured novel framing procedures, under the umbrella of so-called XCF – 5G-Crosshaul Common Frame, both for packet-switching and circuit-switching, raising the potential for exploitation in two new products, namely XPFE – 5G-Crosshaul Packet Forwarding Element, and XCSE – 5G-Crosshaul Circuit Switching Element. The concept of an adaptation unit (XAU – 5G-Crosshaul Adaptation Unit) has also been proposed, to allow for integration between XCSE and XPFE as well as interoperation with other non-XCF technology domains. This might lead to new features that can be exploited in new products. Alongside these innovations, the project has also researched and developed new transmission technologies for high capacity both optical and wireless, and analyzed their respective domain of suitability for a cost-efficient deployment in the service coverage-area.

2. A novel method for common abstraction of the data-plane technologies towards the control infrastructure (so-called XCI), which will help in the design of the south-bound interface of the controller, and in providing a common forwarding model to build upon in the design of the controller. This method aims at exposing in the most common way possible parameters and resources of the underlying data-plane technologies, so that one can facilitate the integration of all these technologies under common control and orchestration. In order to assess the proposed method, a design based on OpenFlow has been provided. This design results in novel extensions proposed to current implementation of OpenFlow Standard, and would hence lead to adoption in future releases of the OpenFlow standard.

3. First novel network applications that can optimize the overall system performance. As an example, the EMMA - Energy Management and Monitoring Application has been designed to consistently optimize the use of the energy consumption of the network infrastructure. This enables a sustainable approach to dynamically activate/deactivate networking resources to reduce energy and hence save costs. Importantly, the framework for the development of novel network applications has been laid down and more applications are under development and hence expected to yield future innovations that can be packaged into new product or service offering.

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. Several (over 30) talks were delivered at key industrial and research events (e.g. NGMN, IWPC, etc.), over 20 scientific articles published or accepted for publications and many others submitted, over 5 workshops organized or co-organized, and over 15 presentations and input contributions to relevant standardization activities (e.g. ITU-T, ETSI MEC, IEEE 802.11ay, IETF) provided. A standardization roadmap has also been developed and presented at ETSI, leading to the identification by ETSI of Xhauling as an important area where there might be a standardization gap to be addressed by ETSI (this is ongoing). Despite the start of the project in July 2015, the project has also been proactive in ensuring a visible presence through early demonstrations (1) at the Mobile World Congress 2016 flagship event, with 4 demonstrations provided by four partners, namely InterDigital, CTTC, Fraunhofer HHI, and CND, and (2) at EUCNC 2016 conference, with 4 demonstrations from Ericsson, Fraunhofer HHI, CND, and ITRI.

3 Patents

The project has registered one Intellectual Property Right in December 2015. NEC and UC3M are the authors of it:

- Costa, X.P. and De La Oliva, A. and Hernandez, J.A., “Ethernet frames encapsulation within CPRI basic frames”, Dec 2015.

4 Dissemination activities

Table 1, lists all peer-reviewed publications in Year 1. Published or accepted for publication materials are reported. As reported, the project has published over 20 peer-reviewed articles in Year 1, with a few more already accepted for publication at the start of the Year 2. This gives an average of approx. 2 papers published or accepted a month.

Table 1: Peer-reviewed publications in Year 1.

#	Type	Month	Description	Leading Partner
1	CNF	Sep’15	“Outage Probability of Beamforming for Multiuser MIMO Relay Networks with Interference”, by S. Zhou, G. Alfano, C.F. Chiasserini, A. Nordio, at IEEE APWC, Turin, Italy.	POLITO
2	CNF	Oct’15	“Future generation of wireless communication systems: requirements and open issues”, by F. Testa,	TEI

			F. Cavaliere, R. Sabella, at Microwave Photonics workshop at ECOC 2015, Valencia, Spain.	
3	MAG	Nov’15	“Xhaul: Towards an Integrated Fronthaul/Backhaul Architecture in 5G Networks”, by A. de la Oliva, X. Costa, A. Azcorra, A. Di Giglio, F. Cavaliere, D. Tiegelbekkers, J. Lessmann, T. Haustein, A. Mourad, P. Iovanna, at IEEE Wireless Communications Magazine, Special Issue on Smart Backhauling and Fronthauling for 5G Networks.	NEC, TEI, NOK-N, FhG-HHI, IDCC
4	CNF	Nov’15	“A Service-based model for the Hybrid Software Defined Wireless Mesh Backhaul of Small Cells”, by J. Núñez, J. Baranda, J. Mangues, at 2nd International Workshop on Management of SDN and NFV Systems (ManSDN/NFV) in conjunction with 11th International Conference on Network and Service Management (CNSM15), Barcelona, Spain.	CTTC
5	CNF	Nov’15	“What role for Photonics in Xhaul networks of 5G systems?”, by P. Castoldi, L. Valcarenghi, F. Cugini, F. Cavaliere, P. Iovanna, at Asia Communications and Photonics Conference, Hong Kong.	TEI
6	JRN	Dec’15	“Software-Defined Wireless Transport Networks for Flexible Mobile Backhaul in 5G System”, by D. Bercovich, L.M. Contreras, Y. Haddad, A. Adam, C.J. Bernardos, at ACM/Springer Mobile Applications and Networks, Special Issue on “Recent Advances on the Next Generation of Mobile Networks and Services”.	TID, UC3M
7	CNF	Jan´16	“ Coexistence of IEEE 802.11n and Licensed-Assisted Access devices using Listen-before-Talk techniques ” , by Claudio Casetti, at 13th IEEE Annual Consumer Communications & Networking Conference (CCNC), Las Vegas, USA.	POLITO
8	CNF	Jan´16	“ A System-level Assessment of Uplink CoMP in LTE-A Heterogeneous Networks ” , by MT Sanij, Claudio Casetti, at 13th IEEE Annual Consumer Communications & Networking Conference (CCNC), Las Vegas, USA.	POLITO
9	CNF	Jan´16	“ Mobility-Aware Edge Caching for Connected Cars ” , by A. Mahmood, C. Casetti, C.F.Chiasserini, P. Giaccone, J. Härri, at the 12th Wireless On-demand Network Systems and Services Conference (WONS) 2016, Cortina d’ Ampezzo, Italy.	POLITO
10	MAG	Feb´16	“An Overview of the CPRI Specification and Its Application to C-RAN-Based LTE Scenarios”, by A. Oliva, J.A. Hernández, D. Larrabeiti, and A. Azcorra, at IEEE Communications Magazine.	UC3M
11	MAG	Mar´16	“ 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.	CTTC

12	CNF	Mar’16	“Hierarchical SDN Orchestration of Wireless and Optical Networks with E2E Provisioning and Recovery for Future 5G Networks”, by R. Vilalta et al., at the Optical Fiber Communication Conference and Exhibition (OFC), Anaheim, California (USA)	CTTC
13	CNF	Mar’16	“Performance Demonstration of Fiber and Wireless Fronthaul Combination with Remote Powering” by Z. Tayq et al. OFC 2016, Los Angeles, California (USA)	ORANGE
14	JRN	Apr´16	“Mobility Management: Deployment and Adaptability Aspects Through Mobile Data Traffic Analysis”, by MI. Sanchez, E. Zeydan, A. de la Oliva, AS. Tan, U. Yabas and CJ. Bernardos, at Computer Communications, 2016	UC3M
15	CNF	May’16	“ Orchestration of IT/Cloud and Networks: From Inter-DC Interconnection to SDN/NFV 5G Services ” , R. Casellas, R. Muñoz, R. Vilalta, R.Martínez, at 20th Conference on Optical Network Design and Modeling (ONDM 2016), Cartagena, Spain.	CTTC
16	CNF	May´16	“ Time-Domain Precoding for LTE-over-Copper Systems ” , by Y. Huang, E. Medeiros, T. Magesacher, S. Host, C. Lu, P. Eriksson, P. Odling and P. Ola Borjesson, ICC 2016, Kuala Lumpur, Malaysia.	ULUND, EAB
17	CNF	May´16	“Dynamic Strict Fractional Frequency Reuse for Software-Defined 5G Networks” , by Anteneh A. Gebremariam, Tingnan Bao, Domenico Siracusa, T. Rasheed, F. Granelli and L. Goratti, ICC 2016, Kuala Lumpur, Malaysia.	CREATE-NET
18	CNF	May´16	“Markovian Models of Solar Power Supply for a LTE Macro BS” , by G. Leonardi, M. Meo, M. Ajmone Marsan, ICC 2016, Kuala Lumpur, Malaysia.	POLITO
19	JRN	May´16	“ Crosstalk Mitigation for LTE-over-Copper in Downlink Direction” , by Eduardo Medeiros, Yezi Huang, Thomas Magesacher, Stefan Höst, Per-Erik Eriksson, Chenguang Lu, Per Ödling and Per Ola Börjesson, in IEEE Communications Letters	ULUND, EAB
20	CNF	Jun´16	“ WiseHAUL: An SDN-empowered Wireless Small Cell Backhaul testbed ” , by J. Núñez-Martínez, J. Baranda, I. Pascual, J. Mangues-Bafalluy, Seventeenth International Symposium on a World of Wireless, Mobile and Multimedia Networks (WOWMOM) 2016, Coimbra, Portugal.	CTTC
21	CNF	Jun´16	“Downlink Transmit Power Setting in LTE HetNets with Carrier Aggregation” , by ZI. Fazliu, CF. Chiasserini, GM. Dell ’ Aera, at Seventeenth International Symposium on a World of Wireless, Mobile and Multimedia Networks (WOWMOM) 2016, Coimbra, Portugal. Best paper award.	POLITO, TI

22	CNF	Jun’16	“Fronthaul Performance Demonstration in a WDM-PON-Based Convergent Network”, by Z. Tayq et al., at EUCNC 2016, Athens, Greece.	ORANGE
23	CNF	Jun’16	“Packet Forwarding for Heterogeneous Technologies for Integrated Fronthaul/Backhaul”, by T. Deiss et al., at EUCNC 2016, Athens, Greece.	NOKIA, UC3M, NEC,IDCC, TEI, NEXTWORKS
24	CNF	Jun’16	“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.	TID, NEC, UC3M, CTTC
25	CNF	Jun’16	“5G-Crosshaul: Towards a Unified Data-Plane for 5G Transport Networks”, by L. Cominardi, J. Baranda, D. Larrabeiti, F. Cavaliere, P. Chanclou, J. Gomes, A. Di Giglio, P. Ödling, HW. Chang, at EUCNC’16, Athens, Greece.	IDCC, UC3M, CTTC, TI, TEI, ORANGE, LUND, ITRI, HHI
26	CNF	Jun’16	“Innovations Through 5G-Crosshaul Applications”, by Xi Li et al., at EUCNC’16, Athens, Greece.	NEC, NEXTWORKS, CTTC, POLITO, ATOS, CREATE-NET, VISIONA, TID
27	CNF	Jul’16	“The Price of Fog: a Data-Driven Study on Caching Architectures in Vehicular Networks,” by F. Malandrino, CF. Chiasserini, S. Kirkpatrick, accepted at the ACM MobiHoc Workshop on Internet of Vehicles and Vehicles of Internet (IoV-VoI), Paderborn, Germany.	POLITO
28	CNF	Jul´16	“SDN/NFV Orchestration of Multi-technology and Multi-domain Networks in Cloud/Fog Architectures for 5G Services”, by R. Vilalta, A. Mayoral, R. Casellas, R. Martínez, R., at 21st Optoelectronics and Communications Conference / International Conference on Photonics in Switching (OECC/PS) 2016, Niigata, Japan.	CTTC
29	CNF	Sep’16	“Efficient Multimedia Broadcast for Heterogeneous Users in Cellular Networks”, by C. Singhal, CF. Chiasserini, CE. Casetti, accepted at the 12th IEEE International Wireless Communications & Mobile Computing (IWCMC 2016), Paphos, Cyprus, September 5-9, 2016.	POLITO
30	JRN	Sep’16	“5G-Crosshaul: An SDN/NFV Control and Data Plane Architecture for the 5G Integrated Fronthaul/Backhaul”, S. González, A. de la Oliva, X. Costa, A. Di Giglioz, F. Cavalierex, T. Deiss, X. Li,	UC3M, NEC, NOK-N, TEI, TI IDCC

			A. Mourad, at Transactions on Emerging Telecommunications Technologies.	
31	CNF	Sep'16	"Performance Demonstration of Real Time Compressed CPRI Transport", by Z. Tayq et al., ECOC 2016, Düsseldorf, Germany	ORANGE
32	CNF	Sep'16	"Experimental Real Time AMCC Implementation for Fronthaul in PtP WDM-PON" by Z. Tayq et al., ECOC 2016, Düsseldorf, Germany	ORANGE
33	CNF	Sep'16	"Experimental Investigation of Compression with Fixed-length Code Quantization for Convergent Access-Mobile Networks", by TBD, ECOC 2016 (poster), Düsseldorf, Germany	ORANGE

Additional materials were also published as the result of 3 master thesis conducted by the partner POLITO, as reported in Table 2.

Table 2: Additional dissemination materials published in Year 1.

#	Type	Month	Description	Leading Partner
1	THES	Jul'15	"Traffic Steering in Wireless Systems through Software Defined Networking", MSc thesis.	POLITO
2	THES	Jun'16	"Simulation of Energy Management Functions in 5G Networks", Advised by C. Casetti	POLITO
3	THES	Jun'16	"Development of Monitoring Mechanisms for Energy Efficient 5G Networks", advised by CF. Chiasserini.	POLITO

Table 3 lists all presentation activities delivered including talks and panels. As reported, more than 30 activities are delivered in Year 1, averaging 2.5 per month.

Table 3: Talks and panels delivered in Year 1.

#	Month	Description	Leading Partner
1	Jul'15	"The Xhaul Project", by A. de la Oliva, at the special session on 5G PPP projects, EuCNC 2015, Paris, France.	UC3M
2	Sep'15	R. Vilalta, et al, "A Research Perspective for SDN Orchestration", IIR Network Virtualization Forum, Madrid, Spain, invited talk, September 2015.	CTTC
3	Sep'15	N. Zein, "Transport Network Evolution towards 5G Solutions and Standardisation" at the Layer123 - Packet Microwave & Mobile Backhaul, London, 22 September 2015.	NEC
4	Sep'15	F. Chen, "METIS II and 5G-Crosshaul Projects in 5G PPP", 2015 Taipei 5G Summit and co-organization of the event, Taipei, 22 September 2015, Taiwan	ITRI
5	Sep'15	J. Mangues, "Programmable Mobile Networks: Why? What? How?", the 7th EAI International Conference on Mobile Networks – Keynote.	CTTC
6	Sep'15	P. Chanclou, "Changes, Challenges and Case studies in the fronthaul network for C-RANs", RAN world event, Cologne, Germany, 29-30 September 2015.	ORANGE

7	Nov'15	L. M. Contreras Murillo, "5G Backhauling", Workshop on Radio and Core Network within the 6th FOKUS FUSECO Forum, Berlin, Germany, 5 November 2015.	TID
8	Nov'15	"Resource management in 5G Transport Networks", by D. Siracusa, at the COMBO Workshop within the 12th Conference of Telecommunication, Media and Internet Techno-Economics (CTTE), Munich, Germany.	CREATE-NET
9	Nov'15	"Millimetre-wave in 5G-Crosshaul" by J. Mangues-Bafalluy, at the TWEETHER project workshop, Valencia, Spain.	CTTC
10	Nov'15	"NEC Vision and R&D activities towards 5G", by X. Costa Perez, at the IEEE 5G Summit, Toronto, Canada.	NEC
11	Nov'15	"5G-Crosshaul and the mobile edge", by D. Castor, at the IEEE pre-industrial workshop on Mobile Edge Cloud, New Jersey, USA.	IDCC
12	Dec'15	"5G Technologies: An introduction", by A. Mourad, at the NGMN IPR workshop on 5G Technologies, Vienna, Austria.	IDCC
13	Jan´16	"5G-Crosshaul Architecture Overview", by X. Costa, at the 5GPPP Workshop on 5G RAN Design, Valencia, Spain.	NEC
14	Jan´16	"Self-backhauling in 5G", by A. Mourad, at the 5GPPP Workshop on 5G RAN Design, Valencia, Spain.	IDCC
15	Jan´16	"Connectivity in 2018 – Fronthaul and Backhaul Challenges for 5G", by X. Costa, at the Germany Connect 2016 Conference, Frankfurt, Germany.	NEC
16	Jan´16	"Opportunities and Challenges for Wireless Fronthaul/Backhaul", by D. Castor, at IWPC workshop on Evolved Transport Networks, Verizon, USA.	IDCC
17	Jan´16	"Coexistence of IEEE 802.11n and Licensed-Assisted Access devices using Listen-before-Talk techniques", by C. Casetti, at the IEEE CCNC 2016, Las Vegas, USA	POLITO
18	Jan´16	"A System-level Assessment of Uplink CoMP in LTE-A Heterogeneous Networks", by C. Casetti, at the IEEE CCNC 2016, Las Vegas, USA.	POLITO
19	Feb´16	"EU 5GPPP Project: 5G-Crosshaul The 5G Integrated Fronthaul/Backhaul", by X. Li, at the ITG 5.2.1 Workshop at NEC Laboratories, Heidelberg, Germany	NEC
20	Mar´16	"5G-Crosshaul Project Overview", by B.K. Lim, at the NGMN Forum meeting, Taipei, Taiwan	IDCC
21	Mar'16	"Mobile Edge Network for Wireless 5G", by F.C. Chen, at the NGMN Forum meeting, Taipei, Taiwan	ITRI
22	Mar'16	"5G-Crosshaul: The 5G Integrated Fronthaul/Backhaul", by L.M. Contreras Murillo, at ETSI MEC ISG #17 meeting, Madrid, Spain.	TID
23	Apr'16	"5G-Crosshaul: The 5G Integrated Fronthaul/Backhaul", by P.H. Kuo, at the ETSI workshop (5G: from myth to reality), Sophia-Antipolis, France	IDCC UC3M
24	Apr´16	"5G Roadmap to backhaul and fronthaul integration and 2016 Trial plans", by A. Mourad, at IWPC Workshop on 5G Trials and Initiatives towards 2020, Seoul, South-Korea.	IDCC
25	May'16	"5G Transport Networks - IEEE ICC 2016 - Workshop Next Generation Backhaul/Fronthaul Networks", panel organization by X. Costa-Perez, at IEEE ICC 2016, Kuala Lumpur, Malaysia.	NEC

26	May'16	"Moving Optical Dynamicity to the Edge" by Juan Pedro, at the 20th International Conference on Optical Network Design and Modeling (ONDM 2016), Cartagena, Spain.	TID
27	May'16	"Control Plane for High Capacity Networks", by Luis Miguel Contreras, 5th International Workshop on Trends in Optical Technologies, Campinas-São Paulo, Brazil	TID
28	May'16	"Standardization Roadmap for the 5G Integrated Fronthaul and Backhaul", by A. Mourad, at ETSI workshop (5G from research to standardization), Sophia-Antipolis, France.	IDCC
29	Jun'16	"Fronthaul requirements of 5G mobile networks", by T. Deiss, at the EUCNC 2016 workshop Towards Converged X-Haul for 5G Networks, Athens, Greece.	NOK-N
30	Jun'16	"Bit-Rate Bound Derivation for compressed time-domain fronthaul", by C. Lu, at the EUCNC 2016 workshop Towards Converged X-Haul for 5G Networks, Athens, Greece.	EAB
31	Jun'16	"Ethernet OAM and SDN: a matching opportunity", by L. Cominardi, at EUCNC 2016 workshop Network Function Virtualisation (NFV) and Programmable Software Networks, Athens, Greece.	IDCC
32	Jun'16	"5G-Crosshaul: a 5G integrated backhaul and fronthaul flexible transport network", by F. Cavaliere, at the EUCNC 2016 workshop Next Generation fronthaul/backhaul integrated transport networks, Athens, Greece.	TEI
33	Jun'16	"5G-Crosshaul Concept and Architecture", by X. Costa-Perez, at the EUCNC 2016 workshop Next Generation fronthaul/backhaul integrated transport networks, Athens, Greece.	NEC
34	Jun'16	"5G-Crosshaul Control and Data planes", by T. Deiss, at the EUCNC 2016 workshop Next Generation fronthaul/backhaul integrated transport networks, Athens, Greece.	NOK-N
35	Jun'16	"Softwarization in 5G Mobile Networks", by Tinku Rasheed, IEEE Lecture Series	CREATE-NET
36	Jun'16	J.P. Fernández-Palacios, "Crosshaul Innovation" (tentative title) in Optical Innovation Forum, hosted by Huawei and Heavy Reading, co-located to IIR's WDM & NG Optical Networiking Event, Nice, France, June 2016	TID

Table 4 lists the workshops organized or sponsored by the project in Year 1. A total of 7 workshops are organized, at the approx. average rate of 1 workshop every 2 months.

Table 4: Workshops organized or sponsored.

#	Month	Workshop	Country
1	May'16	"IEEE ICC 2016 2nd Workshop Next Generation Backhaul/Fronthaul Networks", in conjunction with IEEE ICC'2016	Malaysia
2	Jun'16	"Workshop on Software Defined 5G Networks (Soft5G 2016)", in conjunction with 2nd IEEE Conference on Network Softwarization – NetSoft 2016.	South Korea
3	Jul'16	"OSOMI 2016 workshop On-the-fly services in on-the-fly mobile infrastructures"	Germany

4	Jun'16	1st International Workshop on Elastic Networks Design and Optimisation (ELASTICNETS 2016)	Spain
5	Jun'16	"Workshop Next Generation fronthaul/backhaul integrated transport networks", in conjunction with EUCNC 2016	Greece
6	Jun'16	"Workshop Towards Converged X-Haul for 5G Networks", in conjunction with EUCNC 2016	Greece
7	Jun'16	"Workshop Network Function Virtualization (NFV) and Programmable Software Networks", in conjunction with EUCNC 2016	Greece

Table 5 lists the demonstration activities exhibited by the project in Year 1. A total of 12 demonstrations were exhibited including 4 noticeably at the flagship event of Mobile World Congress 2016.

Table 5: Demonstrations exhibited.

#	Month	Description	Leading Partners
1	Oct'15	Demonstration of 5G-Crosshaul research on orchestration at the 5G-PPP booth during ICT2015, Lisbon, Portugal.	CTTC
2	Oct'15	Wireless SDN proof of Concept demonstration with leading partners at 5TONIC, Madrid, Spain.	UC3M, NEC, TID
3	Dec'15	Video demonstration jointly between 5G-Crosshaul and FP7 iJOIN at Globecom, San Diego, USA.	UC3M IDCC
4	Feb'16	MWC'16 demonstration EdgeHaul Millimeter Wave Gigabit Transport featuring a Telepresence 5G Application.	IDCC
5	Feb'16	MWC'16 demonstration Hierarchical SDN Orchestration of Wireless and Optical Networks	CTTC
6	Feb'16	MWC'16 demonstration OpenEPC 7	CND
7	Feb'16	MWC'16 demonstration mmWave backhaul	HHI
8	Apr'16	2nd ONF PoC on SDN for Mobile Wireless,	TID, NEC
9	Jun'16	EUCNC'16 demonstration Fronthaul Compression, Athens, Greece	EAB
10	Jun'16	EUCNC'16 demonstration RRU/BBU functional split with an Ethernet-based fronthaul, Athens, Greece	CND
11	Jun'16	EUCNC'16 demonstration Optical Wireless Link: Low-cost short-range optical backhaul, Athens, Greece	HHI
12	Jun'16	EUCNC'16 video demonstration of High Speed Train Testbed in Taiwan, Athens, Greece	ITRI

5 Explanation of the work carried out by beneficiaries and Overview of the progress

5.1 Objectives

This section is devoted to present the progress towards the fulfillment 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 IR3.2 [1].
	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 IR4.2 [2] and D1.1. [3]
• 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 [4].
• 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 [5], IR4.2, the evaluation results will be reported in IR4.3 and D4.1.
• Design an SDN architecture that can cope with multiple types of agents (e.g., wireless agents, packet system, optical agents).	WP1	The initial 5G-Crosshaul system architecture including the SDN architecture has been designed, which was described in IR1.2 [6] and D1.1.
• 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 [7]. Refinement of the roadmaps accounting for latest developments in 5G-Crosshaul and in the relevant SDOs identified was reported in D6.1 [8] . First standardization activities were reported in IR6.2 [9] , with both types: dissemination and input contributions. Further dissemination and

		contribution activities into the various SDOs were reported in D6.1.
Verification	**WP**	**Details**
• Report on pros and cons of different hierarchical SDN architectures.	WP3	Investigation of different hierarchical SDN controllers was described in IR3.2.
• 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	• Framework development • Preliminary integration of wireless node, packet, and optical domains under the same hierarchical control. Simplified wireless node with single 802.11ac link. Establishment of an end-to-end path. • Preliminary discussions on joint integration of multiple technology domains and resource management schemes through hierarchical SDN control • Ongoing MANO developments for media distribution, energy and infrastructure management scenarios. • Ongoing developments 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.

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 IR3.2.

• 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 south bound protocol to control the forwarding behavior 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 IR1.2.
• Specify the set of northbound XCI actions (e.g., provisioning of new VPNs) to enable Service Level Agreement (SLA)-level reports, create new virtual 5G-Crosshaul slices for multi-tenancy support.	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 IR3.2.
Verification	**WP**	**Details**
• Prototype of the XCI SBI including multiple technologies (CPRI over WDM, packet over mmWave) and the XCI NBI (capacity reconfiguration).	WP5	• Initial 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. Ongoing work related with NBI: • 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. Ongoing work related with SBI: • 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.

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 IR3.2.
• Support for multi-tenancy in the unified data plane.	WP3	A detailed analysis on multi-tenancy support by chosen XCF is described in IR3.2.
• Design the 5G-Crosshaul Packet Forwarding Element (XFE).	WP3	High-level design of XFE is described in IR3.1 and elaborated in IR2.2 [10].
Verification	**WP**	**Details**
• Prototype including XFE supporting a unified frame format.	WP5	Identification of software switch flavors for XPFE development to be able to support the XCF (Lagopus and OpenvSwitch). Development of XCF-support over Lagopus is ongoing.

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 were described in IR2.1 [11]. Simulations or experiments are included in IR2.3.

- Programmable optical transceivers for flexible bandwidth allocation.	WP2	The programmable optical transceivers for flexible bandwidth allocation is designed based on OFDM. The details were described in IR2.1. Simulations or experiments are included in IR2.3.
- 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. D2.1 [12] 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 IR3.2.
- L1 switching techniques cooperating with L2 switching to guarantee upper bounds on latency.	WP2	Multi-layer architecture has been described in IR2.1. 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 IR2.1.
Verification	**WP**	**Details**
- Proof-of-concept prototype, testing and measurement of each individual technology.	WP5	Preliminary experimental evaluations of technologies (wireless, fixed access, and optical) were reported in IR2.3 Ongoing 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 IR2.3.

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 colorless transmitters were mentioned in IR2.1. Technology scouting output is included in D2.1.
• Silicon photonics.	WP2	Experiments on a Silicon Photonics ROADM prototype are included in IR2.3 and D2.1.
• 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.
• 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	A preliminary 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 D1.1.
• Energy-consumption measurements on prototypes.	WP5	Development of energy monitoring functions in mmwave mesh nodes. Early lab tests for energy monitoring functions at XCI. Preparation of setup for energy measurements in Analogue RoF.

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 is described in IR4.1 and detailed algorithms are described in IR4.2. The evaluation is ongoing and initial evaluation results will be reported in IR4.3.
• Novel 5G-capable routing and traffic engineering algorithms considering inputs such as latency and jitter (across heterogeneous links), RAN and wireless transport interference, user mobility, or RAN measurements.	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), RAN and wireless transport interference, user mobility, or RAN measurements. The design of these applications is described in IR4.1 and detailed algorithms are described in IR4.2. The evaluation is ongoing and initial evaluation results will be reported in IR4.3.
• 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 is described in IR4.1. Their algorithms are described in IR4.2. The evaluation is ongoing and initial evaluation results will be reported in IR4.3.
Verification	**WP**	**Details**

• Simulative proof of scalability and throughput performance of resource management algorithms based on real operator's backhaul network data.	WP4	The evaluation of resource management algorithms is by simulations in the first step. based on real operator‘s backhaul network topology. The evaluation is ongoing, and the first evaluation results will be reported IR4.3.
• 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 ongoing, as well as the energy management policies to be integrated in the EMMA application. • Development of RMA application for FH/BH traffic reconfiguration is ongoing. • Development of TVBA application and required XCI functionality to set up broadcast tree. • Development of CDNMA application and interaction with XCI. Early lab tests of vCDN node deployment on top of which CDNMA algorithms will be used.

Obj.7	**Design essential 5G-Crosshaul-integrated (control/planning) applications**	
Description	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.	
R&D Topics	**WP**	**Details**
• 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.	WP4	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 are described in IR4.1. Their algorithms are detailed in IR4.2. The evaluation of both applications will be based on PoC demonstrators, which are built in WP5, the evaluation plan and some initial results will be reported in IR4.3.

• Energy Manager (controlling optimal scheduling of equipment sleep cycles, routing parameters and function placement, and energy harvesting).	WP4	The definition of EMMA is described in IR4.1. The algorithms are described in IR4.2. The support for EMMA in XCI is described in IR3.1 and IR3.2. EMMA will be evaluated by simulation/emulation in the first step, initial results are provided in IR4.3.
• Techniques for end-to-end monitoring, prediction and enforcement of QoS parameters (such as latency, loss, jitter, bitrate) across heterogeneous 5G-Crosshaul technologies.	WP4	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 IR3.1 and IR3.2.
• Algorithms for planning and dimensioning the overall 5G-Crosshaul hardware infrastructure (split RAN, cloud nodes, switches, routers, links) based on realistic performance and cost KPIs.	WP4	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 is described in IR4.1, and the algorithm is described in IR4.2. The RMA will be evaluated by simulation/emulation in the first step, initial results are provided in IR4.3.
Verification	**WP**	**Details**
• Prototype of software for 5G-Crosshaul infrastructure planning.	WP5	Development of RMA application is ongoing. 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 fulfill requirements.
• Simulative analysis of the Energy Manager.	WP4	EMMA will be evaluated by simulation/emulation in the first step, initial results are provided in IR4.3.
• Demonstrator for "Broadcast as a Service" system.	WP5	Development of TVBA application and required modifications at XCI is ongoing. Early 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	Initial setup of experimental frameworks, including 5GBerlin, was presented in IR5.1 [13]. Continue deployment of mobile and transport, wireless and optical equipment towards final complete demonstrations at the end of the project.
• Experiments with mobile backhaul for moving Small Cells in 12-coach trains along a 400 km high speed (300 km/h) rail track.	WP5	Initial setup of the high-speed train experimental framework. Continue deployment of analogue RoF equipment in high-speed train testbed towards final energy management demonstration at the end of the project.

5.2 Explanation of the work carried per WP

5.2.1 WP1: System Requirements, Scenarios and Economic Analysis

Main activities carried out in the first year of the Project lifetime have been:

- Identification of use cases and the referred requirements for the 5G-Crosshaul network
- Definition of the system design
- Preliminary Economic analysis

WP1, through the definition of the system architecture, is enabling an adaptive, flexible and software-defined architecture for the future 5G transport network integrating the fronthaul and backhaul segments. Multiplexing backhaul and fronthaul traffic is highly advantageous since it enables the use of common infrastructure and control for multiple purposes, with a consequent decrease of the total cost of ownership due to the reutilization of hardware and management techniques. This holds even more in 5G, where new functional split schemes of the radio interface add a plethora of possible intermediate cases in between the pure fronthaul and backhaul scenarios, impossible to manage with dedicated infrastructures. Furthermore, the integrated fronthaul and backhaul transport network bridges the gap between backhaul and fronthaul technologies, reducing the costs derived from running these two unrelated network segments. Finally, said integration enables the use of heterogeneous transport technologies across the network.

Another important task of WP1 is the identification of use case studies, derived from a selection of previous work on the area. We have consider the use cases already provided by EU Projects (e.g., METIS) and standardization activities (e.g., NGMN, 3GPP). This use cases have been further elaborated in order to adapt them to the European situation and to highlight the aspects that may benefit from fronthaul/backhaul integration.

Finally, a preliminary version of a cost model in order to numerically evaluated the Total Cost of Ownership (TCO) of the solutions envisaged by the project has been provided.

The architectural system design allows the 5G-Crosshaul solutions to contribute to all the 5G KPIs and in particular the achievement of 1000 times higher mobile data volume per geographical area, consisting in 10/100 times higher number of connected devices and 10/100 times higher typical user data rate.

The definition of use cases takes into account the 5G requirements about performance (5 times reduced End-to-End latency) and the ubiquitous 5G access including in low-density areas. In addition, one of the most important goals of the Project is the reduction of CAPEX and OPEX of the network by simplifying and unifying the management and control processes across the 5G-Crosshaul infrastructure, WP1 set up a cost model in order to verify the amount of savings, also in terms of energy consumption.

5.2.1.1 Task 1.1 - Use cases and Requirements

Task 1.1, has performed an analysis of use cases and requirements, which have been ordered and prioritized in importance through criteria set forth mainly by the three operators in the consortium, namely Orange, Telefónica and Telecom Italia. The outcome of this analysis and prioritization task is being fed into the other core WPs in order for their respective technologies to be designed accordingly and it is already completed.

As a propaedeutic activity, the project identified two main kinds of stakeholders, grouped into two layers, namely the Service layer and the Transport layer. They include the *end-users* (consumers of the services), the *network operator* (providing access/connectivity to the end-user towards the Internet), the *service provider* (providing basic or value-added telecommunications services to the end-user), and the *application/data provider* (providing complementary services to the end-user, such as video delivery, typically relying on distributed facilities like Content Delivery Networks (CDNs), or cloud computing), as detailed in Figure 3.

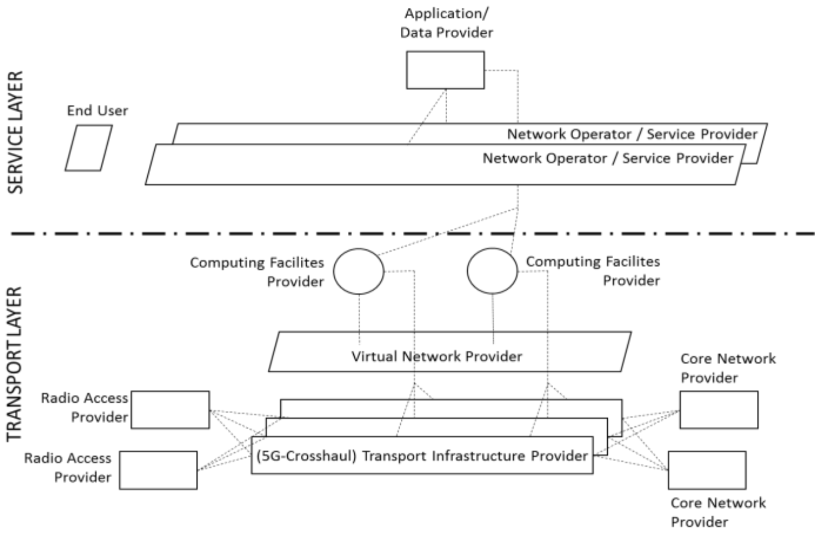

Figure 3 - 5G-Crosshaul stakeholders

Out of all stakeholders, the main focus of the project is on the 5G-Crosshaul infrastructure provider. However, SDN and NFV are re-shaping the way network infrastructure and services are offered to the end-user. As a consequence, the above roles may be played by the same of different organizations, depending on the business role they decide to play.

The use cases selection started by the identification of the most suitable use cases based on the technical innovations proposed by the project. At the early stage of this work a large number (more than 50) of use cases were on the table, taken from previous projects (e.g. METIS), organizations (e.g. NGMN), standardization bodies (e.g. 3GPP) or studies provided by single partners. The criteria for prioritizing and selecting the final reference 5G-Crosshaul use cases aimed to maximize the impact, exploitability and demonstrability of the project concepts and solutions. In particular, the choice was driven by the following considerations:

- Selected use cases should take into account of compatibility with other 5G Projects
- Selected use cases should benefit from 5G-Crosshaul architecture, and demonstrate the expected impacts and KPIs (Key Performance Indicators)
- Selected use cases should be experimentally validated by 5G-Crosshaul

Said selection resulted in the definition of two types of use cases:

- Service-oriented use cases, focused on specific high-demanding applications which are expected to impose strict requirements for 5G networks in terms of capacity and dynamicity.
- Functional-oriented use cases, focused on how to efficiently manage, virtualize and share the 5G-Crosshaul infrastructures, in order to maximize their utilization from operators' perspective.

The service-oriented use cases selected are:

Vehicle mobility (Use Case 1): this use case is focused on both, infotainment and safety applications. The most challenging situations are passengers using 5G services (video in particular) on a very high speed train (about 500 km/h). We also considered in this scenario real time messages among vehicles for emergency and security.

In the high speed train scenario, one or several points of attachment (PoA), such as small cells or Wi-Fi Access Points (APs), will be installed on a high speed train to provide broadband access to the passengers inside each car of the train. The mobile backhaul for the PoA are provided via outbound gateway(s) which connect to the land base stations and the 5G-Crosshaul transport network. The required KPIs are providing high mobility support (e.g. up to or greater than 500 km/h) to a crowd of passengers (e.g. more than 500 people) with satisfying QoE in a cost effective way, and ensuring high availability for mobile networks, e.g. by RAN sharing, on board PoA sharing.

In the case of traffic safety, the idea is to collet safety-relevant information directly from the Vulnerable Road Users (VRU). This can be achieved by exploiting the information sensed by a mobile device such as a smart phone, a tablet, etc. Information is exchanged between the VRU device and the vehicles in order to warn the driver and the VRU about the presence of each other or warnings about the road status (e.g. constructions, weather conditions, road hazards) to actively initiate the necessary actions to avoid an accident. The information exchange between vehicles can also enhance traffic efficiency in terms of increasing traffic flows and reducing fuel consumption and emissions. The main KPI is to ensure high reliable communication and ultra-low latency to receive and process co-operative awareness messages within less than 100 ms.

Media distribution: Content Delivery Networks (CDNs) & TV broadcasting/multicasting (Use Case 2): this use case (see Figure 4) is related to the distribution over 5G networks of media contents, especially video traffic, that is expected to be the dominant contributor to the mobile data traffic demand due to the fact that media distribution is being more and more present in everyday life communications, anywhere, any time and in end-user multi-device environments. This trend will even increase in the future 5G networks. Thus, providing efficient ways of delivering content to end users is a must.

A CDN replicates content from the origin server to cache servers, in order to deliver content to end-users in a reliable manner from nearby optimal surrogates. The CDN would make the media delivery using the 5G-Crosshaul network, deploying replica servers close to the data forwarding elements. The CDN end-points can be distributed across the network saving transport resources and reducing transmission delay. The expected KPIs are to accommodate much higher mobile data volume in a cost efficient manner and deploy CDN service on demand with satisfying QoE to the end users.

Another important scenario where the media distribution is relevant is the case of media/TV broadcasting & multicasting where the next 5G networks will become a good alternative to classical broadcasting networks, with an additional ability to mix with other media content not coming from the broadcasted TV, using the same network and with a controlled quality and offered as a Broadcast-as-a-service (BaaS). The distribution of the content in a BaaS manner, it is key to achieve more efficient (in terms of spectrum efficiency, cost and performance) way of distribution to provide the operators with a new revenue stream coming from distributing TV without needing an additional dedicated network. The KPI in this case is to ensure a real-time delivery with lowest possible delay.

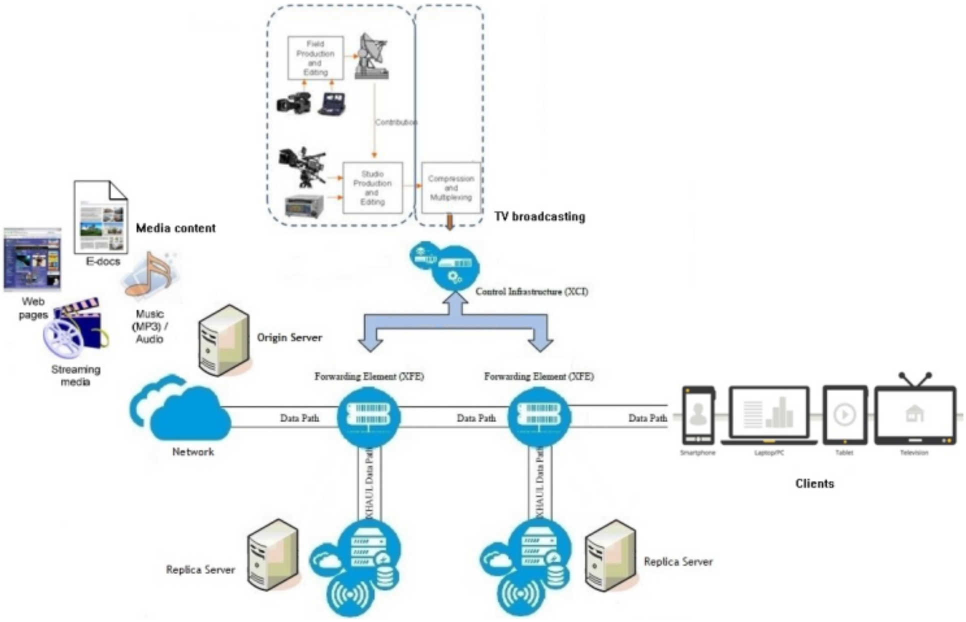

Figure 4 - Media distribution use case

Dense urban information society (Use case 3): this use case takes into account the connectivity required at any place and at any time by humans in dense urban environments, considering both the traffic between humans and the cloud, and direct information exchange between humans or with their environment. The particular challenge lies in the fact that users expect the same quality of experience at their workplace, in public areas such as shopping malls, campuses, hospitals and airports. Further, a particular aspect arising in urban environments is that users tend to gather and move in "dynamic crowds", (e.g. people waiting at a traffic light or at a bus stop) leading to sudden high peaks of local mobile broadband demand. Similar cases might also arise in indoor environments with a spontaneous crowd. The indoor coverage and capacity are often a big issue due to high penetration loss from the outside-in approach. As a result, it is required the deployment of indoor radio systems.

Therefore, in this use case, different locations and types of construction such as in-buildings, roads, park, bus stops, metro, rooftop, etc. will be considered in urban area. Thus, a realistic network deployment scenario will include macro sites, Cloud RAN (C-RAN), virtual RAN (V-RAN), all-in-one small cells (microcells, pico-cells and femtocells) and distributed RRHs (macro, micro and pico). In such an environment different Backhaul/Fronthaul mediums (wired and wireless) will be used including fiber, copper, µWave, mmWave, Free Space Optics (FSO), etc. Besides, different protocols, multiple RAT and multiple access techniques such as CPRI, OBSAI, Ethernet, Crosshaul Common Frame (XCF, such as IQ/CPRI/C&M over Ethernet), 3G, 4G, 5G, massive MIMO, massive aggregation, DAS, OFDM, SCMA, etc. will be considered (see Figure 5).

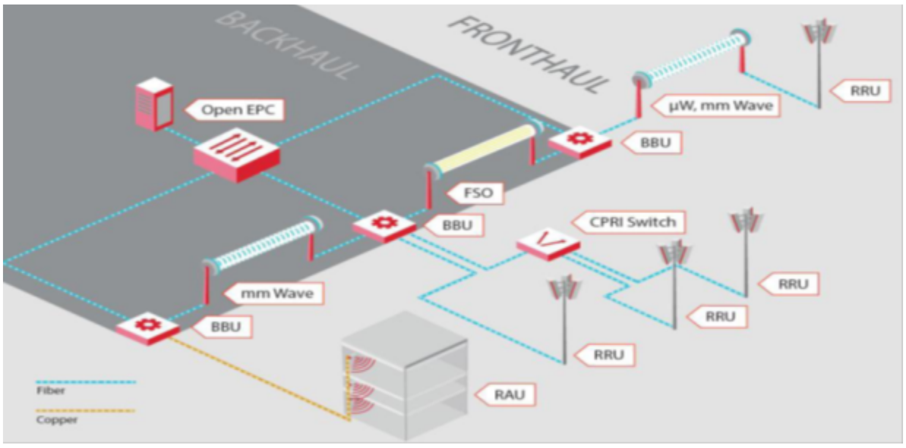

Figure 5 - Pictorial example of dense urban information society with fronthauling and backhauling

So far deployment of small cells (all in one) in urban areas is a big issue for mobile network operators because of lack of coordination between 2 different layers (macro layer and small cell layer). In the context of a 5G network some advanced techniques such as Joint Transmission (JT), Cooperative Multipoint (CoMP) or enhanced Inter-cell interference coordination (eICIC) can be implemented in the virtual RAN for all cooperating cells. Some other functions can be implemented in the 5G-Crosshaul or in the small cells/RRHs to ensure optimum efficiency and for a better QoE. Figure 6 depicts a dense urban deployment scenario where small-cells, macro-cells are connected to form a meshed backhaul/fronthaul network by various wired and wireless links and they are coordinated to provide better services to the end users and ease communication among users and other smart devices. For example, in an urban area, some devices might provide information about the surrounding of the users by measuring a certain phenomenon or by providing information about the presence of certain objects of interest such as energy consumption. Based on the information harvested from surrounding devices and other sources, the UE could provide the user with contextual information in such a way of helping the users to better understand and enjoy their environment. Furthermore, the data collected in, or by the device, can be uploaded to the cloud servers and be shared with others through the cloud, where a tight latency requirement for connectivity will be as important as a high data rate.

The objective is to ease local Cloud-RAN deployment via different wired/wireless mediums and design of scalable resource management algorithms to improve the KPIs on accommodating 1000 times higher mobile data volume per area and connecting 10-100 times higher number of user mobile devices and achieving 10-100 times higher user data rate as well as 5 times reduced end-to-end latency.

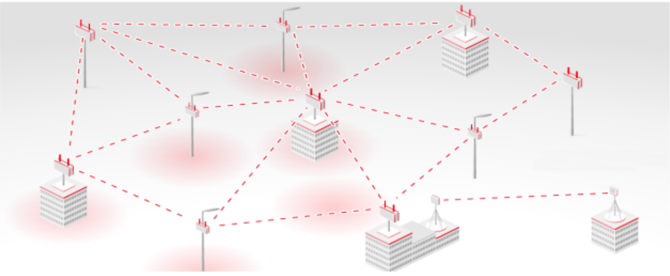

Figure 6 - Dense urban society use case

In addition, two functional-oriented use cases have been defined. These represent transversal scenarios considering a particular use of the 5G-Crosshaul network.

Multi-tenancy (Use Case 4): this use case aims to provide a flexible sharing of backhaul/fronthaul physical resources for multiple virtual network operators (multiple tenants), each owning a slice of the physical resources. It is a key enabler to maximize the utilization of 5G-Crosshaul infrastructure in a cost-efficient manner.

Multi-tenancy technology allows the owner of the 5G-Crosshaul infrastructure [14] (5G-Crosshaul Physical Infrastructure Provider, X-PIP) to provide virtual (computing and networking) resources over its substrate infrastructure to multiple operators (5G-Crosshaul Virtual Network Operators, X-VNOs) through a third party virtual network provider (5G-Crosshaul Virtual Network Provider, X-VNP), as shown in Figure 7.

The main challenge of this use case is to ensure clean isolation across tenants; and manage (create, update, delete) the tenants on demand and thus can allocate the requested virtual resources dynamically and seamlessly without invoking service disruptions. The target is to significantly reduce the CAPEX and OPEX savings by sharing the infrastructure and resources.

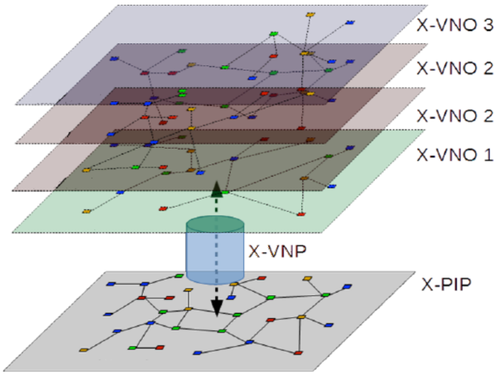

Figure 7 - Multi-tenancy use case

Mobile Edge Computing (MEC, Use Case 5): this use case is focused on the deployment of IT and cloud-computing capabilities within the RAN, in close proximity to mobile subscribers. Content, service and application providers can leverage on such distributed computing capabilities to serve the high-volume, latency-sensitive traffic on dense areas concentrating high number of users. The environment of MEC is thus characterized by low latency, proximity, high bandwidth, and real-time insight into radio network information and location awareness [15].

The introduction of computing capabilities at the edge of the mobile network interconnected through 5G-Crosshaul can improve the service delivery to the end user on one hand, and allow to efficiently deliver the traffic minimizing transport resource consumption (through savings in the backhaul capacity) on the other. The idea of this use case is to illustrate how the integration of fronthaul/backhaul can benefit MEC by facilitating the optimization process of the (re-)allocation of computing resources in a network-aware fashion thanks to a flexible and programmable 5G-Crosshaul architecture. The objective of MEC is to greatly enhance the introduction and provisioning of novel applications and vertical services at the network edge closer to the end users. MEC can enable innovative services such as e-Health, connected vehicles, industry automation, augmented reality, gaming and IoT service.

5G-Crosshaul has elaborated a list of high-level functional and non-functional requirements derived from the use cases described in the previous section. Each requirement has been analyzed with reference to the different use case, in order to identify the associated Key Performance Indicators. Their target values will allow to evaluate and experimentally validate the benefits of the 5G-Crosshaul architecture when applied to each reference use case.

The first step of the requirements analysis has focused on their impact on the different architecture layers of the 5G-Crosshaul infrastructure: data plane, control plane and application plane. Following this approach, the project has defined the characteristics and capabilities required at physical network infrastructure, first step to define the enabling data plane technologies. On the other hand, the features of the 5G-Crosshaul Control Infrastructure (XCI) have been identified, e.g. in terms of network monitoring and topology discovery, infrastructure virtualization and connection provisioning, instantiation and orchestration of virtual network functions and network services, together with a set of relevant applications at the upper layer (e.g. mobility management, energy consumption monitoring and optimization, resource management, etc.).

The second step of the analysis has classified and prioritized the different requirements considering their mapping to the use cases and their relative importance. Each requirement has been evaluated for all use cases and given a relative weight: three levels of importance for each requirement have been identified; *i)* High impact (H) indicating a requirement which is of upmost importance for the use case, *ii)* Medium impact (M) for a moderate level and *iii)* Low impact (L) to indicate that the requirement does not have a substantial impact on the use case. The result of this assessment is provided in Table 6 and Table 7 for functional and non-functional requirements respectively.

Table 6: Prioritization of functional requirements

Requirement	UC1	UC2	UC3	UC4	UC5
FT01: Infrastructure virtualization	H	H	L	H	H
FT02: Virtual – Physical resource dynamic (re-) allocation	H	H	L	H	H
FT03: Virtual –Physical resource synchronization	H	L	M	H	H
FT04: Dynamic resource discovery	M	M	M	H	L
FT-05: On-demand service & infrastructure adaptation	H	H	H	H	H
FT-06: Monitoring & accounting	H	H	L	H	H
FT-07: Latency	H	H	H	L	L
FT-08: Jitter	H	H	H	L	L
FT-09: Data rate	L	M	M	L	L
FT-10: Packet loss	H	H	M	L	L
FT-11: Clock synchronization	L	H	L	--	L
FT-12: Density of connection	L	M	H	--	M
FT-13: Mobility support	H	M	H	--	H
FT-14: Transferred data replication	H	H	--	--	L
FT-15: Energy efficiency	M	L	L	L	H
FT-16: Joint network and computing resource provisioning	L	H	M	H	H
FT-17: Management	M	M	M	L	M
FT-18: Security	H	M	L	L	H
FT-19: Backward compatibility	L	L	L	--	L
FT-20: SLAs mapping and validation	L	M	L	H	L

Table 7: Prioritization of non-functional requirements

Requirement	UC1	UC2	UC3	UC4	UC5
NF01: Programmability	M	H	M	M	H
NF02: Scalability	M	M	M	M	M
NF03: Usability	L	H	L	L	H
NF04: Service offer consistency	L	M	H	L	M
NF05: Robustness of resiliency	M	M	H	M	H
NF06: Responsiveness	M	M	M	M	M
NF07: Availability	H	L	H	H	M
NF08: Planning, design & development	M	M	L	M	M
NF09: Isolation of virtual infrastructures	H	L	L	H	H
NF10: Resource efficiency	M	M	M	M	M
NF11: Convergence	M	M	L	M	M

The previous set of use cases provide an evidence of the very distinct requirements that a common and shared infrastructure sitting on the fronthaul / backhaul network should face. Not being able to properly support certain requirements could make such infrastructure not attractive for a number of service providers, then reducing the commercial scope and the business viability of 5G-Crosshaul providers.

Both functional and non-functional requirements should be fulfilled according the negotiated SLAs between the parties, providing the necessary service guarantees to 5G-Crosshaul customers.

First, a careful planning of all kind of resources (either computing or networking, in a broad sense) has to be performed in advance to support huge variable demands. It is especially important in the access segment of a network. Users mobility or events occurrence shall motivate short periods of high usage of resources followed by longer periods where vacant capabilities could be reused for other purposes. The ever increasing peak-to-average ratio of the traffic patterns observed in current networks will make this situation more frequent and noticeable.

Second, in order to leverage in the above mentioned free resources appearing in some parts of the network, flexible and dynamic control of the infrastructure has to facilitate the programmability of the underlying transport and computing capabilities, as well as the components of a given service, in order to properly exploit existing assets just by re-arranging service graphs without any quality impact. Flexibility is required not only on the forwarding rules to apply to the traffic in 5G-Crosshaul but also in the re-location of network functions.

Third, all the above decisions should be governed taken into account the real state of the network (including computing) and the services deployed on it. In consequence, proper metrics and consistent processing of them are a must, potentially leveraging on big data functionalities running on the existing processing units in 5G-Crosshaul.

Finally, proper separation of traffic and services is essential to preserve service integrity and fulfil contracted SLAs. Multi-tenancy has to be enforced to isolate any kind of impact from one 5G-Crosshaul customer to another. Slicing becomes a key aspect to ensure viability of 5G-Crosshaul concept, including the trading of such slices with other stakeholders.

The work has been provided by all the Partners, since the use cases selection has been done during plenary conference calls. In any case, the most involved partners were: Ericsson Italia, ITRI, Eblink, Interdigital, UC3M, Telefonica, Telecom Italia, NEC, Nextworks and Nokia.

5.2.1.2 Task 1.2 - 5G-Crosshaul System Design

Task 1.2 has defined the high-level architecture of the 5G-Crosshaul network, which will serve as a baseline for all 5G-Crosshaul technology developments. This baseline architecture is evolving during the course of the project through continuous feedback from the different work packages (in particular WP3 and WP4), partners and stakeholders of the project.

The 5G-Crosshaul architecture thus aims to enable a flexible and software-defined reconfiguration of all networking elements through a unified data plane and control plane interconnecting distributed 5G radio access and core network functions, hosted on in-network cloud infrastructure.

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

The design of the data plane architecture needs to reflect the integration of heterogeneous technologies for the fronthaul and backhaul links into a single SDN-based controlled network. The main challenge of the data plane is the need for extended flexibility to adapt to the new fronthaul and backhaul technologies arising with 5G as well as to incorporate legacy technologies through abstraction interfaces. To achieve such a design, our approach is to leverage the state-of-the-art SDN and NFV architectures so as to avoid re-inventing the wheel and maximizing the compatibility and integration of the system design with the existing standard frameworks and reference specifications.

This activity has been very fertile in terms of publications, since some papers have been submitted: joint 5G-Crosshaul/5G-Exchange paper submitted to EuCNC'16, 5G-Crosshaul system design paper for IEEE Communications magazine special issue "5G Radio Access Network Architecture and Technologies".

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 in VMs providing network operators with the ability to dynamically instantiate, activate, and re-allocate resources and functions. Based on these open source initiatives and standards, our 5G-Crosshaul architecture keeps the architecture compatibility with the existing ODL/ONOS and ETSI NFV architecture frameworks. For the overall architecture design, we take a bottom-up approach to evolve from current Management Systems towards the integration of MANO concepts.

The work has been mostly provided by NEC, CTTC, Interdigital, UC3M and Ericsson Italia

5.2.1.3 Task 1.3 -Techno-Economic Analysis

Task 1.3 is ensuring that the Project design is economically viable, reducing the CAPEX and OPEX of front/backhaul networks. This task is interacting with the two previous tasks (T1.1 and T1.2) in order to ensure that use cases, requirements, and system architecture all fit within the Crosshaul framework for reduced network deployment costs.

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

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

where $CAPEX_i$ and $OPEX_j$ are the *i-th* component and *j-th* component of CAPEX and OPEX respectively. In order to harmonize the sum, each CAPEX has to be annualized, splitting the investment by the appropriate *amortization period* (*AP*).

The idea of the methodology for cost evaluation is shown in Figure 8. It consists in dimensioning the legacy and 5G-Crosshaul networks considering the same traffic matrix, in order to better compare the costs. In the legacy situation the backhauling and fronthauling networks are separated and supported by different equipment, while in 5G-Crosshaul architecture the two networks involve the same pieces of equipment integrated in a single one, namely the 5G-Crosshaul Element (XFE).

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

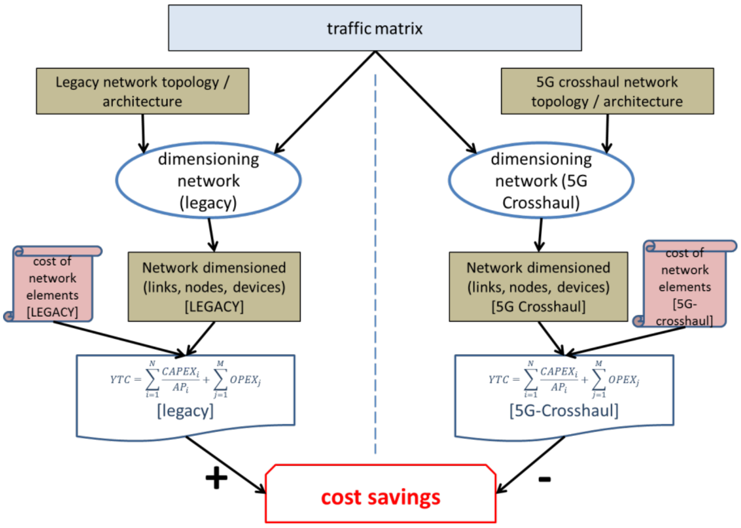

Figure 8 – Proposed methodology for cost savings evaluation

Task 1.3 defined a model able to calculate the cost (CAPEX and OPEX) and the energy consumption for a fronthauling/backhauling network, where the two segments can be separated (legacy situation) or integrated (5G-Crosshaul architecture).

5.2.1.3.1 CAPEX model

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

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

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

1. An average percentage of usage is taken into account, since not the whole installed capacity is used.

2. Some parameters taking into account the design of a network (multiple devices, kms of fibers, etc.) have been considered.

3. A parameter taking into account the real traffic (i.e. the real number of transported bits) has been considered. This is due to different splitting functionality options (between RRH and BBU) that lead to completely different bandwidth occupation (in particular in the fronthauling segment).

4. A parameter taking into account the surplus of resources required for the protection, with an additive percentage parameter. Finally, in order to be able to have a total cost of ownership the CAPEX is divided by the amortization period, to result in a yearly cost.

5.2.1.3.2 OPEX model

The considered items for OPEX evaluations are the following ones:

- the rented space for equipment allocation (also named “footprint”)
- the energy consumption for power supply and cooling
- the maintenance costs
- the renting of some media (e.g., copper)

The hosting costs of equipment can vary from nation to nation and also from urban, suburban or countryside sites.

The prices for power and air conditioning supply are considered apart in this study, in order to better evaluate the cost savings introduced by the 5G-Crosshaul network architecture.

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

5.2.1.3.3 Energy model

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

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

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

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

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

The work has been mostly provided by Telecom Italia, Telefonica, Ericsson Italia and Eblink.

5.2.1.4 Deviations

There has been just one minor deviation of the work planned in the DoA for this WP. Specifically, IR1.1 [16] was planned for M3 but this month concur with the summer vacations from several key participants on the project.

5.2.1.5 Corrective actions

To overcome the issue explained in the previous section, IR1.1 was postponed by 1 month (from M3 to M4).

5.2.2 WP2: Physical and link layer of 5G-Crosshaul

5.2.2.1 Overall WP Progress and main achievements

WP2 pursues the following key objectives defined in the project:

- 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 4: Develop 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

Moreover, it contributes to the design of the 5G-Crosshaul Control Infrastructure (XCI), defining the interfaces to accelerate the integration of new physical technologies trough the South Bound interface (SBI), according to Objectives 1 and 2.

During the reporting period, the work primarily regarded the following topics:

- Identification and analysis of physical and link layer technologies. The analysis was performed in terms of quantitative parameters (capacity, network density, achievable link distance, link budget, energy efficiency, latency) and qualitative aspects (synchronization, cost considerations, operational aspects). It was also paid attention to highlight what technologies can be used in the short term, although with a significant innovation effort and what require more technology advances. The two sets of technologies are in the scope of T2.1 and T2.4, respectively.
- Definition of circuit- and packet- based multiplexing and switching mechanisms to carry both fronthaul and backhaul traffic over the same underlying physical media, guaranteeing the individual requirements of each type of traffic in terms of bandwidth and bounded latency. This is especially important to support the multiple and reconfigurable split of functionalities in the 5G RAN. This activity is in the scope of T2.2 and was carried out in collaboration with WP3.
- Model of the SBI and definition of the protocol extensions to support the 5G-Crosshaul technologies. This activity is in the scope of T2.3 and was carried out in collaboration with WP3.

In general, the collaboration with WP3 was excellent during all the reporting period, with a continuative exchange of ideas and a coordinated effort to define the common topics avoiding unnecessary overlap. Two concrete examples are the collaborations on the 5G-Crosshaul Common Frame (XCF), which ended up in the choice of Ethernet MAC-in-MAC as preferred framework, and the definition of parameters and protocol extensions for the SBI.

More details about the work completed during the study period will be reported in the following. Here we highlight the following results:

- A multilayer data plane architecture, including circuit- and a packet- switched paths. The packet switching path is the primary path for the transport of most delay-tolerant fronthaul and backhaul traffic, whereas the circuit switching path is there to complement the packet switching path for those particular traffic profiles that are not suited for packet-based transporting (e.g. legacy CPRI or traffic with extremely low delay tolerance) or for offloading. This two-paths switching architecture is able to combine bandwidth efficiency, through statistical multiplexing in the packet switch, with deterministic latency ensured by the circuit switch. The modular structure of the 5G-Crosshaul switch, where layers may be added and removed, enables various deployment scenarios with traffic segregation at multiple levels, from dedicated wavelengths to VPN, which is particularly desirable for multi-tenancy support, one of the key feature identified in the project.
- A deterministic delay circuit framing, and a corresponding switch implementation, based

on wavelength- and time division- multiplexing, capable to overcome the limitations of the current optical transport network technologies in fulfilling the requirements of fronthaul signals in terms of introduced jitter and up- and down-link delay asymmetry.

- A novel SBI modelling approach based on the definition of 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. The choice of the parameters sets was careful, neither too small to inhibit some applications nor too wide to negatively affect solution cost and scalability;

During all the study period, the interaction with WP1 was continuous as regards the architectural and performance requirements coming from the use cases, whose definition is under WP1 responsibility. As an example of this joint work, Table 8 summarizes how the different technologies defined in WP2 match with the requirements identified in WP1 for the selected use cases.

5.2.2.2 Task 2.1 - Technology assessment and evolution toward 5G-Crosshaul

The analysis of different technologies led to the conclusion that, even if optical technologies have an important gap in terms of carried bandwidth in comparison with wireless ones, a single link adopting wireless can guarantee up to 10 Gbit/s that can be sufficient for a very distributed scenario or where it is not possible or economically viable to deploy cables. For similar reasons, a wireless technology is more appropriate for indoor solutions. An interesting solution is also the re-use of access technology, both copper and fiber for their low cost and sufficient capacity. However, overall, optical connectivity seems to be the most promising one, because it allows very high capacity (DWDM) or very low cost (CWDM). Therefore, fiber will dominate new deployments (green field). This led to the definition of three deployment scenarios (Figure 9) as data plane framework to map the set of identified technologies.

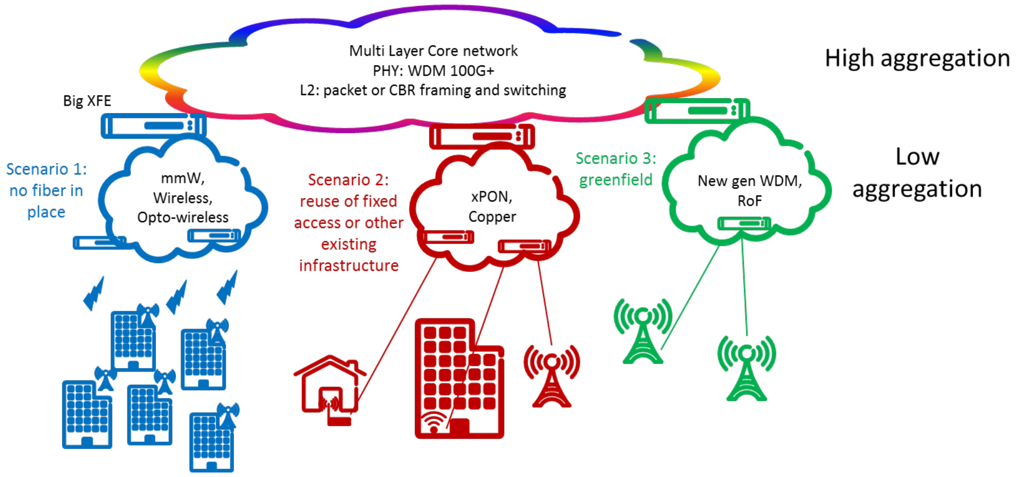

Figure 9: 5G-Crosshaul deployment scenarios.

The introduction of heterogeneous technology scenario allows to deal with practical situations where one-fits-for-all approach does not work but constraints from installed infrastructure and legacy standards matter. This is a must for a project, like 5G-Crosshaul, which has the ambition to lead standardization and industrial plans in the 5G transport area.

In Scenario 1 (UC1 in Table 8), WP2 identified three wireless technology families to face the challenges that 5G poses in terms of increase of capacity (1000x), small cells densification, drop in latency (down to 1ms for some scenarios): millimeter wave small cells backhaul (proposed by IDCC), microwave and millimeter wave fronthaul (proposed by EBLINK) and optical wireless technologies (proposed by HHI). Besides the obvious advantage of avoiding the high cost of fiber deployment, millimeter wave small cells backhaul allows flexible deployment options (e.g. mesh), overcoming the limitations of traditional backhaul architectures based on point-to-point links whose cost effectiveness may not scale for the small cell business case. With mmW point-to-multipoint backhaul using electrically steerable antennas, one can enable the deployment and cost advantages of sub-6 GHz point-to-multipoint non-line-of-sight backhaul systems while providing higher capacity using mmW frequencies. Microwave and millimeter wave fronthaul introduces instead highly spectrally efficient processing techniques in the fronthaul connection to avoid the unmanageable bit-rates that 5G would lead in that segment using traditional constant bit rate framing protocols like CPRI. Besides these two technologies, optical wireless communications (OWC) has been proposed and analyzed in T2.4.

When a fixed access network is already in place (Scenario 2, UC2 in Table 8), for operators it is very convenient to use it to connect base stations and RRHs to a common central office, which fits very well the 5G-Crosshaul scope. However, this is not trivial because the fixed residential infrastructure is typically designed for lower bandwidth and performance than the 5G mobile network. An analysis of the overlay of mobile back- and fronthaul over existing PONs was performed by TELNET and UC3M. The analysis encompassed G-PON, XG-PON1, NG-PON2 and WDM-PON. The analysis concluded that NG-PON2 may be an option for 5G-Crosshual both in point-to-point mode and in point-to-multipoint TWDM-PON, the latter option requiring a TDM-based Dynamic Bandwidth Allocation algorithm for ensuring predictable latency values. More advanced solutions, envisioned for a dense network environment, being capable to concurrently serve a high number of residential users and mobile cells, are proposed by CTTC within T2.4.

Table 8: Summary of matching different technologies with the requirements identified in WP1 for the selected use cases.

	wireless technologies			**Access technologies**		**Optical technologies**		
Technology	Millimetre wave small cells backhaul spectrum range 50-90 GHz	Microwave and millimetre wave fronthaul	Optical Wireless Technologies	Technologies working on optical fixed access infrastructure	Technologies working on copper fixed access infrastructure	Passive multiplexing solutions based on CWDM	DWDM metro networks	Radio over Fibre technologies
UC1 - vehicle mobility	**Good** for monitoring physical parameters. Possibility to remotely switch on/off devices. Energy efficient.	**Poor** due in particular to limited distances	**Good** due to negligible impact of doppler effect limited distances otherwise	**Good** for the bandwidth, in particular NG-PON and excellent for distance.	**Good** for the bandwidth for ETH, **sufficient** DSL. Improbable access to copper nearby streets or railways	**Good** for the bandwidth and for the limited cost. **Excellent** performance (latency)	**Excellent** for the bandwidth and performance (latency)	**Excellent** for its deplyment in tunnels
UC2 -media distribution: CDN and broadcast	**Poor** due to the low bandwidth per user (about 7 Mbit/s)	**Poor** due to the low bandwidth per user (about 8 Mbit/s)	**Poor** the LED solution. **Good** the LASER one	**Good** for the bandwidth, in particular NG-PON and excellent for distance.	**Good** for the bandwidth, in particular NG-PON and excellent for distance.	**Good** for bandwidth, **excellent** for cost	**Excellent** for bandwidth, **good** for cost	**Good** for bandwidth, **excellent** for cost
UC3 - Dense urban society	**Excellent** for indoor, even if limited bandwidth per area should be considered in the open air.	**Excellent** for indoor, even if limited bandwidth per area should be considered in the open air.	**Good** for Small cell backhaul, **Excellent** for indoor with LOS, where radio is not allowed, LED more affordable then LASER	**Good**.High density may imply that it is impossible to reach high bitrate in compressed space	**Good**.High density may imply that it is impossible to reach high bitrate in compressed space	**Good**. Even if high density may imply high denity of fibre deployment	**Good**. Even if high density may imply high denity of fibre deployment and for DWDM implies high costs	**Good**. Even if high density may imply high denity of fibre deployment

The analysis of copper technologies (DSL cables, DOCSIS family, power lines and Ethernet cables) was performed by EAB and ULUND, resulting in Ethernet over copper cables as the most suitable copper technology for the combination of fronthaul and backhaul.

Greenfield scenarios (Scenario 3, UC3 in Table 8) can exploit all the advantages of the optical networks based on WDM technology in terms of aggregate capacity, low latency, number of supported topologies and low energy consumption. CWDM was proposed by ORANGE as the most cost effective optical technology and the only one that works outdoor in any environmental condition. TEI analyzed DWDM technology and networking, providing also an evolutionary perspective based on the latest advances of integrated photonics technologies, which will be explored in T2.4.

5.2.2.3 Task 2.2 – Technology integration and network architecture

The scope of WP2 not only includes the design of the links, but also the definition of the multiplexing strategies that allow to define the fundamental block of the data plane architecture, which is the 5G-Crosshaul forwarding element (XFE). Three families of multiplexing techniques were analyzed: at physical layer, based on cable or wavelength multiplexing (ORANGE, TEI), at time-slot level to guarantee deterministic timing and latency (TEI, TID, ORANGE) and, finally, at packet level (UC3M, IDCC, NOK). OTN was analyzed as incumbent multiplexing technology at time slot level. TEI proposed an alternative framing format, and corresponding circuit switch architecture, tailored on 5G-Crosshaul needs, to overcome the performance penalty introduced by the OTN framing process. The analysis of the packet multiplexing standards, mainly IEEE 802.1, was propaedeutic to the choice of MAC-in-MAC as preferred format for the new packet 5G-Crosshaul interfaces. The analysis of requirements and gaps was done in collaboration with WP1 and WP3. All this work ended up in the definition of a layered switch architecture, able to combine the bandwidth efficiency of the statistical multiplexing in the packet switch with the deterministic latency ensured the circuit switch. Moreover, the modular structure of the 5G-Crosshaul switch, where layers can be added or removed, allows also to deal with a diversified deployment scenario and to guarantee traffic segregation at multiple levels, from dedicated wavelengths to VPN, which is especially desirable in the multi-tenancy use case.

5.2.2.4 Task 2.3 – Interface toward control and management layers

During the study period, WP2 also started, in collaboration with WP3, the specification of a southbound interface (SBI) providing the capability to deal with the variety of technologies included in the 5G-Crosshaul data plane. NOK, TEI, IDCC, UC3M, CTCC were especially active but all partners provided contributions regarding the technology of their competence. The SBI is able to collect and demand information about network topology, node and link capabilities (nominal and available bandwidth, latency, availability, etc., so that upper layers in the SDN architecture can use this information to calculate appropriate paths taking into account the different technology performance in the forwarding elements. At this purpose, WP2 adopted a novel approach, where a set of parameters is defined to model network nodes and transmission technologies, in order to enable the proper operation of applications, such as optimization of resource allocation and energy, running over the whole network infrastructure, as defined in WP3 and WP4. The right choice of the parameters was crucial in so far a too small set could inhibit some applications while a too wide set, exposing unnecessary technology details, could negatively affect solution cost and scalability. The needed protocol extensions were analyzed taking as baseline the latest version of the Open Flow specification, as a relevant example of protocol stack used in SDN developments. The level of provided detail is more exhaustive for Ethernet and optical networks, where Open Flow primarily applies today, while for the wireless technologies, before defining in detail the protocol structure, it has been preferred to wait for ONF, of which some partners of this project are active members, to publish its works on the protocols definition. This will facilitate the adoption of standardized and widely adopted solutions. However, it is important to highlight that the adopted approach is independent on the specific adopted protocol stack, which makes it future proof.

5.2.2.5 Task 2.4 – Novel technologies for 5G-Crosshaul

As mentioned in the previous sections, 5G-Crosshaul encompasses both existing technologies that need to be adapted to meet the performance and cost requirements of the 5G-Crosshaul network, in T2.1, and novel technologies that can lead to disruptive advantages but are still not mature enough for mass deployment. This is the subject of T2.4, where the following technologies have been identified during the reporting period. Due to the explorative nature of this task, it is likely that other technologies will be proposed during the remaining period.

5.2.2.5.1 Optical wireless communications (OWC)

With a completely license free spectrum and its immunity to electromagnetic interference, optical wireless communications (OWC) have attracted high interest recently, especially in security-aware environments. The term OWC encompass Free Space Optics (FSO) communications, where laser diode transmitters are used for high capacity inter-building optical wireless connections, and the novel technology, Visible Light Communications (VLC) where LED-based illumination systems equipped with low-cost high-power LEDs has shown its advantages for indoor communications. The solution proposed by HHI includes an automatic reconfiguration mechanism to ensure that, after a loss of signal, a reconnection is ensured immediately and real-time data rate adaptation. Moreover, first experiments showed availability is 99.99 % over 200m.

5.2.2.5.2 Programmable variable bandwidth transceivers

In fixed optical access networks advanced solutions, envisioned for a dense network environment, being capable to concurrently serve a high number of residential users and mobile cells, are proposed by CTTC, based on programmable sliceable bandwidth variable transceivers, leading to an optimum management of the network elements and flexible spectrum assignment. Among all the options for implementing the sliceable bandwidth variable transceivers, those based on orthogonal frequency Division multiplexing (OFDM) are identified as the most interesting for coping with the flexibility requirements of elastic optical networks.

5.2.2.5.3 Integrated DWDM technology

TEI analyzed DWDM technology and networking, providing also an evolutionary perspective based on the latest advances of integrated photonics technologies, especially those based on silicon photonics. Silicon photonic wavelength switches and new energy- and cost-efficient direct-detection modulation formats for 100 Gbit/s transmissions are two important DWDM components that will be explored in T2.4.

5.2.2.5.4 Analogue Radio over Fiber

Analogue Radio over Fiber (RoF) was proposed by ITRI as a solution for the high speed train use cases. It will be deployed inside the tunnels along the high speed rail to extend the coverage of base stations, as a cost efficient solution for extending the cell coverage.

5.2.2.6 Deviations

No significant deviation from the initial plan. The proposal of a modular multi-layer network architecture, instead of a pure packet network, allowed to trade-off bandwidth requirements and latency performance keeping the costs scalable.

5.2.2.7 Corrective actions

None required.

5.2.3 WP3: 5G-Crosshaul Control and Data planes

5.2.3.1 Overall WP Progress and main achievements

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.

- Initial design of the 5G-Crosshaul data plane, including 5G-Crosshaul Forwarding Elements (XFEs), the 5G-Crosshaul Common Frame (XCF) and adaptation functions (AFs). (UC3M, TEI, ATOS, NOK-N, IDCC)
- Initial design of the 5G-Crosshaul Forwarding Element, consisting of 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 requirements such as traditional fronthaul (e.g., CPRI). (UC3M, TEI, NOK-N, IDCC, TELNET)
- State of the Art analysis for data plane transport proposals like IEEE 802.1TSN, IEEE 1904.3. (UC3M, TEI, ATOS, NOK-N, IDCC)
- Based on the discussions held on Task 1.1 (System Architecture), WP3 provided an initial design of the 5G-Crosshaul Control Infrastructure (XCI), for the single domain case and an initial discussion on the recursive approach for providing services to multiple tenants. WP3 updated the design of the 5G-Crosshaul Control Infrastructure platform (XCI), particularly by updating the services exposed within the XCI towards the application-plane, and defining a set of software components that will be part of initial proof-of-concept prototypes planned by different 5G-Crosshaul partners. (UC3M, NEC, NXW, CTTC, CREATE-NET, ITRI)
- Detailed comparison between the most relevant SDN controllers regarding their use within the XCI. (UC3M, NEC, ATOS, NXW, POLITO)
- Analysis of WP1 use cases and WP4 applications to extract NBI and SBI requirements in terms of WP3 functionality. (TEI, NOK-N, TI, EBLINK, NXW)
- State of the Art analysis for different protocol alternatives of SBI and NBI for the control plane. (UC3M, TEI, IDCC, NXW)
- Description of 5G-Crosshaul Southbound Interface (SBI) protocol candidates to control the data-plane forwarding behavior, namely OpenFlow, and how the project can exploit this protocol to satisfy the requirements of XFEs, XCF, and AFs. (IDCC, EBLINK, NXW)
- Definition of a list of services exposed by the XCI towards the application-plane through a Northbound Interface (NBI). Such services include Topology and Inventory, Provisioning and Flow actions, IT infrastructure and Inventory, Statistics, NFV Orchestration, VNF Management, Analytics for Monitoring, Local Management Service,

and Multi-tenancy. WP3 provided an initial description of the information model and REST-based APIs at the NBI. (UC3M, NEC, ATOS, NXW, CTTC, CREATE-NET, POLITO)

Work on the XCF, XFE design, and XCI SBI has been performed in close collaboration with WP2. Work on the XCI design, services provided, and XCI NBI has been performed in close collaboration with WP4. In both cases collaboration has been excellent and supported by mutual participation in WP telcos and joint meetings at the f2f meetings.

5.2.3.2 Task 3.1 - 5G-Crosshaul Data Plane

The design of the 5G-Crosshaul data plane – developed by UC3M, TEI, ATOS, NOK-N, IDCC – consists of 3 major building blocks, as depicted in Figure 10: *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.

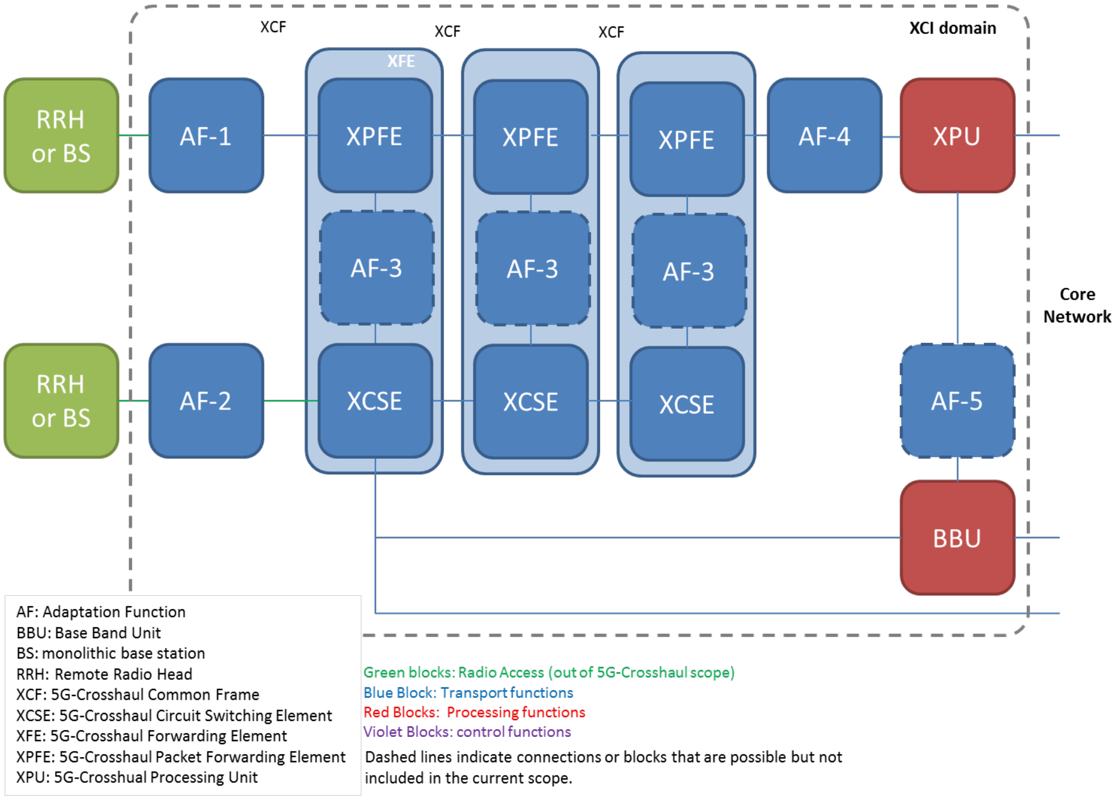

Figure 10: 5G-Crosshaul data plane architecture

The AF1, AF2, AF4, and AF5 perform frame format adaptation to and from the XCF. In addition, these AFs may contain further functionality such as e.g. de-jitter buffers. 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. As a starting point for specifying the XCF, state of the art transport protocols and their extensions (e.g., IEEE 802.1 time sensitive networking or radio over Ethernet (IEEE1904.3)) have been analyzed by UC3M, NEC, NOK-N. A list of requirements was developed by UC3M, NEC, EAB, TI, NOK-N, IDCC. The main categories of requirements were

- Support of multiple functional splits of the radio protocol stack
- Support of multi-tenancy
- Coexistence with existing transport protocols
- Transport efficiency
- Support of management procedures
- Support of multiple media
- Energy efficiency
- Avoidance of vendor lock

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. The chosen XCF is depicted in Figure 11.

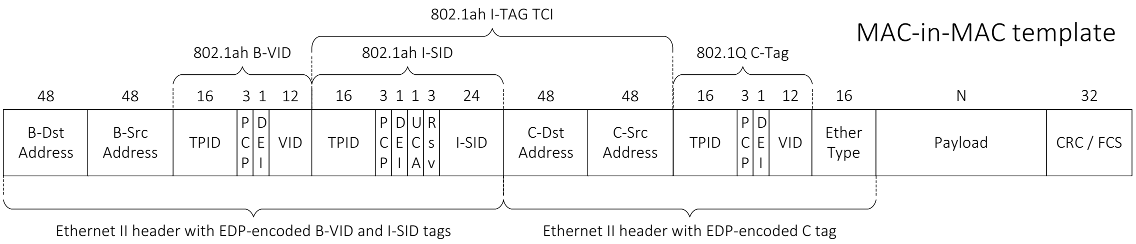

Figure 11: MAC-in-MAC as XCF

Initially, a problem was identified for IEEE802.11ad links as transport links as it was not possible to carry 802.1q tagged Ethernet frames across such links. But this gap will be closed by forthcoming Ethernet amendments, allowing to carry 802.1q tagged frames and thereby also to carry XCF frames across 802.11ad links without losing information.

Satisfying the SLAs (service level agreement) of the different types of traffic is based on a mapping the packets to a small number of different services provided by the 5G-Crosshaul network. This mapping is encoded by the priority code points (PCP) in each packet. The 5G-Crosshaul has to prioritize among these services to actually satisfy the SLAs.

The XFE consists of a packet-switched and a circuit-switched forwarding element, which are both optional. The design was developed by UC3M, TEI, NOK-N, IDCC, TELNET. The circuit-switched forwarding can consist itself of a TDM based forwarding component, e.g. using OTN (optical transport network) and a purely optical switching forwarding component, connecting different wavelengths of ports with each other. The packet switched part allows to utilize statistical multiplexing gains, whereas the circuit-switched part is beneficial for traffic with extremely low latency and jitter requirements. The multi-layer approach of the XFE allows to aggregate traffic flows on the packet level and then feed it into an OTN channel or wavelength of the XCSE part within the same XFE. Different such flows have been investigated within WP3 and are depicted in Figure 12.

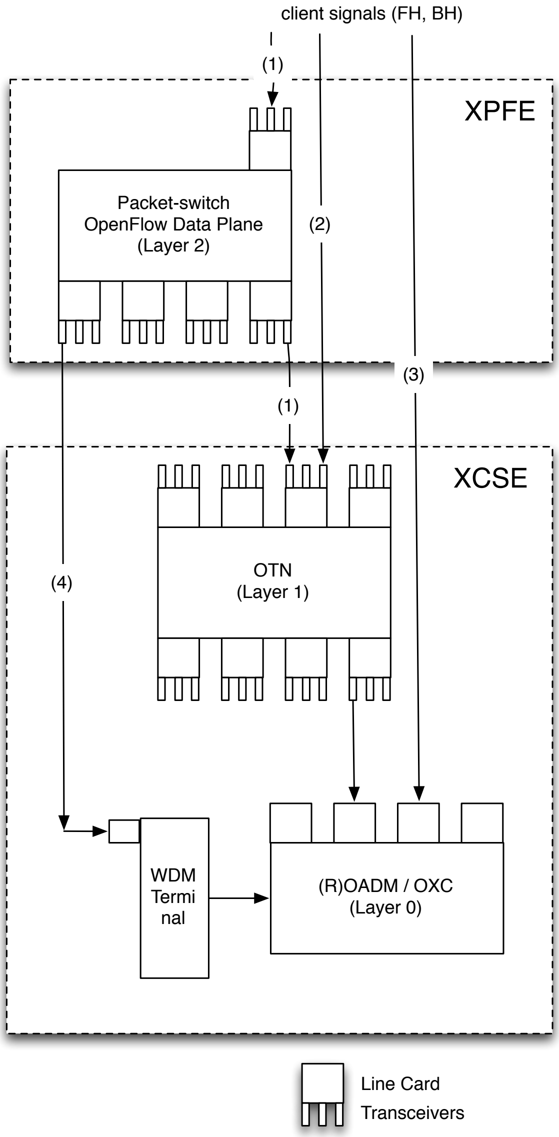

Figure 12: Hardware architecture of the XFE

Different splits of the 4G radio protocol stack are investigated by CND. Initially a deployment of the PHY, MAC, and RLC layers are deployed in the RRU and the PDCP layer and RRM functionality is deployed in the BBU.

5.2.3.3 *Task 3.2 - 5G-Crosshaul Control Plane*

Based on the system architecture described in WP1, WP3 developed an initial design of the XCI. This, and subsequent design iterations, have been done 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 13. Different technological domains as well as different administrative domains could 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 as well, but are not shown here for the sake of brevity.

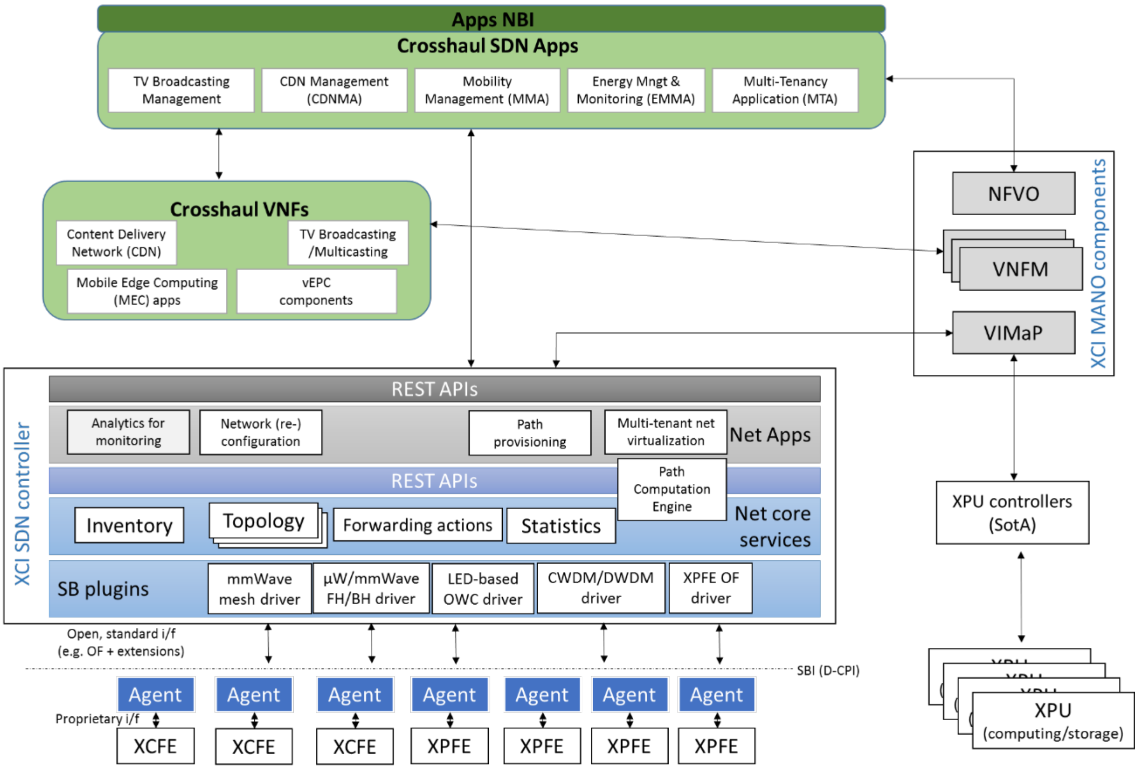

Figure 13: XCI design

Figure 13 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) associated to the different 5G-Crosshaul VNFs, 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.

The controllers, in particular the SDN controller on the network side and the XPU controllers, including both storage and computing, perform the enforcement of VIMaP decisions. XPU controllers rely on State of the Art components (e.g. OpenStack NOVA for computing controllers) and are out of scope for 5G-Crosshaul. SDN controllers are developed or extended within 5G-Crosshaul to provide the required services to the applications.

The work on the SDN controllers started with an in-depth analysis of existing SDN controllers by UC3M, NEC, ATOS, NXW, POLITO on the following aspects:

- The most relevant functions for 5G-Crosshaul,
- Architectural aspects to be considered
- Software aspects
- Impact and popularity of the controllers

OpenDayLight and ONOS have been identified as the most promising candidates.

WP3 analyzed – TEI, NOK-N, TI, EBLINK, NXW – the use cases described in WP1 and the applications to be developed in WP4 and derived requirements on the SBI and NBI from this analysis. The requirements define which functions have to be provided by the XCI and which kind of information has to be carried across these interfaces. Based on the use cases the XCI has to support:

- **Scalability** in terms of number of simultaneous users being served in an area.
- **Dynamicity.** The XCI should dynamically populate convenient forwarding rules to different XFEs in 5G-Crosshaul accompanying the movement of the mobile users, especially to support CDNs. The XCI has to be aware of the physical network elements and connections, their capabilities, status and configuration. New physical resources added at runtime have to be discovered and integrated into the network.
- **Energy efficiency.** The XCI must support the dynamic switch -on and -off of elements, including not only network resources but also computing resources. It must provide the algorithms to detect optimization opportunities.
- **Virtualization** of physical network resources through uniform information models describing logical network resources, aggregation or splitting physical network resources in isolated virtual ones; control the deployment of virtual storage and machines, or coordinate the SDN-based network virtualization with NFV functionalities.

The requirements on the SBI and NBI defined types of information to be exchanged at these interfaces. These requirements have been refined into detailed descriptions of the interfaces by UC3M, NEC, ATOS, NXW, CTTC, CREATE-NET, POLITO. At the NBI, the XCI offers its services through REST-based APIs. The services provided are Topology and Inventory, Provisioning and Flow actions, IT infrastructure and Inventory, Statistics, NFV Orchestration, VNF Management, Analytics for Monitoring, Local Management Service, and Multi-tenancy. A small excerpt of the API of the Topology and Inventory service is shown in Table 9 and the corresponding information model is shown in Figure 14.

Table 9: Topology and Inventory Service API

Prot.	**Type**	**URI**	**Parameters**	
REST	GET	*../topology/default* Retrieve the whole physical network infrastructure. *../ topology/{network_id}* Retrieve the … network topology … network_id.	Input	*network_id* (optional)
			Output	*network_object*
REST	PUT	*../topology/{network_id}* Add subnetwork … *network_id* to the physical network … *network_object.*	Input	*network_id, network_object*
			Output	Success: Status Code of normal end Failure: Error code
…	…	…	…	…

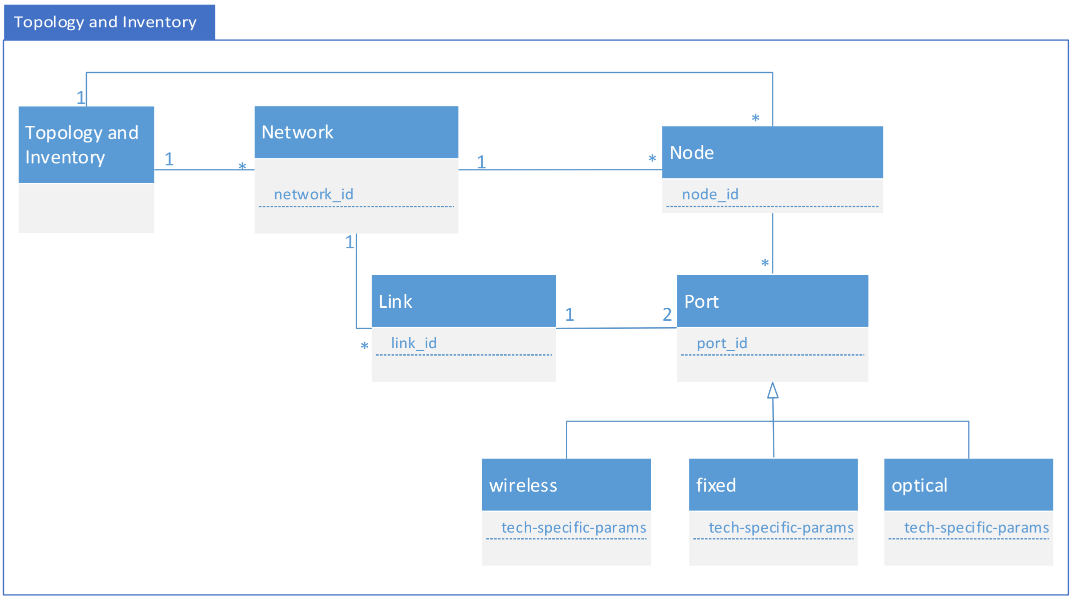

Figure 14: Topology and inventory information model

Regarding the SBI, WP3 – UC3M, TEI, IDCC, NXW – firstly analyzed suitability of protocols for configuration and management on the one hand and forwarding on the other hand. For configuration and management no clear favorite could be identified, there are too many competing approaches in use in the field. For forwarding, OpenFlow was considered as the most appropriate candidate, allowing fine-grain control of the forwarding. More fine-grain control by e.g. dynamically configuring packet parsers was not considered necessary.

Jointly with WP2, WP3 – IDCC, EBLINK, NXW – elaborated extensions for OpenFlow port descriptions for the different technologies investigated in WP2. E.g. for TWDM optical networks port descriptors are extended with a parameter to describe the dynamic bandwidth allocation (dba).

5.2.3.4 Deviations

In addition, in November 2015 the WP3 leader was changed due to Dirk Tiegelbekkers leaving Nokia. Thomas Deiss from Nokia took the leadership of the WP without any perceived effect on its work. We would like to take this opportunity to acknowledge Dirk for his great work and dedication to the project.

5.2.3.5 Corrective actions

None required.

5.2.4 WP4: Enabled innovations through 5G-Crosshaul

5.2.4.1 Overall WP Progress and main achievements

WP4 is focused on designing and developing essential applications for managing the 5G-Crosshaul network including both networking and IT resources, providing context-aware system-wide resource orchestration that ensures optimal service delivery and 5G-Crosshaul resource utilization both cost-wise and performance-wise. In the first reporting period, WP4 has focused on determining initial set of requirements for the Northbound Interface (NBI) of the 5G-Crosshaul Control Infrastructure (XCI) and the design of seven key applications for 5G-Crosshaul: Multi-tenancy Application (MTA), Mobility Management Application (MMA), Energy Management and Monitoring Application (EMMA), Resource Management Application (RMA), Virtual Infrastructure Manager and Planner Application (VIMaP), Content Delivery Network Management Application (CDNMA), and TV Broadcasting Application (TVBA).

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

- Objective 1: Design of the 5G-Crosshaul Control Infrastructure (XCI)
    - Design the Virtual Infrastructure Manager and Planner (VIMaP) as a key MANO component of the XCI.
    - Explore multi-tenancy feature inside the XCI to support multi-tenancy application (MTA) for the deployment of network services or deployment of virtual infrastructures for multiple tenants.
- Objective 2: Specify the XCI's northbound (NBI) and southbound (SBI) interfaces.
    - Specify the requirements for the NBI for the needs of applications
    - Specify the requirements for the SBI for the needs of applications
    - Specify abstraction information model.

- Objective 5: Increase cost-effectiveness of transport technologies for ultra-dense access networks
    - EMMA is designed to control sleep mode and on/off cycles, and dynamically trigger actions in the infrastructure to optimize and minimize the energy footprint so as to reduce energy cost per bit by a factor of 10.
- Objective 6: Design scalable algorithms for efficient 5G-Crosshaul resource orchestration
    - Scalable orchestration algorithms for dynamic joint optimization RAN, routing and function placement (RMA, EMMA, VIMaP, MTA, MMA)
    - Novel 5G-capable routing and traffic engineering algorithms, jointly considering cloud and network resources (RMA, EMMA)
    - 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)
    - Simulative proof of scalability and throughput performance of resource management algorithms based on real operator's backhaul network data (RMA, EMMA, MTA)
    - Prototype of some application algorithms on top of real test network (RMA, MMA, EMMA, CDNMA, TVBA, VIMaP)
- Objective 7: Design essential 5G-Crosshaul (control/planning) applications
    - Novel capacity-minimization and Quality of Experience (QoE) optimization techniques for wide-area media broadcast and multicast (CDNMA, TVBA)
    - Energy Manager (controlling optimal scheduling of equipment sleep cycles, routing parameters and function placement, and energy harvesting) (EMMA)
    - Techniques for end-to-end monitoring, prediction and enforcement of QoS parameters (such as latency, loss, jitter, bitrate) across heterogeneous Crosshaul technologies (EMMA, MTA)
    - 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, EMMA)
    - Prototype of software for Crosshaul infrastructure planning (VIMaP)
    - Simulative analysis and software prototype of the Energy Manager (EMMA)
    - Demonstrator for media distribution systems (TVBA, CDNMA)

Throughout the reporting period, WP4 worked primarily on the following topics.

- Develop algorithms to design and dimension the required physical 5G-Crosshaul infrastructure in terms of sites and links (Objective 4.1)
  So far a number of algorithms are being developed for physical and virtual infrastructure (re-)planning, specifically
    - optimal functional splits between centralized and remote RAN functions and their placement across the 5G-Crosshaul network;
    - optimal placement of virtual machines inter-connected in a given graph across the 5G-Crosshaul network;

  - optimal placement of the requested virtual infrastructures over the available physical infrastructure to maintain energy consumption under configurable thresholds;
  - optimal infrastructure for deployment of CDN and TVBA services.

  Evaluation of the above algorithms is planned for the next step.

- Develop an end-to-end monitoring and prediction framework supplying all relevant metrics (e.g., latency, jitter, loss, capacity) needed for efficient resource orchestration across heterogeneous technologies. (Objective 4.2)
  EMMA is designed to monitor the system power consumption and the energy status of physical and virtual nodes, both network and computing, aiming at energy reduction as one of the project KPIs. At this stage, monitoring methods are being developed for periodically collecting the values of power consumption and the energy status of the physical network nodes (e.g., XPEs, base stations) and the computing nodes (XPUs). A proof-of-concept demo is planned for the second year for evaluation experiments.
- Develop orchestration algorithms for joint optimization of RAN policies, routing policies and function placement (Objective 4.3)
  Different orchestration algorithms are being developed for the goal of various applications on resource management considering networking and IT resources. Evaluation of these algorithms via simulation or PoC demo is planned for the next step.
- Develop algorithms and techniques for efficient media distribution that are Crosshaul-aware (Objective 4.4)
  Content Delivery Network Management Application (CDNMA) and TV Broadcasting Application (TVBA) are developing related algorithms and techniques for efficient media distribution on top of 5GCrosshaul. A CDN demo and a TVBA demo are planned for the second year for carrying out evaluation experiments.
- Specify interface requirements for the technology abstraction layer in WP3 as well as for neighboring network domain controllers (e.g., RAN and core network) (Objective 4.5).
  An initial set of requirements for the NBI of the XCI has been provided.

5.2.4.2 Task 4.1 - Enabling Methods

The goal of Task 4.1 is to develop enabling methods towards (i) solving planning problems by developing algorithms to dimension and plan the overall hardware and software infrastructure setup in order to meet the system performance KPI; and (ii) Crosshaul-wide monitoring solution that supplying all relevant performance metrics (e.g., latency, jitter, loss, capacity) needed for efficient resource orchestration across heterogeneous technologies. To this aim, the RMA, EMMA and VIMaP applications are designed to offer such methods:

5.2.4.2.1 Energy Management and Monitoring Application (EMMA)–POLITO, NXW, CTTC, FhG-HHI

The EMMA is an infrastructure-related application of the 5G-Crosshaul system. It aims at monitoring energy parameters of RAN, fronthaul and backhaul elements, estimate energy consumption and trigger reactions to optimize and minimize the energy footprint of the virtual network while maintaining the required QoS for each Virtual Network Operator (VNO) or end user. EMMA ensures that a complete view of the system energy consumption is available.

- Periodically collecting the values of power consumption and the energy status of the physical network nodes (e.g., XPEs, base stations) and their communication drivers
- Periodically collecting information on the power consumption of the servers (XPUs) due to the currently deployed virtual machines.
- Computing and providing energy-related metrics of interest to the mobile network operator (MNO).

Together with energy-specific parameters like power consumption and CPU loads, EMMA will also collect information about several network aspects: traffic routing paths, traffic load levels, user throughput and number of sessions, radio coverage, interference of radio resources and equipment activation intervals. All these data can be used to compute a virtual infrastructure energy budget for subsequent analysis and optimizations.

5.2.4.2.2 Virtual Infrastructure Manager and Planner (VIMaP) – CTTC, TID

The Virtual Infrastructure Manager and Planning application (VIMaP) is logically part of the 5G-Crosshaul XCI and resides at the lowest level of the application hierarchy. It extends the ETSI/NFV Virtual Infrastructure Manager (VIM) by offering additional services and by implementing logic and policies for the optimal allocation and placement of resources in a pluggable and modular way. The VIMaP implements the mechanisms to instantiate, deploy and provide these resources over the Crosshaul infrastructure. It acts as a bridge between an application requiring a heterogeneous set of resources (e.g., a slice) and the actual interaction with one or multiple underlying controllers. For planning purposes, both services (in the form of distributed VNFs across Crosshaul) and resources (in terms of computing capabilities hosting those VNFs and networking resources connecting them internally and externally to Crosshaul) have to be accounted for in a combined process of allocation, with the additional complexity of satisfying and consolidating demands coming from multiple tenants.

5.2.4.2.3 Resource Management Application (RMA) - CREATE-NET, NEC

This application can be used as a planning tool to decide:

- Optimal functional splits between centralized and remote RAN functions and their placement across the 5G-Crosshaul network.
- Optimal placement of virtual machines inter-connected in a given graph across the 5G-Crosshaul network.

5.2.4.3 Task 4.2 - Context-aware 5G-Crosshaul Resource

Task 4.2 is the central task of this WP aiming for novel context-aware system-wide resource orchestration methods. For this purpose, the following applications have been defined focused on developing orchestration algorithms for optimization of 5G-Crosshaul resources (including networking and IT resources) to achieve multiple different objective metrics.

5.2.4.3.1 Resource Management Application (RMA) - CREATE-NET, NEC

This application provides logically centralized and automated management of 5G-Crosshaul resources to promptly provision transport services corresponding to network changes and to meet the requirements of different client applications (which requests for resource management service) while ensuring effective resource utilization. The RMA relies on the XCI controllers to enforce the RMA decisions in terms of actual provision and allocation of resources. The RMA can operate over physical or virtual network resources, on a per-network or a per-tenant basis, respectively. Essentially, the RMA has two main functional pillars: *i)* dynamic resource allocation and (re-) configuration (e.g., new routes or adaptation of physical parameters) as the demand and network state changes; and *ii)* dynamic NFV placement, e.g., enabling multiple Cloud-RAN functional splits flexibly allocated across the transport network.

5.2.4.3.2 Mobility Management Application (MMA) – UC3M, ITRI

The main goal of MMA is to support mobility management in mobility scenarios such as vehicle mobility, and also to optimize traffic offloading for media distribution services like CDN.

The most challenging scenarios in vehicle mobility use case are the provision of high mobility support (e.g. up to or greater than 500 km/h) to a crowd of passengers (e.g., more than 500 people) using 5G services (video in particular) and satisfying the user QoE in a cost effective way. Handover is a critical operation in mobility management, especially in such environment. The focus of the MMA is to exploit the context information as well as the loading of some candidate target BSs, in determining the target BS and the corresponding resource allocation. The MMA will exploit the deterministic trajectory of the node for the proactive creation of paths in advance, placing cache nodes and even core nodes in the path of movement.

The challenge for traffic offloading is to optimize the location and relocation procedures for services such as CDN in combination with resource management decisions. In this case, Crosshaul mobility will be based on a flat IP network, on which traffic is forwarded to the nearest point of connection to the Internet. The forwarding will be based on direct modification of flow tables at the data path elements, using, e.g., the OpenFlow protocol. The MMA aims to provide traffic offload to the Internet and/or moving the applications to the edge as close as possible to the users. The MMA uses the services offered by the RMA to provide best paths between the different elements of the network, with the main goal to optimize the route or path followed by mobile users' traffic towards the Internet or to a core service provided in a datacenter. The assignment of Points of Connection (PoC) to the Internet and possible points to offload to CDN networks or core nodes will depend on the criteria adopted by each tenant owning the network. After computing the best set of elements to provide a service to the user, the MMA will request the RMA to find the best path connecting these points based on the network status.

5.2.4.3.3 Multi-Tenancy Application (MTA) - NEC, ITRI, CTTC, NXW

Multi-tenancy is a desired feature by 5G-Crosshaul to enable a generalized, flexible sharing of

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

5.2.4.3.4 Energy Management and Monitoring Application (EMMA) - POLITO, NXW, CTTC, FhG-HHI

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

5.2.4.4 Task 4.3 - 5G-Crosshaul-Aware Media Distribution

The goal of this task is to study the impact and improvement potentials for media distribution applications that run on top of 5G-Crosshaul. We focus on developing two major media distribution applications: first, mobile **content delivery networks (CDNs),** i.e., media delivery via networks of content caches which are deployed close to XFEs across the Crosshaul topology, and second, **TV broadcasting**, not via a satellite overlay but rather via the mobile network itself, i.e., going through the Crosshaul topology.

5.2.4.4.1 CDN Management Application (CDNMA) - ATOS

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

5.2.4.4.2 TV Broadcast Application (TVBA) - VISIONA

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

5.2.4.5 Interaction between Applications

The interactions among 5G-Crosshaul applications are exemplified in the figure below, which clearly shows that the application layer is divided into two sublayers.

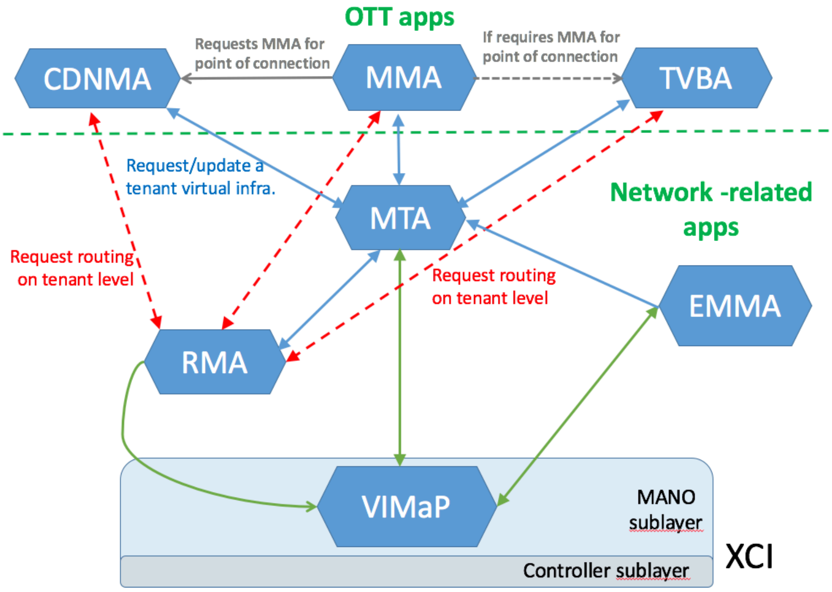

Figure 15: Interaction among 5G-Crosshaul applications

The higher sublayer includes OTT (Over-The-Top) applications, namely CDNMA, MMA and TVBA, which collaborate with each other and interact with lower sublayer applications through their SBI. Interactions among OTT applications are limited to the MMA providing CDNMA and TVBA information regarding the point of attachment, i.e., to give the information related to whether the user(s) moved from one point of connection (i.e. XFE) within the 5G-Crosshaul network to another. These interactions are shown in grey.

The lower sub-layer includes network-related applications: RMA, EMMA and MTA. The interactions among them are more complex than for the OTT apps, and they also interact with the XCI. In the figure, the XCI is functionally divided into two sublayers: a MANO sublayer, where the VIMaP application also resides, integrating the ETSI NFVO, VNFM and VIM, and a Controller sublayer including SDN controller and cloud controller. The VIMaP has the task of instantiating, deploying and provisioning resources (including networking, computing and storage resources) over the 5G-Crosshaul infrastructure, interacting with one or more underlying controllers. Thanks to its placement, the VIMaP can provide the view of the physical 5G-Crosshaul infrastructure, to other applications, enforce the physical mapping between the virtual infrastructure and the physical infrastructure and allocate the corresponding resources for all applications.

5.2.4.6 Interface models of the applications

In order to enable the communications between applications according to their expected interactions, each application requires a south-bound and a north-bound interface, where the south-bound interface was used to *consume* services offered by external applications, while the north-bound interface was used to *provide* services to external applications. To model such interfaces, we specified a set of abstract and protocol independent primitives which must be supported by the applications NBI (specifying the messages, their senders and receivers as well as their parameters) and then proposed a possible interface implementation through mapping of these primitives into REST API messages. The usage of REST APIs is adopted, making use of the HTTP protocol for message transport, YANG language for information model specification and JSON encoding for resource description. This approach allows modelling easily the communication between applications as a service consumer/provider interaction, where the providers act as HTTP servers and the consumers act as HTTP client. In particular, more clients (i.e. applications) can access the services provided through the NBI of a single provider without the need to define a different interface for each couple of interacting applications.

5.2.4.7 Requirements on the XCI Northbound Interface (NBI)

The interaction of the XCI with the Crosshaul applications is done through the NBI. Based on the kind of resource exposed, the XCI provides three types of NBI functionalities to 5G-Crosshaul applications, namely: i) network functionalities offered by the SDN controller, ii) computing and storage functionalities offered by the computing and storage controllers, and iii) unified IT/network service functionalities offered by the NFVO and the VIMaP, located in the MANO layer of the XCI.

Accordingly, we identified a set of main XCI services, which are exposed to the 5G-Crosshaul applications through the NBI. In particular, these services can be classified in two main categories, namely *informative services* and *configuration services*. Both kinds of NBI services can be exposed by APIs offered by the NFVO, VIM, and underlying controllers

The *informative services* are used to collect data about resource availability, monitoring information, or unexpected events in the network and the IT domains of the underlying infrastructure. Depending on the type of information data and their usage at the application layer (e.g. input for medium/long term optimization or reactive and real-time decisions), polling or subscription/notification mechanisms should be implemented. This category includes the following services:

- Network topology service, to collect information about the physical network topology in terms of nodes, ports and links, with their characteristics, capabilities and resource availabilities.
- Mapping between VNF instances and the infrastructure resources.
- IT infrastructure inventory service, to provide a catalogue of computing and storage resources.
- Network monitoring service, to expose raw information collected by the physical network elements, depending on their monitoring capabilities.
- IT infrastructure monitoring service, to expose information related to the usage and performance of the underlying XPUs.
- Monitoring analytics service, to provide more elaborated information, like predictions, estimations of interference level or SNR, detected failures, etc.

The *configuration services* are used by the applications to request provisioning or operational actions for different kinds of resources. These services include:

- Provisioning of virtual infrastructures composed of VMs and virtual networks (IaaS model), to create multi-tenant infrastructure environments, which can be further used for deploying user-level applications.
- Management of templates and VNF packages for 5G- Crosshaul OTT Network Services.
- Provisioning of QoS-enabled network paths, to request customized network connections, with support for path hops specification, proactive scheduling and protection or restoration strategies.
- Enforcement of traffic scheduling, shaping and QoS provisioning, to regulate the traffic typically over already existing virtual infrastructures.
- Creation and management of single VNFs or end-to-end network services, to instantiate, monitor, configure and scale VNFs or Service Function Chains (SFCs).

- Configuration of network devices, enabling a low level access to network elements for a restricted set of commands (e.g., to regulate the power state of the devices for energy management purposes).

For each of the above XCI services we defined the type of interaction (e.g., polling, Subscribe/notify, Configuration Command) and exchanged information for the input and output parameters as expected at the north-bound interface.

5.2.4.8 *Workflow of Application*

Furthermore, each application provides an initial design of required workflows which identify necessary interactions towards other applications and to the XCI services. As an example, the workflow of the EMMA is presented in the following figure. As shown the EMMA needs to interact with several entities, namely, the SDN controller, the NFVO and the VIMaP, either to collect information or to provide commands.

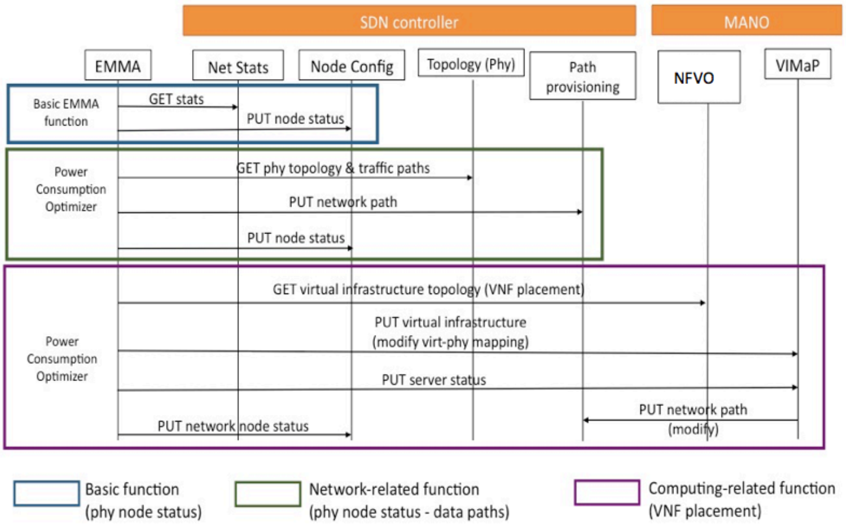

Figure 16: Workflow of EMMA

5.2.4.9 *Implementation of Applications*

The implementation of applications is essential for the next milestone in WP4. Among all applications, MMA, RMA, EMMA, CDNMA and TVBA applications are planned for software implementations. For this purpose, an initial high-level software design of the 5G-Crosshaul applications is provided as guidelines for their implementation. Using EMMA as an example, Figure 17 shows the high-level design of the EMMA application, where the main internal components are described in the table below. Furthermore, a roadmap for the implementation is planned by each application.

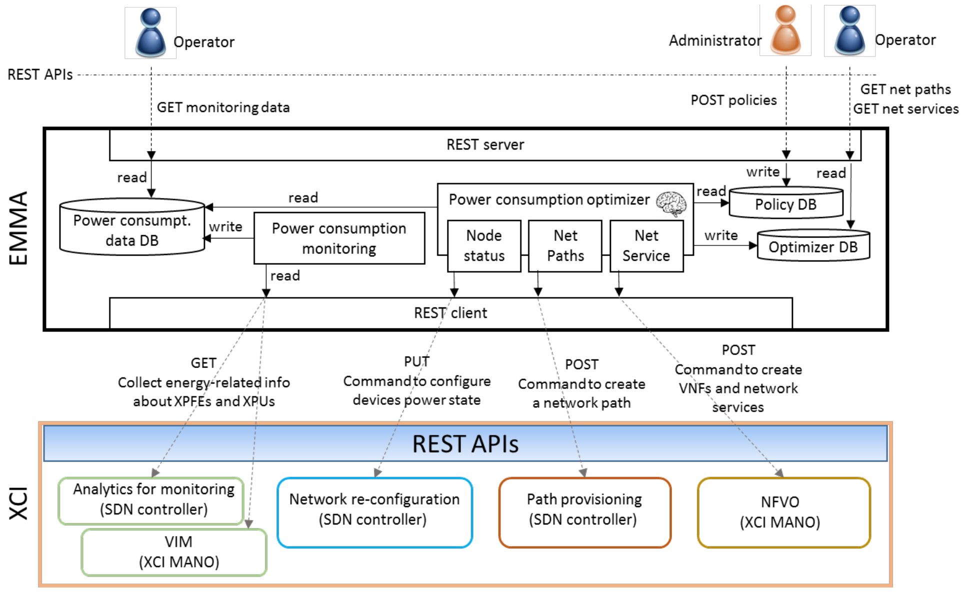

Figure 17: EMMA high-level software design

Table 10: EMMA application components

Component	**Description**
REST Client	Entity in charge of interacting with the XCI components via REST APIs.
Power consumption monitoring	Entity in charge of coordinating the collection of power consumption information from XCI components (i.e. VIM for XPUs and SDN controller for XPFEs), processing and aggregating this information and storing and organizing the results in the internal *Power consumption data DB*.
Power consumption data DB	Internal no-SQL DB to store power consumption data, related to single XPUs or XPFEs, end-to-end network paths, VNFs and Network Services, or physical domains at the physical infrastructure level.
Power consumption optimizer	Entity in charge of computing the optimum allocation and status of physical resources, based on the information stored in the *Power consumption data DB* and the policies configured in the *Policy DB*.
Policy DB	SQL database storing the policies configured by the administrator.
Optimized DB	SQL database storing the device status, network paths and Network Services computed by the *Power Consumption Optimizer*.

REST Server	Entity in charge of implementing the northbound REST API of the EMMA application for retrieving power consumption monitoring data and power optimization actions as well as for configuring energy management policies.

5.2.4.10 Deviations

None detected.

5.2.4.11 Corrective actions

None required.

5.2.5 WP5: Validation and proof of concept

5.2.5.1 Overall WP Progress and main achievements

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 will be integrated into a software-defined flexible and reconfigurable 5G testbed in Berlin. During this period WP5 has expanded its original mission to consider more testbeds (Berlin, Madrid, Barcelona, Taiwan) and start the definition of the different components which can be validated on each testbed.

In addition, WP5 contributed to the following specific objectives:

- Objective 5.1 - Proof of concept of key 5G-Crosshaul technologies. Testbeds have been deployed as the framework over which the proof-of-concept (PoC) will take place. Components towards integrated PoC identified. Early integration efforts and small-scale PoCs already done and demonstrated.

- Objective 5.2 - Integrated demonstration of technologies developed in WP2, WP3 and WP4 in a real environment. Early integration of specific components done. Mid-/long-term integration efforts identified (and under refinement).

- Objective 5.3 - Orchestration of 5G-Crosshaul components through flexible APIs and programmable hardware provided by partners. Some of the early integration work covers orchestration of multi-domain multi-layer networks. Other scenarios identified and under definition and development.

5.2.5.1.1 Detailed description on work carried out

The main goal of WP5 is to integrate the components designed in other WPs and to validate experimentally that all the conceived building blocks of the 5G-Crosshaul solution can work together to fulfill the heterogeneous 5G traffic flow requirements. The proof-of-concepts will be carried out over various testbeds. Initially, the testbed infrastructure included Fraunhofer's 5G Berlin (Germany) as well as ITRI's 5G Testbed in Taiwan. During the progress of the first Task, *T5.1 Testbed Definition and Setup*, it became clear that the testbed infrastructure could be extended with justifiable effort to CTTC's 5G testbed infrastructures EXTREME and ADRENALINE, as well as to UC3M's 5TONIC-Madrid. This will offer 5G-Crosshaul unique capabilities to develop, test and demonstrate novel 5G-Crosshaul features in several testbeds.

On the way to this large-scale integration, the **key technical achievements** of this first reporting interval are:

- The initial efforts have been devoted **to identify all the components provided by partners** that will be integrated. This includes components already available that enable the construction of the experimental frameworks as well as components that will be developed during the project according to the design decisions taken at the application, control infrastructure, and data plane levels.
- Furthermore, **interfaces between components where identified and specified** where required. Enhancements to existing interfaces to support novel 5G-Crosshaul solutions were specified.
- In addition to **preparing the experimental frameworks** required by the project, the above analysis already enabled some **early integration efforts** among a reduced number of components, which have already been demonstrated in various events (e.g., preliminary multi-domain wireless and optical control plane). The key benefits of the early integration efforts are as follows:

    - It allows partners to **get familiar with the 5G-Crosshaul testbed environments and with building blocks developed by other partners**.
    - In addition, this triggers some **preliminary developments of key interfaces and building blocks** that will be further extended during the project lifetime.

  In the end, this results in small-scale proof-of-concepts of key 5G-Crosshaul architectural components in preparation of the large-scale proof-of-concepts.

- Additionally, an **initial list of the demonstrations** that are planned to be carried out over each of the testbeds was discussed and presented in IR5.1. These demonstrations are tightly linked with the use cases defined by the project in WP1, as well as the key performance indicators (KPIs) that have been defined in this project.

5.2.5.2 Task 5.1 - Testbed definition and setup

Since this first reporting period was exclusively devoted to T5.1, except for the last month (M12), most of the above description is directly related with T5.1. Therefore, the identification of components that will be provided by each partner, the preparation of the experimental frameworks over which the PoC will be deployed, as well as the preliminary development of interfaces and building blocks, were done under the framework of task 5.1. Furthermore, an initial list of demonstration setups and demonstrations to be carried out on top of each of these setups was also identified along with the objectives and KPIs that each of the demonstrations tackles. All the above work has been reported in detail in IR5.1 (Testbed, hardware integration and initial demo definition) delivered in M10.

As shown in the figure and tables below, all partners with workload in WP5 identified the components they will bring to the project. However, those partners providing the experimental frameworks of the project had a more relevant role given the effort devoted to its deployment and their participation in multiple integration efforts (HHI, UC3M, CTTC, ITRI). Figure 18 presents the four experimental frameworks that will be used in the project.

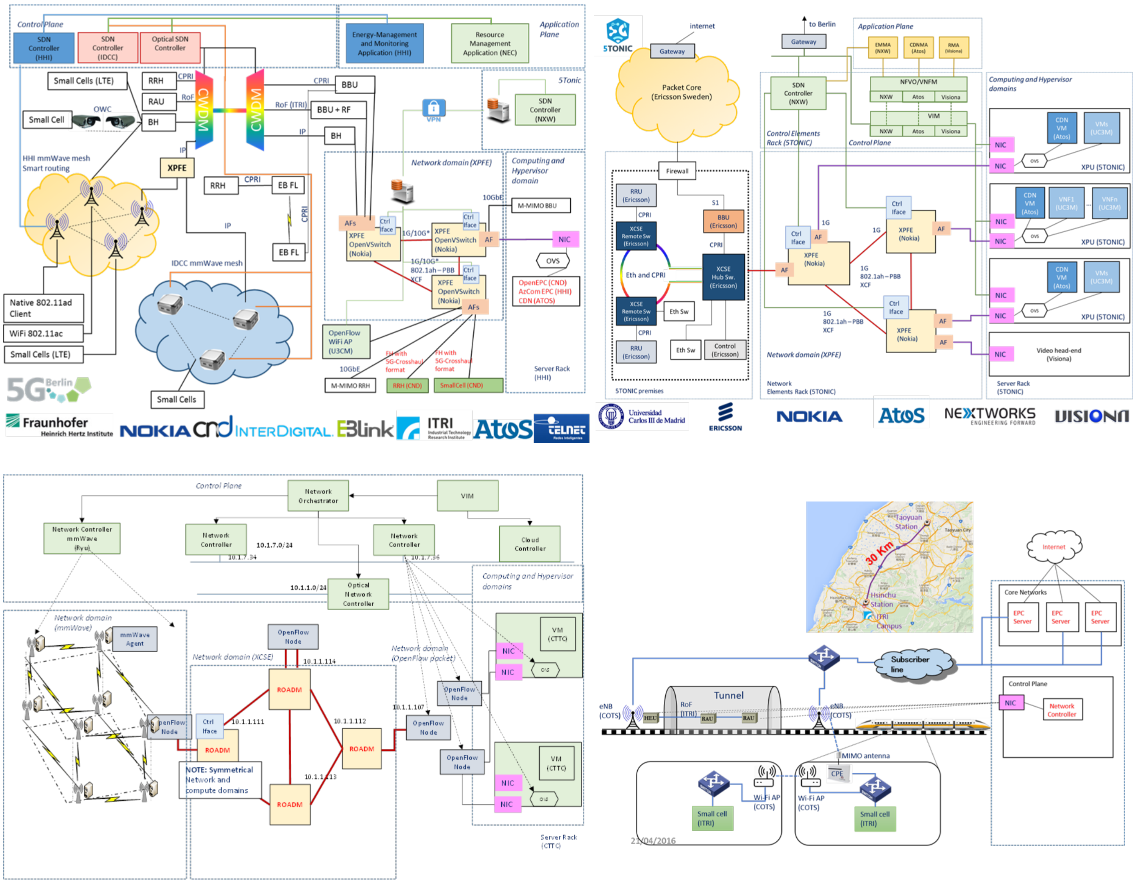

Figure 18. Testbeds build for 5G-Crosshaul (left-to-right and top top-to-bottom: 5G-Berlin, 5TONIC, CTTC, ITRI)

5.2.5.3 Task 5.2 - Integration and proof-of concept

Despite T5.2 officially starts in June 2016, during the first reporting period, some initial integration steps have already been taken by various partners in between T5.1 and T5.2.

Additionally, some of those were demonstrated at various events (e.g., ICT'15). Furthermore, during the Mobile World Congress 2016 (MWC2016), which was held in February in Barcelona, various partners already showcased their technology available for 5G-Crosshaul (CND, CTTC, IDCC, and HHI). Some of these demonstrations will be integrated in one of the testbeds, also with other components to be developed in 5G-Crosshaul.

Some early integration efforts are described in the following per partner involved:

- IDCC, CND and HHI. Fronthaul/Backhaul integration over a millimetre wave multi-hop wireless network. Agreed on the network architecture and location of outdoor equipment. First steps towards final deployment taken.

- EBLink and FhG-HHI. First lab tests between eBLINK and FhG-HHI solution were already conducted to demonstrate the integration into 5G-Berlin with FhG-HHI equipment. The final integration of this work shall be carried out in T5.2.
- EBLink and Orange. Mixed analog/digital radio over fiber. First lab tests of CPRI-to-RF conversion, so that analog signals are transmitted over fiber and the inverse process is done at the other end. Much higher spectral efficiencies are achieved in this way.
- HHI. Optical wireless. LED-based prototype integrated in 5G Berlin with the goal of providing 500Mbps bidirectional over 100m.
- ATOS. Prior to moving them to 5TONIC, ATOS deployed their virtual CDN nodes over virtual machines in their own lab.
- TEI, EAB. Initial plans for deployment of 5G-Crosshaul Circuit Switched Entities (XCSE), BBU, and RRH in 5TONIC as well as their interconnection with the core network in Sweden.
- ITRI. Integration of the analogue radio-over-fiber system with the macro base station and the backhaul network towards the core network.
- CTTC. Preliminary integration of packet-switched wireless equipment with Ethernet-based packet-switched and optical wavelength-switched equipment at the control plane level. Preliminary tests of millimeter-wave nodes.

Furthermore, very preliminary plans for integration of all the components identified have also been presented in IR5.1, though they will be further refined when T5.2 (dealing with integration) starts producing more results. For instance, there are also ongoing discussions that will be reported in IR5.2 (M15) on the integration plan for which the above table will be refined. Some of the integration efforts will be combined and some others have already appeared and will also be reflected in the table.

5.2.5.4 Use of resources

With respect to the use of resources in the first period of WP5, the actual used resources for personnel were approximately the planned resources. Some of the partners, though, reported a bit higher than plan workload mainly due to the fact that testing and setting up of the testbed infrastructure required a bigger effort than initially planned. This is reflected in the booked PMs for Q1 of two of the partners responsible for the testbed infrastructures (UC3M and HHI).

Nevertheless, it is expected that these numbers will adjust to the initial plan, since the main work for setting up the test sites was finalized. Apart from this, no further deviations are expected.

5.2.5.5 Deviations and Corrective actions

As mentioned above, some early integration efforts were made in the initial stages of the project. This is why some partners without workload planned in T5.1 (ATOS) reported some work in this task.

During the progress of T5.1, a few deviations were agreed in order to improve the 5G-Crosshaul results. In contrast to the 5G-Crosshaul testbed definition proposed, the consortium agreed to extend testbed activities to integrate the 5TONIC as well as ADRENALINE and EXTREME testbeds from CTTC. It is expected that the testbed extensions have a higher impact on the work done in 5G-Crosshaul as well as improve synergies between different H2020 projects linked or conducted in the same testbeds.

Due to the changes in the 5G-Crosshaul testbed environment, as well as the increased workload on FhG-HHI as responsible for integrating various components from other partners in the 5G-Berlin testbed, the consortium agreed to hand over the WP5 work package lead to CTTC for inter-testbed coordination. This corrective action frees up resources on FhG-HHI to focus integration and test of components into the 5G-Berlin testbed infrastructure. Additional plans allow interconnecting the various testbeds to demonstrate a more complex architecture, which opens up new possibilities for partners to showcase the flexibility and adaptation of their technologies to a more realistic overall scenario. In particular, a Control/Data-Plane split can be demonstrated within an interconnected testbed.

5.2.6 WP6: Communication, Dissemination and Exploitation Activities

5.2.6.1 Overall WP Progress and main achievements

WP6 started its work actively from day 1 (July 1, 2015) to deliver the first internal report IR6.1 due in month 2 (August 31, 2015). This report was devoted to set the Year 1 work plan for communication and dissemination, standardization, and exploitation activities. It also reported on the first achievements in the first two months as summarized below:

- For communication: (i) Launch of the project portal, Linkedin and Twitter accounts; (ii) Press release on the project kick-off and related communications; and (iii) Video interview posted on the project vision.
- For dissemination: (i) 5 articles published or accepted for publication; and (ii) more than 12 talks scheduled for presentations.
- For standardization: (i) an inventory of standardization activities with potential influence from/to the project; and (2) an initial standardization activity roadmap for each of the three technology planes in the project scope, namely, data, control, and application

planes. This initial roadmap activity was appreciated by the technical work packages WP2, WP3 and WP4, to help in planning their activities.

- For exploitation: (i) a preliminary list compiled for all existing pre-commercial solutions or products from the project partners which might be impacted by the technology anticipated for development in the project; and (ii) a selection of standardization activities with good potential for the project partners to contribute to with enhancements and extensions resulting from the work planned in the project.

Following on this first milestone report (IR6.1), WP6 kept the momentum across all its activities striving for more achievements and at the same time continue fine tuning the work plan for Year 1 as the work progresses. A second milestone on these activities was the second internal report IR6.2 duly delivered at the end of month 6 (December 31, 2015). Amongst the key achievements reported in IR6.2 are:

- Delivering over 15 standardization dissemination materials (10 input contributions inputs, and over 5 presentations/white papers) in various SDOs, such as ETSI, 3GPP, NGMN, BBF, FSAN, IEEE, IETF/IRTF, ITU-T, NGMN, and ONF.
- Exhibiting demonstrations at 3 showcase events, including noticeably the wireless SDN proof-of-concept showcase involving 4 partners from 5G-Crosshaul ONF's first project in addition to other industry organizations.
- Delivering over 15 talks at key R&D events, exceeding the original target set in IR6.1 for the whole of Year 1.
- Delivering 16 articles (7 published, 3 accepted, and 6 submitted), also exceeding the original target set in IR6.1 for the whole of Year 1.
- Participating in various workshops aimed at fostering synergies with other projects such as METIS II 5G-PPP cross-projects workshop, the 1st SINO-EU 5G workshop, and Tweether project workshop.

In addition, WP6 spent efforts in executing on the plan set for the following 6 months (January to June 2016) including noticeably, presence at two major events namely Mobile World Congress 2016 and EUCNC'16. The activities in the 6 months from January to June 2016 are scheduled for reporting in the first public deliverable D6.1, which is under drafting at the time of writing this periodic report. Amongst the noticeable achievements in these 6 months are:

- Successful demonstrations by 4 partners at Mobile World Congress 2016, namely, IDCC, CTTC, HHI and CND. These were accompanied with elevator pitch slides in the slideware, a project flyer, and video shootings including interviews.
- Successful proposals for organization two workshops on the future transport network at EUCNC 2016, one solely organized by 5G-Crosshaul, followed by another one on the same day, co-organized with 5G-XHaul and 5G-icirrus H2020 projects. The organization of the two workshops has been tightly coordinated to ensure maximum impact. In addition, the 5G-Consortium project is co-organizing at least 3 additional international

workshops, namely, ICC Backnets workshop (May 2016), Soft5G symposium (June 2016), and OSOMI workshop (July 2016).

- Delivering over 10 additional standardization dissemination materials noticeably at ETSI MEC ISG, ITU-T, and ETSI and NGMN 5G workshops. This brings the total number of standardization dissemination to over 25 in Year 1 (so an average of 2 per month)
- Delivering over 10 additional talks at key R&D events, bringing the number of talks delivered in Year 1 to more than 25 (so an average of 2 talks per month).
- Delivering over 10 additional articles published or accepted for publication, in additional to several other articles submitted. This brings the total number of articles published or accepted for publication in Year 1 to more than 20 (so an average of approximately 1.5 article per month). In addition, the 5G-Crosshaul technical manager and work package leaders are editing an IET 5G book chapter “Access, Fronthaul and Backhaul Networks for 5G and Beyond” which is expected for publication in 2016.

Noticeably in May 2016, the 5G-Crosshaul project was invited by ETSI to share its initial results on the standardization roadmap for the 5G integrated fronthaul and backhaul. The motivation at ETSI is to see whether there is a standardization gap in the area of xhauling that ETSI needs to kick start. The standardization roadmap included first an analysis yielding a mapping between the areas for technology development in future transport networks and the 5G KPIs as illustrated in the below Figure 19.

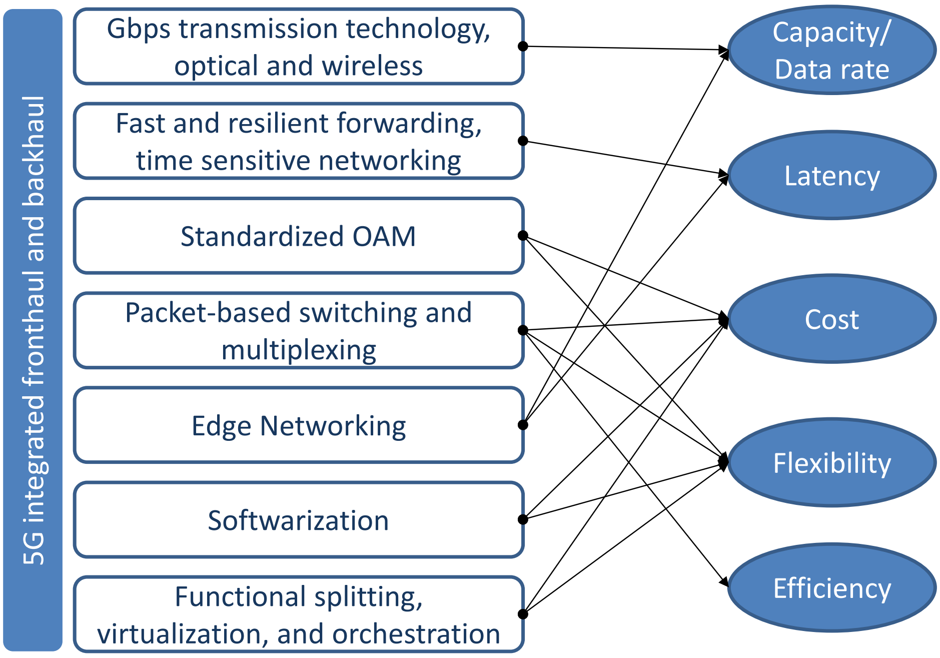

Figure 19: Mapping of technology areas for crosshauling to the 5G KPIs.

A second mapping of the technology development area to relevant ongoing standardization activities was also provided as shown in the table below.

Table 11: Mapping of technology areas for crosshauling and related SDOs.

Technology development area	Standardization groups
Use cases, gaps, requirements, architectures	NGMN, ITU-T 2020 FG, ITU-R WP5D, 3GPP, BBF, SCF
Gbps transmission technology (wired/wireless)	Wired: ITU-T SG15, NG-PON2, 100GE, CPRI Wireless: ETSI mWT, IEEE 802.11ay
Wireless access protocol functional splits	3GPP, IEEE 802.11, SCF
FH/BH traffic packetization (formatting)	Fronthaul: CPRI, NGFI (IEEE 1914.1 << 1904.3) Backhaul: VLAN (IEEE 802.1Q), MPLS
FH/BH traffic forwarding (switching protocols)	IEEE 802.1CM (Time Sensitive Networking), IETF DETNET (Deterministic Networking)
SDN control	ONF (OpenFlow), OpenDayLight, ONOS, IRTF SDNRG, ITU-T SG13, IEEE 802.1CF
NFV-based management and orchestration	ETSI NFV, IRTF NFVRG, OPNFV, OpenMANO, OpenStack
Network applications and API	ETSI MEC, OMA

An attempt to draw a first roadmap including indicative timeline of the standardization activities for crosshauling was also made as illustrated in Figure 20 .

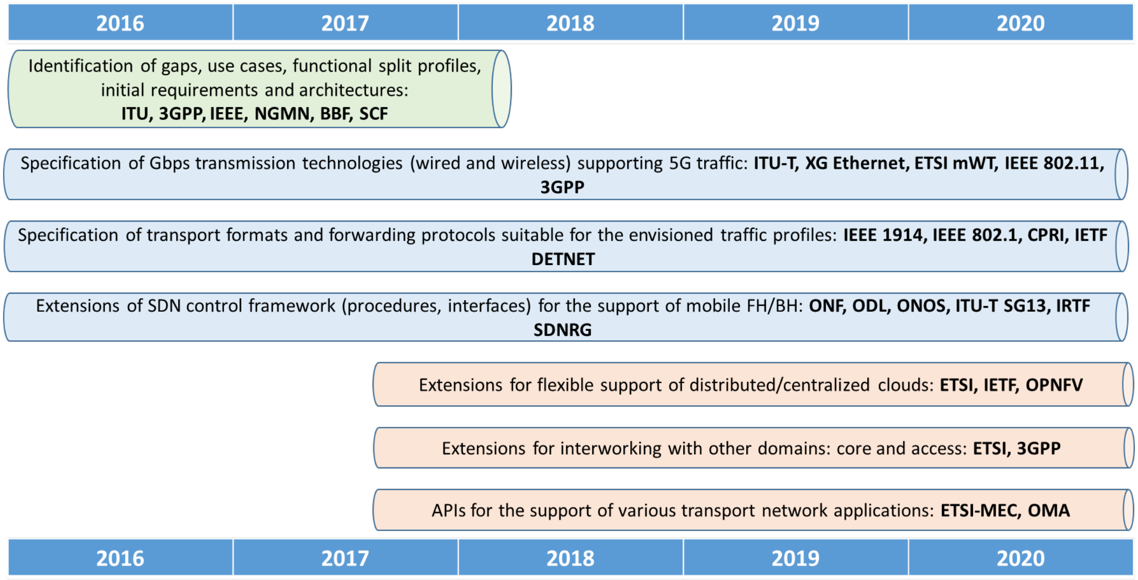

Figure 20: Initial standardization roadmap for 5G-crosshaul.

Following on this activity, some ETSI members have expressed interest to consider an initiative at ETSI for providing a standardization framework for what they call xhauling. This is ongoing through follow-up meetings organized by ETSI.

For exploitation, it is also noteworthy the activity undertaken by the Innovation Manager in identifying the innovations from the project and the potential paths for their exploitation. These are summarized in section 1.3 of this periodic report and also in the EC questionnaire on innovations, so we skip them in this section for the sake of avoiding duplication.

Overall, as appreciated from the above, WP6 made an extraordinary effort in Year 1 to ensure wide reach of its 5G-Crosshaul project concept and first results, making use of every possible venue for dissemination available, with the aim to create impact in the related industry and research communities. Standardization and Exploitation efforts have been particularly driven towards facilitating the creation of an industrial impact. This is helped by the active contribution of key members in the consortium such as Ericsson, NEC, Nokia, InterDigital, Telefonica, Orange, Telecom Italia, and UC3M.

5.2.6.2 Deviations

There has been no deviation in WP6.

5.2.6.3 Corrective actions

Not applicable.

5.2.7 WP7: Project Management

5.2.7.1 Overall WP Progress and main achievements

The management of the project, dedicated WP in the DoA, is led by UC3M.

The main activities in this period 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.

In M1 the Deliverable D7.1 [17]: Project Handbook, was delivered on time. It includes the management procedures for the proper development and implementation of the project.

In this period an amendment is carried out reporting:

- The formal change of the project acronym from Xhaul to 5G-Crosshaul, the project title becoming “5G-Crosshaul: The 5G Integrated Fronthaul/Backhaul” and also the project logo.
- The transfer of some funds (the exact figure will be provided in the official Periodic Report) from direct costs from the cost category of personnel to the cost category of external services, for U. Carlos III. The motivation for this was that the UC3M used this funding to pay for 1/3 of the membership fee of 5TONIC testbed, in order to demonstrate the projects results in it.
- The transfer of some funds (the exact figure will be provided in the official Periodic Report) from of direct costs of personnel from Fraunhofer HHI to CTTC. The motivation for this was that the project is producing more results that will have to be demonstrated over the expected ones, and that the demonstration will now be made in four testbed sites (5GBerlin, 5TONIC, Taiwan and CTTC). This implies a higher inter-testbed coordination work that was out of the scope of the initial WP5 leadership. Fraunhofer therefore preferred to concentrate in its research work and in the coordination of the 5GBerlin trials, and leave CTTC take the role of inter-testbed coordination. CTTC, through Josep Mangues, is the new WP5 leader.
- The decrease in PMs of the partner TELNET from WP3 and WP4, and the increase in PMs of IDCC in PMs of WP5

5.2.7.2 Task 7.1 - Project, administrative, financial, and legal management

In this period (M1-M12) five plenary meeting were held: The Kick-off Meeting and four progress meetings.

- Kick-off Meeting on 1st July 2015 in Paris. This meeting focused on the general aspects of the project, the main objectives and the main activities of each partner. The first activities are related to the definition of scenarios and uses cases.

- 2nd plenary meeting on 8th - 10th September 2015 in Madrid, at UC3M. The meeting focused on the definition of the architecture of the project, the initial study of WP2, WP3, WP4, WP5 and WP6 activities

- 3rd plenary meeting on 15th – 17th December 2015 in Pisa, at Ericsson Pisa. The topics were related to System Architecture design, WP2, WP3, WP4, WP5 and WP6 progress and planning of activities and next deliverables.

- 4th plenary meeting on 5th – 7th April 2016 in Barcelona at CTTC. The meeting was focused on WP1, WP2, WP3, WP4, WP5 and WP6 progress and planning of activities and next deliverables.

- 5th plenary meeting on 30th of June and 1st of July 2016 in Athens

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 planned for the end of the project (M30).

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 group with 95 members https://www.linkedin.com/groups/8344554 (numbers taken at 30/06/2016).

5.2.7.3 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.

5.2.7.4 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 Contribution input to “5G and Media & Entertainment” white paper Contribution input to the definition of Key messages for MWC 2016 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 Vertical sectors involvement: Contribution to whitepapers on automotive, FoF, energy and eHealth. Whitepaper on media & entertainment. Vision dissemination: MWC whitepaper and Talks @EuCNC	TI
Architecture	Regular participation in the conference calls and f2f meetings Contribution input to the Terms of Reference Presentation “An introduction to 5G-Crosshaul” at WG call Presentation “5G-Crosshaul system architecture” at WG call Contribution input to the definition of Key messages for MWC 2016 Triggered possibility for cross-project workshops on architecture, with 5G-NORMA and 5G-Ex Joint White Paper under preparation 5G-Crosshaul project contributing to several sections • Input provided • Participation in teleconferences • In coordination with 5G-Xhaul	NEC
Pre-standards	Regular participation in the conference calls. Input contribution to the 5G-PPP presentation at the 3GPP 5G RAN workshop in Phoenix, USA, September 2015.	IDCC

	Input report on the IEEE pre-industrial workshop on Mobile Edge, New Jersey, USA, November 2015. 5G-Crosshaul supported the WG proposal for EUCNC workshop and serving in the TPC (should plan a contribution to the workshop) 5G-Crosshaul supported the WG call for active participation in the ETSI workshop on 5G from research to standards - 5G-Crosshaul submitted proposal for poster or presentation at the WS	
Spectrum	Regular participation in the conference calls. Input contribution to the Terms of Reference (document pending approval). Input contribution to the 5G-PPP presentation at the international workshop on standards and spectrum cooperation, Lisbon, ICT 2015.	UC3M
Net management, QoS and Security	Submission of proposal for a half-day workshop at EuCNC in June Production of a White Paper on WG topics to be presented at 5G Summit in Beijing or at EuCNC workshop	POLITO/ TEI
Software Networks	Submission of proposal for a full-day workshop at EuCNC in June Participation in regular telcos every 3-4 weeks 5G-crosshaul presented its view on the architecture Questionnaire by Sonata on NFV MANO Adoption Priorities for Software Networks Joint white paper under preparation	NOKIA
KPIs	Participation in two audioconferences to define the common metrics to measure the KPI performance improvements	UC3M

5.2.7.5 Deviations

No deviation has been detected on this WP.

5.2.7.6 Corrective actions

None required.

5.3 Deliverables

Table 12: 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 plans	2016-10-31	X		
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	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	2016-12-31			X
D7.3	Final Project Report	2017-12-31	X		

5.4 Milestones

Table 13: 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	2016-06-30			X

	available. Testbed setup completed. Integration task started.				
MS 4	List of applications running on top of the XCI completed. Initial application implementation. Experimental validation task starts.	2016-10-31	X		
MS 5	Economic Analysis complete. Initial experimental evaluation results.	2017-03-31	X		
MS 6	Consolidated system design. Results from experimental evaluation available.	2017-08-31	X		
MS 7	Final System Design. XFE/XCI and applications design complete. PoC available.	2017-12-31	X		

5.5 Exploitable Results

It is 5G-Crosshaul's ultimate goal to achieve tangible exploitation of its findings and results during the course of the project and afterwards. Various forms of exploitation are in the focus for 5G-Crosshaul, such as pre-commercial proof-of-concepts or commercial products (software and hardware) from 5G-Crosshaul partners, innovations and new features pushed into standards for future products from both inside and outside the 5G-Crosshaul consortium, and the launch of new commercial services building on the 5G-Crosshaul framework. Exploitation of 5G-Crosshaul outcomes by the industries will lead to new products and solutions and to the creation of new job opportunities.

5.5.1 Exploitation on commercial products and PoC developed internally to the Company

A specific exploitation strategy has been defined to maximize the impact on relevant area of products of the major manufacturers participating to the projects. This strategy is envisioned to:

- Identify products and services which might bear a potential impact from/to the innovations targeted by the Project;
- Identify innovations as they 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, and;
- Promote the exploitation of these innovations by the various stakeholders.

In view of the high importance given by the project to the exploitation activities, the project has appointed an Innovation Manager (Dr. Paola Iovanna from Ericsson Italy) to lead the work and ensure successful exploitation of the innovations from the project.

The key innovations identified from the work carried out in the first year of the project have a specific potential mapping in concrete products areas or PoC.

Table 14draws an initial mapping between the innovations identified in Year 1 and related PoCs, products, services and applications, from the project partners.

Table 14: Mapping between project innovations and relevant partners' PoCs, Products, Services and Applications.

Innovation	PoC / Product / Service	Partner
XPFE	eNB with flexible functional split PoC	CND
	Radio Dot System	Ericsson
	Router 6000 family	
	EdgeLink mmWave nodes	InterDigital
	iPASOLINK converged packet radio	NEC
	Flexi Multiradio 10 Base Station	Nokia
	Ethernet VLAN switch	
XCSE	Fronthaul 6000	Ericsson
	Optical forwarding elements	
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	Visiona
	Energy efficiency management and monitoring	Nextworks / Polito
	Mobility management	UC3M / ITRI

Moreover, new features from the project are being implemented in the demos or test-beds planned in the WP5 with the twofold objective that is to assess their performance and to create environments where vendors and operators can share requirements, features, and constraints. In addition to providing specific features that can be implemented in stand-alone products, the project aims at encouraging the cooperation among vendors, operators and universities to create solutions and systems for the 5G. This allows the creation of conditions for fruitful joint work among operators, vendors, universities, and SMEs to define and test solutions.

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

As reported in Table 15 a plan for demo and testbed to assess and demonstrated the key outputs of the 1st year of the project have been realized.

Table 15: Plan for demonstration and testbed

Demo setup	Test bed	Partners	App plane	Control plane	Data plane
mmWave Mesh	5G-Berlin	HHI	Energy management application for mmwave mesh network	Proprietary extensions to open source SDN controller (RYU or OpenDaylight)	Mesh of mmwave links
Packet-based Fronthaul	5G-Berlin	HHI, Nokia, NXW			Extensions to Open source Lagopus software switch to make it become a 5G-Crosshaul Packet Forwarding Entity (XPFE)
5G-Crosshaul over LAN network	5G-Berlin or 5TONIC	EAB, ULUND			Fronthaul compression techniques allowing transmission of stringent fronthaul traffic through conventional Ethernet enterprise networks
mmWave mesh	5G-Berlin	IDCC, CND, HHI		Proprietary extensions to OpenDaylight for dynamically controlling mmwave mesh network nodes through OpenFlow extensions	Mesh of mmwave links that will carry backhaul and fronthaul traffic generated by different RAN functional splits
Wireless fronthaul extension	5G-Berlin	HHI, EBLink, Orange			Transmission of CPRI traffic through microwave and mmwave wireless fronthaul

					transmission scheme
Analogue RoF	5G-Berlin	ITRI			WDM-based multiplexing of analogue radio over fiber between radio frequency front-end and head-end unit with other backhaul and fronthaul signals
Optical wireless	5G-Berlin, 5TONIC	ATOS, UC3M	Management of virtual CDN system by which user requests are redirected to most suitable virtual replica server storing the requested content.	Extensions to proprietary NFV Orchestrator and Virtual Network Functions Manager for offering required service to CDN management application (CDNMA)	

5.5.3 Exploitation on standards

The project has been active in disseminating its concept, challenges, and first results, into various standardization organizations. It has first set a standardization roadmap based on an inventory of standardization activities deemed relevant to the project technology development areas. This standardization roadmap is presented below. It has received the attention of ETSI to help identify standardization gaps and necessary coordination activities across various SDOs.

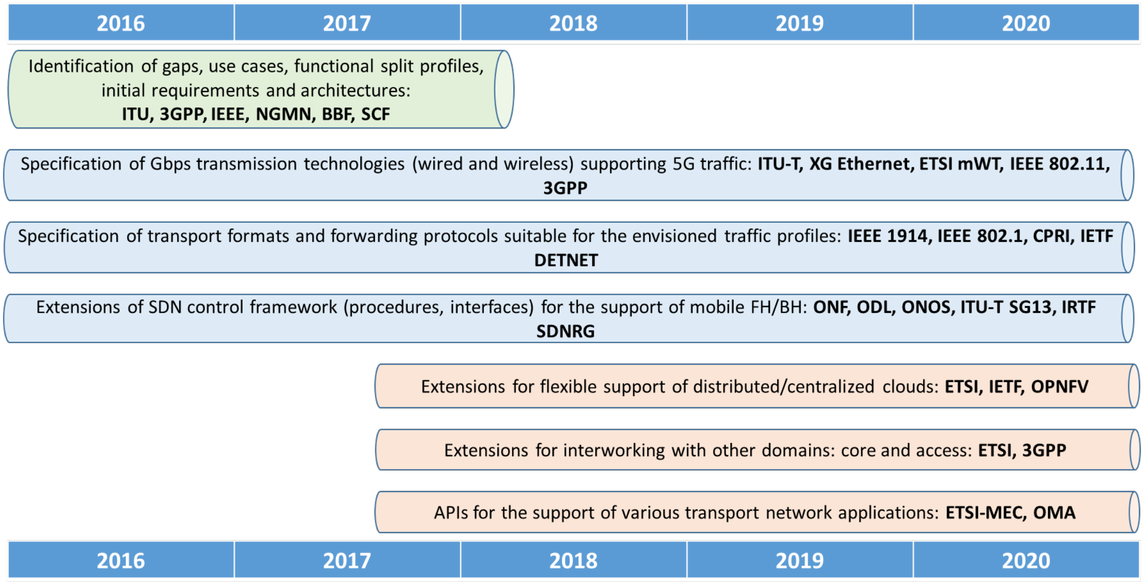

Figure 21: Initial standardization activity roadmap towards 2020.

In addition to the above roadmap, the project partners were active in disseminating and providing contributions to different SDOs. A total of close to 30 standardization materials have been produced by the project partners as reported in the Table 16 and Table 17 below.

Table 16: Standardization dissemination in Year 1

#	Month	SDO	Description	Leading Partner
1	Oct'15	ONF	White Paper on Wireless Transport SDN Proof of Concept, 09 October 2015, ONF website.	TI, NEC, EAB, UC3M
2	Oct'15	FSAN	Presentation on "Mobile evolution and impact on optical access network, at the FSAN workshop, October 2015, Atlanta, USA.	ORANGE
3	Oct'15	BBF	Presentation on "Assessing the Evolution of Cloud RAN with the Support of Fibre", BroadBand World Forum, 22-25 October 2015, London, UK.	ORANGE
4	Nov'15	IEEE	Presentation on "NEC Vision and R&D activities towards 5G" at IEEE 5G Summit, Toronto, Canada, 14. November 2015.	NEC
5	Nov'15	3GPP	Presentation promoting 5G-Crosshaul concept at the 3GPP Asia summit in Taipei, 15 November 2015.	ITRI
6	Nov'15	IEEE	Presentation on 5G-Crosshaul architecture and research related to Mobile Edge Cloud at the IEEE pre-industrial workshop on Mobile Edge Cloud, New Jersey (USA), 16 November 2015.	IDCC

7	Nov’15	BBF	Presentation in BBF 5G BoF Session on “Small Cell Forum & Mobile Edge Computing”, Broadband Forum, 16 November 2015.	NEC
8	Dec’15	NGMN	Presentation “5G Technologies: An introduction”, NGMN IPR Forum workshop on 5G Technologies, Vienna, Austria, 11 December 2015.	IDCC
9	Mar’16	ETSI	Presentation of 5G-Crosshaul, ETSI MEC ISG #17 meeting, Madrid, Spain, 17 March 2016.	Telefonica
10	Mar’16	NGMN	Presentation “5G-Crosshaul Project Overview”, NGMN Forum Meeting, Taipei, Taiwan, 15 March 2016.	IDCC
11	Apr’16	ETSI	Poster “5G-Crosshaul project” at ETSI workshop (5G from myth to reality), Sophia-Antipolis, France, April 2016.	IDCC
12	May’16	ITU-T	Presentation “Introduction to the 5G-Crosshaul project” at ITU-T meeting, Beijing, China.	IDCC
13	May’16	ETSI	Presentation “Standardization Roadmap for the 5G Integrated Fronthaul and Backhaul” at ETSI workshop (5G from research to standardization), Sophia-Antipolis, France, May 2016.	IDCC
14	May’16	ONF	Contribution to the Technical Recommendation TR-528 “Mapping Cross Stratum Orchestration (CSO) to the SDN Architecture”.	CTTC

In addition to the dissemination activities above, the partners have submitted input contributions to standardization working groups, as summarized in Table 17 below.

Table 17: Standardization contributions in Year 1

#	Month	SDO	Description	Leading Partner
1	Oct’15	ITU-T Q6/15	Contribution (WD06-32) by the G.metro Editors, “Version 0.3 of draft new Recommendation G.metro generated at the last SG15 Plenary Meeting in Geneva June/July 2015”.	TEI
2	Oct’15	ITU-T Q6/15	Contribution (WD06-31) by the G.metro Editors in their role as correspondence group coordinators, “Results of correspondence on draft G.metro issues carried out since the last SG15 Plenary Meeting in Geneva June/July 2015”.	TEI
3	Oct’15	ITU-T Q6/15	Contribution (WD06-37), “Results of the break-out group meeting to establish the terms of reference for a correspondence activity to establish a set of requirements for pilot tone frequency and message channel bit rate, traffic signals and their characteristics that should be taken into consideration for the development of application codes in G.metro”.	TEI

4	Oct'15	ITU-T Q6/15	Contribution "Information to Q6/15 on proposals towards Q11/15 and Q14/15 for the communications channel in G.metro".	TEI
5	Oct'15	ITU-T Q6/15	Contribution "Provisional results from an editing session on G.metro".	TEI
6	Nov'15	IEEE 802.11ay	Contribution (IEEE 802.11-15/1399r1), "11ay Functional Requirements for Multi-Hop, Backhaul, and Fronthaul", 09 November 2015.	IDCC
7	Dec'15	IMT2020 FG	Contribution to IMT-2020 Focus Group final report, planned to discuss this report and the way forward during SG13 plenary meeting on 7 December 2015.	TEI
8	Dec'15	IRTF NFVRG	G. Bernini, V. Maffione, D. Lopez, P. Aranda Gutierrez, "VNF Pool Orchestration for Automated Resiliency in Service Chains", NFVRG Interim meeting, December 2015.	NXW TID
9	Feb'16	BBF	X. Li, K. Samdanis, "5G fronthaul and Base Station functional split"	NEC
10	Mar'16	ETSI MEC	Contribution (MECIEG(16)000016), "Changes to MEC Metrics: delay and footprint" at ETSI MECIEG#17, Madrid, Spain.	UC3M NEC TIM
11	Mar'16	ETSI MEC	Contribution (MECIEG(16)000017), "Measurement methodologies for energy and delay" at ETSI MECIEG#17, Madrid, Spain.	UC3M TIM NEC
12	Mar'16	ETSI MEC	Contribution (MECIEG(16)000020r1), "Changes to MEC Metrics: delay" at ETSI MECIEG#17, Madrid, Spain.	UC3M NEC TIM
13	Mar'16	ETSI MEC	Contribution (MECIEG(16)000022r1), "Changes to MEC Metrics: footprint" at ETSI MECIEG#17, Madrid, Spain.	UC3M NEC TIM
14	April'16	BBF	X. Li, K. Samdanis, A. Garcia-Saavedra, "On base station functional decomposition and fronthaul performance requirements"	NEC
15	May'16	IMT2020 FG	Contribution (I-206) "Introduction of 5G-Crosshaul project" including proposed text for adoption in the recommendations, at ITU-T 2020 FG, Beijing, China.	IDCC

5.6 Impact

The 5G-Crosshaul contributions towards the expected impacts described on the section 2.1 of the DoA are in line with respect the results obtained in the first year of the project as reported in the following.

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.

In line with the outputs defined to target the Expected impact 1, the project designed and implemented concrete and relevant outputs that can potentially impact in product areas for the main vendors participating the project.

As described in Section 5.5, two main relevant outputs have been obtained in the first year of the Project: 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.

Such results have been defined in continuous interworking and cooperation of the 5G-Crosshaul partners that includes relevant leading Mobile Network Operators (MNOs), which have business interests 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 Telefónica, 32M Telecom Italia), and manufacturers, namely, Ericsson, Nokia Networks, NEC, and InterDigital that are leading providers of fronthaul and backhaul equipment and solutions for Telecom Operators in Europe and Worldwide.

Relevant to such scope are the several PoC and demos defined or planned in the first year of the project where the 5G-Crosshaul partners jointly participate to assess both the single functions defined in the project in a common architecture.

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**.

Also for the Expected impact 2, 5G-Crosshaul provided in the first year relevant innovation outputs in line with the planned results and detailed in the following:

- Increase resource and energy efficiency by:
    - the realization of a novel data-plane that allows to combine both fronthaul and backhaul traffic in efficient way. Such data plane includes three main components: i) an innovative multi-layer node that combine packet and switching technology to provide differentiate latency, and support also the more challenging among the 5G services with very tight latency; ii) different transmission technology to deal with the several deployment scenarios such as fiber, copper and microwave; and ii) a novel framing to enable the transport to any traffic type including that ones with very low latency requirements.
    - The definition of a suitable South Bound Interface (SBI) that allows for the design of a common control plane that is able to harmonize the different

technology used for the transmission and enable the operation at the control plane.

    - The design of the XCI that enables the capability both to dynamic reconfigure all the transport resources and to provide a common representation of the data plane in a network view in order to facilitate the implementation of Smart method and algorithms for resource optimization and energy consumption. An example of this application is EMMA (Energy Monitoring and Management Application), which has been designed in WP4 (IR 4.1 and 4.2)

- Increase the spectrum of application and services that can be offered at low cost
    - Definition of open API to third parties (the NBI) that enable the unified control infrastructure (XCI) designed to operate in case of heterogeneous technologies and deployment scenarios. An initial set of requirements for the Northbound Interface (NBI) has been performed in order to enable the 5G-Crosshaul Control Infrastructure (XCI) to apply applications, which can provide optimization and reconfiguration of 5G-Crosshaul resources. In particular, the following applications have bend defined: Multi-tenancy Application (MTA), Mobility Management Application (MMA), Energy Management and Monitoring Application (EMMA), Resource Management Application (RMA), Virtual Infrastructure Manager and Planner Application (VIMaP), Content Delivery Network Management Application (CDNMA), and TV Broadcasting Application (TVBA).
- Facilitate the network densification
    - The new architecture and their key components (XFE, common framing and XCI) developed in the 1st year of the project provide a new 5G backhauling/fronthauling network design where operators, vendors, SME and university cooperated together to deal with some key challenging for 5G that is to provide the concurrent support of differentiated services including that one at very low latency at low cost and in heterogeneous deployment scenarios. The demo defined in the framework of WP5 are a concrete result where such new network is assessed in a joint work among the participants.
- Reduce the operational and investment cost
    - The definition of a common data plane by the novel SBI that is able to control multi-layer XFE, and heterogeneous transmission technology, allows to represent an alternative for the RAN that allows to support together both circuit base traffic such as CPRI and packet traffic such as backhauling.

Finally, it is worth emphasizing in this section the effect that 5G-Crosshaul may have on the economy of the union. One of the key results obtained in the first year is a new network architecture that can flexibly and dynamically configured for different mix of backhauling and fronthauling traffic supporting also extreme cases of 5G service in terms of latency and bandwidth. Actually the common abstract model of the heterogeneous data-plane for the SBI enables the dynamic control (XCI) to dynamically configure any mix of traffic according the needs of operators, and for any type of transmission technology in the data-plane. That allows for a drastic reduction of the cost of investment and enables operators to configure their network in efficient way based on actual traffic needs.

5.6.1 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 18 presents the progress towards each KPI and the relation with the objectives of the project.

Table 18: KPI progress and Objectives relation

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/planni	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.

	ng) applications	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.

6 Update of the plan for exploitation and dissemination of result

This point is fully described in the D6.1. already delivered on time.

7 Deviations from Annex 1

7.1 Tasks

In WP1, the IR1.1, and M1, was delivered the 30th of October 2015 instead of the planned day (30th of September 2015 - M3).

7.2 Use of resources

As the first year of the project close the 30th of June, the final information of PMs used in the 12 months will not be available until the 15th of July at least. That is why we include in this deliverable the PMs deviation used until the third quarterly of the project.

The final version of the Periodic Report will be complete before the deadline (28th of August).

8 References

[1] IR3.2, «XFE/XCI design,» April 2016.

[2] IR4.2, «Algorithms and refined requirements on the XCI northbound interface,» April 2016.

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[4] IR3.1, «Features to be integrated in the southbound and northbound interfaces,» December 2015.

[5] IR4.1, «Initial requirements on the XCI northbound interface,» December 2015.

[6] IR1.2, «5G-Crosshaul baseline system architecture,» February 2016.

[7] IR6.1, «Y1 dissemination and exploitation plan,» August 2015.

[8] D6.1, «Report on the dissemination, communication and exploitation activities during the first year of the project,» June 2016.

[9] IR6.2, «WP6 H1'Y1 progress and H2'Y1 plan,» December 2015.

[10] IR2.2, «Features available for integration in the southbound,» April 2016.

[11] IR2.1, «Technologies available for the integration in 5G-Crosshaul,» December 2015.

[12] D2.1, «Detailed analysis of the technologies to be integrated in the XFE based on previous internal reports from WP2 and WP3,» June 2016.

[13] IR5.1, «Testbed, hardware integration and initial demo definition,» April 2016.

[14] Schaffrath et al., «Network Virtualization Architecture: Proposal and Initial Prototype,» *ACM VISA,* 2009.

[15] Mérouane Debbah, Mari Kobayashi, Jakob Hoydis , «Green Small-Cell Network: A Cost-and Energy efficiency way of meeting the future traffic demand».

[16] IR1.1, «Use cases and requirements,» October 2015.

[17] D7.1, «Project Handbook,» July 2015.