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Efficiently offering Unconstrained Services in 6G

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AUTHORS	DIMITRIS UZUNIDIS (UPAT), CHRIS CHRISTOFIDIS (UPAT), KONSTANTINOS MOSCHOPOULOS (UPAT), IOANNIS TOMKOS (UPAT), JOSE MANUEL RIVAS MOSCOSO (TID), SANDRA LAGEN (CTTC), ANA LARRANAGA (CTTC), RAUL MUNOZ (CTTC), DIMITRIS KLONIDIS (UBI), CARLOS CASTRO (INF-G), DAVID LARRABEITI (UC3M)
REVIEWERS	CARLOS CASTRO (INF-G), JOSEP FABREGA (CTTC)



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Executive summary

This document contains the results produced within T2.1, where the Requirements for 6G packet-optical x-haul networks are described and the Key Performance Indicators (KPIs) that will measure the performance of the PROTEUS-6G network and its innovations are defined. This work began in January 2024 (M01 of PROTEUS-6G) and ended at the end of April 2024 (M04 of PROTEUS-6G).

The purpose of this task is to provide the definitions of end-to-end 6G use cases for identifying the requirements of the x-haul, services, and applications that will be studied in PROTEUS-6G. The requirements will be determined end-to-end for the dynamic functional splitting across the Centralized Unit (CU)/ the Distributed Unit (DU) and the Radio Unit (RU) elements of the new software-defined disaggregated Radio Access Network (RAN). The end-to-end requirements will be based on three pillars specifying: a) RAN, b) transport, and c) computing resources.

This task will also define detailed specifications for each target application and functional split option that will feed the PROTEUS-6G architecture and sub-systems design (in Tasks 2.2 and 2.3). The analysis will include also a top-to-bottom approach: starting from the application through the system layer, the goal will be to define application tables for x-haul with high-level system requirements for all three pillars and functional split options (e.g. bandwidth, capacity, latency, reliability, security, privacy, reliability, resilience, and safety) down to subsystem requirements, such as power consumption, cost per bit etc.

Finally, a set of KPIs will be defined to address network platform and service performance, and derived from these, KPIs of the proposed subsystems: reconfigurable Optical Distribution Network (ODN) with spatial, spectral and subcarrier access and lite coherent transceivers, to be used as the principal measures of the success of other tasks within the project.

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LIST OF ABBREVIATIONS

3GPP	3rd Generation Partnership Project
AI	Artificial Intelligence
API	Application Programming Interface
BBU	Baseband Unit
BC	Boundary Clock
BER	Bit Error Rate
BW	Bandwidth
CC	Component Carrier
CLI	Command-Line Interface
CMIS	Content Management Interoperability Services
CN	Core Network
CO	Central Office
CPU	Central Processing Unit
CR	control and scheduling signals rate
CSG	Cell Site Gateway
CU	Centralized Unit
DL	Downlink
DP	Dual Polarization
DSCM	Digital Sub Carrier Multiplexing
DSP	Digital Signal Processing
DU	Distributed Unit
DWDM	Dense Wavelength-Division Multiplexing
eMBB	enhanced Mobile Networks
ESMC	Ethernet Synchronization Message Channel
EVM	Error Vector Magnitude
FDD	Frequency Division Duplexing
FDM	Frequency Division Multiplexing
FFS	Flexible Functional Split
FPGA	Field Programmable Gate Array
GMC	Grandmaster Clock
GNSS	Global Navigation Satellite System
GOPS	Giga Operations Per Second
HARQ	Hybrid Automatic Repeat Request
HTTP	HyperText Transfer Protocol
HTTPS	Hypertext Transfer Protocol Secure
IMT-2030	International Mobile Telecommunications for 2030
IoT	Internet of Things
IQ	Inphase and Quadrature
KPIs	Key Performance Indicators
LITE-COH	LITE-COHerent
M	Modulation
MAC	Medium Access Control
MIMO	Multi Input Multi Output
ML	Machine Learning
mMTC	massive Machine Type Communication
MZI	Mach-Zehnder Interferometer

OC	Ordinary Clock
ODN	Optical Distribution Network
OFDM	Orthogonal Frequency Division Multiplexing
OPM	Optical Performance Monitoring
O-RAN	Open-Radio Access Network
OSNR	Optical Signal-to-Noise Ratio
PDCP	Packet Data Convergence Protocol
PDU	Packet Data Units
PIC	Photonic Integrated Circuit
PON	Passive Optical Network
PR	Peak data Rate
PtMP	Point-To-Multi-Point
PTP	Precision Time Protocol
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QoT	Quality of Transmission
RAMZI	Ring Assisted Mach-Zehnder Interferometer
RAN	Radio Access Network
RBAC	Role-Based Access Control
RE	Resource Elements
RF	Radio Frequency
RLC	Radio Link Control
ROADM	Reconfigurable Optical Add-Drop Multiplexer
RRC	Radio Resource Control
RU	Radio Unit
SC	Nyquist Sub Carrier
SDH	Synchronous Digital Hierarchy
SDM	Space Division Multiplexing
SDN	Software-defined networking
SDPtMP	Spatially-Diverse Point-To-Multi-Point
SLA	Service Level Agreement
SLO	Service Level Objective
SNMP	Simple Network Management Protocol
SONET	Synchronous Optical Networking
SR	Sample Rate
SSM	Synchronization Status Message
SyncE	Synchronous Ethernet
TC	Transparent Clock
TLS	Transport Layer Security
TSN	Time-Sensitive Networking
TTI	Transmission Time Interval
TxOpp	Transmission Opportunity
TXR	transceivers
UE	User Equipment
UL	Uplink
UP	User Plane
uRLLC	ultra Reliable Low Latency Communications
WDM	Wavelength Division Multiplexing
WSS	Wavelength Selective Switch

1. Introduction

Fast-growing network traffic and increasing demand for high-capacity connectivity over the next years require new optical access/fronthaul technologies to build communication systems supporting ultra-high data rates with reduced latencies and enhanced energy efficiency. The demands of a fully connected society (e.g. Internet of Things (IoT)) are characterized by the tremendous growth in connectivity and the density/volume of traffic. In addition, the associated multi-layer densification, and the broad range of more demanding use case categories, as revealed by International Mobile Telecommunications for 2030 (IMT-2030) [1], and business models that are expected, will be key characteristics of next-generation 6G networks incorporating advanced connectivity. The 6G networks need to provide optimal connectivity with respect to access technology and service quality to enable a plethora of relevant services to the customers and run in a highly efficient manner, leveraging network automation to the greatest possible level. Traffic densities of several Tb/s per km are already predicted for the foreseeable B5G access networks in the near future (mid-phase) as expressed by the Next Generation Mobile Networks (NGMN) [2].

This growing traffic, in conjunction with the even greater need for capacity and connectivity growth in wireless access networks, will also be reflected in fronthaul/midhaul networks. In order to increase capacity and improve the coverage of access networks, the physical and interference footprints of RUs must be decreased. Such densification must also be supported by proper optical fronthaul/transport solutions. The RUs (macro as well as small cells or pico/femto cells) are connected to the core network through wired or wireless optical transport networks, often with extreme requirements in terms of capacity, latency, availability, energy and cost efficiency. Current network architectures will not be sufficient to support such requirements, and novel approaches are mandated for the 6G networking.

The PROTEUS-6G aims to develop several innovations to address these requirements. More specifically, it focuses on the development of advanced packet-optical x-haul networking infrastructure, relying on novel software-programmable photonic-integrated-circuit based subsystems operated under an intelligent software management system, capable of simplifying and optimizing network operations and supporting future ultra-high capacity, low-latency and energy-efficient 6G cellular and cell-free Multi Input Multi Output (MIMO) radio access networks. The targeted innovations will enable efficient utilisation of packet and optical resources (spectral subcarriers and spatial lanes), realizing the vision of Flexible Functional Splits (FFSs), adapting the fronthaul/midhaul, under dynamically customizable operational conditions to the network demands, for varying distribution of users, traffic demands and use-cases. To implement the 6G optical-enabled radio-access network, PROTEUS-6G will develop ultra-low energy (low-pJ/bit), ultra-high capacity (0.8 Tb/s) and fast-reconfigurable (sub-ms) software-programmable solutions (i.e. transceivers, multiplexers and fast optical switches integrating tuneable lasers/filters) based on novel photonic processing/switching schemes, to be reconfigured by an intelligent control plane optimizing the utilization of resources across the front-/mid-/back-haul continuum and reducing unnecessary opto-electronic transitions, thus collectively improving performance while minimizing the environmental impact.

1.1 Motivation

While technologies are evolving to meet the expanding needs for capacity and connectivity, many use cases and services with varying requirements must be efficiently accommodated in any given infrastructure. Therefore, an efficient resource allocation is necessary for networks whose circumstances and traffic needs fluctuate to address this problem sustainably. For example, critical functions can be processed closer to the end-users, reducing latency and improving Quality of Service (QoS).

By dynamically adjusting the split between centralized (cloud-based) and distributed (edge-based) functions, operators can efficiently utilize network resources and improve overall network performance, relaxing

requirements, for example in the fronthaul segment. In this sense, it is important that the optimal functional split of each cell-site may be dynamically selected to improve the overall performance of future 6G networks by considering diverging time-varying requirements at each cell-site while accounting for the interference experienced by the User Equipment (UE) during runtime.

An FFS also allows for easy network scalability and upgradeability. Operators may adjust to changing technology and the emergence of new services by simply rearranging the functional split rather than completely redesigning the network. Thus, by placing centralized operations where they work best, operators may maximize the utilization of hardware resources and lessen the need for expensive infrastructure modifications at each cell site.

5G has developed various technologies to improve the flexibility and efficiency of mobile networks. The latest addition is the 5G virtualized base station, which comprises three components strategically positioned across different geographical locations: the RU, the DU, and the CU. The RU and DU are linked via a fronthaul network, while the DU and CU are connected through a midhaul network. Virtualization facilitates functional splitting, determining which protocol layers or baseband functions are deployed in each unit. Depending on the selected splits, baseband functions can be implemented either in the RU or DU, leading to a more distributed setup, or centrally in the CU. Notably, the 3rd Generation Partnership Project (3GPP) specifications have recently outlined functional split Option 2 for CU/DU split [3], focusing solely on the midhaul network with a fixed Packet Data Convergence Protocol (PDCP)/ Radio Link Control (RLC) split. However, there have been studies within 3GPP exploring the trade-offs of different functional split options [4] and examining low-layer splits in detail [5]. On the other hand, the Open-Radio Access Network (O-RAN) Alliance has further defined the new open RU entity and embraced the functional split Option 7.2x (intra-physical (PHY) split) for the DU/RU split [6].

Each functional split presents *varying trade-offs in fronthaul/midhaul/backhaul capacity and latency requirements versus implementation and network performance* [7]. Centralizing baseband functions can provide substantial advantages for network operators. For instance, coordinating protocol layers across different cells can reduce interferences, enhance reliability, or simplify handover procedures, while reducing operational expenses [7]. This consolidation can enhance mobility management through intra-handover procedures and can effectively manage interference through coordinated multi-point operations. However, achieving maximum centralization faces challenges due to constraints such as midhaul network capacity, diverse traffic delay requirements, functional split limitations and asymmetrical computational resources [8],[9]. For example, the induced delays increase with the splits that centralize more processes [10]. This observation is further supported by [8] and [11], highlighting that higher low-latency traffic loads result in lower centralization. Additionally, according to [12], in scenarios characterized by high traffic load and high centralization, the number of Giga Operations Per Second (GOPS) in the CU increases, i.e., its computational cost increases, because of the additional coordination processes. Therefore, the flexibility to choose the optimal functional split is crucial to meet diverse throughput and latency demands across different traffic types and reduce operational costs, while optimizing resource utilization and network performance [13].

In this context, advancing the 3GPP/O-RAN vision, a progressive approach includes the adoption of FFS as conceptually introduced in [14],[15] (see Figure 1). Here, the core idea is to dynamically adjust the functional split according to specific requirements, such as traffic delay, traffic load, CU/DU computational complexity, and midhaul/fronthaul network conditions.

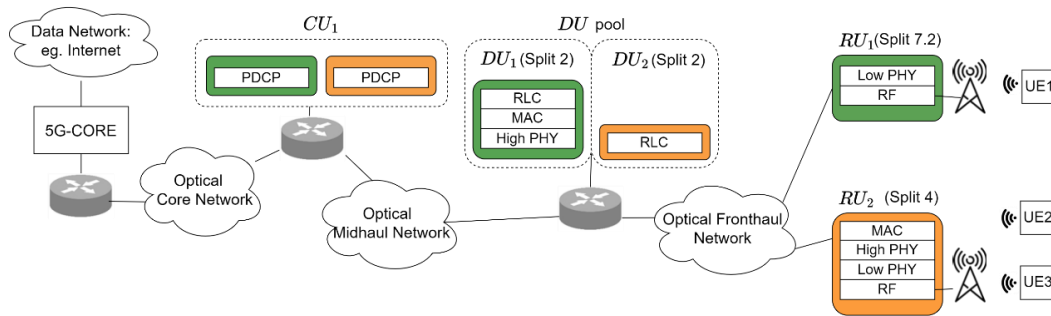


Figure 1. CU-DU-RU example with different functional splits.

1.2 Objective of this deliverable

The main objective of Deliverable 2.1 of the PROTEUS-6G project is to derive the 6G x-haul network requirements and to define the KPIs adopted to measure the performance of the developed sub-systems and the entire PROTEUS-6G network. More specifically, the requirements will be determined end-to-end for the dynamic functional splitting across the CU/DU/RU elements of the new softwarized disaggregated RAN. The end-to-end requirements will be based on three pillars specifying: a) RAN, b) transport, and c) computing resources. The analysis will start from the high-level system requirements shaping the general 6G service categories. Then, the sub-system requirements, such as power consumption, cost per bit etc. will be defined. In addition, a set of KPIs will be defined to address network platform and service performance, and derived from these, KPIs of the proposed subsystems: reconfigurable ODN with spatial, spectral and subcarrier access and lite coherent transceivers.

1.3 Structure of the deliverable

Section 2 first analyzes the use cases of interest for 6G networks and their requirements in order to satisfy the QoS. Next, a general overview of PROTEUS-6G network is performed along with the definition of the two scenarios of interest that will be studied throughout the project. Section 2 also defines the transport network requirements particularly focusing on latency and capacity. The main KPIs that will be achieved throughout the entire duration of PROTEUS-6G to ensure its success are segregated into network, component and techno-economic levels. Section 3 discusses the sub-system level requirements like the optical lite transceiver, the Digital Sub Carrier Multiplexing (DSCM) transceivers, the switch, and the autonomous network control and orchestration, streaming telemetry, and optical performance monitoring of multi-layer (packet/optical) x-haul networks, while section 4 concludes the deliverable.

2. 6G x-haul use cases and requirements

2.1 General overview of the proposed PROTEUS-6G network

PROTEUS-6G introduces a novel architectural approach for the optical fronthaul network, interconnecting a Central Office (CO) to numerous remote cell sites, based on the innovative communication infrastructure device/subsystem/system, technologies and devices that will be developed in the project (Figure 2). More specifically, PROTEUS-6G will design and develop a dynamic, flexible, scalable, cost-effective, high bandwidth, and low-latency packet-optical x-haul (fronthaul/midhaul) architecture for 6G networks to enable the dynamic management of the radio FFS adapting the 6G network to varying environment conditions (new services/use cases, traffic changes, etc.). This advanced network architecture also interconnects multiple access COs via an optical ring network, enabling unique optical pathways to remote access COs.

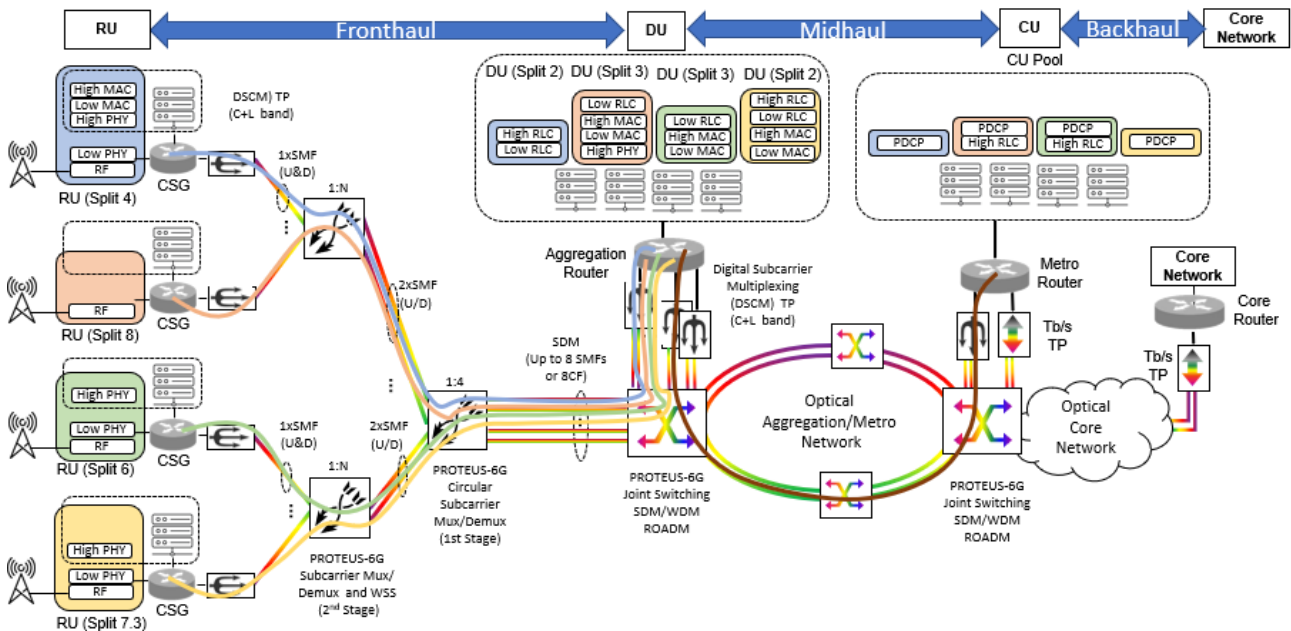


Figure 2. The PROTEUS-6G scenarios: the cell-free massive MIMO supported by the split option 8 and the Flexible Functional Splits supported by the split options 4, 6 and 7.

This allows different functions to be deployed in specific COs and shared across the ring network, providing backup and redundancy. Regional COs on the same optical ring network serve as metro edge-computing data centers, providing a CU pool and a metro router to aggregate traffic from different access COs. The access CO itself consists of an edge computing datacentre deploying a DU pool or a Central Processing Unit (CPU), along with an aggregation router combining traffic from multiple cell sites. At the cell sites, multiple RUs can be connected to a Cell Site Gateway (CSG) router to aggregate traffic and provide connectivity to the far edge computing data center deployed at the site. This comprehensive approach enables efficient traffic aggregation and distribution across the network while also allowing for the rapid deployment of new capabilities and resources as needed. As 6G technology continues to evolve, the PROTEUS-6G fronthaul network provides a flexible and adaptable platform for meeting the needs of users and applications alike. Two different transceiver types are considered for the access COs and the cell sites across the optical fronthaul network: the next-generation DSCM transceivers, and the novel ultra-high-speed, low-cost and power-efficient LITE-COHerent (LITE-COH) transceivers (TXR). Their combination enables a modular approach to flexible bandwidth provisioning. Multiplexing the developed TXR over 8λ-s can provide rates to the edge

sites up to 6.4 Tb/s per fiber, fully exploiting the modularity of the spectral resources. On the other hand, the DSCM TXR is an optical pluggable module, integrated into the IP routers of cell sites and COs, multiplexing multiple subcarriers (e.g., 16) with a fixed capacity per subcarrier (e.g., 25 Gb/s) based on spectrally-efficient multi-carrier Frequency Division Multiplexing (FDM) technology offering fine sub-wavelength granularity for optimal bandwidth-variable traffic allocations. This transceiver replaces several low-speed transceivers on the convergence side with a high-speed coherent transceiver enabled by digital subcarrier technology. A significant advantage of this TXR is that it enables the throughput to/from the access CO to be flexibly shared by multiple lower-capacity transponders located in cell sites, over a Point-To-Multi-Point (PtMP) ODN. This TXR will be used for our dynamic functional split scenario up to option 7-2.

In the rest of this section, we present the end-to-end x-haul requirements from RAN, transport, and computing perspectives, the KPIs that need to be satisfied, the services, as well as the scenarios of interest for the PROTEUS-6G.

2.2 Definition of the end-to-end x-haul requirements, KPIs and services

2.2.1 6G use case categories and requirements

The radiocommunication sector of the International Telecommunication Union (ITU-R), defines the overall objectives, capabilities, and expected use case categories of the (IMT-2030) [1]. This recommendation is the fundamental guideline report for 6G networks. More specifically, IMT-2030 envisions the development of three new categories of use cases: i) *ubiquitous connectivity*, ii) *AI and communication*, iii) *integrated sensing and communications*, in addition to the three categories proposed by IMT-2020 for 5G networks, namely enhanced Mobile Networks (eMBB), now evolved to *immersive communication*, massive Machine Type Communication (mMTC), now evolved to *massive communication*, and massive ultra Reliable Low Latency Communications (uRLLC), now evolved to *hyper reliable and low-latency communication*. All six categories are illustrated in Figure 3 and their details are tabulated in Table 1.

In particular, the use cases included in the Immersive Communication family, require from the 6G network to support high data rate and increased mobility while a high reliability, low latency and high connectivity are a may have requirement. Representative use cases of this category are communication for immersive XR, remote multi-sensory telepresence, holographic communications and synchronization and mixing traffic of video, audio, and other environment data. Next, the use cases included in the Massive Communication class, require from the 6G network to support high connection density while may have requirements are data rate variation, low power consumption, mobility, extended coverage, high security and high reliability. Representative use cases of this class of use cases are smart cities, transportation, logistics, health, energy, environmental monitoring, agriculture and the use cases requiring a variety of IoT devices without battery or with long-life batteries. The third category of use cases, named Hyper Reliable and Low-Latency communication, requires low latency and high reliability while may have requirements including precise positioning and high connectivity. This category can support machine interactions, emergency services, tele-medicine, electrical power transmission and distribution and includes the industrial environment for full automation, control and operation. The Ubiquitous Connectivity category requires high connectivity to address presently uncovered or scarcely covered areas, particularly rural, remote and sparsely populated areas, use cases falling under the umbrella of IoT as well as mobile broadband communication. The AI and Communication class of use cases requires high area traffic capacity and high user experienced data rates while may have requirements are high reliability and low latency, depending on the application. Various use cases are included in this family, such as the assisted automated driving, the autonomous collaboration between devices for medical assistance applications, the offloading of heavy computation operations across devices and networks and the creation of and prediction exploiting digital twins. The sixth and final category of use cases, focuses on the Integrated Sensing and Communication and includes assisted navigation, activity detection, movement tracking, environmental monitoring (e.g. rain/pollution detection), provision of sensing

data/information on surroundings for AI, XR and digital twin applications and must have requirements are the high precision positioning, the range/velocity/angle estimation, the object and presence detection, the localization as well as the imaging and mapping.

These six use-case families are expected to enable a multitude of services to be offered to end users (i.e., humans or machines), contributing to unprecedented growth of the overall mobile communication traffic. More specifically, various sources estimate that the resulting total mobile data traffic will grow from about 200 Ebytes per month in 2023 to over 1000 Ebytes in 2030. This makes evident that to serve these traffic demands in a cost and energy-effective way, several innovations need to be introduced across many different dimensions (network segments and layers) and technologies (software and hardware), associated with the ways that 6G networks are built and operated. Those will assist in enhancing the capabilities (also referred to as key performance indicators - KPIs) that were addressed in 5G (IMT-2020) and the newly introduced ones in 6G, as shown in Figure 3.

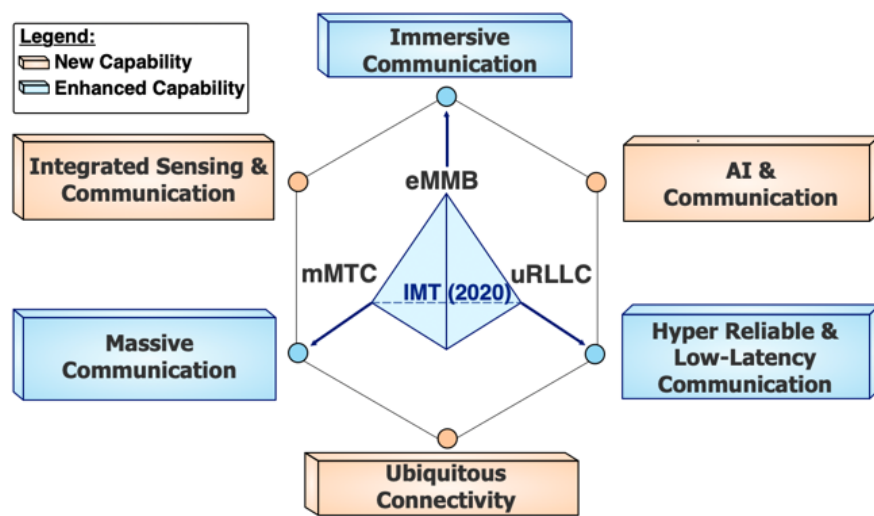


Figure 3. Six envisioned use-case categories by IMT-2030 [1], [16].

Table 1. IMT 2030 use case categories and their details.

Category	Representative use cases	Key requirements
Immersive Communication (eMBB in 5G) <i>rich and interactive video (immersive) experience to users</i>	- communication for immersive XR - remote multi-sensory telepresence - holographic communications - mixed traffic of video, audio, and other environment data synchronized	<u>must have:</u> - high data rates - increased mobility <u>may have:</u> - high reliability - low latency - high connectivity
Massive Communication (mMTC in 5G) <i>connection of a massive number of devices or sensors</i>	- smart cities, transportation, logistics, health, energy, environmental monitoring, agriculture - use cases requiring a variety of IoT devices without batteries or with long-life batteries	<u>must have:</u> - high connection density <u>may have:</u> - different data rates - low power consumption - mobility - extended coverage - high security - high reliability
Hyper Reliable and Low-Latency communication (URLLC in 5G) <i>time synchronized operations</i>	- industrial environment for full automation, control and operation - can support machine interactions, emergency services, tele-medicine, electrical power transmission and distribution	<u>must have:</u> - high reliability - low latency <u>may have:</u> - precise positioning - high connectivity
Ubiquitous Connectivity <i>enhanced connectivity through interworking with other systems</i>	- address presently uncovered or scarcely covered areas, particularly rural, remote and sparsely populated areas - Internet of Things - mobile broadband communication	<u>must have:</u> high connectivity
AI and Communication <i>distributed computing and AI applications</i>	- assisted automated driving - autonomous collaboration between devices for medical assistance applications - offloading of heavy computation operations across devices and networks - creation of and prediction exploiting digital twins	<u>must have:</u> - high area traffic capacity - user experienced data rates <u>may have:</u> - high reliability - low latency
Integrated Sensing and Communication <i>wide area multi-dimensional sensing for unconnected objects and connected devices</i>	- assisted navigation - activity detection - movement tracking - environmental monitoring (e.g. rain/pollution detection) - provision of sensing data/information on surroundings for AI, XR and digital twin applications	<u>must have:</u> - high precision positioning - range/velocity/angle estimation - object and presence detection - localization - imaging and mapping

2.2.2 Transport network requirements

The transport network's capacity and latency requirements vary based on the chosen functional split (see Figure 4). These requirements for midhaul or fronthaul networks are calculated to enable the effective operation of 5G/6G processes. The 3GPP has provided the required transport network capacity and latency values for 5G in [17]. The derivation of the expressions and their values is initially provided in [18], and subsequently refined in [19]. This subsection will explain how these requirements are calculated and will extend the state-of-the-art computations in order to determine the new requirements that the transport network must meet to support 6G, by assuming possible 6G network configurations.

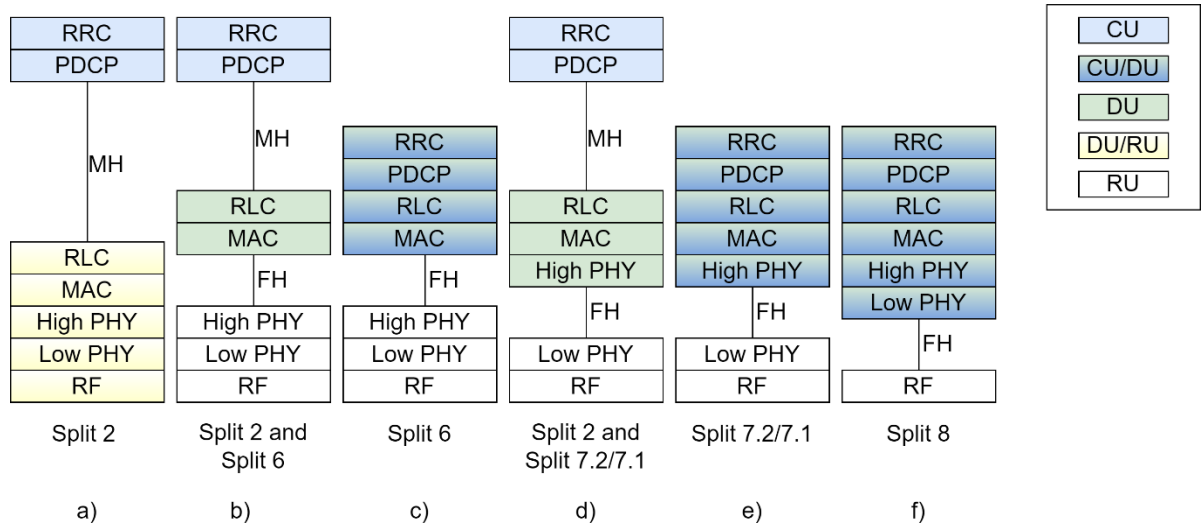


Figure 4. Different functional splits considering CU-DU-RU components.

2.2.2.1. Transport capacity requirements

2.2.2.2. 5G Network

The maximum capacity is calculated based on 4G and 5G configurations. Therefore, we will consider Table 2 reference values to calculate the capacity requirements [17]. The peak data rate (PR) describes the maximum data rate to be supported from a system requirement point of view [20]. The peak data rate is calculated considering the channel Bandwidth (BW), Modulation (M), and number of MIMO layers (N_L).

Through MIMO, 5G can perform multi-layer transmissions, i.e., send multiple data streams (or layers) in the same time/frequency resource. In the PHY layer, the modulated symbols are mapped to N_L spatial layers. All data within the layer is combined and it is redistributed to each antenna port (N_{AP}). These antenna ports are mapped onto one or more physical antenna elements. An antenna port represents a logical concept in which each port generates a resource grid. Then, considering the decision taken by the Medium Access Control (MAC) scheduler, the modulated symbols that have to be transmitted through each antenna are mapped to available Resource Elements (RE). One RE is equal to one subcarrier in the frequency domain and one Orthogonal Frequency Division Multiplexing (OFDM) symbol in the time domain. For each subcarrier, the Inphase and Quadrature (IQ) samples are obtained. The cyclic prefix is added to these IQ samples, and they are converted from digital to analog in order to be transmitted through the wireless channel, with a Sample Rate (SR).

Table 2. Reference values of 4G and 5G networks configuration [17].

	4G		5G	
	DL	UL	DL	UL
Peak Rate (PR)	150 Mbps	50 Mbps	-	
Channel bandwidth (BW)	20 MHz	20 MHz	100 MHz	100 MHz
Modulation (M)	64 QAM (M=6)	16 QAM (M=4)	256 QAM (M=8)	64 QAM (M=6)
Number of MIMO layers (N_L)	2	1	8	8
Number of antenna ports (N_{AP})	8	8	32	32
Sample rate (SR)	-		30.72 M samples/s	

The required transport capacity depends on the functional split, and it increases with centralization. Figure 4 shows different functional splits. Split 8 (Figure 4.f), on the right side, is the most centralized split, while, split 2 (Figure 4.a), on the left side, is the most distributed split among these examples. 5G NR only considers split 2, where the CU and Distributed Unit DU are connected through the midhaul network [21]. 3GPP has studied alternative splits, even if it does not formally incorporate them into the specifications. O-RAN has introduced the RU entity and adopts split 2 for CU and DU split (as in 3GPP), while it employs split option 7.2 for the DU and RU split (as illustrated in Figure 1.d).

Table 3 shows the equations used to calculate the transport capacity depending on the split [21]. Variables in gray and bold indicate the new parameter that must be added to the capacity calculation as the number of functional splits increases. With functional split 1 (Radio Resource Control (RRC)), split 2 (RRC and PDCP), and split 4 (RRC, PDCP and RLC) high protocol layers are centralized. In the case of split 1, the transport network capacity needs to support RRC signaling and User Plane (UP) data. Compared with UP data, RRC signaling is negligible. Therefore, the capacity is calculated considering the data peak reference PR, which is calculated with 4G reference values (BW_{ref} , N_{Lref} , M_{ref} , bandwidth, MIMO layers and modulation, respectively, from Table 2), and scaling with the BW , the number of layers (N_L) and the M used in the 5G network. In the case of split 2, extra signaling is transmitted between the transport network, therefore the needed capacity is incremented with this extra signaling. Then, for splits 2 and 4, the capacity is equal to option 1, and for the case of split 2, the corresponding extra signaling is added to the capacity [19].

Split 6, in addition to RRC, PDCP and RLC, also centralizes the MAC layer. At the same time, the PHY and Radio Frequency (RF) are implemented in the DU/RU, i.e., from this split onwards, the radio resource scheduling is calculated in a centralized way. Therefore, split 6 adds to this equation the control and scheduling signals rate (CR) that are transmitted from the MAC layer to the PHY layer and vice versa. This information contains the radio resource scheduling and Hybrid Automatic Repeat Request (HARQ) process NACK/ACK response, among other information.

Split options 7.x divide the PHY layer internally. Split 7.3 centralizes the channel coding process belonging to the PHY layer [22]. This centralization only affects DL transmissions, as the downlink channel coding is implemented in the CU/DU, while the rest of the PHY functions are located in the DU/RU [17]. Therefore, the transport network must be able to transmit the codified packets or codewords, thus increasing the required capacity. Apart from this, additional MAC information has to be transmitted to the PHY layer to be able to support modulation, multi-antenna processing and PRB allocation in the DU/RU modules [23].

The calculation of capacity undergoes significant changes from split 7.3 to split 7.2 since, in this case, the modulation and spatial layers mapping are applied in the CU/DU. This means the transport network capacity increases significantly. Considering a bandwidth equal to N_{SC} sub-carriers in one OFDM symbol, and the transmission of data is carried out in N_{sym} OFDM symbols, using W bits to represent each sample and the availability of multiple spatial layers (streams, N_L) reusing the same sub-carriers and symbols, then, the

capacity is calculated as shown in Table 3, 7.2 equation. In Split 7.1, the antenna ports are centralized. Until now, transport capacity has been calculated by scaling the MIMO layers, however, for split options 7.1 and 8, the transport capacity is scaled based on the number of antenna ports N_{AP} .

Finally, split 8 divides the RF in the RU, and the rest of the layers are implemented in the CU/DU. Therefore, the RU only processes the RF signal and applies the analog-to-digital or digital-to-analog conversion. Then, the transport needs to transmit IQ samples to the CU/DU [22], increasing the needed capacity, being the most restrictive capacity requirements among the different functional split options.

Considering Table 2 and Table 3, we can calculate the capacity requirements for the 5G network. The resulting values are shown in Table 4, for downlink (DL, core to user) and uplink (UL, user to core) transmit directions.

Table 3. Equations to calculate the transport capacity for the different functional splits.

Option	Capacity
1	$PR \cdot \frac{BW}{BW_{ref}} \cdot \frac{N_L}{N_{L_{ref}}} \cdot \frac{M}{M_{ref}}$
2	$PR \cdot \frac{BW}{BW_{ref}} \cdot \frac{N_L}{N_{L_{ref}}} \cdot \frac{M}{M_{ref}} + \text{signaling}_{PDCP}$
4	$PR \cdot \frac{BW}{BW_{ref}} \cdot \frac{N_L}{N_{L_{ref}}} \cdot \frac{M}{M_{ref}}$
6	$(PR+CR) \cdot \frac{BW}{BW_{ref}} \cdot \frac{N_L}{N_{L_{ref}}} \cdot \frac{M}{M_{ref}}$
7.3 (only DL)	$(PR+CR) \cdot \frac{BW}{BW_{ref}} \cdot \frac{N_L}{N_{L_{ref}}} \cdot \frac{M}{M_{ref}} \cdot \frac{1}{R} + MAC_info$
7.2	$N_{SC} \cdot N_{sym} \cdot W \cdot N_L \cdot 1000 + MAC_info$
7.1	$N_{SC} \cdot N_{sym} \cdot W \cdot N_{AP} \cdot 1000 + MAC_info$
8	$SR \cdot W \cdot N_{AP} \cdot 5$

Table 4. Maximum fronthaul/midhaul capacity requirements for disaggregated 5G networks, in downlink and uplink.

Split	DL (Gbps)	UL (Gbps)
1	4	3
2	4.016	3.024
4	4	3
6	4.133	5.64
7.3	13.2	-
7.2	22.204	21.624
7.1	86.136	86.096
8	157.29	157.29

2.2.2.3. 6G Network

Towards foreseeing 6G transport capacity requirements, we define four 6G scenarios: basic and advanced 6G scenarios with and without multi-band¹ or carrier aggregation (CA) capabilities. In the conservative or basic scenario, we consider the values of 5G advance scenarios for massive MIMO use cases. For the advanced 6G scenario, we extrapolate the values for massive MIMO based on scaling factors derived from previous generation systems (3G, 4G, 5G). Moreover, we explore the single-band and multi-band configurations with multiple Component Carriers (CCs) for both scenarios, as adopted in 3GPP and which

¹ Capability to operate across multiple frequency bands simultaneously using carrier aggregation technique.

significantly increases the aggregated bandwidth that can be used in the air interface, and thus the associated required transport capacity. Table 5 shows the considered reference values for the four scenarios.

Table 5. Assumed 6G network configuration reference values.

	6G Basic				6G Advanced			
	Single-band		Multi-band		Single-band		Multi-band	
	DL	UL	DL	UL	DL	UL	DL	UL
Channel bandwidth (BW)	400 MHz		400 × 16 CCs = 6.4 GHz		1 GHz		1 GHz × 48 CCs = 48 GHz	
Modulation (Mod)	256 QAM (M=8)		256 QAM (M=8)		1024 QAM (M=10)	256 QAM (M=8)	1024 QAM (M=10)	256 QAM (M=8)
Number of MIMO layers (N_L)	8		8		16		16	
Number of antenna ports (N_{AP})	64		64		256		256	
Sampling Rate (SR)	4×30.72 Msamples/s		4×16×30.72 Msamples/s		10×30.72 Msamples/s		10×48×30.72 Msamples/s	

We assume a channel bandwidth BW for 6G basic of 400 MHz for DL and UL transmissions. This BW is already considered in FR2 of 5G NR. For the advanced 6G scenario, we take into account that the most recent 5G standalone release 18 [24] already considers BW of 2 GHz for data transmission when the subcarrier spacing (SCS) is equal to 960 kHz. Therefore, we assumed that BW of 1 GHz will be generic in the 6G advanced network. In scenarios involving multi-band configurations, 5G currently supports transmissions across 16 CCs in 5G NR [25]. Therefore, extrapolating from a basic 6G bandwidth of 400 MHz for a single CC, the supported bandwidth for 16 CCs would be 400 MHz multiplied by 16, resulting in a bandwidth of 6.4 GHz. For the case of advanced 6G multi-band network, we observe that LTE currently supports 5 CCs, whereas 5G NR expands this capability significantly by providing transmissions of 16 CCs. This represents a threefold increase in the number of supported CCs from Long-Term Evolution (LTE) to 5G NR. By extrapolating this trend, we assume that 6G networks will further elevate this capacity, enabling the aggregation of potentially 48 CCs or even more.

In the case of modulation, 256 Quadrature Amplitude Modulation (QAM) is already considered in 5G networks [26], therefore, it is logical to expect that 6G basic will support by large this modulation. For 6G advanced, 5G working groups, such as [27], are already discussing about the potential of 1024 QAM modulation for DL transmissions. Therefore, we assume that 6G advanced will incorporate this modulation in the DL.

In order to configure the number of MIMO layers and antenna ports we have used 3GPP 5G NR values for 6G basic and analyzed the most recent contributions provided by Qualcomm and Ericsson for 6G advanced. On the one hand, we keep the number MIMO layers equivalent to those utilized in 5G for 6G basic scenario, i.e. 8 layers. For 6G advanced, we consider a conservative extrapolation to 16 layers, for both DL and UL (note that 4G used 2 layers for DL and 1 for UL, and 5G used 8 layers for both DL and UL). On the other hand, for antenna ports, Ericsson has already developed 64Tx6Rx equipment and Qualcomm has it working at 3.5GHz band. As this equipment is working currently, we considered that 6G basic will use 64 antenna ports for DL/UL transmissions. Moreover, 256 antenna ports have already been considered in TR 38.801 [17], and Qualcomm has already a prototype for a 6G antenna array that operates at 13 GHz band, with 4096 antenna elements and 256 antenna ports [28]. So, we adopt 256 antenna ports for 6G advanced scenario.

Finally, in terms of sampling rate, we adopted the same proportional scaling as in the *BW* case. Consequently, for 6G basic scenario, we increased the sampling rate by a factor of 4 (from 100 MHz to 400 MHz), while for 6G advanced, we multiplied the sampling rate by a factor of 10 (from 100 MHz to 1 GHz). Additionally, for multi-band configuration, we considered 16 CCs and 48 CCs for 6G basic and 6G advanced, respectively, thus scaling the sampling rate by 4x16 and 10x48, respectively.

Considering the equations from Table 3, we have calculated the maximum transport capacity that 6G will need to support in the fronthaul and midhaul networks depending on the selected functional split and the assumed 6G scenario. These results are shown in Table 6.

Table 6. Maximum fronthaul/midhaul capacity requirements for disaggregated 6G networks, in downlink and uplink, for the four envisioned 6G scenarios (6G basic single-band, 6G basic multi-band, 6G advanced single-band, and 6G advanced multi-band).

	Single-band				Multi-band			
	6G Basic		6G Advanced		6G Basic		6G Advanced	
	DL	UL	DL	UL	DL	UL	DL	UL
1	16 Gbps	16 Gbps	100 Gbps	80 Gbps	256 Gbps	256 Gbps	4.8 Tbps	3.84 Tbps
2	16.01 Gbps	16.024 Gbps	100.02 Gbps	80.024 Gbps	256 Gbps	256 Gbps	4.8 Tbps	3.83 Tbps
4	16 Gbps	16 Gbps	100 Gbps	80 Gbps	256 Gbps	256 Gbps	4.8 Tbps	3.84 Tbps
6	16.53 Gbps	30.08 Gbps	103.33 Gbps	150.40 Gbps	264.53 Gbps	481.28 Gbps	4.96 Tbps	7.22 Tbps
7.3	50.4 Gbps	-	310.80 Gbps	-	794.4 Gbps	-	14.88 Tbps	-
7.2	86.71 Gbps	86.13 Gbps	430.78 Gbps	430.20 Gbps	1.37 Tbps	1.37 Tbps	20.64 Tbps	20.64 Tbps
7.1	688.25 Gbps	688.21 Gbps	6.88 Tbps	6.88 Tbps	11.01 Tbps	11.01 Tbps	330.3 Tbps	330.3 Tbps
8	1.25 Tbps	1.25 Tbps	12.58 Tbps	12.58 Tbps	20.13 Tbps	20.13 Tbps	603.98 Tbps	603.98 Tbps

2.2.2.3.1. Shared fronthaul/midhaul across various RUs/DUs

O-RAN includes the specifications of how many RUs can be connected to a DU, and at the same time, how many DUs can be connected to the same CU. Reference [29] defines different deployments, depending on the use case. Table 7 shows some of these deployments. It is important to highlight that in case that multiple RUs or DUs are aggregated by the same DU or CU, respectively, then the associated fronthaul/midhaul transport link must support the aggregation of the multiple RUs/DUs entities, and so the derived transport capacity requirement sum.

Table 7. Some examples of O-RAN defined RU-DU-CU deployments depending on the use case [29].

Scenario	RAN Intelligent Controller [RIC] to O-CU	Link [O-CU to O-DU]	Link [O-DU to O-RU]	Use case
B	100+	1	32-64	Outdoor deployment of a mix small cell/macrocels in dense urban scenario
C	1	100+	32-64	Outdoor deployment of a mix small cell/macrocels in dense urban scenario
C1&C2	1	320	100	Multi-operator RAN sharing, multi-slice

E	1	-	1	Indoor deployment (future, vo-RU)
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2.2.2.3.2. Transport latency requirements

The transport latency (T_{FH} for fronthaul and T_{MH} for midhaul) requirement is calculated considering the interactions occurring between the protocol layers that are included in CU and DU, or DU and RU². The latency requirement depends on the functional split, and it is based on the most restrictive configuration process in 5G/6G network which requires signal exchange between different units.

2.2.2.3.3. 5G Network

The transport latency requirement in 5G is divided into three groups. The first group consists of split 1 and split 2, where only high protocol layers RRC and PDCP are centralized. In this case, the latency requirement is constrained by network configuration, which happens every tens of ms, and so it is not very restrictive. The second group concerns Split 4, and the third group encompasses low-layer splits including options 6, 7, and 8, as we describe in the following.

Split 4 divides the RRC/PDCP/RLC in the CU/DU pool, while MAC/PHY/Rf layers are stored in different RUs. The most restrictive iteration concerning latency is between the RLC layer and the MAC layer, as the scheduling between these layers is done per Transmission Time Interval (TTI or T_{TTI}) [18]. Each time a packet arrives from the data network, it is stored in the RLC buffer, and the MAC layer is responsible for scheduling the time and frequency radio resources that are going to be used to transmit the packet. This process follows three steps (see Figure 5). First, the RLC layer sends information about the stored amount of data to the MAC layer through the transport (first T_{FH} in Figure 5). Based on the QoS requirements and the amount of data the RLC buffer contains, the MAC layer schedules radio resources to transmit this data. The scheduling process takes T_{sch} time. Then, MAC layer informs the RLC layer about the Transmission Opportunity (TxOpp), this information is sent through the transport again. After receiving TxOpp information, RLC creates Packet Data Units (PDU) to forward them to the MAC layer, entailing a processing time to segment a packet or prepare the multiple packets to be concatenated depending on the allocated TxOpp. Figure 5 shows the interaction between RLC and MAC layers.

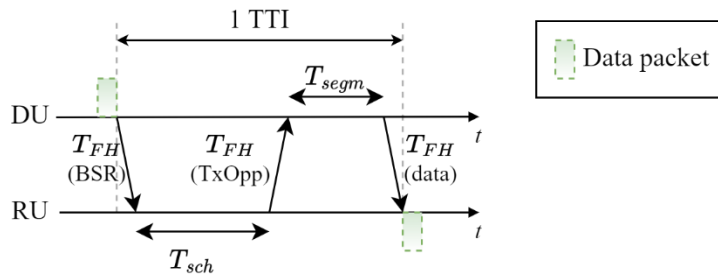


Figure 5. RLC-MAC interaction with split 4 configuration.

Following the Figure 5 we can calculate the required transport latency as it is expressed in the following equation:

$$T_{TTI} \geq T_{FH} + T_{sch} + T_{FH} + T_{segm} + T_{FH} \quad (1)$$

² This subsection figures show splits which divides the RU with the DU and these entities are connected through the fronthaul. If the CU and DU were split, these entities would be connected through the midhaul, but equal transport requirements would be applied.

where the T_{TTI} is equal to 1 ms, the time that MAC layer needs to schedule radio resources for data packets (T_{sch}) is assumed to be equal to 500 μ s, and the packets segmentation time (T_{segm}) is equal to 200 μ s [18]. Then,

$3 \cdot T_{FH} \leq T_{TTI} - (T_{sch} + T_{segm})$, being $3 \cdot T_{FH} \leq 300 \mu$ s. Therefore, $T_{FH} = \frac{300 \mu s}{3} = 100 \mu$ s.

Finally, the splits 6/7.1/7.2/7.3/8 are constrained by the HARQ process [17]. In LTE, the HARQ process in Frequency Division Duplexing (FDD) is fixed to 4 ms [18], i.e., gNB has to send data and receive the corresponding ACK/NACK feedback within 4 ms. In 5G, this time period is determined by $k1$ variable which represents the time between the slot where DL data is transmitted from the gNB to the UE and the slot where ACK/NACK message is received in the gNB. The $k1$ value is selected depending on the numerology. For numerology 0, $k1$ can take values from 2 to 4, while for numerology 2, $k1$ can take values from 6 to 13 [30]. Figure 6 shows the HARQ process followed by the gNB and UE when the MAC layer is centralized, i.e., it is located at the CU/DU.

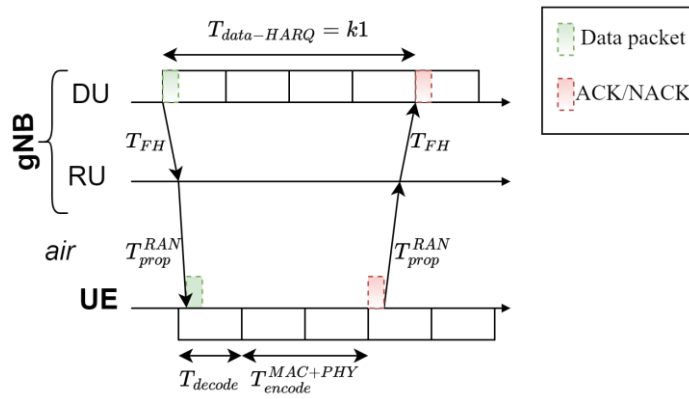


Figure 6. Centralized HARQ process.

Considering numerology 0 and $k1 = 4$ ms, as in LTE, T_{FH} for the split 6 and onwards is calculated considering the following equation:

$$T_{HARQ} \geq 2 \cdot T_{FH} + 2 \cdot T_{prop}^{RAN} + T_{decode} + T_{prop}^{MAC+PHY} \quad (2)$$

The packet is prepared in a centralized way and transmitted through the transport to the RU within T_{FH} time. Then, the packet is sent to the UE through the air (T_{prop}^{RAN}), which we consider negligible. In the UE, the packet is decoded, the UE has to process the data and prepare the ACK/NACK response in order to transmit it to the gNB. This process is done in $T_{decode} + T_{prop}^{MAC+PHY}$ time, which is assumed to be equal to 500 μ s + $2 \cdot T_{TTI}$, according to [18]. The duration of the HARQ process, denoted by T_{HARQ} , is equal to or less than $k1$. Therefore, $T_{FH} = \frac{T_{HARQ} - (2 \cdot T_{prop}^{RAN} + T_{decode} + T_{prop}^{MAC+PHY})}{2} = 250 \mu$ s.

2.2.2.3.4. 6G Network

Previously expressed latency requirements depended on the TTI. However, this TTI can be variable based on the numerology that is used in the 5G NR system. 5G NR already considers TTIs of 1 ms, 500 μ s, 125 μ s for data channels. Even if it is not clear what will happen in 6G, probably these numerologies are going to be included. Considering the latency requirements for transport networks in 5G, we have extrapolated the same requirements for 6G, considering different TTI durations. Table 8 shows the requirements that have to be fulfilled for 6G transport networks.

Table 8. Transport network latency requirements for 6G scenarios, depending on the adopted TTI in the air.

Split options	1 ms TTI	500 μ s TTI	250 μ s TTI	125 μ s TTI
1	10 ms	10 ms	10 ms	10 ms
2	1.5-10 ms	1.5-10 ms	1.5-10 ms	1.5-10 ms
4	100 μ s	50 μ s	25 μ s	12.5 μ s
6	250 μ s	125 μ s	62.5 μ s	31.2 μ s
7.3				
7.2				
7.1				
8				

These latency requirements apply to the transport link in which the functional split is adopted. Therefore, if split 2 is used for midhaul and split 6 for fronthaul, then the previously derived requirements apply, respectively, to each network segment, i.e., being T_{MH} equal to 1.5-10 ms for midhaul and T_{FH} equal to 250 μ s for fronthaul. However, there is a very particular case that needs special attention. In case functional splits 6/7.1/7.2/7.3/ are adopted for both midhaul and fronthaul networks (e.g., split 6 for CU/DU and split 8 for DU/RU), then the derived latency requirements need to be shared across these two transport networks. That is, the 250 μ s requirement, needs to be satisfied by summing the $T_{MH}+T_{FH}$ delay, which is even more restrictive. Figure 7 shows an example for this particular case, where scheduling is performed at the CU, and this information is transmitted to the DU where PHY processes are carried out, such as, codification of data, modulation, and spatial layers mapping, and then, this data is transmitted to the RU in order to convert from digital to analog data and transmit it through the air. In this context, the equation (2) is modified as:

$$T_{HARQ} \geq 2 \cdot (T_{MH} + T_{FH}) + 2 \cdot T_{prop}^{RAN} + T_{decode} + T_{prop}^{MAC+PHY} \quad (3)$$

Such that, $(T_{MH} + T_{FH}) = \frac{T_{HARQ} - (2 \cdot T_{prop}^{RAN} + T_{decode} + T_{prop}^{MAC+PHY})}{2} = 250 \mu s$.

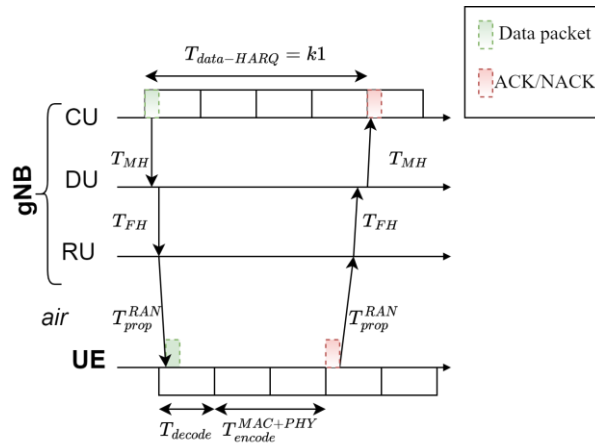


Figure 7. Transport network latency requirement considering split 6 between CU-DU and splits 7.x or 8 between DU-RU.

In the next sub-section, the scenarios of interest of the PROTEUS-6G, along with their requirements, are presented.

2.3 Scenarios of interest and KPIs

2.3.1 Definition of the scenarios of interest

PROTEUS-6G aims at demonstrating two different 6G scenarios: a first scenario providing dynamic flexible functional split; and a second one which associates with an advanced fronthaul infrastructure supporting cell-free massive-MIMO connectivity.

Dynamic functional split

This scenario aims to realize the potential of dynamic functional split as a novel RAN alternative going one step beyond to the fixed functional split adopted by 3GPP and O-RAN. We consider a flexible functional split scenario where the radio Baseband Unit (BBU) is divided into three units, the RU (Located in the cell site), the DU and the CU. The key concept is to enable different functional split options at the RU/DU/CU and dynamically adjust the functional split selections to adapt the 6G network to varying environment conditions (new services/use cases, traffic changes, etc.).

PROTEUS-6G targets a scenario where regional COs are equipped with a metro datacenter, providing a CU pool and a metro router to aggregate traffic from different access COs. The access CO itself consists of an edge computing datacentre deploying a DU pool, along with an aggregation router combining traffic from multiple cell sites. At the cell sites, multiple RUs can be connected to a CSG router and provide connectivity to the far edge computing data center deployed at the cell site. DUs and CUs are dynamically deployed as virtual network functions in the computing servers located in the access and regional COs respectively. As for the RUs, the lowest processing of the PHY layer is performed by hardware, e.g. Field Programmable Gate Array (FPGA), but the other radio processing functions are deployed as software instances in computing servers. A single DU placed in the access CO aggregates traffic from a set of RUs connected in a tree topology. Then a single CU located in a regional CO aggregates traffic from a set of DUs connected also in a tree topology. The PROTEUS 6G x-haul must provide dynamic, flexible, scalable, cost-effective, high-bandwidth, and low-latency transport connectivity services between RU and DU (fronthaul network), and DU and CU (midhaul network) to enable the dynamic management of the radio FFS.

A typical 6G x-haul transport network scenario considering O-RAN functional split is shown in Figure 8. O-RAN adopts the partially distributed deployment option utilized by 3GPP but also deploys a centralized option that employs a fixed functional split option of 7.2 for the DU/RU split and option 2 for the CU/DU split. The transport capacity requirements for the fronthaul segment between the RU and the DU, accounting for both the 6G basic and 6G advanced scenarios and single-carrier setups, ranges from 86 to 430 Gb/s both for DL and the UL considering the functional split option 7.2. A single DU can process traffic from 32 up to 64 RUs. Therefore, the transport capacity requirements of the midhaul transport segment connecting the DU and the CU ranges from 500 Gb/s to 6 Tb/s, based on a number of antennas and considering the functional split option 2. Finally, a single CU can process above 100 DUs. Therefore, the backhaul transport segment between the CU and the Core Network (CN) can range from 50 Tb/s to 600 Tb/s.

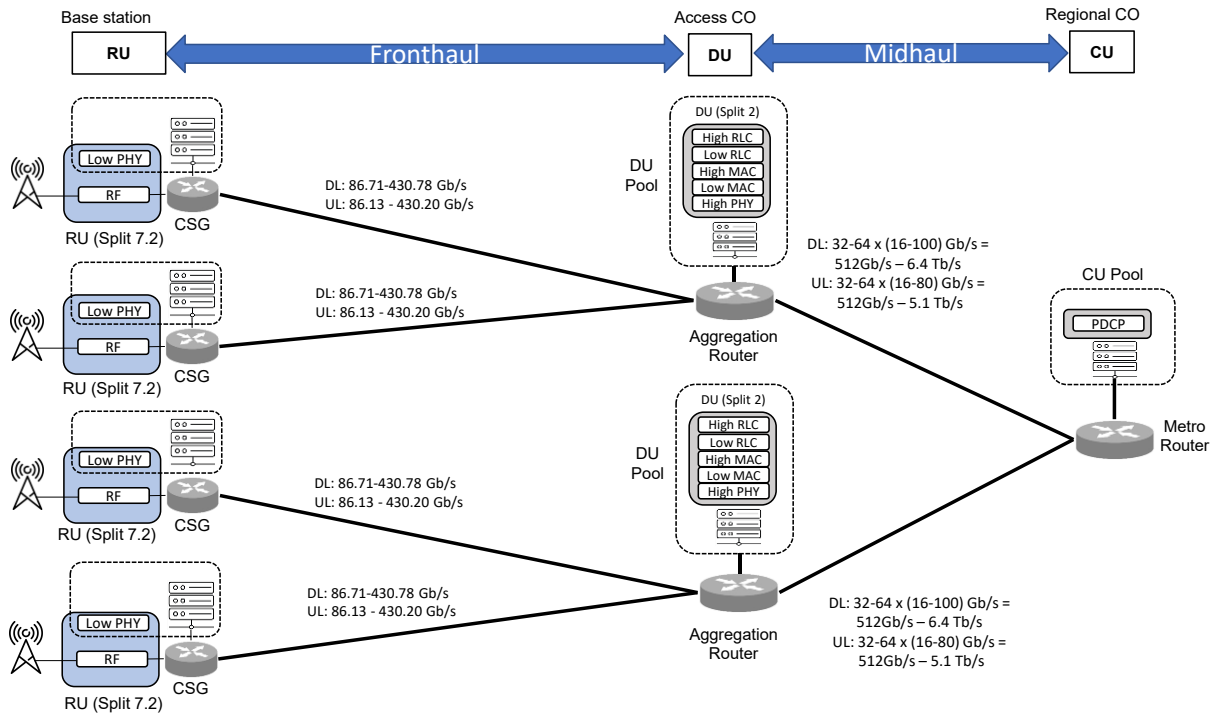


Figure 8. 6G x-haul (front/midhaul) transport capacity requirements network scenario for O-RAN functional split.

Figure 9 shows an example 6G x-haul transport network scenario for dynamic FFS targeted in PROTEUS-6G. It considers various degrees of functional split in the RU/DU/CU, ranging from less restrictive in terms of fronthaul network requirements (blue) to most demanding in terms of capacity and latency (orange). For example, the blue cell site has all PHY and MAC functions at the RU, whereas the RLC functions are hosted at the DU, and the CU only hosts the layer 3 PDCP function. This represents a split option 4 for fronthaul and split option 2 for midhaul, which is a less demanding example in terms of capacity and latency. The peak transport capacity requirements, accounting for both the 6G basic and 6G advanced scenarios are 16-100Gb/s/16-80Gb/s for the DL/UL fronthaul and midhaul connections. In the orange cell site, the RU hosts just the RF and low PHY functions, whereas the DU hosts the high PHY, MAC and Low RLC functions, and the CU is responsible for the high RLC and PDCP functions. This represents a fronthaul split option 7.2, one of the most demanding settings in terms of capacity and latency, and midhaul split option 3.

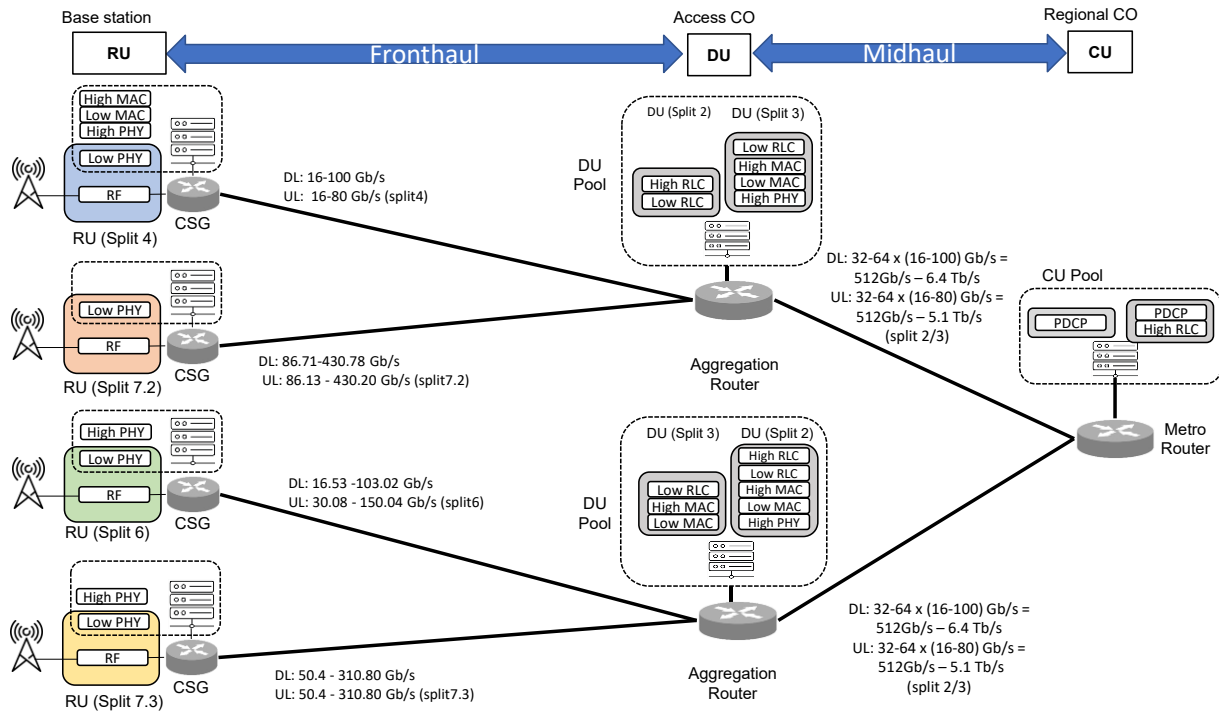


Figure 9. Example of 6G x-haul transport network scenario for dynamic FFS targeted in PROTEUS-6G.

Different functional split options are selectable for each of the cells by adapting the fronthaul/midhaul connections to the required transport capacity, as shown in Figure 10. In the depicted case, the mobile network operator has reconfigured the functional split for two out of the four RANs, according to the specific demands of new services, traffic changes, etc. For example, the blue cell site that was previously configured with functional split option 4 for RU, and split option 2 for the DU, is now reconfigured with split option 7.3 for RU, and split option 3 for the DU. This requires increasing the fronthaul transport capacity, from 16-100Gb/s to 50.4-310.80 Gb/s for the DL, and from 16-80Gb/s to 50.4-310.80 Gb/s for the UL. On the other hand, the yellow RAN has changed the configuration in RU from a function split option 7.3 to 6, and the DU from 3 to 2. It allows to perform joint processing of the green and yellow radio functions in a single DU. In this case, the fronthaul must be reconfigured to decrease the capacity from 50.4-310.80 Gb/s for the DL and UL to 16.53 -103.02Gb/s for the DL and 30.08 - 150.04 Gb/s for the UL. The specific depicted examples epitomize the generalized feasibility of the flexible and high-capacity PROTEUS-6G x-haul network endowed with variable functional splits.

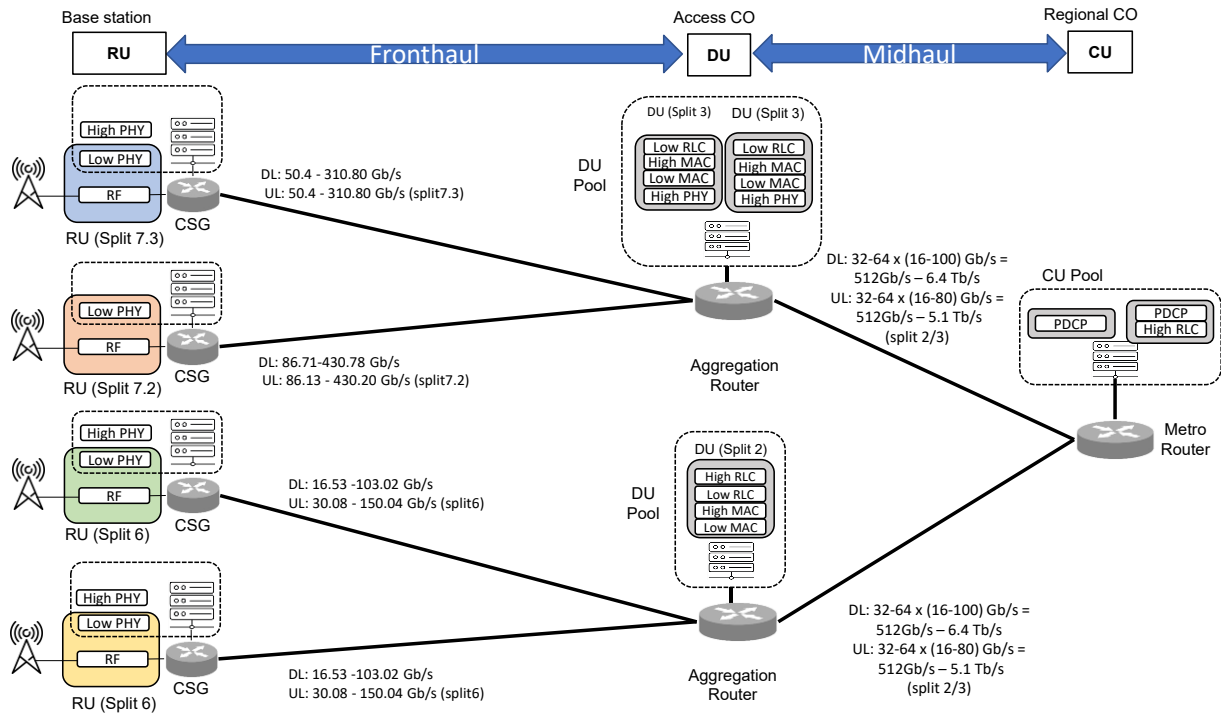


Figure 10. Example of 6G x-haul transport network scenario for reconfiguration of FFS targeted in PROTEUS-6G.

Cell Free Massive MIMO scenario

PROTEUS-6G also supports the high capacities of the cell-free massive MIMO scenario. In this case, the notion of cell disappears, as the UE signal is received and processed by $N \gg 2$ spatially distributed antenna arrays to perform distributed MIMO. The overall PROTEUS-6G transport network scenario in this cell-free massive MIMO is shown in Figure 11. The entire radio signal processing for multiple RUs may now be performed at access COs, enabling advanced MIMO processing at centralized locations (e.g., coordinated multi-point joint transmission, coordinated beamforming, or coordinated scheduling), enhancing radio signal performance in terms of users, capacity, and coverage. To enable such advanced centralized processing, this scenario follows functional split option 8 for the fronthaul interface, whereby RUs only host the RF functions, while access COs comprise CPUs hosting the full set of radio functions covering from layer 1 up to layer 3.

In this scenario, there are two main transport connectivity needs. The first one includes fronthaul connections between the cell sites and the access COs connected in a tree topology, while the second one is for intra-CPU communication between access COs connected in a ring topology, in case of coordination and/or joint processing between CPUs. At the access COs there is an aggregation router that serves to concentrate traffic from the cell sites and enable communication with other CPUs. The peak transport capacity requirements, accounting for both the 6G basic and 6G advanced scenarios are 1.25-6.29 Tb/s for each DL/UL fronthaul connection.

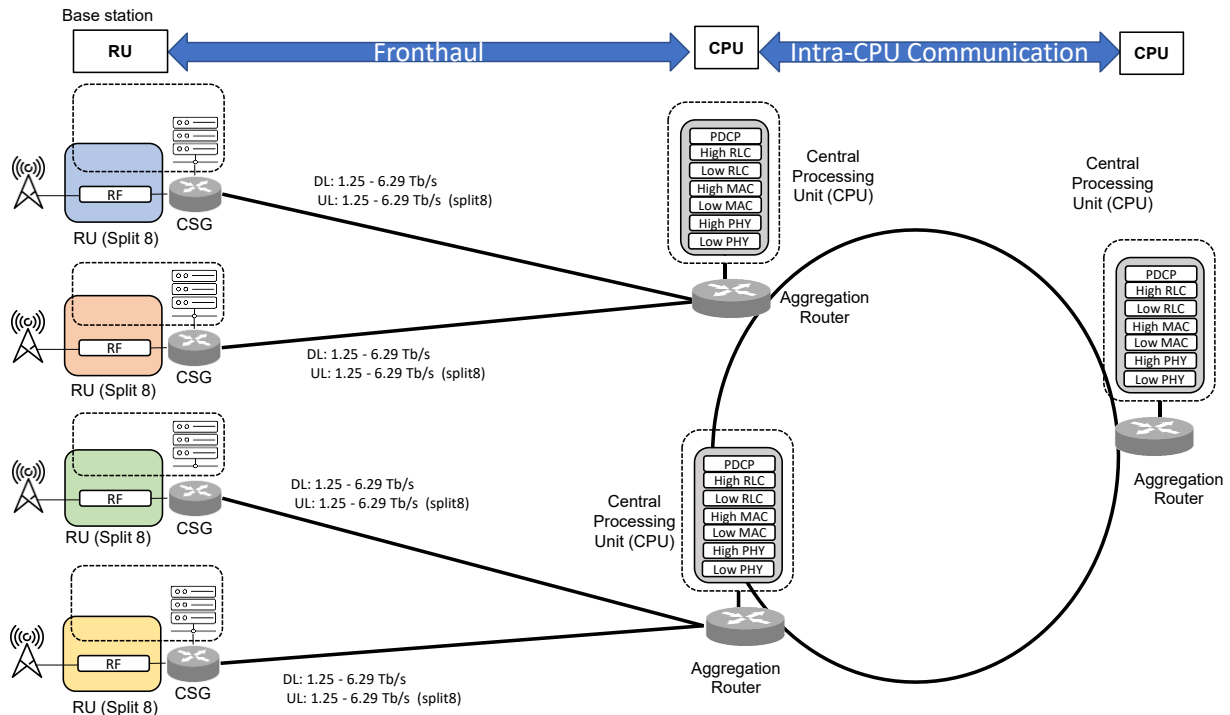


Figure 11. Example of 6G x-haul transport network scenario for cell-free massive MIMO targeted in PROTEUS-6G.

2.3.2 PROTEUS-6G KPIs

The PROTEUS-6G overall approach will be evaluated by satisfying the following KPIs. In this section, we decouple the KPIs into network, component and technoeconomic.

Table 9. KPIs of PROTEUS-6G.

Level	KPI
Network	<i>Architecture and traffic model definition related:</i> ➤ KPI O.1.1: Publish the roadmap for integration of 6G packet-optical x-haul based on packet optical solutions. ➤ KPI O.1.2: Evaluate PROTEUS-6G network capabilities considering real traffic requirements. ➤ KPI O.1.3: Identify the most appropriate architectures/topologies for the two main scenarios. ➤ KPI O.1.4: Model packet based 6G optical network traffic and estimate latency and energy consumption for the novel network architecture. ➤ KPI O.2.1: Develop a fronthaul spatially-diverse point-to-multipoint (SDPtMP) distribution unit, fed by four spatially-parallel Wavelength Division Multiplexing (WDM) inputs, all-optically distributing the datastreams to individual RU elements based on new switched interleaver element at unique functionality (CU/RU interfaced to multiple

	RU/CU), low loss (theoretically lossless), network scaling (by WDM multiplier), compact footprint (~chip: 20×20 mm²), and low-cost. ➤ KPI O.2.2: Variants of SDPtMP based on MCS and M×N contentionless Wavelength Selective Switch (WSS) handling multiple spatial feeds for client distribution, will be compared to our switched interleaver offering. Each option entails unique attributes, to be compared in terms of mid/fronthaul network functionality, loss-budget, cost and size. Management, operation and optimization related: ➤ KPI O.5.1: 2× throughput gain relative to static resource allocation. ➤ KPI O.5.2: Up to 10× energy consumption saving relative to static resource control at low-to-moderate loads. ➤ KPI O.6.1: Modelling of at least two different types of optical devices addressed in PROTEUS-6G (definition of YANG models). ➤ KPI O.6.2: Configuration and monitoring of at least two key PROTEUS-6G different types of devices (definition of protocols and required extensions). ➤ KPI O.6.3: Dynamic management of optical fronthaul/midhaul connections in the PROTEUS-6G x-haul network (provisioning time < 15 s). ➤ KPI O.6.4: Dynamic management of packet-optical fronthaul/midhaul connections integrating the packet and optical Software-Defined Networking (SDN) controllers (provisioning time < 20 s). ➤ KPI O.6.5: Dynamic management of 6G services integrating the non-real-time RAN intelligent Controller and the x-haul SDN orchestrator to enable dynamic functional splits (provisioning time < 1 minute). Test, demonstration and integration related: ➤ KPI O.7.1: Define test scenarios for SDPtMP network distribution element, plasmonic based transceivers and SDN orchestration for the packet-optical x-haul. Test scenarios will cover functional splits up to option 7.2 exploiting DSCM and functional split options 7.1 and 8 using the developed transceivers. A maximum bandwidth up to 200 GHz and peak data rate of about 1 Tb/s is envisioned. ➤ KPI O.7.2: Demonstration activity planning including network control and operation optimization for a specific E2E 6G application. ➤ KPI O.7.3: Integration of SDPtMP, plasmonic lite-coherent transceivers and SDN orchestration in the demonstration testbed.
Component	Interleaver related: ➤ KPI O.3.1: Development of a 2nd order RAMZI interleaver at 64 GHz periodicity and precise spectral positioning (<0.75 GHz error), generating even/odd bands of ≥28 GHz width and >20 dB extinction. ➤ KPI O.3.2: Development of a two-stage interleaver Photonic Integrated Circuit (PIC) for mixing subcarrier groups among four spatial inputs and four spatial outputs at low insertion loss of <-2.5 dB fibre to fibre. ➤ KPI O.3.3: Development of Piezoelectric phase modulators drawing ≤10 μW, featuring low polarization dependency in C/L-band, at ≤ -10 dB polarization crosstalk. ➤ KPI O.3.4: Integration of the HV-DAC driver on the PIC (up to 40 V at 14 bit resolution). ➤ KPI O.3.5: Integration of optical power monitoring taps for in-situ calibration and fault detection. Transceiver related:

	➤ KPI O.4.1: Development of a lite-coherent, dual-polarisation 0.8 Tb/s C/L-band plasmonic transmitter, aboard the silicon photonic (SiPh) integrated platform, with 1 V electrical drive voltages at 200 GBd symbol rate and on-chip insertion losses of <5 dB, enabling EO-bandwidth of >200 GHz for the plasmonic modulators. ➤ KPI O.4.2: Development of a lite-coherent, dual-polarisation 0.8 Tb/s C/L-band plasmonic receiver front-end on a SiPh PIC, featuring photodiodes for 200 GBd symbol rates with >200 GHz bandwidth and responsivity of 0.5 A/W. ➤ KPI O.4.3: Development of a ROSA PIC on the silicon nitride photonic integrated platform implementing all-optical equalization in the C/L-band extending reach up >20 km and dual-polarization tracking >200 rad/sec. ➤ KPI O.4.4: Development of a packaged dual-polarization plasmonic lite-coherent transceiver using all-optical and analog signal processing for Digital Signal Processing (DSP)-free linear drive optics at 0.8 Tb/s data rate and over >20km reach.
Techno-economic	➤ KPI O.8.1: Network scaling study in fronthaul, midhaul and back-haul transmission based on collected data and validating that network reconfiguration in a few seconds meets requirements. ➤ KPI O.8.2: Energy and carbon footprint study of lite-coherent DSP-free transceiver vs. conventional coherent transceivers (based on power-hungry DSP), demonstrating more than 50% reduction. ➤ KPI O.8.3: Study of optical transceiver market to identifying price targets (e.g. 3000€) to overtake market.

2.3.3 6G synchronization KPIs

Although synchronization is not under the research scope of PROTEUS-6G, for the sake of completeness we include also in this deliverable a summary of target synchronization KPIs or requirements towards 6G, given the fact that a fronthaul network design needs to take into account not just capacity and latency, but also support envisioned synchronization mechanisms required for advanced distributed RAN features. In fact, the circuit switching capability of PROTEUS-6G optical technology can provide theoretical improvement in the way nodes are synchronized throughout the RAN w.r.t. a conventional packet-switched fronthaul transport.

The basic reference to the way RAN synchronization is recommended to be implemented in a packet network, in particular, an ethernet-switched network, is the IEEE 802.1CM standard [31], developed by the Time-Sensitive Networking (TSN) working group. This standard specifies the way ethernet bridges need to be configured to prioritize fronthaul traffic, suggests how to compute a bound to the transport latency and analyzes the mechanisms to implement synchronization. Synchronization in the context of 802.1CM involves ensuring that different network elements within a fronthaul network maintain a common understanding of time as an essential functionality for the proper functioning of cellular networks. This is achieved by means of two main instruments: IEEE 1588 Precision Time Protocol, to deliver the global time from a master clock to multiple end nodes, and Synchronous Ethernet (SyncE), to convey the frequency and phase of the clock. The introduction of these elements has become essential for 5G-6G network service providers: the use of a GNSS (Global Navigation Satellite System) provides enough accuracy for most advanced radio applications but is not recommended given the vulnerabilities implied.

2.3.3.1 IEEE 1588 Precision Time Protocol (PTP)

PTP is a widely used protocol for clock synchronization in packet-based networks. 802.1CM leverages IEEE 1588 PTP for synchronizing time across fronthaul networks. It defines profiles and configurations of PTP

optimized for fronthaul networks, considering factors such as timing accuracy requirements and network topology. The IEEE 1588 Precision Time Protocol (PTP) serves as the cornerstone of synchronization in fronthaul networks. It operates by exchanging timing information between network devices to achieve highly accurate time synchronization. In the context of 802.1CM:

- **PTP Profiles:** The standard defines specific profiles of IEEE 1588 PTP tailored for fronthaul networks. These profiles optimize parameters such as message intervals, clock accuracy, and redundancy to meet the synchronization requirements of 6G systems. It is worth highlighting the following profiles:
 - **Default Profile:** this profile serves as a baseline configuration for PTP operation, providing a common set of parameters that are applicable to most network scenarios. It specifies default message intervals, clock accuracy requirements, and priority settings for synchronization traffic. The Default Profile is often used in general-purpose networking environments where precise timing is required but specialized configurations are not necessary.
 - **Telecom Profile:** this profile is tailored specifically for synchronization in telecommunications networks, such as mobile fronthaul and backhaul networks. It defines parameters optimized for stringent timing requirements and high reliability, reflecting the critical nature of timing synchronization in telecom applications. The Telecom Profile may include tighter accuracy tolerances, shorter message intervals, and enhanced fault tolerance mechanisms compared to the Default Profile.
 - **Power Profile:** it is designed for synchronization in power utility and smart grid applications, where precise timing is essential for the coordination and control of distributed energy resources. It incorporates features to mitigate the impact of network disturbances and ensure reliable synchronization in electric power systems. The Power Profile may prioritize fault tolerance, resilience to network disruptions, and support for legacy synchronization protocols commonly used in power utility environments.
 - **Industrial Profile:** the Industrial Profile addresses synchronization requirements in industrial automation and control systems, where precise timing is critical for synchronized operation of distributed sensors, actuators, and manufacturing equipment. It emphasizes determinism, reliability, and interoperability with existing industrial communication protocols such as PROFINET and EtherCAT. The Industrial Profile may include mechanisms for TSN and support for synchronous communication over Ethernet networks.
 - **Financial Profile:** this profile caters to synchronization requirements in financial trading and electronic trading systems, where ultra-low latency and high precision are paramount. It optimizes parameters such as message intervals, timestamping accuracy, and network latency to minimize trading latency and ensure equitable market access. The Financial Profile may include specialized hardware timestamping capabilities and support for high-frequency trading strategies.
 - **Enterprise Profile:** the Enterprise Profile addresses synchronization needs in enterprise networks, including data centers, cloud computing environments, and campus networks. It focuses on providing accurate and reliable timing for applications such as distributed computing, virtualization, and real-time collaboration. Also, it may emphasize scalability, ease of deployment, and compatibility with existing network infrastructure and management systems.

These PTP profiles offer a standardized approach to configuring and deploying synchronization solutions across diverse industries and applications, ensuring consistent performance and interoperability while accommodating specific requirements and constraints of each domain.

- **Multi-domain Synchronization:** 802.1CM supports synchronization across multiple domains, such as RANs, core networks, and edge computing environments. It ensures that synchronization is maintained seamlessly across heterogeneous network segments, enabling coherent operation.
- **Clock Class Hierarchies:** Different clock classes are defined within the IEEE 1588 PTP framework to categorize devices based on their accuracy and stability. The standard specifies mechanisms for clock

selection and synchronization hierarchy management to ensure that higher-quality clocks propagate synchronization to lower-quality clocks efficiently.

- **Accuracy:** Target synchronization accuracy for 6G systems may range from sub-microsecond to nanosecond levels, with an ideal target of 32 nanoseconds or less to support the most demanding radio applications (see Table 10 below).

2.3.3.2 Synchronous Ethernet

SyncE is a joint standard by ITU-T and IEEE. As packet networks replace Synchronous Optical Networking (SONET) and Synchronous Digital Hierarchy (SDH) equipment, frequency synchronization is required to provide high-quality clock synchronization over Ethernet ports, currently the most extended link interface. Thus, SyncE provides the required synchronization at the physical level through bridges (and routers supporting SyncE across them). In SyncE, Ethernet link bit clocks are synchronized to stratum-1-traceable clock signals. In SONET/SDH the communication channel for conveying clock information is Synchronization Status Message (SSM). Similarly, in SyncE ITU-T/IEEE defined the Ethernet Synchronization Message Channel (ESMC).

2.3.3.3 Synchronization Reference Model

The standard IEEE 1588 PTP provides a synchronization reference model that defines various clock roles and their interactions in the network. It includes concepts like the Grandmaster Clock (GMC), Boundary Clock (BC), Transparent Clock (TC), and Ordinary Clock (OC), each with specific responsibilities in maintaining synchronization.

- **Grandmaster Clock (GMC):** The GMC serves as the primary source of time in the network, providing the reference time for synchronization. GMCs are synchronized with Coordinated Universal Time (UTC), the global time standard maintained by atomic clocks operated by national timekeeping laboratories worldwide. In 6G networks, the GMC may incorporate advanced technologies such as atomic clocks or quantum-based time sources to achieve unparalleled accuracy.
- **Boundary Clock (BC):** BCs serve as intermediate synchronization points within the network, distributing timing information received from the GMC to downstream devices, by regeneration of the synchronization signal. They play a crucial role in reducing synchronization propagation delay and maintaining timing accuracy in large-scale deployments.
- **Transparent Clock (TC):** TCs facilitate accurate synchronization in scenarios where packet transit times vary due to network congestion or path asymmetry. They compensate for packet delay variations (PDV) by timestamping packets as they traverse the network, enabling precise time correction at the receiving end.
- **Ordinary Clock (OC):** OCs represent endpoint devices within the network that rely on external synchronization sources, such as BCs or GMCs, to maintain time coherence. They synchronize their clocks periodically based on timing information received from upstream sources, ensuring alignment with the network's global time reference.

Some specific target numbers, considering the requirements of future 6G systems are:

- **Propagation Delay:** Target propagation delay between GMCs and downstream BCs should be kept below 1 microsecond to minimize synchronization latency and maintain time coherence across the network.
- **Clock Stability:** BCs and TCs should exhibit clock stability within 1 part per billion (ppb) to maintain long-term frequency synchronization accuracy and minimize clock drift over time.
- **Class levels of accuracy:** for reference, Class level of accuracy 6B (130ns) is required by NR (FR2) intra-band contiguous carrier aggregation, with or without MIMO or TX diversity [32]. Class level of

accuracy 6C (65ns) is required by LTE and NR MIMO or transceiver diversity transmissions, at each carrier frequency, as internal equipment specification (not a transport network requirement).

2.3.3.4 Time-aware Traffic Shaping

In addition to clock synchronization, 802.1CM addresses the deterministic delivery of time-sensitive traffic, such as fronthaul traffic carrying synchronization information and real-time data. Time-aware traffic shaping mechanisms ensure that such traffic is transmitted within predefined time constraints, minimizing jitter and ensuring predictable performance.

- Synchronization Traffic Classes: The standard defines specific traffic classes dedicated to synchronization messages, ensuring their prioritized handling within the network. These classes guarantee minimal latency and jitter for synchronization packets, even under congested conditions.
- Traffic Shaping Algorithms: Time-aware shaping algorithms regulate the transmission of synchronization traffic based on predefined Service Level Objectives (SLOs). These algorithms dynamically adjust packet scheduling and queuing parameters to meet stringent timing requirements, such as maximum allowable packet delay and jitter.
- QoS Differentiation: 802.1CM enforces strict QoS differentiation for synchronization traffic, segregating it from other data flows to prevent contention and ensure predictable performance. By assigning dedicated network resources to synchronization traffic, the standard minimizes the impact of congestion on timing accuracy.

Some specific target numbers, considering the requirements of future 6G systems are:

- Maximum Latency: Time-aware traffic shaping mechanisms should ensure that synchronization packets experience a maximum one-way latency of 100 microseconds or less, with an ideal target of 10 microseconds for 6G systems.
- Jitter Control: Synchronization traffic should be subject to minimal jitter, with a target jitter budget of 10 nanoseconds or less to ensure predictable transmission timing.

2.3.3.5 QoS for Synchronization

The standard defines QoS mechanisms to prioritize synchronization traffic over other types of traffic in the network. This ensures that synchronization packets are delivered with low latency and high reliability, even in congested network conditions.

- Service Level Agreements (SLAs): 802.1CM establishes SLAs that specify the expected performance metrics for synchronization traffic, including maximum latency, jitter, and packet loss thresholds. These SLAs serve as contractual commitments between network operators and service providers, ensuring adherence to synchronization requirements.
- Performance Monitoring and Management: The standard mandates continuous performance monitoring of synchronization traffic to detect deviations from SLA targets. Network management systems utilize real-time performance data to identify potential bottlenecks, optimize resource allocation, and proactively mitigate synchronization-related issues.
- Resilience and Redundancy: To enhance synchronization robustness, 802.1CM incorporates redundancy mechanisms that provide failover capabilities in the event of network failures or equipment malfunctions. Redundant GMCs, BCs, and communication paths ensure uninterrupted synchronization, maintaining service continuity in mission-critical applications.

Some specific target numbers, considering the requirements of future 6G systems are:

- Packet Loss Rate: Synchronization traffic should experience negligible packet loss, with a target packet loss rate below 0.01% to maintain timing accuracy and reliability.
- Service Availability: The network should maintain synchronization service availability of at least 99.999% (five nines) to ensure uninterrupted operation and meet the stringent requirements of 6G applications.

2.3.3.6 Fault Tolerance and Redundancy

802.1CM includes provisions for fault tolerance and redundancy to ensure continued synchronization in the presence of network failures. Redundant paths, backup GMCs, and mechanisms for graceful degradation of synchronization performance are specified to enhance network reliability.

- Redundant GMCs and BCs: The standard allows for the deployment of redundant GMCs and BCs to mitigate the risk of single points of failure. Redundancy schemes such as active-standby or active-active configurations ensure seamless failover in case of primary node failures, minimizing service disruptions.
- Dual-homing and Link Aggregation: Dual-homing and link aggregation techniques enable devices to establish multiple simultaneous connections to redundant network paths. This redundancy enhances network resilience by providing alternate communication routes for synchronization traffic, thereby reducing vulnerability to link failures or network partitions.
- Graceful Degradation Mechanisms: 802.1CM defines graceful degradation mechanisms that allow synchronization performance to degrade gradually under adverse conditions. By dynamically adjusting synchronization parameters in response to network impairments, the standard ensures that critical timing requirements are prioritized, preserving essential service functionalities.

Some specific target numbers, considering the requirements of future 6G systems are:

- Failover Time: Redundancy mechanisms should enable failover between primary and backup synchronization sources within 100 milliseconds or less to minimize disruption in the event of primary node failures.
- Resilience to Network Partitioning: Dual-homing and link aggregation techniques should ensure seamless synchronization operation even in the presence of network partitions, with a target convergence time of 1 second or less to restore connectivity.

2.3.3.7 Synchronization Requirements and KPIs for 6G

6G networks aim to push the boundaries of performance, requiring even higher synchronization precision and reliability to support innovative applications such as holographic communication, terahertz band utilization, and quantum communication.

Synchronization accuracy targets in 6G may approach the sub-microsecond or even nanosecond range, with synchronization jitter minimized to a fraction of a nanosecond to enable precise coordination in ultra-high-speed communication scenarios. Alongside accuracy, 6G synchronization mechanisms must exhibit robustness in heterogeneous environments, supporting seamless integration of diverse technologies while maintaining coherence across distributed network elements.

By providing these synchronization mechanisms, the 802.1CM standard augments synchronization requirements for 6G systems, ensuring the reliable and deterministic delivery of time-sensitive traffic in fronthaul networks. These mechanisms seamlessly transition from the requirements of 5G to the visionary landscape of 6G, enabling the realization of next-generation mobile communication systems.

Time/Phase Synchronization requirements shall be distinguished between absolute time error (to a common UTC reference) and relative time error (among different RUs with a common synchronization source) as shown in the following figure.

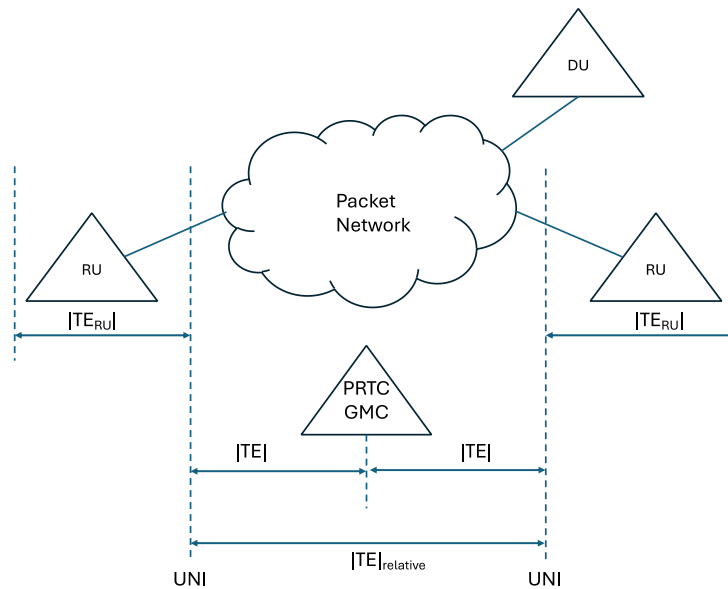


Figure 12. Relative Time-Error vs Absolute Time-Error (adapted from IEEE802.1cm).

There is quite an extensive base of information regarding synchronization requirements for fronthaul. eCPRI defines synchronization categories A+, A, B and C, and this is the reference used in IEEE802.1CM. Although taking into consideration what is stated in [32], depending on the Radio Application (advanced 5G/6G radio feature), these requirements can be summarized as follows:

Table 10. Time-error requirements per Radio Application envisioned for 5G

Radio Application	Time-error	
RU-GMC (DU-GMC)	+/- 1.5 μ sec (+/- 1.1 μ sec)	<i>Absolute</i>
Intra-band non-contiguous CA	+/- 130 nsec	<i>Relative</i>
Inter-band CA	+/- 130 nsec	<i>Relative</i>
Coordinated Multi-Point (CoMP)	+/- 130 nsec	<i>Relative</i>
Intra-band contiguous Carrier Aggregation (CA)	+/- 65 nsec	<i>Relative</i>
MIMO / Transmit Diversity (Cat A+)	+/- 32 nsec	<i>Relative</i>

As mentioned above, these requirements are the basis for 5G mobile communications, and should constitute the basis for 6G services, although it could be assumed more stringent requirements could arise, such as High-Accuracy Positioning Services for industrial precision applications and innovative applications such as holographic communication, terahertz band utilization, and quantum communication, as previously mentioned.

3. Sub-system level requirements

3.1 Optical LITE- transceiver requirements

3.1.1 Transceiver

In the PROTEUS-6G transceiver, the modulated optical carrier from the input fibre is coupled into the PIC and routed towards the active ultra-fast plasmonic PD, converting the received optical signal into the electronic domain, see Figure 13 (right top). The plasmonic PD is particularly advantageous, given its strong light confinement beyond the diffraction limit and efficient light absorption. The reduced active cross-section achieved by plasmonics leads to ultra-short carrier transit times, contributing as a key enabler for highest-speed detection. Additionally, the restriction to crystalline materials on specific substrates is leveraged and amorphous or 2D materials can be incorporated, enabling higher design flexibility for the device and more options for integration. The enhanced absorption in plasmonic PDs enables very short device lengths, yielding ultra-small capacitance, hence high RC cut-off frequency, which is the second key enabler for high-speed detection. Altogether, ultra-high opto-electronic bandwidths of several hundred GHz can be reached [33]. This plasmonic photodetector concept of PROTEUS-6G will be applied to lite-coherent reception (stage-II TXR), where silicon photonics will form a 90° optical hybrid configuration and plasmonics a balanced PD pair.

The configuration of plasmonic devices, wherein ultra-compact metal electrodes form the active area, allows for high-density integration. However, one of the few requirements to realize such a close vicinity, also under the perspective of low power consumption, is of utmost interest to avoid any matched 50 Ω transmission lines. This can be realized once the MODs and PDs are relieved of complex 50 Ω matched travelling wave transmission line electrodes. Thus, plasmonic devices provide an ideal solution since their electrodes are shorter than 20 μm , acting as lumped loads for the driving and receiving electronics. Consequently, the PROTEUS-6G TROSA PIC benefits from ‘perfect’ components in order to realize the most compact and power-efficient transceivers towards a value-chain of multi-Tb/s applications.

Creating an energy-efficient plasmonic platform for high-speed applications in the C/L is a key project goal towards exploitation in diverse applications, which goal is achieved in PROTEUS-6G by enhancing the functionality of the available plasmonic technology platforms. This is best served by a high index-contrast photonic circuit platform such as silicon photonics (SiPh), neatly combined with plasmonic structures. The targeted components are depicted in Figure 13. The novel or optimized components will be realized by means of state-of-the-art inverse designed photonics, 3D simulation tools, and design-of-experiment techniques. Multiple design, fabrication, and testing iterations are planned to ensure the best performance. The goal is to maximize on-chip repeatability and minimize run-to-run variability, crucial to guarantee <10 dB insertion loss for any transmitted channel and 50% external quantum efficiency for any received channel.

The transceiver that will enable all the aforementioned benefits and requirements will be designed and implemented in order to support the capacity requirements mentioned in Section 2. The capabilities of the transceiver are tabulated in Table 11.

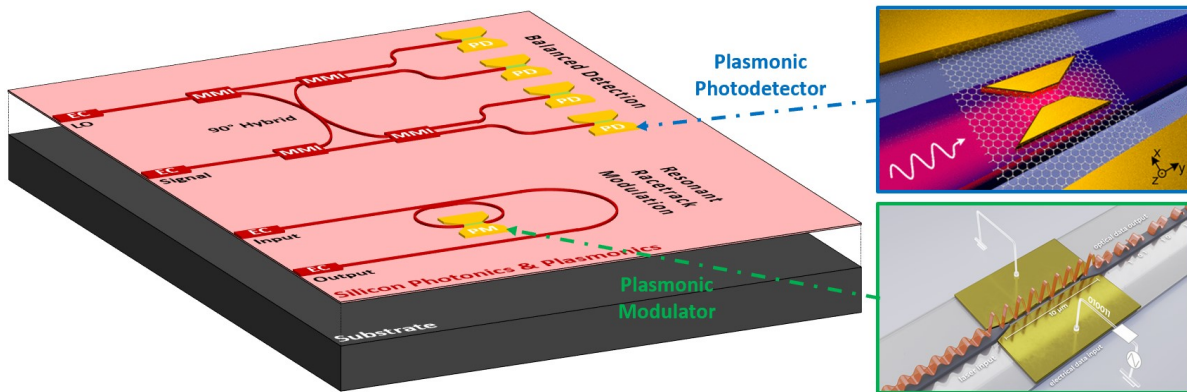


Figure 13. Plasmonic transceiver. Left: Schematic showing the realization of a plasmonic resonant racetrack modulator and plasmonic coherent detector comprising a 90° optical hybrid and balanced photodiode pairs – both are combining SiPh (red) and high-speed plasmonics (gold). Right bottom: 3D-illustration of a plasmonic phase modulator – the key element of any plasmonic modulator – illustrating the encoding of information onto an optical carrier. Right top: 3D-illustration of a plasmonic photodetector – the key element for coherent or direct detection.

Table 11. Details of the transceivers that will be developed in PROTEUS-6G. DP: Dual polarization, PAM: Pulse-amplitude modulation, IMDD: Intensity modulation direct detection, LDO: Linear drive optics, LITE-COH: Lite coherent, TXR: Transceiver.

Transceiver Architectures	Baud Rate	Bit Rate	Mod. Format	Band of Operation	Rx Type	Insertion Loss Tx	Number of Polarizations
DP-PAM4-IMDD LDO TXR	200Gb	0.8 Tb/s	PAM4	C/L	Direct Detection	<5 dB	2
DP-PAM4-IM LDO with phase-diverse LITE-COH Det	200Gb	0.8 Tb/s	PAM4	C/L	LITE-Coherent	<5dB	2

3.1.2 Software interface

The main requirement for the design of the software interface is to provide a standardized way for the control plane to interact with the transceiver element, regardless of its internal implementation details. The two main functionalities include:

- Configuration management:** The software interface receives commands from external systems (such as SDN control) and transmits them to the transceiver, facilitating remote control and configuration of the device. The configuration process can include a range of settings to optimize the device's performance and operation, ensuring flexibility and adaptability to various needs.
- Monitoring and data collection:** The interface collects telemetry data from the transceiver, potentially including key performance metrics and operating values, and forwards this information to external systems for comprehensive monitoring, analysis, and decision-making. It may also allow for real-time monitoring of the transceiver's state, enabling external systems to detect faults and take corrective actions.

A device management interface (hardware level agent) is required to be implemented to manage the device configuration and data collection functions on the device level. According to the transceiver design, the hardware is expected to include a microcontroller capable of reading and writing parameters (bidirectional Communication). A mediator Application Programming Interface (API) is considered to facilitate integration

with the software level agent (e.g. NetConf Agent), which in turn interfaces with the SDN controller. A schematic of the transceiver software interface is depicted in Figure 14.

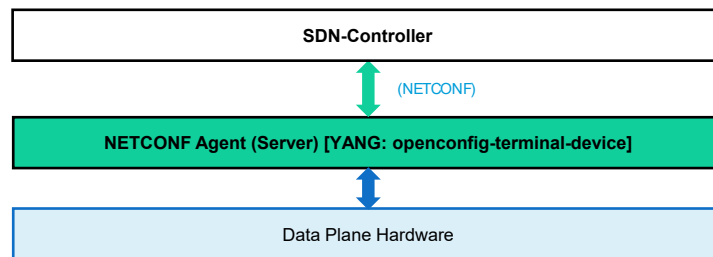


Figure 14. High-Level architecture of transceiver's SDN interface.

A communication protocol (software level agent) is required to be defined to allow the communication and transfer of both data and configuration commands between the device management interface and the control and telemetry element. Potential solutions include NetConf (Network Configuration Protocol), RESTful API (Representational State of Resource), or a proprietary Command-Line Interface (CLI). The consortium has identified NetConf as a more beneficial and well-established model-driven approach that provides a standardized way to interact with the device, regardless of its internal implementation details. Netconf's YANG data model can represent complex data structures and relationships, allowing for more sophisticated device management and monitoring. Moreover, this allows the handling of larger amounts of data and more complex transactions compared to other competing solutions like Simple Network Management Protocol (SNMP), making it better suited for scalable high-performance devices (e.g. arrays of transceivers or large port-count switches).

A key requirement for the software interface relates with the implementation of security mechanisms, such as authentication, authorization, and encryption, to ensure secure communication between the network element and external systems. This is a feature that is fully supported by NetConf which enables SSH and authentication mechanisms and Transport Layer Security (TLS) encryption to protect data in transit. Furthermore, it has a built-in Role-Based Access Control (RBAC) for restricting access to specific features or data.

3.2 DSCM transceivers and subcarrier access

The Open XR optical transceiver employs DSP to divide the transmission and reception of a particular wavelength into multiple smaller-frequency channels known as digital subcarriers. These subcarriers can be individually modulated, controlled, and allocated to different endpoints, facilitating PtMP, direct low-speed to high-speed optical transceiver connectivity, as illustrated in Figure 15. It is possible to allocate one or more digital subcarriers to a specific endpoint to meet the required bandwidth. The open XR optics forum optical transceiver modules are specifically crafted for integration into a wide range of networking equipment, such as Ethernet switches, routers, servers, wireless baseband processing systems, and Passive Optical Network (PON) headend aggregation systems.

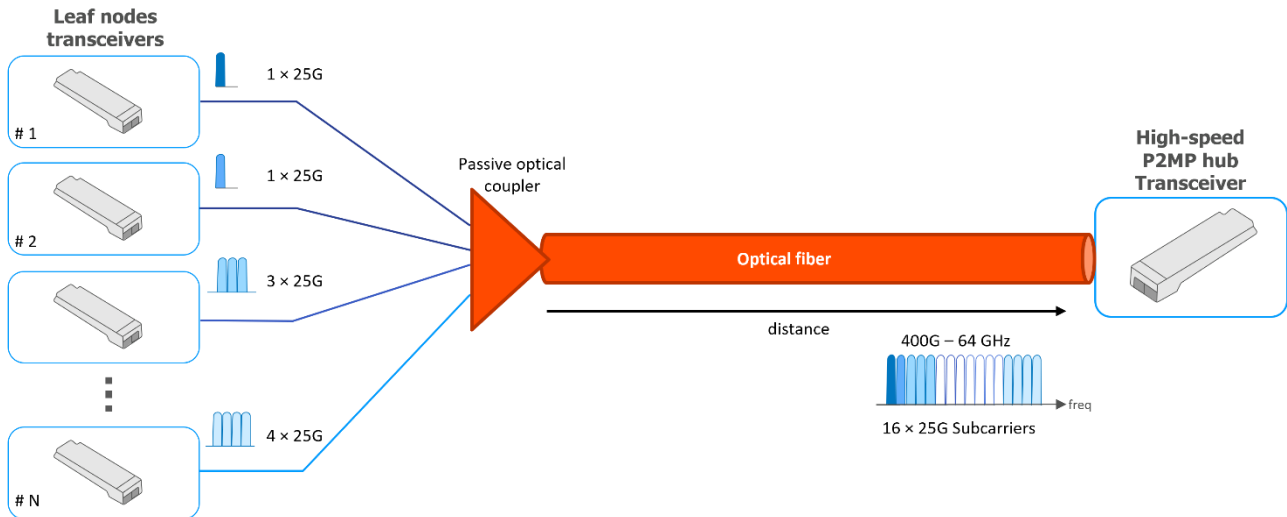


Figure 15. PtMP transmission using DSCM-based coherent transceivers.

DSCM has been adopted in commercial transmission as reported in [34], [35]. Recently, it has been proposed as a solution to enable coherent PtMP transmission to enhance flexibility and simplify the design, for example, of metro-aggregation networks such as the ones reported in [36], [37]. The DSCM solution discussed and described in [36], [37] consists of a single optical interface capable of transmitting up to 16 Nyquist Sub Carriers (SCs) with a maximum aggregated payload of 400 Gbit/s (assuming that each SC operates at 4 GBd and is modulated using up to 16-QAM, and with Dual Polarization (DP)). By locking both the leaf clock and laser frequency to that of the hub node [38], it is possible to transmit the different SCs next to each other, i.e., without the risk of overlapping, thus occupying a total bandwidth, which, depending on the guard band among the subcarriers, can be between 63 – 64 GHz. To increase the flexibility of the network, 100 Gb/s capable optical interfaces (i.e., using up to 4 SCs) are installed in each leaf node. The individual SCs – from each leaf – may have different origins and, consequently, follow different optical paths to the hub node. For example, they can be transmitted over links of different lengths or simply with different power budgets. Therefore, the DSP used at the hub node must be sufficiently robust to compensate for distortions that may be different in terms of impairments among SCs. This includes the compensation of laser with different characteristics among the different leaf nodes connected to the hub. This capability slightly increases the complexity of the DSP, but it has the great benefit, among others, of significantly reducing the need for bookended transceivers in the networks, which might cause, e.g., over-provisioning. This directly impacts costs, especially considering that a P2tP solution enables a pay-as-you-grow model [36]. Ultimately, the reduced number of transceivers results in an overall lower power consumption, which can significantly decrease the carbon and environmental footprint of the network [39].

The flexibility enabled by DSCM, when exploited by an SDN controller aware of the dynamics of the traffic pattern, potentially enables additional savings both in terms of the number of interfaces deployed and power consumption since the SCs can be reassigned to different leaf nodes throughout the network operation (e.g., from residential to industrial areas during the daytime and vice-versa during the night) or simply turned off when not needed [40]. Therefore, by allocating resources dynamically, i.e., optimizing the software-hardware relations, P2TP supported by DSCM networks could provide advantages in terms of resource management, transmission performance, and power efficiency. Such an architecture: i) reduces operational expenditure by lowering the number of human interventions; ii) improves the bandwidth utilization by providing the optimal bandwidth to all users; iii) helps operators in multi-year planning by using automation tools; iv) allows operators to roll out innovative technologies so that data-rate can be increased, while cost is reduced [37], [41]; and finally, it enables inter-generational interoperability among transceivers.

Within the PROTEUS project, methods of simplifying network architecture for x-haul networks by using the DSCM approach will be developed. This will consider scenarios that will be discussed with Telefonica and PIC-advanced, also as part of the standardization of these devices within the open XR forum.

3.3 Switch

3.3.1 Photonic components of interleaver requirements

An interleaver is an optical filter that is periodic in nature and is used to combine or separate a dense comb of signals in Dense Wavelength-Division Multiplexing (DWDM) systems. Unlike single-channel add/drop filters, the interleaver filter's periodicity reduces the number of Fourier components needed for a flat passband and high isolation rejection band. Because the interleaver filter is periodic, it naturally aligns with the periodic structure of the signal comb used in DWDM systems. This alignment means that the filter can achieve the desired frequency response (a flat passband and high isolation rejection band) with fewer individual sinusoidal components (Fourier components) compared to a non-periodic filter. Due to this characteristic, the interleaver can achieve the same flat top, sharp edge response as a higher-order narrow-band filter with fewer sections.

The filter function of an interleaver and its period can be separated. Interleavers have been proven to effectively separate a combination of DWDM frequencies with centers at 100 GHz, 50 GHz, 25 GHz, and 12.5 GHz. The period of the interleaver is determined by the free-spectral range of the core elements, where a narrower channel spacing is achieved by increasing the optical path length. Regardless of the specific technology used for implementation, there are several specifications and design goals that are common to interleavers. The design objectives for the passband include a wide, flat (or nearly flat) top with minimal insertion loss (IL) and a sharp roll off at the band edges. On the other hand, the stopband should provide high extinction across the passband of the alternate port. Achieving this usually involves a tradeoff between maximum extinction and stopband width.

In PROTEUS-6G, we have proposed a novel approach called Spatially-Diverse PtMP (SDPtMP) for the fronthaul. This approach utilizes a sharp interleaver filter network instead of traditional splitters. It enables the distribution of subcarrier groupings from multiple sources to each antenna site in a lossless manner. The proposed architecture offers enhanced flexibility and higher energy efficiency as it eliminates the requirement for signal amplification, which typically complements architectures based on splitters.

The incorporation of one or two or three ring resonators to the arms of an asymmetric Mach-Zehnder Interferometer (MZI) can significantly enhance the performance of an interleaver [42], as also shown in Figure 16 (a) by the illustration of even more sharp transition bands in respect to the increasing number of ring resonators at the structure. While an asymmetric MZI has its two complementary outputs vary as sin/cos functions of differential phase delay, the introduction of one or two ring resonators to the interferometer arms can dramatically improve the interleaver sharpness [43]. Single and dual Ring Assisted Mach Zehnder Interferometer Ring Assisted Mach-Zehnder Interferometer (RAMZI) inject poles to the transfer function, whose position can be optimized for sharpening the interleaver response and achieve 76% and 94% spectral utilization, respectively. The dual-ring RAMZI device has been previously demonstrated for enhancing the spectral resolution of a WSS to support 12.5 GHz- subcarriers [44]. Cascading interleavers in a binary tree structure of different spectral periodicities has been demonstrated for demultiplexing [45], seeding a PON [46], and performing OFDM demultiplexing [47].

In our design, we are using dual-ring RAMZI interleavers at a 32/64 GHz periodicity, as the triple ring choice does not offer significant performance enhancement in comparison with packaging and fabrication issues that are arising. The single ring choice doesn't have appropriate sharp transition bands leading to performance degradation. We obtain 30 GHz channels which support 7 subcarriers of 4 GHz spacing with ± 1

GHz alignment tolerance. With the second interleaver stage having the same spectral periodicity, yet shifting by $\frac{1}{4}$ cycle, we obtain four separated spectral slices of 14 GHz width, supporting 3 subcarriers and sacrificing a subcarrier at channel boundaries. The interleaver network topology is constructed of two-input, two-output complementary unitary devices, when placed into a dual-stage offset topology, results in a circular subcarrier-group interlacer. The same functionality is applied across each of the four inputs, generating four outputs with each subcarrier group originating from a different input source. The interleaver network (or circular subcarrier-group interlacer) remains a complementary unitary device. Since all interleavers share the fundamental 64 GHz periodicity this may raise a concern on the WDM channel plan. Notably, the channel plan need not conform to a 64 GHz-based grid, as the circular nature of the network functions across 16 GHz bands. Therefore, any DSCM channel aligned to the 16 GHz grid would be processed identically. In our case we suggest placing wavelength channels on 80 GHz grid, allowing for 16 GHz guard bands between 64 GHz-wide channels to accommodate wavelength switching using existing WSS

Also, another specification is the optimum subcarrier spacing in order to achieve performance gain in terms of Error Vector Magnitude (EVM) and Bit Error Rate (BER) calculation sacrificing adequate spectral efficiency. The VPI tool was used to obtain the performance simulation results for the SDPtMP ODN. The DSCM transceivers have the capability to operate in the C+L optical bands and can occupy any spectral slot within the range of 1530-1625 nm. These transceivers can carry a bandwidth of 11.4 THz. To achieve PtMP data transmission, subcarrier multiplexing is utilized, with subcarriers spaced at 4 GHz each and a programmable baud rate and modulation format. The employed modulation format is 16QAM and there are 12 Nyquist subcarriers with a roll-off factor of 0.05. The simulation has been conducted with varying baud rates.

In this study, we have explored the potential of the proposed architecture, which utilizes cascaded RAMZI filters to achieve circular spectral interleaving with a bandwidth of 14 GHz. It is important to note that the transmitter does not use the subcarriers that fall on the interleaver transitions. Therefore, only 12 subcarriers per transmitter are operational, out of 16 in a 64 GHz band transmitter. The interleaver processes four CU resources at the same wavelength, with additional capacity enhancements from other wavelengths. Wavelength switches are used to distribute 64 GHz-channels to different RU. Before addressing the key development challenges of the SDPtMP element, it is crucial to determine if the communication performance of the filtering-based network meets the required performance and capacity standards.

The Figure 16(b) illustrating the EVM penalty for an edge subcarrier clearly showcases the minimal impact of reduced baud rates on the performance of filtered channel communication, as detailed in [48]. To investigate the maximum baud rate that can be achieved without compromising performance, we analyzed the EVM penalty while progressively increasing the baud rate of the signal filtered by the interleaver. This study aims to determine the highest possible baud rate for a future fronthaul network that meets the upcoming capacity and reliability demands. The findings indicate that for symbol rates below 3.5 GBaud, the EVM penalty remains under 1 dB, in contrast to scenarios with significantly lower symbol rates. This finding suggests that the proposed architecture can sustain a data rate of 28 Gbps per subcarrier, resulting in an overall capacity of 336 Gb/s. It is worth noting that with advanced forward error correction, the system can potentially operate at 3.75 GHz. However, it is crucial to consider that a potential laser-filter misalignment could lead to a lower symbol rate, in accordance with the laser accuracy specifications and associated costs.

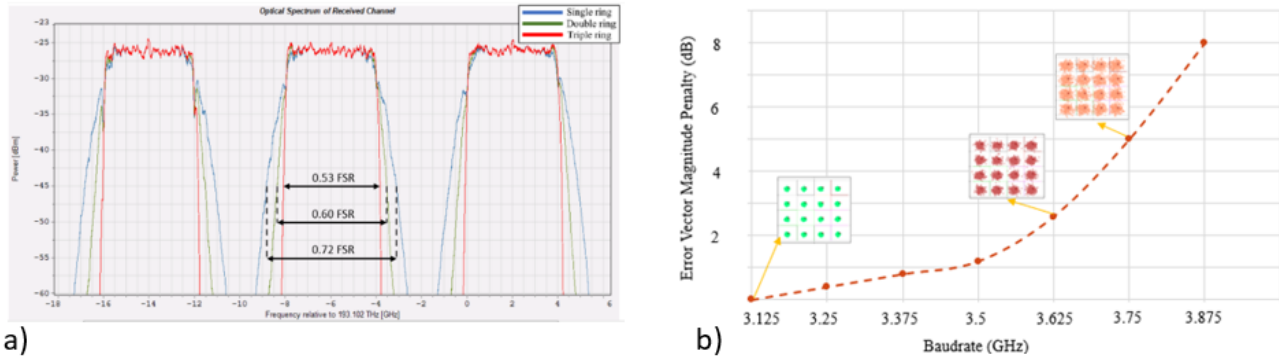


Figure 16. a) The RAMZI filter is sharper with more rings at the structure, enhancing the energy efficiency of the system. b) EVM penalty, as compared to the case of baud-rate of 3.125GHz, for higher baud-rate values.

3.3.2 Software interface

The main requirement for the design of the software interface is to provide a standardized way for the control plane to interact with the switch, regardless of its internal implementation details. The two main functionalities include:

- Configuration management: The software interface receives commands from external systems and sends them to the switch, allowing remote control and configuration of the device.
- Monitoring and data collection: The interface collects telemetry data from the switch, such as performance metrics, alarms, or system health information, and forwards it to external systems for monitoring, analysis, and decision-making. It may allow also real-time monitoring of the switch's state, enabling external systems to detect faults, receive alarm notifications, and take corrective actions.

3.4 Requirements for autonomous network control and orchestration, streaming telemetry and optical performance monitoring of multi-layer (packet/optical) x-haul networks

3.4.1 Introduction towards autonomous network

The low-latency packet optical x-haul network architecture in PROTEUS-6G requires not only the capability to provide the different levels of connectivity needed by the different functional splits, but also the ability to perform an autonomous operation. Unlike traditional networks that require human intervention, autonomous networks can self-configure, self-optimize and self-repair, adjusting in real time to changing conditions. TMF has defined the levels of automation in a network and the steps to achieve it [49]. In the first levels, only repetitive tasks are automated. As the automation level increases, closed loops with pre-defined thresholds are included. In the higher steps of automation, the thresholds are dynamically adjusted, and artificial intelligence is used to assist in the automation.

In PROTEUS-6G, the 6G ready x-haul network needs to adapt to varying environmental conditions, such as supporting a new service, adjusting to traffic changes (e.g. volume, pattern, etc.), and network health. Hence, there are several processes that require automation:

- Planning: The planning process captures the requirements of the services (e.g. expected traffic matrix, expected SLAs, etc), network constraints and, as outcome decides the optimal placement.

- **Provisioning:** It involves the creation of a new service (e.g. connectivity from RU to DU), modification or deletion of existing services.
- **Optimization:** This process involves maintaining the same level of service making better use of the available resources.
- **Recovery:** The recovery process is triggered by events such as component/network element failure or degradation and requires immediate action to avoid failing to meet the service requirements (either the service is stopped or degraded not meeting the desired SLA)

To achieve the autonomous x-haul network, it is required:

- An SDN Control architecture with orchestration capabilities that provides API-based interaction and data-driven abstraction, detailed in sub-section 3.4.2.
- Real time feedback from the network by means of streaming telemetry (detailed requirements covered in sub-section 3.4.3) to understand the network conditions.
- In particular, for the autonomous operation in Proteus, key data will come from the performance monitoring of the optical nodes, covered in sub-section 3.4.4.
- As Proteus introduces the packet-optical nodes at the x-haul layer, it is required to expand the Control architecture, as detailed in sub-section 3.4.5

3.4.2 General control & orchestration framework (building blocks)

The PROTEUS-6G project aims to design and deploy a multi-layer (packet/optical) x-haul (fronthaul/midhaul) SDN orchestration plane architecture with a focus telemetry, intent-based, and autonomic networking functionalities. Next, we define several key requirements and associated KPIs to measure the effectiveness and efficiency of the proposed network control architecture:

- **Coordinated Multi-Layer Management:** Seamlessly integrate and manage the packet and optical layers through a centralized hierarchical SDN orchestrator that can effectively coordinate between the two layers.
- **Dynamic Adaptation:** Implement capabilities to dynamically adapt the packet-optical x-haul network to support various RAN functional splits and centralization levels based on real-time traffic demands and network conditions.
- **Cloud-Native Function Deployment:** Leverage a cloud-native infrastructure to deploy network functions as microservices, ensuring scalability, resilience, and rapid deployment across distributed environments.
- **Advanced Optical Technology Integration:** Integrate and manage advanced optical technologies such as Space Division Multiplexing (SDM)/WDM Reconfigurable Optical Add-Drop Multiplexer (ROADM) and PtMP and ULC transponders within the network, ensuring high efficiency and compatibility with existing network infrastructures.
- **Standardized Control Interfaces:** Utilize standard interfaces (e.g., NETCONF, RESTful APIs) for all control actions to ensure interoperability and vendor neutrality, enabling a more flexible and scalable network architecture.
- **Automated Telemetry and Performance Monitoring:** Implement automated telemetry systems using protocols like gRPC or OpenConfig to continuously monitor and optimize network performance metrics such as signal-to-noise ratios and bit error rates.
- **Flexibility:** Capability to adapt to changing network conditions and requirements dynamically driven by flexible functional split.
- **Reliability:** High availability and fault tolerance to ensure continuous network operations in the x-haul network.
- **Optimization:** Efficient management of packet and multi-granular (WDM/WBDM/SDM) optical network resources to optimize performance, energy consumption and cost.

Next, we define some tailored KPIs that can be considered to evaluate the specific functionalities and challenges of the PROTEUS-6G control and orchestration framework, ensuring that it not only addresses the complex needs of a disaggregated, multi-layer 6G x-haul network but also maintains high standards of performance, reliability, and flexibility.

- Time to Establish End-to-End Connectivity: Measure the time required to establish end-to-end connectivity between any two points in the network, specifically focusing on cross-layer interactions.
- Network Adaptation Latency: Track the latency in network response to changes in traffic patterns or RAN functional split requirements, emphasizing the system's ability to adapt dynamically.
- Microservices Deployment Time: Quantify the time taken to deploy or scale network functions as microservices, reflecting the agility of the cloud-native infrastructure.
- Optical Network Element Integration Success Rate: Evaluate the success rate of integrating and managing new optical network elements like ROADM and transponders within the existing network framework.
- API Efficiency: Assess the efficiency and response times of the SDN controllers' APIs, particularly in scenarios involving complex configurations or high-demand periods.
- Telemetry Update Interval and Accuracy: Measure the frequency and accuracy of telemetry updates, ensuring they provide a real-time and accurate representation of network status.
- Network Resource Utilization: Monitor how effectively the network utilizes its optical and packet switching resources, aiming for optimal performance with minimal waste.
- Fault Detection and Recovery Time: Time to detect and correct faults within the network, particularly in the integration of packet and optical layers.
- Service Downtime During Reconfigurations: Amount of service interruption (if any) experienced during dynamic reconfigurations of the network.

3.4.3 Streaming telemetry requirements

Streaming telemetry involves continuously collecting and transmitting performance data from network devices to a centralized system for analysis. This method provides real-time visibility into network performance, enabling proactive management and optimization. In the context of PROTEUS-6G, telemetry data is information generated by various network elements (transceivers and switches) through specific sensors, describing potentially their operating conditions, performance metrics, or other relevant information. This data comprises critical parameters such as power levels, signal quality, and traffic statistics. Through continuous monitoring of these metrics, the “control” system can foresee potential failures, detect irregularities and failures, as well as optimize the allocation of resources.

The following requirements must be met by the network elements for implementing streaming telemetry in PROTEUS-6G:

- Data Collection: They should support streaming telemetry capabilities, meaning that they should be capable of running the proper mechanisms to generate telemetry data, necessitating the integration of sensors or agents to collect and send (at high frequencies) continuously the needed data.
- Data Exposure: They should offer detailed access to various metrics, including interface statistics, error rates, and resource usage, allowing for comprehensive monitoring. Those metrics should be exchanged utilizing predefined open standards and protocols for ensuring compatibility and seamless integration across the different types of network elements.
- Computational Resources: They must have sufficient CPU and memory to handle the additional load from telemetry activities without degrading their primary functions.

- Telemetry Protocols and Streaming models: They should support efficient telemetry protocols such as gRPC (supports the usage of TLS and token-based authentication), RestConf (over standard HTTP or HTTPS protocols), NetConf (uses secure transport protocols such as SSH or TLS) etc. These protocols have been designed to support high-frequency data transmission. As described above, streaming telemetry should be based on standardized data models for defining the structure of the data being collected. In PROTEUS-6G, NetConf will be utilized to support the streaming telemetry. Although NetConf is not primarily designed for handling telemetry data streams but rather for managing, configuring, and monitoring network devices, it has the capability to be used for collecting and forwarding telemetry data as an additional functionality. Netconf's YANG data model can represent complex data structures and relationships, enabling more advanced device management and monitoring. This would allow a single protocol that is already required to provide a standardized method to configure, modify, and monitor device configurations in a centralized manner using XML messages.

Furthermore, both the network and its infrastructure must fulfill specific criteria to efficiently support streaming telemetry. Sufficient network bandwidth is necessary to handle the continuous telemetry data flow without impacting regular "data plane" network traffic. Additionally, low latency is crucial for ensuring timely data delivery and facilitating real-time analysis.

To this end, the telemetry data streaming models, which are architectural patterns and techniques employed for collecting, processing, and analyzing real-time or near real-time data continuously and without interruption, is crucial and should meet the following requirements:

- Low Latency: Processing and acting upon the data as soon as it is generated helps in real-time decision making and faster response times.
- Scalability: Streaming models can handle vast amounts of data, making them suitable for large-scale telemetry data generation.
- Resilience: They can automatically recover from failures and continue processing data without interruption.

Potential KPIs that can be used to measure the success of streaming telemetry system:

- Data Accuracy: This KPI is defined as the measurement for the accuracy of the telemetry data collected and transmitted by comparing it against their "true" value.
- Data Latency: This KPI evaluates the delay between data generation and its availability for analysis, ensuring that telemetry data is delivered promptly in near real-time.
- System Availability: This KPI can be used to measure the uptime and availability of the streaming telemetry system, ensuring it remains operational and accessible to users under any system condition.
- Data Volume Size: This KPI can be used to observe the volume of telemetry data generated and transmitted by the network element, ensuring it aligns with expected levels and does not exceed system capacity/ resource limits.

3.4.4 Optical performance monitoring requirements

The integration of Optical Performance Monitoring (OPM) techniques/systems at the network nodes will enable the monitoring of the performance of the PHY, contributing to ensuring efficient operation and management of the network. By continuously monitoring various performance metrics such as signal quality, spectral characteristics and/or power levels, OPM can provide valuable insights into the network health and quality. This will enable an efficient and dynamic reuse of network resources, optimized network

performance and enhanced reliability by early detection of eventual faults/issues. This can be achieved by the implementation of non-intrusive OPM systems based on, for example, optoelectronic front-end developments for coherent detection of signals. Coherent-based monitoring schemes will provide extended monitoring capabilities, enabling the retrieval of the signal phase information. There are several key requirements that the OPM systems must meet:

- Extraction of relevant figures of merit: OPM systems should enable the acquisition of suitable figures of merit such as Optical Signal-to-Noise Ratio (OSNR), power, power spectrum, providing feedback to the network service management control and orchestration entities.
- Real-time monitoring: Continuously monitoring capabilities to provide relevant figures of merit extracting key physical/transmission parameters information. This monitoring data could serve to enable early fault detection and response to network anomalies, detect performance degradation towards ensuring end-to-end Quality of Transmission (QoT) and QoS.
- Low-cost and simplified monitoring: Implement low-cost and simplified OPM schemes based on simple subsystems and/or discrete components or even by reusing spare/unused transceivers available at the network nodes.
- Non-intrusive monitoring: Non-intrusive optical probes independent from the modulation format, ensuring compatibility with multiple technologies, to allow continuous monitoring of network performance without disrupting the ongoing data transmission.
- Support of WDM/SDM operation: OPM systems based on technology and on the adoption of different subsystems capable to support WDM/SDM monitoring.
- Scalability, flexibility and dynamicity: The network should be scalable, dynamic and flexible to accommodate the increasing traffic demands and evolving network conditions. To this extent, OPM systems should facilitate dynamic and optimized network allocation, management and operation by efficiently processing the acquired monitoring data.
- Interoperability: OPM systems, located at the network nodes, should ensure interoperability with diverse network devices and systems.
- Efficient network resource utilization: The implementation of OPM solutions at the network nodes will facilitate the extraction of monitoring data that will provide real-time insights into network performance and capacity. This can serve to dynamically optimize/adjust the allocation and utilization of network resources maximizing capacity, performance, and cost-effectiveness.
- Enhancement of measurements by the use of ML/AI techniques: Apply Machine Learning and Artificial Intelligence (ML/AI) approaches to deliver an improved measurement of any of the targeted figures of merit, with precision higher than in conventional performance monitoring systems.

Although all these requirements are desirable to be met in the PROTEUS-6G project, they might be difficult to measure in a clear way to assess the success of the OPM solutions developed and enhanced in PROTEUS-6G. Therefore, in this sense we propose to use the following key performance indicators:

- Accuracy: this KPI is defined as the degree to which a collection of measurements (of a certain figure of merit) resembles its actual value. For instance, if the average value of a series of repeated measurements of the same power is reasonably near to the actual value of the power being measured, the measurements are considered accurate. Generally speaking, systematic errors are linked to accuracy. This source of inaccuracy can be compensated by using signal processing, including ML/AI techniques.
- Precision: Precision refers to how well the measurements of a figure of merit match each other. For example, a series of repeated measurements of the same power is said to be precise if their variance is low.
- Resolution: This KPI is defined as the smallest change a given performance monitoring probe can detect in the figure of merit that it is measuring. For example, it can refer to power increments that can be measured.

- Dynamic range: Dynamic range is defined as the ratio between the largest and smallest values that the performance monitoring probe will be able to provide for a certain figure of merit. For example, the difference between the maximum and minimum power that can be measured.
- Scalability: This KPI can be defined in several ways. However, in order to make it clear and measurable we define it as the number of channels that can be monitored by a given OPM probe, together with the number of figures of merit to be acquired by the same OPM probe.

3.4.5 Packet optical x-haul control requirements

The integration of coherent pluggables in devices that traditionally have been tasked with only packet functionalities brings unprecedented flexibility in the multi-layer network operation. Due to this integration of the transceiver in PROTEUS-6G nodes, it is required to consider packet-optical devices and prepare the control plane to deal with packet devices that can directly terminate optical connections. The following requirements must be met by the PROTEUS control plane:

- Discovery of the coherent pluggable: The PROTEUS-6G node must be able to access the properties of the transceiver and expose them to the controller. The PROTEUS-6G node must access the pluggable information via Content Management Interoperability Services (CMIS) protocol.
- Support of dual management of pluggables: The P2TP transceiver that can be plugged to PROTEUS-6G node provides dual management. That means it has a dedicated interface to configure optical related parameters (such as constellations, number of subcarriers, modulation format, launch power, etc.) and the client-facing (electrical) parameters. Thus, the PROTEUS-6G control plane must be able to collect information both from the host and from the dedicated pluggable control interface
- Multi-layer Network discovery: The control plane should be able to create a network map including L2/L3 packet connections and the underlying L1/L0 optical connections.
- Provisioning of plug-to-plug capacity: The control plane must be able to create, modify and delete an L2 connection with a certain bandwidth between two pluggables in different hosts (e.g. base station and first aggregation router). In order to perform such provisioning, the control plan needs to configure both the packet-related parameters (interface, MTU, speed, QoS, etc.) and the optical ones (central frequency, launch power, etc).

4. Conclusion

This deliverable marks the conclusion of Task 2.1 of work package 2, which focused first on the analysis of the 6G use case categories as proposed by IMT-2030 along with the requirements of each category. Then, the definition of the latency and capacity requirements which are keys in order to satisfy the QoS in the 6G services was discussed first for 5G and then extended to 6G network for different possible options, which are the 6G Basic, the 6G Advanced, both with and without considering Single or Multi-Band capabilities. Based on the developed analytical framework, the maximum transport capacity that 6G will need to support in the fronthaul and midhaul networks depending on the selected functional split and the assumed 6G scenario, was estimated. The estimations showed that for the most capacity demanding functional split which is FS8, the maximum fronthaul/midhaul capacity requirements for disaggregated 6G networks, in downlink and uplink, when Multi-Band is activated, in the extreme case of 6G-Advanced can reach about 600 Tb/s for the 6G Advanced case, and to about 20 Tb/s for the 6G Basic case. Moreover, for single band, these values reach to about 12.5 Tb/s and 1.25 Tb/s for 6G Advanced and 6G basic options, respectively. Next, analytical expressions that estimate the latency requirements in the different functional split options were introduced. Based on this formalism, it was shown that the latency requirements are strongly dependent on the TTI. 5G NR already considers TTIs of 1 ms, 500 μ s, 125 μ s for data channels, and given the fact that currently, it is not clear what will happen in 6G, probably these numerologies are going to be included. Considering the latency requirements for transport networks in 5G, the same requirements for 6G have been extrapolated, considering different TTI durations. Based on the adopted TTI in the air, the most demanding split option, which is option 8, can require latency down to 31.2 μ s for a TTI in the air of 125 μ s and down to 250 μ s for a TTI in the air of 1 ms. Both latency and capacity requirements strongly highlight the need to develop and introduce novel components and management, control and orchestration mechanisms in order to efficiently realize the different functional split options in the x-haul.

Within PROTEUS-6G and to test the developed novel elements, two different 6G scenarios are planned to be demonstrated: a first scenario providing dynamic flexible functional split; and a second one associated with an advanced fronthaul infrastructure supporting cell-free massive-MIMO connectivity. The first scenario aims to realize the potential of dynamic functional split as a novel RAN alternative going one step beyond the fixed functional split adopted by 3GPP and O-RAN. A flexible functional split scenario is considered to enable different functional split options at the RU/DU/CU and dynamically adjust the functional split selections to adapt the 6G network to varying environment conditions (new services/use cases, traffic changes, etc.). The demonstration of an FFS scenario is crucial for 6G as it aims to meet the diverse throughput and latency demands across different traffic types and reduce operational costs while optimizing resource utilization and network performance. In the second scenario (cell-free massive-MIMO), the notion of cell disappears, as the UE signal is received and processed by $N \gg 2$ spatially distributed antenna arrays to perform distributed MIMO. In this scenario, the entire radio signal processing for multiple RUs may now be performed at an aggregation/metro node, enabling advanced MIMO processing at centralized locations (e.g., coordinated multi-point joint transmission, coordinated beamforming, or coordinated scheduling), enhancing radio signal performance in terms of users, capacity, and coverage. As capacity linearly increases with the number of distributed antenna arrays (RUs), this scenario requires the highest transceiver throughput and stringent latency requirements in the fronthaul network. The demonstration of a cell-free massive MIMO scenario is also crucial for 6G as it aims to meet the high capacity and low latency demands, as well as the synchronization challenges.

Next, the PROTEUS-6G KPIs were discussed and decoupled into network, component and techno-economic levels. Achieving these KPIs will positively evaluate the PROTEUS-6G approach. Finally, the requirements of the different components that will be developed in PROTEUS-6G were analyzed, like the optical lite transceiver, the DSCM transceivers, the switch, and the autonomous network control and orchestration, streaming telemetry and optical performance monitoring of multi-layer (packet/optical) x-haul networks, designating that the multi-layer approach adopted in PROTEUS-6G mandates to achieve a number of requirements on each different level.

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