



PROTEUS 6G

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**PROGRAMMABLE RECONFIGURABLE OPTICAL TRANSPORT FOR
EFFICIENTLY OFFERING UNCONSTRAINED SERVICES IN 6G**

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Executive summary

This deliverable outlines the demonstration plans and testbed preparations for WP6 within the PROTEUS-6G project, documenting the outcomes of **Task 6.1**, which focused on planning and organizing activities to align with **Objective 6.1**: planning demonstration activities and defining test scenarios for the spatially-diverse point-to-multi-point (SDPtMP) network distribution element, plasmonic-based lite-coherent transceivers, and SDN orchestration for packet-optical x-haul networks. The work involved defining infrastructure requirements, establishing subcomponent interfaces, and making logistical arrangements to support the planned test scenarios.

The deliverable focuses on two use cases: **Dynamic Functional Split** and **Cell-Free Massive MIMO**, highlighting the integration of SDPtMP nodes, plasmonic-based transceivers, and SDN orchestration to achieve flexible, scalable, and high-capacity x-haul networks. **Dynamic Functional Split** demonstrates adaptable FS using DSCM and SDPtMP nodes, while **Cell-Free Massive MIMO** emphasizes ultra-high-capacity transmission with centralized MIMO processing. Intermediate tests validate critical metrics such as bandwidth allocation, interoperability, and SDN control capabilities.

In line with **Objective 6.1**, Task 6.1 also defined Key Performance Indicators (KPIs) focusing on bandwidth, capacity, latency, and reliability to evaluate the performance of the demonstrations. These KPIs will guide the assessment of subsequent tasks (6.2 and 6.3) and future deliverables (D6.2 and D6.3). The work spanned from June 2024 (Month 6) to April 2025 (Month 18) and fulfills **Milestone MS6.1**: *First definition of test scenarios and plan for final project demonstration completed* (December 2024).



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ABBREVIATIONS

3GPP	3 rd Generation Partnership Project
ACL	Access Control List
API	Application Programming Interface
AOSP	All-optical signal processor
ASE	Amplified Spontaneous Emission
BER	Bit Error Rate
BGP-LS	Border Gateway Protocol – Link State
CO	Central Office
CSG	Cell-Site Gateway
CPU	Central Processing Unit
CU	Centralized Unit
DAC	Digital-to-Analog Converter
DP	Dual Polarization
DSC	Digital Sub-Carrier
DSCM	Digital Sub-Carrier Multiplexing
DSP	Digital Signal Processing
DU	Distributed Unit
DWDM	Dense Wavelength Division Multiplexing
FS	Functional Split
FFS	Flexible Functional Split
FH	Fronthaul
FPGA	Field Programmable Gate Array
gNMI	gRPC Network Management Interface
gRPC	Google Remote Procedure Call
GSMA	Global System for Mobile Communications Association
IETF	Internet Engineering Task Force



IPM	Intelligent Pluggable Manager
IP	Internet Protocol
MPLS	Multiprotocol Label Switching
IPoDWDM	IP over DWDM
KPI	Key Performance Indicator
LSP-DB	Label Switched Path Database
LSP	Label Switched Path
MH	Midhaul
MIMO	Multiple-Input and Multiple-Output
NAAS	Network as a Service
NBI	North Bound Interface
NDU	Network Demarcation Unit
NE	Network Element
Non-RT RIC	Non Real-Time RAN Intelligent Controller
OEO	Opto-Electronic-Opto
ONF	Open Networking Foundation
O-RAN	Open Radio Access Network
OSNR	Optical Signal-to-Noise Ratio
OSS	Operations Support System
P2MP	Point to Multi-Point
P2P	Point to Point
PAM	Pulse-Amplitude Modulation
PCC	Path Computation Client
PCEP	Path Computation Element Protocol
PHY	Physical Layer
PL-DB	Physical Layer Database
PM	Power Monitor



PON	Passive Optical Network
QAM	Quadrature Amplitude Modulation
RAMZI	Ring-Assisted Mach-Zehnder Interferometer
RAN	Radio Access Network
REST	Representational State Transfer
RF	Radio Frequency
ROADM	Reconfigurable Optical Add-Drop Multiplexer
RSA	Routing and Spectrum Assignment
RU	Radio Unit
Rx	Receiver
SBI	South Bound Interface
SC	Sub-Carrier
SDM	Space Division Multiplexing
SDN	Software Defined Networking
SDO	Standards Development Organization
SDPTMP	Spatially-Diverse Point to MultiPoint
SMF	Single-Mode Fiber
SMO	Service Management and Orchestration
TAPI	Transport API
TE	Traffic Engineering
TED	Traffic engineering Database
TFS	TeraFlowSDN
TWI	Two Wire serial Interface
Tx	Transmitter
VPN	Virtual Private Network
WP	Work Package
WDM	Wavelength Division Multiplexing
WSS	Wavelength-Selective Switch



1. Introduction

1.1 Objective of the deliverable

The aim of the deliverable, D6.1, is to outline the planned demonstrations and associated testbeds preparations for WP6 in the PROTEUS-6G project. WP6 is dedicated to integration and demonstration of key technologies developed within the project, specifically focusing on Spatially-Diverse Point to MultiPoint (SDPtMP) network distribution element, plasmonic based-transceivers, and Software Defined Networking (SDN) orchestration and management software. These components form the core hardware and software elements for the demonstrations and are derived from the outcomes of WP3, WP4 and WP5.

The deliverable translates the project's goals into concrete demonstration setups that showcase the advancements made in these areas.

- Hardware elements: SDPtMP subcarrier interlacer from WP3, XR-Optics pluggables, and Dual-Polarization Pulse-Amplitude Modulation (DP-PAM) transceiver prototype from WP4 provide the physical infrastructure for achieving high-capacity and flexible transmission.
- Software elements: Packet-optical and optical SDN control planes from WP5 enable orchestration, management, and control of these network components within an SDN framework.

The core objective of this deliverable is to define two use cases that highlight the unique capabilities of the developed technologies:

1. **Use Case 1: Dynamic Functional Split** – This use case focuses on demonstrating the flexibility and scalability of the developed technologies by enabling dynamic FS, specifically targeting Layer 1 splits at option 7.2 and above. The demonstration aims to showcase how the SDPtMP network element can handle varying FSs while maintaining the required performance and efficiency.
2. **Use Case 2: Cell-Free Massive MIMO** - This use case aims to demonstrate ultra-high-capacity transmission using the developed plasmonic-based transceivers, particularly the DP-PAM transceiver prototype from WP4. It demonstrates advanced Multiple-Input and Multiple-Output (MIMO) processing at centralized locations, with a split architecture that places key radio functions at Central Offices (COs), ensuring high-bandwidth connectivity. The goal is to highlight the technologies' potential in supporting cell-free massive MIMO application scenarios and achieving the defined KPIs.

The demonstration activities for T6.1 span from M06 to M18, focusing on planning and setting up two key scenarios by M12 to test SDPtMP network elements, plasmonics-based transceivers, and SDN orchestration. Task 6.1 involves planning, defining requirements, and making logistical arrangements, which will guide the implementation in Task 6.2. Final demonstrations will occur in Task 6.3 at Fraunhofer HHI and Telefónica's facilities, where the necessary infrastructure will be provided. These two locations are strategically chosen to represent different deployment scenarios and infrastructure requirements, including progress monitoring and coordination meetings.

Serving as a reference handbook for subsequent laboratory setups and integration activities, the deliverable ensures that all partners have a clear understanding of the demonstration objectives and requirements. By translating the use cases into specific demonstration setups, this deliverable paves the way for the successful integration and testing of the developed technologies within the chosen scenarios.

It is important to note that all the tables with "interface specifications" provided in this deliverable are considered preliminary at this stage. During Task 6.2, we will revisit these interfaces in greater detail



and present updated interface descriptions as part of Milestone M6.2, scheduled for Month 18 (June 2025).

1.2 Relation with other Deliverables and Tasks

The successful execution of D6.1 is closely linked to the contributions and results from other work packages and tasks within the PROTEUS-6G project. This deliverable draws upon the outcomes of WP3, WP4, and WP5, which focus on developing and validating the key technologies that are central to the demonstrations in WP6. These outcomes provide the critical hardware and software components that enable the planned demonstration setups and test scenarios.

- WP3: provides the 4-port subcarrier interlacer and SDPtMP node for point-to-multipoint connectivity and dynamic bandwidth allocation, supporting Use Case 1.
- WP4: delivers lite-coherent transceivers and DP-PAM frontends, enabling high-capacity, low-latency transmission for Use Case 2.
- WP5: contributes SDN controllers and the Service Management and Orchestration (SMO) for dynamic resource allocation and orchestration, integrating hardware and software to support both use cases.

Additionally, D6.1 directly informs the activities in Task 6.2 (Integration of components into demonstration setups), where the demonstration setups defined in this deliverable will be implemented. The defined requirements and planned activities in D6.1 also provide the foundation for Task 6.3 (Final Demonstration), where the demonstration setups will be tested and showcased at the host facilities.

Supporting deliverables like D2.1 and D5.1 provide foundational x-haul architecture specifications and SDN/SMO functionalities, while MS6.1 relies on D6.1 to facilitate early integration and validation. Together, these efforts ensure a streamlined path from development to demonstration of PROTEUS-6G technologies.

1.3 Structure of the deliverable

The deliverable is structured into several sections. Section 2 defines the test scenario and experimental setups for Use Case 1, with a focus on achieving dynamic FS, detailing the relevant subsystems, and associated intermediate tests. Section 3 presents the test scenario for Use Case 2, emphasizing the Cell-Free Massive MIMO setup, involved subsystems and intermediate testing. Section 4 concludes with key outcomes and outlines the next steps. Finally, Section 5 establishes the link between this deliverable and the related implementation and work package objectives, highlighting the relevant project milestones.



2. Test scenarios for Use Case 1: Dynamic Functional Split

In this chapter, we outline the planning of the experimental activities required to demonstrate the first PROTEUS-6G scenario of interest, as described in Section 2.3.1 of D2.1. This scenario focuses on designing a Fronthaul (FH) / Midhaul (MH) network capable of supporting dynamic functional splits, surpassing the static configurations defined by the 3rd Generation Partnership Project(3GPP) and Open Radio Access Network (O-RAN). By enabling adaptive reconfigurations, the network can respond to variations in traffic demand driven by user mobility, evolving service requirements, and heterogeneous application needs. Furthermore, it can accommodate temporal and spatial traffic fluctuations, such as diurnal patterns, differences between peak business and residential usage during weekdays and weekends, and localized surges linked to large-scale events like concerts, industrial exhibitions or conferences.

The chapter is organized as follows. First, we present the FH and MH network architecture envisaged for PROTEUS-6G and establish a comparison between this architecture and the testbed designed to demonstrate this scenario. Next, we provide a brief overview of the various subsystems involved in the use case scenario and outline the sequence of tests planned to validate the proposed solution. Finally, we detail how these tests will contribute to the achievement of the related Key Performance Indicators(KPIs), demonstrating the solution's effectiveness and alignment with project objectives.

2.1 Architectural View of Use Case 1

Use Case 1 targets a scenario enabling different functional split options at the Radio Unit (RU), Distributed Unit (DU), and Centralized Unit (CU), which can dynamically adjust the selected functional split to adapt the 6G network to varying environment conditions (new services/use cases, traffic changes, etc.).

In this scenario, as depicted in Figure 1, regional Central Offices (COs), equipped with a metro data center, provide a CU pool and a metro router to aggregate traffic from different access COs. Each access CO consists of an edge computing data center deploying a DU pool, as well as an aggregation router that collects traffic from multiple cell sites. At the cell sites, multiple RUs are connected to a Cell-Site Gateway (CSG) router, which links to the far-edge computing data center deployed at the cell site. DUs and CUs can be 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 Physical Layer (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, which constitutes the core of the PROTEUS-6G project. Likewise, a single CU located in a regional CO aggregates traffic from a set of DUs connected in a ring or meshed topology. The interface between the DU and RU was defined by the O-RAN Alliance as the FH interface, while the interface between the CU and the DU is known as the MH interface. The PROTEUS-6G x-haul network, the architecture that is being defined in WP2, is expected to provide dynamic, flexible, scalable, cost-effective, high-bandwidth, and low-latency transport connectivity services for the FH and MH interfaces, enabling the dynamic management of the radio Flexible Functional Splits (FFSs).

A typical 6G x-haul transport network scenario considering O-RAN Functional Splits (FS) is depicted in Figure 1. For the FH interface we show splits 4 (blue) and 7.2 (orange), while for MH interface we represent splits 2 (blue) and 3 (orange), with the respective processing functions being deployed at the corresponding servers located in the regional and access COs, or at the RU/CSG. An unspecified (generic) functional split is depicted in green color. The scenario involves:



- Digital Sub-Carrier Multiplexing (DSCM) transceivers enabling Point-to-Multi Point (Pt2MP) communication between the aggregation or metro routers and the CSGs (represented by a trident with a purple contour in Figure 1) or Point-to-Point (P2P) communications between the aggregation and metro routers (DU-CU connectivity, with DSCM transceivers represented by a trident with a brown contour),
- Two stages of the PROTEUS-6G 4-port Sub-carrier (SC) group interlacers (represented by a box with a blue contour in Figure 1) forming a tree network topology, to interleave and distribute subcarriers from different Space Division Multiplexing (SDM) and/or Dense-Wavelength Division Multiplexing (DWDM) high-capacity DSCM transceivers hosted at the metro and/or aggregation routers towards lower-capacity DSCM transceivers plugged into the CSG,
- Internet Protocol (IP) routers and servers at the different sites to inject the IP traffic into the network and do the required Radio Access Network (RAN) functional split processing,
- The SDN controllers and orchestrator to manage the IP and optical Network Elements (NE) and perform telemetry functions, and
- The Service Management and Orchestration (SMO), which is responsible for the coordination of the transport and RAN networks and serves as an interpreter between the service layer requests and the SDN orchestrator.

The P2MP connectivity between the DU (aggregation router) and the RU/CSG is represented in Figure 1 by light blue, orange and green lines. A single high-capacity DSCM transceiver plugged into the aggregation router is connected to one of the four input ports of the first-stage PROTEUS-6G 4-port SC group interlacer, which filters and switches groups of its component digital subcarriers towards the four output ports of the interlacer and addresses each of the output ports to a second-stage interlacer, which, with proper configuration, can distribute the SC from a single high-capacity DSCM transceiver among several low-capacity DSCM transceivers plugged into three different CSGs located far apart (light blue to top CSG, green to middle CSG, and orange to bottom CSG in Figure 1). The brown line in Figure 1 represents a P2P connection between high-capacity DSCM transceivers plugged into metro and aggregation routers (DU-CU connectivity). Direct connectivity between the metro routers and the CSGs could be possible in scenarios of densely populated areas where high capacities need to be transported along short distances, in which case DU and CU functions could be co-located.

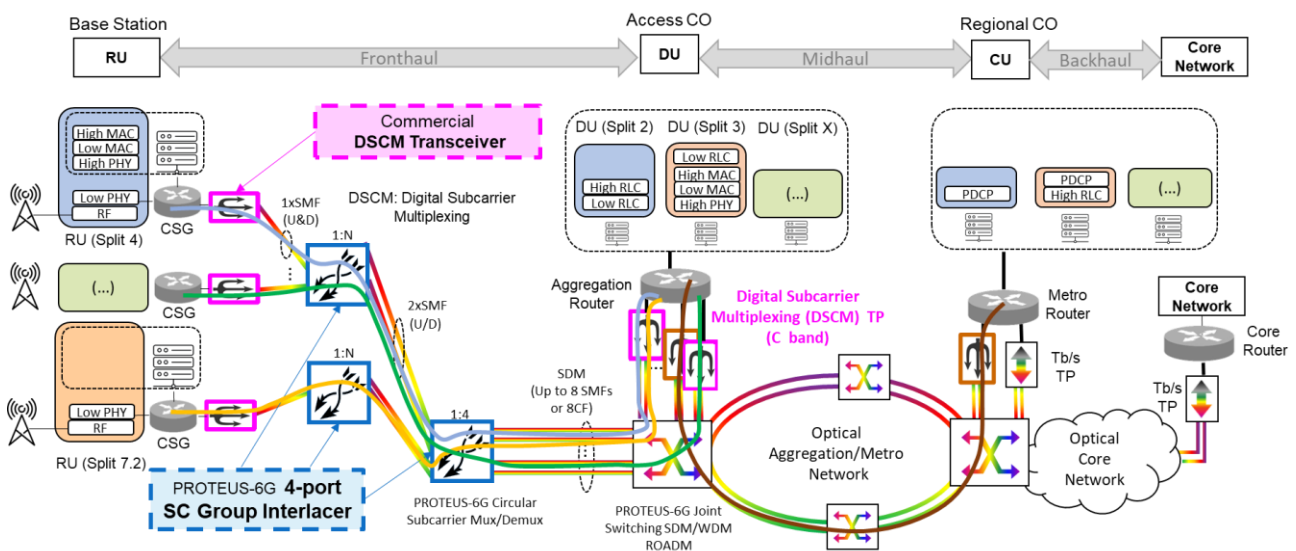
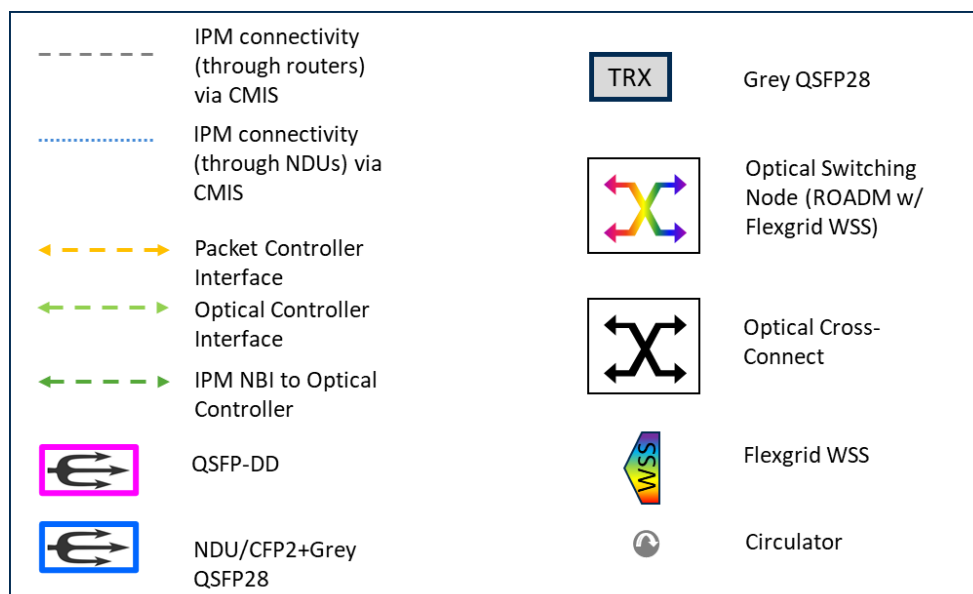


Figure 1. Architectural view of Use Case 1 within PROTEUS-6G overall architecture.

2.2 Derived experimental demonstration setup

The high and low-capacity DSCM transceivers used in Use Case 1 are fully integrated transceivers with real-time interfaces which can be plugged into either commercial routers (QSFP-DD form factor) or Network Demarcation Units (NDUs) (CFP2 form factor) incorporating client interfaces which, by means of grey 100G QSFP28 pluggable modules, can be connected to commercial routers (UfiSpace and Cisco). The demonstration scenario for Use Case 1 deals with the PHY transmission and SDN control of DSCM signals generated by XR pluggable modules from Infinera through the tree topology formed by two stages of PROTEUS-6G 4-port SC group interlacers. Figure 2(top) shows a simplified depiction of the network architecture for use case 1, including one RU/CSG, two stages of 4-port SC group interlacers, one SDM/WDM switching node —connected to one aggregation router and one server (performing DU functions)— at the edge of a four-node ring topology, and one metro router and server connected to one of the remaining two nodes in the ring, implementing DU functions. The figure presents the FH and MH physical-layer connectivity (blue and brown lines, respectively) from one low-capacity DSCM transceiver at the CSG to a high-capacity DSCM transceiver at the aggregation router through a tree topology, and from a high-capacity DSCM transceiver at the aggregation router to another high-capacity DSCM transceiver at the metro router through a ring topology. Moreover, the figure also depicts an optical SDN controller to manage the Infinera Pluggable Manager (IPM) and NEs such as Wavelength-Selective Switches (WSSs) within the SDPtMP node or the switching nodes, Reconfigurable Optical Add-Drop Multiplexer (ROADM)—; the packet SDN controller, to manage the IP routers and the DSCM transceivers directly plugged into the routers, as well as the SDN orchestrator and the SMO.

From such simplified network architecture view, a concrete experimental demonstration setup, shown in the lower part of Figure 2, was derived, using the following legend:



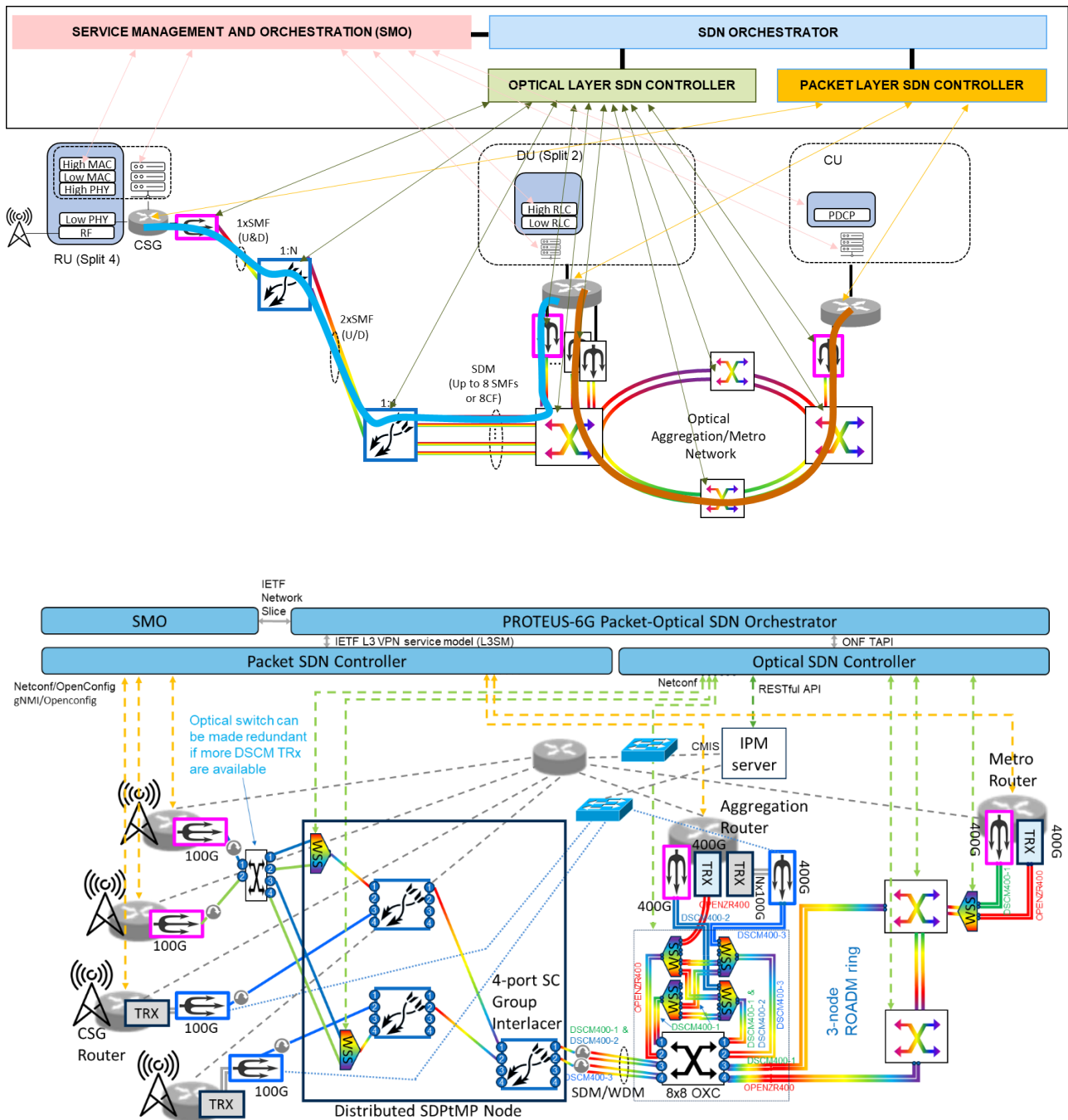


Figure 2. Experimental demonstration setup for Use Case 1. The top diagram provides a simplified representation of the FH and MH physical topology as described in Figure 1, depicting both the control plane and the data plane. The bottom diagram presents a high-level design of the laboratory implementation of the testbed.

2.3 Involved PROTEUS-6G subsystems and relevant interfaces

2.3.1 XR DSCM transceivers

The Open XR optical transceiver employs Digital Signal Processing (DSP) to divide the transmission and reception of a particular wavelength into multiple smaller-frequency channels known as Digital Sub-Carriers (DSCs). These DSCs can be individually modulated, controlled, and allocated to different endpoints, facilitating P2MP, direct low-speed to high-speed optical transceiver connectivity, as illustrated in Figure 3. It is possible to allocate one or more DSCs to a specific endpoint to meet the required bandwidth. The Open XR 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.

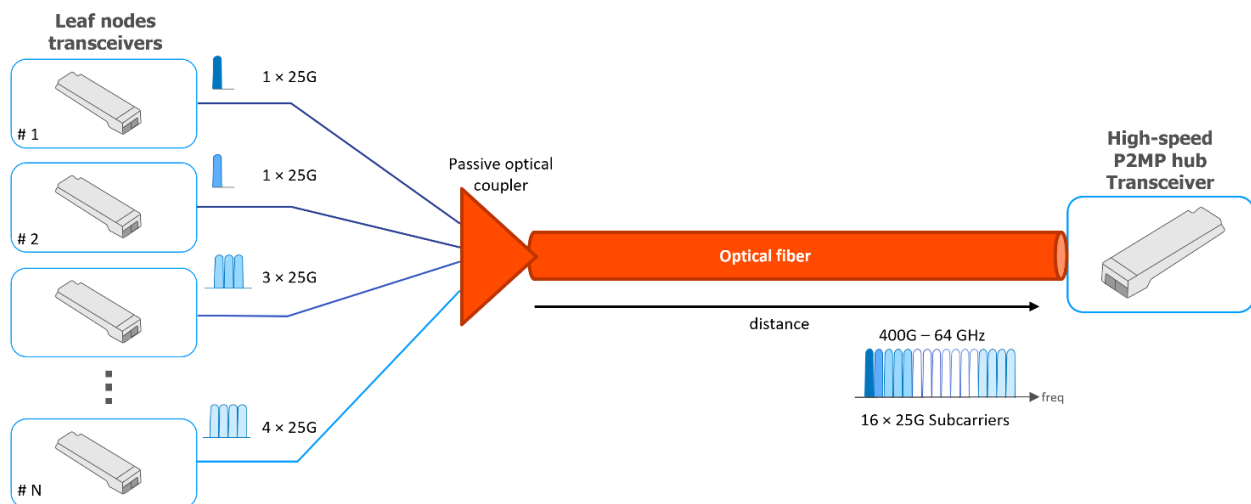


Figure 3. Point-to-multipoint transmission using DSCM-based coherent transceivers.

DSCM has been adopted in commercial transmission as reported in [1], [2]. Recently, it has been proposed as a solution to enable coherent P2MP transmission to enhance flexibility and simplify the design, for example, of metro-aggregation networks such as the ones reported in [3], [4]. For example, DSCs can enable optical aggregation thus reducing the number of Opto-Electronic-Opto (OEO) conversions.

The DSCM solution discussed and described in [3], [4] consists of a single optical interface capable of transmitting up to 16 Nyquist DSCs 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 [5], 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. The DSCs at the receiver side are digitally de-aggregated and each of them is processed in parallel with its own DSP lane. The schematic of the DSP chain of the DSCM-based transceiver is shown in Figure 4, and the details of the employed algorithms can be found in [6].

To increase the flexibility of the network, 100 Gb/s optical interfaces (i.e., using up to 4 DSCs) are installed in each leaf node. The individual DSCs – 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 DSCs. 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 P2MP solution enables a pay-as-you-grow model [3]. 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 [7].

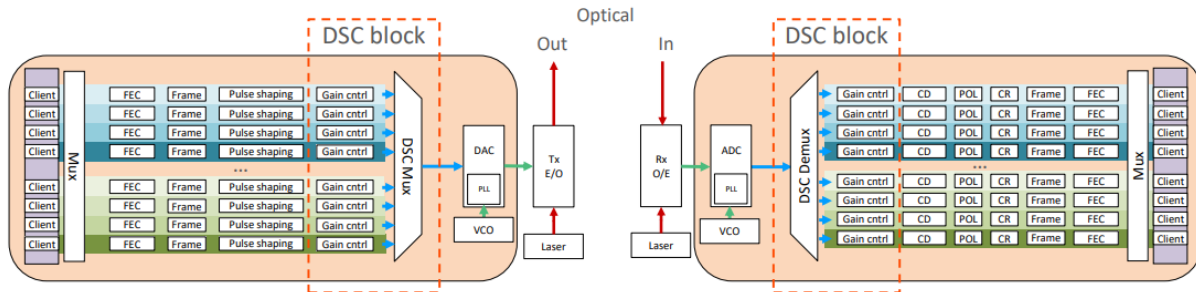


Figure 4. DSCM-based coherent transceiver digital signal processing schematic[6].

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 DSCs 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 [8]. Therefore, by allocating resources dynamically, i.e., optimizing the software-hardware relations, P2MP 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 [4], [9]; and finally, it enables inter-generational interoperability among transceivers.

The DSCM programmable pluggable modules in IP over DWDM (IPoDWDM) scenarios implement a dual management interface as described in [10]. The PROTEUS-6G Packet-Optical SDN Orchestrator can process user requests for P2P and P2MP services. The orchestrator exposes a ONF TAPI-based southbound interface (SBI) towards the Optical SDN Controller that delegates the configuration of the pluggable modules to a dedicated controller (the XR Intelligent Pluggable Manager or IPM) and takes care of the configuration of the optical line. Additionally, the PROTEUS-6G Packet-Optical SDN Orchestrator also exposes an IETF L3VPN Service Delivery interface towards the underlying IP SDN Controller responsible for configuring the packet layer. Table 1 provides a list of the physical-layer and control plane interfaces for the operation of the DSCM transceivers in Demo 1.

Table 1 DSCM transceiver subsystem interfaces

Interface			
Optical IN/OUT	SMF		
Optical input power (min, max)	Type	Min	Max
	400G, 16QAM	-12 dBm	0 dBm
	100G, 16QAM	-17 dBm	0 dBm
Optical output power	Typ: 0 dBm		



Pluggable form factor	QSFP-DD and CFP2
Frequency range	191.3 - 196.1 THz (C-band)
Physical Interface between host and module	Two Wire serial Interface (TWI)
Pluggable control interface with Host	CMIS with P2MP Extensions
Pluggable control interface from Host to controller	Netconf with Openconfig with P2MP extensions
IPM NBI	RESTful API



2.3.2 Four-Port Sub-Carrier Group Interlacer

One of the project's key innovations for increasing the capacity and flexibility of the 6G front-haul is the four-port SC group interlacer element, at the heart of the SDPtMP node bridging between the metro transport and the access segment. We will abbreviate its name here to 'interlacer', for simplicity. The interlacer is composed of a two-stage network of two-input / two-output interleavers, with two interleavers per stage arranged in a butterfly interconnection pattern. The interleavers are designed for square-like half-wave response operating over a 64 GHz free spectral range, having sharp pass-to-block transition bandwidths. Its periodic response periodically exchanges every 32 GHz band between its input and output ports. By cyclically shifting the interleavers of the second stage by $\frac{1}{4}$ cycle, we obtain the interlacer functionality. When the sharp interlacer is applied to an aligned XR DSCM optics signal (64 GHz wide having 16 subcarriers of 4 GHz width) at any of its input ports, the signal is distributed to the four output ports in SC groups of 3 contiguous subcarriers (being 12 GHz wide). When four different XR optics signals are presented at the same time at the four input ports, the SC groups are routed independently to the output ports without collision or blocking, implementing the interlacing functionality across the four XR-optics input signals.

The entire interlacer element is contained within a single programmable photonic integrated circuit (PIC), with the programming feature required to accurately set the phase elements of the interleavers for optimal operation. This means that while the functionality offered by the interlacer is of passive bandwidth routing, the interlacer itself needs to be powered and stabilized at its set position. An implementation of the interlacer with ring-assisted Mach-Zehnder interferometer (RAMZI) interleavers is depicted in Figure 5-A, having four input fibers and four output fibers. Alternative interleaver designs may be substituted, such as lattice filters, without impacting the interlacer functionality as long as the interleavers are sharp and can be set to be on grid or shifted by $\frac{1}{4}$ cycle. Since the interlacer is essentially a passive and lossless bandwidth routing element, it is also reciprocal (as can be seen in the implementation circuit cartoon, which is input/output symmetric) and therefore can operate with optical signals going in any single direction or bidirectionally without interference (up to the device's reflection and backscattering limits, which are expected to be negligible).

We examine the bandwidth routing feature of the interlacer when four different XR-optics signals are simultaneously present on the same optical carrier at its four input ports (Figure 5-B). The interleavers' sharp transitions are designed to fall within a single subcarrier's bandwidth, which means the SC must be forfeited as the data it contains will be filtered. Since each interleaver (or half-band filter) contributes two transitions within a 64 GHz FSR (from pass-to-block and from block-to-pass) and as we cascade two interleaver stages, in total we lose every 4th SC out of the XR optics' 16, leaving four SC groups containing three SC signals (occupying 12 GHz) after the interlacing function. As shown in Figure 5-B, the four input signals A-D are interlaced by the interleaver network, such that, at outputs 1-4, there is a single SC group of size three from each input. Figure 5-B further shows two adjacent WDM channels (depicted in green and blue) at a channel separation of 80 GHz. This spacing is designed to align the interlacer to the next WDM channel (i.e., it falls on a bandwidth grid defined by 16 GHz, or 64/4 GHz, slices). Hence, there is a 16 GHz guard-band between WDM channels for switching with wavelength-selective switches (WSS) in the metro ring using ROADMs equipment, which requires this size guard band for channel addressing given the WSS spectral resolution. The 80 GHz WDM channel grid together with the interlacer's 64 GHz FSR, suggests a 16 GHz shift for the association of input (A-D) to output (1-4) per SC group the WDM channel's center carrier wavelength. But since the wavelength/SC_group port routing is known a-priori, this is just a matter of bookkeeping at the control plane.

Next, we show two scenarios where we use the fact that the SDPtMP node is powered and managed to reprogram the interlacer and bypass one of the four constituent interleavers, whether in the first or second stage (Figure 5-C&D). We note that additional interleaver bypass options exist and we show these two by example. When the second stage interleaver is bypassed, then its input subcarriers are



not interleaved, leaving its two outputs with subcarrier groups originating from two distinct input ports. However, two SC groups from each input appear, doubling the capacity routed from said input ports to said output ports. Moreover, since one filtering operation has been scrapped, then the individual guard-band SC that would have been forfeited to make room for channel transitions can be employed again. This adds two SC, or additional capacity, that can be turned on (these individual SC are marked in bright yellow in the figure). When the first-stage interleaver is bypassed, then, as before, its input SC are not interleaved. The impact of bypassing the first-stage interleaver is now apparent in each of the four outputs, which have SC groups from only three inputs. Moreover, the two inputs that have not been interleaved are only divided into two sets of two SC groups which appear on the output ports, meaning that we can again turn on two additional SC per 16-SC DSCM channel from those two inputs that bypass the first-stage interleaver.

The choice of bypassing of internal interleavers of the interlacer is another degree of freedom available in the routing of SC groups of the XR optics input signals. Since the interleaver processes all wavelengths simultaneously, due to its circular mapping feature, then the decision impacts all WDM channels traversing through it.

The interleaver's four input fibers and four output fibers can support aggregate WDM transmission power levels up to 25 dBm each or 30 dBm total. The interlacer is supported by control electronics that manage the internal phase modulators of the photonic circuit, controlled by a PC running custom software to set the interlacer. See Table 2 for the interlacer interface specifications. We note that the interlacer PIC may have polarization dependency in its response due to waveguide birefringence. If the polarization dependence compromises the interlacer's functionality within the SDPtMP node, then a polarization-diverse implementation will be utilized. The polarization diverse implementation includes polarization splitters and combiners before and after the interlacer (on each of four ports), with two interlacer PICs disposed in between, one per polarization state. This polarization diversity solution should not add significant loss to the interlacer, and the SDPtMP node is oblivious to its presence.

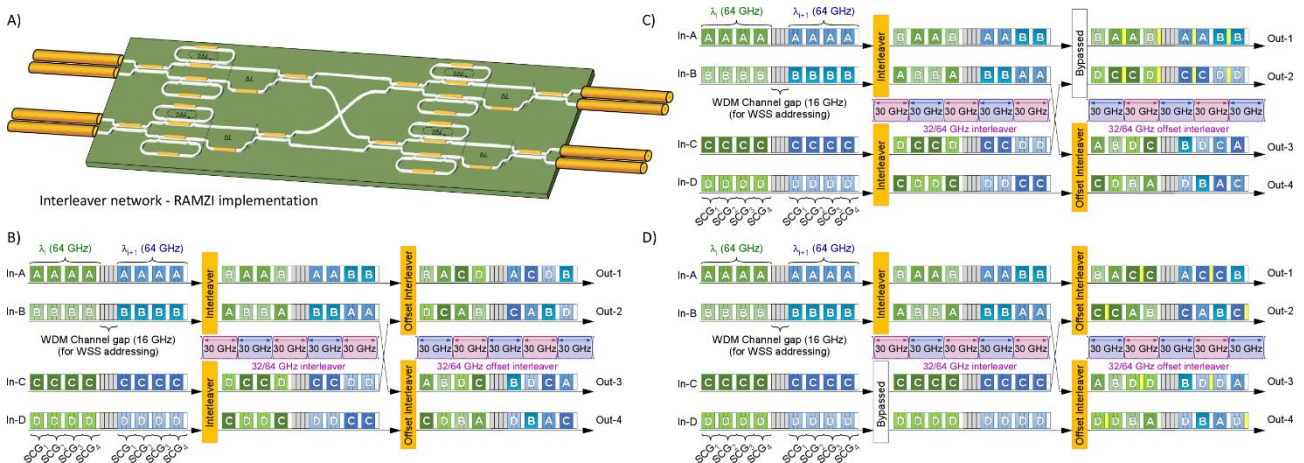


Figure 5. Interlacer element. A) PIC implementation with four input fibers and four output fibers. B) Subcarrier group routing between the input ports (A-D) and output ports (1-4), when all interleavers are operational. C) Subcarrier group routing when one second-stage interleaver is disabled and D) when one first-stage interleaver is disabled.

Table 2 PROTEUS-6G four-port SC group interlacer subsystem interfaces

Interface	Description
Optical IN/OUT	SMF (alternatively, PM fiber)
Optical input power	≤ 25 dBm



Wavelength range	1530 – 1565 nm (C-band)
Expected IL	2-3 dB
Projected PDL	<1 dB



2.3.3 Packet-IP SDN Controller

The Packet-IP SDN Controller in the PROTEUS-6G project is based on the ETSI TeraFlowSDN (TFS) controller's architecture [11]. TFS is an open-source micro-service based on a cloud-native SDN controller. TFS packet-IP SDN is designed to manage IP/MPLS services in a vendor-agnostic manner. It plays a crucial role in provisioning and managing various network services, including Layer-2 VPNs, Layer-3 VPNs, peering services, access control lists, and routing policies. Here are the key components and functionalities of the Packet-IP SDN Controller:

1. The BGP-LS (Border Gateway Protocol - Link State) module is essential for obtaining and maintaining topological information in an IP/MPLS network. This module retrieves topological data using the BGP-LS protocol, allowing administrators and external systems to access a real-time view of the network. Through this information, nodes and links can be identified, which is crucial for efficient traffic management and network planning.
2. The Services component is responsible for creating and configuring the necessary services in response to requests received. This process involves translating the requests into specific configurations for the network devices, ensuring that the required functionalities are correctly implemented.
3. The PCEP module facilitates communication with Path Computation Clients (PCCs), enabling various critical network management functions. Through PCEP, a list of active LSPs (Label Switched Paths) can be obtained, as well as sending and updating related policies. In addition, this component allows the creation, update and deletion of LSPs, as well as the establishment of bidirectional associations between them, which contributes to dynamic traffic management.
4. The Energy Collector plays an important role in periodically collecting data on the energy consumption of devices on the network. Although its specific operation is not detailed, this component is vital for monitoring energy usage and optimizing the overall energy performance of the system. Continuous data collection allows the identification of areas where energy efficiency can be improved.
5. The NBI (Northbound Interface) acts as a connection point between the management system and superior applications or platforms. This interface exports information about the physical inventory and network topology, allowing external systems to have a clear view of the current state of the infrastructure. In addition, it receives services and policies that must be configured on the devices, thus facilitating more centralized and efficient management.
6. The SBI (Southbound Interface) is responsible for interacting directly with network equipment, configuring them according to the services it receives. This component is crucial for implementing the necessary policies and configurations on the devices, ensuring that they are aligned with operational demands. Effective management through this interface allows precise control over how devices behave within the network, optimizing their overall performance.



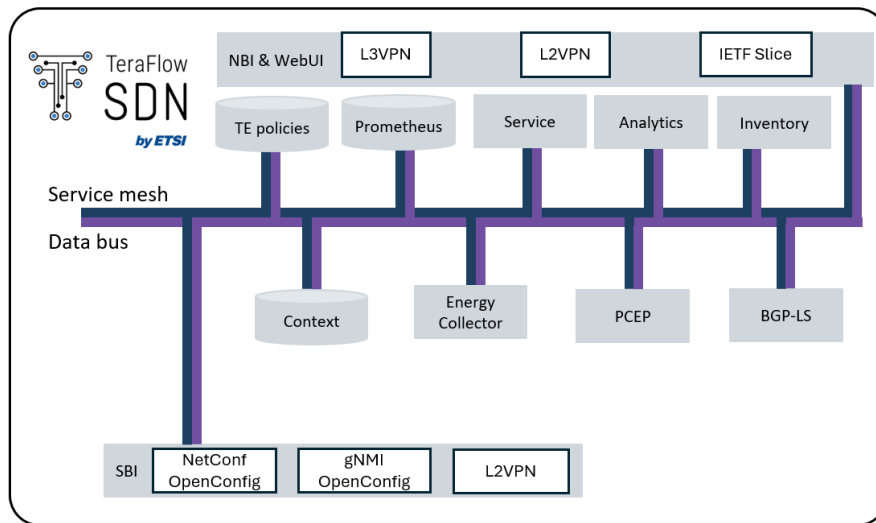


Figure 6. Schematic of Packet-IP SDN Controller subsystem provided for use case 1 demo.

Table 3 Packet-IP SDN Controller subsystem interfaces

Interface	Description
NBI	The NBI performs the import and export functionality: - Exports equipment physical inventory data following the IETF format, logical inventory following a controller proprietary format, L3 topology in IETF format [12], and equipment energy data with a Telefónica proprietary interface. - Imports several services to configure the equipment. These services include L2/L3SM, L2/L3NM [13][14][15], ACL (Access Control List) [16] with controller proprietary format, traffic engineering (TE) policies and interface creation/modification.
SBI to configuration	Netconf/OpenConfig
SBI to monitoring	gNMI/Openconfig

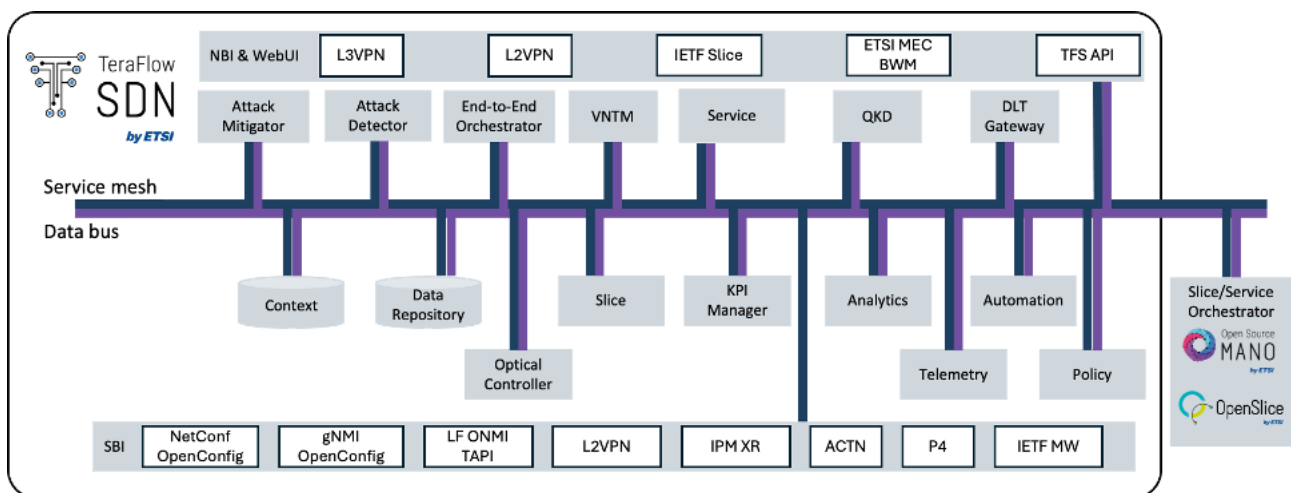


2.3.4 Optical SDN Controller

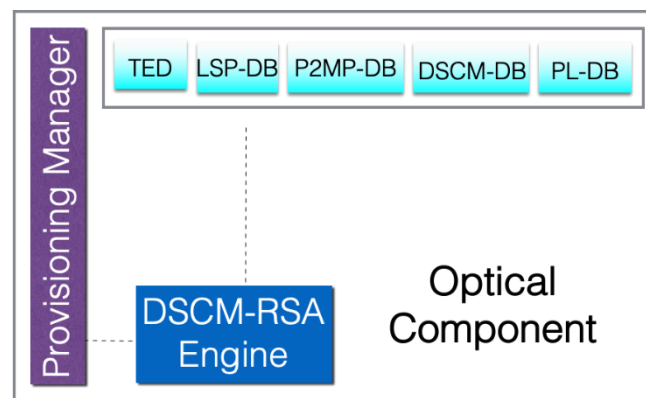
The Optical SDN controller is based on the ETSI TeraFlowSDN controller architecture (reported in Figure 7(a)) and it is built mainly on its Optical component, which can be retrieved from <https://labs.etsi.org/rep/tfs/controller/-/issues/106>. As described in D5.1, at the control plane level, the main innovation in PROTEUS-6G is the control of the DSCM transceivers and the P2MP operation they enable.

- First, the Optical component is designed to perform a resource allocation algorithm accounting for an additional level of granularity/multiplexing: i.e., DSCs.
- Then, a relevant property of DSCM is that it enables traffic aggregation at the optical layer, saving electronic layer-2/3 interfaces, in P2MP configuration. When P2MP connections are activated, a tree will be formed instead of a point-to-point path. As a result, the routing engine can provide a tree as an output.
- In addition, a proper control of the power levels among DSCs within an optical channel is fundamental for correct detection.

Such properties/features are mainly managed by the Optical module, whose architecture is shown in Figure 7(b).



(a)



(b)

Figure 7. (a) TeraFlow architecture. (b) Optical SDN Controller architecture.

The Provisioning Manager is interfaced with the TeraFlowSDN Service component, which feeds the Optical module with optical service requirements (e.g., source and destination pair to be connected).



Upon service request, the Provisioning Manager triggers the DSCM-RSA engine which runs resource allocation algorithm exploiting a series of DBs: the Traffic Engineering Database (TED), the Label Switched Path database (LSP-DB), and Physical Layer database (PL-DB), then the control of DSCM and P2MP imposes the adoption of additional databases, i.e. DSCM-DB holding information of digital sub-carriers, P2MP-DB holding information of established P2MP connections (e.g., tree route, central frequency, used digital sub-carriers). The communication between the modules in TeraFlowSDN takes place through an custom open gRPC-based protocol definition. The interfaces of the Optical SDN controller are summarized in the table below.

Table 4 Optical SDN Controller subsystem interfaces

Interface	Description
NBI (e.g., to SMO)	ONF TAPI [or REST; to be finally decided as part of MS6.2]
SBI to data plane	NETCONF (for direct device control) and REST-API (for IPM control) [assuming IPM to be included in the setup; to be finally decided as part of MS6.2]



2.3.5 SDN Orchestrator

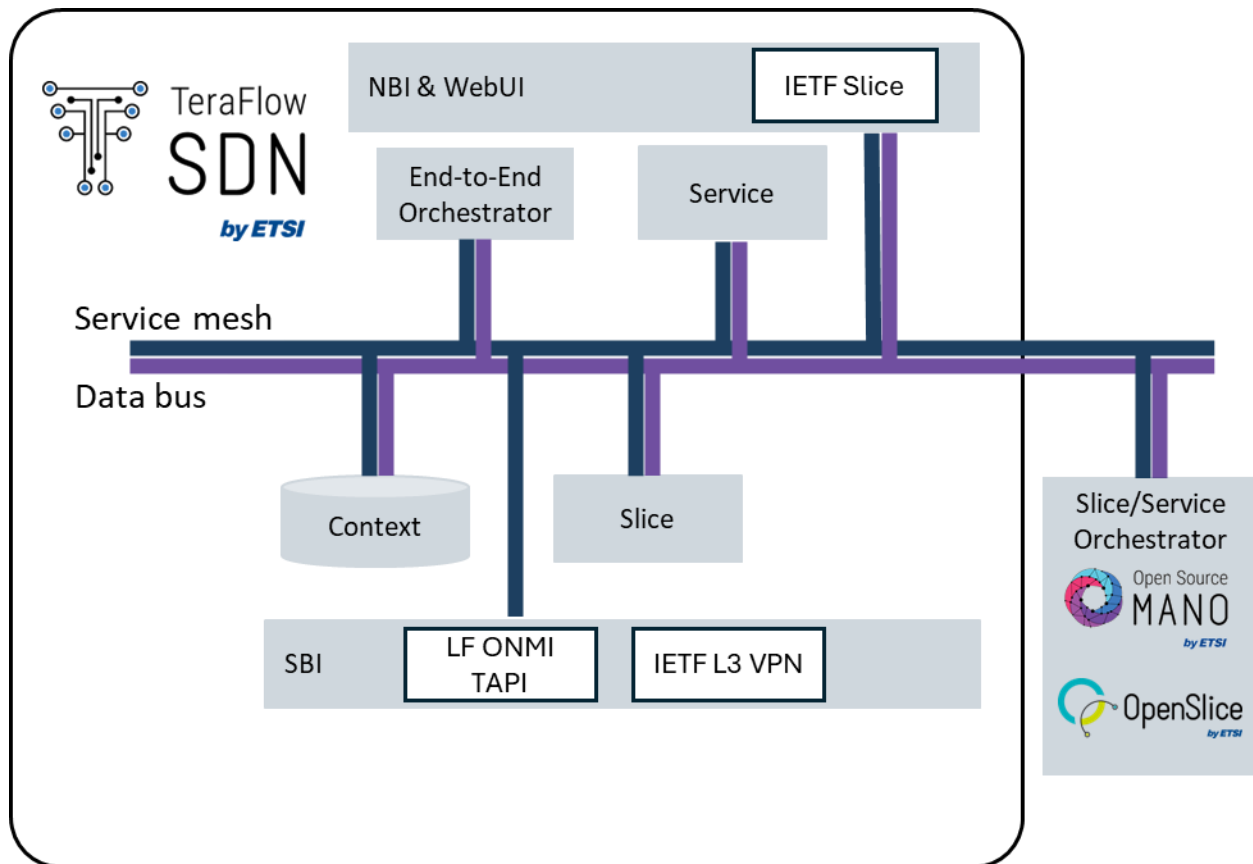


Figure 8. Packet-Optical Xhaul SDN Orchestrator architecture.

The SDN orchestrator for the project will be based on the ETSI TFS controller. The interfacing between the SMO and the SDN orchestrator will be supported by the IETF Network Topology [12] data model for network exposition, and the IETF Network Slice Service draft [17] data model for the service delivery requests. The SDN orchestrator will be in charge of orchestrating both optical and packet controllers. The communication between the SDN orchestrator and the packet SDN controller will be performed by means of the IETF L3VPN Service Delivery [18] data model and by Linux Foundation Open Network Modeling and Interfaces (ONMI) Transport API (TAPI) [19] for the optical SDN controller.

The relevant microservices composing the ETSI TeraFlowSDN controller are described below:

- **Context:** Interfaces with the underlying database to store and manage detailed information on network elements, including configurations, topologies, devices, links, connectivity services, transport network slices, policies, and their attributes.
- **SouthBound Interface (SBI):** Facilitates interactions with network elements via various drivers implemented as plugins, supporting multiple protocols, data models, and APIs, providing versatile connectivity to underlying devices. The component features a Driver API to facilitate integration of new drivers or the extension of existing ones.
- **Service:** Oversees the lifecycle of connectivity services, implementing a Service Handler API to allow network operators to incorporate support for new service types, protocols, and data models. This enables precise control and customization of network services.
- **Slice:** Implements support for managing the lifecycle of transport network slices using both physical and virtual network resources. This includes managing optical and packet domains provided by underlying controllers.



- **End-to-End Orchestrator:** Extends the controller for integration with multiple underlying packet/optical controllers, and orchestrating the operations between them.
- **NorthBound Interface (NBI):** Facilitates the SMO interaction with the orchestrator by means of several available plugins based on RESTConf interfaces.

The NBI where the SDN orchestrator receives the requests is based on the IETF Network Slice Service, which can be used by a provider to expose its Network Slice Services, and by a customer to request, delete, or modify specific transport network slices and adjust their specifications, such as requested bandwidth, maximum latency, and security settings.

The SBI for the packet SDN controller is based on the IETF L3VPN, which will be used for communication between the SDN orchestrator and the packet controller. It enables secure, isolated IP-based virtual networks over shared infrastructure. On the other hand, for the optical SDN controller the LF ONMI TAPI will be used, which provides an open interface for the control, management, and monitoring of optical transport networks (L1-OTN) and photonic media (L0-WDM).

Table 5 SDN Orchestrator subsystem interfaces

Interface	Description
NBI	IETF Network Slice service model
SBI to Packet Xhaul SDN controller	IETF L3 VPN service model (L3SM)
SBI to Optical Xhaul SDN controller	LF ONMI TAPI (Digital Services)



2.3.6 Service Management and Orchestration

The Service Management and Orchestrator (SMO) for the PROTEUS-6G project may leverage the ETSI OpenSlice Software Development Group, an open-source, microservice-based Operations Support System (OSS) designed to deliver Network as a Service (NaaS). OpenSlice aligns with specifications from leading standards organizations such as ETSI, TM Forum, and GSMA. It facilitates the management of 5G network services, spanning from user devices to the core network and cloud, while also orchestrating cloud resources across private and public infrastructures to support enterprise applications. Alternatively, the PROTEUS-6G project may adopt the SMO solution developed by the O-RAN Software Community, a collaboration between the O-RAN ALLIANCE and Linux Foundation, which aims to enable flexible and intelligent management of Radio Access Network (RAN) components through open-source software.

Within PROTEUS-6G project, and especially with regards to this test scenario, as shown in Figure 9, the open-source solution that will be finally adopted will be extended to interface with TFS controller to manage and orchestrate transport networks that would potentially consist of both packet and optical devices. Moreover, SMO will be responsible for the dynamic deployment of functional splits, based on the outcomes of *rApp* that will execute algorithms for RU/DU/CU partition selections, as the ones that will be developed within WP2. In addition, SMO will be responsible for translating service layer requests into the necessary configurations for the SDN orchestrator, mapping the required paths, and configuring network functions—specifically the functional split processes—at targeted points within the FH and MH resources through the Non-RT RAN intelligent controller (RIC).

With regards to the interfaces, the SMO will

- manage the SDN Orchestrator through the IETF Network Slice Service delivery model, and it will be in charge of orchestrating the end-to-end network,
- integrate a Non-RT RIC that will interface with a Near-RT RIC for supporting the dynamic RAN functional splits configurations across RU-DU-CU segments,
- interface with a telemetry system (potentially Prometheus), for retrieving resource metrics over the entire infrastructure.

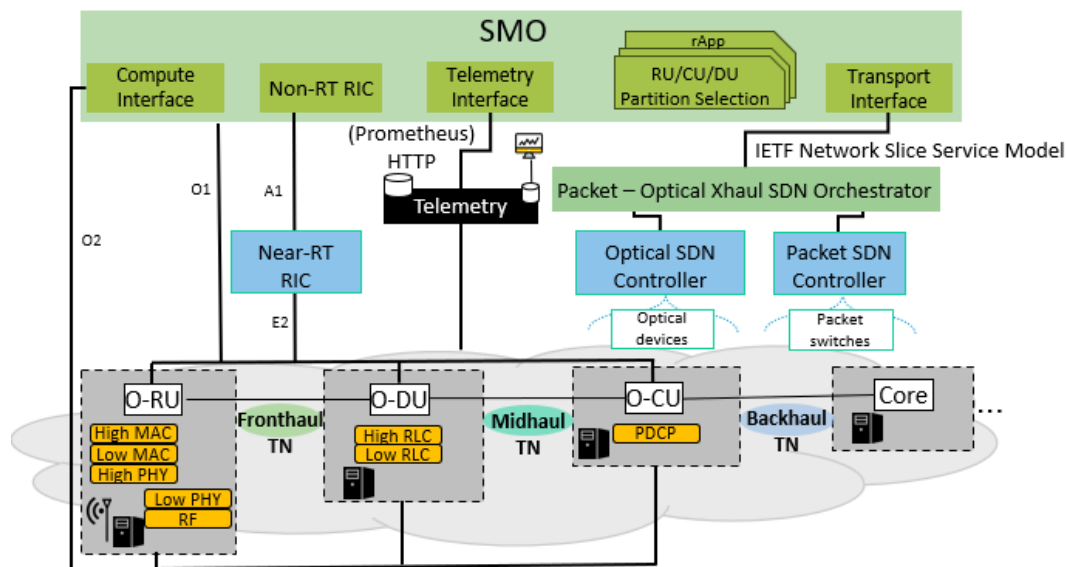


Figure 9. SMO architecture.



Table 6 SMO subsystem interfaces

Interface	Description
NBI	TM Forum REST APIs (OpenSlice) or O-RAN Software Community SMO APIs
SBI to Telemetry	Prometheus REST APIs
SBI to SDN Orchestrator	IETF Network Slice service model
SBI to Compute Resources	O2 Interface (O-RAN specifications)
SBI to O-RU, O-DU, O-CU	O1 Interface (O-RAN specifications)
SBI to Near-RT RIC	A1 Interface (O-RAN specifications)



2.4 Intermediate test scenarios

Given the complexity of the tests to be conducted in the Use Case 1 scenario, where several elements, including the PROTEUS-6G 4-port SC group interlacer, need to be configured and operated together, we have divided the demonstration activities into five tests, the fourth and fifth of which (Test #1.4 and #1.5, as described in sections 2.4.4 and 2.4.5, respectively) integrate the previous three tests and benefit from the knowledge accumulated from them. This strategy will allow us to start demonstrating each of the subsystems listed in section 2.3 individually as they become available. As an example, Test #1.1 (described in section 2.4.1) does not involve the use of a 4-port SC interlacer, which is a PROTEUS-6G development that will only be available towards the end of the project, as it needs to go through a complex fabrication and packaging process outlined in WP3, while the DSCM transceivers used in Test #1.1 are commercial devices by partner Infinera that can be utilised on their own to explore the integration of the control and data planes to enable dynamic bandwidth allocation. The testbed will therefore gradually evolve over time, starting with P2P and P2MP DSCM transceiver dynamic bandwidth allocation. It will then progress to a full FH network implementation, utilizing the SDPtMP node developed in PROTEUS-6G, and ultimately reach its final configuration, integrating both FH and MH networks.

Tests #1.1 to #1.4 are devoted to the dynamic mapping of DSCs between high-capacity DSCM transceivers deployed at the hub nodes and lower-capacity DSCM transceivers deployed at the leaf nodes, targeting the following scenarios:

- Test #1.1: A P2P scenario.
- Test #1.2: A simple P2MP scenario.
- Test #1.3: A P2MP FH scenario implemented with the PROTEUS-6G SDPtMP node.
- Test #1.4: A predominantly P2MP scenario encompassing a FH tree network topology implemented with the PROTEUS-6G SDPtMP node and a MH ring topology.

Test #1.5 deals with the SMO interfacing and a dynamic functional split deployment.

2.4.1 Test #1.1: Dynamic Mapping in a P2P Scenario

Purpose of Test

To enable the dynamic mapping of DSCs from a DSCM transceiver between a hub node and a leaf node in a P2P scenario.

Methodology

Figure 10 illustrates Test #1.1, which consists of both the data plane and control plane. Apart from the data plane setup, the figure includes a diagrammatical representation of the optical and packet controllers, which communicate with the SDN orchestrator (not shown). The interfaces with the optical controller are depicted with green lines, while the interfaces with the packet controller are depicted with yellow lines.

The methodology for the data plane is structured as follows, referring to Figure 10(a):

- In the downlink, data are allocated in 3×25 Gb/s (adjacent) DSCs from the 400G DSCM transceiver at the aggregation router (Cisco) to the 100G DSCM transceiver at the CSG (UfiSpace).
- In the uplink, data are allocated in 3×25 Gb/s DSCs from the 100G DSCM transceiver to the 400G transceiver.
- In both cases, the 4th adjacent DSC in each subcarrier group remains empty to meet the interlacer filtering specifications, which will be tested in upcoming tests.
- The central frequencies of the DSCs must align on both ends of the link to enable communication.



- In this test, communication occurs over a bidirectional duplex SMF link with different lengths compliant with the ITU-T G.652.D recommendation.

Figure 10(b) depicts a scenario with dynamic allocation of SCs to the CSG DSCM transceivers. We replace the 100G DSCM transceivers with 400G DSCM transceivers and demonstrate that they can be allocated 3×25 Gb/s DSCs and 6×25 Gb/s DSCs, according to varying environment conditions, e.g. new services/use cases, traffic changes, etc., at different times.

The methodology for the control plane is structured as follows:

- The optical controller is responsible for configuring the optical service, selecting appropriate optical parameters such as DSCs, frequency allocation, and output power. This configuration is managed through the IPM, which communicates with the DSCM transceivers. Therefore, an API is required to enable interfacing between the optical controller and the IPM.
- The packet controller is responsible for configuring the IP service, including creating the interface on the router port where the DSCM transceiver is plugged, assigning an IP address to the port, and configuring static routing when required.
- Control plane solutions leveraging augmented OpenConfig YANG data modeling are also taken into account demonstrating a vendor-neutral management of digital sub-carriers (thus, independent from the IPM management system).

Alternatively, the line configuration can be done through the packet SDN controller, as is being investigated in WP5.

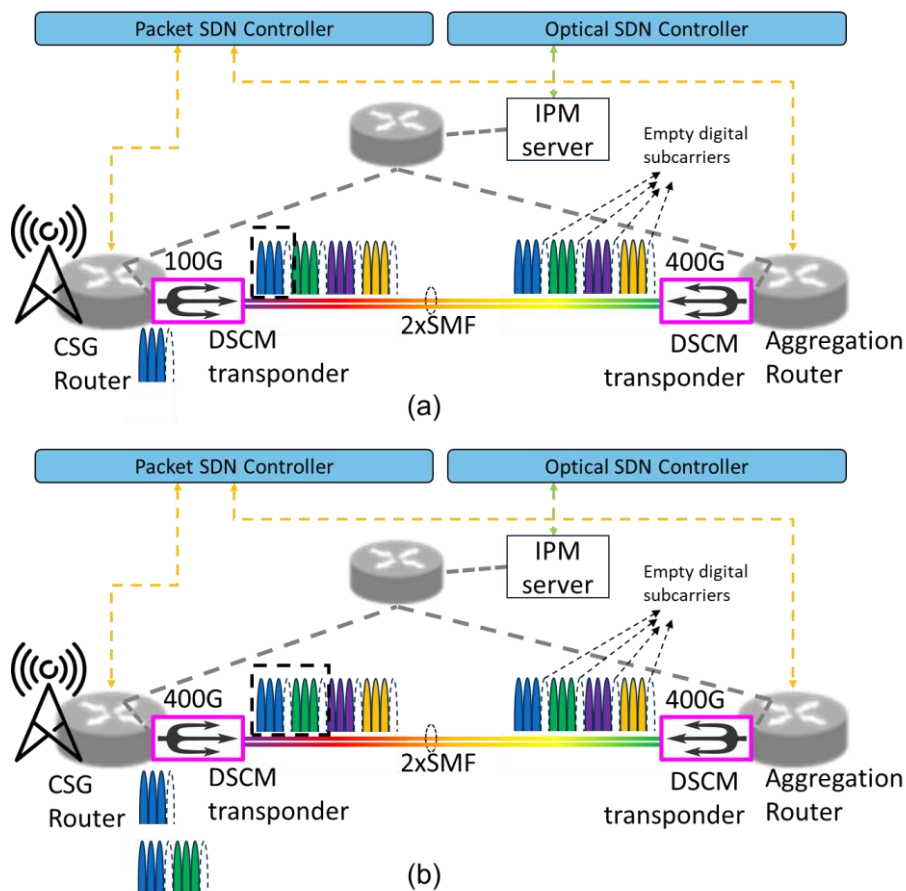


Figure 10. (a) Test #1.1: setup for mapping 3×25 Gb/s DSCs between 400G and 100G DSCM transceivers. (b) Test #1.1 for mapping 3×25 Gb/s or 6×25 Gb/s DSCs between 400G and 400G DSCM transceivers.



Two DSCM transceiver form factors will be considered in the testbed (QSFP-DD and CFP2). The tests will need to be conducted for both of them. In the case of the CFP2, this will be plugged into an ICE-X NDU from Infinera, which will be connected to the Cisco and UfiSpace routers through client 100GE interfaces, as depicted in Figure 2(bottom).

Expected results

The successful communication between the 100G/400G DSCM transceivers at the UfiSpace router and the 400G DSCM transceivers at the Cisco router will be verified by an up to 400GE traffic generator and tester (from Spirent and Ixia), which will be complemented with optical measurements on the data plane using e.g. an optical spectrum analyzer and/or optical power meters.

The quality criterion for successful service establishment will be measuring the Bit-Error Rate (BER) and Q-factors as a function of the received power.

The test will address all issues related to the configuration of the DSCM transceivers (via the IPM server, the packet SDN controller or the augmented OpenConfig-based control) and the dynamic bandwidth allocation before incorporating the interlacers into the setup. This will partially address KPIs O.6.2 ("Configuration and monitoring of at least four key PROTEUS-6G different types of devices (definition of protocols and required extensions)") as far as the DSCM transceiver configuration and monitoring is concerned.



2.4.2 Test #1.2: Dynamic Mapping in a Simple P2MP Scenario

Purpose of Test

To enable the dynamic mapping of DSCs from a hub node hosting a 400G DSCM transceiver to two leaves incorporating 100G/400G DSCM transceivers in a simple P2P scenario.

Methodology

Figure 11 illustrates Test #1.2, including both the data plane and control plane.

In the data plane, the integration of a 4-port SC group interlacer, which enables P2MP communication, is the key difference compared to Test #1.1.

- The interlacer receives the 16x25 Gb/s DSCs from a 400G DSCM transceiver plugged into a Cisco router (hub) through its first port on the metro network side. A group of four SCs (three of which carry data) will leave the interlacer through each of its four ports on the mobile access network side towards two 100G/400G DSCM transceivers plugged into a UfiSpace router (leaves).
- Dynamic bandwidth allocation is achieved through proper configuration of the interlacer, enabling the transmission of three or six data-carrying SCs to each of the two leaves.
- In this test, communication occurs over a bidirectional simplex SMF link with different lengths compliant with the ITU-T G.652.D recommendation. Optical circulators are used in front of each of the DSCM transceivers to enable BiDi transmission. Comparison with the case of transmission over a duplex fibre will be carried out.

Regarding the control plane, the Optical SDN controller is responsible for tree computation to connect the leaves to the hub. Augmented OpenConfig YANG data model for the control of DSCM and P2MP is also taken into account.

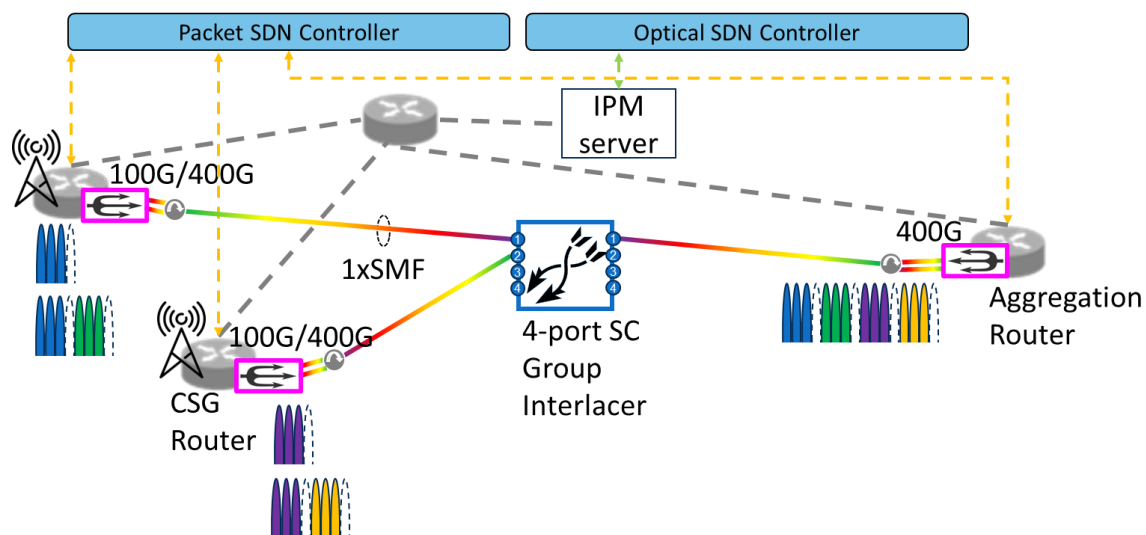


Figure 11. Test #1.2: setup for distributing DSCs from a 400G to two 100G/400G DSCM transceivers.

Expected results

The communication between the 100G/400G DSCM transceivers at the UfiSpace router and the 400G DSCM transceivers at the Cisco router will require the measurement of the optical spectrum of the signals before and after the interlacer to make sure that the SCs are filtered correctly. Once this step is completed, the successful communication between the hub and the two leaves will be verified by



an up to 400GE traffic generator and tester, which should be left running for a long period of time to verify the stability (as well as the calibration and fault-detection features) of the interlacer.

The quality criterion for successful service establishment will be measuring the BER and Q-factors as a function of the received power.

The test will address all issues related to the configuration of the DSCM transceivers (via the IPM server, the packet SDN controller or the augmented OpenConfig-based control) and the dynamic bandwidth allocation in a simple P2MP scenario. Compared with Test #1.1 it had the added complexity of the configuration of the 4-port SC group interlacer. This will partially address KPIs O.6.2 (“Configuration and monitoring of at least four key PROTEUS-6G different types of devices (definition of protocols and required extensions)”) as far as the DSCM transceiver configuration and monitoring is concerned.

2.4.3 Test #1.3: Dynamic Mapping in a P2MP FH Scenario Implemented with the PROTEUS-6G SDPtMP Node

Purpose of Test

To enable the dynamic mapping of DSCs from a hub node hosting 400G DSCM transceivers which, through SDM, can deliver groups of SCs to three or more leaves (theoretically up to 16) incorporating 100G/400G DSCM transceivers in a P2MP scenario implemented with a distributed SDPtMP node.

Methodology

Figure 12 illustrates Test #1.3, including both the data plane and control plane.

In the data plane, the integration of two stages of 4-port SC group interlacers, forming a distributed SDPtMP node, which implements the FH ODN and enables P2MP optical communications, is a first key difference compared to Test #1.2. Another difference is the utilization of SDM multiplexing to allow the transmission of up to four 400G channels with the same central frequency, by connecting them to different first-stage interlacer ports on the metro-network side (in Figure 12, only two SDM channels are used).

- The interlacer receives the 16x25 Gb/s DSCs from two 400G DSCM transceivers with the same central frequency plugged into a Cisco router (hub) through ports 1 and 2 on the metro network side of the first-stage interlacer. Groups of four SCs (three of which carry data) will leave the second-stage interlacers through each of their four ports on the mobile access network side towards three 100G/400G DSCM transceivers plugged into a UfiSpace router (leaves).
- Dynamic bandwidth allocation is achieved through proper configuration of the SDPtMP node, enabling the transmission of three or six data-carrying SCs to each of the leaves. Other configuration options will be explored in line with what was reported in Figure 5-C&D, bypassing a first-stage or second-stage interleaver.
- Proper control of the central frequency of each of the two 400G DSCM channels at the hub node needs to be ensured to avoid excessive filtering of certain SCs by the SDPtMP node.
- In this test, communication occurs over a bidirectional simplex SMF link with different lengths compliant with the ITU-T G.652.D recommendation. Optical circulators are used in front of each of the DSCM transceivers to enable BiDi transmission. Comparison with the case of transmission over a duplex fibre will be carried out if the number of interlacers provided for the demo allows it.

Regarding the control plane, the Optical SDN controller is responsible for tree computation to connect the leaves to the hub. Augmented OpenConfig YANG data model for the control of DSCM and P2MP is also taken into account.



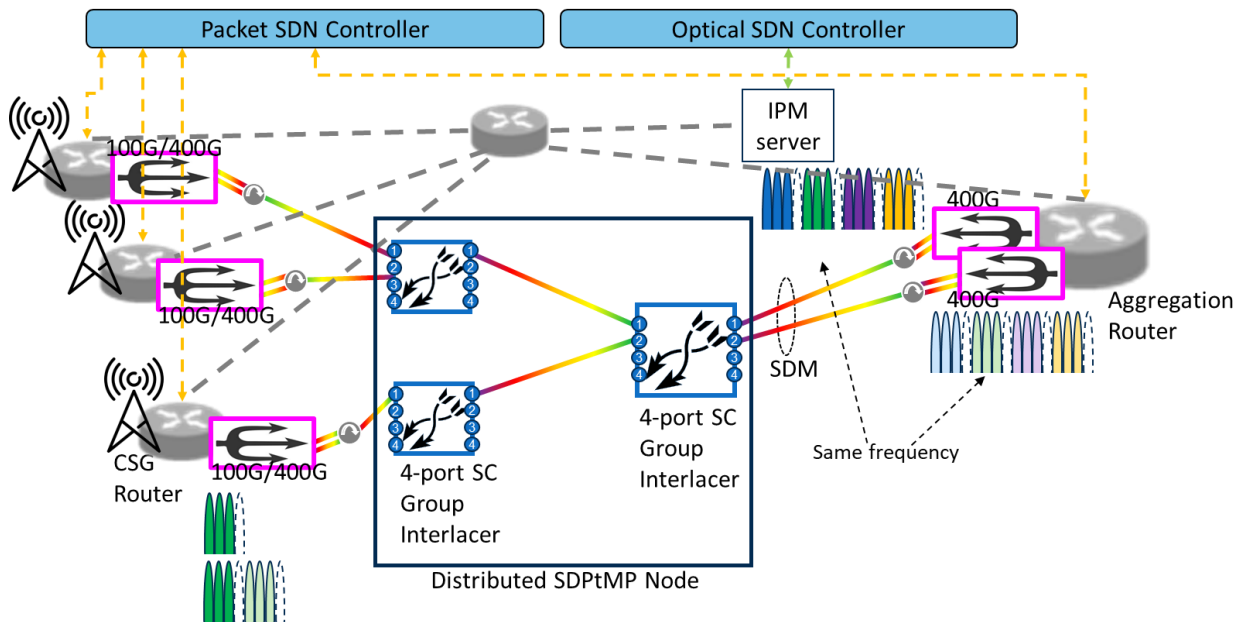


Figure 12. Test #1.3: setup for distributing DSCs from a 400G DSCM transceiver to three leaves with 100G/400G DSCM transceivers.

Expected results

The communication between the 100G/400G DSCM transceivers at the UfiSpace router and the 400G DSCM transceivers at the Cisco router requires measuring the optical spectrum of the signals before and after the distributed SDPtMP node, as well as between the two interlacer stages, to ensure proper filtering of the SCs. Once this step is completed, the successful communication between the hub and the two leaves will be verified by an up to 400GE traffic generator and tester, which should be left running for a long period of time to verify the stability (as well as the calibration and fault-detection features) of the interlacer.

The quality criterion for successful service establishment will be measuring the BER and Q-factors as a function of the received power.

The test will address all issues related to the configuration of the DSCM transceivers (via the IPM server, the packet SDN controller or the augmented OpenConfig-based control) and the dynamic bandwidth allocation in a P2MP scenario with three or more leaves. Compared to Test #1.2, it introduces the added complexity of configuring the distributed SDPtMP node, which incorporates two stages of 4-port SC group interlacers for SC filtering. This will partially address KPIs O.6.2 ("Configuration and monitoring of at least four key PROTEUS-6G different types of devices (definition of protocols and required extensions)") as far as the DSCM transceiver configuration and monitoring is concerned.

2.4.4 Test #1.4: Dynamic Mapping in a Predominantly P2MP Scenario Encompassing a FH Tree Network Topology Implemented with the PROTEUS-6G SDPtMP Node and a MH Ring Topology

Purpose of Test

To enable the dynamic mapping of digital subcarriers from one or more hub nodes (aggregation and/or metro routers) hosting 400G DSCM transceivers which, through SDM and/or WDM, can deliver groups of subcarriers to at least four leaves (theoretically up to 16 without resorting to DWDM demultiplexing in WSSes) incorporating 100G/400G DSCM transceivers in a P2P/P2MP scenario comprising a fronthaul tree network topology implemented with a distributed SDPtMP node and a MH three-node ring topology composed of colourless-directionless ROADMs, where optical communication over the MH network are predominantly carried out over P2P connections.



Methodology

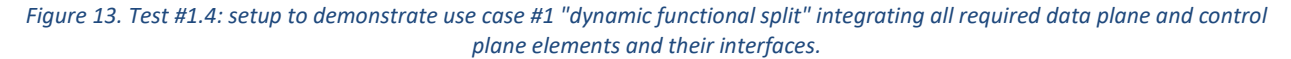
Figure 13 illustrates Test #1.4, including both the data plane and control plane.

In the data plane, there are two main differences with respect to Test #1.3. The first one is the implementation of a metro ring consisting of three colourless-directionless ROADM nodes operating in the C-band, which is connected to the tree-network topology described in Test #1.3. With this addition, we can demonstrate P2P and, fundamentally, P2MP optical communications over a FH and MH network where RU, DU and CU functions can be dynamically deployed. It also enables the placement of hub nodes for the tree topology at different nodes of the metro network, allowing for the most convenient distribution of resources across the transport network. The second difference is the incorporation of DWDM multiplexing into the FH network through the deployment of WSSes at the second stage of the SDPtMP node. This will enable an increase in the number of base stations that can be reached to over 16. The methodology followed to conduct this test is outlined in the following points:

- At least three 400G DSCM channels are transmitted from the aggregation and/or metro routers towards the FH network leaves, which in this scenario amount to at least four. Two of these channels are spectrally multiplexed with a guardband between them of 16 GHz and they are in turn spatially multiplexed with the third 400G channel through the first stage of the SDPtMP node. Groups of four SCs (three of which carry data) leave the second-stage interlacers through each of their four ports on the mobile access network side towards at least four 100G DSCM transceivers plugged into a UfiSpace router (leaves). In some cases, these ports are connected to a WSS, which separates the SCs from different spectrally multiplexed channels and directs them to the intended base station. An optical switch (that is not part of the FH network implementation) might be used in the testbed between the SDPtMP node and the leaves to allow for the (sequential) detection of more groups of SCs than the number of DSCM transceivers would allow. This optical switch will be manually controlled.
- Although in Figure 13, all leaves are implemented with 100G DSCM transceivers (only capable of detecting up to four SCs), tests with 400G DSCM transceivers at the leaves will also be conducted to prove dynamic bandwidth allocation. This will be done by properly configuring the SDPtMP node to allow receiving up to two groups of SCs at some of the access metro side ports of the SDPtMP node. The configuration of the SDPtMP node is not meant to be done by the optical SDN controller as it is not a feature that could be changed during the operation of the network. Different scenarios will be selected, and the appropriate SDPtMP node configuration will be performed at the beginning of each of them. Dynamic management of resources will be carried out as specified in WP5.
- Proper control of the central frequency of each of the 400G DSCM channels (whether they are spectrally and spatially multiplexed) at the hub nodes needs to be ensured to avoid excessive filtering of certain subcarriers by the SDPtMP node. Additionally, the optical controller needs to configure the WSSes integrated into the second stage of the SDPtMP node.
- In this test, communication occurs over a bidirectional simplex SMF link with different lengths compliant with the ITU-T G.652.D recommendation. Optical circulators are used in front of each of the DSCM transceivers to enable BiDi transmission. Comparison with the case of transmission over a duplex fibre will be carried out if the number of interlacers provided for the demo allows it.

The Optical SDN controller is also responsible for tree computation to connect the leaves to the hub. Augmented OpenConfig YANG data model for the control of DSCM and P2MP is also taken into account.





In this final test, communication between the 100G/400G DSCM transceivers at the Ufispac router and the Cisco router is established through all the subsystems described in section 2.3 to fully address Use Case 1 "Dynamic FS." This includes the DSCM transceivers (showcasing their most advanced functionality in this test), the 4-port SC group interlacers (as demonstrated in Test #1.3), to which we incorporated in Test #1.4 WSSs to the second stage of the distributed SDPtMP node for the fronthaul network to handle DWDM-multiplexed 400G DSCM channels, and the SDN controllers, orchestrator and SMO. In this test, we also demonstrate the end-to-end operation of the FH and MH networks, where P2P and P2MP optical communications coexist. To demonstrate signal transmission from the hubs to the leaves (across the SDM/WDM node at the edge of the metro network and the tree topology or also across the metro ring), optical spectrum measurements are required before and after all NEs involved. Once this step is completed, successful communication between the hubs and the four leaves will be verified using an up to 400GE traffic generator and tester. The system should be left running for an extended period to assess the stability of the communication between the end-to-end DSCM transceivers, paying special attention to the SDPtMP node performance when channels from two different hubs are multiplexed.

The test will address all issues related to the configuration of the DSCM transceivers (via the IPM server or the packet SDN controller), the control of the WSSes at the second stage of the SDPtMP node, and the establishment of FH and MH connections with dynamic bandwidth allocation in a P2P and P2MP scenario with at least four leaves. This will address, fully or partially, the following KPIs related to WP5 activities:

- 

- 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).

Likewise, it will address the integration of the SDPtMP node, DSCM transceivers and SDN orchestration in the Use Case 1 scenario, partially fulfilling KPI O.7.3 (Integration of SDPtMP, plasmonic lite-coherent transceivers and SDN orchestration in the demonstration).

2.4.5 Test #1.5: SMO Interfacing and Dynamic Functional Split Deployment

Purpose of Test

The objective of this intermediate test is to evaluate the SMO's functionality and its ability to interface effectively with the other management and orchestration components and subcomponents to enable the dynamic deployment and management of functional splits. This test will specifically focus on verifying the SMO's ability to interface with the needed components, i.e. the SDN Controller (TFS), the Non-RT RIC and the Near-RT RIC (through the Non-RT RIC). It aims to ensure proper orchestration of transport network, including packet and optical devices, and the accurate translation of service layer requests into network configurations. The test will also assess SMO's integration with telemetry systems for resource monitoring and its role in dynamic FS deployment across RU/DU/CU segments.

Methodology

According to Figure 14, this demonstration test setup will feature the interfacing between the management and orchestration software components that will be involved in the dynamic FS use case.

This test can be divided into three distinct steps:

- Setup: Deploy the SMO that will interface with the TFS controller and with the telemetry system, and will integrate a Non-RT RIC for rApp algorithms.
- Execution: Simulate service requests to test SMO's ability to translate them into SDN orchestrator and from there to network paths configurations. Use rApps (developed within WP2) to dynamically determine RU/DU/CU partitioning and configuration, as well as monitor metrics via Prometheus.
- Metrics Collection: Measure SMO interface latency with TFS, with Near-RT RIC and with telemetry system, deployment success rates of functional splits, and resource utilization using the telemetry data retrieving by the infrastructure.

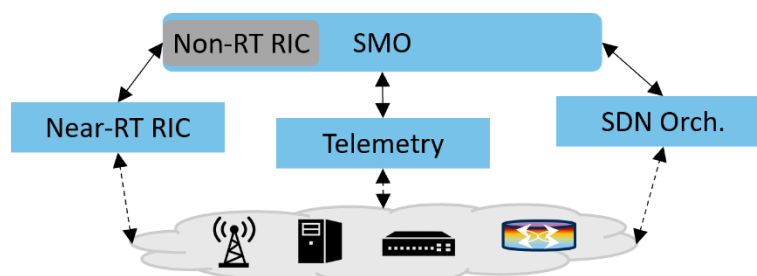


Figure 14. Test #1.5: Management and Orchestration Components Interfaces.

Expected results

The SMO should establish seamless communication with the SDN orchestrator, Non-RT RIC, and telemetry systems, meeting performance benchmarks for latency and reliability. It should dynamically and accurately deploy functional splits based on rApp algorithms, ensuring optimal RU/DU/CU partitioning and translating service requests into SDN orchestrator requests. The objective KPI O.6.4: "Dynamic management of packet-optical FH/MH connections integrating the packet and optical Software-Defined Networking (SDN) controllers (provisioning time <20 s)", described the



requirement regarding the provision time. Moreover, the testing of dynamic management of 6G services through the Non-RT RIC, that will provide adaptations using telemetry data while maintaining stable operations across FH and MH infrastructure, will fulfill the objective 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 FS (provisioning time <1 minute)”. Finally, the system should demonstrate scalability and handle varying network loads efficiently without performance degradation.



3. Test scenarios for Use Case 2: Cell-Free Massive MIMO

As a second use case, PROTEUS-6G supports high capacities of a cell-free massive MIMO scenario. In this scenario, advanced MIMO processing is performed at centralized locations. This scenario follows FS option 8 for the fronthaul interface, i.e. RU only host the Radio Frequency (RF) functions, while access COs comprise Central Processing Units (CPUs) hosting the full set of radio functions covering from layer 1 up to layer 3. For more details on the x-haul architecture see section 2.3.1 of PROTEUS-6G deliverable D2.1.

The “cell-free massive MIMO” scenario poses two main transport connectivity needs, namely 1) FH connections between the cell sites and the access COs in a tree topology, 2) potential intra-CPU communication between access COs in a ring topology (e.g. for coordination and/or joint processing). The peak transport capacity requirements sum up to 1.25-6.29 Tb/s for each downlink/uplink FH connection. In order to provide such high-bandwidth connectivity, PROTEUS-6G is developing in WP4 novel transceiver technology based on high-speed electro-optical frontends which support dual-polarization pulse-amplitude modulation (DP-PAM) using a so-called “lite-coherent” approach for reception. The test scenarios for use case 2 therefore aim at integrating such DP-PAM frontends within the PROTEUS-6G network control framework and demonstrating high-bandwidth connectivity in a realistic system scenario.

3.1 Architectural view of use case 2

The architectural view of use case 2 within the PROTEUS-6G overall network architecture is shown in Figure 15. The “lite-coherent” DP-PAM frontends (shown in red, developed in WP4) are located within optical transponders that are placed at all RU's (antenna sites, left side of schematic) as well as at all involved access CO's. The lite-coherent frontends comprise optical dispersion compensation which supports a reach of up to a maximum of 20 km which suffices for the segment front-haul targeted here. The potential sharing of central processing functionalities between CPUs across an optional metro network would require conventional (coherent) transceivers which are out of the scope of PROTEUS-6G. According to the proposed PROTEUS-6G x-haul architecture, the optical FH connectivity between the CO and the RU is established via SDPtMP distribution nodes (shown in blue, developed in WP3) which can have either single-mode fiber (SMF) interfaces or spatial-division multiplexing (SDM) fiber interfaces, depending on their position within the tree topology. Also shown in Figure 15 on top is the SDN control plane (shown in grey, developed in WP5), which is responsible for orchestrating and controlling the network services and components.

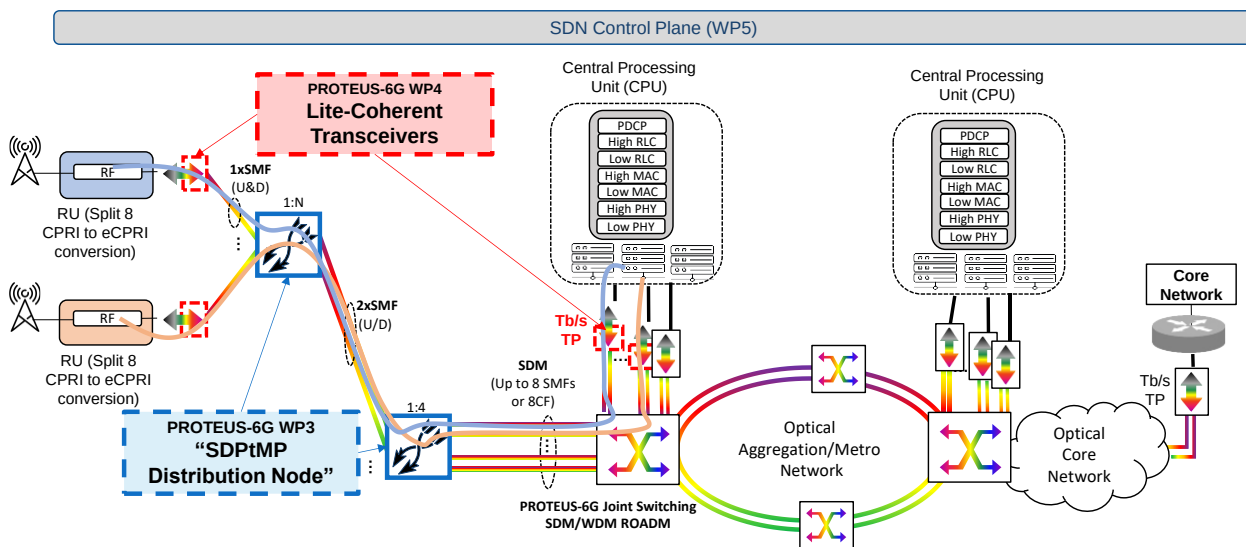


Figure 15. Architectural view of Use Case 2 within PROTEUS-6G overall architecture.

3.2 Derived experimental demonstration setup

Since the lite-coherent front-ends developed in WP4 are not fully-integrated transponders with real-time client interfaces, the demonstration scenario for use case 2 is focusing on the physical layer transmission and SDN control of the involved optical subsystems. Thus, Figure 16 shows a simplified depiction of the network architecture for use case 2 highlighting the optical connection on the physical layer from one lite-coherent frontend at a CO (shown on the right side) to another lite-coherent frontend antenna site (shown on the left side). Moreover, the figure also indicates the necessity of an optical SDN controller, regardless of the fact that IP/packet SDN control is out of the scope of the use case 2 demonstration.

From such simplified network architecture view, the concrete experimental demonstration setup shown in the lower part of Figure 16 was derived. Currently, a unidirectional transmission (from right to left) from the transmit-side of the DP-PAM front-end to the receive-side of (the same) DP-PAM front-end is envisaged. The DP-PAM front-ends will be equipped with a NETCONF agent to provide control and monitoring functionality towards the optical SDN controller. Transmission is realized in its maximum implementation (from right to left) from the PROTEUS-6G DP-PAM front-end transmitter (TX), via an SDM/WDM ROADM, an SDM link, an SDPtMP distribution node, an SMF link, and finally into the PROTEUS-6G All-Optical Signal Processor (AOSP) in front of the PROTEUS-6G DP-PAM frontend Receiver (RX).

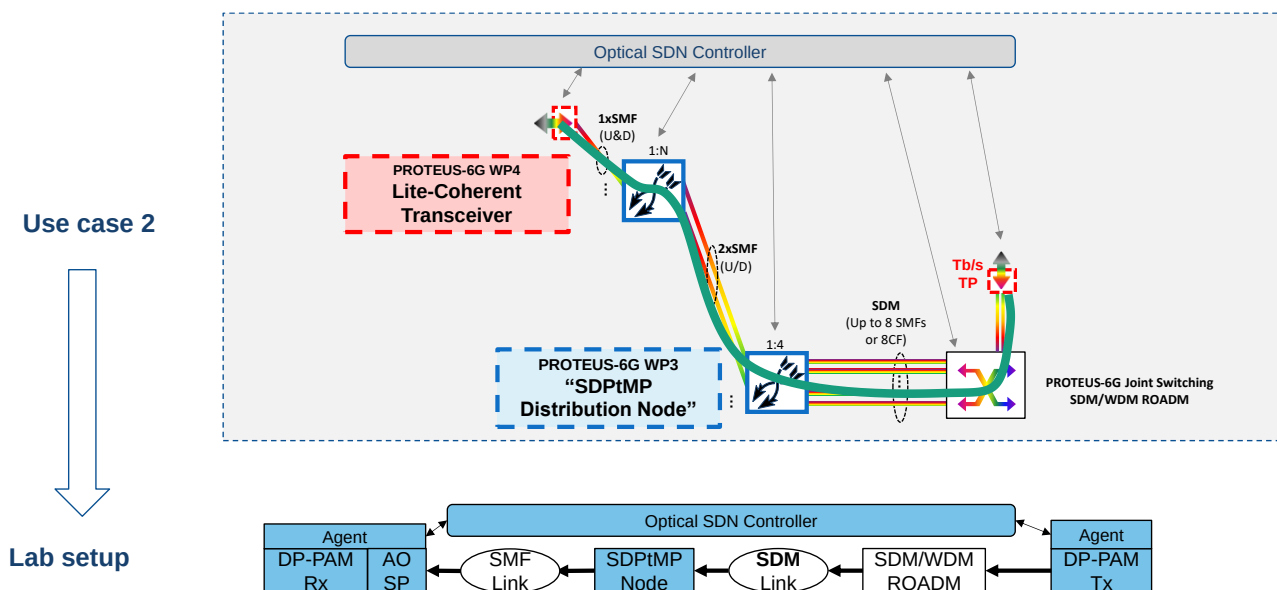


Figure 16: Experimental demonstration lab setup derived from Use Case 2 "Massive MIMO".

3.3 Involved PROTEUS-6G subsystems and relevant interfaces

3.3.1 Dual-Polarization PAM Frontend with All-Optical Signal Processor

The transceiver subsystem will be specified, developed, and validated within WP4 and supplied to WP6 for integral testing in the use-case 2 scenario. A high-level abstraction is provided in Figure 17. The interfaces to the SDN control will be defined more completely in MS6.2 and within WP5 (specifically in D5.1, section 4.6), the optical interfaces are partially specified in WP4 and partially here, as part of WP6.

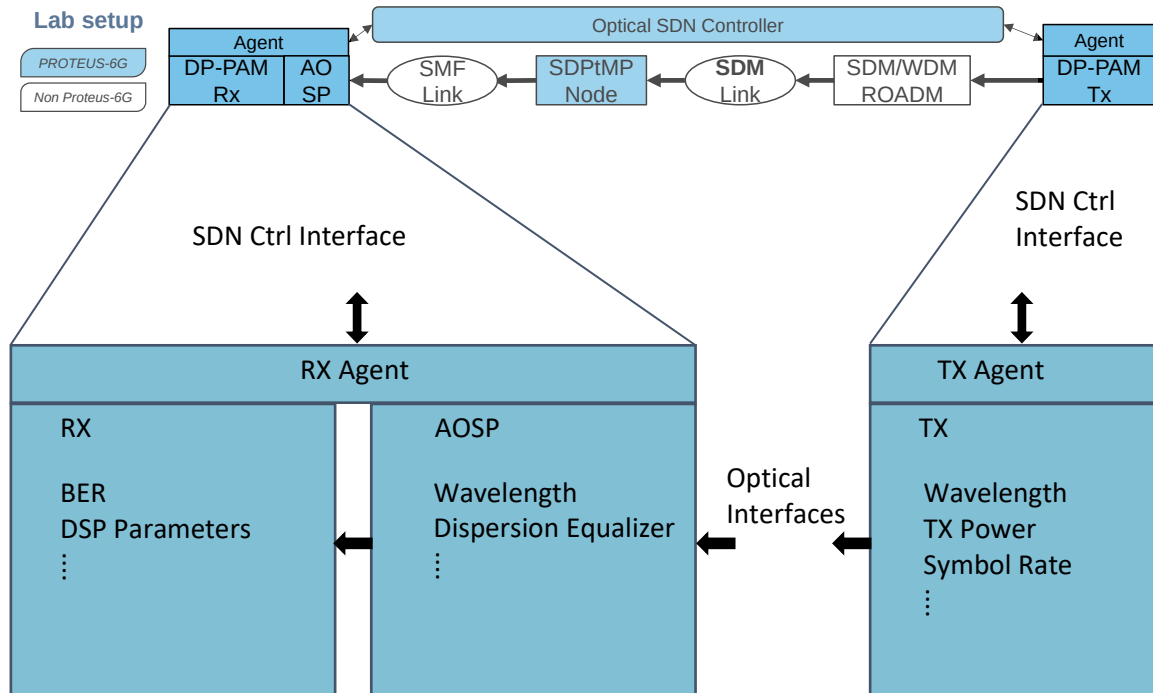


Figure 17. High-level schematic of TRX/AOSP Subsystem provided for use case 2 demo. Some NETCONF-parameters are highlighted, but will not be defined at this stage.

The transmitter is described in more detail in Figure 18, the receiver in Figure 19. The arrows indicate interfaces between subcomponents that need specification. The dashed boxes indicate the boundaries of WP4, whereby the components contained within the boxes are specified as part of WP4 and not further detailed here. Note, that the control PCs in both setups are interfacing across WP5 (SDN), WP4 (TRX Hardware), and WP6 (integral testing), and need careful considerations. Hence to avoid misunderstandings and mismatching components as much as possible they are being developed by a single partner (HHI).



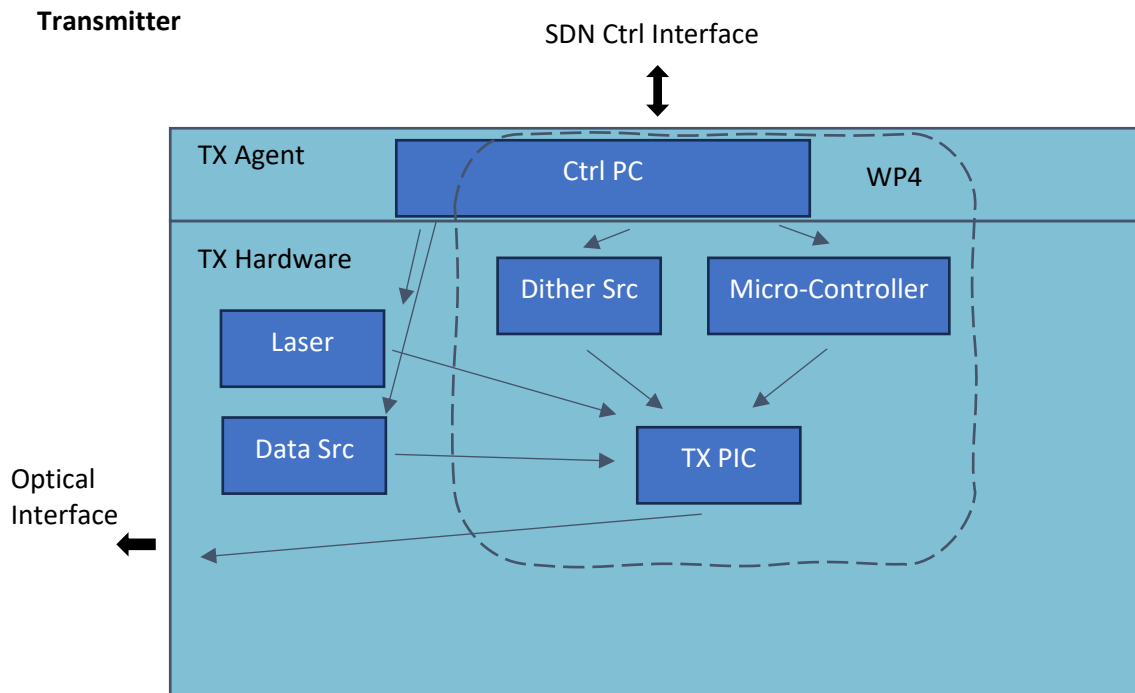


Figure 18. Low-level schematic of TX Subsystem, part of WP4, but integrated into the WP6 demonstration setup.

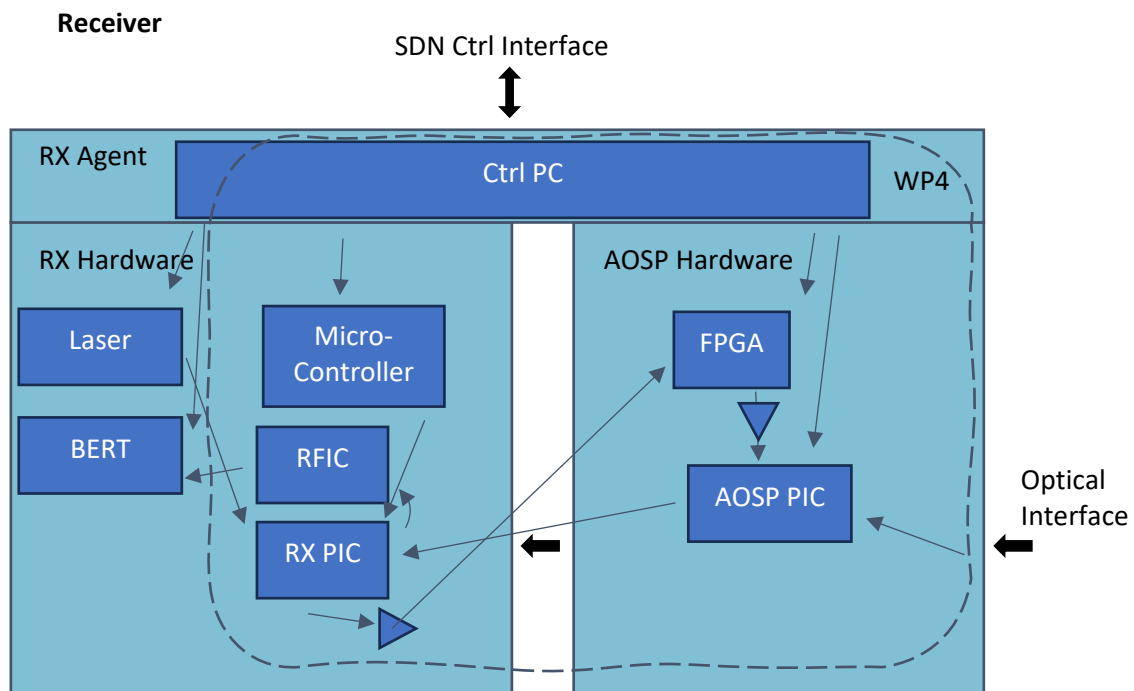


Figure 19. Low-level schematic of RX Subsystem, part of WP4, but integrated into the WP6 demonstration setup.

Interfaces between components of the transceiver subsystem and the WP6 integral testing setup are listed in Table 7. The documentation here is preliminary and deliberately on a high level. More refined documentation will follow e.g. with MS4.1.



Table 7 DP-PAM TRX/AOSP Subsystem interfaces that are relevant for the WP6 setup

Type	Subsystem	Interface	Description
Optical	TX	CW Laser output	Fiber: PMF-Panda, FC-APC POL controller to SMF E2000/APC Connector Power: < 16 dBm
	TX	TX PIC optical output	Fiber: SMF E2000/APC Connector Power < -2 dBm
	RX	AOSP optical input	Fiber: PMF Connector: E2000/APC for main signal path FC/APC otherwise Power: < 25 dBm
	RX	AOSP optical output	Fiber: PMF Connector: E2000/APC for main signal path FC/APC otherwise Power: < 25 dBm
	RX	RX PIC optical input	Fiber: SMF (POL controller needed) Connector: E2000/APC Connector Power: < 20 dBm
Control	TX	Control GUI	Protocol: SCPI python interface • Write: ○ DAC drive voltage ○ TEC voltage/current • Read: ○ Communication (Serial Port) ○ PIC temperature ○ TEC voltage/current
	TX	NETCONF agent	Defined in D5.1
	RX	NETCONF agent	Defined in D5.1
	RX	Control GUI	Protocol: SCPI python interface Parameters: • Write: ○ Bias per PD ○ Gate voltage per PD ○ HV-DAC drive voltage (AOSP) ○ TEC voltage/current • Read: ○ Current per PD ○ Communication (Serial Port) ○ AOSP PIC temperature ○ TEC voltage/current



	RX	FPGA control software	Connector: USB Protocol: t.b.d
RF	TX	Data source output	Connector: 1 mm Coaxial female power level: 1 V _{pp,se} (+4 dBm) 2 Channels, 200 GBd PAM4
	RX	RFIC output	Connector: 1 mm Coaxial female power level: -16 dBm 2(4) Channels, 200 GBd PAM4 (received w/COH RX)



3.3.2 SDPtMP Node

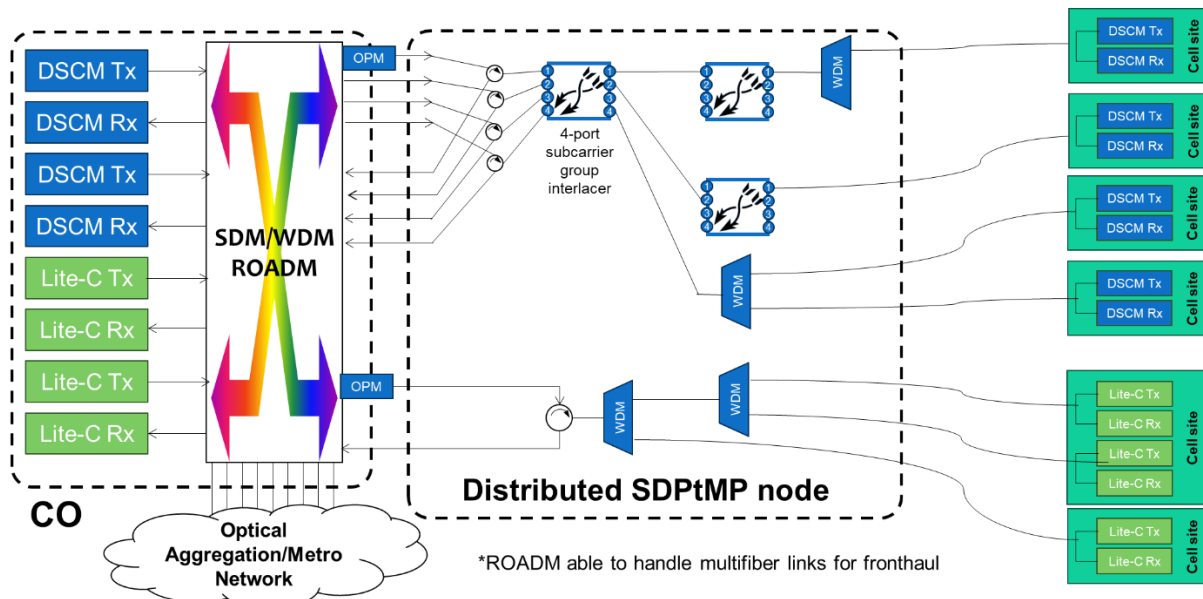


Figure 20. Scheme of SDPtMP subsystem together with relevant network elements.

Figure 20 shows a generic scheme for the SDPtMP node, together with the surrounding network elements. This reflects the actual status of a work in progress inside WP2, that will be reported in D2.2 deliverable on month 18. Therefore, this scheme is subject to modifications.

From left to right, first we have at the CO a pool of different transceivers (Tx/Rx pairs) that would be the end interfaces for the X-haul connectivity. Even though demo-2 is focused on the lite-coherent (Lite-C) transceivers, we include also DSCM for the sake of completeness. All these transceivers are directly connected to an SDM/WDM ROADM meaning that traffic can be either directed to other parts of the optical aggregation/metro network or to the precise segment where the SDPtMP node is located to serve a set of cell sites.

Regarding the SDPtMP node itself, fibers coming from the CO are expected to carry two different kinds of traffic depending on the transceivers that deliver connectivity. All transceivers work in C-band and feature dual fiber duplex, as could be expected to interface to an SDM/WDM ROADM. Therefore, there is the need to combine downstream and upstream in a single fiber prior to connecting them to the segment that covers SDPtMP – cell sites, that features single fiber connections. Traffic coming from both of them can be connected to a pool of circulators to just combine the downstream/upstream traffic into a single fiber. After this combination, for the DSCM traffic, cascaded circular SC interlacers are aimed to demultiplex/multiplex traffic according to the details described in section 2.3.2. As per what refers to the Lite-Coherent transceivers, we envision that traffic coming from their side can be directly connected to cascaded WDM mux/demux stages. Therefore, we are able to deliver precise wavelengths to the intended cell sites, even if the same fiber plant serves traffic for both networking scenarios (cell-free massive MIMO and FFS).

Although not being shown in Figure 20, the SDPtMP node can incorporate optical amplifiers at inputs/outputs in order to minimize the penalties due to insertion losses and ensure the performance of the proposed signal delivery scheme.

Concerning inputs and outputs, we expect that SDPtMP node has several input/output single mode fibers whose inputs might arrive attenuated due to propagation over distances, we expect to compensate that with optical amplifiers. All this is summarized in Table 8.



Table 8 SDPtMP subsystem interfaces

Interface	Description
Optical IN	Single mode fiber
Optical input power	-30...0 dBm
Optical Out	Single mode fiber
Optical output power	0...+10 dBm



3.3.3 Optical SDN Controller

The target is to implement a control of data plane devices leveraging on open-disaggregated interfaces, such as OpenConfig. The experiments will involve two main devices: the coherent pluggable transceiver supporting DSCM and the lite-coherent transceiver. The control/management of these devices leverages OpenConfig YANG data model with ad-hoc augmentations. Indeed, the OpenConfig YANG data model (i.e., the model for the terminal device - *openconfig-terminal-device*) does not encompass full functionalities of PROTEUS-6G devices, such as the management of DSCs. So, OpenConfig will be augmented to enable the Optical SDN controller to manage both the coherent pluggable transceiver supporting DSCM and the lite-coherent transceiver.

Experiments will involve NETCONF SBI towards PROTEUS-6G devices including pluggable transceivers supporting DSCM and lite-coherent transceivers exploiting augmented OpenConfig model.

For a schematic description and depiction of the optical SDN controller please refer to Section 2.3.5 and Figure 7 therein.

Table 9 Optical SDN controller subsystem interfaces

Interface	Description
NBI	REST / TAPI-based
SBI to Lite-Coherent TRX	NETCONF w/ openconfig-terminal-device (augmented for lite-coherent TRX)
SBI to DSCM TRX	NETCONF w/ openconfig-terminal-device (augmented for DSCM P2MP)



3.4 Intermediate test scenarios

Considering the complexity of the envisaged demonstration setup for use case 2 as shown in Figure 16 it is currently foreseen that a number of intermediate test scenarios will be experimentally realized. By means of these intermediate scenarios, the different PROTEUS-6G subsystems as described in Section 3.2 will be successively integrated, one after the other, facilitating dedicated testing of the individual subsystems and their interplay.

3.4.1 Test #2.1: Transmit-Receive under NETCONF control

Purpose of Test

- Test interplay of developed SDN agent with the 1st generation of developed DP-PAM Tx/Rx frontends.
- Test data transmission using 1st gen. DP-PAM Tx/Rx frontends back-to-back and over SMF fiber.

Methodology

According to Figure 21, the DP-PAM Tx frontend will be connected to the DP-PAM Rx-frontend via a SMF connection. Both, the Tx and Rx side of the DP-PAM frontend will be embedded into laboratory measurement equipment (not shown for simplicity) for optical carrier generation (laser source), RF data signal generation (arbitrary waveform generator), RF data signal detection (digital storage oscilloscope) and offline digital signal processing (MATLAB DSP). The DP-PAM frontend as well as the lab equipment will be under software control of the transponder NETCONF agent, which provides a standardized northbound NETCONF interface and exposes relevant control and monitoring parameters of the transponder.

The methodology is to (re-)configure the DP-PAM frontend-based lab transponder by sending NETCONF messages (from a client) to the transponder agent and to verify the execution of the configuration commands by the transponder. Relevant configuration settings are e.g. the optical wavelength, the optical output power and the data rate (modulation format) of the transponders.

It is foreseen that the 1st generation of DP-PAM frontends will have only limited (if any) AOSP capabilities to compensate for chromatic dispersion and/or polarization rotation. Therefore, the SMF link distance will need to be chosen accordingly, and/or compensation can be performed in offline DSP.

Expected results

The successful SDN control of the DP-PAM based transponder will be verified by optical measurements on the data plane using e.g. an optical spectrum analyzer and/or optical power meter.

The quality criterion for successful optical data transmission will be measuring the BER and Q-factors as a function of received power or Optical Signal-to-Noise Ratio (OSNR).

The test will give a first indication regarding the achievability of objective KPI O.7.1 which states “200 GHz bandwidth” and “peak data rate of about 1 Tb/s” for the DP-PAM based lite-coherent transponder developed in PROTEUS-6G.



Figure 21: Schematic of test #2.1: DP-PAM transmit-receive over SMF, under NETCONF control.



3.4.2 Test #2.2: High-rate fronthaul via SDPtMP distribution node

Purpose of Test

- Test data transmission using 1st generation DP-PAM Tx/Rx frontends across SDPtMP node.

Methodology

According to Figure 22, the test setup will be extended with respect to test #2.1 by including a simplified 1st implementation of the SDPtMP distribution node. The node will be placed in-between two SMF connections, i.e. this test will not exploit the spatial-division fiber input foreseen for the final node implementation. Depending on the specific node architecture, which is currently still under development in WP2, some NETCONF-based reconfiguration (not shown) of the node might need to be included to align the wavelength passband of the node to the selected wavelength of the transponders.

The test methodology is to (re-)configure the DP-PAM frontend-based lab transponder by sending NETCONF messages (from a client) to the transponder agent and to verify the alignment with the node passband.

Similar as for test #2.1 is foreseen that the 1st generation of DP-PAM frontends will have only limited (if any) AOSP capabilities to compensate for chromatic dispersion and/or polarization rotation. Therefore, the SMF link distance will need to be chosen accordingly, and/or compensation can be performed in DSP.

Expected results

The quality criterion for successful optical data transmission through the SDPtMP node will be measuring the BER and Q-factors as a function of received power or OSNR.

The test will give a first indication regarding the achievability of parts of objective KPI O.7.3, namely “integration of the SDPtMP node and lite-coherent transceivers into demonstration testbed”.



Figure 22: Schematic of test #2.2: High-rate fronthaul via SDPtMP distribution node.



3.4.3 Test #2.3: SDN-controlled multi-granular environment

Purpose of Test

- Test optical SDN controller to control DP-PAM Tx/Rx frontends
- Test data transmission across SDM link.
- Test interoperability with externally provided multi-granular SDM/WDM ROADM setup

Methodology

According to Figure 23: , the test setup will be extended with respect to. test #2.2 by including an externally provided multi-granular SDM/WDM ROADM node. Such node is supposed to exhibit an SDM fiber interface so that an SDM-fiber link connection can be set up towards an extended version of the SDPtMP node. Depending on the specific node architecture of the SDM/WDM ROADM, it is assumed that such an externally provided node will include a NETCONF agent to allow for NETCONF-based reconfiguration (not shown). For this test, all NETCONF configuration is foreseen to be handled by the actual developed optical SDN controller subsystem as shown in Figure 23 (rather than a simple NETCONF client as before).

The test methodology is to (re-)configure the DP-PAM frontend-based lab transponder using the optical SDN controller and to verify the alignment with the node passbands of both the SDM/WDM ROADM as well as the SDPtMP distribution node. The results will be compared to the previous “client only” test results.

For this test #2.3 is foreseen that the DP-PAM frontends will be accompanied by (at least) some limited AOSP capabilities to compensate for chromatic dispersion and/or polarization rotation. Therefore, longer SMF link distances are expected to be used compared to the previous tests.

Expected results

The successful SDN control of the DP-PAM based transponder and the nodes from the optical SDN controller will be verified by optical measurements on the data plane using e.g. an optical spectrum analyzer and/or optical power meter.

The quality criterion for successful optical data transmission through both nodes will be measuring the BER and Q-factors as a function of received power or OSNR.

The test will give a first indication regarding the achievability of parts of objective KPI O.7.3, namely “integration of the SDPtMP node, lite-coherent transceivers *and* SDN control into demonstration testbed”.

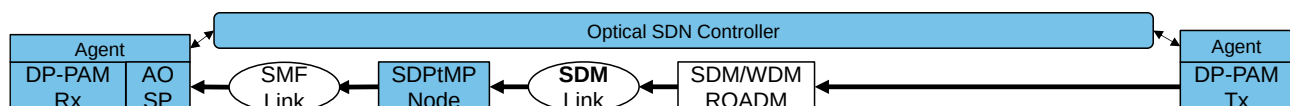


Figure 23: SDN-controlled multi-granular environment.



3.4.4 Test #2.4: Final demonstration of use case 2 scenario

Purpose of Test

- Potential final demonstration of interplay of all network elements in Use Case #2
- Test and demonstrate the interplay of the 2nd generation DP-PAM lite-coherent transponder including 2nd generation AOSP with the SDPtMP node and the optical SDN control.

Methodology

According to Figure 24, the final demonstration test setup will feature data transmission from the PROTEUS6G DP-PAM frontend Tx (embedded in laboratory instruments to emulate an optical transponder, and controlled by a NETCONF agent), via an SDM/WDM ROADM, an SDM link, the SDPtMP distribution node, an SMF link, and finally into the PROTEUS6G AOSP in front of the PROTEUS-6G DP-PAM frontend Rx (again embedded in laboratory instruments to emulate an optical transponder).

The test methodology is to (re-)configure the DP-PAM frontend-based lab transponder using the optical SDN controller and to verify the alignment with all other elements along the transmission path.

This final test #2.4 will feature the 2nd (final) generation of the developed DP-PAM frontends (WP4) with highest available bandwidths. Moreover, it will make use of the final version of the developed ASOP (WP4) to demonstrate all-optical compensation of chromatic dispersion and polarization rotation. Nevertheless, offline DSP will still be required to perform PAM de-mapping and error counting. Therefore, longer SMF link distances are expected to be used compared to the previous tests.

Expected results

The successful SDN-controlled configuration of the complete optical transmission setup from the DP-PAM based transponder via all nodes and fiber segments will be verified by optical measurements on the data plane using e.g. an optical spectrum analyzer and/or optical power meter.

The quality criterion for successful optical data transmission will be measuring the BER and Q-factors as a function of received power or OSNR.

The test shall fulfill objective KPI O.7.1, namely “bandwidth up to 200 GHz and peak data rate of about 1 Tb/s” for the established optical PROTEUS-6G x-Haul connection for functional split 8.

It will also partly fulfill objective O6.2, namely to “set up the demonstration testbed and integrate the plasmonic transceiver and the SDPtMP node”.

Finally, it will partly fulfill objective O6.4, namely to “demonstrate PROTEUS-6G x-haul network solutions including SDPtMP and plasmonic-based transceiver and control software”.

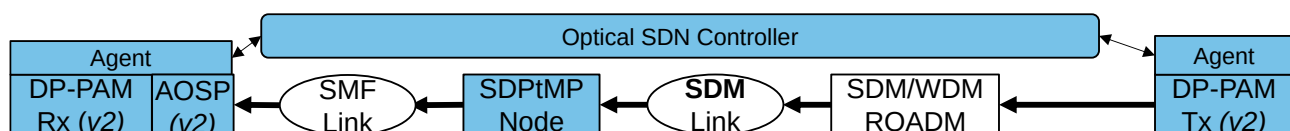


Figure 24: Schematic of test #2.4: Final demonstration of use case 2 scenario.



4. Conclusions

This deliverable presented the planned demonstrations and associated testbed preparations for WP6 in PROTEUS-6G project. It outlined two key use cases - Dynamic Functional Split and Cell-Free Massive MIMO, demonstrating the integration of key technologies such as SDMPtMP network distribution element, plasmonic-based transceivers, SDN and SMO software's. The deliverable provided a detailed plan for the demonstration setups, hardware and software components, and testing scenarios.

This deliverable and the related activities contributed to the WP6 objectives, mainly by defining and planning the integration of core project technologies into cohesive and practical demonstration setups. The outlined scenarios serve as a basis for validating the performance and scalability developed solutions and will guide subsequent tasks in WP6 to ensure successful execution of the planned demonstrations.

Key findings from this deliverable include:

- The identification of two strategic use cases to showcase technological advancements: Dynamic Functional Split, demonstrating flexible functional split management for varying network conditions, and Cell-Free Massive MIMO, emphasizing ultra-high-capacity transmission with centralized MIMO processing.
- Comprehensive test scenarios and experimental setups to validate the interoperability and performance of critical components, such as DSCM transceivers, 4-port SC interlacers, and SDN-controlled optical and packet networking.
- The integration of dynamic bandwidth allocation and resource management using SDN controllers, orchestrators, and SMOs to enhance network adaptability and efficiency.

The outlined scenarios and test plans pave the way for subsequent laboratory integrations and final demonstrations, supporting the achievement of PROTEUS-6G's KPIs and project objectives.



5. Relation to PROTEUS-6G Description of Action (DoA)

5.1 Related implementation objectives

This deliverable **addresses** the following implementation objectives as defined in the DoA (Description of Action):

KPI O.7.1: “Define test scenarios for spatially-diverse point-to-multipoint (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 1Tb/s is envisioned.”

KPI O.7.2: “Demonstration activity planning including network control and operation optimization for a specific E2E 6G application.”

The following implementation objectives will be subject of the upcoming deliverables D6.2 and D6.3:

KPI O.7.3: “Integration of SDPtMP, plasmonic lite-coherent transceivers and SDN orchestration in the demonstration testbed”

5.2 Related work package objectives

This deliverable **fulfills** the following work package specific objectives as defined in the DoA (Description of Action):

O6.1: “To plan the demonstration activities and define test scenarios for the spatially-diverse point-to-multipoint (SDPtMP) network distribution element, the plasmonic based lite-Coh transceiver and the SDN orchestration for the packet-optical x-haul network.”

The following work package specific objectives will be subject of the upcoming deliverables D6.2 and D6.3:

O6.2: “To set up the demonstration testbeds and integrate the SDPtMP, the plasmonic transceiver and the x-haul SDN orchestration into the demonstration testbeds.”

O6.3: “To demonstrate the data-plane functionalities of the SDPtMP using sliceable transceivers based on DSCM in the x-haul segment of the network.”

O6.4: “To demonstrate the PROTEUS-6G x-haul network solutions, including the SDPtMP, the plasmonic-based transceiver and the service management, orchestration and control software with respect to the KPIs.”

5.3 Related project milestones

This deliverable **fulfills** the following project milestones as defined in the DoA (Description of Action):

Milestone #20:

First definition of test scenarios and plan for final project demonstration completed

Due date: Month 12 (December 2024)

Lead beneficiary: 2- CNIT

Means of verification: D6.1



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