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BEYOND 5G – OPTICAL NETWORK CONTINUUM
(H2020 – Grant Agreement № 101016663)

Deliverable D5.1

Final testbed setup, first techno-economics analysis, and first system integration

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Abbreviations and Acronyms

Acronym	**Expansion**
5G	Fifth Generation
5GPPP	5G Infrastructure Public Private Partnership
AAU	Active Antenna Unit
ACO	Access Central Office
ADM	Add/Drop Multiplexer
AI	Artificial Intelligence
AP	Access Point
API	Application Programming Interface
AR	Augmented Reality
ASE	Amplified Spontaneous Emission
B5G	Beyond 5G
BBN	BakcBone Network
BER	Bit Error Ratio
BNG	Broadband Network Gateway
BSS	Business Support System
BVT	Bandwidth/bit rate Variable Transceivers
Capex	Capital Expenditure
CAGR	Compound Annual Growth Rate
CBR	Constant Bit Rate
CDN	Content Delivery Network
CN	Core Node
CNF	Cloud-native Network Function
CO	Central Office
CP	Control Plane
CPT	Coherent Pluggable Transceiver
CPRI	Common Public Radio Interface
C-RAN	Centralized-Radio Access Network
CSG	Cell Site Gateway
CU	Central Unit
DC	Data Centre
DCI	Data Centre Interconnection
DSC	Digital Subcarrier
DSCM	Digital Subcarrier Multiplexing
DSLAM	Digital Subscriber Line Access Multiplexer
DSP	Digital Signal Processing
DSR	Digital Signal Rate
DT	Digital Twin
DTC	DT City
DU	Distributed Unit

DWDM	Dense Wavelength Division Multiplexing
E/O	Electrical to Optical
E2E	End-To-End
EC	European Commission
eCPRI	Enhanced CPRI
EDFA	Erbium Doped Fibre Amplifier
ENP	E-Lighthouse Network Planner
EPA	Enhanced Platform Awareness
Eth.	Ethernet
ETSI	European Telecommunication Standards Institute
ETSI MANO	ETSI NFV Management and. Orchestration
FCAPS	Fault, Configuration, Accounting, Performance, Security
FTTA	Fibre-To-The-Antenna
FTTH	Fibre-To-The-Home
FWM	Four-Wave Mixing
gNB	gNodeB
GW	Gateway
HD	High Definition
HLS	High Layer Split
HSI	High Speed Internet
HTC	Holographic-Type Communications
IBN	Intent-Based Networking
IETF	Internet Engineering Task Force
IIoT	Industrial IoT with cloudification
ILP	Integer Linear Programming
INT	In-band Network Telemetry
ION	Intelligence Operation Network
IoT	Internet-of-Things
IP	Internet Protocol
ISRS	Inter-channel Stimulated Raman Scattering
IT	Information Technology
ITU	International Telecommunication Union
KPI	Key Performance Indicator
KVI	Key Value Indicator
LiFi	Light Fidelity
LLS	Low Layer Split
MAC	Media Access Control
MAN	Metro Aggregation Network
MAS	Multi-Agent System
MB	Multi-Band
MBH	Mobile Back-Haul
MBN	Multi-Band Network
MB-OXC	Multi-Band - Optical Cross-Connect
MCF	Multi-Core Fibre
MCN	Metro Core Network
MCS	Multicast Switch

MDA	Monitoring and Data Analytics
MFH	Mobile Front-Haul
MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
MMH	Mobile Mid-Haul
mMIMO	Massive MIMO
MPLS	Multiprotocol Label Switching
NBI	North Bound Interface
NCC	Network and Computing Convergence
NCO	National Central Office
NE	Network Element
NFV	Network Function Virtualization
NG	Next Generation
NGC	Next Generation Core
NMS	Network Management System
NOS	Node Operating System
NR	New Radio
O/E/O	Optical to Electrical to Optical
OADM	Optical Add/Drop Multiplexer
OD	Origin-Destination
ODN	Optical Distribution Network
OFC	Optical Networking and Communication Conference
OIF-ENMI	OIF External Network to Network Interface
OLA	Optical Line Amplifier
OLT	Optical Line Terminal
ONF	Open Networking Foundation
ONT	Optical Network Termination
ONU	Optical Network Unit
OpEx	Operational Expenditure
OSNR	Optical Signal-To-Noise Ratio
OSS	Operation Support Systems
OTN	Optical Transport Network
OTT	Over-The-Top
OXC	Optical Cross-Connect
P2MP	Point-To-MultiPoint
PCE	Path Computational Engine
PCEP	Path Computation Element Communication Protocol
PE	P-Edge
PM	Project Manager
PMD	Physical Medium Dependant
PO	Project Officer
PoC	Proof of Concept
PON	Passive Optical Network
POP	Point Of Presence
PPP	Point-to-Point Protocol

PM-16QAM	Polarization multiplexed 16-ary quadrature amplitude modulation
PM-QPSK	Polarization-multiplexed quadrature phase-shift keying
PtoMP	Point-to-Multi-Point
PtoP	Point-to-Point
QMR	Quarterly Management Reports
QoE	Quality of Experience
QoS	Quality of Service
QoT	Quality of Transmission
R&D	Research and Development
RAN	Radio Access Network
RAT	Radio Access Technology
RCO	Regional Central Office
RL	Reinforcement Learning
RMSA	Routing, Modulation and Spectrum Assignment
ROADM	Reconfigurable OADM
RoF	Radio Over Fibre
RRH	Remote Radio Head
RRU	Remote Radio Unit
RTT	Round-Trip Time
RU	Radio Unit
S-BVT	Sliceable Bandwidth/bitrate Variable Transceiver
SC	Steering Committee
SDM	Space Division Multiplexing
SDN	Software Defined Networking
SDO	Standards Developing Organization
SD-WAN	Software Defined WAN
SL	Supervised Learning
SLA	Service Level Agreement
SME	Small and Medium-sized Enterprises
SoA	State of the Art
SOA	Semiconductor optical Amplifier
SONiC	Software for Open Networking in the Cloud
SRS	Stimulated Raman Scattering
STIN	Space-Terrestrial Integrated Network
TCO	Total Cost of Ownership
TDM	Time Division Multiplexing
TIP	Telecom Infra Project
TIRO	Tactile Internet and Remote Operations
UE	User Equipment
UNI	User Network Interface
UP	User Plane
uRLLC	Ultra-Reliable Low-Latency Communication
VLAN	Virtual Local Area Network
VM	Virtual Machine
VNF	Virtualized Network Function

VoD	Video on Demand
vOLT	virtual OLT
vPON	virtual PON
VR	Virtual Reality
VV	Volumetric Video
WAN	Wide Area Network
WB	White-Box
WDM	Wavelength Division Multiplexing
WiFi	Wireless Fidelity
WIM	WAN Infrastructure Manager
WP	Work Package
WSS	Wavelength Selective Switch
ZTN	Zero Touch Networking

EXECUTIVE SUMMARY

This deliverable reports on the activities of WP5 during the second year of the project. The work was split into three activities with the following objectives:

- Deploying the experimental setup and generating data sets
- Providing a first techno-economics assessment of the B5G-OPEN solution
- Providing a first integration of HW and SW components for the B5G-OPEN Release 1.0

WP5 also addresses the techno-economic validation of B5G-OPEN proposed architectures. In particular, a detailed state-of-the-art assessment on evolution to multi-band networks, as well as initial dimensioning/optimization results focused on cost and power consumption benefits of multi-band networking and point-to-multipoint interfaces are reported. The latter showcase the type of techno-economic validation frameworks that will be extended to the other target areas of the project, namely packet optical integration, multi-band and point-to-multipoint in access/x-Haul, and benefits of massive monitoring an predictive maintenance. The deliverable also reports on the activity roadmap of techno-economic studies mapped to concrete project KPIs to be done in the project's final year.

TABLE OF CONTENTS

1. INTRODUCTION

This Deliverable addresses the technical validation of the architectural solutions while complementing the experimental demonstrations with theoretical evaluations regarding the expected CAPEX and OPEX benefits of the proposed solutions. Building upon the overall B5G-OPEN architecture, it refines the CAPEX/OPEX modelling based on the device and subsystem specifications (including performance, cost and footprint aspects), and on the control-plane capabilities (with respect to programmability and end-to-end resource visibility) derived from WP3 andP4. It also reports HW/SW components integration (PON-LiFi, Filter-less Metro-Access Network, etc).

Twelve (12) distributed testbeds have been set up by TIM, BT. ADTRAN, NBLF, CNIT, CTTC, UPC, HHI, ELIG, TUe, PLF and TID partners. In what follows, the topology and the components deployed are presented for each testbed deployed. All experimental setups involved HW and SW components provided by almost all project Partners.

The experimental testbeds have been interconnected with secure GRE/VPN tunnels and have been configured among five Partners' labs, enabling the interconnection of Lab resources. These tunnels are used to enable remote access to lab facilities and to interconnect control plane components for large experimentations involving multiple labs. For example, in this deliverable, an experimental dataset for QoT Estimation is reported.

Finally in this deliverable, the intermediate techno-economic validation of the architectural solutions is reported. The technologies and architectures proposed in B5G-OPEN are proposed to be both experimentally demonstrated but also validated through techno-economic studies. This is achieved through B5G-OPEN network dimensioning and optimization studies (Cost/Capacity analysis), leveraging specific B5G-OPEN components (state-f-art analysis) in representative application scenarios (ie multi-band solutions, PtMP networks).

2. EXPERIMENTAL SETUP AND DATA-SET GENERATION

2.1 EXPERIMENTAL SETUP: LAB FACILITIES

The experimental setup involves HW and SW resources provided by almost all project Partners. This includes high-speed optical transport testbeds in NOKIA, HHI, TU/e and ADTRAN Labs, high-speed packet programmability at CNIT, TIM and TID, LiFi systems at PLC, SDN and AI control solutions at CTTC, UPC, and ELIG. This environment will be used to validate the KPIs in an integrated end-to-end scenario. The following subsections summarize the available B5G-OPEN facilities for experimentation.

2.1.1. B5G-OPEN Experimental Setup by TIM

The testbed setup in TIM aims to demonstrate the transport of O-band and C-band services over a metro-aggregation network, where the O-band channels are dedicated to front-hauling traffic, and the C-band channels to other services from 100G to 400G. The experiment will involve TIM providing the general logistics and most of the transport systems, TU-e for the O-band/C-band ROADM prototypes, CNIT for additional switches, optical amplifiers and the SDN controller, and possibly other partners.

The following resources will be available for the demo:

- Two Lumentum RDM-30 to emulate the Optical HUB nodes
- Two JDSU TrueFlex 1x20 WSS to emulate the Optical Access nodes
- Filters for O-band/C-band separation
- Two O-band 2-degree ROADM prototypes provided by TU-e
- One passive Mux/Demux for the O-band channels at the Regional site *(availability to be checked)*
- Two Ethernet switches to emulate the Cell-site gateways and one to emulate the Regional-site Fabric equipped with ethernet pluggable transceivers working in the O-band
- Two Edgecore Switches (possibly + 1 provided by CNIT), equipped with Sonic OS and with several 400G ZR/Open ZR+ pluggable modules for the transport of 400G services
- Three Infinera Groove-30 transponders for the transport of 100G/200G services
- Several SMF spools
- Instruments: 100G and 400G traffic generators/testers, OSAs, VOAs

A possible scheme of the setup is shown in Figure 2.1.

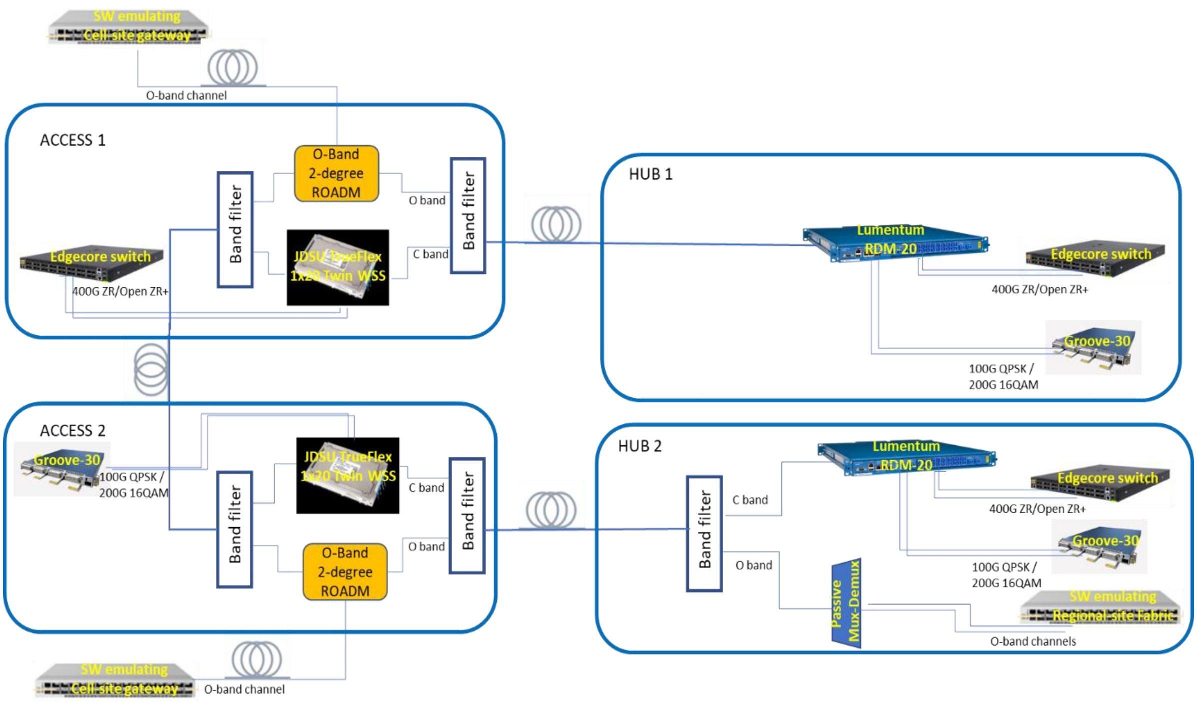


Figure 2.1: TIM Demo setup: metro-aggregation network transporting 100G-400G services over C-band and front-hauling traffic over O-band

2.1.2. B5G-OPEN Experimental Setup by BT (Filter-less Metro-Access Network)

The project deliverable D2.1 showed the topology of a reference network where Access COs are joined to two Regional COs in a Horseshoe topology. This part of the network is known as "Metro-Aggregation" or "Metro-Access" network segment (Figure 2.2).

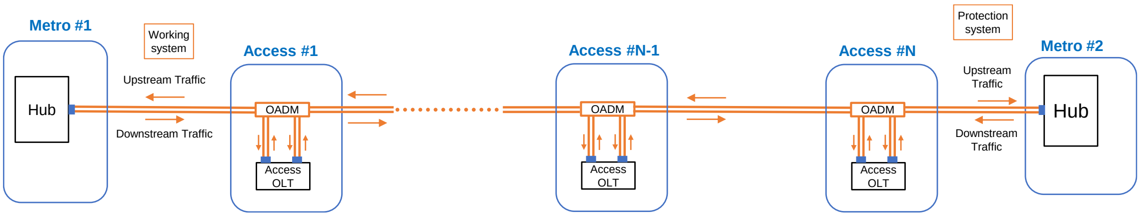


Figure 2.2: Metro-Access horseshoe segment network diagram

Connections between access nodes and the second metro node are typically used for protection purposes. We are not planning to demonstrate network protection so we will not be using a second system for protection purposes.

The project demo that will be built in BT Labs, pictured in Figure 2.2, will show end-to-end network traffic with emphasis on the metro-access and access segments and we have called it "Filter-less Metro-Access Network demo". The project features that the demo is targeting at showing are a) multi-Band operation, b) optical continuum, c) integrated access, and d) e2e network orchestration. The implementation of the ambitious demo is somehow limited due to the finite resources, and therefore these features will also be limited in scope, although enough to show these principles.

The main network systems that will be used are the 400G P2MP coherent pluggable transceiver (CPT) technology, two ITU-T XGS-PON systems, a 5G RAN system, and a newly developed filter-less OADM along the metro-access horseshoe network.

In the control plane, the demo will use the central controller and the system controllers developed in WP4 to control the e2e service traffic, the access PON systems, and the filter-less OADMs. Control of the P2MP CPT system and 5G RAN is not part of the project, and the exact way they will be implemented in the demo is still under discussion.

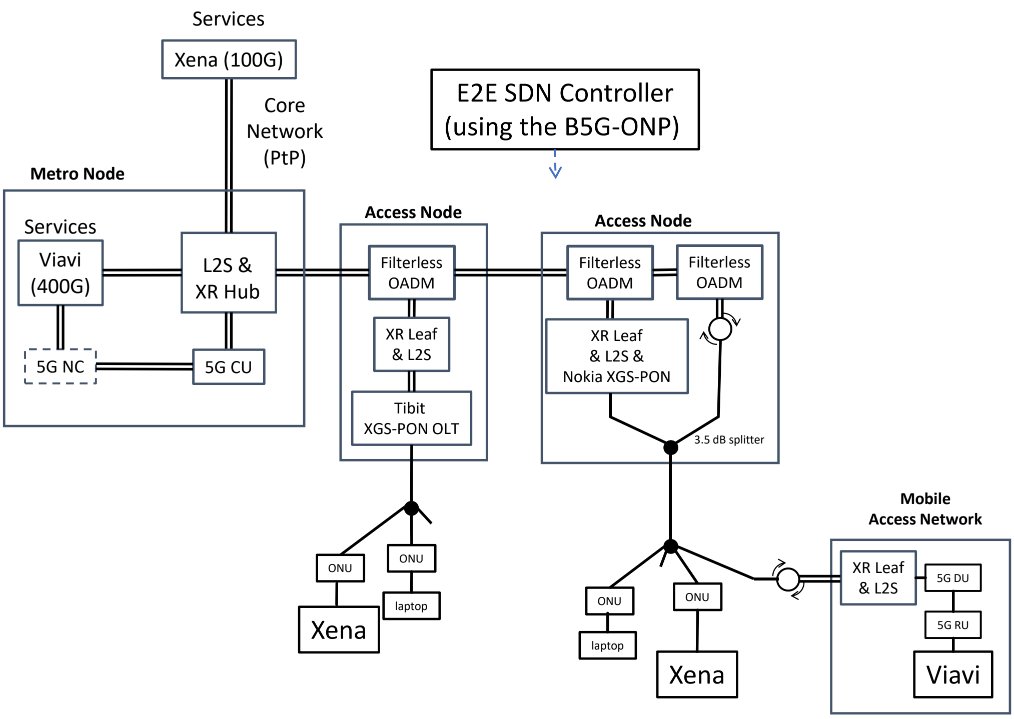


Figure 2.3: Filter-less Metro-Access demo planned setup

2.1.3. B5G-OPEN Experimental Setup by ADTRAN

ADTRAN has built an experimental setup designed for investigating data transmission in the C-band and L-band. Work on an extension by the S-band is currently ongoing. The setup is illustrated in Figure 2.4.

In the setup, lightwaves emitted by nine C-band laser sources are multiplexed and provided to the input of a C-band amplifier. Analogously, lightwaves emitted by four L-band laser sources are coupled into the input of an L-band amplifier after multiplexing. Furthermore, there is one external laser available for the S-band that provides input light to the S-band amplifier. The output of the three amplifiers is combined by a band combiner and the resulting multiband signal is then launched into the transmission fiber where power exchange among the lightwaves happens due to stimulated Raman scattering. Output power of the involved lightwaves is captured by an optical spectrum analyzer (OSA) connected to the output of the fiber. A variable optical attenuator placed between the output of the C-band amplifier and the input of the band combiner allows for changing the composition of the multiband signal for emulating the drop of C-band channels.

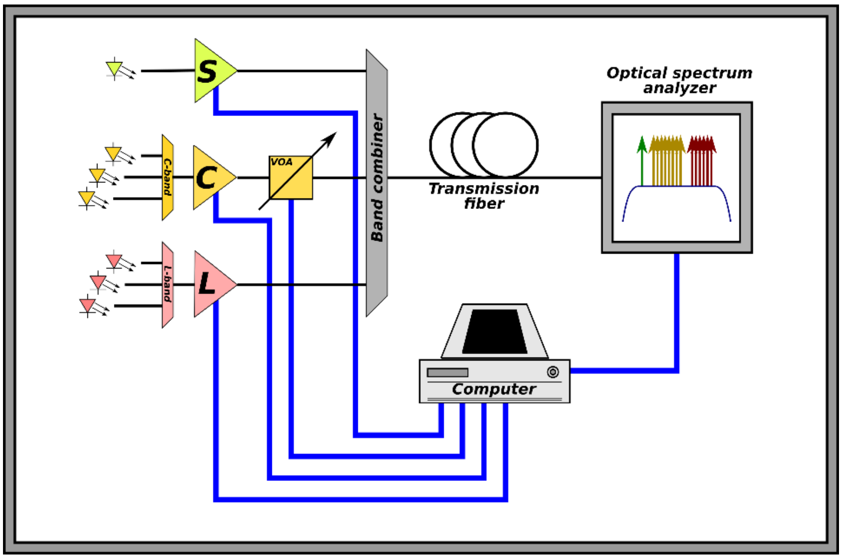


Figure 2.4: Experimental setup for demonstrating transient control in a multiband scenario

The amplifiers for the C-band and the L-band are part of the ADTRAN product portfolio and can therefore be configured by a wide range of protocols supported by this product. The S-band amplifier has been built for laboratory purposes and can be controlled via an Ethernet interface.

Key part of the intended transient control is a feedforward controller which allows for fast reaction to changed input conditions. In order to be efficient, the feedforward controller needs to determine the amplifier setting required after a change of the input power with high accuracy.

The feedforward control used in the experimental setup is based on a set of mathematical equations developed by ATRAN for this purpose. The goal of the experimental setup is to show that the control can determine the new amplifier settings with sufficient accuracy. The calculations are performed on a computer that is connected to all amplifiers, the VOA and the optical spectrum analyzer.

2.1.4. B5G-OPEN Experimental Setup by NBLF

The following optical testbed and equipment are available for B5G-OPEN experimentation at Nokia lab premises. The meshed optical network is built from three vendors (Nokia, Lumentum and a prototype). The architecture of our testbed is depicted in Figure 2.5. It is a seven-node meshed network built from commercial equipment. The physical data plane consists of:

- two Lumentum RDM20 degree boxes aggregated into one virtual 2-degree ROADM (labelled R1);
- one Nokia 1830 PSS-32 shelf, holding 10 iROADM9R cards aggregated into:
    - 4 logical 2-degree ROADMs (labelled R2, R4, R5 and R6);
    - 2 multi-vendor 3-degree ROADMs (labelled R3 & R7) equipped with two iROADM9R and one prototype cards.

All ROADMs except R1 are broadcast & select nodes while R1 is a route & select node.

Channels can be generated from one Nokia 1830 PSI-2T 4-lineport transponder disaggregated by our open device agent ADONIS into 4 independent logical transponders. The channels are flexible and can be configured with different modulation formats (up to 16QAM), baud rates (up to 44GBd), etc. A channel can be launched from any node and received from any node; it is fully programmable.

To provide a programmable spectrum occupancy, the testbed can be loaded with ASE based on additional channels with arbitrary waveforms and aligned on the 50GHz ITU grid. It also brings stability on optical power in each network port. The network testbed can be operated either in a constant power mode, i.e., the output power of nodes is maintained constant regardless of the input power or in constant gain mode.

Moreover, it is fully integrated with offline lab measurement tools. As an example, Variable Optical Attenuators (VOA) and programmable filter can be deployed to emulate optical fiber perturbations. They can be inserted in the middle of a link or in a node.

The outer ring exhibits a total length of 475 km of SSMF fiber while the link between R3 and R7 is made of 80 km of Teralight G.655 fiber. All links between nodes have been fully characterized by its length, dispersion, and attenuation.

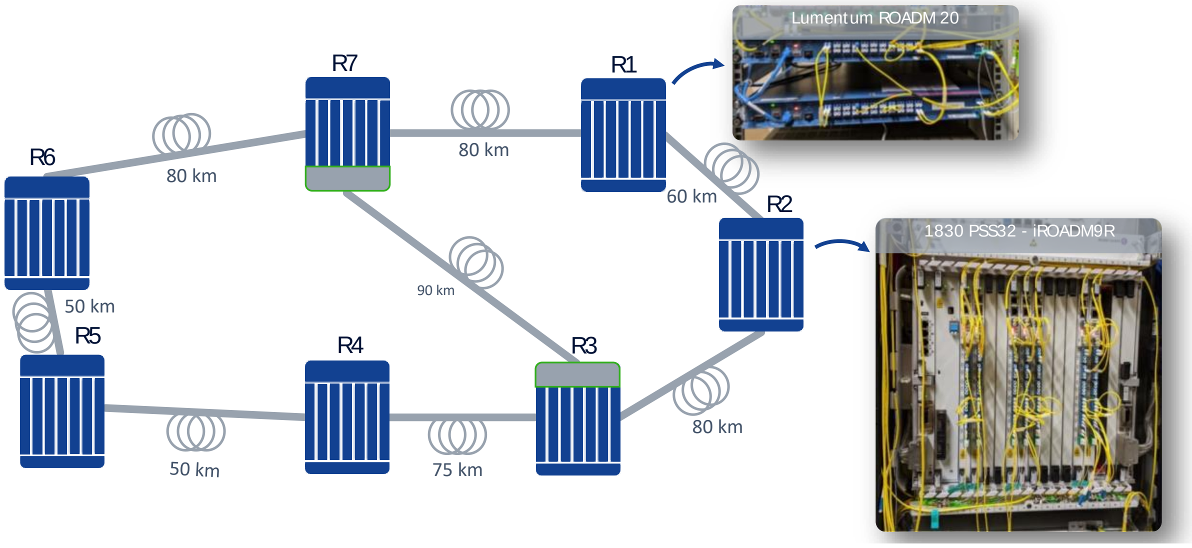


Figure 2.5: Topology of the physical network testbed

2.1.5. B5G-OPEN Experimental Setup by CNIT

The following facilities are available for B5G-OPEN experimentation at CNIT Lab:

- Optical infrastructure: n.4 ROADMs, n.2 coherent 100G muxponders, n.1 600G Muxponder, n.1 400G Edgecore switch with n.2 400ZR+, 400km fiber, OSA, EDFAs,
- ONOS SDN Controller
- Programmable packet infrastructure: 100G switches (n.3 Mellanox Spectrum1/2, n.1 APS Tofino1), P4 100G smart NICs (NVIDIA Bluefield 1 and 2, n.6 NetFPGA Virtex-7)
- Computing resources: n.6 DELL PowerEdge with NVIDIA Tesla GPU,
- Testing: 10G Spirent traffic generator, 400G VIAVI traffic generator
- Infrastructures for verticals (n.2 drones, n.3 SuperDroid 4WD rovers, n.6 HD cameras, Humanoid robot Robotis OP3)

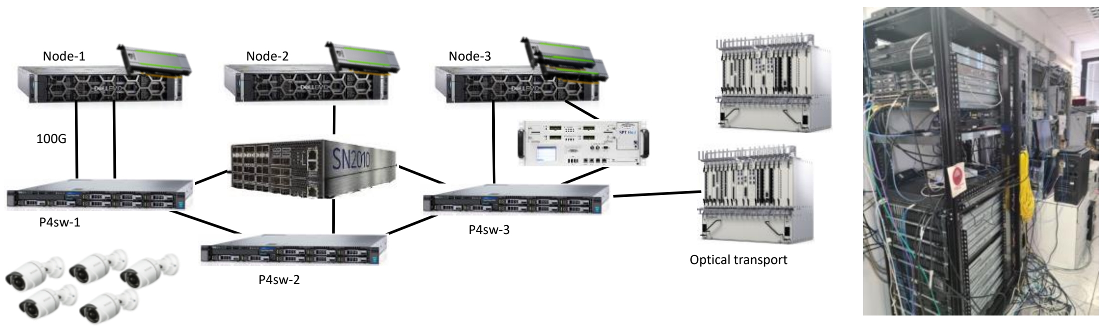


Figure 2.6: CNIT Lab facilities for B5G-OPEN experimentation

2.1.6. B5G-OPEN Experimental Setup by CTTC

The following infrastructure and equipment are available for B5G-OPEN experimentation at CTTC lab premises:

- Multiband sliceable bandwidth/bit rate variable (MB S-BVT) prototype including C- and S-band tuneable laser sources (TLSes), Mach Zehnder modulators (MZMs), C-band wavelength selective switches (WSSes), S-band tuneable filter, band pass filters (BPFs), PIN photodiodes, S-band SOA and TDFA amplifiers, C-band EDFA amplifiers, 100GSa/s OSC, 64GSa/s DAC.
- Optical communication test, measurement and monitoring equipment such as optical spectrum analyzer (OSA), variable optical analyzer (VOA), CD/PMD emulation and analysis instruments, fiber spools of SSMF.
- ADRENALINE testbed®, which includes a photonic mesh network of 4 nodes (2 ROADMs and 2 OXCs) with 5 bidirectional DWDM amplified links of up to 150 km.
- Patch-panels of SM optical fibers, interconnecting with ADRENALINE photonic network.

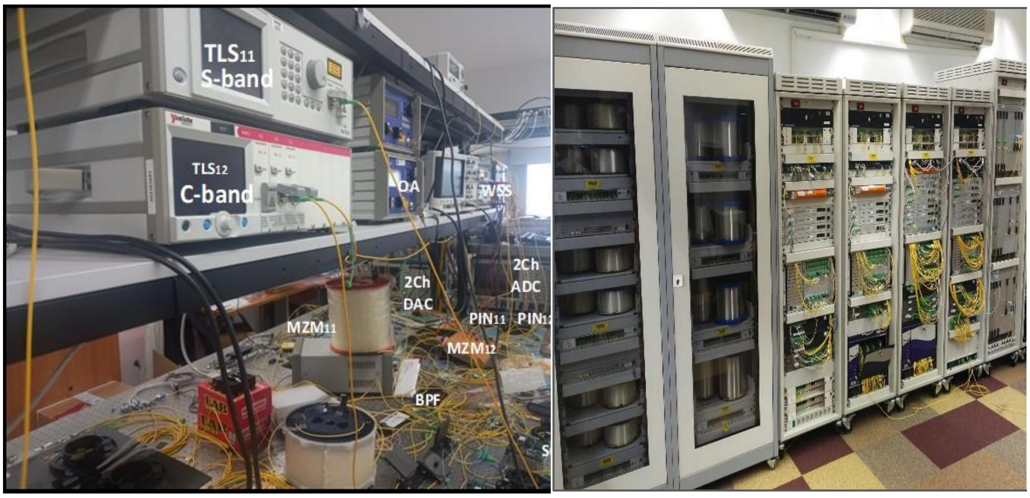


Figure 2.7: CTTC Lab facilities for B5G-OPEN experimentation including ADRENALINE testbed®

2.1.7. B5G-OPEN Experimental Setup by UPC

The GCO-UPC testbed is composed of a collection of compute, storage and network resources used by the research group in different projects. It is based inside the UPC Campus Nord in Barcelona, Spain. OpenStack is used as cloud resource manager providing a shared virtualized environment where workloads can be deployed on-demand. Some bare-metal machines are also available for specific cases where virtualization can't be used.

Researchers can deploy and run their experiments inside VMs deployed in the OpenStack cluster. The infrastructure disposes of an Uninterruptable Power Supply (UPS) protecting the devices from voltage spikes or power supply failure.

Figure 2.8 showcases the GCO-UPC data center, which consists of multiple server racks and two programmable switches allowing the interconnection between the virtualized instances and the external network through a router.

Figure 2.8: GCO-UPC Lab facilities for B5G-OPEN experimentation

The particular characteristics of the devices in the testbed are the following:

- 3x Computing Servers Type A: Intel(R) Core(TM) i9-9980XE CPU @ 3.00GHz (36 cores), 128GiB DDR4 2400 MHz RAM, 1TB + 250 GB SSD NVMe, 2x 1GB NIC.
- 6x Computing Servers Type B: Intel(R) Core(TM) i9-13900K CPU @ 3.00GHz (32 cores), 128GiB RAM DDR4 3200 MHz RAM, 1TB + 500 GB SSD NVMe, 2x 1GB NIC.
- 12x Computing Servers Type C: Intel(R) Core(TM) i7-4770K CPU @ 3.00GHz (8 cores), 16GiB RAM, 2x 500 GB SSDs NVMe, 2x 1GB NIC.
- 2x Programmable Ethernet Switches: Cisco SG220-26P 26-Port Gigabit PoE Smart Plus
- 2x Safran WR-Z16 precise time fan-out for White Rabbit distribution on 1G Ethernet-based networks

An implementation of the Telemetry System based on a framework named GODAI, developed before the project, is also available. GODAI can be customized with the algorithms developed in WP4 for telemetry data processing. In addition, the OCATA Digital twin can be accessed and used, e.g., for failure management.

2.1.8. B5G-OPEN Experimental Setup by HHI

The setup diagram in Figure 2.9 details the available infrastructure and equipment for generating experimental datasets. The characteristics of the setup can be summarized as:

- Modulated channel capable of operating within the C-band at a maximum of 32 GBd;
- ASE-based spectral loading with dummy channels within the C-band;
- Recirculating loop capabilities for long-haul analysis;
- Three spans comprising of 80km of SSMF and EDFA amplification;
- Optical switching for measurement and monitoring flexibility;
- OSA and Waveanalyzer for obtaining spectral measurements over the setup;

- Coherent reception and Fraunhofer HHI's DSP algorithms.

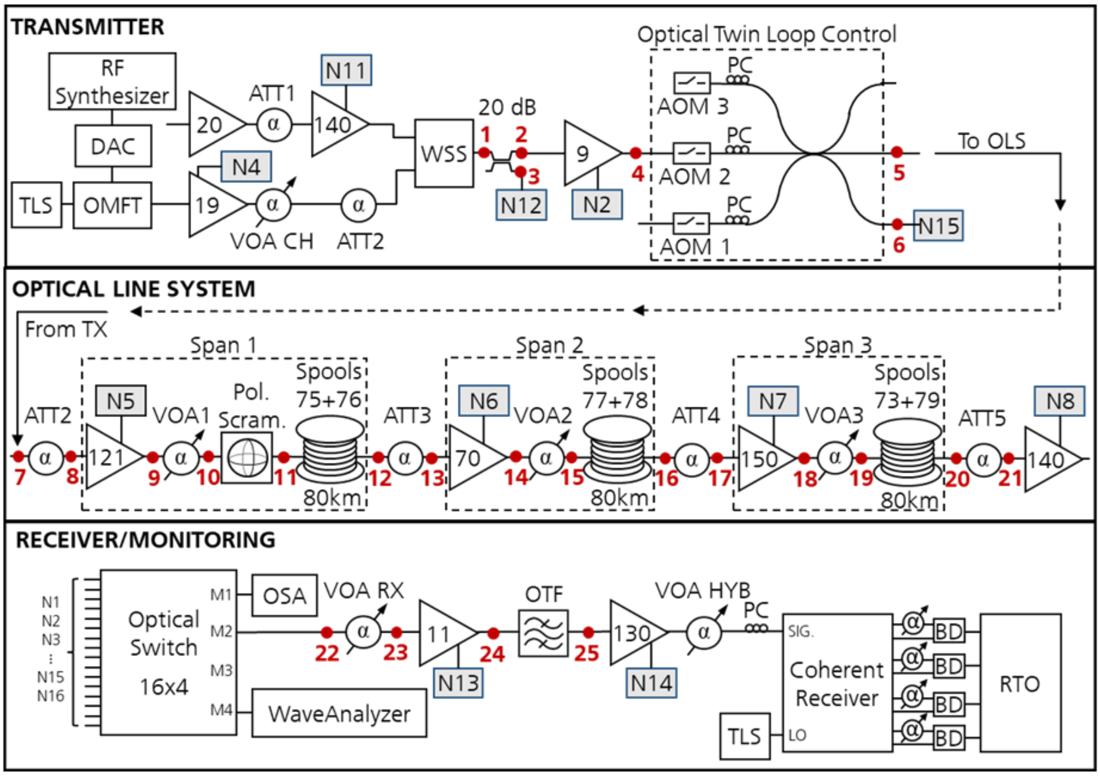


Figure 2.9: Setup responsible for the data collection at Fraunhofer HHI's testbed.

2.1.9. B5G-OPEN Experimental Setup by ELIG

The infrastructure for experimental setup in E-lighthouse dependencies outlines the available equipment for research tasks. The key features on this setup are summarized as follows:

- Network equipment:
  - DIGITUS Gigabit Ethernet Network Switch, 16 Ports, Unmanaged
  - TP-Link Archer C6 - AC1200 WiFi Router, Dual Band (5GHz/2.4GHz), 5x Gigabit Ports.
- UPS (Uninterruptible Power Supply): Salicru SPS One 1100Va V2
- Server: Intel(R) Core(TM) i5-7600K CPU @ 3.80GHz, 16GiB RAM, Samsung SSD 960 EVO 500GB, HD Graphics 630. See Figure 2-1.
- e-Lighthouse Network Planner tool [EligNP]: Optimization tool with resources that serves for the development of the B5G-ONP module based on backend and frontend modules for multi-layer network simulation operations and graphical representation of results.
- 4x personal laptops: Intel(R) Core (TM) i7-7500U CPU @ 2.70GHz, 16(2)/32(2) GiB RAM, Samsung SSD 960 EVO 500GB.

Figure 2.10 -- E-Lighthouse Server Rack

2.1.10. B5G-OPEN Experimental Setup by TU/e

As shown in Figure 2.11 The MB-OADM Prototype consists of a band demultiplexer and multiplexer used to separate and combine the input MB signals. Commercial fused fiber WDM splitters can be utilized to implement the band demultiplexer/multiplexer. After separating the bands, each band's signals are directed to the respective OADMs operating at O-, C-, and L-bands. Each sub-OADM (O-, C-, L-band) is comprised of a demultiplexer, which separates the single-band signals into individual channels, an array of SOAs that selectively and dynamically block or pass each channel (control by FPGA as shown in Figure 2.12), and a multiplexer for combining the channels. The drop stages are realized by a 3 dB splitter before each SOA, and the add stages are realized by a 3 dB combiner after the SOA and before the multiplexing stages. The SOAs compensate for the losses introduced by the muxes/demuxes as well as the 3 dB splitter/combiner.

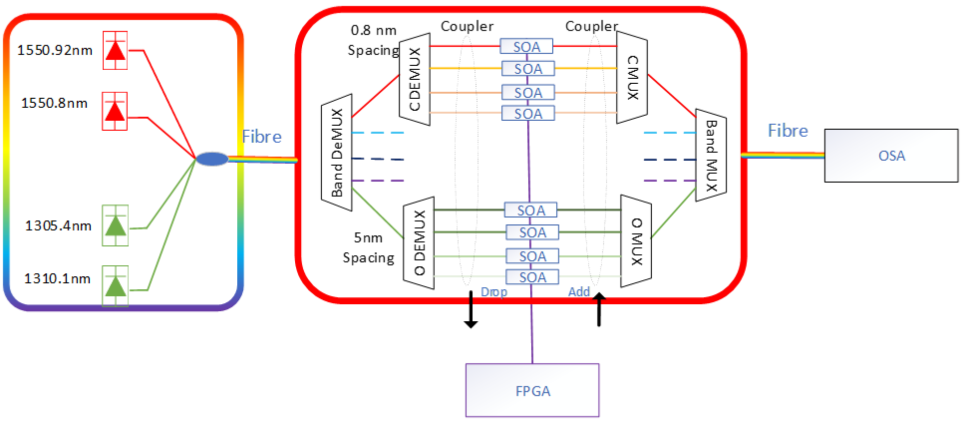


Figure 2.11 Multi-Band RODAM Prototype Demo Experiment Setup

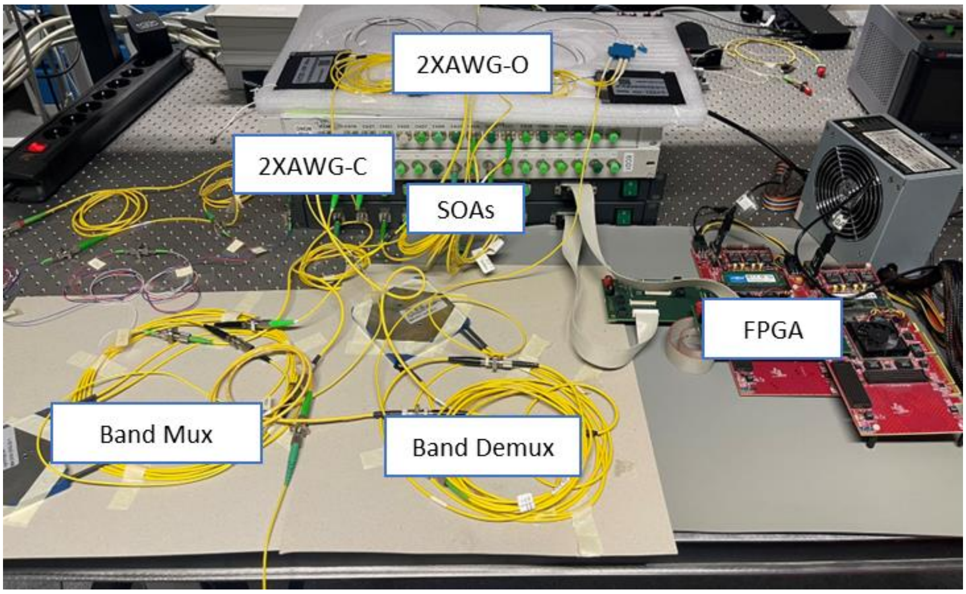


Figure 2.12 Multi-Band RODAM Prototype

2.1.11. B5G-OPEN Experimental Setup by PLF

As shown in Figure 2.13, the LiFI components developed in WP3 and WP4 are integrated in the presented setup diagram.

The experimental setup contains multiple LiFi cells while each cell contains:

- LiFi Access Point (AP). The system architecture of the AP has been reported in WP3 deliverable and to highlight it is integrated with:
  - A Physical layer implementation based on 802.11 OFDM PHY.
  - Digital-to-analogue and analogue-to-digital converters for downlink transmission and for uplink decoding respectively.
  - A MAC layer interface between the PHY and the upper layers, with functions defined in IEEE 802.11. The implemented MAC could be modified to provide full-duplex operation, high protocol efficiency and multiuser support.
- Transmitter driver, for driving the light luminaire.
- LiFi transmitter, which acts as both luminaire for illumination and antenna for optical wireless signals. It is usually an LED lamp for general use cases, and it can be within either visible light spectrum or infrared spectrum.
- In WP4, the LiFi AP has been implemented as NETCONF agent and Prometheus telemetry exporter, which has been reported in D4.2.

On the User end, the user device is a USB dongle which is also known as a station (STA). The LiFi controller, developed in WP4, connects to the APs via a POE+ switch with ethernet cables. It is based on ONOS controller and acts as NETCONF client for retrieving AP data and doing configurations. The whole LiFi setup connects to the PON controller developed by OLC and the integration work is undergoing. The LiFi development has been tested using the first protocol unit as shown in Figure 2.13(a). It is being planned for obtaining other sets of LiFi prototype units in Q1 2024, where full Lab integration test will be carried out and joint experiment with OLC.

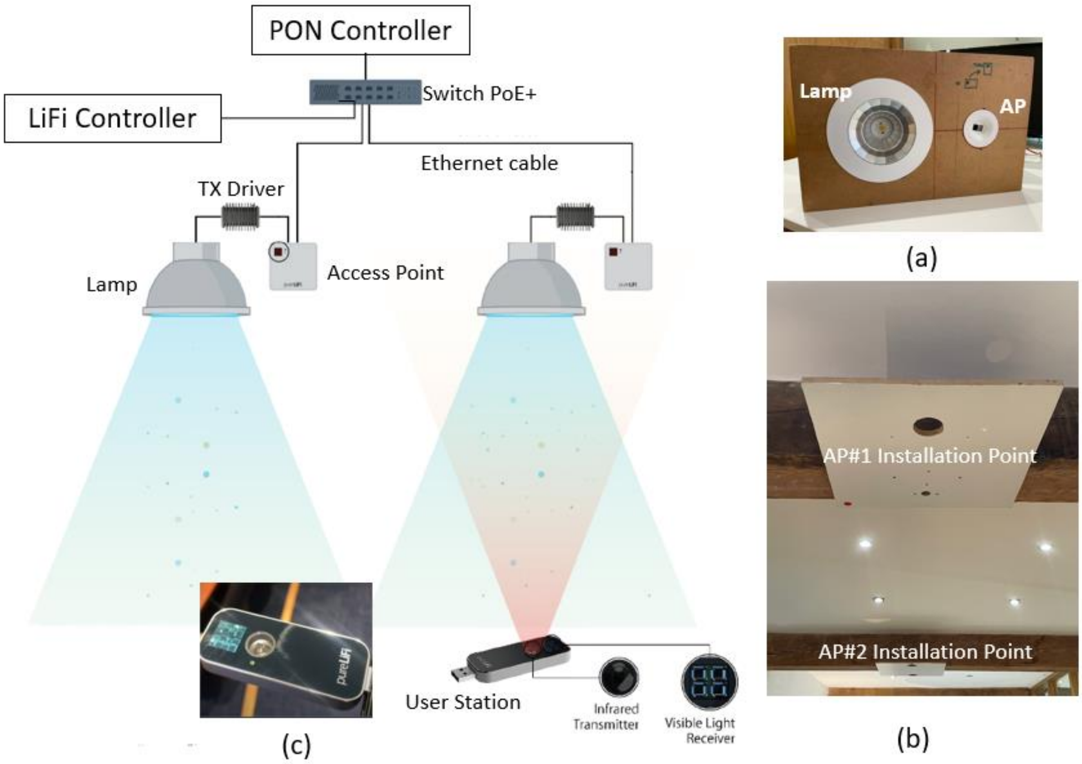


Figure 2.13: LiFi Experimental Setup Diagram: (a) LiFi prototype; (b) multi-AP arrangement; (c) User Station Dongle

2.1.12. B5G-OPEN Experimental Setup by TID

The experimental setup of TID in the Madrid laboratory is aimed at evaluating the performance of the proposed B5G-OPEN architecture in which coherent pluggables are hosted in IP/MPLS routers. The testbed implements a system close to a production network as operated by Telefonica. A commercial Open Line System (OLS) with spans of 80 km, as shown in Figure 2.14.

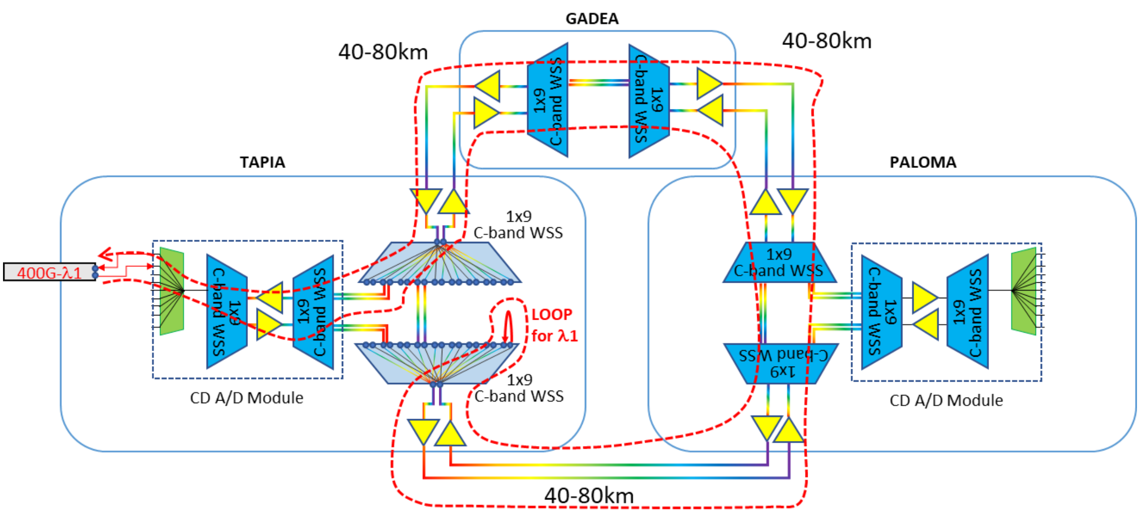


Figure 2.14: Experimental setup in TID Lab

2.2. DATA SET GENERATION

2.2.1. Data set Experimental Setup: Lab interconnection

Secure GRE/VPN tunnels have been configured among five Partners' labs, enabling the interconnection of Lab resources (Figure 2.15). These tunnels are used to enable remote access to lab facilities as well as to interconnect control plane components for large experimentations involving multiple labs. For example, the infrastructure has been effectively utilized to perform the B5G-OPEN joint demo presented at EUCNC '23.

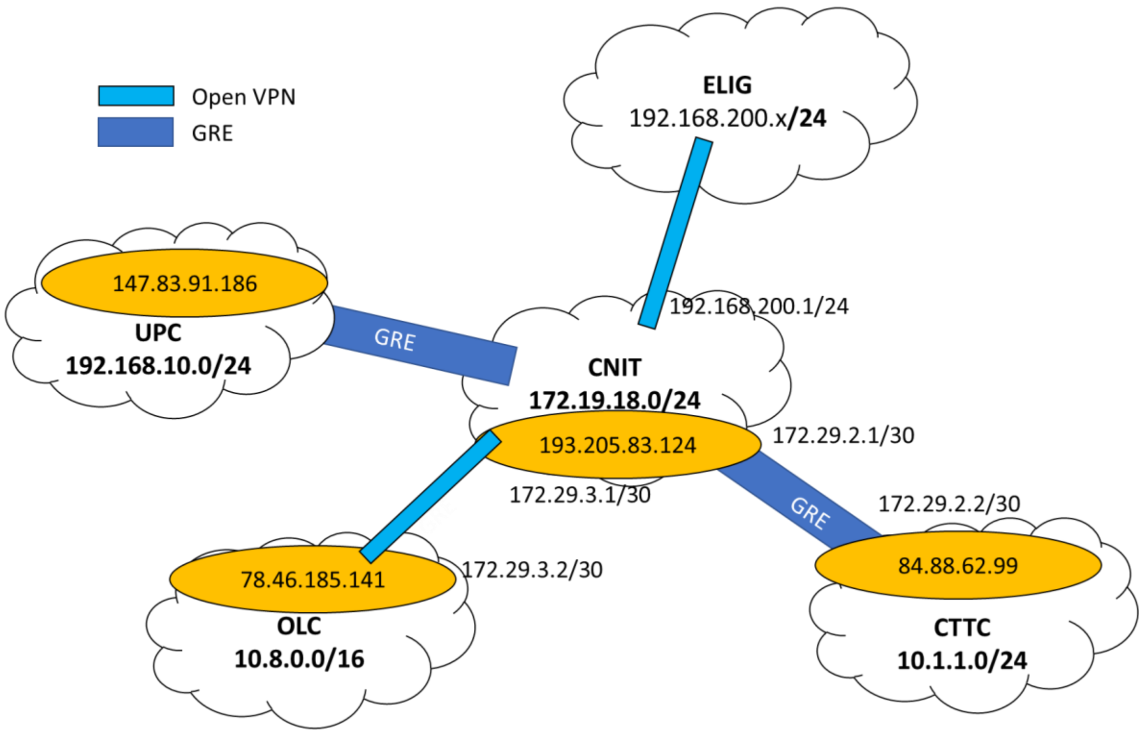


Figure 2.15: Lab interconnection

2.2.2. B5G-OPEN Experimental dataset for QoT Estimation

The dataset is targeted towards usage in data-aided techniques within optical communication systems. All samples were collected from laboratory experiments carried out within the Photonic Networks laboratory at Fraunhofer HHI. Each sample is comprised of an experiment from the straight-line coherent optical setup show in in Section 2.1.8 with the configuration dictated by a permutation of the parameters in Table 2.1. The dataset contains quality of transmission (QoT) information, constellation diagrams and relevant data from the physical layer, digital signal processing (DSP) and spectral profile for each distinct scenario.

Table 2.1: Experimental configuration table

Parameter	Values
Modulation Format	*4-QAM* and *16-QAM*
Symbol Rate (GBd)	28 and 32
Distance (km)	b2b, 80, 160 and 240
Initial Frequency of the WDM Grid (THz)	196.05
Number of Channels in the WDM Grid	80
Channel Spacing (GHz)	50
Channel Under Test Number	1, 10, 20, 30, 40, 50, 60, 70, 80
Distinct channel allocation profiles	88

The permutation of parameters in Table 2.1 yields a total of 12,672 samples stored in comma-separated values (csv) files. The main dataset file contains measurements from all samples, in which each one is individually stored in a single line and given a unique identifier. For each sample, one constellation diagram file is present to visualize the result of the reception by the DSP chain. Three spectral measurement files are present for each sample, one containing the span-wise spectra profiles, another with input and output spectra profile and the last with the filtered channel spectral profile before the optical signal enters the receiver. Table 2.2 demonstrates the QoT parameters of the dataset and the domain of definition for all samples collected.

A visualization of the dataset samples in terms of BER, SNR and OSNR can be observed in Figures 2.16 to 2.18 respectively. The color coding in all figures indicates the transmission distance, from back-to-back (b2b) to 240km. Figure 2.16 shows the lowest transmission distance (b2b) in the lower part of the graphs, indicating a better performance, while the highest distance (240km) is at the upper part of the graphs, indicating inferior performance. As expected, the inverse occurs in Figures 2.17 and 2.18 as these parameters have a different dynamic than the BER for performance evaluation, where a higher number indicates a better performance. The leftmost graph in the figures indicates an analysis of the QoT parameter versus bit width (4-QAM and 16-QAM, in the case of the dataset). For the BER, almost all 4-QAM samples aren't shown in the graph since the bit error count number is not suited to measuring BERs lower than what is shown in the graph's scale boundaries. This is not the case for the SNR and OSNR, where we clearly see all samples, but as can be seen by the similarity in data distribution, these parameters are not heavily affected by the modulation format. The middle figures show the data separated by symbol rate, and it is possible to observe that the BER and SNR samples usually have a better performance at 28 GBd. The rightmost graph indicates the distribution according to the channel loading percentage, where 100% indicates 80 co-propagating channels within the C-band. Some loading configurations between 90 and 100% are also explored in the dataset, so it is possible to observe a higher density of data in this region. An interesting result comes from analyzing the data distribution in Figure 2.17, where the SNR versus channel loading shows an average decay in the SNR as a higher loading is presented, showcasing that more channels tightly packed together slightly reduces the performance of the system in general.

Table 2.2: QoT Parameters collected within the dataset

x_n	Unit	Name	Domain of definition
x_{14}	dB	OSNR	$\{x \in \mathbb{R} \mid 18.51 < x \leq 42.36\}$
x_{15}	dB	SNR	$\{x \in \mathbb{R} \mid 7.82 < x \leq 20.66\}$
x_{16}	1	BER	$\{0\} \cup \{x \in \mathbb{R} \mid 1.11 \cdot 10^{-6} \leq x \leq 7.69 \cdot 10^{-2}\}$
x_{17}	1	EVM	$\{x \in \mathbb{R} \mid 9.27 < x \leq 40.66\}$
x_{18}	dB	Q-factor	$\{\infty\} \cup \{x \in \mathbb{R} \mid 3.08 \leq x \leq 13.50\}$
x_{19}	dB	SNR on X-pol	$\{x \in \mathbb{R} \mid 6.98 \leq x \leq 20.52\}$
x_{20}	dB	SNR on Y-pol	$\{x \in \mathbb{R} \mid 8.74 \leq x \leq 20.81\}$
x_{21}	1	BER on X-pol	$\{0\} \cup \{x \in \mathbb{R} \mid 2.21 \cdot 10^{-6} \leq x \leq 8.71 \cdot 10^{-2}\}$
x_{22}	1	BER on Y-pol	$\{0\} \cup \{x \in \mathbb{R} \mid 2.21 \cdot 10^{-6} \leq x \leq 6.67 \cdot 10^{-2}\}$
x_{23}	1	EVM on X-pol	$\{x \in \mathbb{R} \mid 9.42 < x \leq 44.78\}$
x_{24}	1	EVM on Y-pol	$\{x \in \mathbb{R} \mid 9.11 < x \leq 36.54\}$
x_{25}	dB	Q-factor on X-pol	$\{\infty\} \cup \{x \in \mathbb{R} \mid 2.66 \leq x \leq 13.24\}$
x_{26}	dB	Q-factor on Y-pol	$\{\infty\} \cup \{x \in \mathbb{R} \mid 3.53 \leq x \leq 13.24\}$

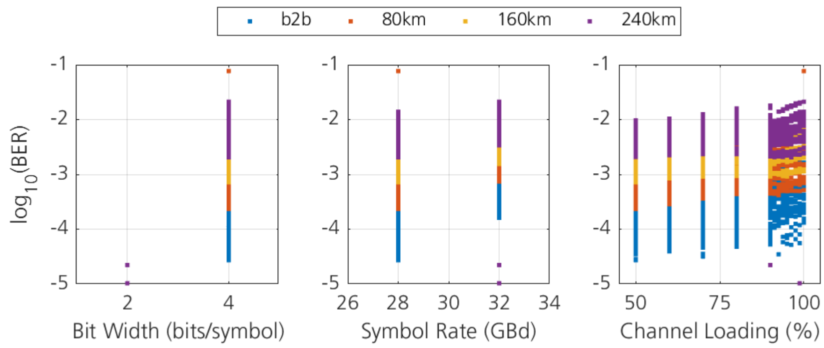


Figure 2.16: BER as a function of bit width (i.e., number of bits per symbol), symbol rate and channel loading, for the multiple samples of the data set, organized by transmission distance.

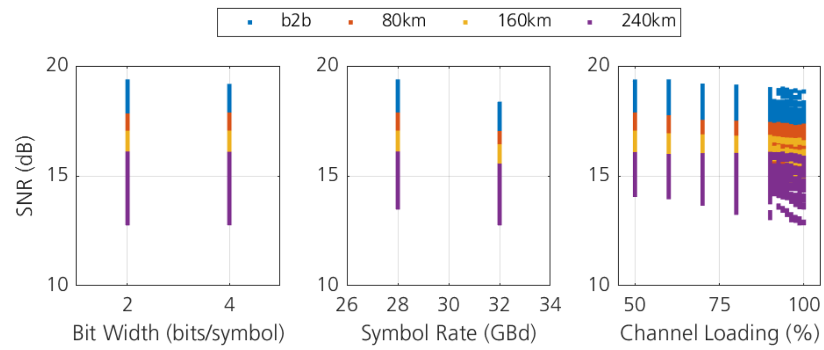


Figure 2.17: SNR as a function of bit width, symbol rate and channel loading, for the multiple samples of the data set, organized by transmission distance.

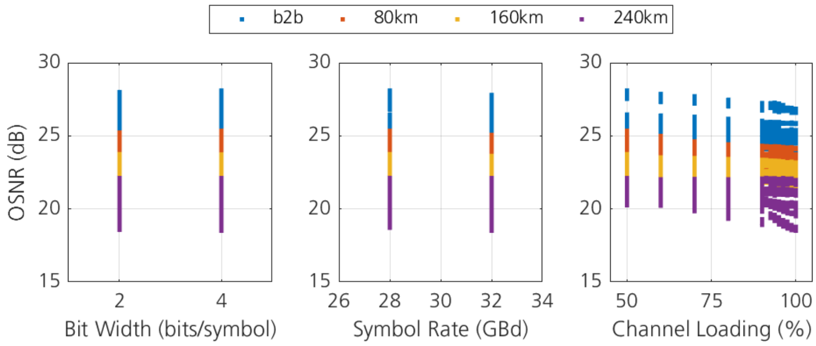


Figure 2.18: OSNR as a function of bit width, symbol rate and channel loading, for the multiple samples of the data set, organized by transmission distance.

2.2.3. B5G-OPEN Data-set on synthetic 16-QAM IQ constellations

A MATLAB-based simulator of a coherent WDM system has been developed to generate IQ constellations for a 16QAM@64GBd signal under different physical path characteristics. Assuming 100 GHz channel spacing and full spectrum occupancy, signal samples containing 2,048 symbols and shaped by a root-raised cosine filter with a 0.06 roll-off-factor are generated at the Tx side. Then, the signal is propagated through standard single mode fiber spans, characterized by optimal power of -1 dBm, attenuation factor of 0.21 dB/km, dispersion parameter of 16.8 ps/nm/km, and nonlinear parameter of 1.14 1/W/km. Spans are modeled by solving the nonlinear Schrödinger equation using the well-known split-step Fourier method, whereas ideal inline optical amplification is modelled as erbium-doped fiber amplifiers with a noise figure of 4.5 dB, introducing linear noise. Finally, at the Rx, a DSP block able to perform ideal chromatic dispersion compensation and phase recovery is considered.
Under the single link scenario, a sequence of up to 25 spans without intermediate ROADMs between Tx and Rx is configured (see Figure 2.19). In particular, the first span has a variable length ranging from 40 km to 80 km and places an optical attenuator after the Tx to adjust the signal power according to such first span length, whereas the remaining spans have a fixed length of 80km. Thus, constellation samples with a total distance ranging from 80 km to 2,000 km have been generated.

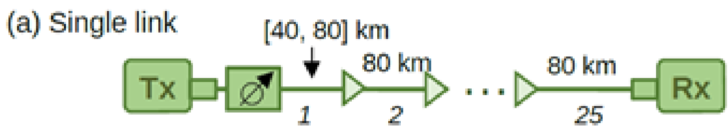


Figure 2.19: Single Link Scenario

Every column is a constellation sample. Every file has 50 columns (constellation samples). Every constellation sample has 2048 symbol samples. Every file has 2048 files (symbol samples). Every cell contains a complex number, with the position in the real (I) and imaginary (Q) axis. The following figure plots the 2048 symbols of the constellation sample 1 (first column) in file "const_4span.csv" belonging to optimal configuration:

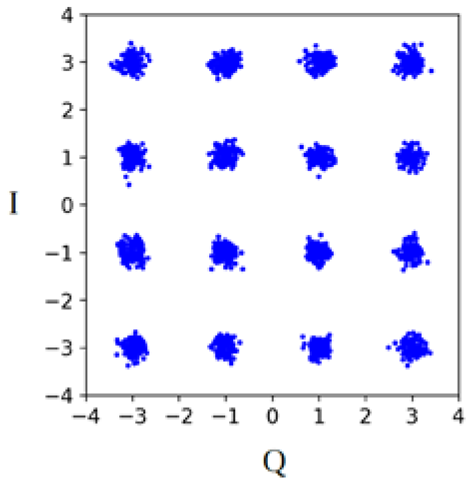


Figure 2.20: Single Link Constellation Plot

The multiple link scenario (see Figure 2.21) introduces intermediate ROADMs between Tx and Rx. The WSSs inside the ROADMs are based on commercially available ones and modelled as described in [OCATA]. In this case, four different optical link configurations in terms of total length and number of spans are considered: 100-km (2x50-km spans), 240-km (4x60-km spans), 400-km (5x80-km spans), and 560-km (7x80-km spans). By generating lightpaths with hop length equal to 4 and obtaining the intermediate constellations before and after every ROADM, signals with a total distance between 100 km and 2240 km have been generated. The figure below shows the name of each position of measurement in the path.

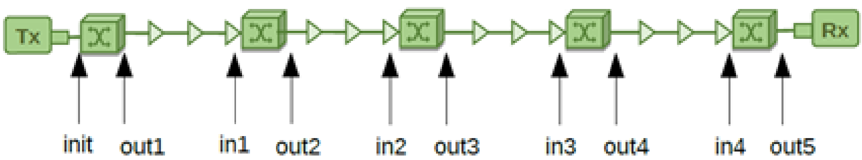


Figure 2.21: Multiple Link Scenario

The dataset and the details of the two exposed scenarios are available on-line [OCATA].

3. TECHNO-ECONOMIC VALIDATION

The technologies and architectures proposed in B5G-OPEN are proposed to be both experimentally demonstrated but also validated through techno-economic studies. The latter seeks to provide quantifiable benefits of the project solutions across metrics such as capacity, cost, power consumption. etc. These studies are intended to build upon the reference architecture and service scenarios defined in Deliverable D2.1 and provide a network-level view of the data- and control-plane devices and subsystems developed in WP3 and WP4.

In the scope of WP5, the techno-economic analysis complements the experimental (qualitative) solution demonstration with extrapolations of the potential impact of the technology on a large scale. This is generically achieved through network dimensioning and optimization studies, leveraging specific B5G-OPEN components in representative application scenarios. It is an element of particular importance in the B5G-OPEN space since the project targets an end-to-end solution suite across multiple network segments (access, metro, core) and develops enabling technologies in this space on multiple parallel fronts (such as e.g. multi-band networking, point-to-multipoint transceivers, packet/optical integration, etc.). Ultimately, it is through this analysis that the expected real-life impact of the project can be gauged against many of the KPIs it proposes to achieve.

Task 5.1, which addresses the techno-economic validation in WP5, started in the second year of the project, directly following the conclusion of activities in WP2 which defined reference architectural scenarios and use-cases for network services. In the initial phase of the task, contributing partners divided their activities in two main components:

- Developing network simulation/dimensioning/optimization frameworks capable of validating specific network scenarios and proposed technologies.

- Defining a common basis for applying the simulation/dimensioning/optimization capabilities within the consortium in such a way that all project KPIs (in the scope of techno-economic validation) can be addressed quantitively and under comparable baseline assumptions (with respect to e.g. traffic, cost, service types and service level requirements, etc.).

The first point is reported in this deliverable by describing the initial techno-economic studies and early results on a subset of the B5G-OPEN network scenarios. These tend to reflect the dimensioning studies where partners have very consolidated optimization capabilities which can be more immediately applied to prototype specific subsets of architecture solutions (e.g., analysis of multi-band networks and benefits of point-to-multipoint applications).

The second point concerns the preparation for the final techno-economic validation to be reported in D5.3, by defining in detail the roadmap of activities to be performed, the project KPIs to be addressed, and the set of common requirements and assumptions across all studies to ensure a consistent interpretation of the results.

Note that given the breadth of B5G-OPEN's scope, both in terms of application space as well as technological solutions, one single encompassing network dimensioning cannot realistically address, with meaningful detail, all the KPIs targeted by the project. Hence, the analysis must be divided between a set of sub-projects with specific focus points, that together cover the full range of the B5G-OPEN ecosystem. But this also makes it even more critically important that all analyses share a common thread that makes their results understandable in broader scope. This deliverable thus reports the proposed set of studies to be performed within T5.1, their expected outcome (mapped to project KPIs), and the baseline assumptions for each of them.

3.1. Initial Techno-Economic Validation Studies

3.1.1. State-of-the-art assessment

A techno-economic study plays a crucial role in the development of robust and sustainable multiband optical fiber networks. It provides valuable insights into cost optimization, resource allocation, return on investment, technology selection, market competitiveness, long-term planning, and regulatory compliance. By understanding the economic aspects, decision-makers can optimize cost, allocate resources effectively, assess potential returns, select cost-effective technologies, ensure market competitiveness, plan for the future, and comply with regulatory requirements. In this regard, a comprehensive review of nine journal, conference, and technical white papers from reputable sources such as IEEE, Optica, and Elsevier has been conducted to provide a state-of-the-art understanding of the techno-economic study of optical fiber networks on multiband systems.

The first study of this topic has been done by B. Shariati et.al in [SHA16a]. Two different mid-term migration scenarios for a core network (Telefónica-Spain national network) had been studied by the authors. In the first scenario, multiband systems, and in the second one the multi-fiber had been considered for traffic increasing. Their studies consider two multi-band systems (being expanded over C+L bands and over S+C+L bands) and two multi-fiber systems (based on a 2-fibre and a 3-fiber system operated in the C-band). Additionally, they considered the case of adding fibers (up to 3 fibers per link in total) only to the congested links. Finally, the case of a single fiber operation over C-band is used for benchmarking purposes. The line cards working bandwidth were considered 50 GHz with the bandwidth variable transceiver (BVT) technology which the modulation format can be changed from PM-QPSK to PM-16QAM. Three bands, each spanning approximately 4 THz and around 32 nm in width (equivalent to roughly 80 channels per band), have been evaluated for deployment within the C, L, and S bands. The Raman-based amps with broad spectrum were considered for the relevant cases of multi-band systems, while typical EDFAs with operation over C-band were considered for the rest of the cases (1-2-3 fibers). For network resource dimensioning, a routing, modulation level and spectrum assignment (RMSA) algorithm was implemented consisting of a diverse routing computation element and a resource allocation module, in which spectral resources are assigned to traffic demands in the form of spectral super-channels (Sp-Ch) following a first-fit strategy, starting from the shortest path and the lowest indexed spectral resource. Moreover, distance adaptive fully loaded link states had been assumed. A 60% and 100% reach increase had been considered for Raman-based systems in C+L and C+L+S. The heterogeneous nature of the traffic matrix is the consequence of demands being mostly exchanged between highly populated transit areas.

In order to alleviate the problem of the hot links (i.e. links with more than twice the average spectrum utilization per link in the network), the authors implemented a load-balancing engine including a request-breakdown element which breaks up connections larger than the capacity of one spectral Sp-Ch. The load-balancing engine distributes big demands proportionally over underutilized and moderately utilized links when the shortest paths between end-nodes become very congested. The inter-channel stimulated Raman scattering (ISRS) had not been considered. Moreover, the doped rare-earth amplifiers (DRAs) had not been considered for C+L and C+L+S scenarios. The performance of each scenario was then compared based on the utilization of fiber pairs, WSSs, and amplifiers relative to the offered traffic load. The C+L+S configuration reduced the number of deployed fibers by 27% compared to a network with three parallel fibers. This also resulted in a 27% reduction in WSSs and a 28% reduction in EDFAs. In the context of the EU project INSPACE, a cost model was developed to estimate the additional cost of migrating to a multi-band and multi-fiber system. Based on the proposed cost model for the network, the estimated cost of a C+L-band or S+C+L-band WSS was 1.5. Additionally, C-band EDFA amplifiers were priced at 0.5, while Raman amplifiers were assumed to cost 1.5 for the C+L band and 3 for the S+C+L band due to specific requirements. Simulation results demonstrated that the multi-band scenario spanning the S+C+L bands could accommodate between 8% and 14% more network traffic compared to the C-band EDFA-based parallel system, depending on the desired reach increase. However, the C+L+S solution incurred higher network migration costs due to the increased expenses associated with WSSs and amplifiers. The point of equilibrium, or breakeven, was determined based on the cost of Raman-based amplifiers. To achieve cost-effectiveness equivalent to a network with three parallel fibers, the Raman amplifier cost was set at 2.3. Alternatively, to match the cost of a system with a maximum degree of parallelism of 3, the Raman amplifier cost was determined to be 1.2.

A similar multi-band study discussed in [SHA16b] presented various switching strategies for space division multiplexing (SDM) over multi-fiber links. These strategies include joint switching, fractional joint switching, and independent switching. The findings indicate that both joint switching (J-Sw) and fractional joint switching (FrJ-Sw) achieve similar spectral occupancy as independent switching (Ind-Sw) in the asymptotic limit. However, using J-Sw or FrJ-Sw can lead to a considerable reduction in switching-related costs.

An evolutionary approach to C+L-band technologies from a network design perspective was presented in [LOP20]. The approach encompasses various aspects, including fiber capacity, network demand optimization, and system performance, offering a comprehensive understanding of the C+L-band technology. Over time, optical fibers have undergone advancements, resulting in improved transmission characteristics through adapted features. C- and L-band are both represented with a combined bandwidth of 4.8 THz, amounting to 384 frequency slots of 12.5 GHz each within each band. For service provisioning and fiber deployment, both heuristic and ILP algorithms have been proposed. In the context of the FP7 IDEALIST project, Telefónica and Telecom Italy have defined the Spanish Backbone Network (SBN) and the Italian Backbone Network (IBN) respectively. The simulation assumes a 10-year network lifetime with planning periods spaced six months apart. Traffic demands of 100 and 200 Gb/s are considered between randomly generated node-pairs, with a traffic growth rate of 26% per year. The analysis focuses on two sets of results. First, it determines the number of fibers required for a C-band only and C+L transmission system. When the capacity is exhausted, the algorithm assumes additional optical fibers will be deployed to accommodate the remaining data. Second, it evaluates the number of carriers needed to fulfill all traffic demands across different planning periods. This enables a comparison between the expected count of line interfaces when considering the two transmission systems (C-band only vs. C+L bands) and the three design strategies. The results indicate that the utilization of fiber pairs can be reduced by employing C+L-band systems.

In [JAN20], the study explores the utilization of C+L bands to boost the capacity of optical backbone networks in comparison to multifiber C bands. Particularly in extensive network areas or geographies, C+L bands present notable advantages, even when factoring in lower fiber lease costs. This research delves into the impact of fiber lease costs on the upgrade in network cost (measured in cost-per-bit metric) for geographically diverse networks—specifically, the BT-UK and Indian networks. The analysis is conducted in the context of operating over C+L bands and is compared with multifiber links. The physical layer modeling incorporates both ISRS and Kerr effects.

The cost analysis considers each equipment's cost relative to a C band EDFA. Specifically, the L band equipment cost is assumed to be 20% higher than that of C band equipment. While the costs of ROADM and EDFA tend to be higher for C+L bands compared to multi-fiber scenario, it is crucial to note that dark-fiber lease costs play a significant role in the multi-fiber scenario. The study takes into account the variation in fiber lease costs based on the network operator's geography. For a European country, the cost is approximately 0.33x (around $1308) per fiber/km/year for a five-year leasing package. In contrast, the lease cost in the Indian network is about 0.007x (approximately $29) per fiber/km/year, significantly lower than in Europe. The subsequent analysis focuses on the BT-UK and Indian networks.

In [JAN20], a biased traffic matrix was created to simulate the traffic flow between high-demand-generating nodes in both networks. In the case of BT-UK, the population and dropped wavelength data of each node to probabilistically selected (?) source-destination pairs were employed. As for the Indian network, a population metric for each city was utilized. The authors have incorporated a semi-static traffic pattern, wherein a light path is randomly established between two nodes with an infinite lifecycle. The establishment of multi-band systems begins with the consideration of C+L band from day one. Additionally, the planner is executed until the blocking probability reaches 1%. The authors examined three flat or uniform launch powers (-5.25 dBm, -3 dBm, and -1.5 dBm). The channel bandwidth for C+L is set at 37.5 GHz, with a guard band of 200 GHz between the C and L bands. The table of the proposed cost model has been reported in Table 3.1.

Table 3.1. Approximate relative cost of different equipment (EON) [JAN20].

EDFA (C band)	x (~$4000)
EDFA (L band)	1.2x
DEMUX	0.04x
MUX	0.04x
EDFA module (C + L band)	2.28x
GFF at EDFA Module	0.2x
WSS (C band)	5x
WSS (L band)	6x
Transponder	36x
Average fiber lease cost (per fiber per km per year)	Nx (N = 0 to 0.5)

The study adopts the same cost model as explored in [KUM22]. It delves into two scenarios: multifiber C-band (nC) and multifiber C+L-band (n(C+L)), utilizing the notation "n" to represent the number of fiber in a multifiber scenario. A techno-economic comparison is conducted between nxC and nx(C+L) concerning capital expenditure and the cost-per-bit of the network. The analysis assumes a bidirectional single fiber pair in all initial network links. The findings indicate that ultra-wideband systems can achieve a 30% total cost savings and require 22.2% fewer upgrades compared to multifiber C band systems.

The same cost model has been considered in [JAN23] (see Table 3.2). The proposed algorithm prioritizes the targeted deployment of cost-effective upgrade solutions across various network links, aiming to minimize the overall upgrade cost. The comparison between deploying optical cables and leasing fibers is considered to enhance the network's capacity with the least cost-per-bit. The presented results demonstrated that a single-fiber C+L-band system can achieve approximately a 66.67% increase in traffic admissibility compared to multi-fiber C-band systems in smaller networks like BT-UK when considering fiber leasing. In cases where operator-owned dark fibers are unavailable in any links, the numerical findings indicate that the multi-fiber C+L-band system in the BT-UK network can still offer CapEx savings of around 40.5% compared to multi-fiber C-band systems. This minimizes the cost-per-bit of the network by approximately 21.9%, achieving the targeted network capacity of 150 Tbps. The paper also explored the impact of longer link lengths on the network upgrade cost. Results show that, for larger geographies like the pan-Europe network, tuning the channel launch power is essential to realize the benefits of the MF C+L-band compared to the MF C-band system. Furthermore, the expense associated with new duct fiber deployment in both urban and rural areas has been addressed in that study. A fixed duct rental, and 8-FC cable purchase/deployment are considered.

Table 3.2. Approximate relative cost of different equipment (EON) [JAN23].

EDFA (C band)	x (~$4000)
EDFA (L band)	1.2x
DEMUX	0.04x
MUX	0.04x
EDFA module (C + L band)	2.28x
8-FC cable purchase	0.05x/km
8-FC cable deployment	0.5x/km
Optical fiber leasing cost	0.33x/fiber/km/year
Duct rental cost	0.0875x/km/year
New duct deployment cost with new fiber roll-out (rural area)	6.58x/km
New duct deployment cost with new fiber roll-out (metropolitan area)	131.65x/km

Various perspectives on transitioning from C to C+L have been suggested in [CIE20] for the end-to-end cost of a 5,000 km Long-Haul network. The monthly/annual Operational Expenditure (OPEX) associated with leasing dark fiber stands out as the most significant element influencing the economics of the network, particularly in Long-Haul (LH) networks. This white paper introduced a model designed for analyzing C/L-band business cases. The goal is to assist network operators whose Outside Plant (OSP) fiber infrastructure relies on leased/Indefeasible Right of Use (IRU) dark fiber. The objective is to determine an optimal architecture that promotes cost efficiency and network scalability. This can be achieved by mitigating dark fiber lease OPEX, especially as network traffic and capacity requirements increase, through the expansion to the L-band. The cost dynamics of a C-band-only solution, particularly in a Long-Haul network, are predominantly influenced by the OPEX associated with dark fiber lease/IRU. To exemplify this, Figure 3.1 depicts the end-to-end cost of a 5,000 km Long-Haul network at capacities of 10, 20, and 30 Tb/s [CIE20]. Assuming a 200G channel bitrate with 76 channels in the C-band, there is adequate spectrum to support 15.2 Tb/s of capacity on a single fiber pair. Capacities of 20 and 30 Tb/s would necessitate two fiber pairs. Across these three network capacities, the dark fiber lease OPEX over a 10-year period averages around 70%, while transmission Capital Expenditure (CAPEX) (network nodes and line system) accounts for only approximately 30%.

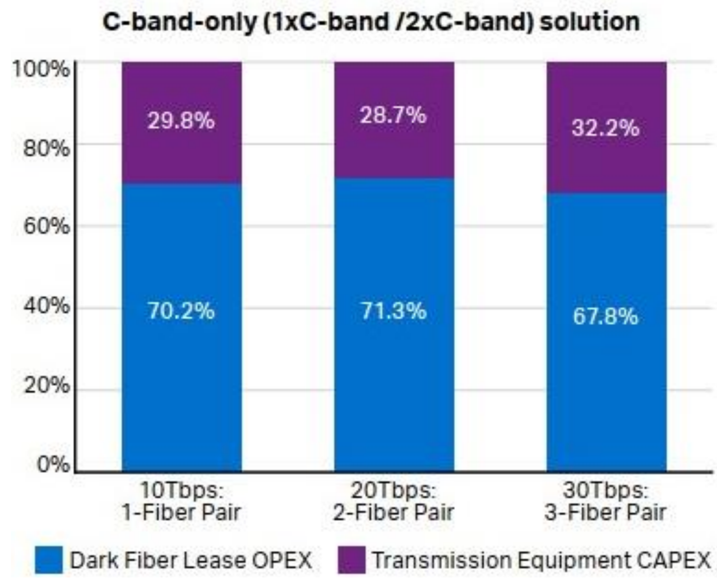


Figure 3.1. C-band-only solution—breakdown of end-to-end network cost for LH network of 5,000 km link distance.

Three migration strategies have been proposed in [CIE20] including (i) 2xC-band (C-band -only) solution (deployed on two pairs of dark fibers), (ii) Modular C+L-band solution (deployed on one pair of dark fibers) (iii) Integrated C+L-band solution (deployed on one pair of dark fibers). In the second scenario, the optical terminal site (Xponders, photonics, and ROADMs) and the optical line systems (EDFAs, RAMAN, and digital gain equalizers) undergo a modular upgrade. To mitigate the impact of the ISRS effect on C-band channel quality of transmission, a design margin must be incorporated from the outset. It's important to note that scenario two does not prioritize the optimization of network performance. Contrastingly, the third scenario incorporates integrated C+L EDFA sites from the outset, ensuring optimal performance for both C- and L-bands. Consequently, the C-band channel performance is taken into consideration for both C-band-only and C+L-band configurations. Additionally, dark fiber lease cost/strand/km/year was considered $120, and a 15 to 20 percent premium was considered for L-band optoelectronics and photonics. The cost model has been proposed based on Table 3.3. A fully loaded link, and 5 Tbps annually growing bit rate were considered for this analysis.

Table 3.3. Approximate relative cost of different equipment.

Cost Type	Component	C-band-only		Day One - Modular		Day One -Integrated	
		Contribution (%)	Price ($)	Contribution (%)	Price ($)	Contribution (%)	Price ($)
OPEX	Fiber Pair	27	1,200,000	24	1,200,000	17	1,200,000
CAPEX	ROADM	10	444,444.4444	10	500,000	6	423,529.4118
	DGE	5	222,222.2222	10	500,000	14	988,235.2941
	RAMAN Amp	8	355,555.5556	10	500,000	14	988,235.2941
	EDFA	25	1,111,111.111	22	1,100,000	22	155,2941.176
	Xponder (200G)	25	1,111,111.111	24	1,200,000	27	1,905,882.353
CAPEX Total Contribution (%)		73	3,244,444.444	76	3,800,000	83	5,858,823.529
Total (US Dollars)			4,444,444.444		5,000,000		7,058,823.529

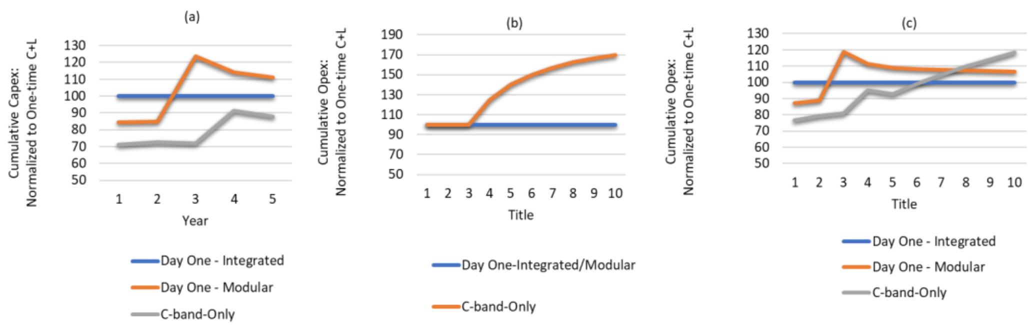


Figure 3.2: Capex and Opex are based on the cost model of [CIE20].

As depicted in Figure 3.2, the Capital Expenditure (Capex) of the C-band-only scenario is approximately 12% lower than the C+L-band integrated (i.e., pay as you grow) scenario in the first five years. Conversely, the Capex of the C+L-band from day one integrated scenario is 10% lower than the C+L modular scenario. However, the Operational Expenditure (Opex) of the C-band-only scenario surpasses that of both C+L scenarios from year 4 to year 10. In summary, the results indicate that the total cost of the C-band-only scenario is around 20% and 10% higher than the integrated and modular day-one C+L model in year 10, respectively.

In [NAK22], an exploration was conducted into the techno-economic performance of a network utilizing S+C+L-bands and employing a wavelength-selective band-switchable optical cross-connect (MB-OXC). In the mentioned paper, the authors conducted a techno-economic analysis, comparing two S+C+L-band networks (utilizing both conventional and proposed MB-OXC) with a 3-fiber C-band network based on the cost-per-bit metric. The study specifically delved into the numerical investigation of the impacts of optical components beyond the C-band and the wavelength-selective band-switching capability. The results indicated that the proposed approach could achieve over a 10% reduction in cost per-bit, even when considering low fiber costs and band-switching induced penalties.

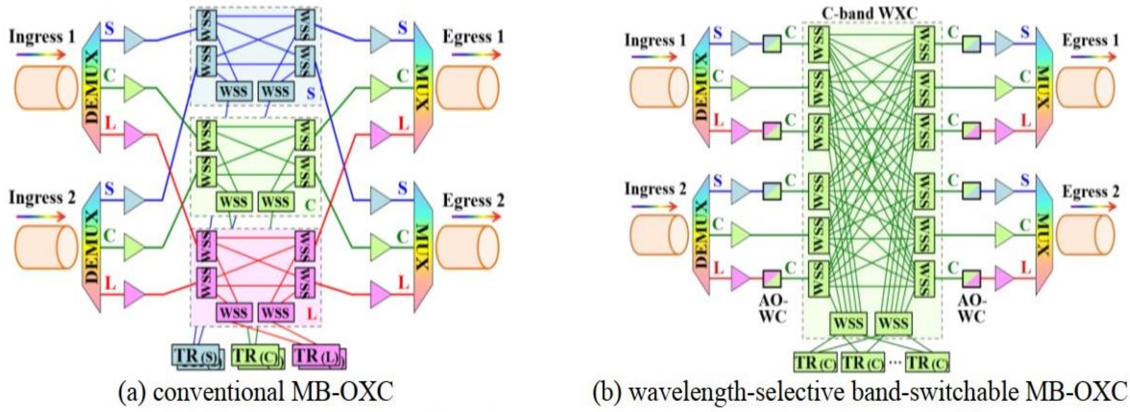


Figure 3.3: MB-OXC node architectures (in the case of 2-degree node).

As depicted in Figure 3.3(a), a conventional Multi-Band Optical Cross-Connect (MB-OXC) adopts a straightforward approach by employing a Wavelength Cross-Connect (WXC) for each band in a parallel arrangement. This configuration includes band de-/multiplexers, amplifiers, WXC components, such as wavelength-selective switches (WSS), and transponders (TRs). Each WXC requires band-specific WSS, and TRs for individual bands are essential for transparently transporting optical signals within each band.

In contrast, the proposed MB-OXC (illustrated in Figure 3.3(b)) utilizes all-optical wavelength converters (AO-WCs) to maximize the use of established C-band technologies. In this setup, AO-WCs convert the spectrum to/from S- or L-band to/from C-band, and C-band signals are managed by a high-port-count C-band WXC. Unlike the conventional approach, the proposed MB-OXC eliminates the need for WSSs other than C-band. Additionally, optical add/drop operations can be performed on the C-band without requiring TRs for bands other than C-band, potentially reducing costs in large networks where numerous TRs are typically deployed.

It's important to note that the proposed MB-OXC allows each incoming optical signal to be output in any direction on any band. Unlike the conventional approach, the transmission band can be switched at intermediate nodes without the need for 3R regenerators, offering significant enhancements in optical-layer flexibility. The key component of the proposed MB-OXC is the AO-WC, enabling multi-wavelength conversion and bit-rate/modulation-format agnostic wideband operation. The authors assert that AO-WCs are becoming available, citing compact devices based on highly-nonlinear fibers or periodically-poled lithium niobate waveguides as potential options. Furthermore, recent discussions on the impact of transmission penalties caused by AO-WCs on network performance are acknowledged, with the authors claiming that the wavelength-selective band-switching capability can significantly improve network performance even when considering AO-WC-induced transmission penalties explicitly.

The NSFNet was considered as a infrastructure network, and the transponders can work based on Table 3.4.

Table 3.4. Modulation Format Candidates for 100-Gbps Capacity [NAK22].

Modulation format	Required spectrum [GHz]	Required GSNR [dB]
2-Carrier 32 GBaud DP-BPSK	100	4.2
32 GBaud DP-QPSK	50	7.2
16 GBaud DP-16QAM	25	13.8

Furthermore, Table 3.5 provides a summary of the relative cost of each component, normalized by the cost of a C-band Erbium-Doped Fiber Amplifier (EDFA), for the calculation of network costs [NAK22]. Similar to [LOP20], the costs of L-band components are presumed to be 20% higher than those of C-band components. In this context, the authors introduced the cost parameters α in {1.2, 1.5}, β in {0.5, 1, 2}, and γ (in [0-0.8]) to analyze parameter sensitivity. α represents a multiplicative factor for the cost of S-band components, indicating the cost increase from C-band. β serves as a scaling factor for the cost of All-Optical Wavelength Converters (AO-WC), with the AO-WC cost estimated as the product of the TR cost and β. Additionally, the cost of fiber strongly depends not only on the country and network size but also on the assumed operational period, and this cost is denoted by γ in this study.

Table 3.5. Relative Component Costs [NAK22].

Component	Relative cost
EDFA (Cband)	1
EDFA (L band)	1.2
TDFA (S band)	α
MUX/DEMUX	0.04
1 x 9 WSS (C band)	5
1 x 9 WSS (L band)	6
1 x 9 WSS (S band)	5α
1 x 20 WSS (C band)	7.5
9 x 18 WSS (C band)	20
9 x 18 WSS (L band)	24
9 x18 WSS (S band)	20α
18 x9 WSS (C band)	20
TR (C band)	36
TR (L band)	43.2
TR (S band)	36α
AO WC	36β
Per Fiber per km	γ

The GSNR of each band was pre-calculated based on Table 3.6.

Table 3.6. Per-band worst-case GSNR in dB after 100-km single span transmission [NAK22].

Scenario	S-band	C-band	L-band
C-band only	-	24.38	-
S+C+L-band	17.45	22.26	23.9

A planning study for a multi-period, multi-band (C+L+S) transparent optical network has been conducted on three European networks—Sweden, Germany, and Spain in [9]. Two deployment approaches, namely flexible bandwidth variable transceivers (Flex-BVTs) and transparent IP over wavelength division multiplexing (IPoWDM), were explored. The findings revealed that Flex-BVTs reduce the equipment in the network by up to 15% while handling up to 20% more traffic. Simple Capital Expenditure (CAPEX) calculations demonstrated that the CAPEX-per-bit for deploying Flex-BVTs is up to 12% lower compared to transparent IPoWDM solutions. Table 7 was considered as a cost model [PAT22]. Table 3.8 shows a comparison study of the above-mentioned references.

Table 3.7. Relative Component Costs [PAT22].

Component	Relative cost
Flex BVT (100-600)	17
CFP2-DCO Transceiver Card (100-400G)	12
Non-coherent IP Router	12 per 400G
Coherent Optics IP Router (With CFP2-DCO Cages)	20 per 400G
C, L-band EDFA	2.8
Band splitter/ combiner pair	0.2
S-band TDFA	5.6

Table 3.8. Summary Chart for Advanced Techno-Economic Analysis of Multi-Band Systems.

No	Year	Indexing	Cost Model	Component	Physical layer modeling	Bands	Migration	Benchmark	Network	Planning strategy	Premium factor
[SHA16a]	2016	OFC	EDFAs, RAMAN, WSSs	EDFAs, RAMAN, WSSs, Fiber Pairs number	Kerr effect	C+L and C+L+S	DayOne	multi-fiber	Spain30	Dynamic (Heuristic)	50% S- and L-band
[SHA16b]	2016	NOC	EDFAs, RAMAN, WSSs	EDFAs, RAMAN, WSSs, Fiber Pairs number	Kerr effect	C+L and C+L+S	DayOne	multi-fiber	Spain30	Dynamic (Heuristic)	50% S- and L-band
[LOP20]	2020	JLT	---	Fiber pair	Kerr effect	C+L	DayOne	multi-fiber	Spain30, Italy44	Multi-Period (Heuristic, ILP)	---
[JAN20]	2020	ECOC	EDFAs, RAMAN, WSSs, fiber pairs, Transponders, Mux/DeMux	EDFAs, RAMAN, WSSs, fiber pairs, Transponders, Mux/DeMux	Kerr effect+ISRS	C+L	DayOne	multi-fiber	BT-UK, Indian backbone	Semi-static (Heuristic)	20% for L-band
[KUM22]	2022	ECOC	EDFAs, RAMAN, WSSs, fiber pairs, Transpo	EDFAs, RAMAN, WSSs, fiber pairs, Transponders,	Kerr effect+ISRS	N x (C+L)	DayOne	multi-fiber	BT-UK	Semi-static(Heuristic)	20% for L-band

			nders, Mux/DeMux	Mux/DeMux						
[JAN23]	2023	JOCN	EDFAs, RAMAN, WSSs, fiber pairs, Transponders, Mux/DeMux	EDFAs, RAMAN, WSSs, fiber pairs, Transponders, Mux/DeMux	kerr effect+ISRS	N x C+L	DayOne	multi-fiber	BT-UK, Pan-Europe	Semi-static(Heuristic)	20% for L-band
[CIE20]	2023	White paper	EDFAs, RAMAN, WSSs, fiber pairs, Transponders, Mux/DeMux, DGE	EDFAs, RAMAN, WSSs, fiber pairs, Transponders, Mux/DeMux	NA	C+L	DayOne	multi-fiber	Point-to-point	Multi-Period (Heuristic)	15-20% for L-band
[NAK22]	2022	OFC	EDFAs, RAMAN, WSSs, fiber pairs, Transponders, Mux/DeMux, AO-WC	EDFAs, RAMAN, WSSs, fiber pairs, Transponders, Mux/DeMux, AO-WC	kerr effect+ISRS (worst case per band)	C+L+S	DayOne	multi-fiber	US-NET	Semi-static(Heuristic)	20% for L-band, 20%-50% for S-band
[PAT22]	2022	OFT	EDFAs, RAMAN, WSSs, fiber pairs, Transponders, Mux/DeMux, AO-WC	EDFAs, RAMAN, WSSs, fiber pairs, Transponders, Mux/DeMux, AO-WC	kerr effect+ISRS (worst case per band)	C+L+S	DayOne	multi-fiber	Sweden, Germany, and Spain	Semi-static(Heuristic)	0

3.1.2. Cost/Capacity Analysis of multi-band-based solutions

One major aspect of B5G-OPEN, and as such of the techno-economic analysis, is the impact of multi-band networking on the cost per bit and achievable capacity of edge, metro, and core networks. To this end, multiple preliminary studies covering aspects related to the efficiency of multi-band networks have been performed. In this Section, some exemplary studies with early results are reported. The analysis covers three planning and operational aspects related to multi-band networks:

- A network traffic capacity evaluation over different time horizons (short/medium/long-term), aiming to identify where capacity extensions resorting to multi-band solutions are most suited, and in which network segments should be deployed first.

- An analysis on migration strategies from standard C-band systems to a C+L systems, discussing the relative merits of introducing additional band(s) incrementally or in one shot.

- A resiliency analysis impact comparing C/C+L/C+L+S deployments, and how the co-existence of bands in the same fiber plant introduces more complex management of optical transients, which can lead to a trade-off between the added capacity and additional OSNR margins per light path.

3.1.2.1. Capacity needed on all bands short/mid/long-term

Within the framework of B5G-Open project, the study published in [Rui23] was carried out to obtain an estimate of the capacity needed in the various network segments and determine the multi-band solutions that could likely be required in different time horizons.

The study, started in WP2 (until November 2022) and continued in WP5, involves the analysis of traffic evolutions over three horizons: short term (approximately 2025), medium term (2028) and long term (2031).

The reference architecture used is the one defined in WP2 [B5GOD2.1] which involves the partitioning of the network into four segments: access, metro aggregation, metro core and backbone.

The three network segments and related nodes considered in the traffic study are:

- the aggregation segment (the Metro Aggregation Network (MAN)) that connects the access central office (ACO) nodes to the regional central office (RCO) nodes (typically, but not exclusively, with horseshoe topologies),
- the core metro segment (the Metro Core Network (MCN)) that connects the RCO nodes to each other and with one or more national central office (NCO) nodes (typically with a mesh topology), and
- the national backbone segment (the BackBone Network (BBN)) that allows the interconnection of NCO nodes with each other and with the gateway points for the exchange of traffic with the outside. Backbone has a mesh topology.

Access remains excluded from the analysis. The traffic generated and its impact on network resources are considered starting from the ACO which aggregate all the traffic coming from both fixed access and mobile access.

There are some clarifications and considerations that must be made before presenting the results of the study and the indications that emerged on the need for multi-band and SDM systems in the different network segments.

The first clarification concerns the fact that the study on the construction of traffic matrices is independent of the technologies used for traffic switching and transport. The study deals with determining the traffic relationships in terms of data rate (bit/s) in the various network segments having as reference the central offices (as physical source and destination points of traffic) without going into detail on how the central offices are made. In this sense the study is agnostic both in terms of technologies (except for the fact that central offices must have an optical component, a packet switching component and possibly (whenever necessary) a data center component) but also in terms of physical topologies of the network in each segment (only the segmentation of network hierarchy is modelled). In other words, what matters is the traffic exchanged between the terminations and not how the traffic is routed on the network. This last aspect is relevant in the network design, although it’s not an issue at this stage; it will be essential in a further phase of the project where technical-economic studies based on the sizing of network systems will be performed.

The second clarification concerns the architecture of the service. Without going into the model's details, we observe that the traffic matrices are strongly influenced by the positioning of Telco and Service functions within the architectural model. The Telco functions of both the fixed (BNG) and mobile (UPF) core are those for which the user traffic collected by the corresponding access networks is recognized at the IP level and forwarded towards the destination, which can be another user (i.e. attached to the same or to another remote Telco function) or a point from where the service is provided (a Service function, local or remote).

The positioning of the Telco and Service functions in the architecture gives rise to a very high number of possibilities and consequently to practically unlimited options for determining how traffic is exchanged and distributed in the network. To limit ourselves to a small but still significant number of cases, three architectural hypotheses were adopted:

- distributed architecture, with Telco and Service functionality present at all levels, i.e. on ACOs, RCOs and NCOs
- semi-distributed architecture, with Telco and Service functionality on the regional and national level, i.e. on RCOs and NCOs
- centralized architecture, with both Telco and Service functionality at the national level, i.e. only on the NCOs

The third clarification concerns services. To construct the traffic matrices, reference was made to three mass market services (web browsing, direct communication, and contents from a Content Delivery Network (CDN)) and two services coming from new use cases (Industrial Digital twinning and Volumetric Video distribution).

These services were grown over the three time horizons with an annual growth rate of 30% for mass market services and with higher percentages (above 50%) for services coming from new use cases given that they start with low volumes in the short term, but noticeable growth is expected for them thereafter.

Finally, before presenting the results, one more aspect should be clarified. The model, that allows mapping services and traffic flows onto the network, involves a two-step methodology. In a first step, the traffic flows between logical entities are determined (i.e. the traffic generation points, the Telco functions, the Service functions - those that provide web services, CDN contents, etc. - and the gateways). In a second step, having identified the macro service architecture (centralized, semi-distributed and distributed) and the consequent mapping of the logical entities onto the physical ones, the actual traffic flows on the physical network (i.e. the traffic matrix between the COs) are obtained.

With the traffic matrices calculated as described above, the estimated necessary capacity on each node and for each network segment for the semi distributed architecture is given in Figure 3.4. The values of node capacities for the other architectures (centralized and distributed) do not differ substantially. Obviously the more distributed the functions are, the less traffic is transported in the internal parts of the network (metro core and backbone) but, at least for general considerations on the bandwidth requirements on nodes and links, these differences are not such as to significantly change the period in which C+L solutions with SDM or multiband (MB) are required in the different segments of the network.

In Figure 3.4(a), the estimated node capacity on the aggregation (MAN) is shown. MAN is assumed made of 8 ACO nodes (the maximum allowed) and two RCO nodes; each of the latter must be capable, for reasons of surviving single node or link failures, to accommodate the entire traffic generated by the ACO nodes. Assuming an enhanced C-band capacity of 24 Tb/s (6 THz at a Spectral Efficiency (SE) of 4 bit/s/Hz), migration to C+L bands and/or SDM will be required as soon as ACO nodes generates 3 Tb/s (and RCOs aggregate 24 Tb/s each). The limit of this option is reached when four parallel fibers (assumed to be available nowadays) are fully occupied with C+L bands, which would trigger the migration to MB and more parallel fibers. That limit is 24 Tb/s for ACOs and 192 Tb/s for RCOs. In view of the figure, it is clear that C+L along with SDM with current fiber deployment is sufficient for MAN in all adoption scenarios (MB is never required), while C band only is sufficient up to mid-term and C+L SDM (<= 4 fibers) is required only in the long term.

In Figure 3.4(b), the estimated node capacity on the metro core (MCN) and on the backbone (Backbone Network (BBN)) is reported. For the MCN and BBN we assume 2.5 Tb/s of traffic generated per node as a reasonable limit for enhanced C-band capacity on network links. This number is purely indicative and has been estimated assuming a typical mesh network with a few dozen nodes and paths from three to four hops (on average) to route traffic flows, see [Qua22] for a study that shows the levels of traffic which cause saturation of C band links in the Italian National backbone of TIM. The assumption is the same for MCN and BBN as they are network of comparable size and shows similar meshed topology; this is true at least in TIM topology case (see reference networks in Section 2 of [B5GOD2.1]). Going beyond that level will require upgrading to C+L and SDM, while 20 Tb/s per node will be sufficient to exhaust four parallel fibers, thus requiring MB solutions. As can be observed, MB and more than four parallel fibers will be required in some segment even for mid-term adoption scenarios.

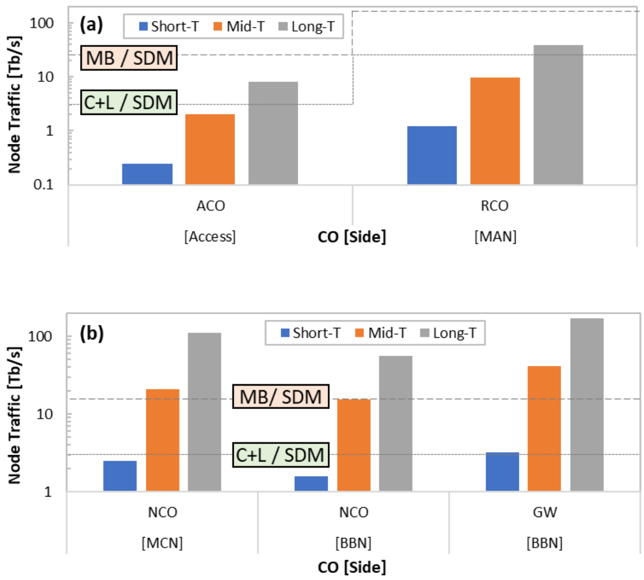


Figure 3.4: Adoption of MB and SDM for semi-distributed scenario.

We discuss hereafter the impact of the traffic calculated with the model presented in the previous sections on the upgrade of the optical transport systems required in the different network segments and in the considered three target periods. The presented conclusions are closely linked to the assumptions made in both the services and network architectures.

Metro Aggregation Network segment

In the short term, the aggregated flow exchanged by an ACO is of the order of a few hundred Gb/s (at maximum, in the urban geotype), and so they are far from causing the saturation of state-of-the-art C-Band systems. In the mid-term, aggregated flows exchanged by ACOs could induce the saturation of C-band systems as ACOs reach 2 Tb/s of DL traffic in the case of the urban geotype (lower or significantly lower values for suburban and rural). This would happen in rare combinations with many nodes in the same metro aggregation network, all offering high traffic, so in most cases C-Band is still enough. In the long term, flows exchanged by ACOs with RCO (semi-distributed scenario) or directly with NCO (centralized scenario) reach values of little less than 10 Tb/s in the urban geotype (order of 2 Tb/s for rural). Then, the introduction of C+L, possibly in combination with the SDM, will be required in most cases.

Metro Core segment (MCN)

In the short term, flows exchanged within MCN should be of the order of a few Tb/s at most, and this approaches the limit for C-band systems. Thus, the use of C+L bands and the targeted use of parallel fibers only where necessary can constitute a strategy to address the capacity need in the MCN in this time frame. Semi-distributed scenarios, which lighten the traffic injected in the metro core by RCOs, could delay for a while the introduction of C+L and parallel fibers in the MCN. In the mid-term, traffic flows in MCN become of the order of 10 or a few tens of Tb/s. Use of C+L band systems and targeted use of parallel fibers can be the solution in some cases; however, it might be not sufficient for situations where traffic is particularly high. Then, full MB capabilities can be required. In the long term, traffic flows exchanged in the MCN (especially the ones terminated at NCOs) will be of up to 100 Tb/s and in some cases even higher. In consequence, they significantly exceed C+L system capacity limits, and therefore, MB will be definitely required in any functional distribution scenario, probably in combination with SDM, as using all bands on a single fiber at the higher spectral efficiency may not be sufficient.

Backbone segment (BBN)

In the short term, traffic exchanged by NCOs between each other or with the GW is of the order of one to a few Tb/s, 821 and once routed in the BBN, line systems could easily reach maximum C-band capacity. The use of C+L bands or SDM (multi-fiber) begins to become necessary, independent of the telco and service functions distribution scenario. In the mid-term, traffic exchanged by NCOs and GW are of the order of dozens of Tb/s, significantly exceeding C-band 8 and even C+L capacity limits. Then, MB or SDM (or a combination of the two in most critical cases) is required in any functional distribution scenario. In the long term, traffic exchanged by NCOs between each other or with the GW is of the order of few dozens of Tb/s (up to 200 Tb/s for the GW towards external networks), which will require the synergy and co-existence of both MB and SDM technologies.

The considerations made above regarding the need for multiband and SDM systems for the three network segments and in the three reference time horizons are summarized in Table 3.9

Table 3.9-: Required Technologies at Different Network Segments and Periods

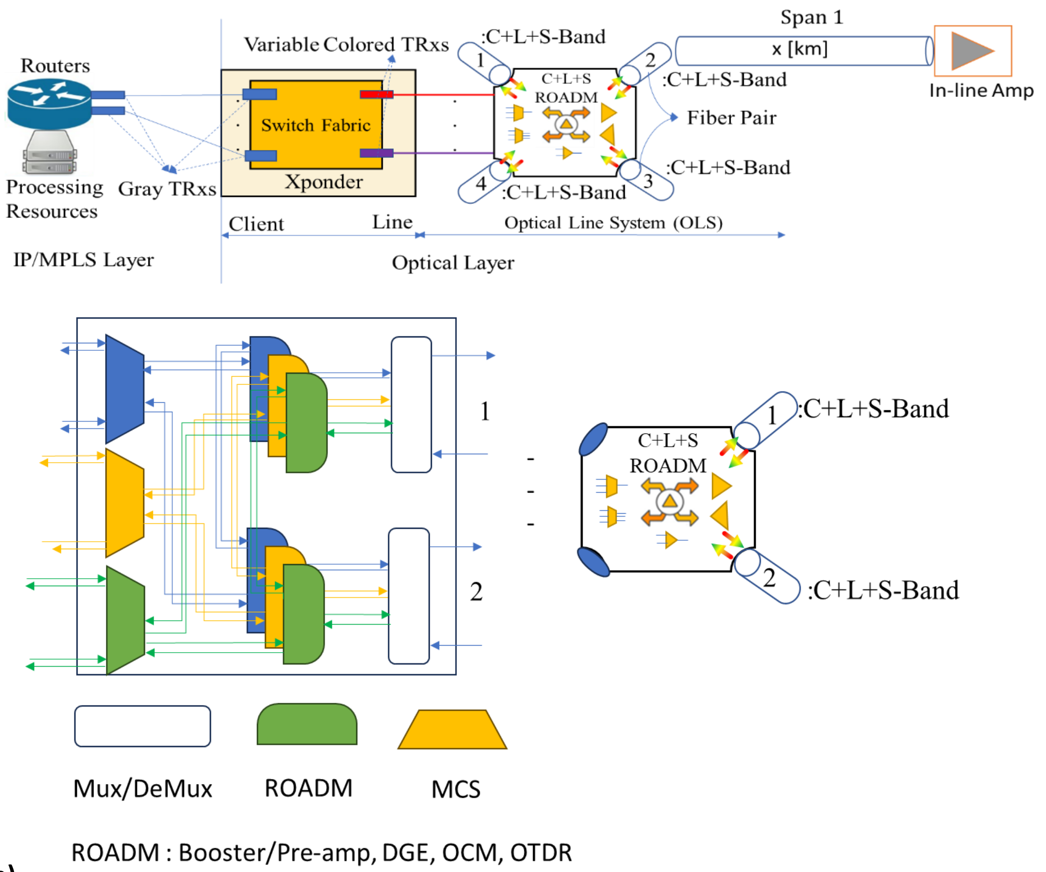
Network Segment	Short -Term	Mid-Term	Long-Term
MAN	C-band	C-band	(C+L)-bands/SDM (≤4)
MCN	(C+L)-bands / SDM (≤4)	MB (S+C+L or C+L) / SDM (≤4)	MB (O+E+S+C+L) / SDM (>4)
Backbone	(C+L)-bands/ SDM (≤4)	MB (S+C+L or C+L) / SDM (≤4)	MB (O+E+S+C+L) / SDM (>4)

3.1.2.2. Migration strategies from C-> C+L

Based on the current discussion in the field, two main migration strategies can be considered for transitioning from a C-band to a C+other-band system: (i) DayOne and (ii) pay-as-you-grow (see Figures 3.5 -to- 3.7). In the DayOne strategy, all optical terminal sites, including transponders/muxponders (Xponders), photonics, and ROADMs, as well as optical line systems (EDFAs, RAMAN, and digital gain equalizers), would be deployed in both the C-band and other bands. The second scenario involves revisiting terminal sites and optical line systems based on network requirements for upgrading. The operator begins with C-band technology, upgrading to other bands link by link if necessary. Currently, L-band technology is commercialized due to its similarity to C-band characteristics and comparable EDFA amplifier performance. The next step could involve the S-band. However, a techno-economic study for other bands is not clear for the moment, due to factors like demand volume and technology maturity for deploying hardware and software in each band.

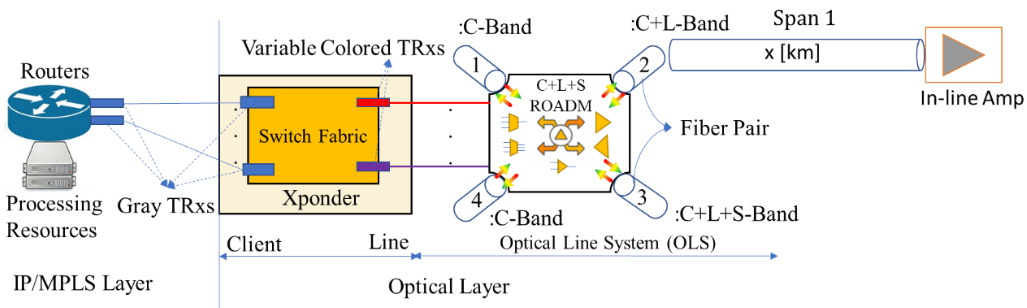
In both migration strategies, the fully loaded link state is recommended by suppliers and operators. This approach ensures that all channels are occupied by real channels, and idle ones are filled with ASE filler components, guaranteeing power profile consistency in each link and reducing network recovery time. Additionally, for migration from C-band to other bands in pay-as-you-grow, consideration must be given to the Quality of Transmission (QoT) degradation of existing C-band lightpaths. Ensuring QoT for these lightpaths can be achieved by introducing a sufficient margin in advance or migrating the C-band lightpaths to the L-band. Power optimization is another crucial aspect to consider in migration, and there are several open topics that should be addressed in future studies.

(a)



(b)

Figure 3.5: DayOne strategy.



(a)

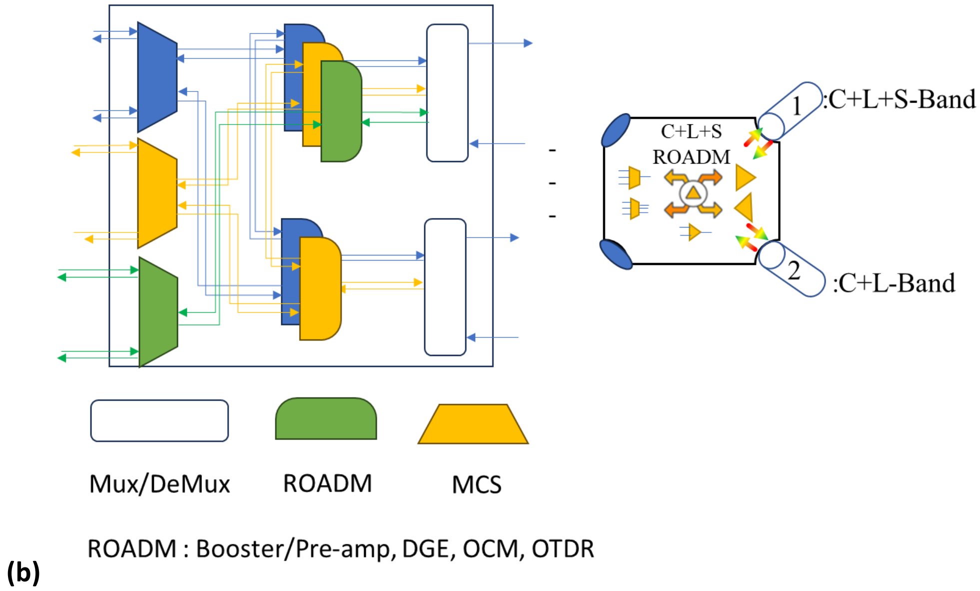


Figure 3.6: Pay-as-you-grow strategy.

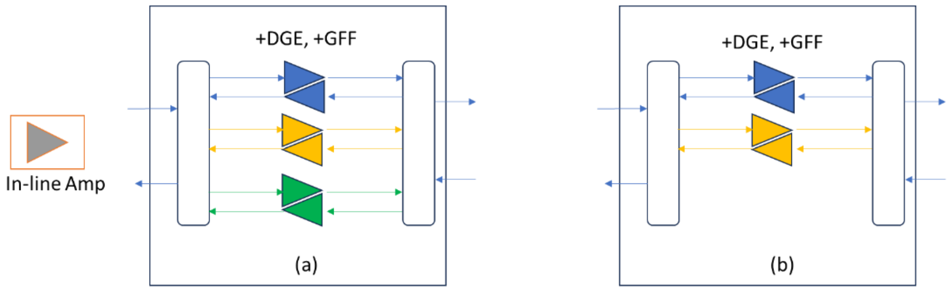


Figure 3.7: In-line amplifier sites for DayOne (a), and (b) Pay-as-you-grow strategies.

3.1.2.3. Resiliency and cost analysis of multi-band networks

The expansion to multi-band networks also has a critical impact on the resiliency requirements of optical transport networks, and hence on the cost of operating them at a given availability level. Notably, multi-band networks introduce additional SRS effects between the bands that make power transients in the event of failures much more impactful on surviving traffic. These transients, typically caused by failures in fibre links, can cause outages not only on the traffic being carried over the affected fibre, but also impact other channels in links downstream from the failure by offsetting their power. This effect is depicted in Figure 3.8a, where the disappearance of the failed channels in downstream links significantly alters the power profile of surviving channels due to reduced SRS effects (i.e. the difference between pre-post/failure spectrum on surviving channels in Figure 3.8a). This effect accumulates systematically over fibre links and can cause traffic outages on these channels until the line system can measure the new power profile and take corrective action.

This effect is much more pronounced in multi-band systems, since the magnitude of the SRS effect increases with the frequency distance. This is exemplified in Figure 3.8b, which shows, for a set of channels uniformly distributed in a C+L simulation over the CORONET topology (shown in Figure 3.8c), the difference in GSNR per optical path on each frequency, considering all possible single-link failures in the network. In the C+L system, extreme cases of almost up to 6dB less SNR are reported, while instances of drops >2dB are relatively common.

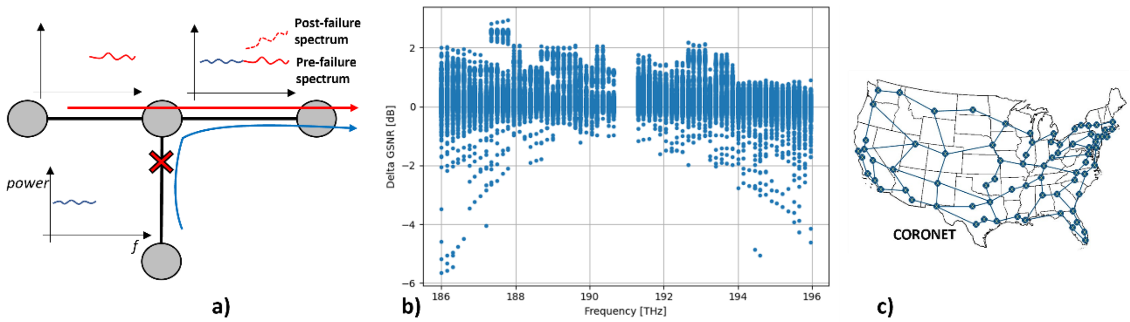


Figure 3.8: a) Illustration of Power Excursion due to SRS; b) Spread of GSNR difference per channel between pre/post failure in a C+L system; c) CORONET topology

The implication of this on network design is that, if operators require optical-layer survivability against this type of power transients (i.e., the effect of link failures on channels not directly affected by the failed link), either the line system must be fitted with transient suppression capabilities (based e.g. on amplified spontaneous emission (ASE) sources that keep the power profile steady in these failure events), or channels must be planned with additional GSNR margin, such that they can withstand the worst-case drop over any link failure. The latter incurs additional transponder costs, since channels will in some cases have to be operated at lower bit-rates, or necessitate intermediate regeneration.

Within this scope, the study in [Eir2023] provides an evaluation of the optical interface requirements for optical protection/restoration in C and C+L systems, assuming designs with and without transient-proof margins. The analysis looks at metro/core network designs implementing line-side optical protection or shared optical restoration. The baseline performance modelling employs the generalized Gaussian noise model (GGN) to estimate per frequency performance in each link and accumulated non-linear impairments. The baseline case assumes the normal operation of the line system wherein the launch powers are adjusted towards their optimized value, with a default system margin of 1dB and no additional margin reserved specifically for power transients. To estimate the required transient margins, each fibre link failure is simulated, and the post-transient state (i.e. with the new power profile before the line system can react) is estimated with the GGN model. The worst link GSNR drop recorded over all possible failures on each frequency is recorded and used to re-plan the network with the corresponding added link margins. Figure 3.9 shows the difference between C and C+L simulation scenarios with respect to the link GSNR differences observed, highlighting how the expected transient margins with C+L are substantially greater (both on average and extreme cases). The planning/re-planning procedures with/without transient margins are made resorting to an ILP model which optimizes the interface count for a given traffic matrix, in deployments with optical protection or shared optical restoration (wherein backup regenerators can be shared by services with link-disjoint working paths).

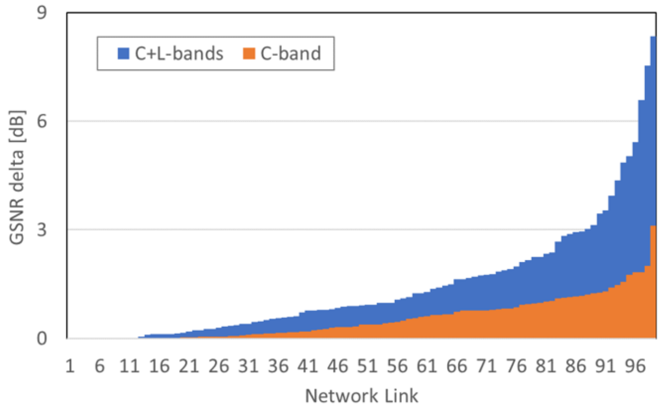


Figure 3.9: Link GSNR delta between pre-post/transient state for C and C+L cases.

The planning procedure applied to the CORONET topology assumes uniformly distributed (across all node pairs) traffic demands, with rates also uniformly divided between 0.1 and 1.6 Tb/s. Total loads of 45 Tb/s and 90 Tb/s were simulated for C and C+L cases respectively. Figure 3.10 shows the interface counts divided between working/backup transponders/regenerators for the C and C+L cases, and with/without transient margins. It is visible that adding the transient margins adds only 5% optical interfaces for the C-band case, but 32% for C+L scenarios. When adding protection or restoration, the increase in optical interfaces between C/C+L goes from +20% to +65% on the protection case, and from +15% to +54% on the restoration case. These results strongly suggest that moving to multi-band environments in resilient backbone networks requires careful pondering between line system transient suppression requirements and optical interfaces due to additional transient margins. The relative price points of each of these will be another key factor on the comparative efficiency of multi-band solutions as a capacity extension mechanism in optical transport.

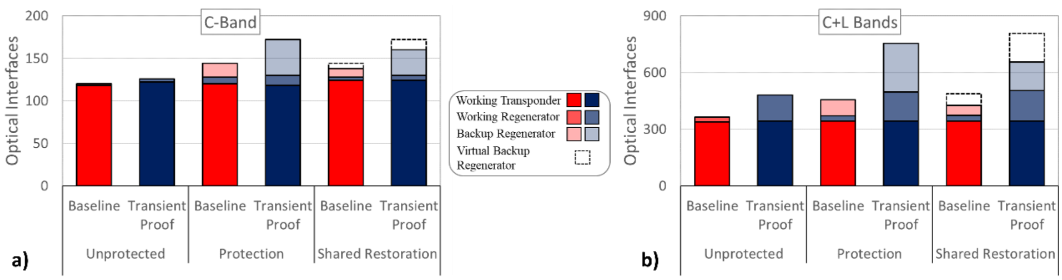


Figure 3.10: Optical interface requirements per protection scheme and band scenario: a) C-band only; b) C+L band

3.1.3. Design and operation of point-to-multipoint based networks

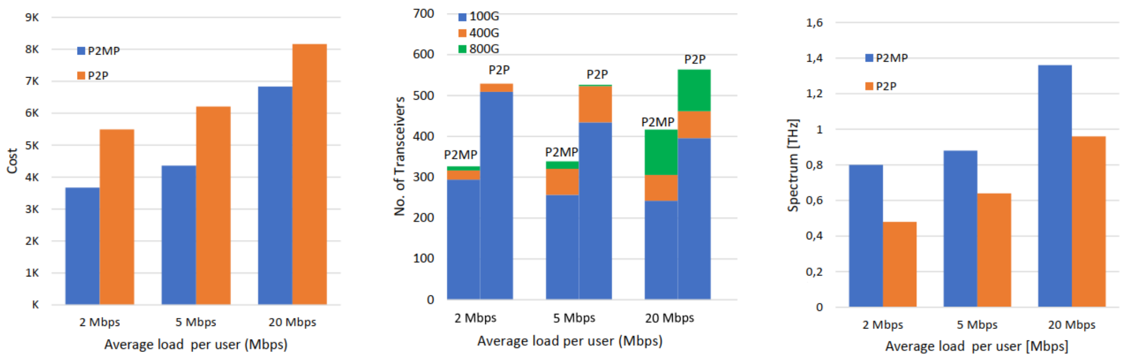
The Point-to-Multipoint (P2MP) architecture is increasingly recognized as a crucial design for modern optical networks, particularly in metro aggregation scenarios with varying traffic profiles. This architecture utilizes Digital Subcarrier Multiplexing (DSCM), enabling significant cost and complexity reduction in optical transport networks. The essential principle of P2MP is the division of a single carrier wavelength into multiple lower-bandwidth Nyquist subcarriers, managed and routed independently to different destinations, thereby optimizing the network efficiency and cost-effectiveness.

The advent of 5G and Machine-to-Machine (M2M) communication has driven the need for networks capable of handling increasingly high-capacity requirements. P2MP coherent optics have shown promise in this regard, notably in fault-tolerant ring network designs, which are vital in ensuring network reliability and resilience. These networks are designed to maintain service continuity even in the event of a node or link failure, a critical requirement for modern telecommunications infrastructure.

3.1.3.1. Design of fault-tolerant P2MP ROADM networks

Within the scope of the B5G-OPEN project, several tasks have been carried out to collectively contribute to a deeper understanding of the potential and practical application of P2MP coherent optics in optical network design, emphasizing its advantages in terms of cost, fault-tolerant design, efficiency, and flexibility over traditional P2P systems.

The study presented in [Pavon23] focuses on the application of P2MP coherent optics in optical networks, with a particular emphasis on tree determination, routing, and spectrum assignment. The research underlines the effectiveness of P2MP technology in enhancing network efficiency and fault tolerance, especially in metro aggregation scenarios. It demonstrates how P2MP optics can be used to optimize network design, showcasing its superiority over traditional Point-to-Point (P2P) systems in terms of capacity, efficiency, and flexibility. The paper employs simulations and case studies to evaluate P2MP system performance, highlighting its potential in cost-effectiveness and network design adaptability applied to fault-tolerant ring-based networks. For instance, Figure 3.11 shows some results of this technoeconomic analysis indicating the benefits of P2MP, where the cost savings are significantly evident in the various network contexts.



(a) (b) (c)

Figure 3.11: The (a) cost, (b) number of transceivers (and transceiver distribution), and (c) spectrum usage in the fault tolerant P2MP and P2P TRSA solutions obtained in [Pavon23]

Also, the work presented in [Pavon22a] introduces a novel network dimensioning algorithm designed specifically for subcarrier-based P2MP coherent optics. The algorithm optimizes network design by efficiently utilizing the capabilities of P2MP coherent transceivers, leading to considerable cost savings and enhanced network performance. The methodology includes developing a comprehensive dimensioning algorithm that addresses the complexities of P2MP transceivers in various network topologies. The effectiveness of this algorithm is validated through simulations in a metro-network case study, demonstrating substantial improvements in network design, particularly in cost reduction and performance enhancement, as depicted in Figure 3.12.

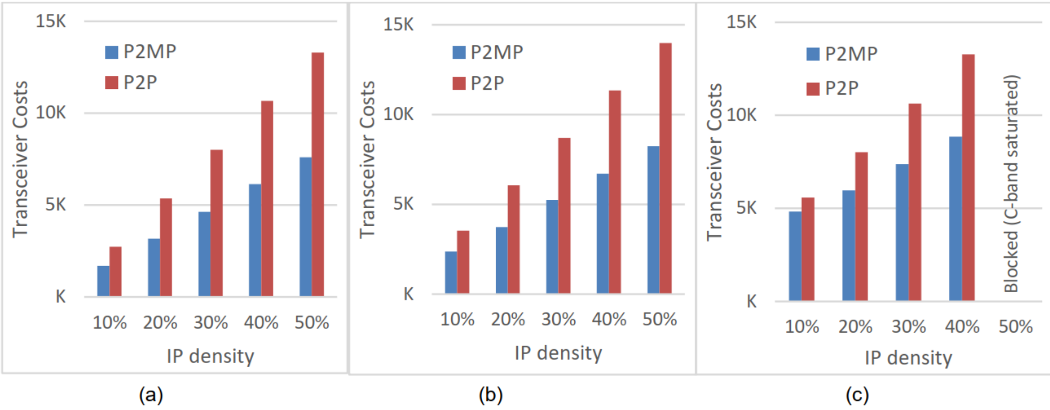


Figure 3.12: Transceiver costs for (a) short, (b) medium and (c) long-term traffic. Source [Pavon22a]

Finally, in the paper published in [Pavon22b] the benefits of P2MP coherent optics are explored within the context of multilayer capacity planning for ring networks with diverse traffic profiles evaluated on fault-tolerant ring networks. The study reveals that P2MP optics can significantly lower total transceiver costs, reduce optical-electronic-optical and IP processing latency, and decrease IP layer equipment costs for various traffic profiles. Figure 3.13 showcases how P2MP optics can lead to a multilayer redesign of networks, characterized by reduced spectrum usage and fewer IP hops. The research uses a mixed integer linear programming (ILP) approach and heuristic methods to conduct a comprehensive analysis, comparing P2MP and P2P transceivers across different network scenarios. The findings underscore the cost savings and network efficiencies (lower number of IP hops) achieved with P2MP technology, particularly in comparison to traditional P2P systems.

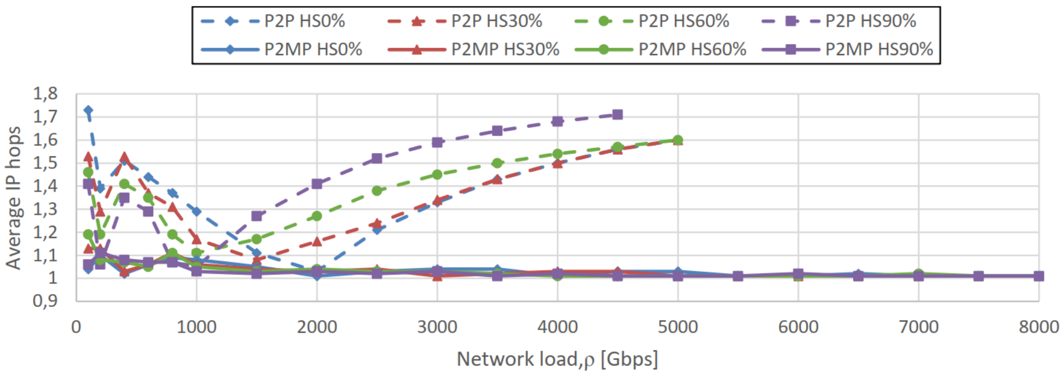


Figure 3.13: The average number of IP hops in the P2P to P2MP solutions. Source [Pavon22b]

3.1.3.2. Design of filterless light trees for P2MP deployment

The potential benefits of P2MP transceivers can also be exploited in simpler filterless topologies, comprised of splitter/combiner modules, as shown in Figure 3.14. These topologies are cheaper to deploy and operate, given the absence of active switching components, at the expense of a reduction in total capacity, due to the used spectrum getting propagated without filtering through links where it is not actively used.

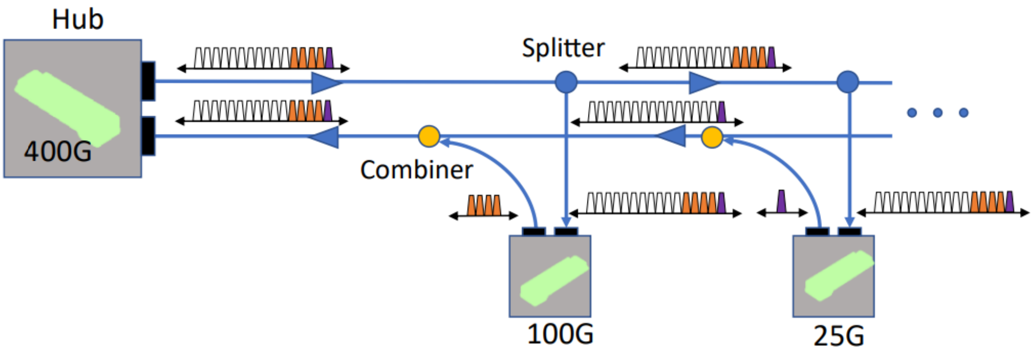


Figure 3.14: P2MP connectivity over filterless splitter/combiner based optical nodes.

Filterless designs can be overlaid over mesh optical topologies by designing filterless *trees*, i.e. network subsegments wherein an optical signal generated within the tree is freely broadcast, but not allowed to propagate outside it. By optimizing the design of the wavelength blockers implementing the tree topologies, it is possible to limit the amount of filtering components in the total mesh topologies and operate most optical nodes as simple splitter/combiner sites.

The design of such trees has been exploited before [Ibr21], inclusively with reliability requirements to provide (via multiple disjoint trees) redundant paths between a source and destination [Ita88]. However, in the context of P2MP transceiver deployment, these strategies need to be augmented with knowledge of the optical performance's impact on capacity. The design of a specific tree, which defines the working/protection paths between a P2MP hub and its multiple leaves, will set the achievable lightpath bitrate over the working/protect paths. This will, in turn, greatly affect the solution cost if trees are designed with generic optimization criteria (based on e.g. number of nodes). This is especially true for the case of P2MP deployments, since multiple hub/leaf protection pairs must be considered simultaneously with the hub as a common denominator. Hence the problem becomes much more intricate, and requires a specific routing, modulation format, and subcarrier assignment to properly minimize transceiver cost over such deployments.

The work in [Hoss22] implements an ILP based optimization method to design survivable filterless trees optimized for P2MP deployment. One visual example of this is shown in Figure 3.15, where working/protection paths between a hub and a leaf are implemented over two disjoint trees, and wavelength blockers are selectively placed in key points to prevent the formation of loops for the signal in each of the filterless domains.

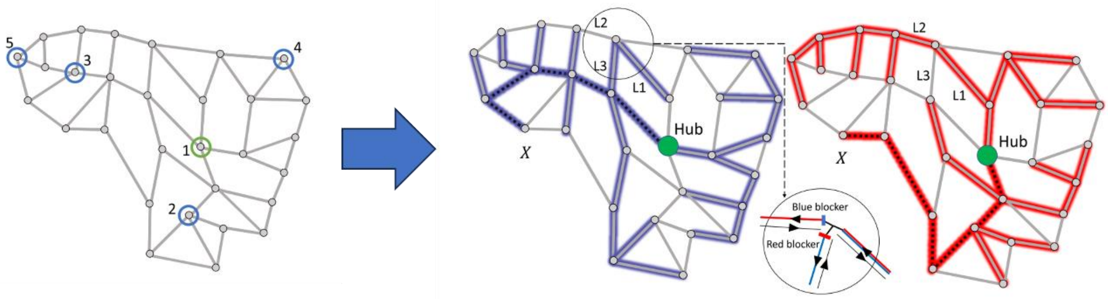


Figure 3.15: Exemplary design of working/protection filterless trees over a meshed topology

The network design based on this approach allows to exploit a critical operational use-case for metro aggregation networks (link failure survivability) while maintaining the cost and complexity of the optical nodes fairly low. The comparison between P2MP and P2P transceivers in this scenario showcases the potential of this technology in rationalizing transceiver cost as a share of the total network cost of ownership. Figure 3.16 shows the transceiver requirements for the survivable design use-case when employing P2P vs. P2MP transceivers. It is visible that, also in this network scenario, P2MP exhibits a better ability to simultaneously handle high capacity paths and lower ones with a single hub interface, without leading to severe underutilization of transceiver capacity whenever sub-100G connections are required. At the same time, the single transceiver on the hub node reduces the density requirements compared to unique P2P connections for every individual node-pair.

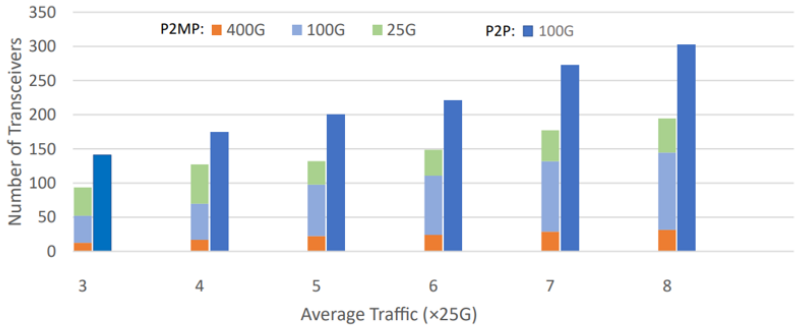


Figure 3.16: Number of transceivers required per traffic load for P2P and P2MP scenarios

Additionally, the reconfigurability of P2MP interfaces allows for interesting design trade-offs between CAPEX and OPEX. As discussed in [Hoss23], P2MP transceivers' flexibility can be exploited by dynamically adjusting the capacity of hub/leaf connections according to traffic requirements, in such a way that transceiver capacity is not underutilized. This can be coupled with a multi-period network design, where the expected traffic capacity evolution (allowing for some uncertainty) is accounted for in the initial design and deployment of the optical interfaces. Figure 3.17a shows the transceiver cost difference between P2MP and P2P based designs when doing an "all-period" planning vs. a single-period one (i.e. based on extensive forecasting vs. period by period). The observable trend is that P2MP exhibit consistent savings, but these are larger (in the region of 30%) for the single-period planning, when traffic uncertainty is higher. P2MP deployments are thus an hedge for operators against traffic evolution uncertainty. In Figure 3.17b, the trade-off between OPEX/CAPEX is exemplified, in a scenario where the P2MP leaf nodes can be relocated between sites at different periods. This operational strategy allows transceiver capacity to be reutilized where it is needed most, at the expense of physically reassigning the transceivers via professional technicians performing these changes in network maintenance windows.

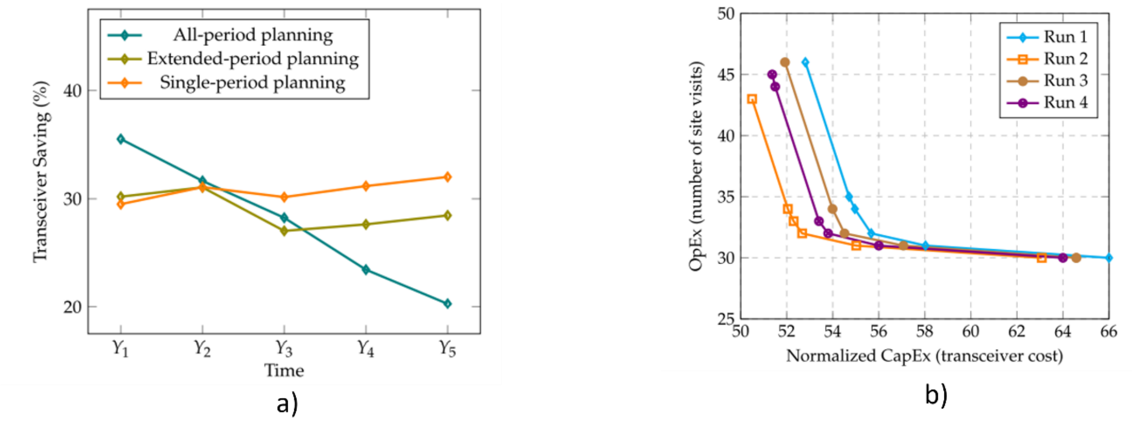


Figure 3.17: a) Transceiver savings per period from P2MP deployments vs. P2P per planning strategy; b) CAPEX/OPEX trade-off according to transceiver relocation strategy.

3.2. Definition of Final Techno-Economic Validation Studies

Based on the project proposal's objectives, several KPIs were defined to address the various impact areas of B5G-OPEN. The generic tracking mechanism and description/status of these KPIs is detailed in Section 6. Amongst these KPIs, some are particularly suited to be addressed via techno-economic validation, as enumerated in Table 3.10:

-Table 3.10: KPIs addressed via Techno-Economic validation.

KPI	Description	Evaluation Mechanism
2.1	Reduction of total power consumption from 30% to 50% with respect to SoA architectures (e.g., H2020 METRO-HAUL results) and legacy solutions	Network dimensioning/optimization study
2.2	CAPEX reduction above 50% in the end-to-end "domain-less" architecture relative to fixed-domain metro-access/regional/core segments	Network dimensioning/optimization study
2.3	2.3: Increase of 10× in-service bandwidth w.r.t. currently deployed C-band transport solutions	Network dimensioning/optimization study
3.1	MB Optical Switching Matrix with bandwidth covering S, C, L and O-band, supporting multiband operation on 50-100 GHz-grid, reducing the overall switching time to < 1 ms, enabling multiband reconfiguration with added flexibility (dynamicity) in order to improve effective and agile usage of the traffic pipes. The modularity of the architecture will help to scale the node capacity to 3 Pb/s in a pay as it grows approach. Moreover, photonic integrated technology improves the power consumption by a factor of >4 ×	Node dimensioning/validation
4.1	50% CAPEX reduction in the X-Haul infrastructure compared to NG-PON2 (baseline: 0,5€ cost per Mb/s, not considering fiber deployment costs), by leveraging on open disaggregated solutions over MB, pluggable technology, and avoiding stand-alone OLT/SBT	Network dimensioning/optimization study

4.2	100x offered capacity increase of fixed-line systems compared to NG-PON2 (baseline: 4x10G) by leveraging on standardized cost-effective 100GHz channel spacing technology and pay-as-you-grow strategy for MB	Network dimensioning/optimization study
5.2	OpEx reduction (in combination with O8 and ZTN) by minimizing the power consumption impact of this massive new monitoring platform	Numerical evaluation
6.3	50% CAPEX reduction by avoiding node solutions entirely designed for the optical market while leveraging and enhancing white box designed for the much wider computing market	Network dimensioning/optimization study
8.2	Reduce overheads/overprovision by >20%, by proactively adapting the capacity to the demand	Network dimensioning and dynamic simulation study
8.3	Reduce OpEx by >20%, by increasing autonomous operations and reducing manual intervention	Cost Modelling and Network simulation
8.4	Improve and guarantee service and network availability (> 6x9s availability will be reached by combining MB and PtMP with anticipated degradation detection and proactive decision making).	Dynamic network simulation

Based on these topics, a set of targeted activities will be carried out in the scope of Task 5.1 towards final reporting in Deliverable 5.3:

- Network dimensioning studies in the **metro-core** segment to assess the cost/capacity/power consumption of multi-band networks, packet-optical integration and "Optical continuum" networks (KPIs 2.1, 2.2, 2.3, 3.1 and 6.3).

- A power consumption evaluation of the multi-band optical node validating the intended 4x improvement factor vs. traditional ROADMs. (KPI 3.1)

- Network dimensioning assessing the cost/capacity and power consumption in access and/or X-Haul segments, leveraging point-to-multipoint interfaces, multi-band capabilities and integrating/virtualizing (KPIs 4.1 and 4.2)

- A dynamic simulation study assessing how much power consumption a distributed traffic monitoring with centralized decision can save against a statically operated network (KPI 5.2)

- A dynamic optimization/simulation study evaluating how point-to-multipoint transceivers based on DSCM can provide sub-carrier level traffic adaptation to reduce the overprovisioning from designing networks for peak capacity. (KPI 8.2)

- A cost model and simulation framework that allows to estimate the OPEX effect of predictive failure analysis by allowing to schedule maintenance windows instead of reacting to failures (KPI 8.3)

- A dynamic network simulation that evaluates the availability by comparing the lightpath service outage time with vs. without failure prediction, assuming some traffic can be preventively protected/restored/re-routed. (KPI 8.4)

4. B5G-OPEN HW AND SW COMPONENTS

4.1. B5G-OPEN WP3 COMPONENTS

This section gives a high-level summary of the developed prototypes for B5G-OPEN data plane, as reported in Milestone MS3.1. For each prototype, the name, the category (i.e. either software or hardware), the partner responsible for its development, the segment it can be applied to and any additional comments, is defined. The summary is reported in Table 3.11.

-Table 3.11mercial hardware to be used

ID	What	SW/HW	Partner	Segments	Comments
C3.1	OLC-E Physical Layer Design Tool	SW	OLC-E	metro / core	impairment validation tool
C3.2	Point-to-multipoint design tool	SW	INF	access / metro	filterless network; to validate P2MP performance
C3.3	Receiver DSP-based line system monitoring	SW	HHI	Metro / core	DSP block
C3.4	Multiband S-BVT	HW	CTTC	metro	using OFDM; 2 slices C+S; API in OpenConfig
C3.5	Programmable packet-optical node with coherent pluggables	HW	CNIT/ TIM	metro	openconfig
C3.6	Point-to-point and point-to-multipoint coherent pluggable	HW	INF	any	
C3.7	S-C-L-band offline transceiver	HW	HHI	metro / core	point-to-point
C3.8	7-node mesh network	HW	Nokia	metro / core	C-band only; 8 real channels else noise loading; openconfig for transponders; openROADM for nodes
C3.9	Filterless OADM PIC	HW	BT/TUE	metro	
C3.10	Reconfigurable multiband ROADM	HW	TUE	Metro / access	up to C+L+S+O with SOA; fixed grid; max 40 channels; OpenROADM 4 prototypes in C band, 2 in O-band, 1 in L-band
C3.11	Multiband optical space switch	HW	TUE	Metro / core	O to L band; 4x16
C3.12	(Semi-) filterless add/drop node	HW	HHI	Metro / core	S+C+L band
C3.13	LiFi system	HW	PLF	access	

4.2. B5G-OPEN WP4 SW Components

This section gives a high-level summary of the developed prototypes for B5G-OPEN control plane, as reported in Milestone MS4.2 and detailed in D4.2. For each prototype, the identifier, the name, the partner responsible for its development, and the purpose of the component is defined. The summary is reported in Table 3.12.

Table 3.12: List of WP4 prototypes

ID	Component	Partner	Purpose
C4.1	B5G-ONP network planner	ELIG	The B5G-OPEN Optical Network Planner (B5G-ONP) component orchestrates both IT and network resources. Within the B5G-OPEN project, the B5G-ONP serves as the hub provides design, optimization, and planning tools to deploying, managing and configuring services and resources.
C4.2	TAPI enabled Network Orchestrator	CTTC	The TAPI-enabled Optical Network Orchestrator is responsible for: i) providing a uniform, open and standard view and interface to the higher levels and components; ii) Compose a complete Context to be consumed by B5G-OPEN network planner and additional consumers combining information retrieved from subsystems and sub-controllers; iii) Enable single entry point for provisioning DSR and Photonic Media services, including externalized path computation and iv) provide an event telemetry data source that reports events that happen asynchronously in the network.
C4.3	Path Computation Element	OLC-E	The Multi-Band Path Computation Engine (MB-PCE) is based on a multi-band routing engine which ensures that: i) routing is implemented by means of an efficient spectrum and modulation-format assignment; and ii) the impact of physical layer effects over the selected optical paths is estimated and the results are benchmarked against QoT target values (BER, OSNIR, OSNR, etc).
C4.4	ONOS Optical Controller	CNIT	The optical controller is based on ONOS open-source project [ONOS] that, besides the control of optical devices, also provides a suitable environment for the control of packet devices (e.g., based on OpenFlow or P4Runtime protocols). The main roles of the optical controller in the B5G-OPEN project are: (i) retrieve devices description from data plane and abstract them toward the upper control layers; (ii) receive the service configuration requests by the upper control layers and translate such requests in a set of configuration messages to be forwarded to each involved device.
C4.5	OLS Controller	Adtran CTTC	The OLS controller used in B5G-OPEN for an Adtran OLS is based on the Adtran Ensemble Network Controller software solution and offers a northbound ONF Transport-API (TAPI) towards the Optical Controller.
C4.6	PON Controller	OLC-E	The Access Controller is responsible for: a) monitor the PON network and receive any requests for PON reconfiguration; b) translate these requests into high level traffic requests that will be reported to the B5G-ONP App; c) execute the appropriate actions in the PON Controller in order to support the new requests. In addition, the Access Controller will

			communicate with the LiFi Controller for retrieving any connection/traffic requests
C4.7	LiFi Controller	PLF	The LiFi controller serves as the central component responsible for managing LiFi APs in the network. It is strategically positioned between the PON controller and the LiFi AP. This specific positioning ensures seamless communication and enhanced coordination between the optical network layer and the wireless LiFi communication layer
C4.8	LiFi agent	PLF	The LiFi Agent acts as a central hub in the architecture of the LiFi AP. With the advancement of NETCONF capabilities, the agent provides a seamless way for the AP to interact with other components, offering a structured interface for configurations and management
C4.9	OpenROADM agent	TIM	The OpenROADM agent is an implementation of a NETCONF server controlling optical network elements using OpenROADM device models
C4.10	OpenConfig agent	CTTC CNIT	OpenConfig agent is an implementation of an SDN agent using NETCONF/YANG with the OpenConfig data models. It implements a subset of the data models, namely the OpenConfig platform and optical transport as well as some extensions devised in the context of B5G-OPEN to report details about the transceiver operational mode
C4.11	SONiC based packet optical node	CNIT	The Software for Open Networking in the Cloud, i.e., SONiC, [SONIC] is considered as the Network Operating System (NOS) to be deployed on packet-optical IPoWDM nodes operated in metro/aggregation networks. Within the B5G-OPEN project SONiC has been extended with several components provided in the form of docker containers.
C4.12	AI/ML models for PSD and Power Management	NOKIA	Machine learning application towards augmented optical networks and is called "Automatic power correction"
C4.13	Telemetry System	UPC CTTC Adtran Nokia	B5G/OPEN distributed telemetry system integrates measurements and event data collection and supports intelligent data aggregation nearby data collection, so agents receive and analyze measurements before sending to a centralized manager.
C4.14	Mesarthim – Failure management Using a SNR Digital Twin	UPC	MESARTHIM compares the QoT measured in the transponders with the one estimated using a QoT tool. Those deviations can be explained by changes in the value of input parameters of the QoT model representing the optical devices, like noise figure in optical amplifiers and reduced Optical Signal to Noise Ratio in the Wavelength Selective Switches. By applying reverse engineering, MESARTHIM estimates the value of those modelling parameters as a function of the observed QoT of the lightpaths
C4.15	Ocata - Digital Twin for the Optical Time Domain	UPC	OCATA is a deep learning-based digital twin for the optical time domain that is based on the concatenation of deep neural networks (DNN) modelling optical links and nodes, which facilitates representing lightpaths. The DNNs model linear and nonlinear noise, as well as optical filtering

5. B5G-OPEN HW-SW INTEGRATION

5.1. FILTER-LESS METRO-ACCESS NETWORK

5.1.1. Description

Figure 5.1 shows both the hardware and software elements that have been successfully integrated in a preliminary demonstration showcasing the innovative B5G-OPEN filterless metro-access network.

The hardware components of the demo consist of:

- the Infinera XR optics that will be hosted by Nokia 7750 SRS1 routers.
- the service traffic generators will be a Viavi with 400G ports and a Xena with 100G ports.
- the optical access systems will be a Tibit and a Nokia XGS-PON systems.
- the filter-less OADMs as described in D3.2, developed within the consortium.
- We will be using 5G RAN components (i.e. CU-DU-RU) hosted in the BT wireless research laboratory that will be connected to the optical network research laboratory via PtP fibres.

The software components of the demo consist of:

- The B5G-OPEN network controller B5G-ONP that will be hosted by E-Light, developed within the project.
- The XGS-PON controllers developed by OLC-E within the project.
- The Filter-less OADM controller using TAPI.

The other demo components will not be connected to the B5G-ONP as outside the project and other methods will be used (e.g. P2MP CPT technology will be controlled using CLI).

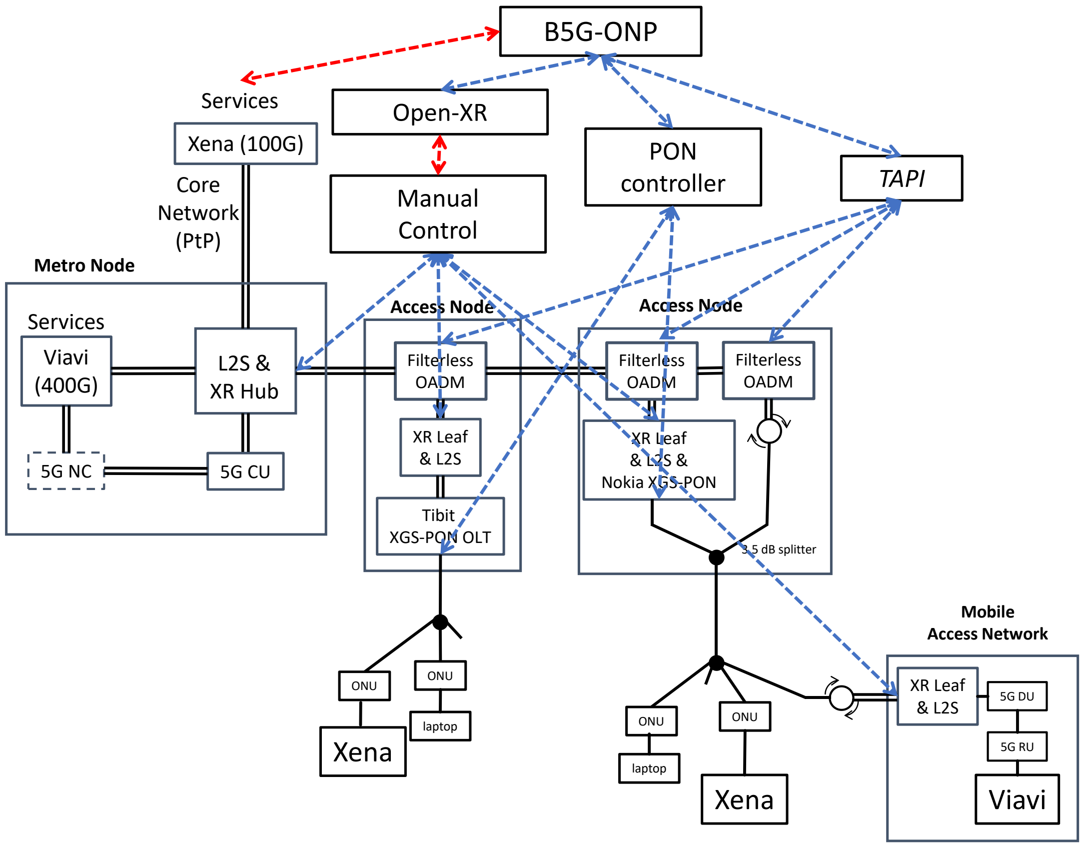


Figure 5.1: Network Control demo setup

5.1.2. Status of integration and next steps

The control aspects of the demo are being developed within WP4.

The integration of the P2MP CP technology and the Nokia routers in a P2MP configuration is currently being tested.

5.2. PON-LIFI INTEGRATION

5.2.1. Description

In the seamless integration of PON technology with LiFi infrastructure, a harmonious orchestration between LiFi AP, LiFi Controller, Access Controller, and the PON Controller is planned to ensure efficient network capacity allocation and utilization. The following steps delineate the integration process:

1) LiFi AP Activation: LiFi APs are activated and inform the LiFi controller.
2) Capacity Estimation by LiFi Controller: The LiFi Controller estimates the data transmission requirements of the activated LiFi APs. This estimation, denoted as 'X Mbp/s,' reflects the anticipated demand for LiFi communication to ensure smooth operation.
3) Request to Access Controller: The LiFi Controller communicates the estimated capacity demand to the Access Controller through a REST/JSON interface. This request signifies the need for additional network capacity to support LiFi communication.
4) Capacity Planning and Forwarding to PON Controller: The Access Controller, upon receiving the request from the LiFi Controller, evaluates the impact on the access network and

estimates the additional capacity required in the Optical Network Units (ONUs). Subsequently, it forwards the capacity augmentation request to the PON Controller, including details about the estimated capacity demand and the affected network elements.

5) DBA Parameter Estimation by PON Controller: The PON Controller calculates the necessary Dynamic Bandwidth Allocation (DBA) parameters to meet the increased demand for data transmission. These parameters ensure efficient utilization of optical network resources.
6) ACK from PON Controller to Access Controller: The PON Controller acknowledges the capacity augmentation request, confirming its understanding and acceptance. This acknowledgment is sent back to the Access Controller.

7-1) ACK from Access Controller to LiFi Controller: The Access Controller communicates the acknowledgment of the capacity request to the LiFi Controller. This exchange ensures that the network elements are synchronized, and preparations can be made for LiFi AP activation.

8-1) LiFi AP Activation by LiFi Controller: With the received acknowledgments and the assurance of enhanced network capacity, the LiFi Controller proceeds to activate the LiFi APs. This step enables the LiFi APs to contribute to data transmission within the network.

7-2) Traffic Update Notification to B5G-ONP: Simultaneously, the Access Controller notifies the B5G-ONP about the updated traffic conditions resulting from the LiFi AP activation. This update ensures that the broader network is aware of changes in the traffic pattern.

8-2) Capacity Adjustment Request by B5G-ONP: The B5G-ONP, having received the notification, may initiate a request to adjust the overall network capacity based on the updated traffic conditions. This step ensures the overarching network can adapt to variations in demand effectively.

The storyline for PON integration with B5G-ONP and LiFi is as described. The integration optimizes network resources, dynamically allocating capacity to support the demand for LiFi communication within the network ecosystem. The orchestrated collaboration between LiFi components and PON technology facilitates a responsive and adaptive network infrastructure.

This integration work contains the following development from other work packages: PON controller, Access controller, LiFi prototype with LiFi controller and LiFi agent.

WP3 component: C3.5 Programmable packet-optical node with coherent pluggables

WP4 component: C4.4 ONOS Optical Controller, C4.9 OpenROADM agent, C4.10 OpenConfig agent,

5.2.2. Status of integration and next steps

The message sent by LiFi controller which communicates to the Access Controller covering the capacity demand through a REST/JSON interface contains the following information:

- The field “onu_id” will be fixed.
- The field "Up Service Limit" is the maximum latency (in ms).
- "Down Sustainable Data Rate" is the Average expected throughput in Downlink in Mb/s
- "Down Max Data Rate" is the Max throughput in Downlink in Mb/s
- "Up Sustainable Data Rate" is the Average expected throughput in Uplink in Mb/s
- "Up Max Data Rate" is the Max throughput in Uplink in Mb/s

An example is given below:


```
{
  "sla": {
    "onu_id": "3fa85f64-5717-4562-b3fc-2c963f67afa3",
    "Down Sustainable Data Rate": 30,
    "Down Max Data Rate": 43,
    "Up Sustainable Data Rate": 25,
    "Up Max Data Rate": 43,
    "Up Service Limit": 128,
  }
}
```


The next step the integration of LiFi components with Access controller which is scheduled for Q1 2024.

5.3. IPoWDM Access/Aggregation

5.3.1. Description

This section describes the first integration of the programmable packet-optical hardware node with coherent pluggables (B5G-OPEN Component C3.5) with the control plane components in charge of configuring it (Components C4.4, C4.10, C4.11).

Figure. 5.2 shows the reference network scenario reproducing the *Single* SDI Architecture investigated within B5G-OPEN and later on adopted by the Telecom Infra Project in the MANTRA working group [MANTRA]. Router consists of a Edgecore 400Gb/s IPoWDM white box equipped with 400ZR and 400ZR+ coherent pluggable modules. The white box runs the open-source NOS SONiC version 20220819. This version of SONiC includes the support to OIF CMIS version 5 and C-CMIS version 1.1 implementing the interface between the NOS and the pluggables. In addition to the default SONiC applications (i.e., swss, soniccfggen, pmon, syncd, and redis database), the innovative B5G-OPEN implementation includes, as containerized function, the NETCONF agent providing both configuration and monitoring of optical pluggable transceivers. The agent leverages on the OpenConfig model to describe hardware characteristics including packet-based interfaces and coherent pluggable modules. All the deployed SDN controllers (i.e., IP-C, Opt-C and Hier-C) are based on ONOS. They rely on specifically designed applications enabling the communication between IP-C and Opt-C, through the Hier-C. The Hier-C exploits a specifically designed Hierarchical App (H-App) developed in WP4. It stores the network status and it communicates with both IP-C and Opt-C via REST APIs. In particular, the H-App encompasses a module to discover and manage child controllers and to locally store network element information on link and devices, including details about the coherent optical modules installed in the router that represent the demarcation point between the packet and the optical domain. Furthermore, when a new connection request arrives, the H-App performs end-to-end path computation across both the IP and WDM layers. Finally, the H-App stores the result of the connections installed in the network. The IP-C also exploits a specifically designed IP-C App which (i) manages the communication with the Hier-C and (ii) provides NETCONF connectivity to retrieve and configure the configurable optical parameters of the pluggable modules, including their type, location, and status. For example, dedicated software modules are responsible to notify the Hier-C in case of intent enforcement or changes to link status upon discovery or failure.

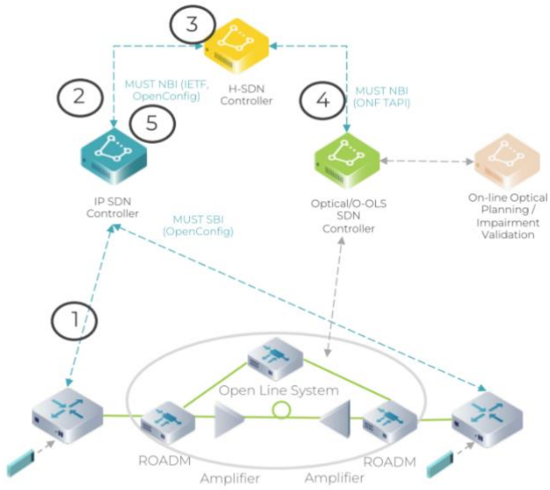


Figure 5.2. Control Performance of coherent pluggable modules in IPoWDM white box [D4.1, MANTRA]

The preliminary experimental validation of the MANTRA IPoWDM Convergent SDN Architecture has been assessed at the TIM Lab considering both control and data plane performance. From a control plane perspective, the *Single* solution has been validated analyzing the interactions among the three controllers. Controller communicate using REST APIs to: (i) discover the network topologies; (ii) discover detailed parameters of pluggable modules and their interconnection points to the optical layer; (iii) setup an optical connectivity; (iv) configure the pluggable modules; and (v) set up the packet connectivity. The whole experimental procedure to setup an end-to-end connectivity service involving the activation of a new lightpath and traversing two distinct packet islands has been repeated ten times taking an average time of about 4 Fig. 1. MANTRA Single SBI management of IPoWDM routers [9], [10] seconds. This time includes the time required to exchange all the control messages but does not include the time needed to physically activate the laser in the pluggable modules. From a data plane perspective, focus has been devoted to the performance of 400ZR/ZR+ transceivers in terms of configuration time. During the experimental evaluation, the setup of an end-to-end connectivity has been repeated several times, performing the variation of the central frequency adopted for the optical connection. More specifically, the optical carrier has been moved, performing the (re)-configuration using the library provided by SONiC. The frequency shifts have been performed considering both nearby frequencies and distant frequencies in order to check whether the reconfiguration time depends from the frequency gap to be covered. The optical configurations have been performed considering the two types of pluggable transceivers (i.e., two ZR and two ZR+ modules). For each run, two time interval values have been collected: the first (named prompt in the table) is the time interval taken by SONiC to receive the command and return the prompt after a frequency change command; the second (named laser in the table) is the time interval passed form the command issue and the signal detection at the RX. In addition, an Optical Spectrum Analyzer (OSA) has been adopted on the optical link to monitor the spectrum occupancy. Considering the two ZR modules, performing a frequency reconfiguration with 2 THz gap (passing from 193.0 THz to 195.0 THz) has taken around 10 seconds (10.39 and 9.6 seconds, respectively) at the prompt level, while a longer time interval (around 67.6 seconds) has been experienced to have the optical signal successfully transmitted to the other module.

		ZR sample 1		ZR sample 2		ZR+ sample 1		ZR+ sample 2	
Start F	Stop F	prompt	laser	prompt	laser	prompt	laser	prompt	laser
THz	*THz*	*s*	*s*	*s*	*s*	*s*	*s*	*s*	*s*
193.0	195.0	10.39	67.65	9.60	67.63	9.78	16.15	9.45	15.69
195.0	193.0	9.67	67.87	9.46	70.58	9.38	15.31	9.46	13.20
193.0	193.1	9.50	69.43	9.39	69.54	9.45	15.26	9.52	15.70
193.1	196.0	9.78	68.04	9.47	69.54	9.64	15.66	9.51	19.10
196.0	192.0	9.47	71.06	9.79	67.34	9.51	15.90	9.52	15.21

Figure 5.3. Control Performance of coherent pluggable modules in IPoWDM white box

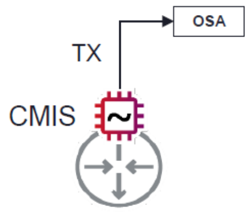
The reverse operation, passing from 195.0 THz to 193.0 THz, has presented similar time for the reconfiguration, with a command issuing time of about 9.5 seconds (respectively 9.67 and 9.46 seconds) and a laser activation time slightly greater that 67 seconds (respectively, 67.87 and 70.58 seconds). Even considering smaller frequency gap (from 193.0 Thz to 193.1 THz with 0.1 THz of gap) or bigger frequency gap (from 196.0 THz to 192.0 THz, with 4 Thz of gap) has not differently impacted the reconfiguration time, with values collected in the same order of magnitude (prompt issuing time around 10 seconds and laser activation time around 70 seconds). Considering instead the two ZR+ modules, the frequency reconfiguration with 2 THz gap (passing from 193.0 THz to 195.0 THz) has achieved similar performance in terms of prompt results (respectively 9.78 and 9.45 seconds). However, significantly better performance has been experienced considering the optical transmitted signal achieving configuration time around 15 seconds (i.e., 16.15 and 15.69 seconds, respectively). As collected for the ZR modules, the reverse operation, passing from 195.0 THz to 193.0 THz, has presented similar time for the reconfiguration, with the prompt issuing time in the order of 10 seconds (respectively, 9.38 and 9.46 seconds, respectively) and a shorter laser activation time (respectively, 15.31 and 13.20 seconds). Even considering small frequency gap (from 193.0 THz to 193.1 THz with 0.1 THz of gap) or bigger gap (from 196.0 THz to 192.0 THz, with 4 THz of gap) has not differently impacted the reconfiguration time, with similar values collected: prompt issuing time around 9.5 seconds and laser activation time around 15.5 seconds). Further analyzing the results collected using the two classes of pluggable transponders (e.g., the ZR and ZR+ modules), it is clear that the modules present considerable differences. Specifically, ZR+ modules guarantee a faster laser activation time. Moreover, the table shows that the (re)-configuration time interval does not depend on the gap between the starting and stop frequencies. In addition, the collected results show that modules of the same type present similar behavior, showing a stable and uniform configuration time. During the experiments, the modules presented some issues on configuring the frequency values at the extremes of the tuning bands, with respect to the nominal values configured and stored in the transceivers. This produced some critical states: in some cases the modules became unavailable and a manual intervention was needed in order to remove and reinsert the modules in the box to make them again available.

The preliminary integration work described in this section has been published in R. Morro, E. Riccardi, D. Scano, A. Sgambelluri, P. Castoldi, F. Cugini, A. Giorgetti, “First Demonstration of MANTRA IPoWDM Convergent SDN Architecture using SONiC White Box and 400ZR/ZR+ Pluggables”, ONDM Conference 2023.

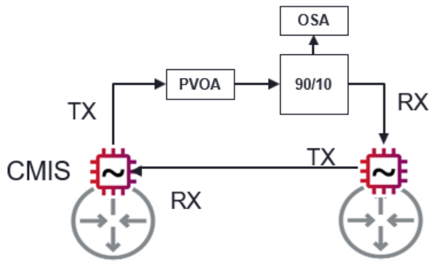
Additional performance assessment of IPoWDM solutions have been performed at the TID Lab. Furthermore, in order to investigate if the proposed architecture is suitable for the reference networks of B5G-OPEN, a set of additional performance tests are being executed at the TID lab described in Section 1.

Four different tests have been executed:

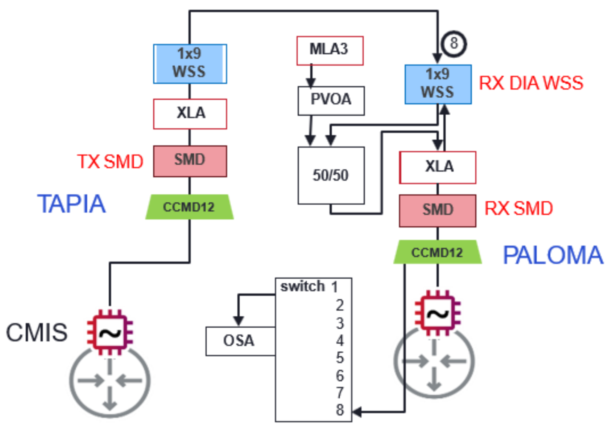
1) Transmission Performance: To test the TX OSNR and assess the laser tunability for full FlexGrid support. See test diagram below.



2) RX Optica Power Sensitivity: To evaluate the technical specifications compliance and to validate the amount of optical power required at the DCO pluggable receptor before the appearance of Pre FEC errors. See the test diagram below.



3) RX OSNR Sensitivity: To characterize the technical specifications compliance and to validate the amount of noise present at the DCO pluggable receptor before the appearance of Pre FEC errors. See the test diagram below.



4) Transmission Performance Testing: This test provides information about the maximum number of hops and ROADMs the signal can go through and the distance the DCO pluggable can reach.

To summarize, from the tests we have carried out so far in the laboratory environment with the different manufacturers, we have the following preliminary results:

- All ZR+ -10dbm pluggable suppliers can reach up to 160km across two ROADMs.
- The list of pluggable is significantly reduced to reach distances greater than 240km with optimal OSNR margin conditions.

- Some suppliers using ZR+ -10dBm pluggable, have achieved lengths of 320km and passed through 4 ROADMs.
- We are currently running tests of ZR+ 0dBm pluggable with which we can feasibly achieve distances greater than 480km with optimum OSNR levels and 6 ROADMs.
- Regarding control plane, the telemetry of the optical parameters is being tested. A dashboard with Grafana has been prepared to show it.

Figure 5.4: Sample of telemetry from coherent plugable.

The list of used B5G-OPEN Components are:

WP3 component: C3.5 Programmable packet-optical node with coherent pluggables

WP4 component: C4.4 ONOS Optical Controller, C4.9 OpenROADM agent, C4.10 OpenConfig agent,

5.3.2. Status of integration and next steps

Integration progressing well. Control of hardware modules (e.g., coherent pluggables) is operational in terms of central frequency and output power. Work is ongoing to:

(i) enable the control of the operational mode (also called application code)

(ii) provide a complete integration among the overall B5G-OPEN control plane solutions (e.g., including the path computation element, TAPI Controller, etc)

5.4. Computing and Networking Integration

5.4.1. Description

The focus of this section shifts to the progression of the integration phase on computing and networking subsystem orchestrated by the B5G-ONP (component C4.1) described in WP4 and outlined in Figure 5.5. This integration phase emphasizes the successful functional validations of the B5G-ONP component, underscoring its role in facilitating cohesive interactions with other entities in the B5G-OPEN framework, TAPI enabled Network Orchestrator (C4.2), Path Computation Element (C4.3), OLS Controller (C4.5) and the PON Controller (C4.6). The computing domain is assumed to be given as part of the operator infrastructure and managed by the container orchestrator.

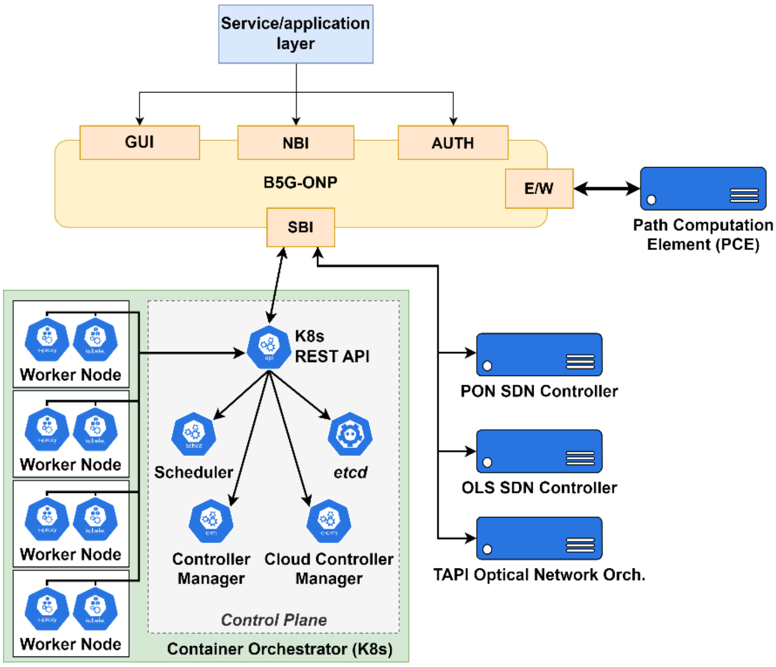


Figure 5.5: Architecture and interconnection of B5G-OPEN computing and networking subsystem

The primary objective of the computing and networking subsystem is to efficiently and harmoniously manage both IT and network resources within the overall infrastructure in network slice provisioning operations. This is aimed at achieving a comprehensive optimization of the infrastructure's usage. Within the B5G-OPEN framework, resource management is conducted collaboratively from two distinct management plane perspectives:

- IT resources, which may be distributed across one or more clusters at various locations within the IT infrastructure, are managed by the container orchestrator system.
- Network resources, encompassing different layers and domains, are governed by controllable SDN controllers.

According to Figure 5.5, The B5G-ONP connects with the application/service layer (operators) using the Graphical User Interface (GUI) and the Northbound Interface (NBI) and with the PCE by using the standard TAPI server - OPCE interface. Additionally, it interacts with other control plane elements, including the PON Controller, OLS Controller, TAPI Optical Network Orchestrator, and the container orchestrator, through the Southbound Interface (SBI).

5.4.2. Status of integration and next steps

The current status of the integration of the components mentioned in this use case is detailed in deliverable D4.2 and is mainly targeted to demonstrate the interaction of the B5G-ONP, implemented as part of the e-Lighthouse Network Planner [ENP], and the rest of component by using the defined and available interfaces. The main findings are outlined below:

- **Kubernetes Integration**: B5G-ONP utilizes the REST API of the *kube-api server* for automating deployment, scaling, and management of applications. This integration is aimed at constructing more efficient and scalable IT infrastructures. The endpoints provided by Kubernetes are crucial for resource discovery, resource provisioning, and retrieval of performance metrics within the Kubernetes cluster. So far, the B5G-ONP component is able to register K8s in its internal model and to orchestrate basic commands by using the *kube-api* interface.
- **TAPI Optical Network Orchestrator**: it provides a standardized method for gathering information from subsystems and sub-controllers like B5G-ONP, using TAPI 2.1.3 to export the optical topology. B5G-ONP can perform the complete topology discovery and trigger the provision of TAPI-based connectivity services. This integration has been validated in demonstrations of B5G-OPEN SDN demonstrations [EuCNC23][Gio23].
- **OLS controller**: based on the Ensemble Network Controller software, offers a northbound ONF Transport-API (TAPI) towards the Optical Controller. The OLS controller's topology is based on the ONF TAPI 2.1.3 model, and B5G-ONP can import the OLS topology from this model, in a similar way than in the TAPI Optical Orchestrator. The integration of the OLS controller in B5G-ONP is seen as a starting point.
- **PON SDN Controller Integration**: The PON SDN Controller is responsible for network management and automation within its domain. It utilizes NETCONF/REST server interfaces for the B5G-ONP component to provision and configure Passive Optical Networks (PONs). This integration is planned for future stages of the project.
- **Path Computation Element**: The Optical Path Computation Element evaluates technical variables to estimate the optimal route for optical connections. The B5G-ONP uses the standard TAPI server - OPCE interface to for impairment validations in the optical routes. This integration is currently in active testing phase, expected to be validated in the next B5G-OPEN demonstration works.

In summary, the integration phase of the IT and network subsystem is running on schedule and successfully.

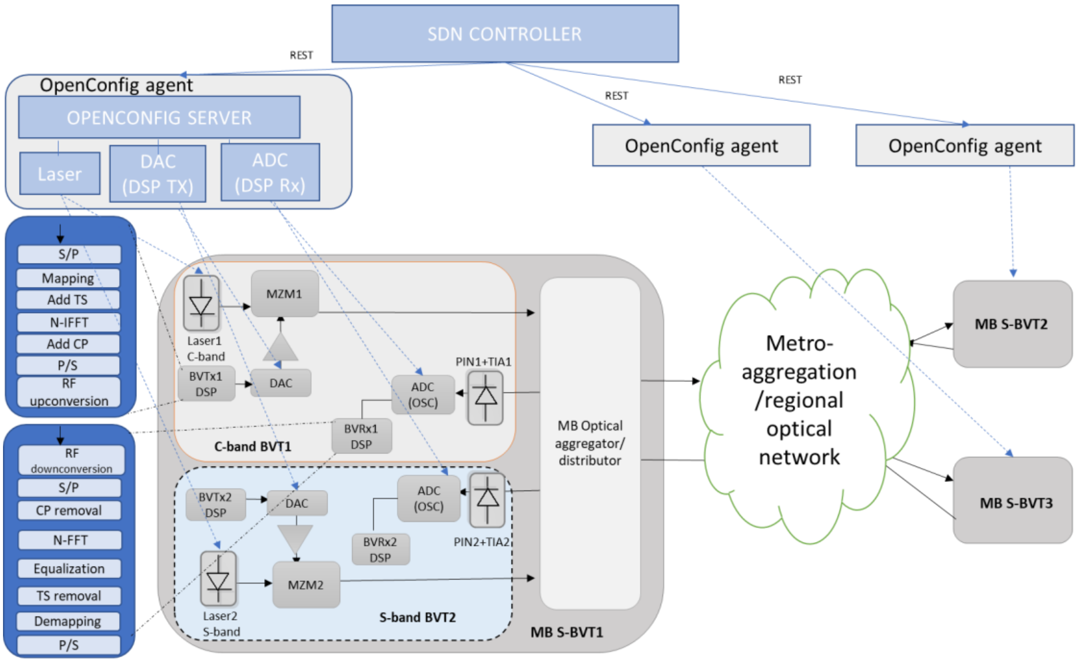
The list of used B5G-OPEN Components are:

WP4 components: B5G-OPEN Optical Network Planner (C4.1), TAPI enabled Network Orchestrator (C4.2), Path Computation Element (C4.3), OLS Controller (C4.5) and the PON Controller (C4.6).

5.5. MB SLICING

5.5.1. Description

The MB slicing demo consists of the implementation and integration of an OpenConfig-based agent with ONOS SDN controller (WP4) to configure the multi-band (MB) sliceable bandwidth/bitrate variable transceiver (S-BVT) prototype (B5G-OPEN component of WP3, detailed in D3.2). The OpenConfig agent is an SDN agent that uses NETCONF/YANG and implements a subset of the OpenConfig data models with some extensions envisioned in B5G-OPEN to include details about the transceiver operational modes as described in deliverable D4.2 and here summarized.



-Figure 5.6: MB slicing demo setup

In particular, the OpenConfig data model is composed of abstract modules, each representing specific capabilities and features of a network device. In this demo, we focus on the specific abstract modules related to packet and optical SDN operations such as Platform and Optical transport. This last module will include the information about the model definition of the MB S-BVT which can be used by the SDN controller to perform optical planning and impairment validation of the end-to-end transmission. Firstly, the SDN controller will retrieve a list of components from the OpenConfig platform model, in particular from the operational mode datastore, and list the supported operational modes by the MB S-BVT in order to understand the structure, interfaces, configuration and features/capabilities supported by the device. The information extracted from the operational mode datastore can include details about the current operational state and configurations of MB S-BVT such as: i) characteristics of the transceiver (modulation format, FEC, bit rate...) and relevant parameters for the physical impairment validation (OSNR Rx sensitivity, CD/PMD tolerance and penalties) and ii) transmission configuration constraints such as central frequency range, frequency grid and power. Then, after discovering the device, the SDN controller can use the information from the operational datastore to configure optical channels, involving the configuration of different source/destination MB S-BVTs. The configuration is performed in different phases/operations including optical channel configuration, which involves setting parameters such as central frequency, target output power, and operational mode, and logical channel assignment between a client port and a line port.

Different programmable parameters and optical elements can be modified to configure the MB S-BVT with the SDN controller by means of the OpenConfig SDN agent, as depicted in Figure 5.6. In particular, at the transmitter side the power and central wavelength of the laser sources can be modified and the digital-to-analog converter (DAC) channels, of each MB S-BVT building block, can be enabled/disabled. At the receiver side, the analog-to-digital converter (ADC) can be reconfigured.

Specifically, for the demo, the B5G-OPEN S-BVT agent component will also include a module extension for physical layer characterization. This takes into account operational mode extensions, of the OpenConfig data model, to include key MB S-BVT attributes. In particular, modulation format (i.e. MODULATION-FORMAT-QPSK), Bit-rate (i.e. TRIB-RATE-40G), Baud-rate(i.e. 20GBd QPSK), Optical-channel-spectrum-width (i.e. 50 GHz), Min-tx-OSNR (i.e. 40 dB), Min-rx-OSNR (i.e. 33 dB), Min-input-power (i.e 0 dBm), Max-input-power (i.e. 9 dBm), Max-chromatic-dispersion (i.e. 2000 ps/nm), Max-differential-group-delay (i.e. 1 ps), Max-polarization-dependent-loss (i.e. 0.12 dB) and configuration constraints such as Min-central-frequency (i.e. 191675803.99 MHz in C-band), Max-central frequency (i.e. 205281058.6 MHz in S-band), Grid-type (i.e. FLEX), Adjustment-granularity (i.e. G-50GHz), Min-channel-spacing (i.e. 50 GHz), Min-output-power (i.e. 0 dBm) and Max-output-power (i.e. 25 dBm).

The B5G-OPEN S-BVT agent will be integrated with ONOS SDN controller, which is responsible for mapping the information about Operational modes into its North Bound Interface (NBI) so that the transport API (TAPI) Network Orchestrator can consume and query it to offer connectivity between two different MB S-BVTs distributed into the network.

The list of used B5G-OPEN Components are:

WP3 component: MB S-BVT with id 3.4.

WP4 component: OpenConfig agent C4.10 and dedicated controllers C4.4 and C4.5

5.5.2. Status of integration and next steps

A basic initial implementation of the OpenConfig-based agent has been developed focusing on key aspects such as component discovery, optical channel configuration and operational mode characterization based on B5G-OPEN extensions. This implementation is a fundamental step in enabling the reconfiguration and programmability of the MB S-BVT prototype developed within B5G-OPEN. The MB S-BVT relies primarily on multi-adaptive programmable digital signal processing and multicarrier modulation allowing for versatile MB (C+S) and point-to-point/point-to-multipoint operations.

Successful assessment has been already performed considering the basic OpenConfig agent implementation. Specifically, after device discovery, two different OpenConfig operations have been implemented: (i) optical channel configuration and (ii) logical channel assignment. With the first operation an optical channel with a particular central frequency, power and operational mode was suitably configured, also configuring the source/destination MB S-BVTs. Whereas with the second operation a client port was assigned to an optical channel to establish a connection between two MB S-BVTs/terminal devices. This work is detailed in [Nad23].

As we progress toward the final demonstration phase, several crucial steps are identified:

i) **Module extension for physical layer characterization**: The first step involves enhancing the OpenConfig-based agent by including a module extension dedicated to physical layer characterization within the MB S-BVT agent component. This extension will contribute to a more comprehensive understanding and manipulation of the prototype's physical layer attributes.

ii) **Integration of the extended OpenConfig-based agent with ONOS SDN controller:**

The subsequent step is the integration of the extended OpenConfig-based agent with the ONOS SDN controller. Functional tests will be conducted to ensure the effective configuration of the MB S-BVT prototype. This requires the ONOS SDN controller to connect to the OpenConfig agent to discover basic blocks and operational modes.

iii) **Performance evaluation for MB transmission over the fiber:** The final step involves the performance evaluation of the SDN-enabled MB S-BVT, specifically focusing on MB transmission over the fiber.

5.6. Disaggregated Multi-band Optical Network Control Plane

5.6.1. Description

In this section, we report on the integration of multiple B5G-OPEN control plane components, provided by multiple B5G-OPEN Partners (CNR, CNIT, OLC-E, ELIG, TID, TIM, and CTTC). The components are integrated in a modular architecture designed to enable dynamic control of multi-band disaggregated optical networks through open-source software and standard interfaces. Such integrated control plane is demonstrated in a distributed testbed including real IPoWDM nodes, ROADMs and transponders.

Introduction and objectives

The recent evolution of transmission technology is driving the introduction of new solutions in optical networks such as: (i) multi-band operation, that allows to provision services using the several bands available in optical fibres, e.g., O-, E-, S-, C-, L-band; (ii) optical continuum, allowing to transparently cross different network segments and domains; (iii) coherent pluggable transceivers installed in the so-called IPoWDM packet-optical nodes that enable effective packet-level traffic aggregation at the edge of the optical domain. The introduction of such solutions poses new requirements to the network control plane. For instance, multi-band operation not only means being able to map and exploit the devices' multiband capabilities but also requires more accurate tools for the estimation of non-linear physical impairments. On the other hand, the optical continuum requires the ability to setup connections in a transparent manner across multiple domains and network segments, and typically requires extending SDN principles to networks composed of several technological layers.

This section demonstrates how the control plane architecture designed within the B5G-OPEN project can address the requirements. Indeed, the proposed architecture relies on a modular organization where the inter-operation among control plane elements is guaranteed through open interfaces. This approach facilitates the scaling of the architecture towards complex multi-segment and multi-domain networks and allows the seamless introduction of specialized element in the control plane, e.g., dedicated to path computation and estimation of physical impairments or dedicated to continuous collection of telemetry information, that could be used to feed AI algorithms facilitating the network automation. Two novel contributions are here reported:

- implementation of a data information flow to transport device and fiber impairments description from the data layer, through the SDN controller, up to path computation and orchestration level

- extension of the OpenConfig model to properly map the supported operational modes to transponders and IPoWDM ports.

The primary objective is to showcase the integration of the multiple control plane modules developed withing the B5G-OPEN project, targeting the dynamic provisioning and release of connectivity services. More specifically, we aim to demonstrate the following key aspects:

- Implementation of a service orchestrator able to retrieve multiple domains information through T-API standards.
- Implementation of a T-API network orchestrator translating lower domains proprietary network descriptions in the standard T-API representation and requesting path computation to an externalized entity.
- Implementation of a dedicated path computation and physical impairment estimation element.
- Extension of the ONOS SDN controller to support flex-grid, multi-band operation and exportation of physical parameters.
- Implementation of SDN agents based on extended OpenConfig and OpenROADM YANG models, for the control of ROADMs, IPoWDM nodes and transponders.

Data plane

The testbed is composed by 4 ROADMs, 4 transponders (one connected to each ROADM), and two IPoWDM nodes. All the ROADMs expose an OpenROADM model to the controller, two of them are implemented exploiting real devices (i.e., a Lumentum ROADM-20 and a Finisar Waveshaper), the others are emulated. Two transponders are implemented exploiting real devices, the others are emulated. Multi-band (MB) sliceable bandwidth/bitrate variable transponders (S-BVT), capable of generating two slices in the S- and C-bands, are considered. The IPoWDM nodes are physical white-boxes running the SONiC NOS. All devices are deployed in the CNIT premises, except the two transponders that are located at CTTC premises.

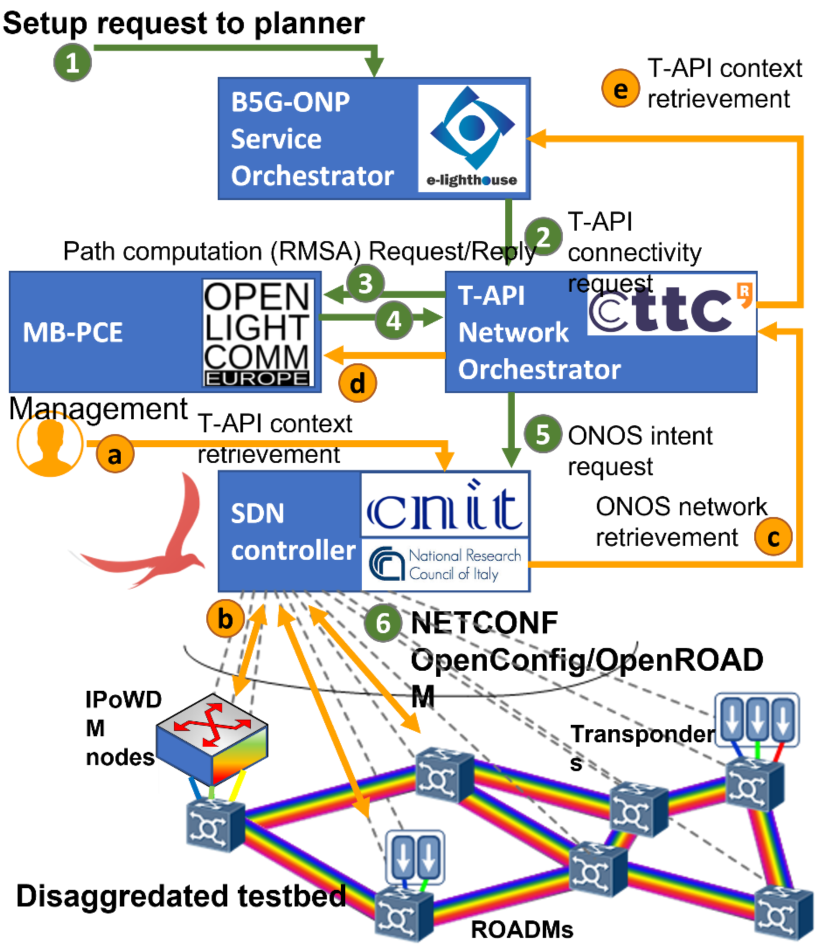


Figure 5.6: Proposed control plane architecture and workflow for: the control plane initialization, steps (a-e); the activation of a new connectivity service, steps (1-6).

Control plane

Figure 5.6 showcases the proposed control plane architecture. The key elements are the B5G-ONP service orchestrator, the T-API network orchestrator, the MB path computation element (PCE), and the SDN controller.

The optical SDN controller is based on ONOS, version 3.0.0, which provides a solid base to control disaggregated optical networks. The controller supports the following functions:

- retrieval of key abstraction parameters of the data-plane sub-systems and distribution of them to the upper layers
- to receive service configuration requests from the upper layers and translate them into a set of configuration messages using the appropriate format for each device.

Several extensions are applied to the official ONOS distribution:

- in the Southbound Interface (SBI), the OpenConfig drivers may now retrieve the description of the supported OpenConfig operational modes allowing to associate the operational mode to specific ports
- the controller core is upgraded to support flex-grid and multi-band operation

- the Northbound Interface (NBI) is upgraded with a set of REST APIs supporting seamless communication with the TAPI orchestrator, e.g., now it is possible to export the list of operational modes supported by a device and the status of each wavelength channel registered on a link.

The TAPI network orchestrator is a functional element of the architecture that is responsible for the following functions:

- providing a uniform, open and standard view and interface to higher control levels
- composing a complete context to be consumed by the B5G-ONP and additional consumers combining information retrieved from subsystems and sub-controllers (e.g., by the SDN controller)
- enabling single entry point for provisioning connectivity services, including externalized path computation
- providing an event telemetry data source that reports events that happen asynchronously in the network

The multi-band PCE (MB-PCE) is a dedicated element designed to complete computationally intensive operations. The MB-PCE consists of a routing engine that exploits a Physical Layer Impairment-aware Routing, Modulation and Spectral Assignment Algorithm (PLI-aware RMSA) and it is equally applicable to both transparent and translucent paths. The MB-PCE retrieves network topology from the TAPI network orchestrator. The PLI-aware RSA also gets as input the deployed optical transmission system parameters and the traffic components of the existing services. The physical layer modeling (also developed in the context of B5G-OPEN project) estimates the impact of ASE accumulation, and the nonlinear propagation effects like the in-band FWM terms (XCI, SCI) and inter-band effects like SRS. Upon receiving a connectivity request, the PLI-aware RMSA assesses the performance of the candidate lightpath (that ought to be above a suitably chosen threshold) and it estimates the impact of this new lightpath on the already established ones. As soon as viable path is deduced, the MB-PCE returns the path in terms of links, number of frequency slots and selected transmission system parameters.

The B5G optical service orchestrator and planner (B5G-ONP) is the topmost component of the B5G-OPEN control plane that orchestrates IT and network resources. This component provides design, optimization and planning capabilities to deploy, manage and configure services and resources, facilitating integration with external entities. The key aspects of this module are:

- discover and assimilate the topology of underlying network segments and domains by exploiting the NBI of TAPI orchestrator (and other possible network controllers), allowing it to discern the availability of services and their inter-dependencies
- perform an intelligent analysis of available resources and interacts with the other elements of the control plane for network provisioning procedures
- display information through a friendly GUI, which offers an aesthetically pleasing layout, and intuitive, straightforward navigation.

Control plane workflow

The integration of the components has been successfully validated in a demo presented at ECOC 2023. The demo showed two distinct phases as illustrated in Figure 5.7, the control plane initialization and the setup/release of several connectivity services. The former procedure is illustrated in steps (a-e): the management layer provides the devices' location (step a), the device details discovery is then performed using NETCONF protocol by the SDN controller (step b); thus, the TAPI orchestrator can retrieve the network topology from the SDN controller (step c) and propagate it to the MB-PCE (step d) and to the B5G-ONP (step e). The latter procedure is illustrated in steps (1-6).

A connectivity service is requested to the B5G-ONP (step 1), the request is forwarded to the TAPI orchestrator (step 2) that forwards it to the MB-PCE (step 3) which replies with the computed path (step 4). Thus, the TAPI orchestrator forwards the request, including computed path and selected network resources to the SDN controller (step 5) that properly configures each involved network element (step 6).

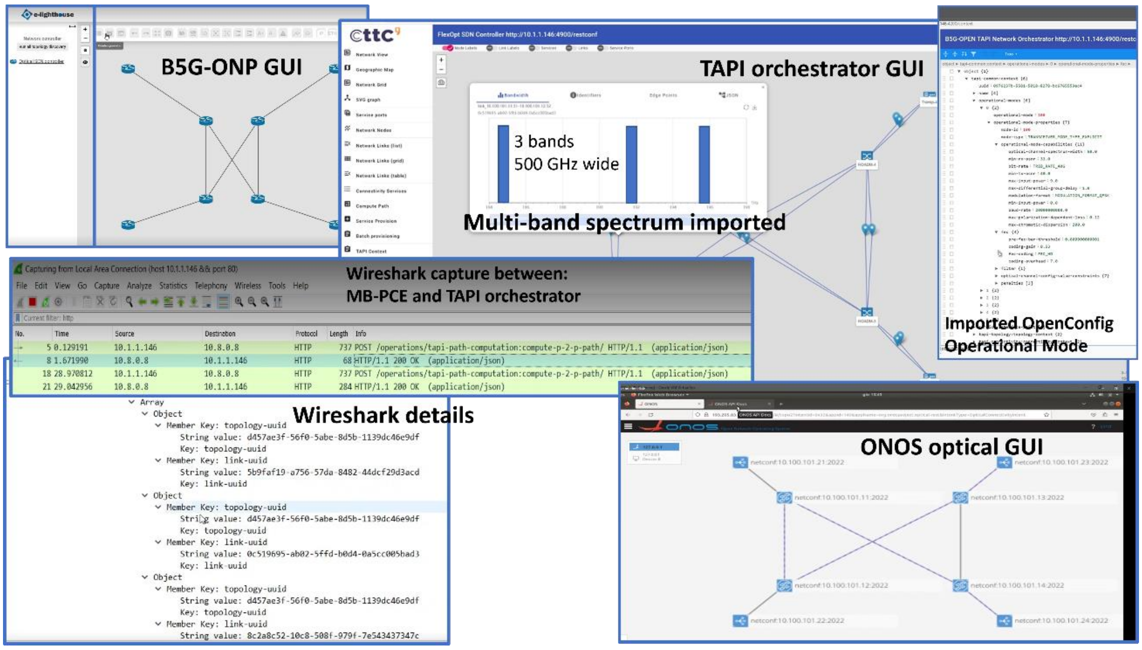


Figure 5.7: A collection of screenshots of the four control plane elements involved in the demo, including a Wireshark capture.

The demo paper has been published in:

[Gio23] A. Giorgetti, A. Sgambelluri, F. Cugini, E. Kosmatos, A. Stavdas, J. M. Martinez-Caro, P. Pavon, O. Gonzalez De Dios, R. Morro, L. Nadal, R. Casellas, “Modular Control Plane Implementation for Disaggregated Optical Transport Networks with Multi-band Support”, ECOC 2023.

The list of used B5G-OPEN Components are:

WP3 component: C3.1 OLC-E Physical Layer Design Tool, C3.4 Multiband S-BVT, C3.5 Programmable packet-optical node with coherent pluggables.

WP4 component: C4.1 B5G-ONP network planner, C4.2 TAPI enabled Network Orchestrator, C4.3 Path Computation Element, C4.4 ONOS Optical Controller, C4.9 OpenROADM agent, C4.10 OpenConfig agent, C4.11 SONiC based packet optical node

5.6.2. Status of integration and next steps

The first integration of multiple B5G-OPEN control plane components, provided by multiple B5G-OPEN Partners, successfully demonstrated an innovative modular architecture designed to enable dynamic control of multi-band disaggregated optical networks through open-source software and standard interfaces. The next step will be the evolution of such architecture to support multi-domain multi-band operations.

5.7. Telemetry and Close-Loop Integration

5.7.1. Description

Multivendor data source integration has been demonstrated with two testbeds producing measurements telemetry and an SDN controller generating event telemetry. In particular, three different data sources from Nokia Bell Labs, ADTRAN TPs and CTTC SDN controller have been integrated.

The Nokia Optical Network testbed combines more than 400 km optical fiber with 7 optical nodes. OSAs are deployed at each node ingress and egress ports and collected data are injected in the telemetry system. Samples are processed by a feature extraction algorithm that characterizes the mean (μ) and the standard deviation (σ) of the power around the central frequency (fc±Δf), as well as a set of features computed as: i) equalized noise level (e.g., -60dB + equalization level); ii) edges of the signal computed using the derivative; and iii) a family of power levels computed with respect to μ minus a number of dB. Each of these power levels generates a couple of cut-off points $f1_{(\cdot)}$ and $f2_{(\cdot)}$.

SDN controller runs in CTTC and reports changes of state of the controlled system to another (usually superior) management-control entity. In this case, events are TAPI entities, i.e., YANG sub-trees and allow a client to achieve and maintain eventual consistency with the state of the controlled system. In particular, the TAPI proxy SDN controller will act as data source. For this, the internal architecture of the software is modified to report asynchronous events that happen in the network.

Figure 5.8 presents the reference network scenario, where an SDN architecture controls several TPs and optical nodes in the data plane. Note that the SDN architecture might include a hierarchy of controllers, including optical line systems and parent SDN controllers. A centralized telemetry manager is in-charge of receiving, processing and storing telemetry data, including measurements and events. The telemetry database (DB) includes two repositories: *i*) the measurements DB is a time-series (TS) DB that stores measurements; and *ii*) the events DB is a free-text search (FT) engine. In addition, telemetry data can be exported to other external systems. Every node in the data plane is locally managed by a node agent, which translates the control messages received from the related SDN controller into operations in the local node and exports telemetry data collected from observation points (labelled M) enabled the optical nodes or in specific optical devices, like OSAs. In addition, events can be collected from applications and controllers (labelled E).

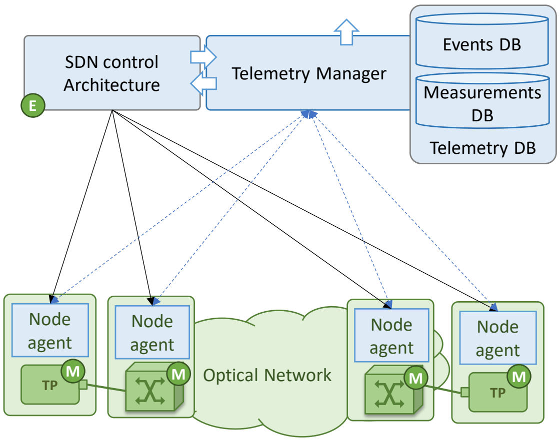


Figure 5.8: Overall network architecture

A detailed architecture of the telemetry system is presented in Figure 5.9. The internal architecture of telemetry agents and the telemetry manager is shown. Telemetry agents can be integrated with node agents in the case of measurements telemetry or be deployed as separate elements for event telemetry. Internally, both, telemetry agents and telemetry manager are based on three main components: *i*) a *manager* module configuring and supervising the operation of the rest of the modules; *ii*) a number of components that include *algorithms*, e.g., data processing, aggregation, etc. and *interfaces*, e.g., gRPC; and *iii*) a *Redis DB* to communicate the different modules among them. This solution provides an agile and reliable environment that simplifies communication and integrates new modules. A gRPC interface is used for the telemetry agents to export telemetry to the telemetry manager, as well for the telemetry manager to tune the behaviour of algorithms in the agents.

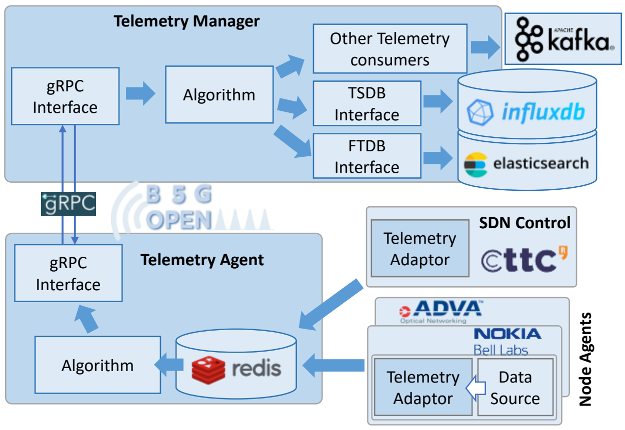


Figure 5.9: B5G-OPEN Telemetry Architecture and Data Source Integration

The list of used B5G-OPEN Components are:

WP3 component: C3.8 7-node mesh network

WP4 component: C4.13 Telemetry System, C4.4 ONOS Optical Controller

5.7.2. Status of integration and next steps

The integration between the Nokia and ADTRAN telemetry measurements, the telemetry events from the CTTC SDN Controller and the telemetry architecture has been tested.

Next steps include the use of a Digital Twin to generate recommendations based on streaming telemetry generated from the data sources already specified. These recommendations will be forwarded to the CTTC SDN Controller which in the end will apply the suggested changes on the network topology. The reconfiguration of the network implies also the reconfiguration of the telemetry system agents in case of deleting or adding new nodes and/or links. This final integration will demonstrate a close-loop scenario where soft failures are detected and changes are applied on the network infrastructure before facing a hard failure.

5.8. Towards Final Demo MB Integration

5.8.1. Description

This demo aims to showcase the B5G-OPEN solution, providing a comprehensive view from the network perspective. It will take advantage of the large-scale photonic testbed in Berlin, while been extended by different SW and HW components developed within the project by different partners. By utilizing this robust infrastructure, the demo will demonstrate the capabilities of the B5G-OPEN solution in enabling multiple services to be established simultaneously. One of the key highlights of this demonstration is the utilization of the MB spectrum resources and the flexible data plane capabilities.

The use case that will be demonstrated involves the end-to-end infrastructure sharing of B5G resources among multiple services. It highlights the ability of the B5G-OPEN solution to facilitate efficient resource sharing and allocation. During the demonstration, emphasis will be placed on validating the most relevant control and management operations involving the MB optical infrastructure and its multi-domain integrated control and orchestration. The performance of these operations will be evaluated against the Project Key Performance Indicators (KPIs) to ensure the effectiveness and efficiency of the B5G-OPEN solution.

Specifically speaking, as shown Figure 5.10, the demonstration architecture comprises two domains. One of the domains offers multi-band connectivity covering S-, C-, and L-bands and is built by hardware prototypes developed during the project. The second domain supports only C-band and comprises commercial ROADMs. In order to offer multi-domain services, two EdgeCore switches are envisioned that support high data rate pluggables (i.e., 400G ZR+) that offer IP over WDM services. The data plane devices will be controlled and orchestrated by the software components developed within the project.

Among other, the demonstration will showcase:

- end-to-end provisioning and monitoring of IPoverWDM services crossing both domains and running on C-band portion of the spectrum
- end-to-end service provisioning and monitoring of WDM services in the multi-band domain leveraging the prototypes (i.e., C3.7, and C3.12) developed in the project
- band switching using the developed multi-band node prototype
- reconfiguration of the running services levering the telemetry data collected and upon detecting anomalies in the testbed.

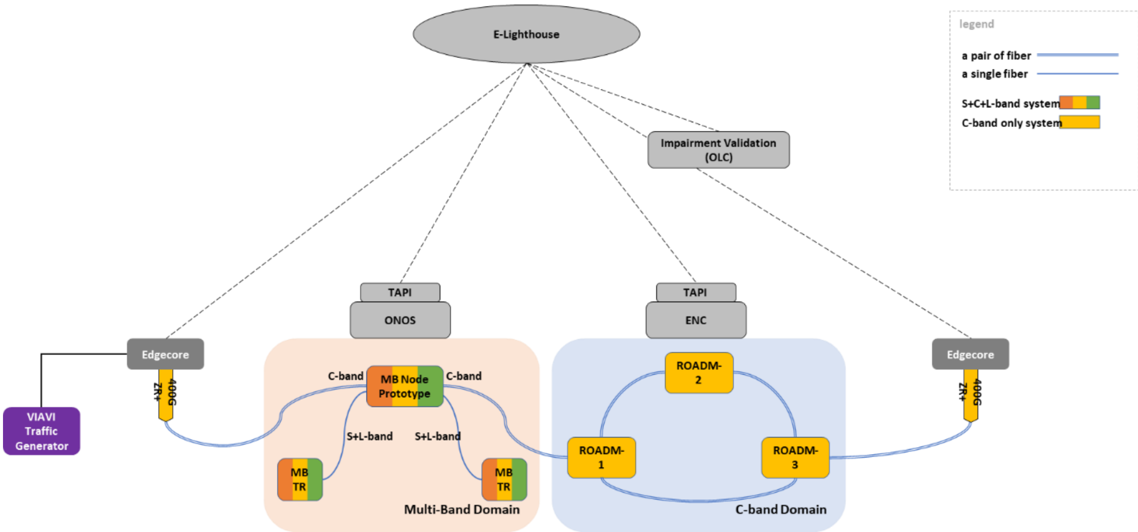


Figure 5.10: Final Demo Initial Architecture

The following B5G-OPEN components are considered used in the demonstration. Additional components might be added during the demo execution that will be reported in later deliverables.

ID	What	SW/HW	Partner
C3.1	OLC-E Physical Layer Design Tool	SW	OLC-E
C3.7	S-C-L-band offline transceiver	HW	HHI
C3.12	(Semi-) filterless add/drop node	HW	HHI

ID	Component	Partner
C4.1	B5G-ONP network planner	ELIG
C4.2	TAPI enabled Network Orchestrator	CTTC
C4.3	Path Computation Element	OLC-E
C4.4	ONOS Optical Controller	CNIT
C4.5	OLS Controller	Adtran CTTC
C4.10	OpenConfig agent	CTTC CNIT
C4.11	SONiC based packet optical node	CNIT

C4.13	Telemetry System	UPC CTTC Adtran Nokia

5.8.2. Status of integration and next steps

The component integration for the final demo has already started. The C-band domain, which consists of three ROADMs and three transponders, is operational. The multi-band domain is yet to be operational, while the prototypes (i.e., C3.7 and C3.12) are ready. These components are physically located at HHI premises in Berlin. The integration of the EdgeCore switches and the 400G ZR+ pluggable transceiver into the demo testbed is still pending. Regardless of the data plane components, the control plane components have not yet been integrated. The next immediate steps are: i) finalize the data plane of the multi-band domain and make them operation, ii) integrate the EdgeCore switches and the ZR+ pluggable transceivers in the testbed, iii) deploy the control plane components in the testbed, iv) integrate the control plane components with the data plane components of the testbed, v) run experiments and carry out the demo, and vi) collect KPIs and prepare the final report.

6. Towards KPI Validation

In the following table the status of the relevant to WP5 KPIs is presented.

KPI ID	KPI DESCRIPTION	ACTIVITIES TO MEASURE KPI	OWNER	KPI Status
2.1	Reduction of total power consumption from 30% to 50% with respect to SoA architectures (e.g. H2020 METRO-HAUL results) and legacy solutions	Network dimensioning study comparing legacy solution against multi-band + continuum + IPoDWDM solution (to be clarified if single dimensioning or separate analysis)	INF-P	Under Assessment. Will be reported in D5.3
2.2	CAPEX reduction above 50% in the end-to-end "domain-less" architecture relative to fixed-domain metro-access/regional/core segments	Network dimensioning study comparing legacy solution against multi-band + continuum + IPoDWDM solution (to be clarified if single dimensioning or separate analysis)	UC3M	Under Assessment. Will be reported in D5.3
2.3	Increase of 10x in-service bandwidth w.r.t. currently deployed C-band transport solutions	Capacity analysis on reference operator networks of multi-band solution (using superC + L + S + O + E), including performance impact on the co-existing bands	TIM	Under Assessment. Will be reported in D5.3
3.4b	Pluggable solutions fully integrated within the white box enabling the removal of stand-alone network elements (e.g. xPonders, OLTs, etc.) to reduce footprint	Configuration and connectivity provisioing of white box encompassing coherent pluggable modules	CNIT	Preliminary Achieved and assessment is reported in D5.1.
4.3	50% energy reduction in small cell deployments as of today, by leveraging on power efficient Li-Fi small-cells and Aibased throughput optimization algorithms	Bits /sec / J in a reference small cell scenario	PLF	Under Assessment. Will be reported in D5.3

4.4	LiFi handover: QoS-guaranteed handover with minimum throughput higher than 50% of the capacity by predicting the mobility and anticipating flow rerouting and parallel delivery to adjacent APs. In case of blockage of the line-of-sight link, the auto-reconnection time <2× blockage period	Numerical measured results with the implemented LiFi networks covering: 1) the throughputs when a LiFi handover occurs between LiFi cells; 2) the system auto-reconnection time when the light path is blocked on the user end for a given period.	PLF	Under Assessment. Will be reported in D5.3
5.1	10x more physical monitored data than what is today available in the field	Numerical evaluation combining distributed telemetry system and intelligent data aggregation to reduce both telemetry period and data rate per data source, thus achieving more monitoring data sources supported by a single telemetry interface	UPC	Achieved. Will be reported to D5.3
5.2	20% OPEX reduction (in combination with O8 and ZTN) by minimizing the power consumption impact of this massive new monitoring platform	Numerical evaluation combining: distributed traffic monitoring and centralized decision making for dynamic operation	UPC	Achieved. Will be reported to D5.3
5.3	Accurate measurements over different bands, e.g. < 1.5 dB uncertainty of OSNR measurements	Measurement of monitored accuracy: power profile accuracy among several band	NBLF	Under Assessment. Will be reported in D5.2
6.2	Service Provisioning. Multi-vendor operations through fully specified models and APIs, enabling seamless support of optical adaptation	Validation of the SDN Agent module running on the white box and enabling the successfull	CNIT	Partially achieved. Will be reported in D5.2

	functionalities within the packet-optical white box	configuration (including adaptation of transmission parameters) of pluggables provided by different vendors		
7.1	High level service provisioning (e.g. interconnected cloud native functions and containers) relying on low level service setup performed in the sub-second time scale (data connectivity services, leveraging on the MB fully integrated packet-optical infrastructure and supported predictive capabilities)	Decouple in two: - time it takes to instantiate two instances of a CNF on two computing nodes of different PoPs (cluster or DC), which may be controlled under the same K8s master or not. - instantiation time of an L3VPN where the end points are the IP addresses of the containers. - total time to complete a full service, which involves the two parts above, and the optical connections that are measured in other KPIs.	WP5 (ELI)+ CNIT/UPC	Not achieved
7.2	Reduction on the average setup time of connectivity service by 30% compared to serialized provisioning, exploiting approaches relying on parallelism and concurrency	multidomain scenario (provision 2 domains in paralel)	CTTC (as WP4 Leader)	Pending
7.4	10x rate of e2e provisioning supported services (e.g. number of requests per hour) leveraging on telemetry-empowered SDN Controller communication across multiple domains of visibility and cluster-based deployments for load sharing between controllers	provisioning time of a complete service: from the time it is ordered, until it is completed in all its parts as seen by the B5G-ONP	ELI	Under Assessment. Will be reported in D5.2

8.1	Speed of decision-making in the sub-second scale by placing the intelligence near the devices, applying advanced AI/ML techniques, accurate model training based on simulation tools, and knowledge sharing among controllers	Numerical evaluation combining local constellation data analysis to achieve real time actions, as well as a centralized lightpath modelling using a digital twin to achieve intelligent operation	UPC	Under Assessment. Will be reported in D5.2
8.3	Reduce OpEx by >20%, by increasing autonomous operations and reducing manual intervention	Analysis of predictive failure impact on the amount of planned/ unplanned interventions and overall OpeX impact	UPC + TID	Partially achieved. Will be reported in D5.3
8.4	Improve and guarantee service and network availability (> 6x9s availability will be reached by combining MB and PtMP with anticipated degradation detection and proactive decision making)	Compare the outage time (minutes in a scenario without any predictive analysis vs. a failure prediction which enables to prevent the outage (e.g. through re-routing)	UPC	Achieved. Will be reported in D5.3

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CONCLUSIONS

This deliverable pursues two main goals, namely the validation of the proposed solutions from a techno-economic and impact perspective and the validation through experimentation, achieved by integrating, testing, and demonstrating the B5G-OPEN technologies and solutions.

Building upon the overall architecture defined in T2.2, reported in D5.1 work has refined the CAPEX/OPEX modelling based on the device and subsystem specifications provided in WP3 (including performance, cost and footprint aspects), and the control-plane capabilities (with respect to programmability and end-to-end resource visibility) derived from WP4. The network dimensioning activities have also leveraged the resource optimization algorithms and frameworks developed in the scope of T4.3 for the specific evaluation of the operational.

In summary D5.1 completes the following project objectives:

- Establishment of the distributed testbed and lab facilities: twelve testbeds are reported
- Interconnection of the experiment facilities for dataset generation: secure GRE/VPN tunnels have been configured among five Partners' labs (i.e for experimental dataset for QoT Estimation)
- Validation of the proposed B5G-OPEN end-to-end solution from a techno-economic and impact perspective: achieved through B5G-OPEN network dimensioning and optimization studies (Cost/Capacity analysis), leveraging specific B5G-OPEN components.
- HW/SW components (WP3/WP4) integration

REFERENCES

[B5GOD2.1] Deliverable D2.1 of B5G-Open project

[CIE20] White paper: "A Model for Business Case Analysis of C/L-band Network Architectures in Fiber Optic Networks based on Leased/IRU Dark Fiber", Ciema.com, 2020.

[Eck21] T. Eckert, "Network 2030 Focus Group at ITU T for SG13-Presentation at 2nd Visions for Future Communications Summit" Lisbon, Portugal, 27 November 2019 https://futurecomresearch.eu/slides/Toerless_Eckert.pdf (accessed 21 January 2021)

[Eir23] A. Eira, A. Souza and J. Pedro, "Flexible Survivability in Next-Generation Multi-Band Optical Transport Networks," 2023 Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 2023, pp. 1-3, doi: 10.1364/OFC.2023.M1G.1.

[ENP] E-Lighthouse Network Planner. [Online] https://e-lighthouse.com/products/networkplanner

[EuCNC23] B5G-OPEN, EuCNC Demo, June, 2023, Gothenburg, Sweden

[FG30] ITU website, https://www.itu.int/en/ITU-T/focusgroups/net2030/Pages/default.aspx

[FG-R1] ITU-T SG13 FG-NET2030-Sub-G1, "Representative use cases and key network requirements for Network 2030", ITU-T Technical Report, January 2020

[Gio23] - A. Giorgetti, A. Sgambelluri, F. Cugini, E. Kosmatos, A. Stavdas, J. M. Martinez-Caro, P. Pavon, O. Gonzalez De Dios, R. Morro, L. Nadal, R. Casellas, "Modular Control Plane Implementation for Disaggregated Optical Transport Networks with Multi-band Support", Demonstration in European Conference on Optical Communication (ECOC), Glasgow, Oct., 2023

[Hoss22] M. M. Hosseini, J. Pedro, A. Napoli, N. Costa, J. E. Prilepsky and S. K. Turitsyn, "Optimization of survivable filterless optical networks exploiting digital subcarrier multiplexing," in Journal of Optical Communications and Networking, vol. 14, no. 7, pp. 586-594, July 2022, doi: 10.1364/JOCN.451182.

[Hoss23] M. M. Hosseini, J. Pedro, A. Napoli, N. Costa, J. E. Prilepsky and S. K. Turitsyn, "Multi-period planning in metro-aggregation networks exploiting point-to-multipoint coherent transceivers," in Journal of Optical Communications and Networking, vol. 15, no. 3, pp. 155-162, March 2023, doi: 10.1364/JOCN.475902.

[Ibr21] M. Ibrahimi, O. Ayoub, F. Albanese, F. Musumeci, and M. Tornatore, "Strategies for dedicated path protection in filterless optical networks," in IEEE Global Communications Conference (GLOBECOM) (IEEE, 2021).

[Ita88] A. Itai and M. Rodeh, "The multi-tree approach to reliability in distributed networks," Inf. Comput. 79, 43–59 (1988).

[JAN20] R. K. Jana *et al.*, "When Is Operation Over C+L Bands More Economical than Multifiber for Capacity Upgrade of an Optical Backbone Network?," *2020 European Conference on Optical*

Communications (ECOC), Brussels, Belgium, 2020, pp. 1-4, doi: 10.1109/ECOC48923.2020.9333276.

[JAN23] R. K. Jana, A. Srivastava, A. Lord and A. Mitra, "Optical cable deployment versus fiber leasing: an operator's perspective on CapEx savings for capacity upgrade in an elastic optical core network," in *Journal of Optical Communications and Networking*, vol. 15, no. 8, pp. C179-C191, August 2023, doi: 10.1364/JOCN.483200.

[KUM22] R. Kumar Jana *et al.*, "Multifiber vs. Ultra-Wideband Upgrade: A Techno-Economic Comparison for Elastic Optical Backbone Network," *2022 European Conference on Optical Communication (ECOC)*, Basel, Switzerland, 2022, pp. 1-4.

[LOP20] V. Lopez *et al.*, "Optimized Design and Challenges for C&L Band Optical Line Systems," in *Journal of Lightwave Technology*, vol. 38, no. 5, pp. 1080-1091, 1 March1, 2020, doi: 10.1109/JLT.2020.2968225.

[MANTRA] O. Gonzales De Dios et al., "Mantra whitepaper IPoWDM convergent sdn architecture - motivation, technical definition challenges," in Telecom Infra Project White Paper version 3, 2022

[MHD2.4] António Eira and João Pedro (Editors), "Techno-economic Analysis and Network Architecture Refinement", EU Project Metro-Haul Deliverable D2.4, 20 April 2020

[Nad23] L. Nadal, R. Casellas, J. M. Fàbrega, F. J. Vílchez, and M. Svaluto Moreolo, "Capacity scaling in metro-regional aggregation networks: the multiband S-BVT," J. Opt. Commun. Netw. 15, F13-F21 (2023)

[NAK22] M. Nakagawa, T. Seki and T. Miyamura, "Techno-Economic Potential of Wavelength-Selective Band-Switchable OXC in S+C+L Band Optical Networks," *2022 Optical Fiber Communications Conference and Exhibition (OFC)*, San Diego, CA, USA, 2022, pp. 01-03.

[NGMN18] Richard MacKenzie (Editor), "NGMN Overview on 5G RAN Functional Decomposition", NGMN Alliance, 24 February 2018

[OCATA] Ruiz , Marc; Velasco , Luis ; Sequeira, Diogo , "Optical Constellation Analysis (OCATA)", https://doi.org/10.34810/data146, CORA.Repositori de Dades de Recerca, V2, 2022 https://dataverse.csuc.cat/dataset.xhtml?persistentId=doi:10.34810/data146

[PAT22] S.K. Patri et al., " Multi-band transparent optical network planning strategies for 6G-ready European networks," in Optical Fiber Technology, vol. 74, 2022, https://doi.org/10.1016/j.yofte.2022.103118.

[Qua22] M. Quagliotti, A. Chiadò Piat, R. Morro and A. Pagano, "Applicability of a new generation of photonic devices in backbone network scenarios," 2022 Italian Conference on Optics and Photonics (ICOP), Trento, Italy, 2022, pp. 1-4, doi: 10.1109/ICOP56156.2022.9911726.

[Rui23] *M.* Ruiz *et al.*, "Network traffic analysis under emerging beyond-5G scenarios for multi-band optical technology adoption," in *Journal of Optical Communications and Networking*, vol. 15, no. 11, pp. F36-F47, November 2023, doi: 10.1364/JOCN.492128.

[SHA16a] B. Shariati *et al.*, "Investigation of mid-term network migration scenarios comparing multi-band and multi-fiber deployments," *2016 Optical Fiber Communications Conference and Exhibition (OFC)*, Anaheim, CA, USA, 2016, pp. 1-3.

[SHA16b] B. Shariati *et al*., "Options for cost-effective capacity upgrades in backbone optical networks," *2016 21st European Conference on Networks and Optical Communications (NOC)*, Lisbon, Portugal, 2016, pp. 35-40, doi: 10.1109/NOC.2016.7506982.

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