SEASON

Self-Managed Sustainable High-Capacity Optical Networks

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Deliverable D5.1

Report on the integration and functional validation of integrated SEASON 1.0 solution

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EXECUTIVE SUMMARY

D5.1 deliverable presents a comprehensive overview of the integration and functional validation of the SEASON 1.0 solution, designed to create self-managed, sustainable high-capacity optical networks. The document addresses the following key areas:

Data Plane Development (Section 2): Focuses on enhancing network capacity and flexibility through optical cross-connects, wavelength selective switches (WSS), and arrayed waveguide gratings. These components support multiband and spatial division multiplexing (MBoSDM) and are integrated into the SEASON framework to meet future traffic demands

Telemetry, Control, and Orchestration (Section 3): Covers the development of solutions for close-loop automation and self-management including multi-domain orchestration solutions, software-defined networking (SDN) controllers, and various SDN agents. Key innovations such as the Kubernetes Service Orchestrator and the RAN Intelligent Controller (RIC) contribute to automated network configuration, self-healing, secure device control, and optimal resource utilization.

Preliminary KPI Assessment (Section 4): Evaluates the performance of the integrated SEASON solution, focusing on metrics such as network connectivity service creation time, switching capacities of MBoSDM nodes, energy efficiency, and the scalability of optical transceivers. Initial results indicate significant progress towards project targets, its potential to handle high-capacity traffic while maintaining energy efficiency and scalability.

Integration Activities (Section 5): Provides a comprehensive update on the integration activities critical for the upcoming demonstrations. It covers the integration of MBoSDM nodes with control agents, the incorporation of IPM P2MP pluggable modules, and the fusion of 5G with IPoWDM P2MP technologies. Highlights include the integration of Passive Optical Networks (PON) with the TeraFlow SDN Controller (TFS) and the implementation of energy-aware AI/ML models within the SDN control plane, underscoring the project's commitment to enhancing network intelligence and efficiency.

Final Demonstrations (Section 6): Details planned demonstrations at HHI and WEST. The HHI demo focuses on automated reconfiguration of network resources in response to failures, utilizing band and fiber switching mechanisms. While the WEST demo showcases an end-to-end solution for delivering AR/VR services, integrating spatial PON, dynamic Distributed Unit (DU) scaling, and edge offloading to ensure energy-efficient and reliable communication. These demonstrations are pivotal in showcasing SEASON's innovative capabilities and practical applications in real-world scenarios.

Complementary Demonstrations (Section 7): Describes additional demos, such as the standalone MBoSDM node prototype, to illustrate dynamic service provisioning in multi-band optical networks. These activities support the validation of SEASON's flexibility and scalability, ensuring a comprehensive coverage of various network scenarios and configurations. The integration of the MBoSDM node within the ADRENALINE testbed and the development of

specific SDN agents for flexible switching operations are highlighted as key activities supporting these demonstrations.

In summary, D5.1 highlights SEASON's innovative capabilities and its potential to handle high-capacity traffic efficiently and sustainably.

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1 INTRODUCTION

Deliverable D5.1 presents a comprehensive report on the integration and functional validation of the SEASON 1.0 solution, a foundation in developing Self-Managed Sustainable High-Capacity Optical Networks. This report describes the integration of advanced data plane and control plane components, ensuring seamless interoperability and enhanced network performance across the SEASON ecosystem. At the core of SEASON 1.0 is the Multi-Band over Spatial Division Multiplexing (MBoSDM) technology, which significantly augments network capacity and flexibility.

The integration of key data plane elements such as optical cross-connects, Wavelength Selective Switch (WSS), and arrayed waveguide gratings are addressed. These components are meticulously incorporated into the SEASON framework to support multiband and spatial division multiplexing, thereby addressing the escalating traffic demands of next-generation optical networks. Parallel to the data plane advancements, the report extensively covers the integration of the control plane architecture, which is pivotal for achieving close-loop automation and self-management. This includes the deployment of multi-domain orchestration solutions, robust Software-Defined Networking (SDN) controllers, and intelligent SDN agents. Noteworthy integrations include the Kubernetes Service Orchestrator, which manages containerized applications across diverse network environments, and the Radio Access Network (RAN) Intelligent Controller (RIC), which enhances real-time network optimizations and service quality. Additionally, energy-aware Artificial Intelligence / Machine Learning (AI/ML) models are integrated into the SDN control plane, facilitating optimal resource utilization and proactive network management.

A significant portion of D5.1 is dedicated to the preliminary Key Performance Indicator (KPI) assessment, which evaluates critical metrics such as network connectivity service creation time, switching capacities of MBoSDM nodes, energy efficiency improvements, and the scalability of optical transceivers. Initial assessments reveal substantial progress towards the project’s objectives, demonstrating the SEASON 1.0 solution's capability to handle high-capacity traffic while maintaining energy efficiency and scalability. Furthermore, the deliverable outlines the status of ongoing integration activities essential for upcoming demonstrations. These demonstrations are designed to validate SEASON’s practical applications, such as automated network reconfiguration in response to failures and the delivery of end-to-end Augmented Reality / Virtual Reality (AR/VR) services through dynamic resource scaling and edge offloading. The integration of Passive Optical Network (PON) with the TeraFlow SDN Controller (TFS) controller and the fusion of 5G with IP over Wavelength Division Multiplexing (IPoWDM) Point-to-Multipoint (P2MP) technologies are highlighted as pivotal advancements supporting these demonstrations.

Additionally, D5.1 encompasses complementary demonstrations, including the standalone MBoSDM node prototype, which underscores the solution’s flexibility and scalability across various network scenarios. The integration of the MBoSDM node within the ADRENALINE testbed and the development of specific SDN agents for flexible switching operations are elaborated, showcasing the consortium's commitment to comprehensive validation and real-world applicability.

In summary, Deliverable D5.1 encapsulates the SEASON consortium's efforts in integrating and validating a state-of-the-art optical network solution. By advancing both the data and control planes and leveraging intelligent orchestration and AI/ML-driven optimizations, SEASON 1.0 sets a new benchmark for sustainable high-capacity optical networks, paving the way for future innovations in the telecommunications landscape.

2 WP3 DATA PLANE COMPONENTS

The SEASON WP3 focuses on the development and optimization of data plane components essential for high-performance, scalable, and resilient network infrastructures. This WP is dedicated to advancing optical transmission systems, node prototypes, and comprehensive monitoring approaches to ensure efficient data handling and transmission across the network. By leveraging cutting-edge technologies such as MBoSDM, Spatial PONs, and intelligent monitoring systems, WP3 aims to enhance network capacity, flexibility, and energy efficiency. The components developed under WP3 are pivotal for enabling seamless data flow, robust network performance, and proactive management in multi-domain and multi-layered network environments.

The Table 2-1 provides details of the components developed in WP3, including node prototypes, optical transmission systems, monitoring approaches, and research activities. For further details, please refer to D3.2.

Table 2-1: List of Data Plane Components.

Component Name	Involved Partner(s)	Description
Node prototypes		
MBoSDM node prototype	CTTC	The multiband over spatial division multiplexing (MBoSDM) node prototype developed in SEASON supports spectral (band and wavelength) and spatial granularities, using fixed- and flex-grid WDM technologies, C-band AWG and WSS devices, and 1x3 MB filters for S-, C-, and L-band bidirectional transmission. SDM is achieved with a 19-core multi-core fiber (MCF) and fan-in/-out devices, enabling core switching and add/drop operations via an 18x18 optical matrix. The node prototype is integrated into the ADRENALINE testbed, which operates within the C-band, and enables optimized resource utilization. Its scalable design, leveraging broader spectrum coverage and spatial channels, ensures high-capacity, efficient, and dynamic switching for future network demands. **[Ref: Section 7.1 in WP3 – D3.2]**
Multi-granular optical node prototype	HHI	A multi-granular node architecture leveraging on MB over SDM to enhance scalability and cost efficiency. The add/drop prototype is based on a 18x18 optical matrix switch which can exploit 3 bands (S-, C- and L-) and 2 spatial dimensions. The prototype is cost effective, consisting of four bundles containing two SMF, eight multiband (S + C + L) multiplexers (MB Mux and MB Demux) and an optical matrix switch responsible for routing the bands accordingly. Monitor couplers are also introduced for effective monitoring of the ports during the validation and the operation of the prototype. A first round of assessment is posted in the above referenced section, this was done during the preparation of the integration for the demo in HHI. **[Ref: Section 7.2 in WP3 – D3.2]**
Spatial PON node	WEST	WEST has developed a Spatial PON node prototype within the SEASON project, enabling dynamic resource management and energy-efficient operations in optical access networks. The prototype supports MCF technology and allows flexible configurations of optical distribution networks over multiple spatial lanes, including 2x2 and 2x1 setups for spatial lane aggregation and disaggregation.

		The key components of the prototype include a spatial switch for dynamic routing, splitter/combiners for lane aggregation, OLT ports for transceiver activation and deactivation, and ONU layers for end-user connectivity. These elements are integrated into a modular architecture, supported by REST and NETCONF interfaces for seamless SDN control and monitoring. The system also incorporates a power measurement device to evaluate energy savings in real-time. **[Ref: Section 7.3 in WP3 – D3.2]**
Optical transmission systems/prototypes		
MB(oSDM) S-BVT	CTTC	A MB(oSDM) sliceable bandwidth/bit rate variable transceiver (S-BVT) developed in SEASON operates across the S, C, and L bands enhancing capacity scalability through its modular architecture. It is based on orthogonal frequency division multiplexing (OFDM), intensity modulation (IM), and direct detection (DD), with adaptive digital signal processing (DSP) to ensure higher flexibility and performance. The transceiver architecture enables point-to-point (P2P) and point-to-multipoint (P2MP) connectivity, while providing flexible and efficient bandwidth allocation across spectral and spatial channels, meeting the demands of future optical networks. **[Ref: Section 7.4 in WP3 – D3.2]**
Multiband amplifier	ADTRAN	A predictive maintenance (PdM) prototype for optical amplifiers was developed in SEASON, which is tailored to the use case of the EDFA. The PdM utilizes three components, anomaly detection (AD), remaining useful life (RUL) prediction and fault condition (FC) diagnosis. The PdM system uses the parameters of the application system (EDFA) and processes them using modern ML algorithms so that a real-time analysis of the system status is possible. This work has laid the foundations for an application of the PdM approach to multiband amplifiers. **[Ref: Section 7.6 in WP3 – D3.2]**
Monitoring approaches		
DSP Rx-based monitoring	HHI	The SEASON project aims to enhance optical network monitoring by improving the resolution and accuracy of longitudinal power profile estimation using DSP-based techniques. The new focus in SEASON is to implement the Linear Least Squares (LLS) method, which promises higher accuracy in anomaly localization. This new method is currently in progress in [C3.5] and will replace the older correlation-based approach, which had lower resolution. The goal is to achieve sub-km (<500 m) and sub-dB (<0.5 dB) resolution in estimating fiber attenuation points and amplifier gain. The first version of the LLS approach is expected by the end of November 2024, with testing to follow in D3.3.
Monitoring system and telemetry	ADTRAN	Fiber-optical networks are essential for digital transformation, but they require constant monitoring to ensure they are always available. Most fibers are underground and can be damaged by human activity, like excavation or rodents. Continuous monitoring of power levels helps identify faults without needing new hardware. A mobile optical time domain reflectometer (OTDR) can pinpoint the exact location of a fiber cut, though it can delay data restoration. A new technique has been developed in SEASON that quickly identifies the location of a cut with minimal extra costs, using existing amplifier hardware. This method allows for fast repair and ensures ongoing availability of fiber networks. **[Ref: Section 7.7 in WP3 – D3.2]**
Research activities		
Pluggable amplifiers	TEI	Pluggable EDFAs are cost-effective amplifiers mainly used in Data Center Interconnect applications for basic point-to-point connectivity. In multi-span DWDM systems, they face two main limitations: a lack of variable gain and flatness control, which impacts the OSNR and requires span padding, and the absence of gain flattening filters, leading to gain variation across channels.

		This limits their channel support, often to around eight channels, especially when dual amplifiers are integrated. Despite these drawbacks, pluggable EDFAs are beneficial in network access scenarios, where they help extend signal range without large investments. **[Ref: Section 7.8 in WP3 – D3.2]**
SmartNIC with coherent pluggable	CNIT, INF	In the SEASON project, we propose the use of Network Interface Card, possibly augmented with smart capabilities (SmartNIC, also called Data Processing Unit - DPU) to be equipped with P2P and P2MP coherent transceivers as an innovative cost-effective *edge solution* providing converged packet, optical and computing resources in a single platform. A relevant use case of an edge node equipped with NIC/DPU encompassing coherent transceivers refers to the implementation of Distributed 5G Units (DU). As key benefit, the cell site GW is removed thanks to the use of NIC/DPU equipped with P2MP coherent pluggable transceiver. **[Ref: Section 7.9 in WP3 – D3.2]**

3 WP4 Control Plane Components

The SEASON WP4 focuses on Telemetry, Control and Orchestration for close-loop automation and self-management. This includes the development of various control plane components and applications driving towards (a) automatic network configuration, (b) self-healing during failure, (c) secure access and control of the devices, and (d) optimal use of network resources to make the network truly self-managed.

The following tables gives details of the components developed in WP4 for multi-domain control/orchestration, SDN control of packet/optical domains, SDN agents, and other key components. For further details, please see D4.2.

Table 3-1: List of Control Plane Components.

Component Name	Involved Partner(s)	Description
Multi-Domain Control and Orchestration		
Kubernetes Service Orchestrator	WINGS	The Kubernetes is used as the service orchestrator, and it automates the deployment, scaling, and management of containerized applications across various network environments, including cloud and edge computing. Kubernetes ensures consistency and reliability by managing microservices and applications, automatically scaling them based on demand, and providing self-healing capabilities. It also facilitates service discovery and load balancing. Integrating Machine Learning Operations (MLOps) into Kubernetes enhances decision-making by enabling continuous development, deployment, and monitoring of AI/ML models, optimizing resource utilization, and improving network performance and reliability. **[Ref: Section 3.3.2 in WP4 - D4.2]**
Network Orchestrator	TID	The Transport Network Orchestration (TNO) in SEASON uses the TeraFlow SDN Controller framework to manage the transport network from PON to metro-core. It helps create end-to-end services with the aid of domain network controllers. The main service provided is the "slice" service, which ensures connectivity between endpoints with specific Service Level Objectives (SLOs) like guaranteed minimum bandwidth and maximum latency. The TNO exposes a Service Attachment Points (SAP) topology, showing where connectivity services can be attached and delivered to customers. **[Ref: Section 3.3.1 in WP4 - D4.2]**
SDN Controllers		
RAN Intelligent Controller	ACC	The RAN Intelligent Controller (RIC) is a key part of the Open Radio Access Network (O-RAN) architecture. It improves the performance, flexibility, and management of the Radio Access Network (RAN) by enabling dynamic and automated control of RAN functions. The RIC supports real-time and long-term network optimizations, reduces latency, and enhances service quality. It allows third-party applications to manage RAN elements in real time, fostering innovation. The RIC comes in two forms: Near-Real-Time RIC for immediate control tasks and Non-Real-Time RIC for higher-level management and long-term improvements. **[Ref: Section 3.2.6 in WP4 - D4.2]**
Spatial PON Controller	WEST	The Passive Optical Network (PON) Controller in the SEASON framework manages and configures PON infrastructures. It acts as an intermediary, simplifying hardware complexity and enabling flexible service configurations.

Dissemination Level	SEN (Sensitive - limited under the conditions of the Grant Agreement)

		The controller uses a RESTful API for integration with orchestration platform. It communicates with PON hardware via NETCONF over SSH, ensuring secure and reliable operations. The API allows for device configuration, operational data access, and advanced P2P link provisioning, facilitating efficient management of Calix E7-2 devices and supporting advanced PON use cases. **[Ref: Section 3.2.4 in WP4 - D4.2]**
IPoWDM Controller	TID	The TFS controller is used as an IP Controller with extensions to support control of IPoWDM devices. In SEASON D4.1, TFS was enhanced with an OpenConfig SBI driver module for topology discovery and device onboarding. In deliverable D4.2, we contributed enhanced feature details. This includes adding three new features to support OpenConfig white boxes and DPU/SmartNICs with coherent pluggables, including a REST API for configuring transceivers and automatic discovery of these transceivers. **[Ref: Section 3.2.5 in WP4 - D4.2]**
Optical Controller for P2P and P2MP pluggable devices	CTTC	The FlexOpt optical SDN Controller works under a transport Network Orchestrator to manage optical networks. It abstracts the Intelligent Pluggable Manager (IPM) details and provides a TAPI interface to the Orchestrator. It also coordinates the configuration of P2MP pluggables and spectrum services using an OLS controller. The FlexOpt controller handles user requests for P2P and P2MP services, computes paths, allocates resources, and manages service lifetimes. **[Ref: Section 3.2.3 in WP4 - D4.2]**
MBoSDM SDN Controller	CTTC	The Multi-Band over Spatial Division Multiplexing (MBoSDM) Optical Controller is designed to handle the increasing traffic in optical networks by using advanced technologies like Sliceable Multidimensional transceivers. It supports two main types of networks: single-level networks, which use parallel links such as fiber bundles or multi-core fibers, and multi-level networks, which allow switching at different levels like wavelength, waveband, or fiber. Multi-level networks are more efficient and scalable but require more complex control systems. The MBoSDM Optical Controller helps manage these networks by extending existing SDN frameworks to handle new challenges, including advanced node models, virtual link management, and algorithms for efficient resource allocation. **[Ref: Section 3.2.1 in WP4 - D4.2]**
Ensemble Controller	ADTRAN	The Adtran Ensemble Network Controller (ENC) is used in the control plane as an Optical Line System (OLS) control. This controller is also integrated to ONF TAPI-driver for northbound interfaces and native definitions for southbound interfaces. The controller facilitates optical configurations. The Adtran TAPI implementation supports a flat topology model that combines all network layers into a single view, simplifying service configuration. The ENC with TAPI allows easier channel configurations and is integrated to northbound optical controller using TAPI. **[Ref: Section 3.2.2 in WP4 - D4.2]**
SDN Agents		
SDN Agent for SmartNIC	CNIT	The advancement in transmission technologies and network programmability are enabling the integration of optical, packet, and computing resources, enhancing edge-to-edge and edge-to-cloud connectivity. Coherent pluggable transceivers and IPoWDM switches are key innovations, reducing costs, latency, and power consumption. These technologies, along with SmartNICs/DPUs and network programmability (e.g., P4, DOCA), support scalable, real-time telemetry and dynamic network reconfigurations. In SEASON WP4, we developed an SDN Agent for configuring coherent pluggables in SmartNICs/DPUs, facilitating a comprehensive framework for pervasive telemetry and accelerated networking, ensuring high throughput and low latency. **[Ref: Section 7.9 in WP3 – D3.2]**

SDN Agent for IPoWDM nodes in ROADM-free networks	CNIT	Hyperscale cloud providers have significantly advanced IP over WDM (IPoWDM) technologies, particularly coherent transceivers and packet-switching ASICs, driven by increased data center traffic. This progress is prompting Telco Operators to explore ROADM-free networks, which simplify control procedures and enhance failure recovery by eliminating multi-layer processes. A novel control plane solution, the Optical Line Controller (OLC), has been designed for these networks, enabling decentralized configuration and monitoring of point-to-point optical links without centralized Optical SDN Controllers. Preliminary validation shows efficient setup and operation, highlighting the potential benefits of this approach. **[Ref: Section 3.1.2 in WP4 - D4.2]**
SDN Agent for the MBoSDM node prototype	CTTC	The SDN Agent for the MBoSDM node prototype is the software agent/component that maps high level configuration operations from the SDN controller into the device configuration operations (typically at lower level) and provides a given device model abstraction. The SDN agent exports an Application Programming Interface (API) to higher layers enabling remote configuration and device programmability. The SDN agent allows the configuration of the data plane in terms of "cross-connections" that can happen at the level of optical spectrum or fiber/port switching. **[Ref: Section 3.1.3 in WP4 - D4.2]**
FlexTelemetry Agent	ADTRAN	The FlexTelemetry agent is a Python-based app for managing real-time and historical data from network devices. It uses NETCONF and SNMP for data collection and supports plugins for databases and message brokers like Influx DB, Kafka, MQTT, and Redis. It integrates with Telegraf for real-time access and storage, ideal for analytics and machine learning. Python's multiprocessing handles high-frequency telemetry streams efficiently, and Grafana supports real-time data visualization by subscribing to Influx DB. **[Ref: Section 3.1.4 in WP4 - D4.2]**
OpenROADM Agent for smart pluggables	FiberCop[1]	The OpenROADM agent for smart pluggable enables the configuration of OCh (optical channel) parameters (channel frequency and transmitter power) of pluggable transceivers hosted in a SONiC based switch, according to the OpenROADM MSA. It also allows the configuration of the parameters (destination groups, sensor groups, subscriptions) needed to start a streaming-telemetry session using the so called dial-out mode. Data are collected from the pluggables directly from the CMIS interface and sent via gRPC to the collector. A telegraf input plugin is also available to store stream data into an influxdb database.
OpenROADM Agent for MBoSDM	FiberCop[1]	The agent allows the creation of cross-connection between ports of an optical switching fabric by implementing appropriate extensions to the OpenROADM models. It has been locally tested to control a GlimmerGlass optical switch but can also be used for the MBoSDM prototype described in sect.
Other Key Components		
Telemetry System (MQTT Broker)	CTTC	Telemetry streaming offers continuous data flow for network monitoring, providing real-time updates and detecting subtle performance changes. It reduces data exchange by generating events for specific network changes. The CTTC FlexOpt SDN controller uses MQTT to export telemetry data, which an MQTT subscriber processes to update a network topology database (TED). This TED supports an AI/ML Path Computation Server, ensuring accurate path computation without constant polling. **[Ref: Section 4.1 in WP4 - D4.2]**

[1] FibeCop (PIC 875619777) formally starts its commitment in SEASON in September 2024, assuming final approval of Amendment AMD-101096120-18 (submitted 29/11/2024) stating the partial takeover of activities and financial resources previously assigned to TIM.

OCATA Optical Layer Digital Twin	UPC	The classical OCATA architecture for C-band uses Deep Neural Networks (DNN) to model signal propagation and noise levels for a reference channel. It extracts features from optical signals to estimate quality indicators like pre-FEC BER and SNR. The novel OCATA MB architecture adapts this for multi-band scenarios by selecting a few reference channels to represent different spectrum areas. It uses these to estimate features for any channel, enabling efficient quality of transmission (QoT) estimation and channel selection. An algorithm then selects the best channel based on QoT requirements and route characteristics. **[Ref: Section 3.4.1 in WP4 - D4.2]**

4 Preliminary KPI Assessment

This chapter delves into the Preliminary KPI Assessment, systematically evaluating the key performance indicators essential for the success of the SEASON 1.0 solution. This assessment focuses on critical metrics such as network connectivity service creation time, switching capacities of MBoSDM nodes, energy efficiency improvements, and the scalability of optical transceivers. Initial results indicate significant progress towards the project's objectives, demonstrating SEASON 1.0's capability to handle high-capacity traffic while maintaining optimal energy efficiency and scalability. These findings affirm the effectiveness of the integrated data and control plane components, highlighting the solution's readiness to support next-generation optical networks. Table 4-1 depicts the detailed assessment of these KPIs, providing a comprehensive overview of the solution's performance across various benchmarks.

Table 4-1: List of Control Plane Components.

KPI ID	KPI DESCRIPTION	PRELIMINARY ASSESSMENT
2.3	Network connectivity service with creation time < 3 min combining control and data planes.	Not yet addressed, it requires all Project components.
3.1	Design and implement flexible and modular MBoSDM node prototypes able to switch/add/drop channels in at least 3 different bands (e.g., S, C, L) in an SDM/MCF fibre infrastructure featuring up to 10 fibres/cores, able to cope with switching capacities scalable up to between 2.4-3.6 Pb/s (considering a 4-degree node with 50% local add/drop and depending on the number of used bands and SDM cores/fibers), mid-term evo ~2028], by approaching (fractional) space-wavelength flexible architectures.	Validation studies of MBoSDM node architectures enabling Pb/s switching capacities are presented in section 4.2 of D3.2 (WP3). Two different MBoSDM node prototypes (C3.1 and C3.2), were developed and validated, as described in Sections 7.1 and 7.2 of D3.2. A scalability analysis for a 3-degree node prototype C3.1 is performed, envisioning 0.5 Pb/s capacity considering S+C+L bands and 19-cores of a multicore fiber (MCF). Considering a higher degree node, the target KPI switching capacities of 2.4-3.6 Pb/s could be envisioned. More details on the KPI assessment can be found in section 2.3 of D3.2. The node prototype C3.2 is ready and a first characterization results are included in D3.2. The experimental assessment for C3.2 will be included in deliverable D3.3, along with alignment and analysis focused on meeting KPI 3.1. The prototype is also on track regarding the integration with the control plane for the demo preparation later on in the project. This additional evaluation will provide further confirmation of the architecture's capability to meet the KPI, demonstrating that the SEASON project is on track to deliver a scalable, flexible, and high-capacity MBoSDM infrastructure capable of supporting next-generation optical networks.
3.2	MBoSDM transceivers able to increase the capacity of SoA transceivers up to 2× - 4× by exploiting enhanced wavelength/space dimensions while enabling appropriate slice/band/core/fibre selection according to the network path.	A programmable MB(oSDM) S-BVT prototype has been implemented and validated in WP3 (component C3.4 described in section 7.4). A scalability analysis has been implemented, demonstrating potential capacity upgrades of 2x–4x through the use of MB (S+C+L bands) and SDM. A capacity of 41 Tb/s is envisioned on a single core of a 19-core MCF by fully populating the S-, C-, and L-bands, respectively. More details on the KPI assessment can be found in section 2.3 of D3.2.

3.3	Optimized DSP for metro/core coherent applications, able to increase 4× data-rate, reaching up to 1.6Tb/s per port with power consumption suitable for future pluggable modules.	A first version of the DSP has been successfully tested in lab experiments for operation at symbol rates up to 160 GBaud. The DSP incorporates state-of-the-art techniques, including data-aided frequency domain equalization, 1^{st} and 2^{nd} order group velocity dispersion (GVD) compensation, carrier phase recovery, and a decision-directed least mean square (DD-LMS) de-skew module at the receiver. At the transmitter, nonlinear predistortion is applied to the signal prior to modulation. Additionally, the lab prototype transceiver can be controlled via software-defined networking (SDN), which is achieved by interfacing the data plane with an SDN control environment through a NETCONF agent. This agent, designed using YANG models such as OpenConfig, facilitates both the configuration of essential parameters - frequency, output power and operational mode - and the monitoring of DSP performance metrics like BER and OSNR.
4.3	400Gb/s RAN fronthaul ports capacity.	The study addresses the deployment of coherent pluggable 400G transceivers in DWDM networks. The low-power version of the transceiver delivers -10 dBm, while the high-power version achieves +3 dBm by integrating an optical amplifier and potentially a noise-removal filter. Low-power transceivers encounter limitations due to fixed gain operation and low output power, which affects the OSNR and receiver sensitivity at high data rates. To ensure network feasibility, low-power transceivers can support 4 nodes, but require equalization through a fixed attenuator, which diminishes the power budget. Conversely, high-power transceivers enhance performance by supporting up to 6 nodes, improving OSNR, and extending reach by reducing the need for attenuation. While the network can sustain up to 6 nodes at 400G, it can accommodate up to 10 nodes at 200Gb/s. The introduction of variable gain amplifiers could further optimize network adaptability and scalability, albeit at a higher cost.
6.2	>40% reduction of O/E/O conversions in edge-edge and edge-cloud communications by developing smart edges with high-speed coherent intelligent pluggables and by moving 5G functions closer to the cell sites	A suitable scenario for significant reduction of O/E/O conversion has been identified and anayzed. It consists of the 5G infrastructure serving railway systems. In SEASON we propose to provide the edge computing node hosting the virtualized CU with optical pluggable modules. This way, termination and electronic aggregation at cell site gateways can be avoided. In this railway scenario, the expected number of O/E/O conversion will be halved. Joint study CNIT-TIM in progress. Scientific paper in preparation.
7.1	Intelligent data aggregation to provide data compression >90% without significant information loss.	Intelligent data aggregation for dimensionality reduction (volume and velocity) has been proposed for measurements with large size, i.e., optical spectrum and IQ constellations. Three techniques have been explored: i) supervised FeX; ii) data compression using AE; and iii) data summarization. Those techniques introduce negligible error (MSE=4e-5), while achieving compression > 99%.
7.2	Reduction on the average setup time of converged connectivity service by 30% compared to serialized provisioning, exploiting approaches relying on parallelism and concurrency. Network Connectivity Service (point to point across different segments	The E2E IPoWDM pluggable service has been designed and partially implemented to create IETF connectivity services. It enables device/optical channel configuration via OpenConfig. Connectivity can be parallelized in both sides (PON + IPoWDM).

	(PON/backhaul) considering control plane only < 1 second (not considering hardware configuration latencies).	The service time is calculated with the time of all the services (IP, Optical and PON). The hardware time must be removed from the total time.
7.4	Demonstration of CI/CD approach with < 10 minutes pipeline execution time after committing or detection of network change (new node/pluggable, LOS, …), including device configuration modification, testing, validating, and deploying of infrastructure configuration compared to ~ 30 minutes of manual configuration via CLI or SDN intent creation, execution and testing using REST-APIs.	The NetDevOps pipeline has been designed to simplify and automate network management in optical transport networks. It enables device/service configuration with automated pipelines and achieves configuration of optical terminals using OpenConfig and Optical Line System (OLS) components through TAPI. Additionally, a custom API server has been developed within the NetDevOps framework. This server mirrors TAPI functionality and extends its capabilities by enabling seamless communication with other optical controllers. Additionally, the pipeline's rollback mechanism ensures network stability by allowing reversion to a previously stable state in case of configuration errors or failures.
8.1	Autonomous operation based on multi-agent systems to reduce >25% OpEx w.r.t. manual/static operation	In DWDM networks using EDFAs, managing amplifier modes is crucial. Constant Power mode offers precise power control but requires real-time channel counting, often using OCM or WSS. Constant Gain mode does not need channel counting but requires accurate loss estimation to set gain, with errors impacting channel quality. In simpler networks without extensive monitoring, Constant Gain mode is common. Automation tools like OLCs help adjust gains using AI, reducing manual work. Gain setting relies on measuring span loss, but methods like using photodiodes or OSCs have accuracy challenges. Manual adjustments are labor-intensive. Overall, automation and intelligent algorithms enhance network performance by optimizing amplifier settings, reducing manual interventions, and ensuring reliable channel operation.
8.2	Near-real time local (inside a node) control loops, including data collection, analysis, and decision making in <10 ms, as compared to seconds for control loops involving the SDN controller.	A distributed control architecture based on MAS to assist the SDN controller to make autonomous near-real-time decisions has been proposed and experimentally assessed. For the control of p2mp systems, the MAS has showed near-optimal decision making, while adding the capability for asynchronous decision making. Then, while SDN-based decision making must wait until telemetry data from all the leaves in the p2mp collect, process and convey telemetry data to the controller to make a decision, MAS agents can make local decisions as soon the local telemetry data is available (few ms). This makes MAS-based solutions more scalable and agile than SDN-based decision making.
8.3	Optical layer digital twin for gradual soft-failure detection and localization with at least 1min before major impact on the service. >90% accuracy in soft-failure identification.	The OCATA Time Domain Digital Twin exploits the comparison of features extracted from the received IQ constellations, with those extracted from generated constellations for the lightpath under analysis. The ability of OCATA to estimate the pre-FEC BER is used. Overall accuracy of 95% in soft-failure identification has been demonstrated. In addition, OCATA has shown to provide estimated severity that progressively converges to the actual time-to-failure, giving accurate estimations with enough lead time to enable scheduling maintenance activities.
8.4	Service creation < 90 min (such as ETSI Network Service or Micro-services application deployed with Kubernetes)	A Kubernetes-based deployment pipeline was successfully implemented, enabling the automated creation of ETSI Network Services and microservices in approximately 70

		minutes, thus meeting the <90-minute KPI. Key optimizations included parallel deployments and resource pre-allocation to enhance efficiency. Automated testing and validation steps were integrated to ensure service reliability. Future efforts will focus on deploying the pipeline in live network environments and further reducing deployment times through advanced orchestration techniques.

5 Status of Ongoing Integration Activities Towards Demonstrations

5.1 MBoSDM node integrated with control

In SEASON a multiband over spatial division multiplexing (MBoSDM) node prototype has been designed and implemented towards addressing the growing capacity and traffic demands of future optical networks. More details and features of the proposed switching solution can be found in deliverable D3.2. The proposed MBoSDM node, shown in Figure 5-1, is integrated with a software defined networking (SDN) control plane enabling suitable reconfiguration of the network.

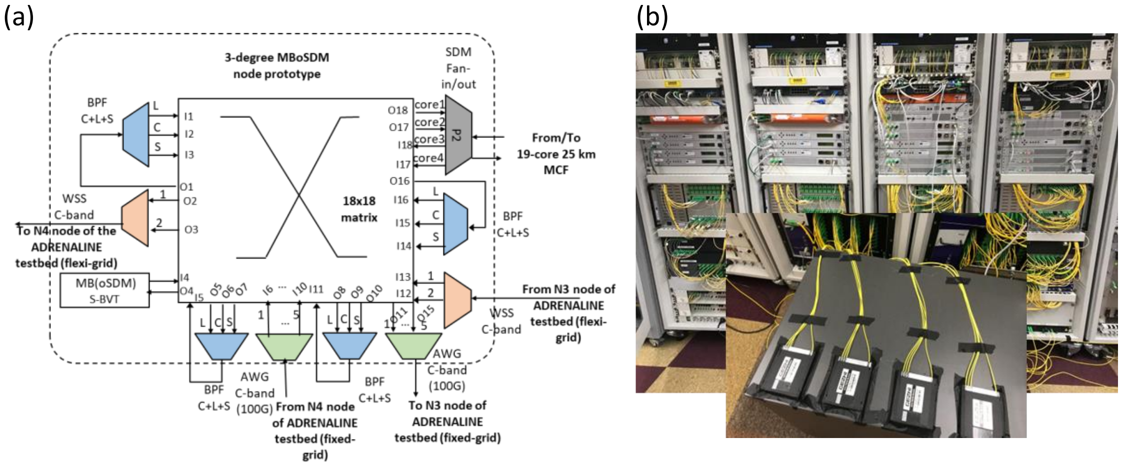

Figure 5-1: MBoSDM switching (a) architecture with the main building blocks and (b) prototype integrated in the ADRENALINE testbed.

The proposed modular node architecture enables MB (S+C+L), SDM and WDM (within the C-band) technologies providing high capacity, flexibility and scalability. Spectral (band and wavelength) and spatial granularities are enabled by means of key components including an optical cross connect (OXC), wavelength selective switches (WSS), arrayed waveguide gratings, band pass filters and fan-in/-out devices.

This prototype has been integrated into the ADRENALINE testbed, available at CTTC premises (see deliverable D3.2). It enables bidirectional flex- and fixed-grid C-band connections between different ADRENALINE nodes. Four cores of a multicore fiber (MCF) of 19-cores and 25 km is connected by means of fan in-/-out devices to the MBoSDM node to enable spatial switching operation.

From an SDN controller, considering a control-enabled view, the node can be abstracted as follows, with the API that needs to be supported from the SDN agent.

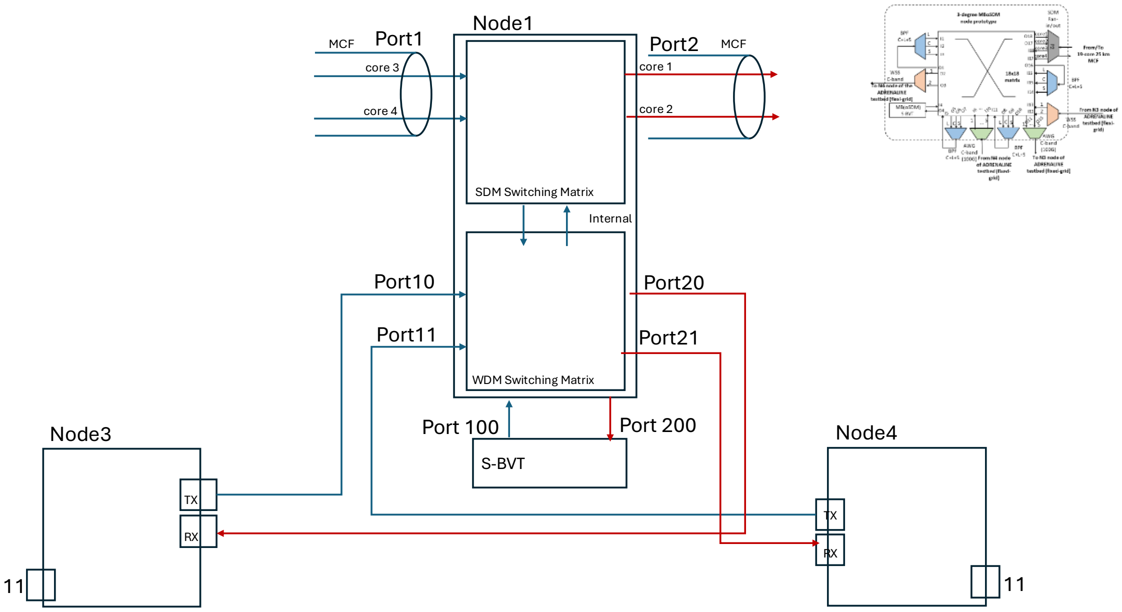

Figure 5-2: Abstracted view of the MBoSDM node prototype in terms of input/output ports to define logical, high- level operations.

5.1.1 Considered high level operations

In the context of this PoC, the operations that are currently defined based on the existing hardware are:

- Core Switching Operations from one core port to another core port:
  - Input Port: 1
  - Input Core : c3 or c4
  - Output Port: 2
  - Output Core : c1 or c2

- Optical Band Add
  - Input Port: 100 (from the S-BVT)
  - Band: C or L or S
  - Output Port: 2
  - Output Core : c1 or c2

- Optical Band Drop
  - Input Port: 1
  - Input Core: c3 or c4
  - Band: C or L or S
  - Output Port: 200 (to the S-BVT)

- Spectrum Switching
  - Input Port: 10 or 11
  - Output Port: 20 or 21
  - ITU-T flexi-grid slot (within C-band n,m) or fixed grid channel.

- Spectrum Add
  - Input Port: 10 or 11
  - Output Port: 2
  - Output Core Port: c1 or c2
  - ITU-T flexi-grid slot (within C-band n,m) or fixed grid channel.

- Spectrum Drop
  - Input Port: 1
  - Input Core: c3 or c4
  - Output Port: 20 or 21
  - ITU-T flexi-grid slot (within C-band n,m)

- Spectrum Add
  - Input Port: 100
  - Output Port: 20 or 21
  - ITU-T flexi-grid slot (within C-band n,m) or fixed grid channel.

- Spectrum Drop
  - Input Port: 10 or 11
  - Output Port: 200
  - ITU-T flexi-grid slot (within C-band n,m) or fixed grid channel.

5.1.2 Control Architecture

The proposed control architecture is in line with SEASON control plane as shown in D4.1 and D4.2. this includes

- An SDN Controller, in this case the FlexOpt SDN controller, properly augmented to perform DWDM, band or SDM (core) switching. This component is provided from WP4 and extended according to the hardware device model
- An SDN Agent based on NETCONF implemented within the project. The SDN agent maps the high-level operations to the configuration of matrices and WSS and related subsystems. The controller facing part is based on Net2peer opensource framework and is written in python.
- Yang model for the device. A specific yang model is being developed for the identified high-level operations in the previous section. The yang model is the reference and contract between the SDN controller and the agent and supports the identified Create/Read/Update/Delete (CRUD) operations on Cross-connections, with constraints in terms of input ports / output ports and type / layer of cross-connection

5.1.3 Yang model

Based on the previous considerations, an initial Yang model has been developed for the SDN agent that captures the basic information to perform operations on the device. The following snippet shows the Yang model in tree format.

```
module: season-mbosdm-node
  +--rw node
  |  +--rw address        inet:ip-address
  |  +--rw node_id        yang:uuid
  |  +--ro ports
  |  |  +--ro port* [id]
  |  |     +--ro id            uint32
  |  |     +--ro name?         string
  |  |     +--ro direction?    season-mbosdm-types:port-direction
  |  |     +--ro type?         season-mbosdm-types:port-type
  |  +--rw connections
  |     +--rw connection* [name]
  |        +--rw name            string
  |        +--rw input_port      uint32
  |        +--rw output_port     uint32
  |        +--rw input_core      uint32
  |        +--rw output_core     uint32
  |        +--rw band?           enumeration
  |        +--rw n               int16
  |        +--rw m               uint16
  +--ro info
     +--ro software_version?   string
     +--ro hardware_version?   string
```

In summary, progress on the design and development of the agent is as expected. We expect the first integrations in Q1 2025, once the low-level details of the MBoSDM

5.2 MBoSDM NODE INTEGRATED WITH CONTROL AGENT

In SEASON, we designed a passive 2×2 MBoSDM node prototype that is capable of band and space/fiber switching. The prototype is currently being integrated to an SDN agent and supports selective band switching as well as add/drop functions for the S-, C-, and L-bands.

The prototype is based on a fixed and static optical band-selective filter architecture combined with a fully configurable optical cross-connect (i.e., an optical matrix switch). The node functions as a hierarchical network node, providing a fast route-and-select architecture at the band level while maintaining backward compatibility with legacy transport schemes and traditional wavelength-selective switching for each band. The design incorporates eight multiband multiplexers or splitters/combiners (MB Mux and MB Demux) and a 12×12 optical matrix switch that allows flexible band routing. This is shown in Figure 4.2- 1 (a). Upon assembly, the prototype was characterized, for more details, refer to D3.2. The assembled prototype is shown in Figure 4.2- 1 (b).

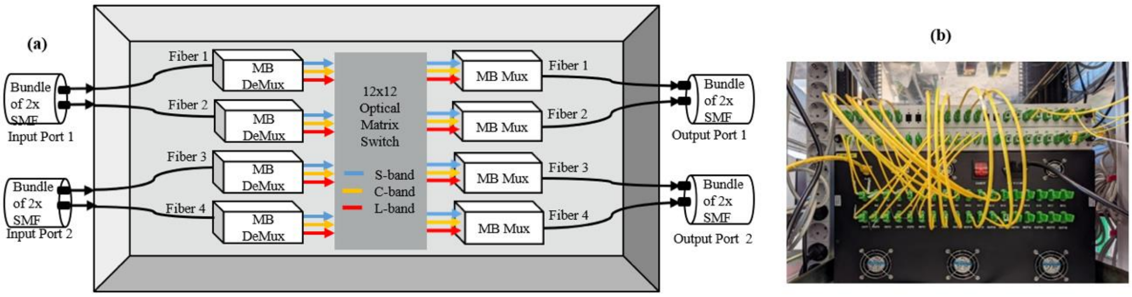

Figure 4.2- 1: (a) Prototype design. (b) Prototype after assembly.

The prototype will be fully programmable through a state-of-the-art SDN agent. The SDN agent includes a NETCONF server that can receive commands from a NETCONF client or an SDN controller equipped with a NETCONF driver for OpenROADM [OpenROADMMSA24]. This interface allows the node to receive standard NETCONF Remote Procedure Calls (RPCs), translating these into specific switching and add/drop operations, thereby enhancing operational flexibility within the node's hierarchical architecture.

5.3 IPM P2MP PLUGGABLE WITH IPM INTEGRATION

The experimental setup has been implemented in Telefonica's Future Network Laboratory utilizing two IPoWDM routers: a Cisco NCS 57B1 running IOS 24.3.1 and an Ufispace router with Drivenets software. Both were equipped with 400G QSFP-DD ports and 400G and 100G P2MP programmable pluggables. The interconnection between nodes is achieved through a fiber optic structure incorporating a 1:4 splitter and a 1:8 splitter.

In terms of system management, intelligent pluggable manager (IPM) has been deployed on a virtual machine, connected to the routers via a switch. Additionally, an intermediate router serves as a management interface; this device is a whitebox router running Adtran software. The IPM facilitates the programming and control of P2MP pluggables within the experimental environment.

For service configuration, the SEASON hierarchical controller is employed, which communicates with both the SEASON IP SDN controller and the SEASON optical SDN controller (FlexOpt). The optical SDN controller is located in the CTTC laboratory and connected to the Telefonica's laboratory via a VPN, ensuring seamless integration and control across the distributed experimental setup.

The FlexOpt orchestrator periodically obtains the IPM OpenID token and proceeds with the discovery of hosts (routers) and pluggable devices (modules) using a REST interface over HTTPs. Discovered network elements are mapped to TAPI network nodes nodes and module Ethernet client ports are mapped to TAPI DSR Service-Interface-Points (SIPs). The Optical Line System is modelled as a single TAPI abstracting media channel switching and can represent a ROADM based network controlled by e.g. a TAPI-enabled OLS controller node or a transparent optical splitter. In this case, 7 modules are discovered.

The establishment of a 100 Gb/s service between breakout port 1 of the Cisco router and port 1 of the UfiSpace router necessitates a specific configuration process.

To facilitate the 100 Gb/s service, it is imperative to configure the breakout mode on the interfaces involved in the service, specifically those utilizing a 400G pluggable. This configuration results in the creation of four subcarriers, each capable of supporting an individual link. The procedure entails:

- Activation of breakout mode on the 400G QSFP-DD ports of both the Cisco and the UfiSpace router.
- Allocation of one of the four available subcarriers (in this instance, subcarrier 1) for the requisite 100 Gb/s service.
- Configuration of appropriate frequency and modulation parameters for the selected subcarrier to accommodate the 100 Gb/s data rate. Figure 5-3 illustrates the state before and after frequency configuration, going from noise to a configured channel.
- Establishment of the logical connection between the designated breakout ports on each router.
- Verification of link status and performance metrics to ensure the operational integrity of the 100 Gb/s service.

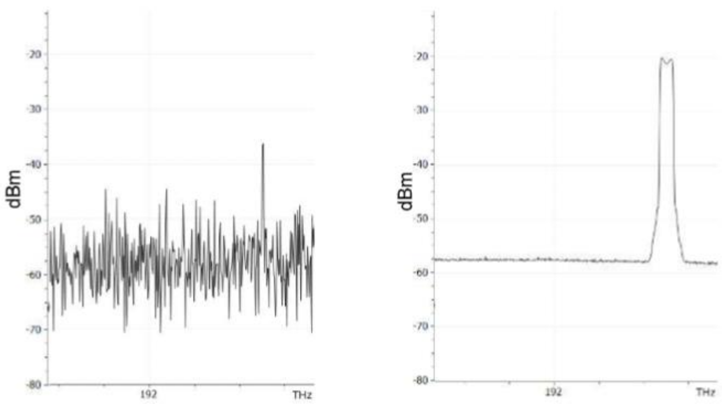

Figure 5-3: Spectrum: noise (left); service (right).

The frequency is obtained through the optical controller, which performs the corresponding frequency assignment to the equipment involved. This method enables efficient utilization of the 400G pluggable capacity, facilitating the provisioning of multiple high-speed services on a single physical port.

This methodology enables efficient utilization of the 400G pluggable capacity, facilitating the provisioning of multiple high-speed services on a single physical port. The remaining subcarriers may be allocated for additional services or reserved for future capacity expansion, thus providing flexibility in network resource allocation.

5.4 INTEGRATION OF 5G AND IPoWDM P2MP

Open RAN (Open Radio Access Network, O-RAN) is an architectural approach for 5/6G networks that aims to create an open and interoperable RAN infrastructure. In Open RAN, the Centralized Unit (CU) handles higher-layer protocols and centralized processing for user mobility management while the Distributed Unit (DU) manages real-time, lower-layer operations closer to the Radio Units (RU) at the cell site. CU and DU are nowadays emerging as virtualized elements operating on general-purpose computing platforms, with the CU typically deployed in a Cloud environment while the DUs run on edge computing platforms which are typically located close to the RUs. The mid- and front-haul networks from CU to DU and RU have been envisioned based on optical transport network (OTN) technology [Che23], passive optical network (PON), Wavelength Division Multiplexing (WDM) [Sal20], and time-wavelength division multiplexed (TWDM) PON [Mon22]. In [Wel21], an alternative solution exploiting innovative coherent Point-to-MultiPoint (P2MP) technology based on Digital Subcarrier Multiplexing (DSCM) was proposed. This solution is considered and investigated within the SEASON project.

In this work, we present the first experimental implementation of Open RAN X-haul using P2MP transceivers on horseshoe optical networks. The solution leverages the dynamic activation of 5G DUs and P2MP leaf transceivers based on real-time cell traffic conditions. By adapting to varying traffic loads, the system manages resource utilization, improving energy efficiency without compromising network performance. This work relies on the first integration of selected SEASON components including the 5G infrastructure and the RIC Controller by Accelleran, the IPoWDM solution by CNIT, and the P2MP transceivers by Infinera. This work poses the basis for the aforementioned final demo in the city of L'Aquila.

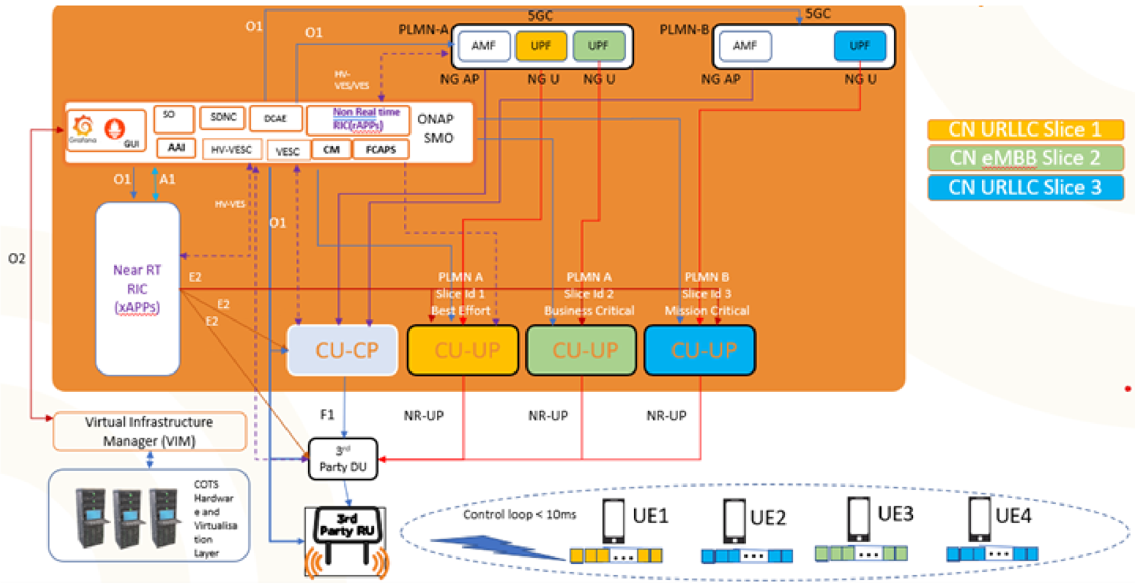

Figure 5-4: O-RAN architecture supporting dynamic DU activation.

O-RAN Infrastructure enabling dynamic DU activation

Figure 5-4 shows the considered O-RAN 5G Automation Platform managing, monitoring and deploying network functions in mobile network. The telemetry data (3GPP 28.552 stats) is available at both near Real Time (RT) RAN Intelligent Controller (RIC) for xAPPs (via interface E2) and non-RT RIC for rAPPs (via ONAP High Volume-VES interface i.e. dotted purple arrows). xApps or rApps use Kafka bus telemetry received from the E2 termination nodes. The exposed telemetry data, abstracted in standard JSON format, can report on the traffic between components of a particular network slice. For example, the telemetry data captured by the gNB-DU, gNB-CU-UP/CP can be based on counters that are available in each E2 node, such as number of RRC connections, number of PDU sessions, average DL delay, UL/DL SDU loss rate, average DL/UL throughput, total PRB usage, and active UE per cell.

In this work, a novel xApp is implemented to monitor cell parameters and dynamically trigger, for energy saving purposes, the concurrent (de)activation of both the 5G DUs and the P2MP optical transceiver that serves such DU. When selected cell parameters are below pre-defined thresholds for a configurable OFF period, the xAPPs in the non-RT RIC triggers a cell (i.e., its DU) to be switched OFF. When the load of nearby cells exceeds a second threshold, the CU-UP can dynamically reactivate the DU. Concurrently, the xApp triggers through a specifically designed API the (de)activation of the optical connectivity between CU and related DU, i.e. the P2MP coherent transceiver at the IPoWDM node located at the horseshoe leaf. This dynamic behavior is particularly relevant in dual frequency networks with umbrella coverage provided by a macro cell, where small/additional cells (DU and RU) can be completely switched OFF based on activity patterns during certain time of the day to save energy. This way, energy and cost savings can be achieved at the optical, computing and wireless infrastructure during quite periods when user plane activity is very low for such slices (e.g., during the nights).

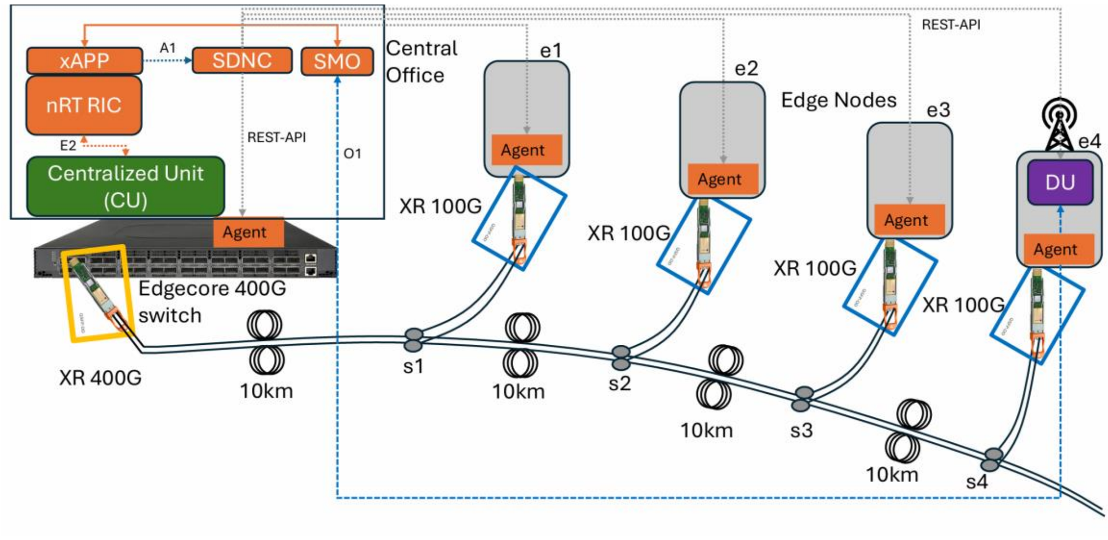

Figure 5-5: O-RAN xHaul solution deployed on a bidirectional horseshoe optical network.

O-RAN deployment on P2MP Horseshoe

The considered O-RAN solution is deployed on a bidirectional optical horseshoe network, as shown in Figure 5-5. The CU runs in a Telco Central Office (CO) including computing resources and IPoWDM equipment. Each DU is operated on an edge computing node at Telco Local Offices (LOs, Ex edge nodes in the figure). CU to DUs communication from a central hub (i.e., CO) to multiple leaf locations (i.e., LOs) leverage P2MP digital subcarrier multiplexing. In particular, the ports at hub location are split into lower rate sub-ports (e.g., a single 400G port can be divided into 4x100G ports), with each sub-port independently routable to different endpoints. In this work, pluggable optical modules supporting P2MP configurations are managed and controlled by the IPoWDM host equipment through the Common Management Interface Specification (CMIS). To enable communication between hub and leaf locations in a P2MP configuration, the provisioning routine leveraging CMIS registers proceeds through the following steps. First, the application code, central frequency and Tx output power are configured at the hub node. Each pluggable module has a unique set of application selection codes that define its capabilities, making it essential for the selected code to match the host system's capabilities. Both the host and the module must align in their traffic application selection. For example, to configure a 400G module to operate in a 4x100G mode, the port is first divided into four sub-ports, each capable of transmitting 100G. After the appropriate application code is selected at the leaf node, the P2MP service intent is established by associating port specific information with the carrier frequency of the leaf. For example, if the central frequency of the hub is configured to 195 THz, one of the leaf nodes would be configured to 195.01875 THz, requesting service from the hub and its corresponding port. The embedded control plane at the hub then checks the availability of the client port and allocates the group of subcarriers to connect a leaf node to the target port. Additionally, the Tx output power of the leaf nodes is initially set to a default value (e.g., -99 dBm), as the control plane at the hub manages and adjusts the leaf output power. The leaf configuration procedure (i.e., selection of the appropriate central frequency for enabling P2MP service intent) is then repeated for the remaining leaf nodes.

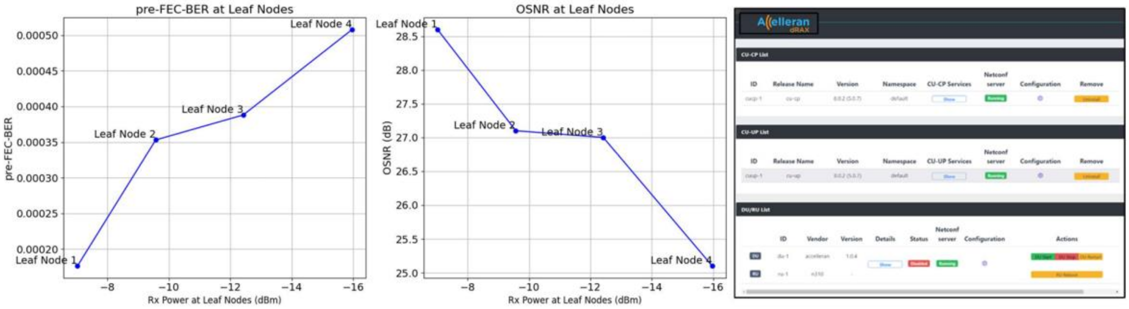

Figure 5-6: Evolution of the pre-FEC-BER (left) and OSNR values (center) at leaf nodes. View of the RIC after DU switch off (right).

Experimental validation

A bidirectional optical horseshoe network, described in Figure 5-5, is implemented using a series of fully passive 1:2 splitters that connect the hub module to its corresponding leaf nodes. Communication between the hub and the leaf nodes is established by following the provisioning procedure outlined in the previous section. The transmission frequency of the hub node is set at 194 THz, while the transmission frequency of the first leaf node is configured at 194.00625 THz, with subsequent leaf nodes incrementing by 12.5 GHz. Due to the varying distances of the leaf nodes and the number of splitters they traverse in a horseshoe topology, each leaf node is expected to experience different received power levels, which in turn affects performance parameters such as OSNR. The transmission optical power at the hub node is configured to -4 dBm, resulting in a received power of -7.02 dBm at the first leaf node. At this node, the pre-FEC-BER is measured at 1.76E-4, with an OSNR of 28.6 dB.

Figure 5-6 illustrates the evolution of pre-FEC-BER and OSNR values at different stages of the horseshoe topology. Although the pre-FEC-BER values experience a slight increase as the leaf nodes pass through more splitters, they remain within a similar range, indicating good signal quality at the leaf nodes. The edge node connected through Leaf Node 4 hosts the dockerized monitored DU. When the number of User Equipment goes below a predefined threshold (T=1 in the experiment, i.e. no UE connected), the proposed xAPP within the O-RAN 5G Automation Platform triggers the energy saving procedure switching off the vDU. Furthermore, the xApp, through the SDN Controller, switches off the P2MP transceiver, exploiting the implemented CMIS REST plugin within SONIC. The estimated power saving is in the order of 15-25W for a transceiver, 50 to 100W for a vDU and 100 to 500 of the connected RU. The deactivation process of both vDU and P2MP transceivers is successfully concluded in less than 50s, while the re-activation takes around 2 minutes.

5.5 PON SDN INTEGRATION WITH TFS

The integration of PON with TFS in SEASON aims to enable dynamic and automated control over Passive Optical Network (PON) systems, enhancing the adaptability and energy efficiency of the access network. The architecture builds upon the integration of the TeraFlow SDN Controller (TFS) and the PON Controller, achieving advanced functionalities for resource management and service provisioning. Figure 5-7 depicts the architecture and setup of the spatial PON integration with TFS, highlighting its main components and functionalities.

At the center of the architecture, the Spatial Aggregator/Disaggregator dynamically handles the aggregation and disaggregation of spatial lanes across multiple OLT ports. The *Spatial PON Controller* communicates with TFS using a northbound REST interface to receive service requests. These requests are mapped into specific actions, such as activating or deactivating spatial lanes. Through NETCONF-based southbound interfaces, the Spatial PON Controller directly interacts with the OLT ports and the Spatial Switch, enabling precise control over the lane configurations.

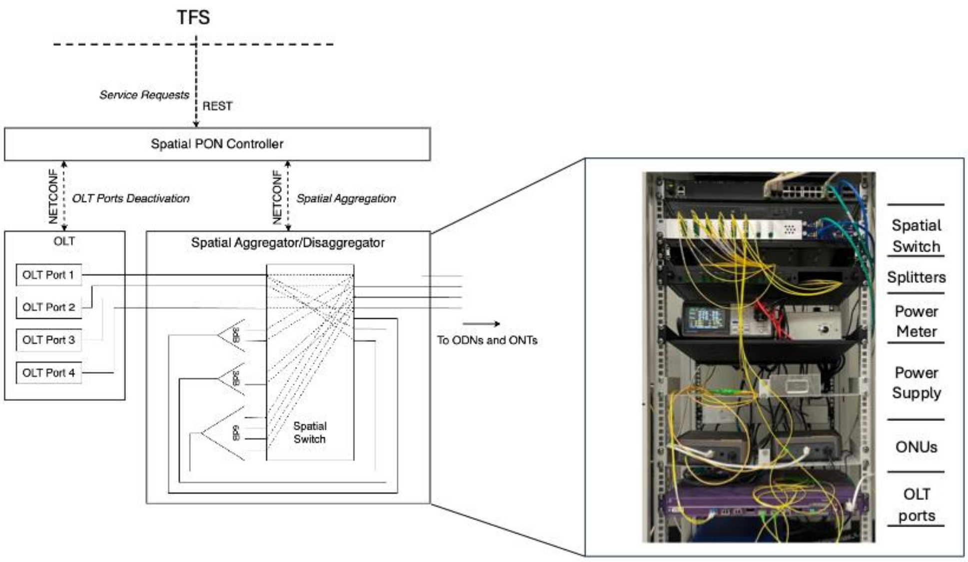

Figure 5-7: TFS Spatial PON Controller Integration.

The figure showcases the setup's physical implementation, where the spatial switch interconnects multiple OLT ports, splitters, and ONUs. This design allows the system to scale dynamically according to traffic demands, optimizing the use of active spatial lanes. In periods of lower traffic, the architecture deactivates unused lanes to reduce energy consumption while ensuring service availability. Additionally, the energy efficiency is further assessed using the integrated *Power Meter*, which measures the impact of spatial lane deactivation.

A significant feature of this integration is the **algorithm for mapping northbound requests into spatial lane activations and deactivations**. The PON Controller interprets the high-level service requests received from the TFS through REST APIs and translates them into low-level configurations, dynamically adjusting the number of active spatial lanes based on traffic conditions. This operation allows efficient resource utilization while ensuring optimal energy savings in PON systems.

The workflow for the Spatial PON - TFS integration can be summarized as follows:

- The TFS issues high-level service requests, such as a need for increased bandwidth or resource scaling.
- The PON Controller maps these requests to specific spatial lane configurations, determining which spatial lanes need to be activated or deactivated.
- The PON Controller communicates the configuration changes to the PON hardware using NETCONF, enabling real-time adjustments in the network.

This integration supports energy-efficient spatial PON solutions, aligning with the SEASON goal of minimizing energy consumption. By dynamically adjusting the active spatial lanes in response to traffic demands, the solution reduces unnecessary energy expenditure while maintaining service performance. The approach complements the overall SEASON architecture, where energy savings are achieved across multiple layers of the network through SDN-based automation.

5.6 MBoSDM S-BVT INTEGRATION WITH SDN CONTROL PLANE SUPPORTED BY ENERGY-AWARE AI/ML MODELS

A power efficiency analysis/modelling of the proposed MB(oSDM) S-BVT SEASON prototype (component C3.4) has been developed in the framework of WP3. Power consumption transceiver measurements have been performed, included in deliverable D3.2, towards supporting the development of a software-defined networking (SDN) control plane supported by energy-aware artificial intelligence (AI) and machine learning (ML) models (developed in the framework of WP4) [Nad24]. The core objective of an SDN controller is to manage the lifecycle of connectivity services, including their autonomous creation, upgrading, recovery, and deletion. For this purpose, the SDN controller integrates a set of control functions and APIs, as shown in Figure 5-8 (a). Upon receiving a connectivity service request, a workflow with a set of control functions is executed, which includes:

- Retrieving an updated view of the transport network devices (e.g., MB(oSDM) S-BVT, ROADMs) via well-defined APIs in the SouthBound Interface (SBI) with the SDN agents [Cas23]. These APIs are based on the interoperability data models defined in OpenROADM [OpenROADM] and OpenConfig [OpenConfig]. Specifically, for the MB(oSDM) S-BVT device, OpenConfig offers a vendor-neutral data model to activate/program a specific optical-band BVTx/BVRx, including the configuration of the optical carrier frequency and power, etc.

- Executing a path computation and resource selection approach to determine not only the configuration parameters for BVTx/BVRx programming but also to identify the ROADMs and optical links constituting the route, along with the optical spectrum allocation, to meet the service requirements such as guaranteed bandwidth.

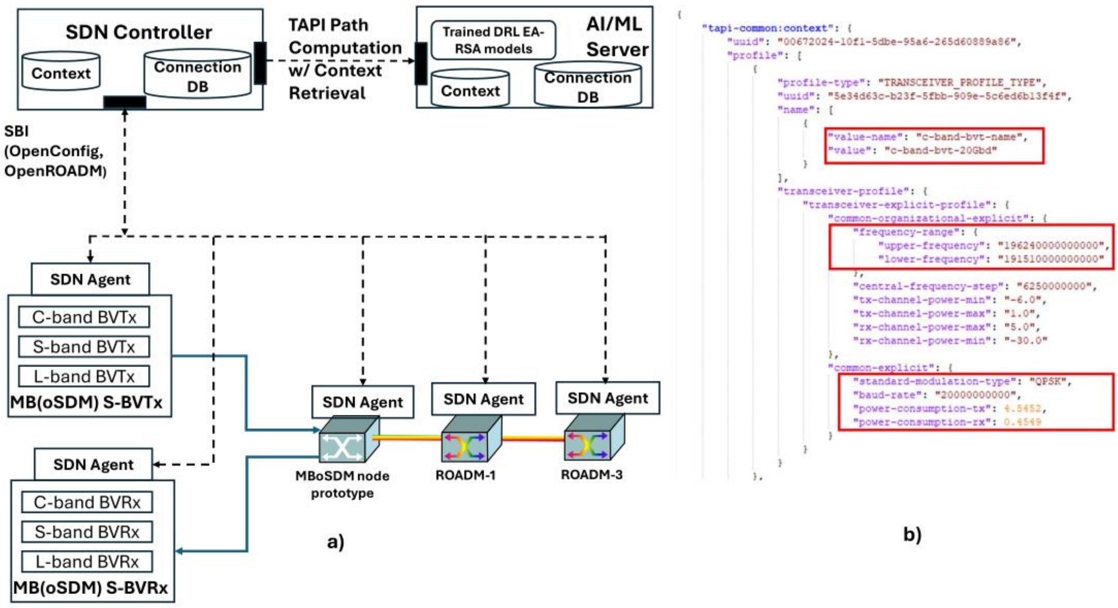

Figure 5-8: a) SDN controller architecture and APIs; b) TAPI Context Profile proposed object extension for detailed MB(oSDM) S-BVT attributes.

The path computation mechanisms/algorithms must achieve efficient utilization of optical resources across different bands while reducing overall network power consumption when establishing a new connectivity service. This poses a multi-objective problem with significant complexity, where AI/ML trained models can be leveraged for optimized decision-making [Nal23]. Given its computational intensity, the path computation function is offloaded to a specialized entity known as the AI/ML server, see Figure 5-8 (a). The interactions between the SDN controller and the AI/ML server operate on a client-server model, facilitated by the implementation of the ONF Transport API [ONF]. The SDN controller delegates the routing function to the AI/ML server. Before triggering the algorithm/trained model, the AI/ML server polls the SDN controller to synchronize its Context database (see Figure 5-8 (a)) to retrieve an updated view of the network topology and resources state [Cas23][Her23]. The topology context consists of the network nodes specifying their Node Edge Points (NEPs), along with the links interconnecting every pair of NEPs. For each NEP, relevant information used as input for the path computation operation is provided, such as the available/occupied optical spectrum.

To conduct energy-aware routing computation, it is essential to extend the current TAPI Context information to include specific and relevant power consumption attributes of the underlying transport devices, such as the considered S-BVT BVTx/Rx. In [Nad24], we present such an extension, specifying the power consumption (in Watts) for both the BVTx and BVRx operating at every optical C-, L-, and S-band for every NEP hosted in the S-BVT. The proposed extension is depicted in JSON format in Figure 5-8 (b). TAPI profiles, which offer static and invariant information that can be referenced by other TAPI objects, such as nodes' NEPs, are used for this purpose. Specifically, we expand the TAPI transceiver profile list to include the power-consumption-tx and power-consumption-rx parameters for both BVTx and BVRx at a particular optical band. In the example shown in Figure 5-8 (b), the transceiver profile in the C-band includes: the measured power consumption for both transmitter and receiver (in Watts), the supported frequency range (upper and lower frequencies in Hz), the modulation format (set to QPSK), and the symbol rate (in GBaud). Analogous transceiver profiles are built for the S- and L-bands.

The retrieved TAPI Context information, including extended MB(oSDM) S-BVT power consumption characteristics, is utilized by the AI/ML server for two purposes: 1) conducting an offline training process to derive an optimized policy/model for energy-aware routing, and 2) using the resulting trained model for online path computation upon receiving an SDN controller-initiated request. A promising AI/ML strategy for this purpose is Deep Reinforcement Learning (DRL). The DRL agent interacts with a defined environment, typically comprising the retrieved TAPI Context, which includes the network's topology, available optical resources, power consumption of the MB(oSDM) S-BVTs, ROADMs, and optical line amplifiers, along with the connectivity service requirements such as bandwidth. Through exploration and exploitation processes, the DRL agent selects actions associated with candidate feasible paths. In the targeted scenario, candidate routes differ based on the programmed source and destination BVTx and BVRx devices (using a specific optical band) and/or the path, i.e., set of ROADMs and links, to accommodate the connection. For example, candidate routes over different optical bands can be computed using a modified k-shortest path Routing and Spectrum Assignment (RSA) algorithm, aiming to find solutions that fulfill the service requirements while simultaneously conserving power consumption.

Upon selecting an action, the agent receives feedback, i.e., a reward. In energy-efficient routing, rewards can favor actions that increase network throughput (successfully served connections) while reducing or conserving network power consumption. The training is iterated over several epochs across heterogeneous network states to maximize the accumulated rewards. Consequently, the agent's knowledge improves, enabling enhanced decision-making during online path computation to improve the trade-off between network throughput and power consumption. The advantages of adopting a trained DRL agent for energy-aware routing, considering the power consumption of ROADMs and optical line amplifiers for dynamic connectivity services with diverse bandwidth and latency requirements, were outlined in [Mar24]. The aim is to extend that work by incorporating the power consumption values of the deployed MB(oSDM) S-BVT addressed in [Nad24].

5.7 MONITORING PARAMETERS FOR THE RIC

Telemetry, in this context, refers to the automated collection, monitoring, and transmission of operational data from network components to centralised or distributed systems for analysis and decision-making. Telemetry plays a critical role in ensuring the efficient operation, monitoring, and optimization of O-RAN systems. Telemetry in O-RAN systems is typically used for real-time system monitoring, capturing system performance metrics and feeding AI/ML models residing within the RAN Intelligent Controller (RIC) or within external 3rd party components.

The Telemetry Collector (TC) is a key component in Accelleran's dRAX™ RAN software suite. It is designed to gather, process, and distribute telemetry data across a diverse range of network components. The TC supports network components that are both compliant and non-compliant with O-RAN standards. The TC architecture comprises three main blocks: Input Interfaces, Translators, and Output Interfaces. These blocks work together to ensure seamless data collection, transformation, and dissemination, supporting real-time network optimisation and decision-making processes.

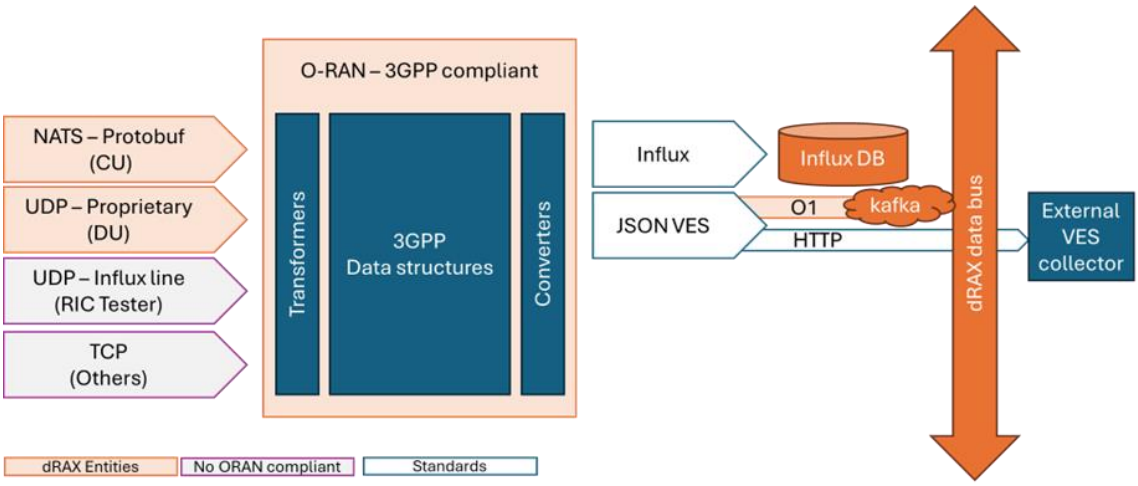

Figure 5-9: Accelleran Telemetry Collector - Input Interfaces, Translators, and Output Interfaces.

5.7.1 Input Interfaces

The input interfaces are responsible for collecting telemetry data from various sources within the network, including O-RAN-compliant and NON- O-RAN compliant or legacy components. The following key input interfaces are integrated into the system:

- E2 Interface: This interface is a core component for collecting telemetry data from O-RAN elements like the DU (Distributed Unit), CU (Centralized Unit), and RU (Radio Unit). The E2 interface facilitates real-time data transmission between these RAN elements and the Near-RT RIC, enabling critical operations such as resource management, mobility control, and interference handling.

- NATS Protobuf: This interface is an internal interface and it is in charge of supplying information from the Accelleran CU in a timely fashion to enable rapid telemetry interaction.
- Proprietary UDP: This input interface supports high-speed data collection from custom-built or non-standardized components. It is tailored for specific use cases where existing protocols may not suffice, ensuring that proprietary network elements can still contribute telemetry data to the system. It is part of the dRAX™ family of interfaces that connect the RIC with the DU.
- InfluxDB Line Protocol: This interface is used primarily for time-series data collection. It supports the integration of performance metrics and sensor data into the telemetry system. It is particularly useful for monitoring network health over time and feeding data into AI-driven decision-making processes. It is also useful for integrating KPI values that are not defined in 3GPP metrics.
- TCP-based Input Interfaces: These interfaces provide compatibility with legacy or non-O-RAN-compliant systems. The use of general-purpose TCP protocols allows the system to ingest telemetry data from older network elements that do not follow O-RAN standards, ensuring backward compatibility.
- NATS Messaging: NATS is used as a messaging protocol to facilitate real-time data transport between distributed components of the network. It is a lightweight and scalable approach to providing low-latency telemetry.

These various input interfaces support for linking together a wide variety of telemetry sources to feed data into the system, ensuring that both traditional and modern network elements can be monitored and optimised in real-time.

5.7.2 Translators and Data Processing

Once the telemetry data is collected from the input interfaces, it enters the translator and data processing block. The primary role of this component is to standardize and transform the data into a more homogeneous format so that they can be processed and acted upon by the network's AI-driven systems.

- Translators: These components convert proprietary or non-standard data formats into formats compatible with 3GPP data structures and O-RAN-compliant systems. For instance, data collected from legacy equipment or custom-built devices might use different protocols, but the translators ensure that this data can still be utilized effectively within the broader network architecture.
- Transformers: The transformers are responsible for pre-processing the telemetry data, performing functions like filtering, aggregation, and normalisation. These processes

ensure that only the most relevant data is passed on to the decision-making components, reducing the processing load while maintaining high accuracy.

- Converters: Are responsible for re-formatting telemetry data in a representation that is understood by external (non-3GPP/O-RAN) network entities.

This block ensures that data from all sources is presented in a uniform, actionable format, which is then delivered to the output interfaces for distribution to the appropriate decision-making entities.

5.7.3 Output Interfaces

The output interfaces are responsible for disseminating the processed telemetry data to various consumers within the network and to external systems. The primary output interfaces include:

- O1 VES (Kafka): This interface streams telemetry data in real time to event-driven systems using the VES (VNF Event Streaming) protocol over Kafka. It allows for integration with third-party systems that require real-time telemetry for analytics, monitoring, or optimisation purposes.
- HTTP for External VES Collectors: External collectors and monitoring systems can access the telemetry data via HTTP-based interfaces. This makes the data easily consumable by external applications that might not be part of the O-RAN ecosystem but require access to network performance metrics or health data.
- Future Expansion for 6G Systems: The architecture is designed with future-proofing in mind, supporting future enhancements such as WebSockets for 3GPP-compliant streaming and high-volume data flows. This ensures that the system can scale and adapt to the needs of emerging 6G technologies, which will require even more sophisticated telemetry systems.

These output interfaces ensure that telemetry data is readily available to key consumers, such as the RICs (Near-RT and Non-RT), AI/ML systems, and external monitoring platforms, facilitating real-time network optimization and troubleshooting.

5.7.4 Potential Telemetry for use by Energy Saving xApps

The precise details of the telemetry that will be used as inputs for Energy Saving xApp algorithms are still under discussion. At the time of writing, the following 3GPP defined metrics are expected to form the basis of any future implementation.

Table 5-1: List of Data Plane Components.

Name	3gpp name	Unit	3GPP Ref
Energy saving	-	%	-
DL Total PRB Usage	RRU.PrbTotDl	#PRB	TS 28.552 Sec 5.1.1.2.1
UL Total PRB Usage	RRU.PrbTotUl	#PRB	TS 28.552 Sec 5.1.1.2.2
Average DL UE throughput in gNB	DRB.UEThpDl	Mbps	TS 28.552 Sec 5.1.1.3.1
Average UL UE throughput in gNB	DRB.UEThpUl	Mbps	TS 28.552 Sec 5.1.1.3.3
Number of active UE per cell	DRB.MeanActiveUe	#UE	TS 28.552 Sec 5.1.1.23.1
Power Consumption (avg)	PEE.AvgPower	W	TS 28.552 Sec 5.1.1.19.2
Energy consumption	PEE.Energy	kWh	TS 28.552 Sec 5.1.1.19.3
Mean Transmission power of a NR Cell	CARR.MeanTxPwr	dBm	TS 28.552 Sec 5.1.1.29.1
Cell Status	CellState	On-off	
Packet drop rate	DRB.RlcPacketDropRateDl	%	TS 28.552 Sec 5.1.3.2.2

The energy savings percentage is defined as indicated in Eq. 1.

$$EnergySaving = \frac{EC_{noEM} - EC_{EM}}{EC_{noEM}} \qquad \text{Eq. 1}$$

Where EC_{noEM} is the Energy Consumption without any energy Management xApps and EC_{EM} is the power consumption when the Energy Management xApps are operational.

6 Summary and Path Towards Final Demos

6.1 HHI Final Demo

6.1.1 Demo Architecture and Components

Figure 6-1 shows the architecture for Demo 1 that will be performed at HHI. The data plane comprises multiple domains. The C-band domain contains three Micro and three CloudConnect ROADMs connected in rings, as well as Quadflex and Teraflex transponders from ADTRAN. The Space Division Multiplexing – Multi Band (SDM-MB) domain contains MBoSDM node prototype and two MB transceivers that are developed at HHI. It also contains a filter to add impairment for testing the network reconfiguration based on events happening in the network. In order to control the MBoSDM node and MB transceivers, NETCONF agents are developed. A virtualized SDM-MB domain also exists which contains a Docker agent that implements fiber switching. The testbed is connected to a 5G network where 5G Core and DU/CU functions are virtualized in an edge cloud. The access points of 5G network are connected using two optical access branches which are based on XGS-PON and Passive WDM solutions. Two Edgecore switches exist in the testbed which are equipped with 100G coherent pluggable transceivers. The Nvidia-Mellanox aggregation switches are used for aggregating the traffic from various segments of the network. The traffic generator from VIAVI is used to inject traffic of multiple patterns in the network. Finally, two Linux boxes with Docker runtime are connected where the Docker containers for providing different types of services can be instantiated.

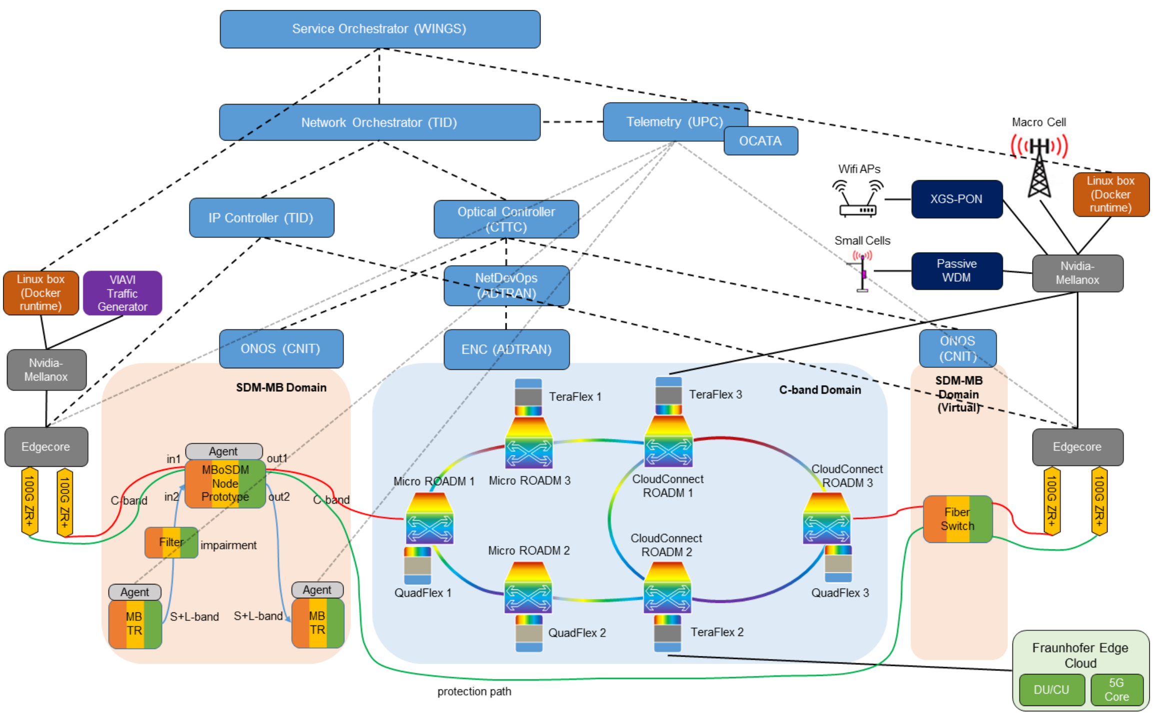

Figure 6-1 HHI Demo Architecture.

Dissemination Level	SEN (Sensitive - limited under the conditions of the Grant Agreement)

The testbed is controlled and managed using a sophisticated control plane solution developed in the project. The service orchestrator is responsible for service instantiation. It instantiates Docker containers in the Linux boxes and asks the network orchestrator for providing connectivity between them. The network orchestrator manages the connectivity resources in the network and interacts separately with controllers of both IP and optical domains. The IP controller manages the Edgecore switches and coherent pluggable transceivers. The optical controller interacts with different domain controllers to provide optical connection in each domain. A separate instance of ONOS manages each of the SDM-MB domains. The C-band domain is managed using ADTRAN Ensemble Controller (ENC) which has a specialized interface for controlling the ADTRAN devices. The interaction of optical controller with ENC takes place via the NetDevOps tool which can help to perform CI/CD-based monitoring and deployment with testing in digital twins. Finally, the telemetry system with OCATA digital twin is used for monitoring different parameters from the network, which can trigger the network orchestrator to perform network reconfiguration in case some issues are detected in the network.

The hardware and software components to be used in this demo are listed below:

Data Plane HW Components

- C-band components
    - Micro/CloudConnect ROADMs
    - Quadflex/Teraflex transponders
- MB components
    - node prototype
    - transceivers
    - filter
    - virtualized fiber switch
- 5G Network
    - Core
    - DU/CU
    - access points
- Optical access
    - XGS-PON
    - Passive WDM
- Edgecore switches with coherent pluggable transceivers
- Nvidia-Mellanox aggregation switches
- VIAVI traffic generator
- Linux boxes with Docker runtime

Control Plane SW Components

- Service orchestrator
- Network orchestrator
- IP controller
- Optical controller
- NetDevOps
- Ensemble controller

- ONOS
- Telemetry with OCATA

6.1.2 Use Case

The use case considered for this demo validates the overall architecture of SEASON by demonstrating the capabilities of both data plane and control plane solutions developed within the project. In particular, it demonstrates the automated reconfiguration of network resources when a failure occurs in the network by utilizing the capabilities of band and fiber switching. In order to avoid the interruption of traffic, it is switched to a protection path when a failure occurs. The traffic is then switched back to the original path when the failure gets fixed. The detailed workflow of this use case is as follows:

- Service orchestrator gets an end-to-end service creation request
- Service orchestrator asks for instantiation of Docker containers in both Linux boxes, and requests the network orchestrator to provide connectivity between them
- Network orchestrator provisions the red path (as shown in Figure 6-1) by interacting with IP and optical controllers
- A failure (in C-band domain) and an impairment (in SDM-MB domain) are introduced in the network
- Telemetry system gets notification about the failure (via Edgecores) and impairment (via OCATA digital twin)
- Telemetry system informs the network orchestrator about the failure and impairment
- Network orchestrator provisions the green protection path (as shown in Figure 6-1) that bypasses the C-band domain, and switches the traffic to the green path
- Network orchestrator asks the optical controller to fix the failure by configuring the C-band domain via NetDevOps and ENC
- Once the failure gets fixed, the network orchestrator switches the traffic back to the red path and removes the green path

Summary of SEASON Innovations

With respect to the previous work and concluded projects, this demo shows the following innovations of the SEASON project:

- Multiple rings in the C-band domain comprising both Micro and CloudConnect ROADMs
- MBoSDM node prototype showing band and fiber switching
- Integration of the testbed with 5G network
- NetDevOps tool for CI/CD based deployment and digital twin

6.2 WEST FINAL DEMO

6.2.1 Demo Architecture and Components

Figure 6-2 shows the considered network scenario for Demo 2. It consists of two domains. The metro network domain provides high speed optical connectivity leveraging on IPoWDM packet-optical switches. The 5G access domain relies on passive optical networks. The 5G Core is deployed in the metro (/core) domain, the 5G Centralized Unit (CU) is deployed at the border between metro and access, while the 5G Decentralized Unit (DU) is deployed close to the cell site.

The architecture illustrated in Figure 6-2 demonstrates an end-to-end network solution to deliver AR/VR services hosted at the edge, enabling energy-efficient and reliable communication for users equipped with head-mounted displays. At the far left of the architecture, users with AR/VR headsets initiate the service request. These devices require high bandwidth and low latency connections to ensure seamless delivery of immersive content. Given the computational intensity of AR/VR applications, the architecture integrates an edge offload mechanism, shifting computational load from the headsets to edge servers. This reduces device processing requirements, improves synchronization, and ensures a better user experience.

In the access segment, a spatial Passive Optical Network (PON) is deployed, which supports dynamic aggregation and disaggregation of spatial lanes to efficiently match the bandwidth demand. When an additional Distributed Unit (DU) is activated representing a small cell overlay over the macro cell coverage of the other RU/DU, the spatial PON responds by activating an additional spatial branch. This capability ensures that resources scale on demand, while unused spatial lanes can be deactivated to minimize power consumption, thereby enhancing energy efficiency. The Radio Access Network (RAN) in this architecture is controlled following O-RAN principles. A RAN Intelligent Controller (RIC) continuously monitors traffic conditions and dynamically triggers DU scaling operations when increased capacity is needed. This traffic-driven decision-making not only activates the required DUs but also coordinates with the PON system to enable a corresponding spatial lane, supporting the additional bandwidth required for the AR/VR service.

To transport the data between the RAN and edge resources, the architecture leverages a point-to-multipoint (P2MP) midhaul network. This solution aggregates traffic from multiple DUs and efficiently routes it toward the edge computing infrastructure, reducing the number of physical links while ensuring scalable and reliable connectivity. The AR/VR application is hosted at the edge, as shown in the right part of the figure, and delivers computation offload capabilities that alleviate the burden on end-user devices. This reduces latency, improves synchronization, and guarantees optimal performance for high-demand AR/VR applications.

The SEASON architecture integrates multiple innovative components, including the spatial PON, O-RAN-based DU scaling, and midhaul connectivity, to provide an energy-efficient and scalable solution for edge-based AR/VR services. By combining dynamic resource activation with efficient traffic management, the system achieves significant energy savings and ensures the delivery of reliable, high-bandwidth connectivity required for next-generation immersive applications.

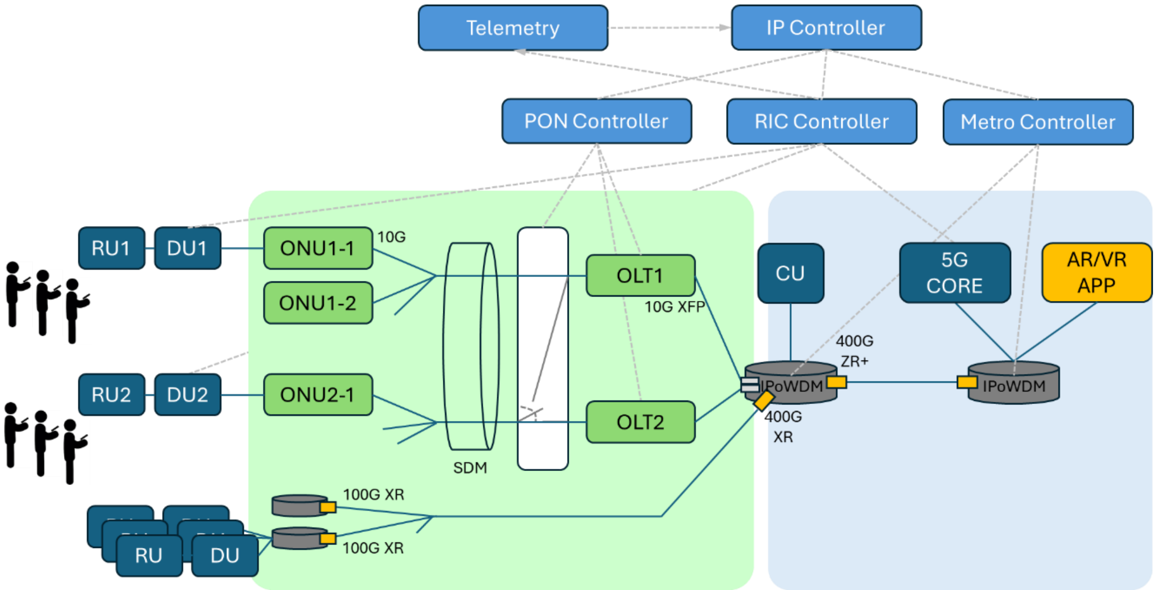

Figure 6-2: WEST Demo Architecture.

Data Plane HW Components

- XGS-PON Calix E7 with 2 OLT Ports
- Season Spatial Aggregation Node for spatial PON
  - Polatis Spatial Switch
  - PLC splitters
- O-RAN
  - 2 RU
  - 2 DU
  - 1 CU
- Multicore Fibers four cores uncoupled
  - 6Km in-field deployed ring
- IPoWDM EdgeCore Switches equipped with 32 ports at 400B7S, 400ZR+ and 400XR transceivers, SONiC OS, and the SEASON OpenConfig SDN agent.
- OpenXR 400G/100G Point to MultiPoint transceivers

Control Plane SW Components

- TeraFlow (TFS) SDN Controller as hierarchical IP Controller, coordinating the PON Controller, the RIC, and the Optical Metro Controller.
- Passive Optical Network (PON) Access Controller
  - NETCONF
  - RESTful API
- Real Time RAN Controller (RIC)
- TFS Controller as IPoWDM Metro Network Controller

- Telemetry System
- WEST VR Application

6.2.2 Use Case

The use case demonstrates the SEASON architecture's ability to support energy-efficient and dynamic communication services for AR/VR applications, leveraging spatial PON, dynamic DU scaling, and edge offloading. The scenario validates the coordinated operation of the access network, RAN, and edge computing components to meet high-bandwidth and low-latency demands while optimizing energy consumption. The detailed workflow of this use case is as follows:

- **Service Request**: Users equipped with AR/VR headsets initiate a request for AR/VR services, which are hosted on the edge computing platform.
- **Traffic Monitoring**: The RAN Intelligent Controller (RIC) continuously monitors the traffic load generated by the users' AR/VR services.
- **Dynamic DU Scaling**: Upon detecting increased traffic demand, the RIC triggers the activation of an additional Distributed Unit (DU) to meet the bandwidth requirements.
- **Spatial Lane Activation**: The activation of a DU signals the spatial PON to dynamically enable an additional spatial lane to provide the necessary bandwidth for the increased load.
- **Edge Offload**: The AR/VR service computation is offloaded to the edge platform, reducing the processing burden on the users' headsets and ensuring low-latency service delivery.
- **Traffic Aggregation in Midhaul**: The traffic generated by the newly activated DU is transported to the edge platform through a Point-to-Multipoint (P2MP) midhaul network, optimizing connectivity between the RAN and the edge infrastructure.
- **Energy Efficiency**: During periods of reduced traffic demand, unused spatial lanes in the PON are deactivated, ensuring energy savings while maintaining service availability.

This workflow highlights SEASON's capability to dynamically manage resources through spatial PON and RAN integration, while leveraging edge offloading for AR/VR services. By scaling resources only when needed and efficiently managing spatial lanes, the system achieves significant energy savings without compromising the performance and reliability required for immersive AR/VR applications.

Summary of SEASON Innovations:

With respect to the previous work and concluded projects, this demo shows the following innovations of the SEASON project

- WEST VR Service over SEASON Access + Metro solutions
- Spatial PON Mid-hauled O-RAN
- RU/DU scaling
  - Small over Macro architecture
  - Small cell activation based on observed traffic
- Spatial lanes activation/deactivation
- Backhauled segment supported by P2MP inter-router connectivity

7 Additional Complementary Demos

7.1 MBoSDM node Prototype

This standalone demonstration is described here given the impossibility to move the optical hardware that constitutes the SEASON designed optical node from CTTC premises. It complements the SEASONs two main demonstrations in terms of service provisioning in MBoSDM scenarios.

In short, a demonstration related to dynamic service provisioning in MBoSDM optical networks will be performed at CTTC lab premises during the last year of the project, and the current evolution and integration is reported in Section 5.1. The current activities are:

- The programmable MBoSDM node prototype developed in SEASON, within WP3, will be integrated with the corresponding control plane addressing scalability challenges through spatial and spectral dimensions.
- Specific SDN agents will be developed, in the framework of WP4, to control and reconfigure the MBoSDM node prototype to enable flexible and efficient switching operations. Main details of the switching device are included in deliverable D3.2.
- Different uses cases/scenarios and node configurations will be demonstrated in order to validate different node operations and functionalities. This will include MB (S+C+L), WDM (fixed-/flex-grid operation) and SDM (core switching) configurations.

Let us note that a demonstration regarding the control plane capabilities regarding MBoSDM was shown during RP1 review and submitted to the OFC demo zone for OFC'25.

7.1.1 Network scenario

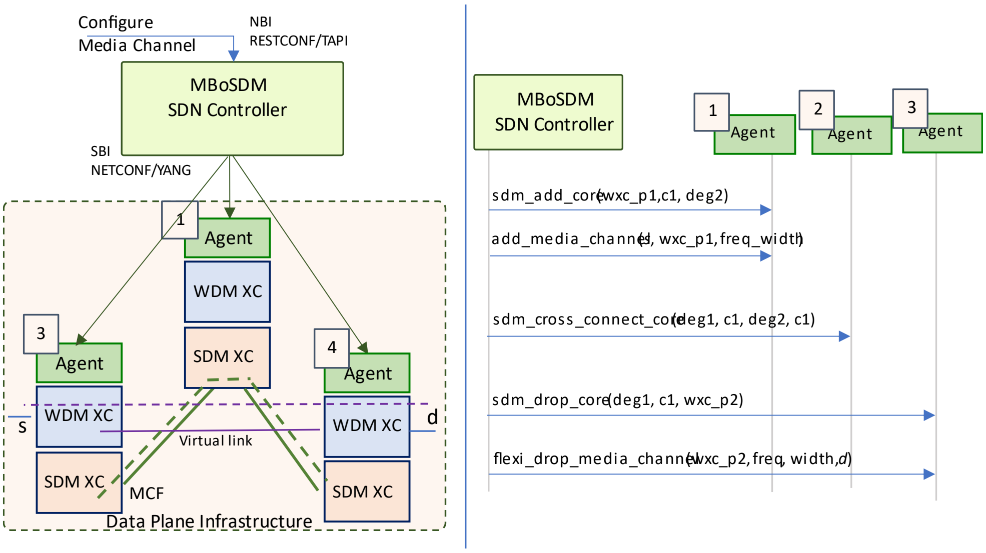

Figure 7-1: Scenario targeted by the MBoSDM demonstration with 3 nodes within the ADRENALINE testbed. The SDN controller will rely on the SDN agent in the nodes for the service provisioning (under development).

The MBoSDM node will be integrated as part of the ADRENALINE testbed. In the scenario, the MBoSDM node will be part of a 3-node topology (see Figure 7-1) integrated with additional neighbors in order to provision services in a multi-layer context. The topology shall include:

- Multi-band S-BVT
- Node 1: MBoSDM node developed in WP3
- Node 3 and Node 4: ROADM nodes, connected to Node 1

The objective of the demo is to demonstrate the provisioning of flexi-grid services (see Figure 7-2) on top of a SDM, including a hardware device.

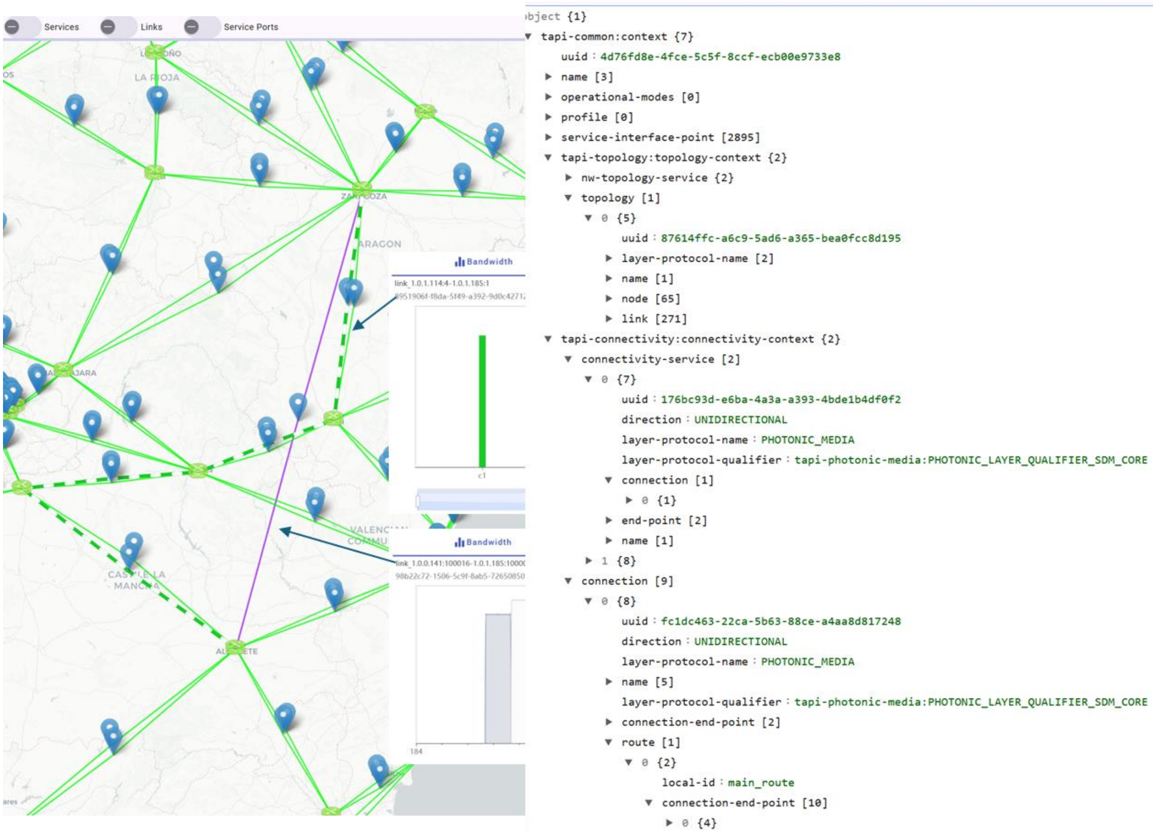

Figure 7-2: Illustration of a WDM service on top of a MBoSDM scenario, showing the provisioning of an SDM service (core or fiber switching) supporting a virtual DWDM link on top of which optical spectrum resources are allocated.

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8 CONCLUSION

This chapter presents the conclusions of this deliverable by summarizing the progress achieved, evaluating the current status, and outlining the next steps in the SEASON project. Building on the work discussed in previous chapters, it highlights the successful integration of key components such as the MBoSDM nodes with the SDN control plane, the development of energy-aware AI/ML models, and the implementation of NetDevOps-based configuration solutions. Furthermore, the chapter connects these advancements to other deliverables, providing a cohesive overview of the project's development and setting the stage for the upcoming demonstrations at HHI and WEST.

MBoSDM node integrated with control

The design and development of an SDN enabled MBoSDM node – along with its integration with an SDN control plane based on a controller that exports a north bound interface allowing dynamic connectivity service provisioning -- is progressing well and according to the initial plan. The target objective is to carry out experimental evaluation and demonstration of the integrated solution (as shown in Section 7.1).

The key functionalities of the MBoSDM hardware have already been demonstrated [Nad24] and detailed in D3.2. Additionally, the SDN controller capable of managing MBoSDM nodes has also been successfully demonstrated with ideal nodes during RP1 review, and a recent version of this controller has been submitted to OFC'25 demo zone, reported in D4.2.

The work in thus defined in two axes: first, development of the SDN agent for the node prototype. Based on hardware specifications, we have derived a set of operations that basically correspond to “cross-connect at SDM layer”, “cross-connect at the flexi-grid/fixed-grid DWDM layer” or add/drop to/from the outgoing/incoming ports. At this stage we have defined a basic Yang model and validated with a basic NETCONF agent framework. The main work is to map high level operations from the SDN agent towards the hardware low level configurations. Second is to develop the South Bound Interface (SBI) in the optical controller to support the new SDN agent.

Finally we will develop the network scenario and workflow for the actual demonstration.

MBoSDM node integrated with control agent

The second MBoSDM node prototype C3.2 is ready from the hardware perspective. The prototype is currently being integrated to an SDN agent in order to make it fully programmable. The SDN agent includes a NETCONF server that allows the node to receive standard NETCONF messages, translating these into specific switching and add/drop operations, thereby enhancing operational flexibility within the node's hierarchical architecture. The integration of node prototype with the SDN agent is on track and aligned with the initial plan of this activity.

IPM P2MP pluggable with IPM integration

This deliverable has introduced the first experimental implementation of Open RAN X-haul using P2MP transceivers on horseshoe optical MANs. The scenario leverages dynamic activation of 5G Distributed Units (DUs) and P2MP leaf transceivers based on real-time cell traffic conditions, enhancing resource utilization and energy efficiency without compromising network performance. The integration of key SEASON components, including Accelleran's 5G infrastructure and RIC Controller, CNIT's IPoWDM solution, and Infinera's P2MP transceivers, forms the foundation for a future demonstration in L'Aquila.

The experiments show that despite varying distances and splitter traversals in the horseshoe topology, leaf nodes maintain good signal quality with pre-FEC-BER values remaining within an acceptable range. The system demonstrates effective energy-saving capabilities, with an xAPP in the O-RAN 5G Automation Platform triggering the deactivation of vDUs and P2MP transceivers when user equipment falls below a predefined threshold1 This process results in estimated power savings of 15-25W for a transceiver, 50-100W for a vDU, and 100-500W for the connected RU, with deactivation completed in less than 50 seconds and reactivation taking around 2 minutes. These findings underscore the potential of this integrated approach in enhancing the efficiency and flexibility of 5G networks.

Integration of 5G and IPoWDM P2MP

An innovative 5G Automation Platform is implemented and experimentally validated to dynamically activate 5G DUs according to cell traffic conditions, for energy saving purposes. The platform leverages a novel xApp triggering the concurrent activation of the P2MP leaf transceiver on the IPoWDM node serving the related DU. Next step deals with the integration of the pluggable control directly in the server hosting the DU.

PON SDN integration with TFS

The integration of the Spatial PON with the TeraFlow SDN controller (TFS) is currently in progress within the SEASON project. The architectural framework, combining the PON Controller and TFS, enables dynamic and automated control over spatial lanes for efficient resource utilization and energy savings. The integrability through REST APIs has been demonstrated in test scenarios, as detailed in Deliverable D4.2.

From a technical standpoint, the southbound NETCONF-based communication with the PON hardware has been implemented and tested, enabling real-time reconfiguration of spatial lanes. The northbound interface between TFS and the PON Controller has been realized and implements basic REST APIs, while more complex service creation calls are currently under definition

The next steps include refining the PON Controller's decision-making algorithms to enhance responsiveness and accuracy in spatial lane management. Additional efforts will focus on integrating service setup REST APIs and telemetry feedback into the TFS framework to enable real-time performance monitoring and further energy optimization.

MBoSDM S-BVT integration with SDN control plane supported by energy-aware AI/ML

The development and integration of the MBoSDM S-BVT with the SDN control plane, supported by energy-aware AI/ML models, have made significant strides in addressing the challenges of power-efficient optical networking. The successful implementation of power consumption measurements of tranceivers and modeling for the MB(oSDM) S-BVT prototype marks a crucial milestone in the project's evolution. Integrating these measurements into the SDN control framework, particularly by extending TAPI Context information to include power consumption attributes, demonstrates a practical approach to energy-aware network management.

Currently, the fundamental architecture for energy-efficient routing is in place, with the successful implementation of the SDN controller's core functions and APIs, including the critical interaction between the controller and the AI/ML server. Extending TAPI profiles to incorporate power consumption parameters for different optical bands (C-, L-, and S-bands) provides the necessary foundation for energy-aware decision-making. Establishing a comprehensive framework for DRL agent training and deployment represents a significant advancement in achieving optimal network resource utilization while minimizing power consumption. The goal is to develop a trained DRL-based Routing, Modulation, Band, and Spectrum Assignment (RMBSA) model to assist the SDN controller in dynamically managing heterogeneous bandwidth-demand connectivity services. The computed RMBSA solutions must ensure an acceptable QoT level at the receiver (e.g., OSNR or pre-FEC BER). The trained DRL model will be validated and benchmarked against heuristic approaches based on key performance indicators, including blocked bandwidth ratio, average network power consumption, and average network throughput.

NetDevOps based Device and Service Configuration

The proposed NetDevOps CI/CD based solution for network management by automating device configuration and service provisioning (< 10 mins) reduces manual effort and human error. Its compliance with standardized protocols like NETCONF/RESTCONF and data model including OpenConfig, ONF-TAPI ensures interoperability, while features such as Git-based rollbacks and digital twin testing enhance reliability and pre-deployment validation. The ability to perform parallel execution significantly reduces configuration time, addressing scalability challenges in large-scale networks.

Monitoring parameters for the RIC

Automated collection, monitoring, and transmission of operational data from network components to centralised or distributed systems for analysis and decision-making has been examined to ensure the efficient operation of the network. The proposed O-RAN solution involves the RIC, which is in charge of telemetry data collection, translation and processing, ensuring that data from identified sources is presented in a uniform and actionable format. The resulting harmonised data can then be consumed by different algorithms, e.g., for energy saving purposes.

GLOSSARY

Acronym	Description
2G	Second Generation
3GPP	Third-Generation Partnership Project
4G	Fourth Generation
AI/ML	Artificial Intelligence / Machine Learning
API	Application Programming Interface
AR/VR	Augmented Reality / Virtual Reality
AWG	Arrayed Waveguide Grating
BER	Bit Error Rate
BVT	Band Variable Transceiver
CMIS	Common Management Interface Specification
CU	Centralized Unit
DD	Direct Detection
DD-LMS	Decision-Directed Least Mean Square
DNN	Deep Neural Network
DPU	Data Processing Unit
DRB	Data Radio Bearer
DRL	Deep Reinforcement Learning
DU	Distributed Unit
ENC	Ensemble Controller
FC	Fault Condition
FEC	Forward Error Correction
GVD	Group Velocity Dispersion
GW	Gateway
IPM	Intelligent Pluggable Manager
IPoWDM	IP over Wavelength Division Multiplexing
K8s	Kubernetes
KPI	Key Performance Indicator
LLS	Linear Least Squares
MAS	Multi-Agent Systems
MBoSDM	Multi-Band over Spatial Division Multiplexing
MCF	Multi-Core Fiber
MLOps	Machine Learning Operations
NATS	NATS Messaging Protocol
NEP	Node Edge Point

NETCONF	Network Configuration Protocol
OFDM	Orthogonal Frequency Division Multiplexing
OLC	Optical Line Controller
OLL	Optical Line Layer
OLT	Optical Line Terminal
OLT	Optical Line Terminal
ONAP	Open Network Automation Platform
ONOS	Open Network Operating System
OPENROADM	OpenROADM Multi-Source Agreement
O-RAN	Open Radio Access Network
OSC	Optical Supervisory Channel
OSNR	Optical Signal-to-Noise Ratio
OTDR	Optical Time Domain Reflectometer
P2MP	Point-to-Multipoint
P2P	Point-to-Point
PdM	Predictive Maintenance
PON	Passive Optical Network
PRB	Physical Resource Block
QoT	Quality of Transmission
RAN	Radio Access Network
rApps	Applications for Non-Real-Time RIC
REST	Representational State Transfer
RESTful API	Representational State Transfer Application Programming Interface
RIC	RAN Intelligent Controller
RMBSA	Routing, Modulation, Band, and Spectrum Assignment
ROADM	Reconfigurable Optical Add-Drop Multiplexer
RUL	Remaining Useful Life
SAP	Service Attachment Point
SBI	South Bound Interface
S-BVT	Sliceable Bandwidth Variable Transceiver
SDM	Spatial Division Multiplexing
SDN	Software-Defined Networking
SLO	Service Level Objective
SNMP	Simple Network Management Protocol
SONiC	Software for Open Networking in the Cloud
TAPI	Transport API
TFS	TeraFlow SDN Controller
TWDM	Time-Wavelength Division Multiplexed
UC	Unified Communications (Not explicitly defined; assumed)

UL	Uplink
VDSL	Very-high-bit-rate Digital Subscriber Line
VNF	Virtual Network Function
WDM	Wavelength Division Multiplexing
WSS	Wavelength Selective Switch
xApps	Applications for Near-Real-Time RIC

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