Autonomous Service Provisioning and Self-Healing in Multi-Band Multi-Domain IPoWDM Networks

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Abstract: We report on a large-scale demonstration across access, metro, and core networks, using commercial and prototype of multi-band components, achieving significantly reduced provisioning time for live video traffic through seamless IP and optical layer orchestration. © 2025 The Authors

1. Introduction

The increasing demand for high-bandwidth and low-latency services, including video streaming and those beyond 5G, requires the development of networks that efficiently manage diverse traffic across access, metro, and core domains. The shortcomings of traditional segmented architectures have led to the necessity for unified and scalable solutions [1,2]. Multi-band optical networks, leveraging S-, C-, and L-band with IP over Wavelength-division multiplexing (IPoWDM) technologies, have the potential to address these challenges by optimizing resource utilization and reducing latency [3-5]. While unified orchestration across multiple domains and bands has been explored [6], many efforts remain confined to limited domains or virtual environments rather than real hardware implementations.

This work presents a large-scale integration of control and data plane technologies within a multi-band and multi-domain IPoWDM network, unifying commercial WDM systems, IPoWDM pluggables, and novel multi-band components for fully autonomous service provisioning across access, metro, and core networks. Our approach supports both parallel and sequential provisioning, enabling the network to adapt to varying demands and optimize setup times. Furthermore, we implement a robust self-healing mechanism that autonomously detects and mitigates network anomalies, ensuring continuous high performance and reliability. Using a hierarchy of controllers and newly developed software defined networking (SDN) agents, we demonstrate the system's ability to operate autonomously.

To validate our approach, we conducted experiments with live traffic, including video streams from cameras, which mimicked real-world network conditions. The results confirmed the network's ability to autonomously provision services and adapt to dynamic demands, while maintaining high performance. Our findings revealed significant improvements in provisioning speed, network resilience, and the integration of IP and optical technologies within an end-to-end framework.

2. Data Plane

The data plane architecture facilitates end-to-end traffic flow that originating from traffic generation at the access network and extends through the multi-band (Domain 1) and C-band (Domain 2) domains, ultimately reaching the destination nodes. This integration enables the network to dynamically manage and route traffic across various optical bands (S, C, and L), depending on real-time demands and network conditions. A central innovation in this domain is the SDN-controlled multi-band (semi-) filter-less add/drop node prototype, which enables efficient traffic management across S-, C-, and L-bands. The node's architecture features multi-band multiplexers and an optical matrix switch, allowing for selective band bypass and add/drop operations. Integrated into a multi-band (S+C+L) testbed, the node was subjected to intensive testing, supported by single-band lumped amplifiers and continuous monitoring via an optical spectrum analyzer (OSA). Specification of the MB-Node is presented later in the paper.

The C-band domain employs a ROADM-based (Reconfigurable Optical Add-Drop Multiplexer) optical network with commercial components. This domain handles high-capacity traffic and supports dynamic wavelength routing and traffic management, efficiently adapting to changing traffic patterns. Detailed analysis of the C-band ROADM network is provided in [7]. At the network edge, the access network handles live traffic, including high-bandwidth video streams from cameras. Inter-domain switches convert this IP traffic into optical signals for efficient routing. Integrated with the control plane, these devices enable real-time traffic adjustments, ensuring optimal resource use and service quality. Further details on the IP domain part of the network are provided in [8].

3. Control Plane

The control plane, shown in Fig. 1, features a hierarchical structure to manage the multi-band, multi-domain IPoWDM network. At the top, the IPoWDM Orchestrator oversees the entire IP and optical network, coordinating with domain-specific controllers via standardized interfaces. This ensures synchronized management across access, metro, and core

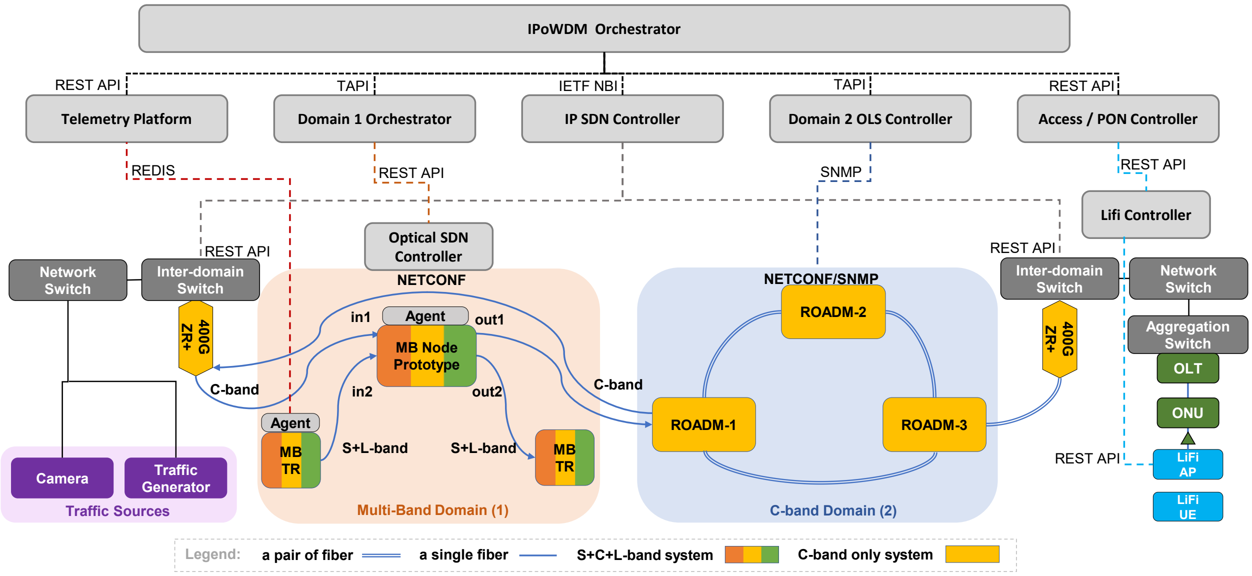


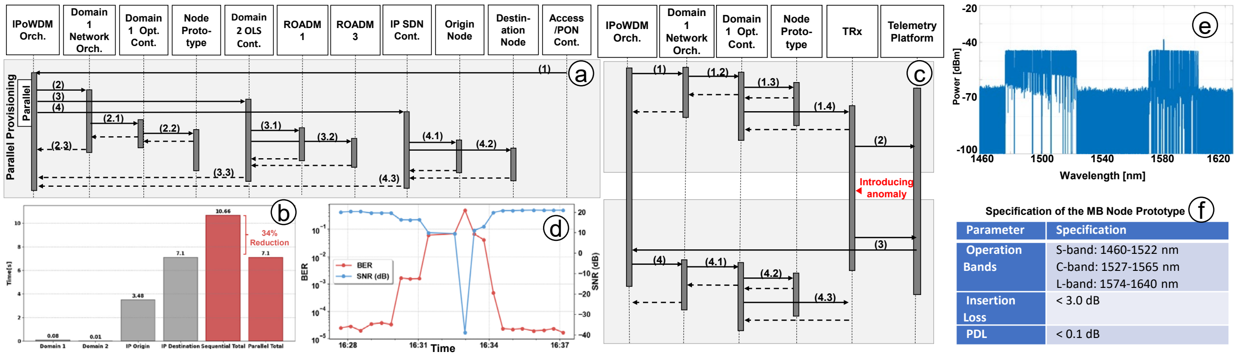
Fig. 1: Demo Architecture

domains. In the optical Domain 1 (multi-band domain), the Domain 1 Orchestrator communicates southbound with the optical SDN Controller. The optical SDN Controller, based on ONOS open-source project [9], manages the SDN-enabled multi-band (MB) Node Prototype and Transceivers (TR). The system utilizes standard protocols and data models, with OpenConfig used to control the transceivers and OpenROADM employed for managing the MB-node. Additionally, newly developed SDN agents handle switching, add/drop operations, and optimize performance across the S-, C-, and L-bands. The Domain 1 Orchestrator aggregates topology data from the optical SDN Controller and reports it to the IPoWDM Orchestrator using TAPI (Transport Application Programming Interface). The optical Domain 2 (C-band domain) is managed by the Optical Line System Controller (OLS), which handles the ROADMs via SNMP (Simple Network Management Protocol) and native YANG (Yet Another Next Generation) definitions using NETCONF. It also communicates directly with the IPoWDM Orchestrator using an integrated TAPI driver via RESTCONF. The IP SDN Controller oversees the management of inter-domain switches (origin and destination nodes), integrating IP traffic with the optical domains and thereby ensuring efficient end-to-end service delivery. This controller interacts with the IPoWDM Orchestrator, facilitating dynamic traffic routing and resource allocation. Additionally, the Access/PON (Passive Optical Network) Controller and LiFi (Light Fidelity) Controller manage traffic at the network's edge, adjusting resources in response to real-time demands. A Telemetry Platform offers real-time monitoring, enabling proactive management and triggering self-healing mechanisms to reconfigure the network, such as shifting traffic from a degraded S- to a stable L-band.

4. Experimental results

To validate the IPoWDM network's integration of control and data planes, we explored different provisioning scenarios to demonstrate automated management of connectivity services across domains, including parallel and sequential workflows as well as a scenario with autonomous adaptation as depicted in Fig. 2. These scenarios provide insights into network performance and efficiency. The process begins with the PON Controller notifying the IPoWDM Orchestrator about an increase in traffic demand (a-1). In response, the orchestrator updates its traffic metrics and initiates a service provisioning process that spans across the multi-band domain (Domain 1), the C-band domain (Domain 2), and the IP domain.

In the first set of experiments (Fig. 2 a) provisioning is executed in parallel, with the orchestrator simultaneously coordinating across all three domains (a-2, 3, 4). In Domain 1, the IPoWDM Orchestrator requests the Domain 1 Orchestrator to begin the provisioning (a-2). This request is passed to the Domain 1 Optical Controller (a-2.1), which configures the multi-band node prototype (a-2.2). The node handles the optical channel by routing it through the input port *in1* and output port *out1* (Fig. 1), directing the signal towards the C-band domain. The control plane facilitates this operation through OpenROADM based NETCONF commands. At the same time, in Domain 2, the orchestrator directs the Domain 2 OLS Controller to establish a connection across the ROADMs (a-3). This step involves configuring the ROADMs from the controller, setting up the optical path between ROADM-1 and ROADM-3 (a-3.1,3.2). Simultaneously, in the IP domain, the orchestrator directs the IP SDN Controller to establish IP adjacency between the origin and destination nodes (a-4), configuring them to create the necessary IP paths for smooth traffic



Specification of the MB Node Prototype

Parameter	Specification
Operation Bands	S-band: 1460-1522 nm C-band: 1527-1565 nm L-band: 1574-1640 nm
Insertion Loss	< 3.0 dB
PDL	< 0.1 dB

Fig. 2: Sequence diagram of parallel provisioning (a), Provisioning times (b), Sequence diagram (c), Optical Spectra (d) and Performance Metrics (e) for scenario of autonomous adaptation, Specification of the MB-Node (f)

flow. Once these tasks are completed, the orchestrator finalizes the service by adjusting traffic values to meet the new demand (a-4.1, 4.2). Time analysis (b) confirms that the parallel provisioning reduces the setup duration by an average of 34% compared to the sequential method, where the domains where provisioned in a consecutive manner.

The MB node prototype specification in (f) shows an average Insertion Loss (IL) below 3 dB and Polarization Dependent Loss (PDL) below 0.1 dB across all bands. Gaps in band transitions arise from overlapping transfer functions of the MB Mux and Demux filters, making these regions outside the device's operating specifications.

In the second set of experiments (Fig. 2 c), we examine the network's ability to autonomously adapt to declining performance metrics through the provisioning of an S-band optical connection, introducing an anomaly, and the subsequent reconfiguration of the network to migrate the service to the L-band. The IPoWDM Orchestrator configures the multi-band node through a sequence of controllers and SDN agents to route the S-band signal from input port *in2* to output port *out2*. Simultaneously, the multi-band transceivers are configured with the necessary parameters (c-1.4), including setting the frequency and output power to establish the optical channel. During this period, the transceivers are continuously pushing performance monitoring metrics (c-2), such as bit error rate (BER), signal-to-noise ratio (SNR) to a Redis-based data lake within the telemetry platform. In order to assess the system's adaptive capabilities, an anomaly is manually introduced in the lab using a variable optical attenuator, which significantly degrade the performance metrics. The impact of this anomaly is evident in the provided plot (e), showing a sharp decline in SNR and an increase in BER. The telemetry platform, detecting these changes, triggers a notification to the IPoWDM Orchestrator (c-3), recommending a migration to the L-band to restore service quality. In response, the orchestrator initiates a reconfiguration process (c-4). The multi-band node is instructed to drop the S-band connection and establish a new L-band connection (c-4.2). A new L-band optical channel is provisioned, with the wavelength set appropriately to ensure optimal performance (c-4.3). The spectrum obtained following the reconfiguration confirms the successful migration (d), illustrates the presence of the new L-band signal at 1580 nm. This scenario demonstrates the network's autonomous self-healing capability, effectively managing Quality of Service (QoS) degradation and ensuring continuous service by dynamically reconfiguring the optical connection.

5. Conclusion

This work demonstrates a fully integrated, multi-band, multi-domain IPoWDM network featuring SDN-enabled prototype components and smart optical pluggables. The system autonomously provisions services across multiple domains and optical bands, efficiently handling dynamic traffic demands, including live video traffic, while achieving significant time savings through parallel provisioning. Its successful self-healing capability, demonstrated by the automatic migration from a degraded S-band to a stable L-band, confirms the system's robustness and scalability, positioning it as a strong candidate for high-capacity, low-latency network deployments.

Acknowledgements

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