Field Trial of Transparent Multi-band Multi-domain Disaggregated IPoWDM Networks

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Abstract *First field trial of IPoWDM optical continuum between access, horseshoe aggregation, and metro mesh networks operating over multiple bands. Hierarchical control plane is extended to enforce transparent end-to-end paths across multiple domains, bands, and layers. ©2024 The Author(s)*

Introduction

Multi-band optical networks allow to simultaneously attain higher capacity and richer node connectivity[1]–[6]. In parallel, the introduction of IPoWDM technologies exploiting coherent pluggable transceivers is rapidly leading to effective convergence of the IP and photonic layers[7]. Preliminary studies have shown the benefits of transparent traversal across network domains, exploiting dedicated analytical tools for end-to-end estimation of non-linear physical impairments, including multi-band operation[3]. Indeed, the multi-band transparent interconnection between network segments has the potential to reduce the number of expensive and power-hungry opto-electronic conversions[8]. However, no comprehensive validation has been demonstrated yet that integrates multi-band data and control planes. For example, the work in[9] does include control and data plane, but limited to C-band only.

In this paper, we propose, implement, and validate the first field trial of a multi-band disaggregated optical network transparently interconnecting cell-site access in O band, an aggregation horseshoe operating with both C and O bands and a C-band metro-core network. O band extends transparently from local exchange in the access domain to include antenna sites to be front-hauled to one of the hub of the horseshoe. The C band extends transparently from aggregation to metro avoiding electronic regeneration.

Demonstrated solution for access-metro multi-band continuum

Fig. 1 shows the proposed data plane architecture, realistically reproducing next generation Operator's access-metro networks. The access domain consists of cell-site nodes connected to a horseshoe network including up to ten aggregation nodes (two in the experiment, $Aggr_1$ and $Aggr_2$) with one Hub node at each end (Hub_1 and Hub_2). Aggregation nodes are in the range of 5 to 10 km, serving an area of few kilometers for both broadband and 5G access. Each node operates in two optical bands, C and O. In each direction, each Aggr node includes (i) a pair of passive band splitter/couplers, (ii) a degree-two ROADM with Add/Drop module operating in the C band and (iii) a prototype of SOA-based ROADM operating in the O band. The O-band OADM comprises two AWGs with an LWDM grid, two O-band SOAs, two 50:50 splitters for dropping and adding data channels and a microcontroller to control the OADM. The SOAs function as gates and amplifiers for dynamically blocking or passing each channel. Each Hub node, for what concerns the aggregation segment, includes one band splitter/coupler and a degree-one ROADM in each band. Hub nodes also represent the entry point of the metro network, i.e. they include elements controlled by either the Agrr or the Metro SDN Controller. The metro domain consists of a mesh network, where links are few tens of km long and nodes consist of multi-degree ROADMs in C band only. In this experiment, the metro segment is in the field, including a metro-regional link of 80 km of fiber in the Turin area. Transmission systems in the C band include 100/200 Gb/s transponders and IPoWDM switches equipped with SONiC operating system and 400ZR(+) transceivers. In the O-band, LWDM 25G transceivers are adopted in Layer3 switches.

Traditionally, access and metro systems are managed as separate domains from both data and control plane perspective, with inefficient elec-

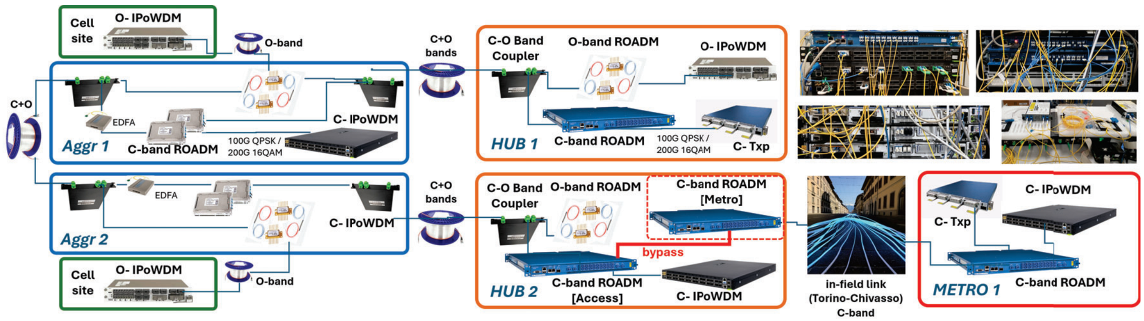

Fig. 1: Aggregation horseshoe in O and C bands from Hub1 to Hub2, including two access cell sites. In-field metro network in C band from Hub2. Optical aggregation-metro continuum transparently bypassing IPoWDM at Hub2.

tronic termination at Hub central offices. In this work, optical bypass of the IPoWDM box at Hub2 is implemented for a C-band channel, which transparently reaches remote metro sites. This way, the O band serves traffic confined within the access and aggregation segments, while the C band can also be used for high-speed connections transparently crossing the boundary between aggregation and metro.

Demonstrated control solution

To support the proposed optical continuum, several control plane extensions have been designed and implemented. Fig.2a shows the proposed control plane architecture. In particular, the following control elements, specifically enhanced to manage both intra- and inter-domain IPoWDM connectivity across multiple bands/layers, are included:

Per-domain Optical SDN Controller. The optical SDN controllers are based on ONOS, version 3.0.0. One controller is deployed for the aggregation domain and another controller is deployed for the metro segment. The controller has been further extended with respect to the one used in[8]. Current version also supports: (i) devices operating on multiple bands; (ii) establishment of lightpaths using ROADMs ports as endpoints. The latter feature is required to support transparent multi-domain intents.

The *TAPI Network Orchestrator* is based on CTTC FlexOpt SDN controller and is responsible for inter-working with the per-domain SDN controller. It retrieves topological information from such controller using the controllers' native interface, including devices, ports and per-band spectral information and exports a north bound interface based on standard TAPI data models to the inter-domain, hierarchical controller. TAPI interfaces have been enhanced to support multi-band networking (multiple media channel pools for a single Optical Multiplex Session, each with its own frequency range) and to include Physical Layer Impairments (PLI).

The *Multi-domain IPoWDM network orchestrator* is based on the E-lighthouse Network Planner (ENP) software. It interacts with the NBI of a prototype IP SDN controller (based on IETF model RFC 8345), the NBI of the TAPI Network Orchestrators providing access to both optical domains, and an external inventory database with interdomain links and pluggable-to-ROADM connections. It has been enhanced to correlate transparent multi-domain optical and IP layers providing a unified IPoWDM multilayer network view and control.

The *optical PCE* receives a domainless optical infrastructure view from the IPoWDM orchestrator, and uses a routing engine to derive the optimal operational parameters regarding the intended maximum transparent length per band and the optical transmission technology. In detail, on request for a new connection establishment from IPoWDM orchestrator, it retrieves the optical network topology and configuration from the IPoWDM orchestrator and it executes a PLI-aware RSA computation in order to calculate the path, the selected band and the frequencies assignment. Then, PCE sends a response to IPoWDM orchestrator including the aforementioned information. In this work, simulated annealing is introduced to also estimate the end-to-end optimal launch power per channel/band.

Finally, a distributed intelligence is used to collect and analyze measurements close to the data sources. Measurements are compared to the expected performance obtained using transmission models, so any degradation can be soon detected and its root cause be localized[10]. In particular, specific transmission models have been developed for the different bands, thus improving the accuracy of the detection and localization.

Experimental results

The experimental assessment of the multi-band access-metro continuum is validated through the setup of a number of connectivity services.

Fig. 2b illustrates first the IPoWDM topology discovery and then the provision of a cross-domain IP adjacency. In the topology discovery phase, the IPoWDM orchestrator requests in parallel to the TAPI orchestrators and IP SDN controller the topology IP and optical information. The TAPI propagates this request towards the SDN controllers.

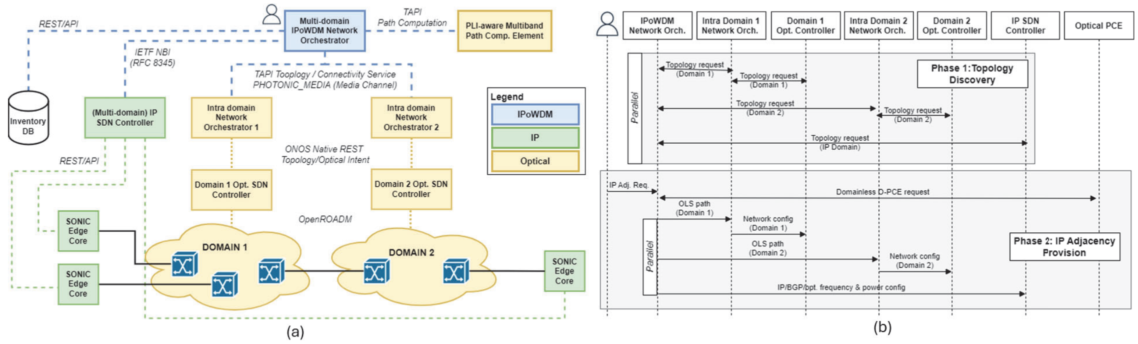

Fig. 2: Control plane architecture (a) and workflow (b)

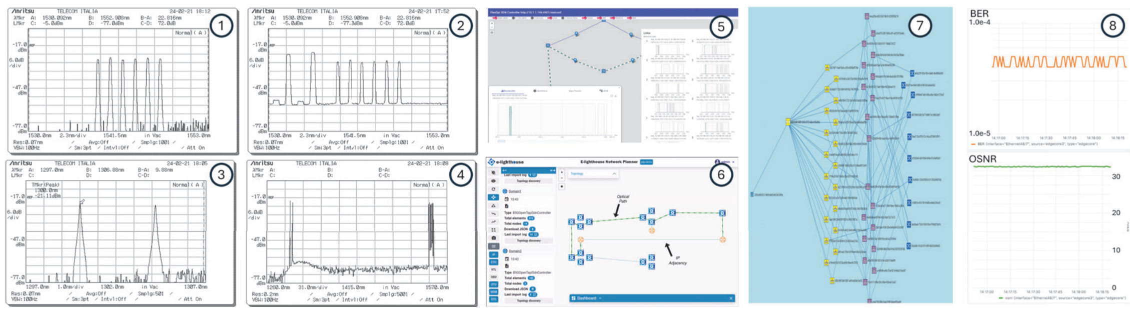

Fig. 3: Experimental results: optical spectra (1-4), Orchestartors' views (5-7), monitoring data on 400ZR (8)

In the cross-domain IP adjacency provision, (i) the user requests an IP adjacency, (ii) the IPoWDM orchestrator provides the PCE a unified (so-called domainless) optical view of both domains and requests the optical path, spectrum and power computations. For multi-domain optical paths, (iii-a) the IPoWDM provisions in parallel the respective intra-domain OLS paths, that place the intents in the Optical SDN controllers. In parallel, (iii-b) it configures the IP/BGP router aspects, as well as the pluggable frequency and transmission power via the SDN controller. This operation of the IP SDN controller corresponds to the *Single SBI management* proposal in the TIP MANTRA working group. The provisioning procedure is successfully applied to six 100G channels among C-Tpx transponders in Aggr and Metro nodes (see OSA view n.1). Then, the two 400ZR channels among IPoWDM node are successfully established, transparently crossing aggregation-metro boundary (n.2). Finally, the O-band channels from Access to Hubs are established (n.3 and n.4).

In each domain, the optical path set-up provisioning time is less than 1 second. Moreover, PCE latency is measured to be in the range between 0.5s and 0.6s and it is due to: a) the time needed to retrieve network topology and; b) the time needed for the PLI-aware RSA algorithm to return the selected path, band, channel frequency assignment, and optimal launch powers. The IP/BGP and pluggable configuration requires less than 4 seconds.

From a data plane perspective, the loss of the O-band OADM is 11dB (including the multiband mux/demux). The 10 km fiber loss is 4dB between two Aggr Nodes, and the 5km fiber loss is 2dB from the Access to the Aggr Node. The input power of the data channels at the OADM was 0dBm. During bypass operation, SOA is ON and provides 17dB gain to compensate for the OADM and fiber loss transmission. In the drop operation, the SOA is OFF (no current) and blocks the wavelength. An ON/OFF ratio of 60 dB has been measured which guarantees high isolation and very low cross-talk for wavelength reuse of the added data at the same wavelength. The measured received optical power at the drop port was -15 dBm/ch, which allows error-free of the received Ethernet frames. The 400ZR C band transceivers operate at around 3.6E-5 pre-FEC BER. Ethernet 25G O band services at cell sites were error free (overall latency of 60 and 114 us was measured in Aggr1 and Aggr.2 nodes respectively, in compliance with fronthaul requirements).

Conclusions

A field trial of disaggregated IPoWDM networks transparently interconnecting access and metro segments and operating over both C and O-bands is demonstrated, including SOA-based O-band switching. The network is operated through an innovative hierarchical control plane solution extended to compute and enforce transparent end-to-end paths across multiple domains, bands, and layers.

Acknowledgements

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