An Optical SDN Controller for Transport Network Virtualization and Autonomic Operation

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***Abstract*—This paper proposes an architecture for Software Defined Optical Transport Networks. The SDN Controller includes a network abstraction layer allowing the implementation of cognitive controls and policies for autonomic operation, based on global network view. Additionally, the controller implements a virtualized GMPLS control plane, offloading and simplifying the network elements, while unlocking the implementation of new services such as optical VPNs, optical network slicing, and keeping standard OIF interfaces, such as UNI and NNI. The concepts have been implemented and validated in a real testbed network formed by five DWDM nodes equipped with flexgrid WSS ROADMs.**

Keywords: SDN, Optical, GMPLS, Virtualization.

I. INTRODUCTION

Optical Networking Technologies are enabling a continued increase in high capacity connectivity [1] in access, metro and long haul at a very high pace. The main telecommunications system vendors are already shipping optical systems equipped with coherent 100Gbps transponders, ROADMs (Reconfigurable Optical Add-Drop Multiplexer) with CDC (Colorless, Directionless, Contentionless) and flexgrid support, integrated with OTN Switches (e.g., [2], [3]). Additionally, IP router vendors have introduced equipment with integrated DWDM interfaces, and with integrated IP-Optical Control Plane, enabling network optimization, for instance, with optical bypass strategies (e.g, [4], [5]). Therefore, optical networks operation is changing from static point-to-point systems to mesh topologies, with dynamic and diverse wavelengths, modulation formats, services, as well as from a layered approach to a unified one, where the network layers have a tighter coupling in order to allow resources optimization.

This evolving scenario presents many challenges to the optical network control plane, including mechanism for impairments and signal aware RSA (Routing and Spectrum Allocation), optical equalization, and for an UCP (Unified Control Plane) enabled for multi-layer control, cross-layer optimizations, network services virtualization, and others. Standardization bodies such as IETF (Internet Engineering Task Force) and OIF (Optical Internetworking Forum) are working in adaptations to the GMPLS (Generalized Multi-Protocol Label Switching) protocols to fulfil new requirements, such as flexgrid, as well as to support OTN Switching features [6], [7], [8].

At the same time, there is a momentum around SDN (Software Defined Networking) as an architectural approach to separate network control planes from the data/forwarding plane by means of a simple, standardized interface (e.g., OpenFlow). Promising benefits of SDN include overall network simplification, virtualization capabilities (i.e., isolated/transparent resource sharing), automation of network operations via programmable interfaces, and easier deployment of new services based on control-plane defined features implemented in software.

In this paper, we propose an architecture for Software-Defined Optical Networks, enabling virtualization and autonomic operation. The SDN Controller implements a network abstraction layer acting as an Optical Network Operating System (O-NOS) that allows network applications, such as our EDFA Cognitive Gain Control [9], to access topology and measurements required for its operation and to perform the required configuration and interactions with transport network elements. Additionally, the abstraction layer implements the concept of network slicing, allowing the implementation of VON (Virtual Optical Networks). As many features provided by GMPLS are not initially supported by pure SDN approaches, such as network discovery, lightpath establishment, and others, we have virtualized our GMPLS implementation to run at the SDN controller. The implementation has been validated in a testbed composed by five DWDM nodes formed by multi-degree ROADMs equipped with flexgrid WSS (Wavelength Selective Switch) modules, optical amplifiers, optical channel monitors, and supervisor boards. Each node runs the node controller daemon implementing a ROADM abstraction layer based on the YANG [10] language, providing a NETCONF [11] interface, which are both the basic building blocks of our network abstraction layer. In order to avoid manual configurations, LLDP (Link Layer Discovery Protocol) [12] has been extended to run on top of the Optical Supervisory Channel, performing network discovery, which is propagated automatically to the O-NOS.

This paper is organized as follows. Section II presents related work and our previous achievements. Section III details the proposed optical SDN controller architecture. Section IV describes the optical testbed and the experimental work. Finally, Section V concludes the paper with final remark and presenting some avenues for future work.

II. Related and Previous Works

Recent research on applying SDN/OpenFlow to carrier-grade networks [13] has advanced the state of the art with the introduction of hierarchical SDN controller designs (i.e., hierarchical control plane) allowing “slicing” of networks and services. The concept of Virtual Optical Networks (VONs) [14] has been proposed to address the off-line planning problem of optimal allocation of a set of VONs over an all-optical network substrate. Another related recent work [15] has proposed PLI (physical layer impairments) assessment models for intra and inter-VON impairments. Additionally, a recent publication [16] demonstrates Optical Networks configuration via OpenFlow, and another [17] proposed an SDN based architecture for a UCP (Unified Control Plane) using the concept of a Network Operating System controlling packet and circuit switches via a switch-API (Ex.: OpenFlow), abstracting layer and vendor specific interfaces while providing a flexible forwarding plane for manipulation by a common control plane.

The concept of OTS (Open Transport Switch) [18] has been introduced based on an OpenFlow interface for a specific P-OTN Switch, which combines MPLS, OTN and Lambda Switching in the same platform. The same author argues that current transport networking paradigm already employs centralized control assisted by distributed GMPLS functionalities, such as network discovery, network state updates, dynamic restoration, and others. Therefore, the development of Transport SDN solutions will need to consider migration strategies as well as the best location for specific networking functions such as network discovery, path computation, and service protection & restoration. In this sense, the author proposes multiple abstraction approaches for multilayer integration at the SDN controller, including OpenFlow interfaces with border nodes of each networks (e.g., MPLS and DWDM), keeping the current control plane for each one, and a more granular approach, where all network elements present an OpenFlow interface to the SDN controller.

Cognitive optical networks are being studied [19] as viable solutions to enable future optical networks to support the increasing requirements in flexibility and heterogeneity in terms of supported services and technologies. Therefore, a control plane framework for cognitive optical networks has been proposed using the concept of a centralized Cognitive Decision System (CDS), fed with network information by an extended GMPLS control plane. Similarly to this line of research, in our previous work [9], we demonstrated a cognitive gain control for EDFA optical amplifiers, through GMPLS extensions. Additional related previous works of our group include [20] with the demonstration of a GMPLS control plane implementation with extensions to support DWDM networks, [21], which demonstrates the implementation of RWA algorithms with constraints consideration, and [22], with the demonstration of an optical network testbed composed by five multi-degree ROADMs, with flexgrid support, equipped with a virtualized GMPLS control plane.

III. System Architecture

The system architecture, presented in Figure 1, is comprised of Optical Network Elements (O-NEs) and an Optical SDN Controller (O-SDNC). The O-NEs run a node controller daemon for node abstraction and control via NETCONF, and LLDP (Link Layer Discovery Protocol) [12] for neighbor discovery, allowing automatic network bootstrap. The O-SDNC aims to allow autonomic control of the optical network, network slicing, providing standard ASON/GMPLS interfaces, while simplifying and offloading the O-NEs.

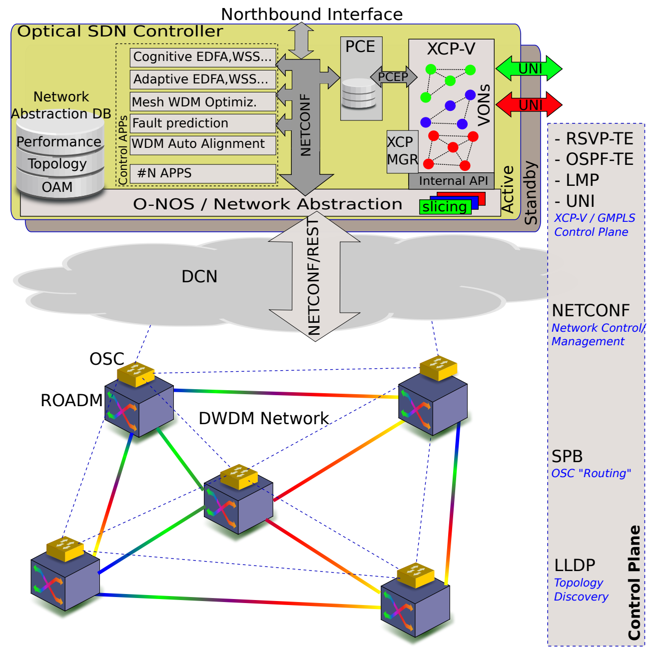

Fig. 1. System Architecture

The main components of the architecture, including the Optical SDN Controller building blocks, are described in the following sections.

A. Optical Network Operating System - O-NOS

Optical Systems, such as CDC-ROADMs are a composition of multiple components interconnected via optical intra-node connections. The main components are: WSS switch, optical channel monitor (OCM), erbium doped fiber amplifier (EDFA), and multicast switch (MCS). By modeling these FRU (Field Replacable Units) using the NETCONF-modeling language YANG, we gain the possibility to export or transform the data that is needed for their configuration, as well as to model their interconnections and restrictions. The ROADM is being modeled in YANG to provide a node abstraction layer that exposes NETCONF/REST interface to the O-NOS [23]. In turn, the O-NOS elaborates a simplified point of view by concatenating the O-NEs YANG model in a single tree that results in an integrated model of the network. In the integrated tree, the different O-NEs are separated in the same way that multi-chassis systems are modeled, where the whole network is analogue to a multi-chassi NE, while an O-NE is analog to a linecard in a chassi.

This principle of recursivity is similar to the hierarchical design of logical xBar [24] proposed to extend SDN/OpenFlow to large-scale networks. The recursive aggregation of logical building blocks naturally introduces a hierarchy on the network that provides a clean separation of concerns (e.g., routing, access control, traffic engineering, failure detection/handling) and allows for locally-scoped control planes (e.g. for fast failure reaction) in order to achieve large scale and overall facilitate the extensibility and manageability of not just network elements but of the network as a whole.

The O-NOS has two NETCONF/REST interfaces: southbound and northbound. The southbound interface allows configuration management and retrieval of operational information from the O-NEs, performing synchronization of configuration and state data between the O-NOS and the O-NEs, while the northbound interface allows external applications such as NMS (Network Management System) to provision the network through the SDN controller. The O-NOS is designed to provide optical network resources slicing, via separation of, for instance, wavelength, node and link spaces. The network slicing is performed separating the different slice YANG model subtrees in different "Network Chassis".

B. XCP-V (eXtended Control Plane Virtualized)

The GMPLS control plane runs in a virtualized environment, offloading node complexity, while allowing the deployment of advanced features, including Optical VPNs, network slicing, software upgrades without interruption, and others. Link-layer management and correlation will be performed by LMP, which runs at the controller. The O-NOS allows the instantiation of several XCP-V daemons, one per network node per slice, enabling the configuration of different optical VPNs, each one with an independent GMPLS control plane, and consequently with a different set of UNI/NNI. The communication between the virtual XCP-V instance and the O-NOS is performed using a proprietary API, normally used for communication of FRUs and the node controller via node internal network. The XCP-V instances have been virtualized using LXC (Linux Containers) in order to allow scaling dozens of nodes in the same physical machine for the SDN controller. Nevertheless, the architecture allows to spread XCP-V instances over different machines, increasing the scalability.

In order to allow XCP-V auto-configuration, including virtual O-NE instantiation and GMPLS TE-links, the O-NE relies in LLDP (Link Layer Discovery Protocol) [12] for topology discovery, running over the optical supervisory channel - OSC (100BaseFX at 1510 nm wavelength, out of the C-Band data spectrum). New nodes can be configured with minimal parameters, including Node ID and Node Type, which can be OLS (Optical Line System node) or OXC (Optical Cross-Connect node). With this configuration, the nodes start a self-configuration and neighbor discovery processes. Each DWDM node has supervisory channel controller equipped with N x Ethernet 100BaseFX ports, where N is the numbers of directions of the ROADM. Each direction is configured as a different VLAN, according to the following rule: (DIR 1, VLAN 100; DIR 2, VLAN200; DIR N, VLAN N). The controller is composed by an Ethernet Switch and a supervisory board. The connection between the Switch and the supervisory board is configured as a dot1q trunk carrying "N" VLANs. The supervisory board is configured with "N" sub-interfaces, one attached to each VLAN. Therefore, there is an Ethernet broadcast domain for each point-to-point connection. This configuration, allows a LLDP process running at the supervisory board to discover the neighbors. Each device configured with an active LLDP Agent sends periodic messages to a specific multicast MAC address on all physical interfaces enabled for LLDP transmission, and listens for LLDP messages on the same interfaces. Each LLDP message contains information identifying the source ports and a proprietary TLV identifying the neighbor Node ID and Node Type. This information is stored in the local NETCONF Database, and automatically reflected and consolidated at the O-NOS. Therefore, the eXtended Control Plane (XCP) Manager is able to instantiate XCP virtual nodes and GMPLS TE-links among the virtual nodes, where the virtual TE-links topology is exactly the same as the physical ROADMs topology.

C. Control Applications

The SDN controller provides a NETCONF/REST interface for plugging control applications to perform specific tasks, taking advantage of the network abstraction. The applications we are developing focus on cognitive and adaptive controls for autonomic optical adjustments such as global equalization, global EDFA gain control, DWDM system auto alignment, fault prediction and preventive actions.

Networks need to be self-aware in order to provide resilient applications and services. These networks should exhibit cognitive properties that guide the actions based on reasoning autonomic operations, adaptive functionality and self-management. Cognitive networks are different from intelligent networks, where the first drive the network actions with respect to end-to-end goals, in cognitive systems, the network observes the conditions and based on a prior knowledge obtained from previous actions, plan, decide and acts [25]. We have pursued this concept in [9] to provide an adaptive gain control for erbium doped fiber amplifiers. A cognitive network was demonstrated using GMPLS control plane to read and control amplifiers analyzing the transponders bit error rate in heterogeneous optical networks scenario. However, only the EDFAs were used to develop adaptive and cognitive optical networks using a complete proprietary and not standardized protocols along the network element and management communication.

The O-NOS provides standardized means to monitor and act at the network elements, enabling the development of new adaptations using several network elements beyond the EDFA such as: Transponders, Reconfigurable optical-add-drop modules (ROADM), multi-cast optical switches (MCS), optical switches, tunnable dispersion compensator module (TDCM), variable optical attenuators (VOA), tunnable filters, Optical channel monitoring (OCM) and in-band OSNR monitors.

The next section presents the Optical Network testbed used for validating the implementation, and the test results. Additionally to the testbed, PCE, XCP, Node Configuration Daemon, and others, the following implementations have been performed exclusively in the scope of this paper: network abstraction, including synchronization of configuration and state with real nodes, network slicing, network discovery with LLDP have been extended to support VLAN tags, XCP Manager and XCP virtualization with LXC. Additional developments such as GMPLS UNI, LMP, and further cognitive and adaptive controls are work-in-progress.

IV. Testbed and Experiments

The experimental network, shown in Figure 2, is composed by five DWDM nodes and the Optical SDN Controller. Each node includes a multi-degree ROADM, optical amplifiers, supervisory channels (through Ethernet switches with 1510nm SFPs) and optical transponders. It is worth to note that while WSS cards have flexgrid support, all experiments upfront were performed with the standard 50 GHz channel grid. The Optical SDN Controller, running the O-NOS and Virtualized XCP instances is equipped with a Intel Core i7, 2.8GHz CPU, with 8GB of RAM.

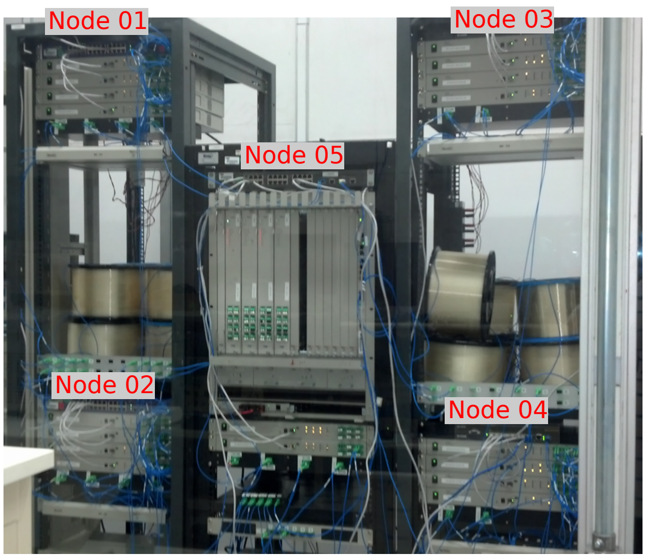

Fig. 2. Testbed composed by five WSS ROADMs

All the WSSs (Figure 3) and EDFAs line cards used at the testbed were designed, prototyped and coded at CPqD (optics, electronics and firmware). This fact enables control functions to change any possible parameter at the line cards, since we are able to expose them via line card command set.

Fig. 3. WSS ROADMs line card

A. Topology Discovery and VON instantiation

Figure 4 shows a capture of LLDP packets at Node 02. The messages from Nodes 01 and 04 contains one TLV of type 127 identifying themselves. Using the information received by the neighbors, including remote node ID, local and remote VLANs, the local node, in this case Node 02, populates the local YANG database.

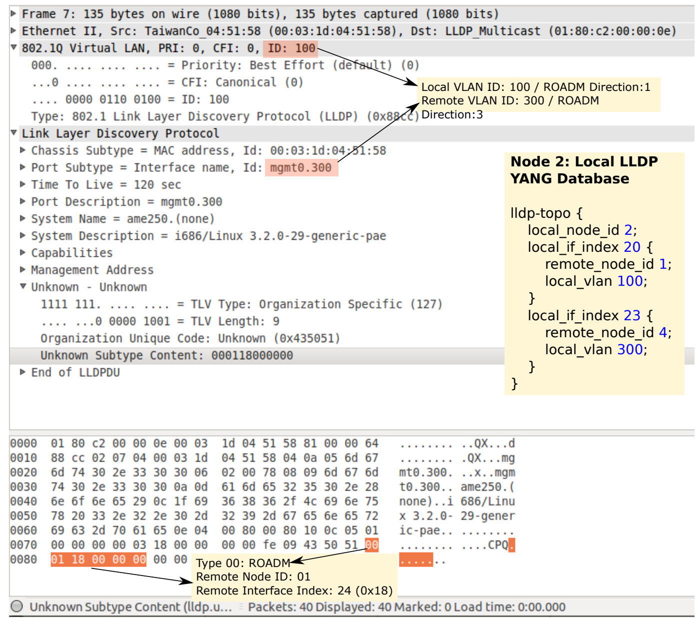

Fig. 4. LLDP packets and YANG Topology Database

The topology discovery information from all the nodes is consolidated automatically at the O-NOS, and used by the XCP Manager daemon in order to instantiate the “Main VON”, containing all ROADM Nodes and DWDM links. Therefore, one LXC Virtual Machine is instantiated for each real node. Additionally, the XCP Manager starts the GMPLS stack in each VM, and creates TE-Links connecting the control planes, according to the physical topology.

Currently, additional VONs can be instantiated using VON descriptors in XML. Figure 5 shows the “Main VON” and respective TE-links auto-configured by the XCP manager. Additionally, the figure shows a VON named HS-VON which includes Nodes 01, 03 and 04. At the bottom of the figure the TE links state from Node 01 to 03 are shown, using the O-NOS CLI. As can be observed, each VON has a subset of the wavelengths available for LSP creation.

B. VON-Aware Virtualized GMPLS Control Plane Operation

In order to demonstrate the operation of the control plane over the O-NOS, supporting the different VONs, a set of 20 LSPs have been established in the “Main VON”, where 10 were routed directly from Node 02 to Node 04, and another 10 passed through Nodes 01 and 03. On the other hand, in the second VON, named HS-VON, a total of 7 LSPs have have been established from Node 01 to Node 04 passing through Node 03. All the path computation and path signaling procedures were described in ours previous works [20] and [21]. Figure 6 shows the RSVP-TE message flow for one path establishment at Node 01 for a LSP from HS-VON.

Figure 7 shows results of listing, at the O-NOS CLI, the cross-connections performed at the Network Elements (ROADMs), due to LSP creation for both VONs.

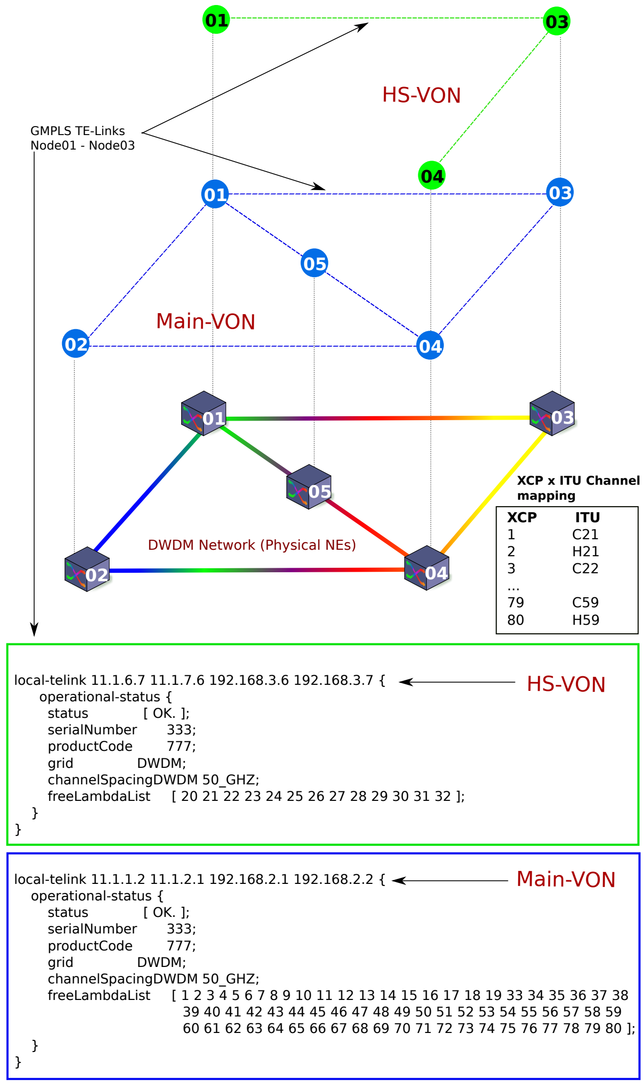

Fig. 5. Two VONs with their TE-Links

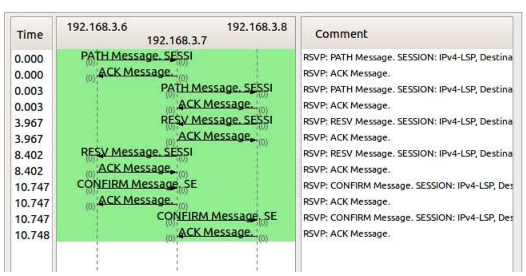

Fig. 6. RSVP messages during LSP establishment

Since the WSS cards are flexgrid, the connections are shown using a flexgrid representation as denoted in ITU-T G.694.1 standard [26]. For the flexible DWDM grid, the allowed frequency slots have a nominal central frequency (in THz) defined by: 193.1 THz + (n x 0.00625 THz), where "n" is a positive or negative integer including 0, and 0.00625 THz (6.25 GHz) is the nominal central frequency granularity and a slot width is defined by: (12.5 x m), where "m" is a positive integer and 12.5 is the slot width granularity in GHz. Any combination of frequency slots is allowed as long as no

```
% show config system von-ne roadm cross-connections |tab

VON     NODE                          CC
ID      ID     CC LABEL               CHANNEL   IN       OUT
-------------------------------------------------------------
1       1      D1-IN-D3-OUT-312       312       D1-IN    D3-OUT
               D1-IN-D3-OUT-328       328       D1-IN    D3-OUT
               D1-IN-D3-OUT-344       344       D1-IN    D3-OUT
               D1-IN-D3-OUT-360       360       D1-IN    D3-OUT
               ...
1       2      D1-ADD-D1-OUT-312      312       D1-ADD   D1-OUT
               D1-ADD-D1-OUT-328      328       D1-ADD   D1-OUT
               D1-ADD-D1-OUT-344      344       D1-ADD   D1-OUT
               D1-ADD-D1-OUT-360      360       D1-ADD   D1-OUT
               ...
1       3      D1-IN-D3-OUT-312       312       D1-IN    D3-OUT
               D1-IN-D3-OUT-328       328       D1-IN    D3-OUT
               D1-IN-D3-OUT-344       344       D1-IN    D3-OUT
               D1-IN-D3-OUT-360       360       D1-IN    D3-OUT
               ...
1       4      D1-ADD-D1-OUT-312      312       D1-ADD   D1-OUT
               D1-ADD-D1-OUT-328      328       D1-ADD   D1-OUT
               D1-ADD-D1-OUT-344      344       D1-ADD   D1-OUT
               D1-ADD-D1-OUT-360      360       D1-ADD   D1-OUT
               ...
2       1      D1-ADD-D1-OUT--8       -8        D1-ADD   D1-OUT
               D1-ADD-D1-OUT-24       24        D1-ADD   D1-OUT
               D1-ADD-D1-OUT-40       40        D1-ADD   D1-OUT
               D1-ADD-D1-OUT-56       56        D1-ADD   D1-OUT
               ...
2       3      D1-IN-D3-OUT--8        -8        D1-IN    D3-OUT
               D1-IN-D3-OUT-24        24        D1-IN    D3-OUT
               D1-IN-D3-OUT-40        40        D1-IN    D3-OUT
               D1-IN-D3-OUT-56        56        D1-IN    D3-OUT
               ...
2       4      D1-ADD-D1-OUT--8       -8        D1-ADD   D1-OUT
               D1-ADD-D1-OUT-24       24        D1-ADD   D1-OUT
               D1-ADD-D1-OUT-40       40        D1-ADD   D1-OUT
               D1-ADD-D1-OUT-56       56        D1-ADD   D1-OUT
               ...
```

Fig. 7. ROADM Cross connections per VON/NE

two frequency slots overlap. This experiment considers "m" equals to 8 slots for all channels (50 GHz channel spacing). For instance, channel -160 represents ITU-T channel C21 (192.1 THz).

In order to demonstrate VON operation, a set of 40 channels modulated in 112Gbps with DP-QPSK were connected to the ADD ports of Nodes 01 and 02. The physical topology, channels added/dropped for both VONs and LSPs are shown in Figure 8.

V. Conclusion and Future Works

This paper presented a proposal, implementation and validation of an SDN Controller for Transport Network Virtualization and Autonomic Operation. An Optical Network Operating System (O-NOS), based in Netconf/YANG acts as a network abstraction layer, allowing control applications to have a complete and/or sliced view of the network, enabling the deployment of Virtual Optical Networks. In order to maintain current Control Plane functions, the GMPLS protocol stack have been virtualized at the SDN Controller, in a way that it is possible to run different instances of the control plane for each network slice. Therefore, there is a control plane instance for each VON.

In order to provide automatic bootstrap, LLDP provides automatic topology discovery, allowing the initialization of the O-NOS, and the "Main VON" Control Plane, including TE-Links instantiation. This architecture allows for centralized optimization algorithms with global network view, such as amplifier gain control based on global network knowledge, as demonstrated in our previous work [9]. The concepts have been validated over the testbed network, comprised by five flexgrid multidegree WSS ROADMs, where a set of 112Gbps DP-QPSK channels have been routed.

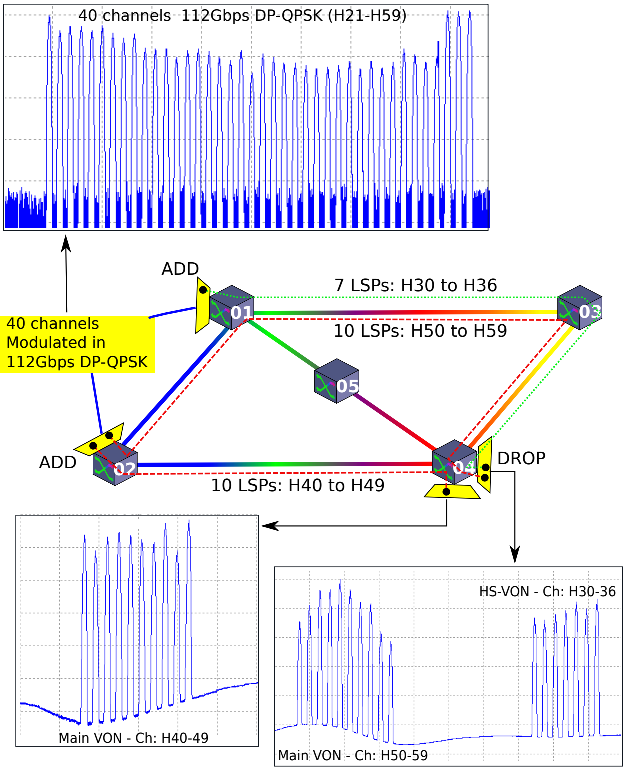

Fig. 8. Optical Spectrum at nodes 01, 02 and 04

As future works, we propose to include LMP (Link management Protocol) and an Optical UNI (User to Network Interface) to the Virtualized Control Plane. The former will provide link verification at the transport layer, allowing standardized fault management, and the second will allow different clients (such as Routers) to request services in the scope of its VON. Additionally, we are implementing autonomic applications for controlling the experimental testbed, employing adaptive and cognitive approaches, and designing a Policy-Based engine for allowing the enforcement of policies that govern the Controller mechanisms behavior, such as policies for: spectrum defragmentation, VON wavelength sharing, channel equalization, and others. Finally, we intend to design and implement a mechanism for SDN Controller redundancy, increasing system robustness, while allowing the implementation of mechanisms for control plane upgrade and new services implementation in a simple and non disruptive way.

ACKNOWLEDGMENT

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