Experimental Testbed of Reconfigurable Flexgrid Optical Network with Virtualized GMPLS Control Plane and Autonomic Controls Towards SDN

Juliano Oliveira, Marcos Siqueira, Giovanni Curiel, Alberto Hirata, Fabian van 't Hooft, Diego Macedo, Marcio Colazza and Christian Rothenberg
CPqD Telecom R&D Center - Campinas, SP, CEP 13086-902
Emails: jrfo,siqueira,gcuriel,ahirata,fabian,dmacedo,marcio,esteve@cpqd.com.br

***Abstract*—This paper demonstrates a testbed of a reconfigurable optical network composed by four ROADMs equipped with flexgrid WSS modules, optical amplifiers, optical channel monitors, and supervisor boards. A controller daemon implements a node abstraction layer based in the YANG language, providing NETCONF and CLI interfaces. Additionally we demonstrate the virtualization of GMPLS control plane, while supporting automatic topology discovery and TE-Link instantiation, enabling a path towards SDN. GMPLS have been extended to collect specific DWDM measurement data allowing the implementation of adaptive/cognitive controls and policies for autonomic operation, based on global network view.**

Keywords: ROADM, Flexgrid, GMPLS, SDN, Virtualization.

I. Introduction

The pace of evolution of optical network technologies continues at a very high rate. The main DWDM (Dense Wavelength Division Multiplexing) vendors are already shipping systems equipped with 100 Gb/s transponders, and there are experiments in 400G and 1Tb/s per wavelength. Additionally, ROADMs (Reconfigurable Optical Add-Drop Multiplexers) with CDC (Colorless, Directionless, Contentionless) and flexgrid (flexible grid) support started to be installed in production networks. Therefore, optical networks operation is changing from static point-to-point systems to mesh topologies, with dynamic and reconfigurable wavelengths, modulation formats, and services. This new scenario presents many challenges to the network control plane, including mechanism for impairments and signal aware RSA (Routing and Spectrum Allocation), optical equalization, cross-layer optimizations, spectrum defragmentation, network services and functions 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 fulfill new requirements, such as flex-grid, as well as to support OTN (Optical Transport Network) switching features. On the other hand, there is a momentum about SDN (Software-Defined Networking) as being a way to separate network control from the data plane, allowing simplification and automation of network operation and new services deployment. ONF (Open Networking Forum) and OIF started new working groups for discussing and/or standardizing SDN and virtualization in the context of optical networks. The current discussions include the definition of candidate interfaces within the transport network controller. Some proposals include a subset of ASON (Automatically Switched Optical Network)/GMPLS interfaces and protocols embedded at the controller, instead of running at the NEs (Network Elements).

On the other hand, with the increased optical networks complexity and dynamics, autonomic mechanisms capable of performing configurations for optical power gain and equalization adjustments, reactively and pro-actively, are required based on a global view of the network state in order to allow/enhance the end-to-end QoS (Quality of Service) of each lightpath and global network health.

In our previous work [1] we demonstrated an EDFA Gain Control mechanism using cognitive algorithms for autonomic and predictive operation using proprietary communications protocols, in [2] we have introduced our GMPLS Control Plane implementation with RSVP-TE and OSPF-TE support, and in [3] we have demonstrated the implementation RWA algorithms with multiple constraints consideration. In this paper, we demonstrate a testbed of a reconfigurable optical network composed by five DWDM nodes. One of the nodes is an OLS (Optical Line System) composed by optical line amplifiers, and the remaining nodes are ROADMs (Reconfigurable Optical Add-Drop Multiplexers) equipped with flex-grid 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 in the YANG [4] language, providing a NETCONF [5] interface. Additionally we demonstrate the virtualization of GMPLS Control Plane, while supporting automatic topology discovery and TE-Link instantiation by means of LLDP (Link Layer Discovery Protocol). GMPLS has been extended to collect specific DWDM measurement data allowing the implementation of adaptive/cognitive controls and policies for autonomic operation, based on global network view, enabling a path towards SDN enabled Optical Networks. Finally, a set of applications for autonomic configuration of the amplifiers gain aiming global BER (Bit Error Rate) minimization have been deployed.

This paper is organized as follows: section II details the system architecture, section III presents the optical testbed and experiments, and section IV presents the conclusion and future works.

II. System Architecture

The system architecture, presented in Figure 1, aims to allow autonomic control of the optical network, while simplifying and offloading the NEs (Network Elements). The NEs run LLDP (Link Layer Discovery Protocol) [6] over the optical supervisory channel (100BaseFX at 1510 nm wavelength, out of the C-Band data spectrum) for basic network discovery and the Node Controller Daemon, for node abstraction and control via NETCONF. The Centralized Control Station runs a virtualized XCP (eXtended GMPLS Control Plane) with extensions to collect monitoring data for the lightpaths, such as optical power at different points of the network, as well as the autonomic network control applications, such as the adaptive/cognitive EDFA gain controller described in [1] .

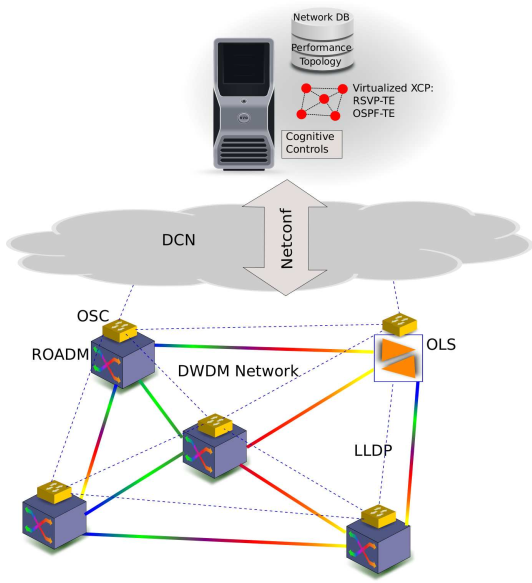

Fig. 1. System Architecture

A. Optical node Abstraction

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 multi-cast 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. Reference [7] describes with details the modeling of our ROADM in YANG.

The Node Controller Daemon with the deployed YANG models acts like a node abstraction layer for ROADM control agents such as GMPLS protocols and the management and control station.

B. XCP-V (eXtended Control Plane - Virtualized)

The GMPLS control plane runs in a virtualized environment, offloading node complexity, while paving the way to the deployment of advanced features towards SDN, 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 communication between the virtual XCP instance and the node controller daemon is performed using a proprietary API, normally used for communication of FRUs and the node controller via node internal network. As future work, we plan to perform all the communications via NETCONF.

In the current version, the XCP instances have been virtualized using hardware virtualization approach, but we will migrate to LXC (Linux Containers) in order to scale dozens of nodes in the same physical machine.

C. Topology discovery and TE-link auto-configuration

The GMPLS control plane relies in LLDP (Link Layer Discovery Protocol) for topology discovery. New nodes must 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. Therefore, the topology discovery agent 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.

D. Autonomic Adaptive/Cognitive Controls

To network applications and services appropriate provide fully utilization optical networks, different requirements are needed. This fact had motivated the research on active and programmable networks in early 1990s [8]. Despite this, networks still have to be managed by human administrators. This occurs due the lack of network awareness, self knowledge and aim target to provide networks means to process and apply the needed actions to achieve the aim target in an autonomic and/or cognitive way. Current optical networks perform reactive adaptation by responding to changes in the environment after a problem has occurred [9].

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 network conditions and based on a prior knowledge gained from previous actions, plan, decide and acts on this information [10].

However there is a performance issue regarding these networks since such systems would not reach their performance level instantly; there is an adaptation step (which provides higher resilience towards critical errors).

In [1], following this concept, an adaptive gain control for erbium doped fiber amplifiers was developed and 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.

This optical network testbed will provide 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.

At the time of this writing, we had implemented all the network discovery mechanism, TE-link auto-configuration, GMPLS Control Plane extensions, node abstraction and EDFA cognitive gain control. Additional developments such as GMPLS UNI, LMP, and further cognitive controls are work-in-progress.

III. Testbed and Experiments

The experimental network, shown in Figure 2, is composed by five DWDM nodes. Each node includes a multi-degree ROADM, optical amplifiers, supervisory channels (through Ethernet switches with 1510nm SFPs) and optical transponders. For the tests performed in the scope of this paper, one of the nodes was configured as OLS (Optical Line System), providing only line amplification, and the others were configured as multi-degree ROADMs. It is worth mentioning that the WSS cards support flex-grid, nevertheless the experiments were performed with the standard 50 GHz channel grid.

All the WSSs (Figure 3) and EDFAs line cards used at the testbed were designed at CPqD, including hardware (optics and electronics) and firmware (embedded Linux). This was intentionally performed to provide fully and custom control and operation of the line cards from the testbed, allowing the development of end-to-end QoS enhancement algorithms changing any possible parameter at the line cards.

The transponders (not shown in Figure 2) were connected to Node 01, Node 02 and Node 04. Node 03 has been configured as OLS (Optical Line System), meaning it is performing only optical amplification. The physical topology is shown in Figure 7.

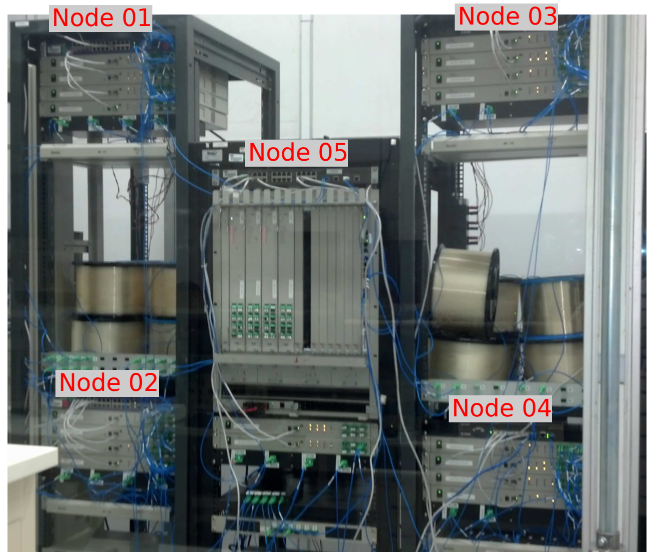

Fig. 2. Testbed composed by five WSS ROADMs

Fig. 3. Testbed WSS ROADMs line card

The Network Controller, running the Virtualized XCP instances is equipped with a Intel Core i7, 2.8GHz CPU, with 8GB of RAM. Each XCP Virtual machine was configured with 256MB of RAM and was limited to one CPU with maximum of 50% of utilization.

A. Topology Discovery

At first, the LLDP protocol was initiated in all nodes, starting sending frames through all configured interfaces in each node. Figure 4 shows a capture of LLDP packets at Node 2. The messages from nodes 04 and 05 contains one TLV of type 127 identifying themselves. On the other hand, the messages coming from site 03 have one TLV of type 127 with two node type/IDs: the first of type 00 (ROADM) and another of type 01 (OLS), allowing site 02 discover the next ROADM site (site 01), connected after the OLS site. Therefore, GMPLS TE-Links were auto-configured based on LLDP topology discovery mechanism.

Figure 5 shows the TE links auto-configured by the topology discovery mechanism mapped to the physical topology of

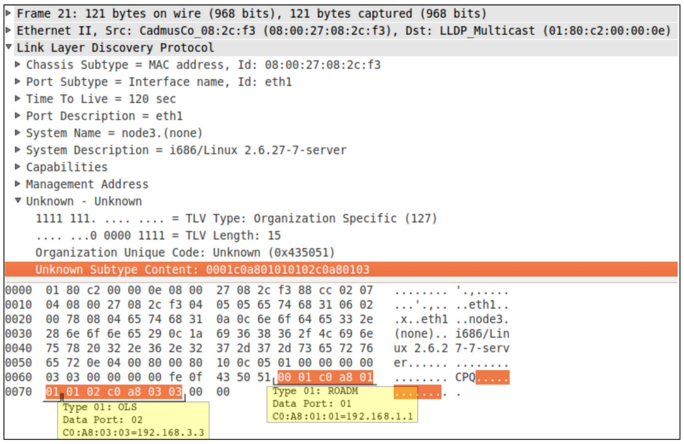

Fig. 4. Topology discovery packets

ROADMs. At the bottom of the figure the TE links state at nodes 03 and 04 is shown, using the node's CLI.

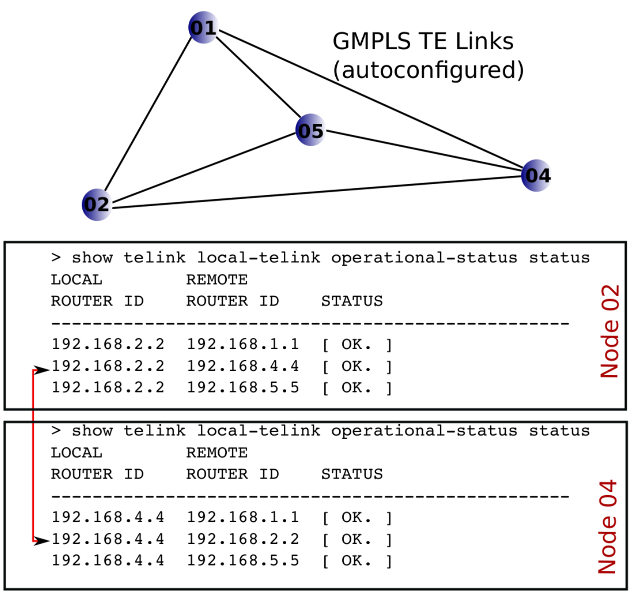

Fig. 5. Topology discovery

B. Virtualized GMPLS Control Plane

In order to demonstrate the operation of the control plane, a set of optical LSPs have been configured from Node 01 to Node 02 (6 LSPs) and Node 04 (21 LSPs). All the path computation and path signaling procedures were described in ours previous works [2] and [3].

Figure 6 shows the RSVP-TE message flow for one path establishment at Node 02 for a LSP from Node 01 to Node 04.

Figure 7 shows the optical spectrum at nodes 01, 02 and 04. At node 02, all channels passing through and being dropped at this node are shown. This is because drop ports in all WSS cards used in this experiment are passive, i.e., the signal present at a LINE-IN port in a WSS ROADM will be splitted and forwarded to its drop and interconnection ports.

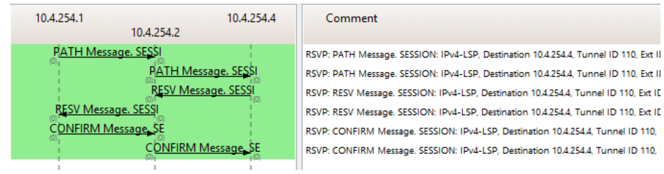

Fig. 6. RSVP messages during LSP establishment

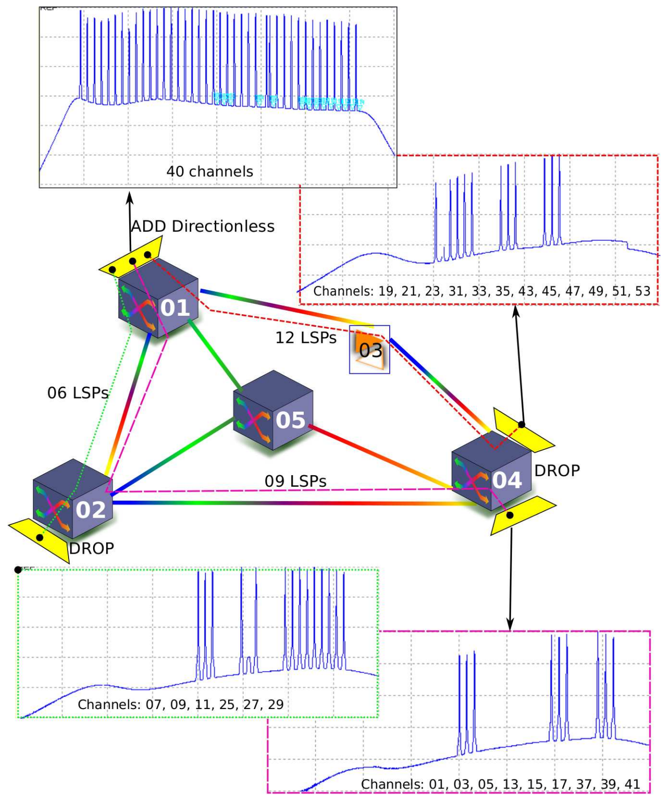

Fig. 7. Optical Spectrum at nodes 01, 04 and 03

Below, the LSPs created at Node 02 by the GMPLS control plane are listed using the node's CLI:

```
% show config system roadm cross-connections cross-connection |tab
                 CC    CC
CC LABEL         CHANNEL  ATTENUATION  IN    OUT
-----------------------------------------------------------
D1-ADD-D1-OUT      -112      0.0       D1-ADD  D1-OUT
D1-ADD-D1-OUT      -80       0.0       D1-ADD  D1-OUT
D1-ADD-D1-OUT      -96       0.0       D1-ADD  D1-OUT
D1-ADD-D1-OUT      32        0.0       D1-ADD  D1-OUT
D1-ADD-D1-OUT      48        0.0       D1-ADD  D1-OUT
D1-ADD-D1-OUT      64        0.0       D1-ADD  D1-OUT
D1-IN-D1-DROP     -112       0.0       D1-IN   D1-DROP
D1-IN-D1-DROP     -80        0.0       D1-IN   D1-DROP
D1-IN-D1-DROP     -96        0.0       D1-IN   D1-DROP
D1-IN-D1-DROP     32         0.0       D1-IN   D1-DROP
D1-IN-D1-DROP     48         0.0       D1-IN   D1-DROP
D1-IN-D1-DROP     64         0.0       D1-IN   D1-DROP
D1-IN-D3-OUT      -128       0.0       D1-IN   D3-OUT
D1-IN-D3-OUT      -144       0.0       D1-IN   D3-OUT
D1-IN-D3-OUT      -160       0.0       D1-IN   D3-OUT
D1-IN-D3-OUT      -32        0.0       D1-IN   D3-OUT
D1-IN-D3-OUT      -48        0.0       D1-IN   D3-OUT
D1-IN-D3-OUT      -64        0.0       D1-IN   D3-OUT
D1-IN-D3-OUT      128        0.0       D1-IN   D3-OUT
D1-IN-D3-OUT      144        0.0       D1-IN   D3-OUT
D1-IN-D3-OUT      160        0.0       D1-IN   D3-OUT
D3-IN-D1-OUT      -128       0.0       D3-IN   D1-OUT
D3-IN-D1-OUT      -144       0.0       D3-IN   D1-OUT
D3-IN-D1-OUT      -160       0.0       D3-IN   D1-OUT
D3-IN-D1-OUT      -32        0.0       D3-IN   D1-OUT
D3-IN-D1-OUT      -48        0.0       D3-IN   D1-OUT
D3-IN-D1-OUT      -64        0.0       D3-IN   D1-OUT
D3-IN-D1-OUT      128        0.0       D3-IN   D1-OUT
D3-IN-D1-OUT      144        0.0       D3-IN   D1-OUT
D3-IN-D1-OUT      160        0.0       D3-IN   D1-OUT
```

Since the WSS cards are flex-grid, the connections are shown using a flex-grid representation as denoted in ITU-T G.694.1 standard [12]. 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 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).

Figure 8 shows traffic measurements between the controller station running all the instances of the virtualized XCP during the establishment and removal of the 27 lightpaths shown in Figure 7. As can be observed, the traffic peaks are in the order of 600 kbps, and average is 220 Kbps during establishment or removal. The setup of the 27 lightpaths takes approximately 100 seconds. These times include RWA, control logic, and WSS switches configuration. It is observed that, since for path removal there is no RWA computation, the total time is approximately 10 seconds smaller.

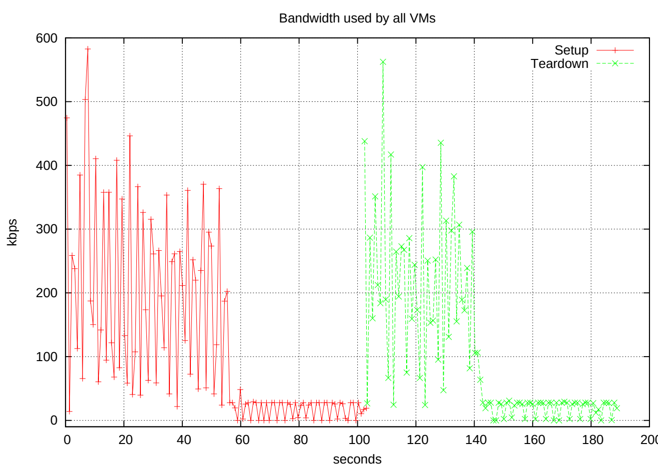

Fig. 8. Control Traffic between XCP-V plane and real nodes for establishment and removal of 27 lightpaths

IV. Conclusion and Future Works

This paper presented a testbed of a reconfigurable flexgrid optical network enabled for autonomic operation. The testbed has been equipped with a Virtualized eXtended GMPLS Control Plane (XCP-V), with automatic topology discovery and TE-Link instantiation, and results have shown that it's feasible to run the GMPLS protocols at a centralized controller, paving the way to Software Defined Optical Networking for Transport Networks. 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 [1]. The concepts have been validated over the testbed network, where functional and performance results have been presented.

As future works, we propose to design and implement a Software Defined Controller for Optical Networks with a network abstraction layer, acting as a Network Operating System, evolving the Virtualized GMPLS Control Plane and autonomic applications for controlling the experimental testbed to interact with this layer, and not directly with the Network Elements. This approach will allow the implementation of features such as network slicing and optical VPNs. Additionally, we plan to include LMP (Link Management Protocol) to the Virtualized Control Plane, with DWDM support (as specified in [11]), for link verification at the transport layer, allowing standardized fault management. Finally, we intend to implement a mechanism for SDN Controller redundancy and OSC (Optical Supervisory Channel) routing scalability, increasing system robustness, while allowing the implementation of mechanisms for control plane upgrade and new services implementation in a simple and disruptive way.

Acknowledgment

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