

# Dynamic and Adaptive Control Plane Solutions for Flexi-grid Optical Networks based on Stateful PCE

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**Abstract**—Adaptive flexi-grid optical networks should be able to autonomously decide where and when to dynamically setup, re-optimize and release elastic optical connections, in reaction to network state changes. A Stateful Path Computation Element (PCE) is a key element for the introduction of dynamics and adaptation in GMPLS-based distributed control plane for flexi-grid DWDM networks (e.g. global concurrent reoptimization, defragmentation, or elastic inverse-multiplexing), as well as for enabling the standardized deployment of the GMPLS control plane in the Software Defined Network (SDN) control architecture. First, this paper provides an overview of passive and active stateful PCE architectures for GMPLS-enabled flexi-grid DWDM networks. A passive stateful PCE allows for improved path computation considering not only the network state (TED) but also the global connection state (LSPDB), in comparison with a (stateless) PCE. However, it does not have direct control (modification, rerouting) of path reservations stored in the LSPDB. The lack of control of these LSPs may result in sub-optimal performance. To this end, an active stateful PCE allows for optimal path computation considering the LSPDB for the control of the state (e.g. increase of LSP bandwidth, LSP rerouting) of the stored LSPs. More recently, it has also been proposed an active stateful PCE architecture that exposes the capability of setting up and releasing new LSPs. It is known as active stateful PCE with instantiation capabilities. This paper presents the first prototype implementation and experimental evaluation of an active stateful PCE with instantiation capabilities for the GMPLS-controlled flexi-grid DWDM network of the ADRENALINE testbed.

**Index Terms**—Path Computation Element (PCE), control plane, Generalized Multiprotocol Label Switching (GMPLS), Software Defined Networks (SDN), stateful PCE, stateless PCE, OpenFlow, Flexi-grid optical networks.

## I. INTRODUCTION

**W**AVELENGTH Switched Optical Networks (WSO) are based on a fixed ITU-T DWDM grid (e.g. a 50 GHz channel spacing is the most common approach for 100Gb/s transmission, requiring 37.5 GHz with a DP-QPSK modulation). However, this rigid, grid-based approach is not adapted to the spectrum requirements of optical signals for long-reach transmission and high-speed data rates beyond 100Gb/s (e.g. a 400 Gb/s signal using DP-QPSK does not fit in the 50 GHz DWDM grid) [1]. Although such 400Gb/s signal could be demultiplexed into four 100Gb/s signals in order to fit in the

50GHz DWDM grid, this approach is particularly inefficient in terms of spectrum efficiency due to the strict guard bands required between optical channels in DWDM systems in order to properly multiplex/demultiplex the optical signals. To overcome this major limitation, WSONs are evolving towards Spectrum Switched Optical Networks (SSON) with a flexible ITU-T DWDM grid, in which the optical spectrum is characterized by a frequency grid having Nominal Central Frequencies (NCF) with a lower spacing granularity (6.25 GHz) and the required amount of optical bandwidth for an optical channel can be dynamically and adaptively allocated, in multiples of a given slot width granularity (12.5 GHz) determined by the signal modulation format and its data rate [2]. The so called media channel "frequency slot", allocated to an (elastic) optical connection is fully characterized by its nominal central frequency and slot width.

The key elements of the SSON or flexi-grid optical networks are two: first, the bandwidth-variable transponders (BVT), which generate optical signals supporting multiple modulation formats and bit-rates that can be dynamically modified according to the needs of the client signal and network conditions [3]. For example, a distance-adaptive transmission allows to dynamically allocate the minimum frequency slot to an elastic optical connection, taking advantage of the fact that the same bit-rate can be achieved with different spectral efficiency modulation formats, requiring different spectrum widths. However, high spectral efficiency modulation schemes will only allow short-reach transmission distances. For example a 400Gb/s signal transmitted over 300km may need a robust modulation format like DP-QPSK requiring 150GHz of optical spectrum, while a 20Km transmission may use a spectrally-efficient modulation format like DP-16QAM requiring only 75GHz. Thus, there is a clear trade-off between distance/bit-rate and required spectrum. Rate-adaptive transmission allows to dynamically allocate the minimum spectrum resources to an elastic optical connection according to the client traffic demand (e.g. a 400Gb/s request may require 75GHz of optical spectrum using DP-16QAM, while a 200Gb/s request would only require 37.5 Gb/s using also DP-16QAM). The second key element are the bandwidth-variable (BV-) OXCs, which are able to switch an optical signal based on a frequency slot rather than on a fixed wavelength [4].

Adaptive flexi-grid optical networks are able to autonomously decide where and when to dynamically setup, re-optimize and release elastic optical connections, in reaction to network state changes (e.g. based on both monitoring the resource status and traffic forecasts) with little to no operator intervention. An adaptive network management system (Adap-

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tive NMS) for elastic optical connectivity services is responsible of monitoring the current network resource status and traffic forecasts, and adaptively planning and deciding which existing elastic connections need to be modified (e.g. bit-rate, avoid a link/node, etc), which elastic connections need to be added or removed, or when to optimize the entire or a subset of the existing elastic connections, for example in the event of network defragmentation [5]. From a control plane perspective [6], it is required to dynamically compute a path applying Routing Modulation and Spectrum assignment (RMSA) algorithms (physical route - nodes and links-, modulation format parameters and required optical spectrum/ frequency slot) for a connection requesting a specific bit-rate, and to provision the elastic optical connection by configuring the bit-rate and modulation format of the BVT, and the frequency slot of the BV-OXCs. Additionally, the adaptation capability requires that the control plane can dynamically reroute existing optical connections modifying partially or integrally the route (i.e., nodes and/or links), and/or modify the connection attributes (bit-rate, modulation format and frequency slot).

Two control plane architectures are active subjects of research, namely GMPLS and SDN. The GMPLS architecture is based on a distributed control plane (signaling, routing and link management), and has been extended to support delegating the path computation function to a path computation element (PCE) [7] through an open and well-defined protocol named PCE protocol (PCEP) [8]. On the other hand, the SDN architecture allows controlling the network using software running on a logically centralized controller [9], often using an open and well-defined protocol named OpenFlow to remotely install forwarding behavior in network devices [10].

A Stateful Path Computation Element (PCE) is a key element for the introduction of dynamics and adaptation in GMPLS-based distributed control plane for flexi-grid DWDM networks, as well as for enabling the standardized deployment of the GMPLS control plane in the Software Defined Network (SDN) control architecture. In Sec.II, we provide an overview of passive and active stateful PCE architectures and interfaces for GMPLS-enabled flexi-grid DWDM networks, and in Sec.III we present some examples of the applicability of the active stateful PCE, such as global concurrent reoptimization, defragmentation, inverse multiplexing or integration with the Software Defined Networking (SDN) control approach. After that, we show in Sec. IV the first prototype implementation and experimental evaluation of an active stateful PCE with instantiation capabilities. Finally, we conclude the paper in Sec.V.

## II. ARCHITECTURE OF THE STATEFUL PCE

Under GMPLS-based distributed control, each optical node has a controller which executes several collaborative processes (e.g., routing controller, connection controller, link resource manager, hardware abstraction layer, etc.). A data communication network based on IP Control Channels (IPCC) is required to allow the exchange of control messages between GMPLS controllers. Each GMPLS Routing Controller (RC) maintains its own network state information (topology and resources),

collected in a local TED repository. The GMPLS OSPF-TE routing protocol disseminates changes in the network state (topology and resources) through the exchange of TE LSAs, allowing the synchronization of the GMPLS RC controllers' TED repositories to maintain an unified view. In flexi-grid networks, OSPF-TE disseminates TE attributes on a per TE link basis, and it is then possible to operate either aggregated (flooding information on the total unreserved optical spectrum) or enabling the dissemination of the status of the NCF and the availability of frequency slots. The provisioning, modification and release of end-to-end connections is performed by the GMPLS Connection Controller (CC) through the RSVP-TE signalling protocol, employing messages processed hop-by-hop from the source to the destination node and back. Each GMPLS Connection Controller (CC) only manages the state of all the connections (i.e., Label Switched Paths - LSPs) originated, terminated or passing-through its corresponding node, stored in the local LSP Database (LSPDB). Preliminary pre-standard GMPLS signalling and routing protocol extensions for flexi-grid optical networks were proposed in [11] and [12]. Other collaborative processes are the link resource manager (LRM) that is in charge of the management of the node resources or the hardware abstraction layer (HAL) managing the interface between the GMPLS controller and the hardware of the node.

A (stateless) Path Computation Element (PCE) can be used for centralized and dedicated path computation [7]. The PCE executes dynamic RMSA algorithms [13], [14] to compute a physical route (nodes and links), assign the needed set of modulation parameters (i.e., format, bits per symbol, FEC), and allocate the required spectrum resources to an elastic path, based on the network state information (i.e. TED). Typically, a PCE may obtain the TED by participating as a OSPF-TE passive listener or by sniffing the OSPF-TE TE LSA exchange, but it could also rely on an out-of-band synchronization mechanism (e.g. a topology server to retrieve the TED). Detailed information on the physical transmission impairment constraints (e.g., PMD, OSNR, CD, etc.) may be stored in an extended TED (ETED) at the PCE. The PCE would need the information about the optical impairments along the computed physical route, together with the requested bitrate, to dynamically assign the modulation parameters and the required spectrum to the computed path. Path Computation Clients (PCCs) such as GMPLS Controllers or the Adaptive NMS may request the computation of an explicit route using the PCE Protocol (PCEP). However, in the stateless PCE case, the outdated TED, lack of global LSP state information (e.g., LSP route and reserved resources) and the lack of control of path reservations (i.e., provisioning, modification or release of a connection) may result in sub-optimal path computations. These limitations are motivating the introduction of statefulness in the PCE [15].

### A. Passive Stateful PCE

A stateless PCE, by definition, does not store detailed information of the established paths (i.e., LSP state information) and the lack of global LSP state view (i.e., per LSP route and

reserved resources) may result in higher connection blocking probability: a stateless PCE only operates with network state information (topology and resources) collected in the TED, which may, due to network dynamics, not be synchronized with the actual network state, e.g. due to recently established LSPs for which the network change has yet to be fully disseminated. With this lack of statefulness, the same resources may be assigned to different connections, leading to resource contention during the connection provisioning. The lack of global LSP state information may also result in sub-optimal path computation. For example, the non-linear effects of optical fibres such as Cross-talk (XT), Cross-Phase Modulation (XPM) or Four-wave mixing (FWM) generate adjacent wavelength / frequency slot interference that may cause that the provisioning of a new optical connection degrades the quality of service (QoS) of the in-service connections. Thus, impairment-aware RSA algorithms should compute new paths that ensure an acceptable QoS of the existing ones. To this end, impairment-aware RSA algorithms must also know the existing LSPs in order to recompute the considered QoS parameters (e.g., Q factor) of LSPs adjacent to the computed path, and verify whether it still satisfies a given threshold.

also the global LSP state (LSPDB) (Fig.1.a). It requires a strict synchronization mechanism to allow the stateful PCE to build the global LSPDB, based on the local LSPDBs stored in the GMPLS controllers. In [16], it is proposed to extend PCEP with a new message named Path Computation State Report (PCRpt) to allow a stateful PCE to learn the LSP state (i.e., the PCCs report about the state of the LSP whenever there is a change in their LSPDB, or under request). Another alternative is to use Network Configuration Protocol (NETCONF) [17]. NETCONF is an IETF network management protocol that provides a mechanism to install, manipulate and delete the configuration of network devices based on a defined (configuration) data model. YANG [18] is an extensible data modeling language designed to write data models for the NETCONF protocol able to model configuration data, state data, operations, and notifications. Thus, NETCONF queries can offer the same functionality of PCRpt via notifications. The main limitation of this approach is that currently no standard data model for the LSPDB has been defined. Finally, the PCE could also build its global LSPDB interacting directly with the network the devices through proprietary Command Line Interfaces (CLI), but this approach is clearly too vendor and/or model specific. The main advantages of relying on PCEP to synchronize the LSPDB are; extensions to PCEP are being standardized within the IETF; a LSP model is implicitly defined, mainly characterized by the ERO and other attributes; reuse of existing PCEP object encoding; and finally, to extend existing protocol implementations is simpler than to develop a new protocol.

In this control approach, whenever the adaptive NMS decides to provision/reroute/modify a new/existing LSP, it uses the PCE protocol (PCEP) to send a Path Computation Request (PCReq) message to the PCE (Fig.1.b). The PCReq message specifies the endpoints (source and destination node addresses), objective function (requested algorithm / optimization criteria), along with the associated constraints such as traffic parameters (e.g. requested bandwidth), the switching capability, and the encoding type. It is also possible to include or exclude network nodes, links or whole domains (Include Route Object - IRO - and Exclude Route Object - XRO - respectively), or re-optimize existing paths avoiding resource double-booking using the Reported Route Object (RRO). A PCReq message can request the computation of a path or a set of paths. The use of the Synchronization VECtor (SVEC) list in the PCReq message allows requesting synchronized computation, that is, the PCE avoids assigning the same resources to the previous computed paths of the same set. A Global objective function and global list of constraints applied to the complete set of requested path computation can also be performed through Global Concurrent Optimization (GCO), as defined in [19]. Additionally, specific PCEP extensions for RSA have been proposed in [12] and [14]. In this scenario, the passive stateful PCE is then able to execute such RSA algorithm to find the route. If the PCE finds a suitable route, it replies (in a response within a PCRep message) with the computed path/s including their respective Explicit Route Objects (EROs). Then, the adaptive NMS may proceed with the provisioning of new LSPs, or rerouting/modification

(a) Control network architecture

(b) Example of elastic optical connection provisioning/rerouting/modification

Fig. 1: GMPLS control plane with Passive Stateful PCE

A Passive stateful PCE allows for improved path computation considering not only the network state (TED) but

of existing LSPs by requesting directly the source GMPLS controller (head-end of the connections). The adaptive NMS is also responsible for requesting the release of existing LSPs. The elastic paths are provisioning by the GMPLS control plane using the RSVP-TE signalling protocol, through the exchange of Path and Resv messages. LSP reroute in GMPLS can be based on Break-before-Make (BBM) or Make-before-Break (MBB). Once provisioned/rerouted/modified, the head-end GMPLS controller notifies the Adaptive NMS, and reports about the state of new/existing LSP to the stateful PCE using the PCRpt message.

### B. Active Stateful PCE

A passive stateful PCE maintains a global LSPDB that is only used as input for new path computations. Thus, a passive stateful PCE does not have direct control (modification, rerouting) of path reservations stored in the LSPDB. However, the lack of control of these LSPs may result in sub-optimal performance, since the PCE could not re-optimize (i.e., reroute and/or reassign the frequency slot) some of the existing elastic connections during the path computation process. This re-optimization would allow the PCE first to release resources that could later be use when computing the requested path to either perform a more efficient resource allocation (e.g., spectrum) or to avoid the blocking due to the lack of resources. For example, Flexi-grid DWDM networks show two well-known problems that penalize the network performance, namely, the Spectrum Continuity Constraint (SCC) and spectrum fragmentation. To satisfy the SCC, the PCE tends to compute longer paths and, since more robust modulation formats are required to compensate the optical impairments, such long paths end up also requiring more spectrum. On the other hand, the spectrum fragmentation is due to the dynamic establishment and release of elastic connections. A fragmented spectrum leads PCE to block the new path computation requests, since no continuous spectrum can be allocated. Thus, these problems could be minimized if the PCE could reroute and/or reassign the frequency slot of some of the existing elastic connections before performing the actual computation of a requested path.

To this end, an active stateful PCE (Fig.2.a) may in addition control the state (e.g. increase of bandwidth, rerouting) of the stored LSPs. Since under distributed control LSPs are only managed by the GMPLS controllers, this approach requires that the GMPLS controllers can temporally delegate the control of a set of active LSPs to an active stateful PCE. A delegation mechanism based on the PCRpt is proposed in [16] for PCEP. If the Delegation flag is set to 1, the PCC delegates the control of the LSP to the PCE. Otherwise, the control of the LSP is kept at the PCC.

To allow an active stateful PCE to request the modification/rerouting of the existing LSPs to the source GMPLS controllers, [16] also proposes a new PCEP message named Path Computation Update Request (PCUpd), sent from the PCE to the PCC. Upon reception of a PCUpd message, the PCC triggers the modification of the LSP in the GMPLS controller, using signalling procedures. It is worth noting that it could also be performed through NETCONF queries offering

(a) Control network architecture

(b) Example of PCE-based path computation modifying an existing LSP

Fig. 2: GMPLS control plane with Active Stateful PCE

the same functionality of PCUpd via sending configurations or through vendor-proprietary CLI. Fig. 2.b provides an example of PCE-based path computation modifying an existing LSP. In the figure, the adaptive NMS request a path computation to the PCE using the PCReq message. The PCE executes a RMSA algorithm using both the TED and LSPDB, but it cannot find a solution. The PCE may now try to optimize some of the existing LSP that were previously delegated to it, in order to find a solution for the requested path. In the example of Fig.2.b, the PCE finds a solution that requires to modify an existing LSP. To this end, the PCE sends a PCUpd message to the source GMPLS controller. Once the new state is reported back to the PCE, the PCE replies to the adaptive NMS with the computed path specified by means of Explicit Route Objects (EROs) carried in a PCRep message. Then, the adaptive NMS requests the provisioning of new LSPs to the source GMPLS controller, following the same procedure as for the passive stateful PCE explained in Sec.II-A.

### C. Active Stateful PCE with instantiation capabilities

Additionally, an active stateful PCE may expose the capability of setting up and releasing new LSPs ([20]). It is known as active stateful PCE with instantiation capabilities (Fig.3.a). In [21] it is proposed to extend PCEP with a new message named LSP Initiate Request (PCInitiate) to allow the PCE to request the creation of new LSPs directly to the GMPLS controllers. Deletion of PCE-initiated LSPs is performed also with the same message, with a deletion flag active. As mentioned in the previous section, NETCONF could also be used to configure the head-end GMPLS controllers to request the provisioning of new LSPs, or could even be used to configure each node directly, supplanting RSVP-TE for the LSP provisioning. In such scenario, the Adaptive NMS can directly request to the active stateful PCE the provisioning, rerouting/modification and release of the elastic optical connections, with the added benefit that it is possible to reuse the PCEP itself. Thus, the PCE becomes the interface to obtaining services from the underlying GMPLS-controlled network. Fig.3.b provides an example of a LSP created and later removed by the PCE. First, the adaptive NMS request the provisioning of a new LSP to the PCE using the PCInitiate message. The PCE, using the RMSA algorithms, computes an optimal path (it is worth noting that the PCE could modify an existing LSP in order to find a path solution, as mentioned in the previous section). Then, the PCE triggers the provisioning of the new LSP by sending a PCInitiate to the source GMPLS controller of the LSP. Once provisioned by the GMPLS control plane, the source GMPLS controller reports about the state of the LSP to the PCE using the PCRpt message with the Delegation flag set to 1. After that, the PCE notifies the Adaptive NMS.

## III. APPLICABILITY OF THE ACTIVE STATEFUL PCE

### A. Global Concurrent Reoptimization and Defragmentation

In the scope of a GMPLS control plane with a stateful PCE, the re-optimization process can be defined as the process by which the stateful PCE affects the state of currently active connections in the network, by changing some of their attributes. Such attributes are tied to the actual reserved resources and changing them may involve, for example, shifting the nominal central frequency of the frequency slot allocated to a connection and/or adjusting its allocated width (i.e., due to a change of modulation formats or bitrate) or allocating a new physical route (also referred to as explicit route). The main purpose of the process is to improve the utilization of the network resources, since the main observable result is a sub-optimal network throughput. This process can be triggered either manually by a network operator or based on automated maintenance process.

The term *defragmentation* refers to such reoptimization process, and it is justified when the allocation and subsequent deallocation of connections has resulted in a situation in which the currently allocated frequency slots at a given time are disperse in the optical spectrum, resulting in wasted spectrum (i.e., unusable frequency ranges). Such situation may prevent the PCE from routing new connections, thus increasing the blocking rate. Although efficient algorithms can be conceived

(a) Control network architecture

(b) Example of an LSP created and removed by the PCE

Fig. 3: GMPLS control plane with Active Stateful PCE with instantiation capabilities

to mitigate this problem, the effects due to the random nature of connection requests that come and go in a network with dynamic and on-line routing cannot be fully suppressed. Consequently, it has been assessed in several works (e.g. in [22] and [23]) that executing such defragmentation process is an effective means to improve resource utilization. However, rearranging connections in an optical network is known to cause instabilities and the process must be taken with care. The time scales required are significantly higher than in other (electrical) technologies, and determined by the optical hardware, which requires complex power compensation processes when more than one active connection is present in a given link. It is worth noting that a particular case, known as *hitless rerouting* applies when there is no change in the physical path of a connection, and the PCE wishes to change some of the media channel attributes, such as its nominal central frequency or slot width and when this process can be carried out without affecting client traffic [24].

From the perspective of the control plane and related

protocols, the currently defined PCEP RFCs and ongoing drafts have support for such optical spectrum defragmentation, both in terms of a stateless or stateful PCE. In short, at the expenses of more complex implementations and the need to synchronize and maintain a stateful LSPDB, the degree of flexibility and control that a stateful PCE can provide cannot be matched by a stateless PCE, including, for example, the ordered control and the autonomous triggering of the defragmentation process. When constrained to a stateless PCE, Global Concurrent Optimization (GCO), was introduced in [19] to calculate multiple paths concurrently so as to improve network resource efficiency. By taking into consideration the network topology as well as existing TE LSPs information, GCO can (re)optimize the entire network simultaneously. Alternatively, GCO can be applied to (re)optimize one or a subset of existing TE LSPs.

[19] defines how to extend the PCReq message to convey a list of requests to be jointly optimized. Each request includes the associated request parameters, endpoints and all relevant constraints such as BANDWIDTH, or network elements to avoid (included in the Exclude Route Object or XRO object) and, where appropriate, the current route that the paths are using (included in the Record Route Object or RRO). The requests are logically grouped by a synchronized vector object (SVEC). Note that a new Global Objective Function (GOF) can be defined to convey the desired network-wide GCO related criterion, such as Minimize the load of the Most Loaded Link.

The use of GCO with a stateful PCE implies that, in order to optimize network resource usage dynamically, an entity should send such a request group to PCE together with detailed path/bandwidth information of the LSPs that need to be concurrently optimized. This would require the adaptive NMS to determine when and which LSPs should be optimized and provide the relevant information. This may present some scalability issues if the number of connections is large. Given all of the existing LSP state information kept at a stateful PCE, it allows automation of this process. Moreover, since a stateful PCE can maintain the information regarding to all LSPs that are currently under signaling, it makes the optimization procedures be performed more intelligently and effectively.

### B. Inverse Multiplexing

Another alternative to minimize the spectrum fragmentation problem is to split the traffic demand into multiple flows which can be routed via multiple independent paths, as proposed in [25] by the authors, combining the flexible capacity coming from the new concept of sliceable BVTs (S-BVT) [26] and the inverse-multiplexing techniques for OTN to exploit such flexibility. On the one hand, a S-BVT support the generation of multiple optical flows with different modulation formats and bit-rates (e.g., a 400Gb/s transceiver can be sliced in three virtual transceivers at 100Gb/s, 100Gb/s and 200Gb/s). On the other hand, though the OTN standard [27] primarily deals with the multiplexing of lower rate into higher rate signals, inverse-multiplexing is typically considered as well. Thus it is reasonable to assume that the new frame structure under discussion

inside ITU-T for the evolution of the hierarchy beyond 100G would allow the segmentation of fat line interfaces in thinner pipes (e.g., in step of 100G). An attractive option, among others, is the so called ODUcn/ OTUCn achieved interleaving 'n' 100G basic frames in an SDH-like manner. Thus, when there is not a contiguous portion of spectrum sufficient for the entire bandwidth, the OTUCn signal (made up of 'n' basic frames) could easily be distributed across 'm' (independent) media channels which can be either co-routed inside the same fiber/cable or diversely routed. For example, a 400Gb/s flow could be inversely multiplexed into two OTUC2 (200G) or one OTUC3 (300G) plus one OTUC1 (100G), or even four OTUC1 (100G). Thus, this technique can increase the number of served connection requests. However, the main drawback is the differential delay, caused when a traffic demand is routed via multiple paths that are not transported into the same fiber/cable. The differential delay is defined as the difference between the longest and the shortest path delay. It causes the need of deploying high-speed buffers at the terminating OTN equipment to store the data from the shortest paths until the longest path reach the destination, in order to synchronize the reception of all paths. In [28], we proposed and experimentally evaluate novel differential delay aware RMSA algorithms for elastic multi-path provisioning in GMPLS Flexi-grid DWDM networks in order to quantify the tradeoff between the increase of the served connections and the need of buffer capacity.

In [25], we proposed a GMPLS/PCE control plane architecture for dynamic computation and provisioning of inverse-multiplexed elastic optical connections. It relies on a distributed GMPLS control plane with a stateless PCE. We introduced two new elements in the proposed architecture, namely, the inverse-multiplexing connection controller (IMCC) and the inverse-multiplexing provisioning manager (IMPM). The IMCC is responsible for the splitting of the requested OTUCn bandwidth into m sub-bandwidths and route them into one or multiple paths. The PCE is responsible for synchronously computing a set of elastic paths (i.e., spatial path, modulation parameters and spectrum allocation) for each one of the m sub-bandwidths considered by the IMCC. Finally, the IMPM is responsible for the synchronized provisioning of the multiple elastic paths, one for each sub-bandwidth, in a Flexi-grid DWDM network.

In the considered control approach, when the IMCC receives a bandwidth connection request from the NMS, it requests to the PCE a single path to serve the requested bandwidth (Step 1 in Fig.4). Since the PCE cannot find a path (2), the IMCC splits the bandwidth into two sub-bandwidths, and requests to the PCE the computation of the two paths (3). The PCE can find a solution, and replies to the IMCC (4) with the full path information (spatial path, modulation parameters, etc). Then, the IMPM requests the provisioning of the two elastic paths to the head-end node of the paths (i.e., ROADM-1 - (5,7)). The elastic paths are provisioning by the GMPLS control plane. Once provisioned, the head-end node notifies to the IMPM (6,8). The use of an active stateful PCE instead of a passive stateful PCE would allow to remove the IMCC and the IMPM elements, since their functionalities would be carried out by the Active Stateful PCE. Thus, the Adaptive NMS would interface

Fig. 4: Example of provisioning of an inverse-multiplexed elastic optical connection

physical infrastructure can be sliced in such a way that specific virtual networks can be offered upon application demands.

We propose an active stateful PCE as a key enabler for Optical Transport SDN. The particular orchestration of active stateful PCEs from an SDN Controller becomes an opportunity which is motivated by the following reasons:

- A flexible, mature and feature-complete protocol (PCE communication protocol, PCEP [8]) acting as a SDN southbound interface. The addition of LSP instantiation capabilities to PCEP allows the end-to-end LSP provisioning within the domain controlled by the active stateful PCE.
- The leverage between network programmability and key GMPLS benefits (e.g., such as short restoration times or distributed LSP provisioning).
- The PCE has also been extended and adapted in order to become the entity responsible for allocating, dynamically and upon request, network resources for virtual optical networks (VON), as detailed in [30].

The considered SDN Controller architecture is shown in Figure 5. It can be observed that the SDN Controller acts as a network orchestrator, being responsible for end-to-end transport service provisioning across several domains. In this figure, we propose an OpenFlow-enabled Ethernet domain and a GMPLS/PCE Flexi-Grid domain. Each domain can be controlled by the SDN Controller with different southbound interface plugins (e.g., OpenFlow and PCEP southbound plugins can be expected). The SDN Controller abstract each domain information to provide an integrated network view, which is offered to SDN applications by means of a Northbound interface.

#### IV. EXPERIMENTAL VALIDATION OF AN ACTIVE STATEFUL PCE

An active stateful PCE has been implemented and evaluated in the ADRENALINE control plane testbed, configured as a single domain flexi-grid optical network. The deployment model involves a single PCE for the domain, where the different GMPLS controllers maintain a PCEP session with the PCE. All the systems (PCE and GMPLS controllers) run on Intel/PC servers running the Linux Operating System. For performance reasons, the underlying TCP sockets that support the PCEP connections are configured for fast acknowledgements (using the QUICK\_ACK socket option) and disabling the Nagle algorithm (TCP\_NODELAY option) to reduce latency. The PCEP handshake is thus performed once, between the PCE and the corresponding control plane nodes, when the system is started. In this particular scenario, the PCE is also capable of instantiating LSPs, requesting the establishment of connections to the underlying control plane.

The interface between the path computation client (PCC) component located at each node and the corresponding connection controller (CC) is proprietary with XML-encoded messages, allowing flexibility when requesting the establishment, re-route and release of LSPs. Such XML messages are bound to the corresponding PCEP messages sent by the PCE to the PCC.

Fig. 5: SDN Controller with Active Stateful PCE

directly with the Active Stateful PCE.

#### C. Integration with Software Defined Networking

The Software Defined Networking (SDN) architecture is based on the separation of the data and control planes [29]. In this architecture, a logically centralized controller can control the behavior of the different network elements (e.g., the forwarding tables of the different elements). Application Programming Interfaces (API) are exposed to end applications by the SDN Controller, allowing a better match between application requirements and network behavior. This fulfills the idea of network programmability, where network devices can have their behavior changed or reconfigured dynamically, by software. Finally, SDN is also related to the concept of network and infrastructure virtualization. The underlying

Fig. 6: PCEP message flow between the stateful PCE and the PCCs, mapped to XML triggering signaling actions.

Fig. 7: Network Topology representing a 14-node Japan national network

For robustness, the PCE pro-actively updates its TED modifying the status of the nominal central frequencies upon reception of PCRpt messages, avoiding assigning the same slot to almost concurrent requests. Nonetheless the actual state is also updated upon parsing the OSPF-TE Link State advertisements (LSAs), which, in turn, have been extended to include TE attributes that refer to the status of the TE links, such as, notably the status of the central frequencies. The PCE ensures concurrent access to its TED (allowing read access for path computation algorithms and write access to processes that participate and listen to the instance of the OSPF-TE routing protocol that is only used as the TED synchronization mechanism). In other words, TED access from different control plane components is synchronized via mutual exclusion.

The system has been evaluated in a 14-node testbed, which represents a national Japan network, as shown in Figure 7.

Figure 8 shows the list of the active PCCs that have a PCEP session with the PCE and the identifier of the node (GMPLS controller) that they represent. Such list is populated when the system is started, during the initial handshake. This information is needed by the PCEs in order to map, for a given

Fig. 8: List of active PCC connections to the stateful PCE.

request, an endpoint as it appears in the TED to a given PCEP connection to which send the corresponding PCEP message.

In the specific scenario, DWDM links have 128 nominal central frequencies (slices). The stateful PCE is able to perform RMSA using a distance-adaptive, iterative, two-phase approach, combining off-line path characterization with dynamic spatial path computation assuming CO-OFDM transmission stored in pre-cached tables, depending on requested bitrate, and the computed path hop count and distance [12], requiring for the considered client data rates 1, 3, 6, 7 or 14 slices of 6.25 GHz. Figure 9 shows the topology seen by the PCE once it has synchronized the information from the OSPF-TE routing protocol. Note that, since there is no standard support in the OSPF-TE with GMPLS extensions protocol to disseminate arbitrary link attributes, physical distances (in Km) of the links are provisioned in an extended database that the PCE uses for its path computation.

Each test corresponds to a set of requests, following a Poisson arrival process. At each request, the PCE computes a path, sends the corresponding PCInitiate message to the ingress node and asynchronously awaits for the report (PCRpt) message, which is sent back by the ingress node once the path has been established via the RSVP-TE signaling protocol. The asynchronous nature of PCEP message processing allows the PCE to process other PCEP messages while the ingress node processes the PCInitiate message and sets up the connection. Figure 10 shows the Wireshark capture of the process, including the subsequent release of the connection.

At the PCE, the LSPDB is implemented as a abstract data type, implemented in terms of a container maintaining multiple indices. Upon request from the northbound interface, a temporary entry is allocated in the LSPDB, indexed by the unique symbolic-name, along with its instantiation timestamp. The entry is updated upon reception of the PCRpt message, completing its PCC assigned local identifier, record route, and effective frequency slot. A created timestamp is used to compute the setup delay as seen by the PCE. The PCE stores, as a bare minimum, the physical route (ERO object) along with the allocated frequency slot for each LSP (cfr. Figure 11). The frequency slot coding shown in Figure 11 is the sequence of contiguous NCF allocated.



Fig. 9: Network Topology seen by the PCE drawn as a directed graph. The PCE has a web based interface that allows to export internal tables and for monitoring purposes.

Fig. 10: Wireshark capture of the establishment, triggered by the PCE of an elastic connection between nodes 10.0.50.1 and 10.0.50.2. Upon the reception of the PCE initiate message, the ingress node sends a Path message. When the Resv message is received, the connection has been established and the report is sent back to the PCE.

We evaluate the blocking probability (BP) in function of the offered traffic load considering a dynamic stochastic model of requests: the arrival process is Poisson with avg. inter-arrival set to 1s; the holding time follows a negative exponential distribution. Requests are randomly selected between distinct node pairs, with a random bandwidth profile mapped to CO-OFDM transmission. In the first test (T1), client data rates are uniformly random selected [1-100] Gbps, mapped to 10, 40 or 100 Gbps. In the second test (T2) client data rates are fixed to 100 Gbps.

Figure 12 shows the obtained blocking probability in both cases, showing a higher value for the highest bandwidth profile (i.e., 100Gbps). Regarding average route hop count shown in Figure 13, both tests are stable around 2.4 and 2.5 hops,

with a local average hop count maximum at 60 and 80 Er. respectively. At a higher offered traffic successful connections tend to use shorter paths. Avg. setup delay is 8ms, with min and max ranging, typically, from 3 ms for a single-hop connection to 20 ms max values (cfr. Figure 14 for T2 at 20 Erlangs with 20k requests).

The presented experimental validation has, on the one hand, allowed us to assess the feasibility of the approach and to evaluate key performance indicators, namely, the blocking probability, set up delay and hop count in a selected (yet reduced) number of scenarios. On the other hand, however, we can draw some initial conclusions, and the purpose of the remainder of this section is to discuss the obtained values and how the architecture relates to existing and prospective

Fig. 11: Example of LSPDB seen by the PCE when several connections are active.

Fig. 13: Average hop count for the two carried tests.

Fig. 12: Blocking probability for the two carried tests.

Fig. 14: Setup delay cumulative distribution function (CDF) and histogram for the test T2, 20 Erlangs

technologies.

Let us start by stating that the choice of a stateful PCE is a technological choice, driven by the maturity of standards, and by the potential deployments and impact on industry. Nonetheless, for the purposes of the analysis of the results, the actual choice of interface and protocol is not a limiting factor, provided that other alternatives are similar in terms of requirements and features (control plane bandwidth, latency, serialization and de-serialization and processing). The important aspect in the approach is related to: a) the centralized nature of the PCE (in practice, and for the deployment model selected in this work); b) the size of the network and its scaling properties, and c) the availability of information related to the status of resources and existing connections, which is not constrained by existing TE information available as disseminated by distributed TED synchronization mechanisms and protocols based on existing standards. We say "in practice", since nothing precludes the use of several PCEs, although scenarios with multiple stateful PCEs are still a topic for further study and show inherent issues such as inter-PCE synchronization. In other words, conceptually similar architectures (e.g. based on a centralized NMS) exploiting proprietary interfaces and directly interacting with the network elements would be expected to have similar behavior, whereas fully distributed approaches (e.g. source routing) would not.

The dynamic properties of traffic is a first criterion to determine the feasibility of the approach. We have selected an incoming arrival rate with an average value of 1 second, which, for a network of the selected size, is already challenging for the TED synchronization mechanism of using e.g. OSPF-TE. Although this value was selected for practical purposes, and although smaller values would be possible and would highlight the benefits of a centralized TED management not relying of distributed synchronization, we believe that operating these networks at these timescales would not realistically reflect the current practice and expected operational work-flows.

The stateful PCE is, by definition, able to use the LSPDB to deploy algorithms that reduce the blocking probability of the network and maximize network throughput, as compared to source routing approaches which, in the technological context defined by GMPLS, have only detailed state information of paths crossing the ingress node. However, this requires that specific algorithms be developed in order to fully exploit the availability of the information. In this sense, the algorithms deployed here are relatively simple and could be deployed in a fully distributed, source routing based path computation approach and we expect the results would be similar. In other words, only algorithms actually using the information stored in the LSPDB would clearly show this particular advantage,

compared to relatively straightforward approaches based on shortest path with continuity constraint which, inherently, only require the knowledge of the TED. The results shown here mainly illustrate that off-line, pre-computed tables not available via TED synchronization can be used, with a single point of configuration while insisting on the potential of the approach.

The set up delay is, obviously, generically affected whether path computation takes place in a centralized PCE. While this is mainly true in scenarios where the path computation function is delegated to a (passive) PCE, let us note that, in this approach, path computation happens before the provisioning request is sent to the ingress node. If path provisioning time is determined starting from the initial operator interaction, alternative approaches (e.g. based on source routing) would have a similar behavior, assuming that a signaling protocol is still used. The obtained values, ranging from 3 to 20 ms approximately have two main components: the network latency from the PCE to the ingress node, and the inherent delay associated with the subsequent signalling. It is worth noting that approaches based on directing configuring the forwarding behavior of nodes (i.e., directly configuring the cross-connects by using a protocol such as OpenFlow with the proper extensions) are indeed able to reduce the setup delay, notably if the requests can be parallelized, to the point that the measured delay would be mainly related to the slowest node. However, it is also of uttermost importance to state that the obtained values do not take into account the hardware setup delay, which, in real scenarios, it can be orders of magnitude higher, taking into account complex procedures related to e.g. power equalization. In this case, the provided value allows to roughly estimate the component associated to the control plane but it is not a limiting aspect, and should be used only as a rough guideline.

The obtained hop count shows an effect that can be mapped to the path computation algorithm, and is characteristic of circuit switched optical networks with continuity constraint: as we have previously seen, the average hop count experiences a slightly concave shape, which shows that, as traffic load increases, the algorithm selects longer and longer paths, since existing established connections prevent incoming request from selecting the shorter paths while meeting the spectrum continuity. As traffic load increases, even those longer paths become unfeasible, and the average hop count, which only takes into account successfully established paths, decreases.

Finally, another important point to be highlighted is the fact that the network operator needs to carefully design, dimension and optimize the control plane. Although this is true also in fully distributed approaches, it is a key limiting factor with the PCE, which risks becoming a bottleneck, not only in provisioning requests but also in recovery.

## V. CONCLUSIONS

We have provided an overview of the stateful PCE architectures, considering both passive and active approaches. We have also presented some examples that justify the need and illustrate the applicability of the stateful PCE in GMPLS-

controlled Flexi-grid DWDM networks, such as global concurrent reoptimization, defragmentation or inverse multiplexing. Additionally, the stateful PCE is also a key element of the SDN control architecture in order to enable the seamless interworking between OpenFlow and GMPLS domains. We have also experimentally demonstrated the feasibility of a stateful PCE by implementing and evaluating the performance of an active stateful PCE with instantiation capabilities that relies on a GMPLS control plane for the actual provisioning of elastic connections in a flexi-grid DWDM network. It is based on experimental extensions to PCEP and enables more advanced and concurrent path computations. Quantitative performance indicators have been obtained, such as the blocking probability and the setup delay. The combination of stateful and active capabilities renders the PCE a very promising functional element in SDN and GMPLS based networks.

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