OpenFlow and PCE Architectures in Wavelength Switched Optical Networks

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Abstract—The GMPLS protocol suite, originally designed to fully operate in a distributed fashion, is currently the reference control plane for WSONs. Recently, the requirement of effective traffic engineering solutions has led to the standardization of the PCE architecture, thus joining the distributed GMPLS control plane with a centralized network element devoted to path computation. However, the common need of network carriers to keep the network under a centralized control in strict relationship with the NMS has prevented the wide deployment of GMPLS in currently working optical networks.

OpenFlow proposal has been recently designed for controlling Ethernet-based access/metro networks. However, thanks to its potential ability of configuring the flow table of generic switching nodes, the OpenFlow extension for enabling the control of WSONs is currently a hot research topic.

In this work, OpenFlow is seen as a promising alternative for controlling WSONs. In particular, two OpenFlow-based solutions are considered and compared against GMPLS. The first solution comprises direct configuration of the optical nodes and extends OpenFlow protocol to improve the lightpath reservation. The second solution integrates OpenFlow with GMPLS protocols exploiting communication between the OpenFlow controller and the GMPLS controller of optical nodes. Simulations results show the ability of the OpenFlow-based solutions to enable traffic engineering while providing fast lightpath setup and assuring control plane scalability.

Index Terms—Optical networks, control plane, OpenFlow, GMPLS, PCE, WSON.

I. INTRODUCTION

The Generalized Multi-Protocol Label Switching (GMPLS) control plane enables Traffic Engineering (TE) solutions in Wavelength Switched Optical Networks (WSONs) with the final target of guaranteeing effective resource utilization [1]. In GMPLS-controlled WSONs, a routing protocol (i.e., the Open Shortest Path First with TE extensions, OSPF-TE) is used to advertise connectivity and resource availability information; while a signaling protocol (i.e., the Resource Reservation Protocol with TE extensions, RSVP-TE) is employed for performing connection setup in the data plane. In particular, the WSON data plane is composed of transparent optical nodes (e.g., optical cross-connects, OXCs) interconnected by wavelength-division multiplexed (WDM) links. Connections established in the optical domain are named lightpath.

Both the aforementioned control plane protocols, i.e., the OSPF-TE and the RSVP-TE, have been designed to operate in a distributed way, i.e., each network node has the potential to (i) retrieve routing information, (ii) perform path computation, and (iii) perform resource reservation. The fully distributed approach of the GMPLS architecture, although extremely reliable, presents some drawbacks. A first drawback refers to the limited efficiency and manageability of distributed path computations [2]. To address this issue, the Path Computation Element (PCE) architecture has been introduced and typically applied to perform path computation, on behalf of network nodes, in a centralized way [3]–[5]. Moreover, as reported in [6], network carriers tend to prefer a centralized control because it is simpler and more manageable. In particular, it may be easier to migrate and update from the current network management system (NMS) architecture. Therefore, distributed routing and signaling protocols have not been widely deployed in WSONs and proprietary NMS-based centralized solutions are still in place for the control of the optical networks.

For these reasons, although originally designed for Ethernet-based access/metro networks, the OpenFlow proposal [7] is regarded as a promising candidate for a novel centralized control plane of heterogeneous networks, including WSONs [8]. In OpenFlow-based networks, a centralized controller exploits the OpenFlow protocol to directly communicate with network elements (e.g., Ethernet switches) using TCP. In particular, the controller is able to configure the forwarding table of the switches by applying one or more flow tables [9]. In this way, distributed routing and signalling protocols are not required.

The first applications of OpenFlow in the context of WSONs are reported in [6], [8], [10]–[12]. The works in [8], [11] propose OpenFlow as an unified control plane for packet and circuit switched networks providing also a practical demonstration. In particular, while the demonstration in [8] considers SONET/SDH as circuit switched technology, the work in [11] considers a simple optical circuit switched network composed of a single Wavelength Selective Switches (WSS) node. Authors of [6], [12] focus more specifically on WSONs. In particular, [6] provides the demonstration of an OpenFlow-based control plane supporting lightpath setup and release, and routing and wavelength assignment, in WSON composed of four OXCs. Finally, the work in [12] presents an integration of OpenFlow and GMPLS control planes. In this case, the OpenFlow controller does not directly configure the optical nodes but communicates with the GMPLS controller of the lightpath source node that starts the lightpath setup using RSVP-TE signaling. Therefore, several solutions are currently under investigation for allowing OpenFlow control of WSONs.

This paper performs a detailed comparison among the afore-
Upon reception of the PCRep routing blocking and the lightpath request is refused (i.e., PCRep replies with a NO-PATH object), the source node by using a PCEP computation request to the PCE. The PCE computes both a path and the suggested wavelength and communicates them to the source node by using a PCEP message. Conversely, if the PCE fails in computing a path with available resources, it replies with a PCRep message including a NO-PATH object, and the lightpath request is refused (i.e., routing blocking). Upon reception of the PCRep message, the source node triggers the RSVP-TE signaling along the computed path, to actually reserve resources [17].

The RSVP-TE signaling is based on the utilization of Path and Resv messages, sent in the forward and backward directions, respectively. In the considered scenario, the Path message includes the Explicit Route, the Suggested Label, and the Label Set standard objects [17]. The Explicit Route and the Suggested Label objects respectively contain the path and the wavelength selected by the PCE. The Label Set object is created at the source node and updated along the path so that, when the destination node is reached, it contains the wavelengths that are available on the end-to-end path. Upon reception of the Path message the destination node performs the wavelength assignment. In particular, the wavelength indicated in the Suggested Label object is selected if it is included in the Label Set. Otherwise, another wavelength contained in the Label Set is selected, according to a specific wavelength assignment strategy (e.g., first fit). After wavelength assignment, the destination node sends back a Resv message to effectively reserve the selected wavelength on each link of the path. Once the Resv message reaches the source, the lightpath is established and data transmission can take place.

Similarly, lightpath release is performed in a distributed way through RSVP-TE signaling.

Using the described setup procedure, the RSVP-TE instance may be blocked during both forward and backward signaling phases [2], [18], [19]. Blocking during the forward phase (i.e., forward blocking) is due to wavelength unavailability on the path. It happens when the updated Label Set results to be empty in an intermediate node or at destination. Blocking during the backward signaling (i.e., backward blocking) is due to wavelength contentions. Contentions are caused by the concurrent attempt of two or more RSVP-TE instances to reserve the same wavelength on the same link. Indeed, under dynamic traffic conditions, the list of available wavelengths contained in the Label Set object of the Path message may be already outdated when the destination node is reached.

### II. GMPLS Lightpath Setup with PCE

The PCE is a centralized network element used, for instance in GMPLS-controlled WSONs, to perform path computation [3], [13], [14]. The PCE communication Protocol (PCEP) is used for exchanging messages between the GMPLS controller of each network node and the PCE. The PCE maintains a Traffic Engineering Database (TED) with detailed wavelength availability information, i.e., the status (reserved or available) of each wavelength channel on every link [4]. Such TE information is retrieved by listening to OSPF-TE advertisements. In particular, new updates (i.e., new Link State Advertisements - LSAs) are generated by network nodes when a wavelength status change occurs on a link. However, once an LSA has been generated for a given link, any change detected on such link before a timeout (i.e., the MinLSInterval timer) is elapsed is not advertised [15], [16]. Besides path computation, the PCE is also enabled to perform wavelength assignment by suggesting to the source node the wavelength to be used for the computed path.

More in detail, upon lightpath request, the source node exploits a PCEP PCReq message for submitting a path computation request to the PCE. The PCE computes both a path and the suggested wavelength and communicates them to the source node by using a PCEP PCRep message. Conversely, if the PCE fails in computing a path with available resources, it replies with a PCRep message including a NO-PATH object, and the lightpath request is refused (i.e., routing blocking). Upon reception of the PCRep message, the source node triggers the RSVP-TE signaling along the computed path, to actually reserve resources [17].

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### III. OpenFlow Lightpath Setup

This study considers two control plane solutions based on the OpenFlow architecture. Both solutions use a centralized OpenFlow controller that receives the lightpath requests and is responsible for path computation, wavelength assignment, and lightpath setup. The controller maintains a centralized TED with detailed wavelength availability information. Every time the controller successfully performs a path computation, it updates its TED assuming the successful lightpath establishment along the computed path on the selected wavelength. Since all TE parameters are stored and updated within the controller, in both solutions, the OSPF-TE protocol is not employed (Tab. I).

In the first solution, called OF (see Sec. III-A), the OpenFlow controller directly configures the optical nodes [6]. In the second solution, called OF-RSVP (see Sec. III-B), the OpenFlow controller communicates with the GMPLS controller of the source node that uses RSVP-TE signaling to

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**Table I**

<table>
<thead>
<tr>
<th>Scheme</th>
<th>RSVP-TE</th>
<th>OSPF-TE</th>
<th>PCEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMPLS-PCE</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>OF-timer</td>
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<td>no</td>
<td>no</td>
</tr>
<tr>
<td>OF-ack</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>OF-RSVP</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>
actually reserve resources [12].

A. OF solution

In the OF solution, the OpenFlow controller exploits direct communication between the OpenFlow controller and the network nodes to perform lightpath setup. In particular, upon lightpath request, the controller performs path computation and wavelength assignment, then it triggers several instances of the OpenFlow protocol to reserve the required resources and set the proper cross connection in all the nodes (i.e., OXC) traversed by the computed path. In particular, messages of type \texttt{OFPFC\_ADD} are used to configure a new flow in the flow table of the nodes [9]. Thus, in this scheme, the RSVP-TE protocol is not used. Two schemes are considered using the OF solution: the OF-timer scheme and the OF-ack scheme.

1) OF-timer scheme: this scheme considers the standard OpenFlow protocol (designed for Ethernet switches) that does not feature a reply message from network nodes to the controller after the addition of a new flow [9]. However, in WSONs data transmission cannot be started before having a fully configured lightpath. Therefore, in the OF-timer scheme the OpenFlow controller assumes a fixed delay before considering the lightpath as established. In particular, when the controller sends the \texttt{OFPFC\_ADD} messages a downtimer of $T_{\text{oxc}}$, $\text{ms}$ is started. The lightpath is considered established when the timer is over. The time $T_{\text{oxc}}$ should account for the transmission, propagation, and processing delay of the \texttt{OFPFC\_ADD} messages and for the actual OXC switching time (i.e., few tens of milliseconds).

2) OF-ack scheme: this scheme proposes an extension to the OpenFlow protocol. In particular, a confirmation message (i.e., \texttt{OFPFC\_ACK} message) is introduced to be sent from nodes to the controller upon successful resource reservation and OXC switching. In this way the controller consider the lightpath as established when the \texttt{OFPFC\_ACK} message has been received from all the nodes traversed by the lightpath. This scheme guarantees additional reliability and may reduce the setup time, however it requires an higher amount of control plane messages that need to be elaborated by the controller.

For both aforementioned schemes the lightpath release is performed by the OpenFlow controller exploiting using \texttt{OFPFC\_DELETE} messages. Confirmation messages are not generated upon lightpath release.

B. OF-RSVP solution

In the OF-RSVP solution, there is not a direct communication between the OpenFlow controller and the network nodes. Conversely, the controller communicates the computed path and the selected wavelength to the GMPLS controller of the source node which then initiates the distributed lightpath setup using RSVP-TE signaling.

The lightpath is established when the source node receives the RSVP-TE Resv message. Therefore, in this solution, additional delay or explicit confirmation messages to the controller are not required when the signaling is successful. Indeed, the source node is enabled to start data transmission when the signaling RSVP-TE signaling terminates.

Similarly, lightpath release is triggered by the OpenFlow controller through a communication with the GMPLS controller of the source node. The source node uses RSVP-TE signaling to actually release the resources.

IV. SIMULATION STUDY

The aforementioned schemes have been evaluated by means of simulations. Simulations are performed with a custom-built C++ event-driven simulator. Two WSON topologies have been considered. (i) The network illustrated in Fig. 1 has 27 nodes and 55 bidirectional WDM links. (ii) The network illustrated in Fig. 2 has 75 nodes and 290 and bidirectional WDM links. In both topologies each link supports 32 wavelengths per direction. Nodes do not support wavelength conversion. Lightpath requests are generated according to a Poisson process and uniformly distributed among all node pairs. Both, inter-arrival and holding times are exponentially distributed. The average holding time is fixed to 180 seconds, the average inter-arrival time is varied from 0.225 $s$ to 3.6 $s$. The LSA update timeout
is fixed considering the minimum value allowed by the OSPF-TE standard [15], i.e., $\text{MinLSAInterval} = 5s$. Both the PCE and the OpenFlow controller perform first-fit wavelength assignment.

Tab. I resumes the considered schemes and for each scheme lists the used GMPLS protocols. For the OF-timer scheme the value of the timer $T_{\text{oxc}}$ has been estimated by simulations considering transmission, propagation, and processing times of packets and $10\, ms$ of fixed time required to perform the switching of an OXC [20]. Performed simulations provided the following values of $T_{\text{oxc}}$: for the topology in Fig. 1 $T_{\text{oxc}} = 55\, ms$; for the topology in Fig. 2 $T_{\text{oxc}} = 70\, ms$.

In all the schemes the same routing algorithm is used by the PCE or by the OpenFlow controller. For a lightpath request between the node pair $(s, d)$, the path is selected among the set $P_{s,d}$ of pre-computed paths. In particular, the path guarantying the highest number of wavelength-continuous channels is selected, possible ties are broken randomly. The set $P_{s,d}$ includes all the paths whose hop length is within one hop from the shortest path.

Four types of figures are obtained from simulations: (i) Lightpath blocking probability vs. network load (i.e., Fig. 3, Fig. 7); (ii) Lightpath setup time expressed in $ms$ vs. network load (i.e., Fig. 4, Fig. 8); (iii) Control plane traffic expressed in processed packet per second vs. network load (i.e., Fig. 5, Fig. 9); (iv) Control traffic processed by the PCE/OpenFlow controller expressed in processed packet per second vs. network load (i.e., Fig. 6, Fig. 10).

Simulations run until the confidence interval of $5\%$ at $95\%$ confidence level or the maximum number of independent trials (i.e., $2 \times 10^3$) is reached. Each trial includes the generation of $2500$ lightpath requests. All simulation points are plotted in the figures with the reached confidence interval at $95\%$ confidence level.

Fig. 3 depicts the lightpath blocking probability obtained using test network A, (Fig. 1). The figure clearly shows that, especially for low network loads, all the OF schemes provide significant blocking improvement with respect to the GMPLS-PCE scheme. Indeed, in the GMPLS-PCE scheme the PCE performs routing based on a TED updated using OSPF-TE. Since the considered inter-arrival rate is significantly faster than the generation rate of OSPF-TE LSA (i.e., $\text{MinLSAInterval} = 5\, s$), the information stored in the TED can be out-of-date thus increasing the blocking probability during the RSVP-TE signaling phase. In particular, a backward
blocking contribution in the order of $10^3$ is experienced due to resource contention. This contribution is almost independent on the traffic load [2]. Conversely, all the OF schemes provide similar blocking, indeed those schemes use a TED which is locally managed by the controller and updated immediately after each path computation.

Fig. 4 depicts the lightpath setup time obtained using test network A, (Fig. 1). The figure shows that the two schemes using the RSVP-TE signaling (i.e., GMPLS-PCE and OF-RSVP) feature higher setup time in the range 80 – 90 ms. Moreover, since RSVP-TE signaling flows throughout the path, the setup time provided by those schemes is dependent on the path length. Indeed, it decreases with the network load because at higher loads the average length of established lightpaths is shorter. Conversely, the lightpath setup time provided by the OF-timer and the OF-ack schemes is reduced and does not depend on the path length, since OpenFlow messages are sent in parallel to each node belonging to the path. Finally, the average setup time provided by the OF-ack scheme is significantly shorter (i.e., about 32 ms) with respect to the one provided by the OF-timer scheme (i.e., about 55 ms). Indeed, the utilization of a confirmation message allows an exact estimation of the lightpath setup time at the OpenFlow controller.

Fig. 5 depicts the control plane traffic obtained using test network A, (Fig. 1). The figure clearly shows that, all the OF schemes significantly reduce the control plane traffic. In fact, most of the control plane traffic generated with the GMPLS-PCE scheme is OSPF-TE traffic. Among the OF schemes, the OF-timer scheme does not use RSVP-TE signaling and avoids confirmation messages and is therefore the scheme generating the least amount of traffic. However, all the OF schemes appear quite scalable.

Fig. 6 depicts the control traffic processed by the PCE/OpenFlow controller obtained using test network A, (Fig. 1). The figure shows that in the GMPLS-PCE the PCE processes the highest amount of traffic, most of which is OSPF-TE. However, also in the OF-ack scheme, where OSPF-TE is not used, the OpenFlow controller processes a high amount of traffic. Indeed, for each processed lightpath requests the OpenFlow controller sends an `OFPFC_ADD` message to each node and waits for the related `OFPFC_ACK` message. In the OF-timer scheme, confirmation messages are avoided, thus, controller processes almost half of the traffic with respect
to the OF-ack scheme. Finally, in the OF-RSVP scheme the controller processes the least amount of traffic. Since, with OF-RSVP, OpenFlow messages are sent only to the lightpath source node.

Fig. 7, Fig. 8, Fig. 9, and Fig. 10 validate the simulation results on a more complex network topology (i.e., test network B, Fig. 2).

Summarizing the simulation results, the OF based schemes guarantee low lightpath blocking probability, reduce the lightpath setup time, and strongly reduce the overall traffic on the control plane. In particular, the OF-ack scheme, using the proposed OpenFlow OFPFC_ACK message is the scheme that guarantees the best lightpath setup time. Also the traffic addressed to the central controller is reduced with respect to the GMPLS-PCE scheme, however this traffic is still relevant and therefore the software and the hardware of the central controller requires an accurate design to address scalability issues that typically arise in centralized approaches.

V. CONCLUSION

This paper performed a detailed comparison among possible solutions for controlling WSONs networks. The current standard solution based on the utilization of a distributed GMPLS control plane is compared against two solutions based on OpenFlow. In particular, the OpenFlow controller is used to directly configure the optical nodes or to communicate with GMPLS controllers. Also an extension to the OpenFlow protocol is proposed to be used in the former case.

The three solutions have been evaluated by means of simulations considering realistic topologies of core optical networks. Simulation results show that, in the considered scenarios, using OpenFlow can significantly improve the performance of the distributed GMPLS control plane and that the proposed extension to the OpenFlow protocol is able to significantly reduce the lightpath setup time.

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