Proactive H-PCE Architecture With BGP-LS Update for Multidomain Elastic Optical Networks [Invited]

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***Abstract*—The hierarchical path computation element (H-PCE) architecture has been proposed to perform effective end-to-end path computation in multidomain elastic optical networks (EONs). In the H-PCE architecture a single parent PCE is responsible for inter-domain path computations, while a dedicated child PCE performs intra-domain path computations within each domain. In this scenario, effective inter-domain path computation is achieved only if detailed and updated intra-domain resource availability information is locally stored or retrievable by the parent PCE. Border Gateway Protocol has been recently extended to transport link state information (BGP-LS) that can be used to update the resource availability information at the parent PCE, thus improving scalability and effectiveness of the H-PCE architecture. Specifically, BGP-LS speakers located at each child PCE have been demonstrated to update the parent PCE with per-link spectrum slices availability information triggered by the reception of local Interior Gateway Protocol (IGP) advertisements. This paper proposes a proactive scheme to update the parent PCE, in which the generation of BGP-LS updating messages is not dependant on the IGP advertisements but automatically triggered by path computation requests at the child PCEs. The proposed scheme is applied during provisioning and restoration phases in a multidomain EON scenario and compared against two reference schemes. Simulation results show a significant reduction in terms of blocking probability and amount of exchanged control plane messages.**

***Index Terms*—Elastic optical network (EON); GMPLS; Hierarchical PCE; Multi-domain; Provisioning; Restoration.**

I. Introduction

Optical transport networks are gradually evolving to enable a more efficient utilization of the spectrum provided by optical fibers. To this extent, elastic optical networks (EONs) exploit the recently standardized flexible grid where the fiber spectrum is organized in fine granularity *spectrum slices* of 12.5 GHz together with sliceable bandwidth-variable transponders (SBVTs) and spectrum selective switches (SSSs) [1–3]. Using these technologies, EONs allow allocation of the spectrum for establishing each optical connection (i.e., *lightpath*) using the most appropriate and effective transmission parameters (bitrate, modulation format, etc.), finally leading to higher spectral efficiency and increasing the amount of supportable traffic [4,5].

Extensions to the generalized multiprotocol label switching (GMPLS)/PCE control plane, originally standardized for wavelength-switched optical networks (WSONs), have been proposed so far to support EON operation [6,7]. In particular, the path computation element (PCE) functionalities have been significantly extended to support path computation and instantiation with proper spectrum slot suggestion and active/stateful operations that are typically required in EONs to enable dynamic re-optimization of established lightpaths [8]. This latter functionality is specifically required to alleviate the issue of spectrum fragmentation that typically emerges in EONs supporting dynamic establishment/release of lightpaths with arbitrary spectrum utilization [9–11].

In the context of multidomain operation, the hierarchical PCE (H-PCE) architecture has been proposed to perform effective end-to-end path computation in GMPLS-based WSONs [12–14] and recently extended to support EONs [9,15]. In the H-PCE architecture, a single parent PCE (pPCE) is responsible for interdomain path computations, while in each domain a child PCE (cPCE) locally performs intradomain path computations and forwards interdomain lightpath requests to the pPCE. In this scenario, effective interdomain path computation is achieved only if detailed and updated intradomain traffic engineering (TE) information (e.g., spectrum slices status) is dynamically retrievable by the pPCE [16]. To this extent, a procedure based on PCE Protocol (PCEP) communication between pPCE and cPCEs has been defined in [12], enabling the pPCE to request path computation of specific intradomain segments to the cPCE of each traversed domain. However, this approach introduces control plane scalability concerns due to the high number of PCEP messages required to perform each path computation.

The recent introduction of link state extensions to Border Gateway Protocol (BGP-LS) opened new possibilities to update the traffic engineering database (TED) stored at the pPCE that can improve scalability and effectiveness of the H-PCE architecture [17,18]. Specifically, BGP-LS speakers located at the cPCEs have been

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successfully demonstrated to update the pPCE in a point-to-point fashion with per-link spectrum slices status information [15,18]. In this solution, BGP-LS update messages are triggered at the cPCE by the reception of local Interior Gateway Protocol (IGP) advertisements, e.g., link state advertisements (LSAs) flooded by the Open Shortest Path First with Traffic Engineering (OSPF-TE) routing protocol. Therefore, the spectrum slice availability information stored at the pPCE may be significantly outdated because the generation of BGP-LS updates is dependent on the OSPF-TE timers. This can imply a considerable network performance degradation in a scenario where path computation is performed at different locations (i.e., pPCE and cPCEs) because, in the case of inconsistent information, the same resources can be tentatively assigned to several lightpaths. This issue is especially relevant during dynamic restoration when a number of disrupted lightpaths has to be recovered as soon as possible and typically contend the available resources along few alternate paths. Moreover, it is worth noting that the performance degradation deriving from information inconsistency may be more relevant in EONs with respect to WSONs because the time required to set up a lightpath is typically longer [19,20].

To improve network performance in terms of achievable blocking probability and control plane scalability, this paper proposes a proactive scheme to update the spectrum slice information stored at the pPCE, in which BGP-LS updating messages are used in a limited number of cases and are not dependent on the OSPF-TE advertisements but are directly triggered by the path computation requests. The proposed scheme is compared with the most effective PCEP-based method proposed in [16] and with the standard BGP-LS method based on IGP trigger [9] during both the provisioning and restoration phases. Achieved results show that the proposed proactive method is able to significantly reduce the blocking probability due to resource contentions and, thus, particularly during recovery, it is able to improve network performance.

This paper extends the work published in [21] with a detailed previous work section and by including the recovery scenario in the simulation analysis. The rest of this paper is organized as follows. Section II reviews the previous work on multidomain WSONs and EONs controlled by a GMPLS/PCE control plane. Section III details the H-PCE architecture and describes the proposed scheme and the two reference schemes. Section IV describes the simulation scenario and presents the obtained results. Finally, Section V concludes the paper.

II. Related Works

Several TE solutions have been proposed in past years to be applied in GMPLS-based single-domain WSONs. In such networks, the routing protocol (e.g., OSPF-TE) advertises connectivity and resource availability information [22,23]. Therefore, effective path computation can be performed either locally by the lightpath source node or by a dedicated PCE. On the other hand, the first solutions proposed for the multidomain scenario were based on Border Gateway Protocol (BGP), which only exchanges reachability information not considering resource availability. Therefore, effective path computation strategies were inhibited for interdomain lightpaths, thus impacting overall network resource utilization [14]. To address this issue, the PCE architecture has been extended to support interdomain path computation using a coordinated PCEP communication process among PCEs. As an example, the Backward Recursive Path Computation (BRPC) procedure has been proposed to identify the optimal path, considering also current resource utilization [24,25]. However, those procedures assume that the sequence of domains to be traversed is known in advance.

More recently, the H-PCE architecture has been proposed to coordinate interdomain path computation and include the selection of the sequence of domains within the routing process, while considering also the current availability of network resources [12,26]. Originally, the pPCE has been designed with a hierarchical TED (H-TED) including only interdomain connectivity information (e.g., interdomain links with resource availability information), to determine the sequence of domains. However, several works demonstrated that intradomain resource information is required to achieve effective interdomain path computation [14,16,27–29]. Therefore, several solutions have been proposed where the pPCE is allowed to dynamically ask cPCEs for the path computation of the several edge-to-edge segments considering intradomain resource information. However, this solution may introduce control plane scalability concerns because of the high number of PCEP messages required between pPCE and cPCEs [13,16,30]. Specifically, in [13] the authors propose to limit the sequence of domains considered by the pPCE so that the number of generated PCEP messages is reduced. Also the work in [30] proposes a strategy for reducing the generated PCEP messages, e.g., cPCEs do not resort to the pPCE if the destination node is located in an adjacent domain. In summary, all the aforementioned works propose a reduction of the generated PCEP messages but imply a degradation of the lightpath blocking probability. However, some experimental works demonstrated that the aforementioned procedures are feasible in realistic multidomain WSONs even if they significantly increase the PCEP traffic [31–33].

Afterward, the data plane of optical transport networks evolved from WSON toward EON architecture. Thus, after appropriate control plane extension to support the EON architecture, new proposals emerged to enable effective interdomain path computation without requiring extensive communication among PCEs. Specifically, the inclusion of intradomain information directly in the H-TED has been proposed [17], where such information is provided to the pPCE by resorting to the recently proposed TE Link State Information extension to BGP (BGP-LS), as experimentally demonstrated in [15,18]. However, this BGP-LS solution is still based on OSPF-TE advertisements and can therefore suffer in dynamic traffic scenarios, such as during restoration. As an example, the work in [34] considers dynamic restoration in multidomain EONs and demonstrates a blocking probability of several percentage points, also with very low traffic load.

With respect to the aforementioned works, this paper proposes a novel solution to update the H-TED maintained at the pPCE, making a limited use of BGP-LS updates. The proposed solution further reduces the amount of messages required among PCEs while making the BGP-LS updates independent of OSPF-TE, also with the objective of decreasing the blocking probability during provisioning and restoration.

III. H-PCE Architecture and Schemes for Multidomain EONs

This section describes the considered schemes that exploit the H-PCE architecture to perform end-to-end path computation, lightpath establishment, and dynamic recovery in transparent multidomain EON networks. All the schemes consider spectrum continuity and contiguity constraints during the routing procedures [5]. Specifically, in the considered scenario, a separate OSPF-TE instance is active in each domain, advertising the status (i.e., reserved/available) of each spectrum slice along every network link. Therefore, each cPCE resorts to a local TED dynamically updated by received OSPF-TE LSAs to perform routing and spectrum assignment (RSA) of intradomain lightpath requests. Conversely, in the case of interdomain lightpath requests, cPCEs forward them to the pPCE that performs the interdomain RSA. PCEP is used among network nodes and PCEs to request the path for establishing new lightpaths (i.e., `PCReq` message), to communicate the computed path (i.e., `PCRep` message), and to notify the establishment/release of lightpaths (i.e., `PCNtf` message) [35]. After path computation Resource Reservation Protocol with Traffic Engineering extensions (RSVP-TE) is used to actually establish the end-to-end lightpath.

In all the schemes the H-TED stored at the pPCE includes detailed resource availability information of interdomain links. Moreover, depending on the considered scheme, the H-TED may include an abstraction of the intradomain topologies or a representation of the real intradomain topologies, including detailed spectrum availability information [26].

The first considered scheme (here called the *PCEP scheme*) is described in Subsection III.A; in this case the pPCE locally stores only interdomain information and it uses the PCEP protocol to dynamically retrieve the required intradomain information from cPCEs [16]. In the other two schemes, BGP-LS is used among cPCEs and pPCE to periodically update the intradomain spectrum availability information stored in the H-TED. Specifically, Subsection III.B describes the *BGP-LS* scheme, whereas Subsection III.C describes the proposed *PROACTIVE H-PCE* scheme.

A. H-PCE Architecture Based on PCEP

The procedure considered in this section is compliant with the description in [12]. Figure 1 illustrates the procedure applied for establishing an interdomain lightpath from node *A* in domain 1 to node *O* in domain 3 using the PCEP scheme.

1) Node *A* receives an interdomain lightpath request to node *O*; it generates a `PCReq` message to the local cPCE that, in turn, forwards the request to the pPCE.
2) Upon reception of the `PCReq` message, the pPCE uses the H-TED to compute the possible domain sequences from domain 1 to domain 3. Considering the computed domain sequences, the pPCE sends a number of `PCReq` messages to the involved cPCEs for computing all the possible edge-to-edge segments. Specifically, in Fig. 1 the pPCE asks cPCE 1 for a path from the source node toward the two possible edge nodes `PCReq(A,D)(A,C)`; it asks cPCE 2 for a path from the ingress edge node to the two egress nodes `PCReq(E,I)(E,H)`; it asks cPCE 3 for a path from the two ingress edge nodes to the destination node `PCReq(M,O)(L,O)`.
3) Each cPCE replies with a number of `PCRep` messages including the computed segments and the corresponding spectrum availability information.

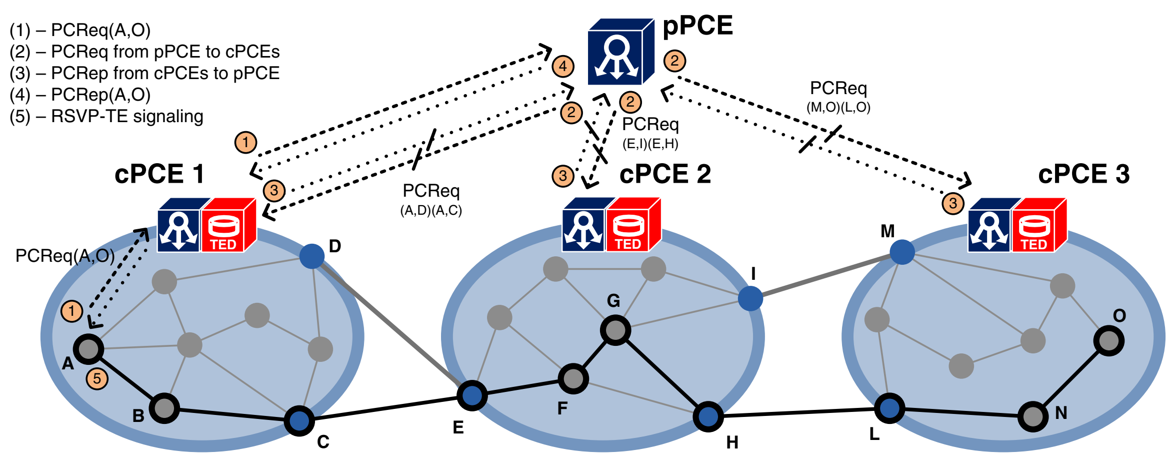

Fig. 1. PCEP scheme: example of procedure to establish an interdomain lightpath between node *A* and node *O*.

4) The pPCE collects all the replies and correlates them to elaborate an end-to-end path; then it replies to cPCE 1 with a `PCRep(A,O)` message including the path, i.e., *A–B–C–E–F–G–H–L–N–O*, with the suggested spectrum assignment; the `PCRep` message is then forwarded by cPCE 1 to the source node *A*.
5) Source node *A* triggers the actual RSVP-TE signaling along the computed path, to establish the lightpath. Actual spectrum assignment is performed by the destination node upon reception of the RSVP-TE signaling.

By using this procedure, different intradomain information can be included in the reply messages that cPCEs provide to the pPCE. Our previous work in [16] demonstrates that, to achieve effective performance in WSONs, detailed wavelength availability information along the computed path has to be provided to the pPCE. This way, the pPCE can elaborate the end-to-end path considering wavelength continuity constraints. Thus, in the EON scenario, we assume that the cPCEs reply to the pPCE, including detailed spectrum availability information so that the path can be computed at the pPCE considering spectrum continuity and contiguity constraints.

This procedure may generate a large number of PCEP messages. For instance, considering the network topology depicted in Fig. 4 below and a lightpath request between domain *D*1 and domain *D*9, there are six shortest domain sequences, each one traversing five domains (e.g., *D*1–*D*3–*D*7–*D*6–*D*9) and the number of edge-to-edge segments to be requested to cPCEs is 55 (e.g., 12 requests are sent to cPCE of domain *D*7). As stated in [13,30] this PCEP-based procedure may therefore introduce network scalability issues and excessively delay lightpath establishment.

B. H-PCE Architecture Based on BGP-LS Update

Figure 2 illustrates the procedure applied for establishing an interdomain lightpath from node *A* in domain 1 to node *O* in domain 3 using the BGP-LS scheme, as described in [17], where BGP-LS is triggered at the cPCE by the reception of OSPF-TE LSAs.

1) Node *A* receives an interdomain lightpath request to node *O*; it generates a `PCReq` message to the local cPCE that, in turn, forwards the request to the pPCE.
2) The pPCE performs the path computation using the locally stored H-TED, considering spectrum continuity and contiguity constraints, and suggesting the spectrum assignment; then it sends a `PCRep` message to cPCE 1, which forwards it to source node *A*.
3) Source node *A* triggers the actual RSVP-TE signaling to establish the lightpath. Actual spectrum assignment is performed by the destination node upon reception of the RSVP-TE signaling.
4) When resources are effectively reserved by the signaling protocol, traversed nodes generate OSPF-TE LSAs according to the local timers; when LSAs are received by the local cPCE, it elaborates them and forwards the received information to the pPCE using a BGP-LS message. Upon arrival of the BGP-LS messages the pPCE consequently updates the H-TED.

In the case of intradomain lightpaths, the procedure is the same but the path is locally computed at the cPCE. With the same procedure (i.e., forwarding of received LSAs by the cPCEs), the pPCE is automatically updated when a lightpath is released.

In this procedure the number of required messages is reduced, but, since the BGP-LS messages used to update the H-TED are triggered by the OSPF-TE LSAs, the information stored at the pPCE may be outdated and this can degrade network performance, especially in dynamic traffic conditions such as during restoration.

C. Proactive H-PCE Based on BGP-LS Update

Figure 3 illustrates the procedure applied for establishing an interdomain lightpath and an intradomain lightpath considering the proposed PROACTIVE H-PCE scheme where the use of BGP-LS messages is limited to the cases of lightpath release, intradomain lightpath setup, and signaling error.

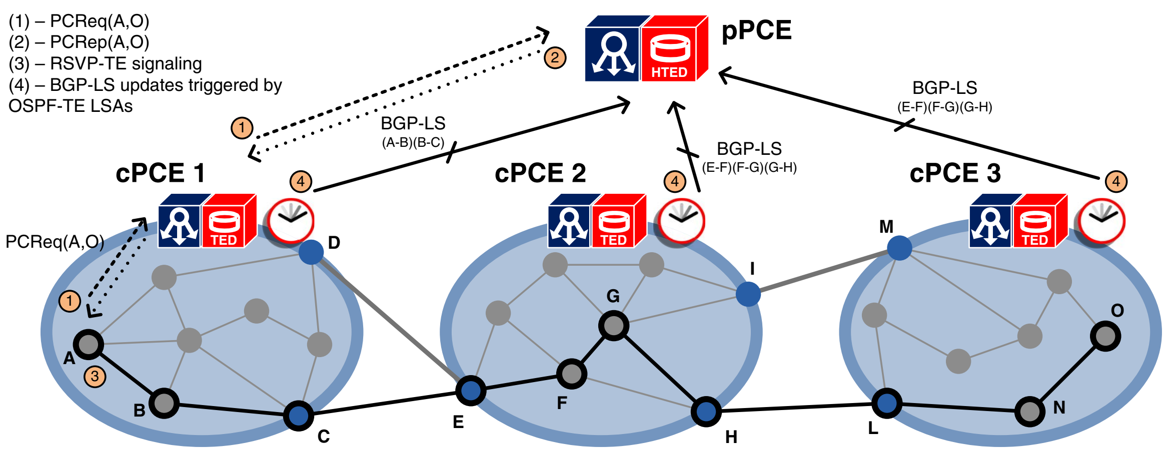

Fig. 2. BGP-LS scheme: example of procedure to establish an interdomain lightpath between node *A* and node *O*.

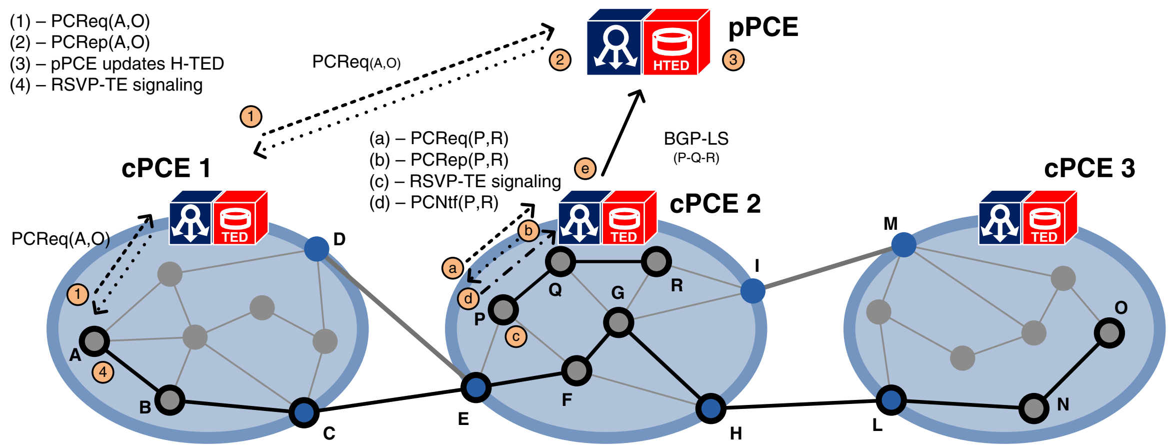

Fig. 3. PROACTIVE H-PCE scheme: example of procedure to establish an interdomain lightpath between node A and node O and an intradomain lightpath between node P and node R.

1) Node A receives an interdomain lightpath request to node O; it generates a `PCReq` message to the local cPCE that, in turn, forwards the request to the pPCE.
2) The pPCE performs the path computation using the locally stored H-TED, considering spectrum continuity and contiguity constraints, and suggesting the spectrum assignment; then it sends a `PCRep` message to the cPCE 1 that forwards it to source node A.
3) Immediately after path computation, the pPCE assumes that the lightpath will be successfully established using the assigned resources and consequently update the H-TED.
4) Source node A triggers the actual RSVP-TE signaling to establish the lightpath. Actual spectrum assignment is performed by the destination node upon reception of the RSVP-TE signaling.

Since the update of the H-TED is done proactively without waiting for confirmation of successful signaling, in the case of signaling errors a communication is required to align the H-TED to the real network status. Specifically, when signaling is blocked or a lightpath is established using a different spectrum slot with respect to the one suggested by the pPCE, the source node notifies its local cPCE with a properly extended `PCNtf` message that forwards the received information to the pPCE using BGP-LS.

In the case of an intradomain lightpath request:

a) node P receives a lightpath request to node R and sends a `PCReq` message to the local cPCE;
b) the path and the suggested spectrum assignment are locally computed at the cPCE; then the cPCE replies to the source node with a `PCRep` message;
c) the source node actually establishes the lightpath using RSVP-TE signaling;
d) upon successful signaling, the source node notifies the cPCE with a `PCNtf` message to inform it of the established lightpath; and
e) the cPCE elaborates the received `PCNtf` message and sends a BGP-LS message to the pPCE to inform it of the resources used by the established intradomain lightpath.

Finally, in the case of release of interdomain and intradomain lightpaths, a BGP-LS update is also required from the local cPCE to the pPCE.

IV. Performance Evaluation

The aim of the simulation study described in this section is to compare the considered schemes in terms of blocking probability, lightpath setup time, and amount of generated control messages during both the provisioning and the restoration phases.

A. Simulation Scenario

Schemes are evaluated using a custom built event-driven C++ simulator. The considered multidomain EON is depicted in Fig. 4, with 75 nodes and 146 bidirectional links with 256 spectrum slices per direction covering the whole C-band. The network is divided into nine domains. Each cPCE is co-located within a domain node; the pPCE is co-located with the cPCE of domain $D7$. Traffic is uniformly distributed among node pairs, lightpath requests arrive following a Poisson process, and mean holding time is fixed to 1 h. Two lightpath granularities are considered with the same generation probability: 100 Gbps lightpaths require three spectrum slices, and 400 Gbps lightpaths require nine spectrum slices [36]. The OSPF-TE LSA generation rate is set to the minimum value allowed by the standard (i.e., 5 s). To perform a fair comparison, the same RSA algorithm is used for the three schemes: the least congested path is selected at the PCE within a precomputed set of paths $P_{s,d}$ that, for each source–destination pair (s,d), includes all the paths within one hop from the shortest path; spectrum assignment is first-fit.

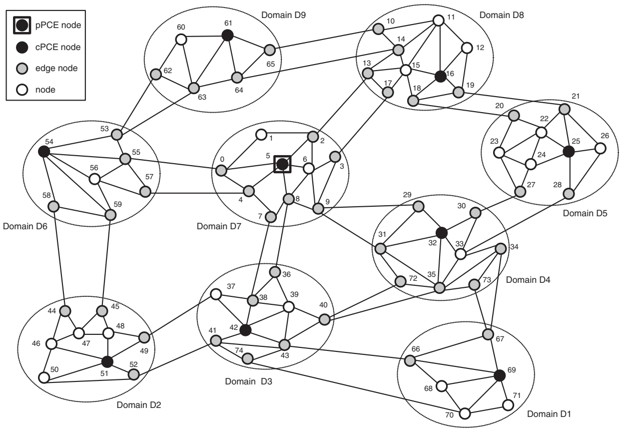

Fig. 4. Multidomain EON test network topology.

Simulation results are collected until the confidence interval of 10% at 90% confidence level is achieved or the maximum number of independent trials (i.e., 2500 in the provisioning phase, and 10^4 in the restoration phase) is reached. All results are then plotted with the confidence interval at 90% confidence level.

B. Simulation Results: Provisioning

Figure 5 shows the received control packets at the pPCE (RSVP-TE, OSPF-TE, PCEP, and BGP-LS messages are considered). The figure shows that the proposed PROACTIVE H-PCE scheme generates the lowest control traffic, thus guaranteeing increased scalability of the control plane. Conversely, the PCEP scheme generates the highest control traffic because, for each path computation, a high number of PCEP messages between pPCE and cPCEs is exchanged.

Figure 6 shows the mean lightpath setup time, which is defined only for effectively established lightpaths as the time between the generation of the lightpath request and the conclusion of the related RSVP-TE signaling. Simulations consider message propagation, transmission and queuing times, typical processing time of control messages (i.e., 10 μs for packets that are just forwarded, 2 ms for packets requiring a local processing), typical node configuration time in EONs (i.e., 100 ms), and typical path computation time (i.e., 10 ms) [19]. The figure shows that the BGP-LS scheme and the PROACTIVE H-PCE scheme achieve the same result by decreasing the PCEP scheme setup time (e.g., 10% at 400 erlang). Indeed, by using BGP-LS, the pPCE immediately performs the path computation upon reception of the request without requiring additional PCEP communication with cPCEs. Finally, the three curves present a decreasing slope; indeed, at higher loads the average length of established lightpaths is typically shorter.

Figure 7 shows the achieved lightpath blocking probability. At low loads, blocking during the backward RSVP-TE signaling phase dominates [37]. In this phase the PROACTIVE H-PCE scheme significantly reduces the blocking with respect to the other two schemes (i.e., 90% at 400 erlang). Indeed, by proactively updating the H-TED, the BGP-LS PROACTIVE scheme reduces the probability of resource contentions during the RSVP-TE signaling [23]. The residual blocking probability providing a blocking floor of the order of 10^{-5} is mainly due to communication delays between cPCEs and a pPCE. Indeed, it occasionally happens that a resource seen as available at

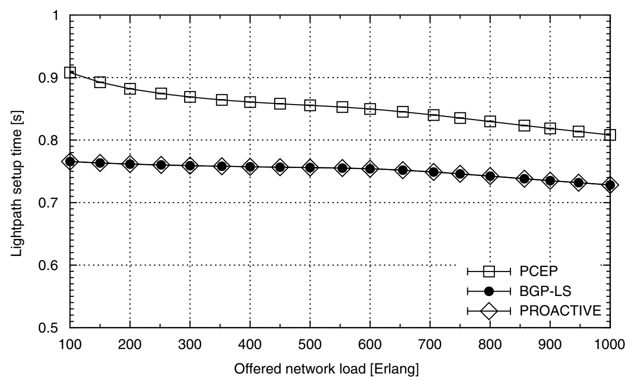

Fig. 6. Average lightpath setup time as a function of network load.

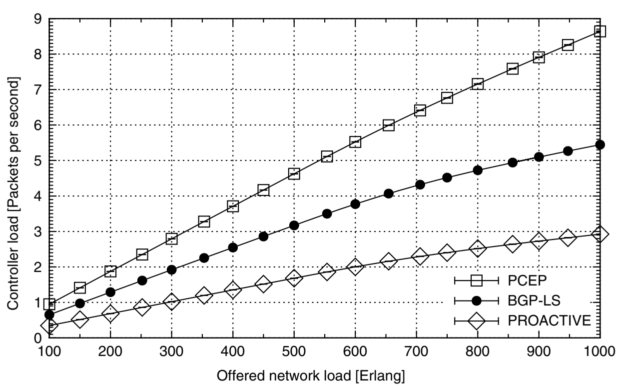

Fig. 5. Average controller load expressed in terms of number of packets processed per second as a function of network load.

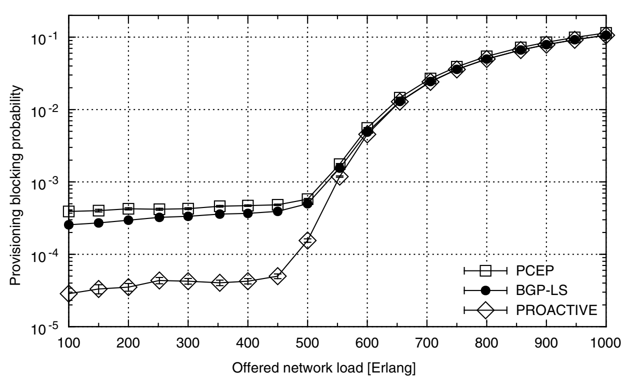

Fig. 7. Provisioning blocking probability as a function of network load.

the pPCE has just been assigned to an intradomain lightpath by the correspondent cPCE.

C. Simulation Results: Restoration

A failure scenario is simulated with a series of independent single link failures uniformly distributed among the whole set of network links. Upon failure, the nodes attached to the disrupted link perform failure detection and send an RSVP-TE notification to the source node of each disrupted lightpath. In turn, the source node sends a `PCReq` message to the local cPCE to compute the recovery path; the computation procedure of the recovery path is performed as described in Section III, depending on the considered scheme. Three RSVP-TE signaling attempts are performed for each disrupted lightpath using the crankback procedure before considering the lightpath as not recoverable [38].

Figure 8 shows the mean lightpath recovery time measured for all the successfully recovered lightpaths as the time between the failure and the time at which the RSVP-TE signaling is successfully terminated. The figure shows that the PCEP scheme provides the worst result due to the distributed path computation procedure, which requires significant communication among PCEs. With respect to the lightpath setup time shown in Fig. 6, during restoration the proposed PROACTIVE H-PCE scheme is able to decrease the recovery time with respect to PCEP scheme (e.g., 25% at 400 erlang) and with respect to BGP-LS scheme (e.g., 8% at 400 erlang). This is mainly due to the fact that, when using the PROACTIVE H-PCE scheme, a higher number of lightpaths are recovered at the first signaling attempt, thus reducing the average recovery time.

Figure 9 shows the lightpath blocking probability during restoration. This statistic is computed, for each failure, as the ratio between the number of not recoverable lightpaths and the number of disrupted lightpaths. Since during restoration the main source of blocking is the resource contention during the backward RSVP-TE signaling phase, the PROACTIVE H-PCE scheme significantly reduces blocking during restoration at low and medium network load (i.e., 95% at 100 erlang and 90% at 400 erlang).

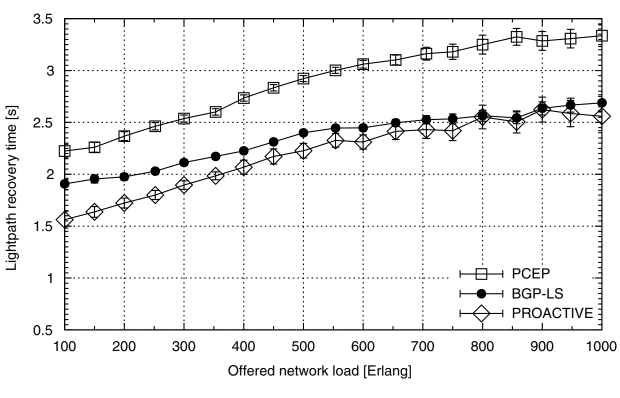

Fig. 8. Average lightpath recovery time as a function of network load; three recovery attempts are allowed.

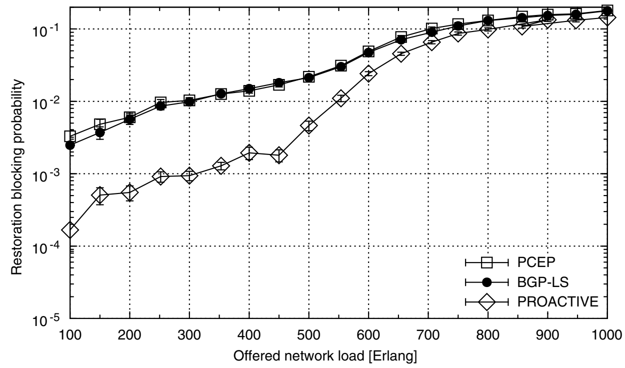

Fig. 9. Restoration blocking probability as a function of network load; three recovery attempts are allowed.

V. Conclusion

This paper considered the use of the hierarchical PCE architecture in EONs with a GMPLS/PCE control plane and proposed a novel scheme to update the H-TED stored at the pPCE using a limited number of BGP-LS messages. The proposed scheme is applied during the provisioning and restoration phases and its performance is compared against an effective PCEP-based method proposed in the literature and against the standard BGP-LS method based on an IGP trigger.

Provisioning phase simulations evaluated the control load, the lightpath setup time, and the blocking probability; restoration phase simulations evaluated the lightpath recovery time and the blocking probability after three signaling attempts. During provisioning, the obtained results showed that the proposed scheme is able to significantly reduce the lightpath blocking probability due to resource contention and to decrease both the lightpath setup time and the control plane load. The benefit of the proposed scheme is also relevant during restoration in terms of both blocking probability and recovery time.

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