Assessment and Performance Evaluation of PCE-based Inter-Layer Traffic Engineering

Sebastian Gunreben
University of Stuttgart - IKR
Pfaffenwaldring 47
70569 Stuttgart, Germany
email: gunreben@ikr.uni-stuttgart.de

Franz Rambach
Nokia Siemens Networks GmbH & Co. KG
COO RTP NT NCT MLR
Otto-Hahn-Ring 6
81730 München, Germany
email: franz.rambach@nsn.com

***Abstract*—Multi-layer (ML) and multi-domain networks require Path Computation Elements (PCE) for constraint-based path calculation. In this paper we introduce and evaluate qualitatively as well as quantitatively the PCE scenarios newly proposed by the IETF for PCE-based inter-layer traffic engineering. Requirements on additional communication, on hardware and on optimality of path computation serve as the qualitative metrics in our comparison. The path setup delay is derived analytically and serves as the quantitative metric. We derive the results using simulations on the ML German reference network with 17 nodes and back-up our results by two different ML TE routing algorithms. We show that one Single ML PCE performs best in the overall qualitatively and quantitatively comparison.**

I. Introduction

Core networks of the future will be multi-layer networks consisting of an optical physical layer and of one or more electronic upper layers. The lower layer is realized by reconfigurable WDM, while the upper layers are realized by a connection switched technology (e. g., SDH) or by a packet switched technology (e. g., MPLS, Ethernet).

Path computation includes multiple layers for TE purpose. The literature proposes many ML TE routing algorithms to optimize network resources [1]–[6]. These algorithms have in common a computational complexity with at least quadratic dependency in the number of links. Constraint-based path computation and the large number of TE-links in a ML network even increase this complexity.

This complexity usually exceeds the computational capabilities of label switched routers (LSR). A special network node called Path Computation Element has been proposed by the IETF to overcome this problem. The PCE serves as a computing entity, specialized for constraint-based path computation. The network node requesting the PCE service is called a Path Computation Client (PCC, [7]). The requirements and a draft specification for the protocol between both entities is proposed in [8], [9]. The PCC request includes source node and destination node and additional path constraints. The PCE response includes a NO-PATH object if no path is found or otherwise it includes a list of strict or loose hops.

In this paper we evaluate qualitatively as well as quantitatively five different PCE approaches with respect to the path setup delay. To our knowledge it is the first time of such evaluation.

Section II introduces the five different PCE approaches. Section III compares them qualitatively while section IV shows our quantitative results. Section V concludes this paper.

II. PCE-based inter-layer path computation

We introduce different PCE-based inter-layer path computation approaches of the newly available IETF draft by Oki et al. [10]. We evaluate these approaches in a common network scenario. We assume an intra-domain scenario with one administrative domain. The domain refers to an autonomous system of one single operator. [11] studies the inter-domain and inter-operator scenarios.

We assume a ML network, in which each network node is capable of two switching regions. We denote the upper switching region as higher layer (HL) and the lower switching region as lower layer (LL). On each layer there is only one switching region available. Thus we use interchangeably the terms switching region and layer. The HL node and the corresponding LL node, deployed at the same site, communicate internally, which is out of scope of this paper.

A unified GMPLS control plane controls both network layers. This includes the signaling and routing protocols, RSVP-TE and OSPF-TE, respectively [12]–[15]. These routing and signaling protocols use a common data communication network (DCN). The topology of the DCN is equal to the physical topology of the network. The LSRs and the PCEs participate in this DCN.

The routing protocol advertises LL p2p connections in the HL as TE-links, i. e., forwarding adjacencies [16]. A LL p2p connection may span multiple nodes if switched transparent on intermediate nodes. These connections form the virtual network topology (VNT) of the HL. Connection requests occur on the HL only. They are routed in the HL VNT.

Each PCE is co-located with a traffic engineering database (TED). The TED keeps the state of the topology and the state of the TE-links. Several possibilities exist to construct and update the TED, e. g.:

- the TED participates in the routing protocol extracting topology information of the network.
- the network management system updates the TED.
- a mixture of both approaches.

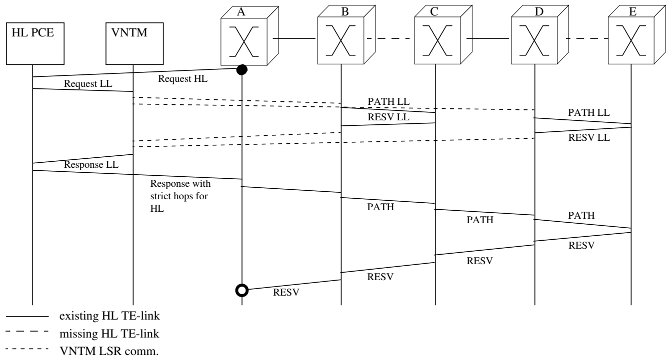

Fig. 1. PCE/VNTM cooperation

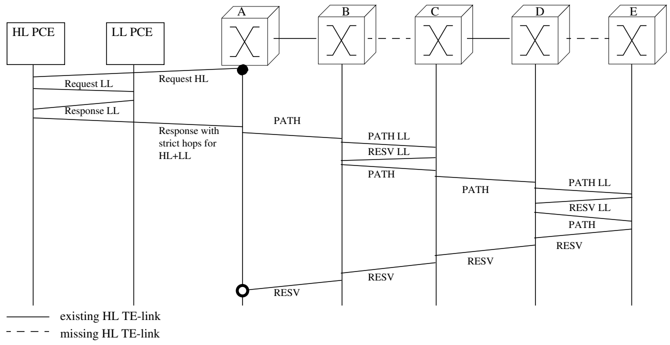

Fig. 2. Multiple PCEs with inter-PCE communication

We assume that the TED participates passively in the routing protocol. The TED itself does neither advertise link states nor router states. We further assume, that the TED only stores information about the network part the PCE is in charge of.

We classify the PCE approaches in two different classes. The first class includes centralized path computation (CPC), the second class distributed path computation (DPC).

A. Centralized Path Computation

A single PCE in the network or a single PCE realized by several parallel PCEs for load balancing purpose at the same location represent a CPC scenario.

1) Single ML PCE: The Single ML PCE includes HL as well as LL TE-links for path computation. The TED of this PCE maintains the TE-link states of all switching layers. If the path calculation process is successful, it responds with an explicit path including HL as well as LL interfaces [9].

The signaling process reserves capacities in downstream direction on the HL until the end of the HL TE-link is reached. Then the resources on the LL are occupied first until further downstream signaling on the HL. This hierarchical reservation process is described in [17].

2) PCE/VNTM cooperation: This approach is depicted in Fig. 1. The responsibilities of the HL and the LL are separated in two devices. The virtual network topology manager (VNTM) is in charge of establishing and tearing-down LL connections. It constructs the LL topology, which is advertised in the HL as available TE-links.

The PCE is in charge of path computation on the HL VNT only. If calculation on the HL is impossible, the HL PCE response to the PCC includes either a NO-PATH object or the HL PCE requests the VNTM to establish LL TE-links. On reception of a connectivity request, the VNTM calculates itself a path or uses a LL PCE for calculation. On success it communicates with the corresponding LL switching nodes and triggers the signaling process there.

In case of several LL connections, the communication and signaling process is parallelized. The VNTM informs the PCE on the success of the connection establishment on the LL. Including this information the HL PCE responds with a list of strict HL hops to the PCC.

B. Distributed Path Computation

More than one PCE deployed in the network represents a DPC scenario. These PCEs partition the path computation responsibility. We distinguish between horizontal and vertical separation of this responsibility. If one PCE calculates paths on one switching layer, the PCE responsibilities are separated horizontally, i. e., mono-layer PCEs are deployed. If PCE path computation includes several layers of a subset of nodes, the responsibilities are separated vertically [18]. Also a mixture of both approaches is possible.

In this paper we consider horizontal PCE responsibilities. Thus, each PCE is a mono-layer PCE. The PCE calculates paths on one switching layer. The PCE responsible for the HL is called HL PCE, while the PCE responsible for the LL is called LL PCE.

1) Multiple PCEs with inter-PCE communication: Fig. 2 shows the message sequence chart of this approach. If the path calculation on the HL is successful, the HL PCE responses an explicit route to the PCC. This corresponds to the Single ML PCE approach.

If the path calculation on the HL includes gaps, the HL PCE requests paths for these gaps from the LL PCE. On success the response of the LL PCE includes an explicit route on the LL. In this case the HL PCE acts as a PCC, which is foreseen by the PCE communication protocol specification [8]. The HL PCE responds to the PCC with an aggregated route including explicit nodes on the HL as well as on the LL.

2) Multiple PCEs without inter-PCE communication: Fig. 3 shows the message sequence chart of this approach. The HL PCE calculates a path on the HL VNT. If there is no continuous path available on the HL, the HL PCE responds with loose hops to the PCC. With this response the PCC starts the signaling process.

Every time a TE-link edge node in the HL VNT is reached the edge node forwards the connection request to the corresponding LL switching node. The LL switching node acts as a PCC and requests the LL PCE for an explicit path between these loose hops. On success the LL PCE replies with a LL path including explicit hops. The LL TE-links are established next. The signaling process on the HL proceeds afterward. This process repeats every time an edge node in the HL VNT is reached. If there is no LL path available, the signaling process

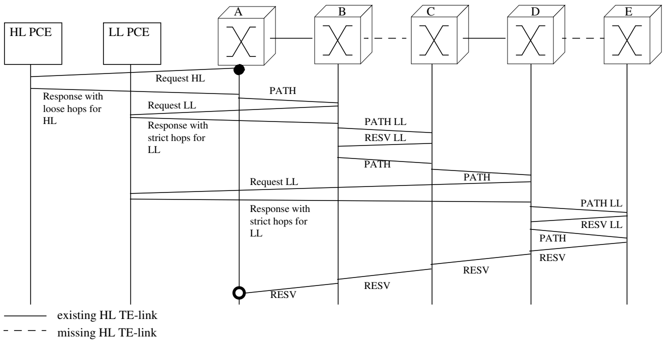

Fig. 3. Multiple PCEs without inter-PCE communication

stops and the LL PCE response includes a NO-PATH object to cancel the signaling process.

3) Multiple ML PCE: In the Multiple ML PCE approach, a ML PCE is co-located with every network node. Each ML PCE is able to compute paths including all layers. The functionality is the same as described in section II-A1, but the communication between PCC and PCE drops out as both are co-located in the same node.

This scenario is our reference scenario. We assume full path computation capabilities in every LSR. With respect to any communication delay it is a lower bound. In response to the costs it is highly expensive and thus very unlikely.

III. Qualitative comparison

In this section we compare qualitatively the different PCE approaches introduced in section II. Table I summarizes the properties of the different PCE approaches. We compare these with respect to the co-located TED, the assured path connectivity and with respect to an optimal path criteria.

First, the TED is investigated. In the single ML PCE and the multiple ML PCE approach the TED processes routing messages of all layers. This results in large TEDs. The remaining PCE approaches restrict the TED to one single layer, which results in small TEDs.

All approaches, except the multiple PCEs without inter-PCE communication approach, guarantee connectivity of the calculated path. Since the computed path includes loose hops the HL PCE cannot assure any connectivity.

The optimality of the computed path is guaranteed if the single ML PCE, the multiple ML PCE or the multiple PCEs with inter-PCE communication approach is used. In the Single ML PCE and the Multiple ML PCE approaches the PCE(s) maintain information about all layers. Therefore a PCE may compute an optimal path without any collaboration with other PCEs. However, in case of multiple PCEs with inter-PCE communication the optimal path computation is quite complex, because many requests must be issued from the HL PCE to the LL PCE to take into account all paths, i.e., all possible combinations of HL and LL paths. The other two approaches cannot guarantee an optimal path. The PCE and the VNTM maintain only information about one single layer and the properties of the LL paths are not taken directly into account in the path computation process.

TABLE I
Properties of the different PCE approaches

PCE approach	TED	Assured connectivity	Optimal path
CPC			
Single ML PCE	ML TED	Yes	Yes
PCE + VNTM	SL TED	Yes	No
DPC			
Multiple PCEs with inter-PCE comm.	SL TED	Yes	Yes
Multiple PCEs w/o inter-PCE comm.	SL TED	No	No
Multiple ML PCE	ML TED	Yes	Yes

All approaches except the multiple layer PCE without inter-layer communication compute a complete ML path without any loose hops. This is advantageous, because loose hops trigger additional path computation in the signaling phase.

The multiple PCEs without inter-PCE communication is the simplest approach. However, no real ML TE is possible, since no optimal path and not even connectivity is assured.

The different approaches need besides the RSVP signaling additional inter-PCE, PCE/VNTM and/or VNTM/LSR communication, which introduces additional delay. Only the Multiple ML PCE approach needs no additional communication. In the Single ML PCE approach the PCC/PCE communication requires a delay. In the multiple PCE with inter-PCE communication approach communication between the PCC and PCE and between the PCEs is required. In the case without inter-PCE communication additionally to the PCC PCE delay the communication between the LL PCCs, i. e., LSRs, and LL PCE must be taken into account. The collaboration of the PCE and VNTM introduces the PCC/PCE delay, the PCE/VNTM delay and VNTM/LSR delay. For these different approaches, the analytic expression for the complete signaling time is presented in section IV-A.

An advantage of the PCE/VNTM approach is the fact that at the moment the PCC receives the computed path, all lower layer LSPs are already established and thus the signaling of the path does not trigger any further computing or additional signaling of other paths. Hence, the signaling process triggered by the PCC after receiving the route object will be finished in a shorter time compared to the other approaches.

IV. Performance evaluation

This section evaluates quantitatively the different PCE approaches with respect to the path setup delay. First, it introduces our methodology to derive the path setup delay. Second, it describes the simulation scenario and the simulation parameters in detail. The last subsection presents our results and highlights the most advantageous PCE approach.

A. Methodology

A path response may include HL and LL sections. HL sections describe established TE-links in the HL VNT (e. g., in Fig. 2 the link A – B). LL sections describe TE-links in the LL (e. g., in Fig. 2 the link B – C).

N^{LL} is the number of LL sections. The physical length of each section i is L_i^{LL}. The number of nodes per LL section is n_i^{LL}. N^{HL} is the number of HL sections. The length of each section j is L_j^{HL}. It is derived of the corresponding physical length of the LL TE-links. The number of nodes per HL section is n_j^{HL}.

The time to process the signaling messages on the HL is p^{HL} on the LL it is p^{LL} per node. The delays for the configuration of the switching matrix in the HL as well as on the LL is denoted by m^{HL} and m^{LL}, respectively. Please note that a two-way reservation protocol like RSVP triggers the configuration of the switching matrix in upstream direction. We assume the node not to wait until the configuration process has been ended but sends the signaling message in upstream direction immediately. This process is parallelized, as the source node has to configure its switching matrix, too.

The delay between the PCC to the PCE is denoted as d_{c2e}. It is a mean delay based on the topology of the DCN and also holds for the delay between any LSR and the PCE or VNTM. The delay between the co-located PCEs and the delay between PCE and VNTM is denoted as d_{e2e}.

With these variables we construct the signaling time on the HL. S^{HL} denotes the processing delay at each node, the propagation delay between the nodes and the configuration of the HL switching matrix. Therein, c^* refers to the propagation speed in the medium:

$$S^{HL} = m^{HL} - p^{HL} + 2 \sum_{i=1}^{N^{HL}} \left\{ n_i^{HL} \, p^{HL} + L_i^{HL}/c^* \right\}$$

Note that the processing delay at the egress node is counted only once. S^{LL} denotes the signaling time on the LL composed by equivalent components. Note that these delays contribute per LL section.

$$S^{LL} = \sum_{i=1}^{N^{LL}} \left\{ m^{LL} + (2\, n_i^{LL} - 1)\, p^{LL} + 2\, L_i^{LL}/c^* \right\}$$

The overall path setup delay T_s is calculated for every PCE approach.

Single ML PCE: Additionally to the signaling delay the delay between the PCC and the PCE contributes: $T_s = S^{HL} + S^{LL} + 2\, d_{c2e}$.

Mult. PCE with inter-PCE comm.: Compared to the Single ML PCE the delay between HL PCE and LL PCE contributes: $T_s = S^{HL} + S^{LL} + 2\, d_{c2e} + 2\, d_{e2e}$.

Mult. PCE without inter-PCE comm.: Each LL section contributes with an additional PCC/PCE delay: $T_s = S^{HL} + S^{LL} + 2\,(1 + N^{LL})\, d_{c2e}$.

PCE/VNTM cooperation: The signaling process on the LL is parallelized, thus contributes only with the maximum delay. Again an additional PCE/PCE delay contributes to the overall path setup delay: $T_s = S^{HL} + 2\,(2\, d_{c2e} + d_{e2e}) + \max_i \left((2\, n_i^{LL} - 1)\, p^{LL} + 2\, L_i^{LL}/c^* + m^{LL}\right)$

Mult. ML PCE: No additional delay is included here. Only the signaling time contributes: $T_s = S^{HL} + S^{LL}$.

B. Simulation scenario

All studies are performed with the 17 node German backbone reference network [19]. On the HL we assume SDH technology, i. e., switching of SDH connections. On the LL we assume reconfigurable WDM technology, i. e., switching of wavelengths.

In our simulation we use two different ML routing algorithms to generalize our findings. The weighted integrated routing algorithm (WIR, [2]) and the routing algorithm proposed by Zhu (UCD, [1]). Both routing algorithms are able to calculate ML paths as well as SL paths.

A wavelength has capacity to transport at maximum STM-64, i. e., a line rate of 10 Gbps. The granularity of a SDH connection demands are fractions of STM-64. It follows the chosen traffic mix distribution.

C. Simulation parameter

We obtain the results from the simulation after the network state has reached a steady state. The measurement samples are averaged on ten batches, each consisting of 10^6 connection requests.

The German backbone network has been dimensioned for a total network traffic of 5 Tbps, which corresponds to 100% network load. A population based traffic matrix generates the network load. The number of wavelengths is calculated using the Erlang B formula to satisfy a connection blocking probability of at least 10^{-6} on all links at the 5 Tbps load scenario.

The number of transponders between the optical and electrical node equipment is unlimited.

The distribution of the traffic mix is: 50% STM-1, 20% STM-4 and 30% STM-16. This reflects the large number of small capacity connections as in [19].

The signaling message processing time is $p^{HL} = p^{LL} =$ 10 ms for signaling messages on the LL as well as on the SDH nodes, which corresponds to the values mentioned in [20].

The configuration of the SDH switching matrix needs $m^{HL} = 20$ ms. The configuration of the WDM switching matrix needs $m^{LL} = 50$ ms, which includes positioning and oscillations of the mirrors.

We assume the PCE in average distance of 413.50 km to each node. As the HL PCE, the LL PCE and the VNTM are co-located, we assume a fixed delay of $d_{e2e} = 5$ ms, which represents packet encapsulation and propagation delay. The propagation speed c^* is 2/3 of the speed of light.

D. Simulation Results

In our simulations we measure the number of WDM and SDH sections N^{LL} and N^{HL} for a calculated path. This also includes the number of hops, n^{LL} and n^{HL} per section. The section length is calculated by the mean hop distance. Based on this measurement values and the formulas of section IV-A, we calculate the path setup delay and compare the different PCE approaches in respect to the overall path setup delay.

We show the dependence of the path setup delay on the network load. Therefore, we vary the network load parameter

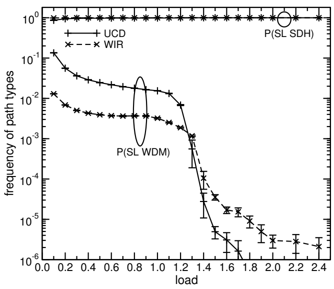

Fig. 4. SL path characteristic

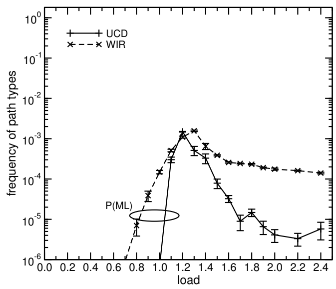

Fig. 5. ML path characteristic

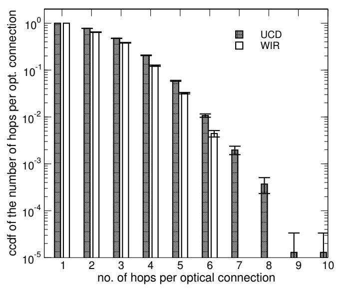

Fig. 6. Optical path characteristic

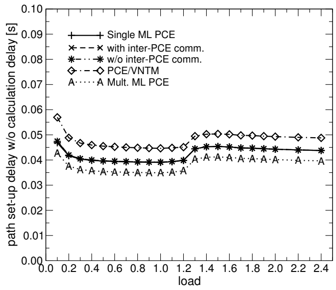

Fig. 7. UCD: Mean setup delay

from 0.1 up to 2.4 including network operation points in low load, medium load and overload scenarios. We argue these load scenarios with the path classification as explained next.

The response path of the PCE, independent of the PCE approach, is classified into three different groups:

SL SDH: The path is routed on the SDH VNT only. It consists of an arbitrary number of HL sections. No LL section has to be established first, i. e., $N^{LL} = 0 \land N^{HL} > 0$.

SL WDM: The path consists of exactly one LL e2e section, which has to be established first to serve as a TE-link in the HL. On the SDH layer exactly this path is used after its setup. $N^{LL} = 1 \land N^{HL} = 1$

ML: The calculated paths are pure ML, they consist of both, already established SDH TE-links and WDM TE-links, which have to be established first, i. e., $N^{LL} > 0 \land N^{HL} > 0$.

Fig. 4 and Fig. 5 depict the frequency of these different path types for both routing schemes. Fig. 4 shows at the top the frequency of a SL path on SDH layer. It is nearly constant for the whole load range for both algorithms. Only in very low load ranges, there is a very small knee visible. As a consequence we state that the great majority of paths consist of single layer paths, which are routed in the SDH layer only.

In contrast to this, the figure shows the graphs for routing only on the WDM layer (SL WDM), too. In very low load ranges the amount of pure optical connections gets an amount of nearly 10%. If load increases the amount of pure WDM connections is reduced to below 10^{-4}. In low load situations the optical connections have to be established first to serve the SDH connection requests. In high load situations the network's resources become rare to grant SL WDM connections. Both algorithms show a different behavior. When applying the WIR algorithm, the amount of pure optical connections is smaller than, when applying the UCD algorithm. For loads beyond 1.0 this behavior swaps.

Fig. 5 shows the frequency of ML paths. ML paths occur first to an amount larger than 10^{-6} in load situations larger than 0.9. The amount of ML paths increases up to a maximum load of 1.3. Beyond a load of 1.3 the amount of ML paths decreases again. In these load situations the ML paths are able to exploit the few remaining resources in the network. The overall frequency of ML paths does hardly exceed 10^{-3}. Thus the frequency to compute a ML path, taking into account both layers is also below 10^{-3}. In all other cases a single layer view is sufficient to establish a suitable path. No communication with LL PCE or VNTM is necessary.

In these rare cases, when additionally WDM links are setup, we further investigate the length of these links in number of hops. In Fig. 6 we depict the complementary cumulative distribution function of the number of WDM hops on condition that a new optical link has to be established. The network load for this scenario is 1.0. The bar chart shows both routing strategies. More than 90% of the LL connections have four or less hops per section. Note that each section of a path contributes to this statistic individually. It is also worth noticing that even much longer TE-links are established. The large number of links contributes to the path setup delay as each link contributes to propagation delay and each node adds processing delay.

We translate the results from Fig. 4 and Fig. 5 in the path setup delay. We distinguish between the minimum path setup delay (min), the mean path setup time (mean) and the maximum path setup delay (max).

min: The min path setup delay includes the signaling and processing delays only on the SDH layer. No additional WDM connection is required. This corresponds to a SL SDH path.

mean: The mean path setup delay is described as the expected path setup delay. It includes the ML as well as the SL paths weighted by their frequencies.

max: The max path setup delay always includes the average number of new WDM sections and hops and the average number of SDH links and hops. The max path setup delay reflects the average time to establish a ML path.

Fig. 7 shows the expected mean path setup delay. It depicts the results for the UCD algorithm but in general these hold also for the WIR algorithm as the difference of both algorithms is negligible. The multiple ML PCE approach again is the reference scenario. The remaining PCE approaches are overlapping in this scenario due to the small frequency of WDM paths. The difference between these two curves is again the additional PCC/PCE communication delay. Regarding the mean setup delay the VNTM/LSR delay contributes additionally to the setup delay. The minimum path setup time is equal for all approaches except the Multiple ML PCE as the signaling delays in the optical layer vanish.

Fig. 8 and Fig. 9 show the maximum setup delay for the PCE approaches of section II. They include the results for the UCD and the WIR routing algorithm, as the results differ in the load range smaller than 1.4. We observe a common behavior

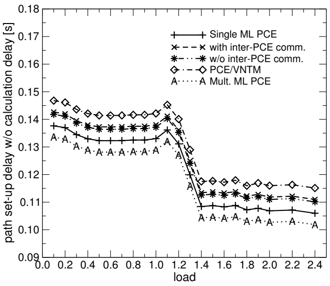

Fig. 8. UCD: Max setup delay

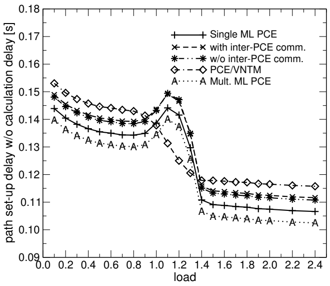

Fig. 9. WIR: Max setup delay

of the five PCE approaches in the whole load range. At the beginning the setup delay increases slightly as the frequency of WDM paths increases. Around load 1.0, a sharp knee points to the transition to the overload situation. In the overload situation the path setup delay decreases for all approaches as the frequency of WDM paths and ML paths is reduced.

The order of the five PCE approaches is intuitive in the UCD scenario of Fig. 8. The multiple ML PCE approach performs the fastest setup as there is no additional signaling delay. Second is the Single ML PCE approach. There, only one additional PCC/PCE communication delay is added. Third and fourth are the PCE approaches with and without inter-PCE communication. They are overlapping as the amount of LL signaling is nearly negligible. The PCE/VNTM approach introduces the largest delay because of both the PCE/VNTM and the VNTM/LSR communication.

In the PCE/VNTM approach both algorithms differ. In the load range of 1.0 to 1.4 the PCE/VNTM approach out performs all the other approaches when applying the WIR algorithm (Fig. 9). The setup delay using WIR is smaller compared to the UCD algorithm. This is because the WIR algorithm limits the maximum path length while the UCD algorithm does not. This shows evidence for the dependence of the path setup delay on the routing algorithm.

V. Conclusion

In this paper we compared five different PCE approaches newly proposed by the IETF quantitatively as well as qualitatively. We found that the amount of ML paths, which legitimate the argument of PCEs, is very low in a representative core network scenario. Thus, PCEs are legitimated more by the complexity of constraint-based path computation requests and by the reduced computation time than by ML path computation.

Because of the small frequency of ML paths the minimum and mean path setup time do not show much difference. The expected path setup delay is in the order of tens of milliseconds. The maximum path setup delay (representing ML paths) triples the path setup delay in certain scenarios.

We found that among all PCE deployment scenarios one Single ML PCE performs best. In the simulated cases path setup delays are far less than a second even in case of ML paths. Small communication overhead and the reduced number of needed PCEs back-up this decision qualitatively.

VI. Acknowledgment

The work reported in this paper has been funded by the European IP NOBEL Phase 2 FP6-IST-027305.

References

[1] H. Zhu, H. Zang, K. Zhu, and B. Mukherjee, "A novel generic graph model for traffic grooming in heterogeneous WDM mesh networks," *Networking, IEEE/ACM Transactions on*, vol. 11, no. 2, 2003.

[2] M. Necker, C. M. Gauger, and S. Bodamer, "A new efficient integrated routing scheme for SDH/SONET-WDM multilayer networks," in *Proceedings of the Optical Fiber Communication Conference (OFC)*, vol. 2, 2003.

[3] W. Colitti, K. Steenhaut, and A. Nowe, "An integrated multilayer traffic engineering scheme in the new generation GMPLS based optical internet," in *Internet, 2005.The First IEEE and IFIP International Conference in Central Asia on*, 2005.

[4] M. Kodialam and T. Lakshman, "Integrated dynamic IP and wavelength routing in IP over WDM networks," in *INFOCOM 2001. Twentieth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, vol. 1, 2001.

[5] G. Retvari, P. Fodor, J. Tapolcai, and T. Cinkler, "Multi-layer traffic engineering schemes in GMPLS networks," in *Transparent Optical Networks, 2005, Proceedings of 2005 7th International Conference*, vol. 1, 2005.

[6] K. Zhu, H. Zhu, and B. Mukherjee, "Traffic engineering in multigranularity heterogeneous optical WDM mesh networks through dynamic traffic grooming," *IEEE Network*, vol. 17, no. 2, 2003.

[7] A. Farrel, J.-P. Vasseur, and J. Ash, "A Path Computation Element (PCE)-Based Architecture," IETF, RFC 4655, Aug. 2006.

[8] J. Ash, Ed., J. L. Roux, and Ed., "Path Computation Element (PCE) Communication Protocol Generic Requirements," IETF, RFC 4657, Sep. 2006.

[9] J. Vasseur and J.-L. L. Roux, "Path Computation Element (PCE) communication Protocol (PCEP)," draft-ietf-pce-pcep-08.txt, work in progress, IETF, Jul. 2007.

[10] E. Oki, J.-L. L. Roux, and A. Farrel, "Framework for PCE-Based Inter-Layer MPLS and GMPLS Traffic Engineering," draft-ietf-pce-inter-layer-frwk-05, work in progress, IETF, Sep. 2007.

[11] F. Aslam, Z. Uzmi, and A. Farrel, "Interdomain Path Computation: Challenges and Solutions for Label Switched Networks," *Communications Magazine, IEEE*, vol. 45, no. 10, pp. 94–101, 2007.

[12] D. Awduche, L. Berger, D. Gan, T. Li, V. Srinivasan, and G. Swallow, "RSVP-TE: Extensions to RSVP for LSP Tunnels," IETF, RFC 3209, Dec. 2001.

[13] D. Papadimitriou and A. Farrel, "Generalized MPLS (GMPLS) RSVP-TE Signaling Extensions in Support of Calls," IETF, RFC 4974, Aug. 2007.

[14] D. Katz, K. Kompella, and D. Yeung, "Traffic Engineering (TE) Extensions to OSPF Version 2," IETF, RFC 3630, Sep. 2003.

[15] K. Kompella, Ed., Y. Rekhter, and Ed., "OSPF Extensions in Support of Generalized Multi-Protocol Label Switching (GMPLS)," IETF, RFC 4203, Oct. 2005.

[16] K. Kompella and Y. Rekhter, "Label Switched Paths (LSP) Hierarchy with Generalized Multi-Protocol Label Switching (GMPLS) Traffic Engineering (TE)," IETF, RFC 4206, Oct. 2005.

[17] A. Banerjee, J. Drake, J. Lang, B. Turner, K. Kompella, and Y. Rekhter, "Generalized Multiprotocol Label Switching: An Overview of Routing and Management Enhancements," *IEEE Communications Magazine*, vol. 39, no. 1, 2001.

[18] F. Cugini, A. Giorgetti, N. Andriolli, F. Paolucci, L. Valcarenghi, and P. Castoldi, "Multiple Path Computation Element (PCE) Cooperation for Multi-Layer Traffic Engineering," in *Optical Fiber Communication Conference*, March 2007.

[19] A. Betker, C. Gerlach, R. Huelsermann, M. Jaeger, M. Barry, S. Bodamer, J. Späth, C. M. Gauger, and M. Köhn, "A set of typical transport network scenarios for network modelling," in *Proceedings of the 5. ITG Symposium on Photonic Networks*, Leipzig, May 2004.

[20] Q. Song, I. Habib, and W. Alanqar, "Performance evaluation of connection setup in GMPLS IP optical network," in *Optical Fiber Communication Conference, 2005. Technical Digest. OFC/NFOEC*, vol. 3, 2005.