Hierarchical Stateful Path Computation Element (PCE).
draft-ietf-pce-stateful-hpce-11

Abstract

   A Stateful Path Computation Element (PCE) maintains information on
   the current network state, including: computed Label Switched Path
   (LSPs), reserved resources within the network, and pending path
   computation requests. This information may then be considered when
   computing new traffic engineered LSPs, and for associated and
   dependent LSPs, received from Path Computation Clients (PCCs). The
   Path computation response from a PCE is helpful for the PCC to
   gracefully establish the computed LSP.

   The Hierarchical Path Computation Element (H-PCE) architecture,
   provides an architecture to allow the optimum sequence of
   inter-connected domains to be selected, and network policy to be
   applied if applicable, via the use of a hierarchical relationship
   between PCEs.

   Combining the capabilities of Stateful PCE and the Hierarchical PCE
   would be advantageous. This document describes general considerations
   and use cases for the deployment of Stateful, and not Stateless, PCEs
   using the Hierarchical PCE architecture.

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1. Introduction

1.1. Background

   The Path Computation Element communication Protocol (PCEP) [RFC5440]
   provides mechanisms for Path Computation Elements (PCEs) to perform
   path computations in response to Path Computation Clients' (PCCs)
   requests.

   A stateful PCE is capable of considering, for the purposes of path
   computation, not only the network state in terms of links and nodes
   (referred to as the Traffic Engineering Database or TED) but also the
   status of active services (previously computed paths, and currently
   reserved resources, stored in the Label Switched Paths Database
   (LSP-DB).

   [RFC8051] describes general considerations for a stateful PCE
   deployment and examines its applicability and benefits, as well as
   its challenges and limitations through a number of use cases.

   [RFC8231] describes a set of extensions to PCEP to provide stateful
   control. A stateful PCE has access to not only the information
   carried by the network's Interior Gateway Protocol (IGP), but also
   the set of active paths and their reserved resources for its
   computations. The additional state allows the PCE to compute
   constrained paths while considering individual LSPs and their
   interactions. [RFC8281] describes the setup, maintenance and
   teardown of PCE-initiated LSPs under the stateful PCE model.

   [RFC8231] also describes the active stateful PCE. The active PCE
   functionality allows a PCE to reroute an existing LSP or make changes
   to the attributes of an existing LSP, or delegate control of specific
   LSPs to a new PCE.

   The ability to compute shortest constrained TE LSPs in Multiprotocol

Label Switching (MPLS) and Generalized MPLS (GMPLS) networks across
multiple domains has been identified as a key motivation for PCE
development. [RFC6805] describes a Hierarchical PCE (H-PCE)
architecture which can be used for computing end-to-end paths for
inter-domain MPLS Traffic Engineering (TE) and GMPLS Label Switched
Paths (LSPs). Within the Hierarchical PCE (H-PCE) architecture
[RFC6805], the Parent PCE (P-PCE) is used to compute a multi-domain
path based on the domain connectivity information. A Child PCE
(C-PCE) may be responsible for a single domain or multiple domains,
it is used to compute the intra-domain path based on its domain
topology information.

This document presents general considerations for stateful PCEs, and
not Stateless PCEs, in the hierarchical PCE architecture. In
particular, the behavior changes and additions to the existing
stateful PCE mechanisms (including PCE-initiated LSP setup and active
PCE usage) in the context of networks using the H-PCE architecture.

In this document, Sections 3.1 and 3.2 focus on end to end (E2E)
inter-domain TE LSP. Section 3.3.1 describes the operations for
stitching Per Domain LSPs.

1.2. Use-cases and Applicability of Hierarchical Stateful PCE

As per [RFC6805], in the hierarchical PCE architecture, a P-PCE
maintains a domain topology map that contains the child domains and
their interconnections. Usually, the P-PCE has no information about
the content of the child domains. But if the PCE is applied to the
Abstraction and Control of TE Networks (ACTN) [RFC8453] as described
in [I-D.ietf-pce-applicability-actn], the Provisioning Network
Controller (PNC) can provide an abstract topology to the Multi-Domain
Service Coordinator (MDSC). Thus the P-PCE in MDSC could be aware of
topology information in much more detail than just the domain
topology.

In a PCEP session between a PCC (Ingress) and a C-PCE, the C-PCE acts
as per the stateful PCE operations described in [RFC8231] and
[RFC8281]. The same C-PCE behaves as a PCC on the PCEP session
towards the P-PCE. The P-PCE is stateful in nature and thus maintains
the state of the inter-domain LSPs that are reported to it. The
inter-domain LSP could also be delegated by the C-PCE to the P-PCE,
so that the P-PCE could update the inter-domain path. The trigger for
this update could be the LSP state change reported for this LSP or
any other LSP. It could also be a change in topology at the P-PCE
such as inter-domain link status change. In case of use of stateful
H-PCE in ACTN, a change in abstract topology learned by the P-PCE
could also trigger the update. Some other external factors (such as a
measurement probe) could also be a trigger at the P-PCE. Any such

update would require an inter-domain path recomputation as described
in [RFC6805].

The inter-domain LSP could be set up using the end-to-end signaling
as described in [RFC6805]. Additionally a per-domain stitched LSP
model is also applicable in a P-PCE initiation model. Section 3.1,
Section 3.2, and Section 3.3 describe the end-to-end Contiguous LSP
setup, whereas Section 3.3.1 describe the per-domain stitching.

1.2.1. Applicability to ACTN

[RFC8453] describes a framework for the Abstraction and Control of TE
Networks (ACTN), where each Provisioning Network Controller (PNC) is
equivalent to a C-PCE, and the P-PCE is the Multi-Domain Service
Coordinator (MDSC). The Per Domain stitched LSP as per the
Hierarchical PCE architecture described in Section 3.3.1 and Section
4.1 is well suited for ACTN deployments.

[I-D.ietf-pce-applicability-actn] examines the applicability of PCE
to the ACTN framework. To support the function of multi domain
coordination via hierarchy, the hierarchy of stateful PCEs play a
crucial role.

In the ACTN framework, a Customer Network Controller (CNC) can
request the MDSC to check whether there is a possibility to meet
Virtual Network (VN) requirements before requesting for the VN to be
provisioned. The H-PCE architecture as described in [RFC6805] can
support this function using PCReq and PCRep messages between the
P-PCE and C-PCEs. When the CNC requests for VN provisioning, the MDSC
decompose this request into multiple inter-domain LSP provisioning
requests, which might be further decomposed to per-domain path
segments. This is described in Section 3.3.1. The MDSC uses the LSP
Initiate Request (PCInitiate) message from the P-PCE towards the
C-PCE, and the C-PCE reports the state back to the P-PCE via a Path
Computation State Report (PCRpt) message. The P-PCE could make
changes to the LSP via the use of a Path Computation Update Request
(PCUpd) message.

In this case, the P-PCE (as MDSC) interacts with multiple C-PCEs (as
PNCs) along the inter-domain path of the LSP.

1.2.2. End-to-End Contiguous LSP

Different signaling methods for inter-domain RSVP-TE signaling are
identified in [RFC4726]. Contiguous LSPs are achieved using the
procedures of [RFC3209] and [RFC3473] to create a single end-to-end
LSP that spans all domains. [RFC6805] describes the technique to

establish the optimum path when the sequence of domains is not known
in advance. It shows how the PCE architecture can be extended to
allow the optimum sequence of domains to be selected, and the optimum
end-to-end path to be derived.

In case of a stateful P-PCE, the stateful P-PCE has to be aware of
the inter-domain LSPs for it to consider them during path
computation. For example, a domain diverse path from another LSP.
This is the Passive Stateful P-PCE as described in Section 3.1.
Additionally, the inter-domain LSP could be delegated to the P-PCE,
so that P-PCE could trigger an update via a PCUpd message. The update
could be triggered on receipt of the PCRpt message that indicates a
status change of this LSP or some other LSP. The other LSP could be
an associated LSP (such as protection) or an unrelated LSP whose
resource change leads to re-optimization at the P-PCE. This is the
Active Stateful Operation as described in Section 3.2. Further, the
P-PCE could be instructed to create an inter-domain LSP on its own
using the PCInitiate message for an E2E contiguous LSP. The P-PCE
would send the PCInitiate message to the Ingress domain C-PCE, which
would further instruct the Ingress PCC.

In this document, for the Contiguous LSP, the above interactions are
only between the ingress domain C-PCE and the P-PCE. The use of
stateful operations for an inter-domain LSP between the
transit/egress domain C-PCEs towards the P-PCE is out of scope of
this document.

1.2.3. Applicability of a Stateful P-PCE

[RFC8051] describes general considerations for a stateful PCE
deployment and examines its applicability and benefits, as well as
its challenges and limitations, through a number of use cases. These
are also applicable to the stateful P-PCE when used for the inter-
domain LSP path computation and setup. It should be noted that though
the stateful P-PCE has limited direct visibility inside the child
domain, it could still trigger re-optimization with the help of child
PCEs based on LSP state changes, abstract topology changes, or some
other external factors.

The C-PCE would delegate control of the inter-domain LSP to the P-PCE
so that the P-PCE can make changes to it. Note that, if the C-PCE
becomes aware of a topology change that is hidden from the P-PCE, it
could take back the delegation from the P-PCE to act on it itself.
Similarly, a P-PCE could also request for delegation if it needs to
make a change to the LSP (refer to
[I-D.ietf-pce-lsp-control-request]).

2. Terminology

The terminology is as per [RFC4655], [RFC5440], [RFC6805], [RFC8051],
[RFC8231], and [RFC8281].

3. Hierarchical Stateful PCE

   As described in [RFC6805], in the hierarchical PCE architecture, a
   P-PCE maintains a domain topology map that contains the child domains
   (seen as vertices in the topology) and their interconnections (links
   in the topology). The P-PCE has no information about the content of
   the child domains. Each child domain has at least one PCE capable of
   computing paths across the domain. These PCEs are known as C-PCEs
   and have a direct relationship with the P-PCE. The P-PCE builds the
   domain topology map either via direct configuration (allowing network
   policy to also be applied) or from learned information received from
   each C-PCE.

   Note that, in the scope of this document, both the C-PCEs and the P-
   PCE are stateful in nature.

   [RFC8231] specifies new functions to support a stateful PCE. It also
   specifies that a function can be initiated either from a PCC towards
   a PCE (C-E) or from a PCE towards a PCC (E-C).

   This document extends these functions to support H-PCE Architecture
   from a C-PCE towards P-PCE (EC-EP) or from a P-PCE towards C-PCE
   (EP-EC). All PCE types herein (i.e., EC-EP or EP-EC) are assumed to
   be "stateful PCE".

   A number of interactions are expected in the Hierarchical Stateful
   PCE architecture, these include:

   LSP State Report (EC-EP): a child stateful PCE sends an LSP state
      report to a Parent Stateful PCE whenever the state of a LSP
      changes.

   LSP State Synchronization (EC-EP): after the session between the
      Child and Parent stateful PCEs is initialized, the P-PCE must
      learn the state of C-PCE's TE LSPs.

   LSP Control Delegation (EC-EP,EP-EC): a C-PCE grants to the P-PCE
      the right to update LSP attributes on one or more LSPs; the C-PCE
      may withdraw the delegation or the P-PCE may give up the
      delegation at any time.

   LSP Update Request (EP-EC): a stateful P-PCE requests modification
      of attributes on a C-PCE's TE LSP.

   PCE LSP Initiation Request (EP-EC): a stateful P-PCE requests C-PCE
      to initiate a TE LSP.

Note that this hierarchy is recursive and thus a Label Switching
Router (LSR), as a PCC could delegate the control to a PCE, which may
delegate to its parent, which may further delegate it to its parent
(if it exist or needed). Similarly update operations could also be
applied recursively.

[I-D.ietf-pce-hierarchy-extensions] defines the H-PCE Capability TLV
that is used in the OPEN message to advertise the H-PCE capability.
[RFC8231] defines the Stateful PCE Capability TLV used in the OPEN
message to indicate stateful support. The presence of both TLVs in
an OPEN message indicates the support for stateful H-PCE operations
as described in this document.

Further consideration may be made for optional procedures for
stateful communication coordination between PCEs, including
procedures to minimise computational loops. The procedures described
in [I-D.litkowski-pce-state-sync] facilitate stateful communication
between PCEs for various use-cases. The procedures and extensions as
described in Section 3 of [I-D.litkowski-pce-state-sync] are also
applicable to Child and Parent PCE communication. The
SPEAKER-IDENTITY-TLV (defined in [RFC8232]) is included in the LSP
object to identify the Ingress (PCC). The PLSP-ID used in the
forwarded PCRpt by the C-PCE to P-PCE is same as the original one
used by the PCC.

3.1. Passive Operations

Procedures as described in [RFC6805] are applied and where the
ingress C-PCE (Child PCE), triggers a path computation request for
the LER in the domain where the LSP originates, sends a request to
the P-PCE. The P-PCE selects a set of candidate domain paths based on
the domain topology and the state of the inter-domain links. It then
sends computation requests to the C-PCEs responsible for each of the
domains on the candidate domain paths. Each C-PCE computes a set of
candidate path segments across its domain and sends the results to
the P-PCE. The P-PCE uses this information to select path segments
and concatenate them to derive the optimal end-to-end inter-domain
path. The end-to-end path is then sent to the C-PCE that received
the initial path request, and this C-PCE passes the path on to the
PCC that issued the original request.

As per [RFC8231], PCC sends an LSP State Report carried on a PCRpt
message to the C-PCE, indicating the LSP's status. The C-PCE may
further propagate the State Report to the P-PCE. A local policy at
C-PCE may dictate which LSPs to be reported to the P-PCE. The PCRpt
message is sent from C-PCE to P-PCE.

State synchronization mechanism as described in [RFC8231] and

[RFC8232] are applicable to a PCEP session between C-PCE and P-PCE as
well.

We use the sample hierarchical domain topology example from [RFC6805]
as the reference topology for the entirety of this document. It is
shown in Figure 1.

```
    -------------------------------------------------------------------
   |    Domain 5                                                       |
   |                            -----                                  |
   |                           |PCE 5|                                 |
   |                            -----                                  |
   |                                                                   |
   |    ----------------    ----------------    ----------------       |
   |   | Domain 1       |  | Domain 2       |  | Domain 3       |   |  |
   |   |                |  |                |  |                |   |  |
   |   |       -----    |  |       -----    |  |       -----    |   |  |
   |   |      |PCE 1|   |  |      |PCE 2|   |  |      |PCE 3|   |   |  |
   |   |       -----    |  |       -----    |  |       -----    |   |  |
   |   |                |  |                |  |                |   |  |
   |   |         ----|   |----         ----|   |----            |   |  |
   |   |        |BN11+---+BN21|        |BN23+---+BN31|           |   |  |
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   |   |    -    ----|   |----         ----|   |----      -      |   |  |
   |   |        |BN12+---+BN22|        |BN24+---+BN32|           |   |  |
   |   |         ----|   |----         ----|   |----            |   |  |
   |   |                |  |                |  |                |   |  |
   |   |       ----     |  |                |  |    ----        |   |  |
   |   |      |BN13|    |  |                |  |   |BN33|       |   |  |
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   |                     |       -----    |                           |
   |                     |      |PCE 4|   |                           |
   |                     |       -----    |                           |
   |                     |                |                           |
   |                     | Domain 4       |                           |
   |                      ----------------                            |
   |                                                                   |
    -------------------------------------------------------------------
```
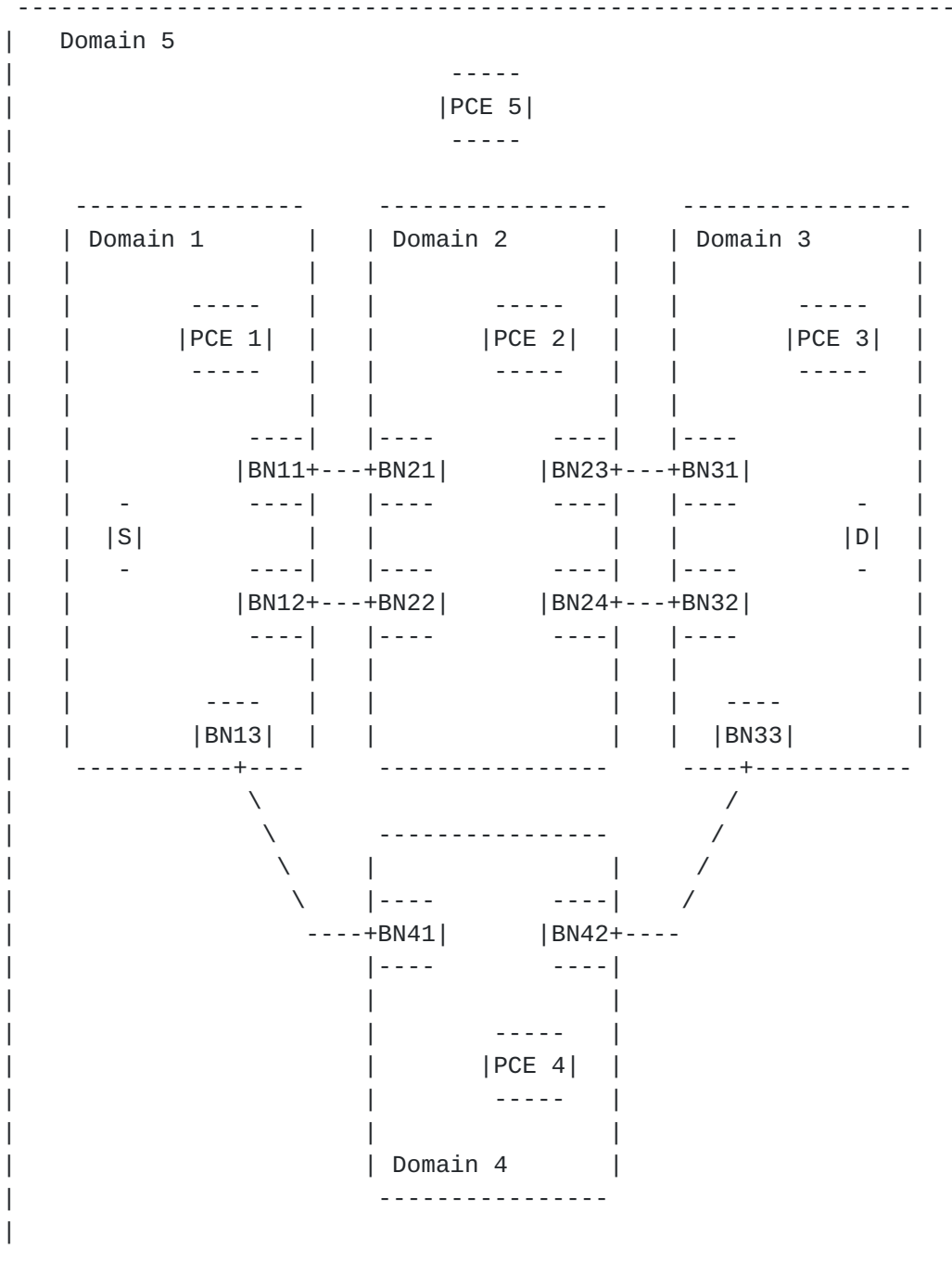
                Figure 1: Sample Hierarchical Domain Topology

Steps 1 to 11 are exactly as described in section 4.6.2 (Hierarchical
PCE End-to-End Path Computation Procedure) of [RFC6805], the
following additional steps are added for stateful PCE:

(A) The Ingress LSR initiates the setup of the LSP as per the path
     and reports to the PCE1 the LSP status ("GOING-UP").

(B) The PCE1 further reports the status of the LSP to the P-PCE
     (PCE5).

(C) The Ingress LSR notifies the LSP state to PCE1 when the state is
     "UP".

(D) The PCE1 further reports the status of the LSP to the P-PCE
     (PCE5).

The Ingress LSR could trigger path re-optimization by sending the
path computation request as described in [RFC6805], at this time it
can include the LSP object in the PCReq message as described in
[RFC8231].

3.2. Active Operations

[RFC8231] describes the case of active stateful PCE. The active PCE
functionality uses two specific PCEP messages:

o Update Request (PCUpd)

o State Report (PCRpt)

The first is sent by the PCE to a Path Computation Client (PCC) for
modifying LSP attributes. The PCC sends back a PCRpt to acknowledge
the requested operation or report any change in LSP's state.

As per [RFC8051], Delegation is an operation to grant a PCE,
temporary rights to modify a subset of LSP parameters on one or more
PCC's LSPs. The C-PCE may further choose to delegate to P-PCE based
on a local policy. The PCRpt message with "D" (delegate) flag is
sent from C-PCE to P-PCE.

To update an LSP, a PCE sends an LSP Update Request to the PCC using
a PCUpd message. For LSP delegated to the P-PCE via the child PCE,
the P-PCE can use the same PCUpd message to request change to the C-
PCE (the Ingress domain PCE), the PCE further propagates the update
request to the PCC.

The P-PCE uses the same mechanism described in Section 3.1 to compute
the end to end path using PCReq and PCRep messages.

For active operations, the following steps are required when
delegating the LSP, again using the reference architecture described
in Figure 1 (Sample Hierarchical Domain Topology).

(A) The Ingress LSR delegates the LSP to the PCE1 via PCRpt message
     with D flag set.

(B) The PCE1 further delegates the LSP to the P-PCE (PCE5).

(C) Steps 4 to 10 of section 4.6.2 of [RFC6805] are executed to
     determine the end to end path.

(D) The P-PCE (PCE5) sends the update request to the C-PCE (PCE1)
     via PCUpd message.

(E) The PCE1 further updates the LSP to the Ingress LSR (PCC).

(F) The Ingress LSR initiates the setup of the LSP as per the path
     and reports to the PCE1 the LSP status ("GOING-UP").

(G) The PCE1 further reports the status of the LSP to the P-PCE
     (PCE5).

(H) The Ingress LSR notifies the LSP state to PCE1 when the state is
     "UP".

(I) The PCE1 further reports the status of the LSP to the P-PCE
     (PCE5).

3.3. PCE Initiation of LSPs

[RFC8281] describes the setup, maintenance and teardown of PCE-
initiated LSPs under the stateful PCE model, without the need for
local configuration on the PCC, thus allowing for a dynamic network
that is centrally controlled and deployed. To instantiate or delete
an LSP, the PCE sends the Path Computation LSP Initiate Request
(PCInitiate) message to the PCC. In case of inter-domain LSP in
Hierarchical PCE architecture, the initiation operations can be
carried out at the P-PCE. In which case after P-PCE finishes the E2E
path computation, it can send the PCInitiate message to the C-PCE
(the Ingress domain PCE), the PCE further propagates the initiate
request to the PCC.

The following steps are performed, for PCE initiated operations,
again using the reference architecture described in Figure 1 (Sample
Hierarchical Domain Topology):

(A) The P-PCE (PCE5) is requested to initiate a LSP. Steps 4 to 10
     of section 4.6.2 of [RFC6805] are executed to determine the end
     to end path.

(B) The P-PCE (PCE5) sends the initiate request to the child PCE
     (PCE1) via PCInitiate message.

(C) The PCE1 further propagates the initiate message to the Ingress
     LSR (PCC).

(D) The Ingress LSR initiates the setup of the LSP as per the path
     and reports to the PCE1 the LSP status ("GOING-UP").

(E) The PCE1 further reports the status of the LSP to the P-PCE
     (PCE5).

(F) The Ingress LSR notifies the LSP state to PCE1 when the state is
     "UP".

(G) The PCE1 further reports the status of the LSP to the P-PCE
     (PCE5).

The Ingress LSR (PCC) would generate the PLSP-ID for the LSP and
inform the C-PCE, which is propagated to the P-PCE.

3.3.1. Per Domain Stitched LSP

The Hierarchical PCE architecture as per [RFC6805] is primarily used
for E2E LSP. With PCE-Initiated capability, another mode of
operation is possible, where multiple intra-domain LSPs are initiated
in each domain which are further stitched to form an E2E LSP. The
P-PCE sends PCInitiate message to each C-PCE separately to initiate
individual LSP segments along the domain path. These individual per
domain LSP are stitched together by some mechanism, which is out of
scope of this document (Refer [I-D.dugeon-pce-stateful-
interdomain]).

The following steps are performed, for the Per Domain stitched LSP
operation, again using the reference architecture described in Figure
1 (Sample Hierarchical Domain Topology):

(A) The P-PCE (PCE5) is requested to initiate a LSP. Steps 4 to 10
     of section 4.6.2 of [RFC6805] are executed to determine the end
     to end path, which are broken into per-domain LSPs say -

     o S-BN41

     o BN41-BN33

o BN33-D

It should be noted that the P-PCE may use other mechanisms to
determine the suitable per-domain LSPs (apart from [RFC6805]).

For LSP (BN33-D)

(B) The P-PCE (PCE5) sends the initiate request to the child PCE
     (PCE3) via PCInitiate message for LSP (BN33-D).

(C) The PCE3 further propagates the initiate message to BN33.

(D) BN33 initiates the setup of the LSP as per the path and reports
     to the PCE3 the LSP status ("GOING-UP").

(E) The PCE3 further reports the status of the LSP to the P-PCE
     (PCE5).

(F) The node BN33 notifies the LSP state to PCE3 when the state is
     "UP".

(G) The PCE3 further reports the status of the LSP to the P-PCE
     (PCE5).

For LSP (BN41-BN33)

(H) The P-PCE (PCE5) sends the initiate request to the child PCE
     (PCE4) via PCInitiate message for LSP (BN41-BN33).

(I) The PCE4 further propagates the initiate message to BN41.

(J) BN41 initiates the setup of the LSP as per the path and reports
     to the PCE4 the LSP status ("GOING-UP").

(K) The PCE4 further reports the status of the LSP to the P-PCE
     (PCE5).

(L) The node BN41 notifies the LSP state to PCE4 when the state is
     "UP".

(M) The PCE4 further reports the status of the LSP to the P-PCE
     (PCE5).

For LSP (S-BN41)

(N) The P-PCE (PCE5) sends the initiate request to the child PCE
     (PCE1) via PCInitiate message for LSP (S-BN41).

(O) The PCE1 further propagates the initiate message to node S.

(P) S initiates the setup of the LSP as per the path and reports to
     the PCE1 the LSP status ("GOING-UP").

(Q) The PCE1 further reports the status of the LSP to the P-PCE
     (PCE5).

(R) The node S notifies the LSP state to PCE1 when the state is
     "UP".

(S) The PCE1 further reports the status of the LSP to the P-PCE
     (PCE5).

Additionally:

(T) Once P-PCE receives report of each per-domain LSP, it should use
     suitable stitching mechanism, which is out of scope of this
     document. In this step, P-PCE (PCE5) could also initiate an E2E
     LSP (S-D) by sending the PCInitiate message to Ingress C-PCE
     (PCE1).

Note that each per-domain LSP can be setup in parallel. Further, it
is also possible to stitch the per-domain LSP at the same time as the
per-domain LSPs are initiated. This option is defined in
[I-D.dugeon-pce-stateful-interdomain].

4. Security Considerations

The security considerations listed in [RFC8231],[RFC6805] and
[RFC5440] apply to this document as well. As per [RFC6805], it is
expected that the parent PCE will require all child PCEs to use full
security when communicating with the parent.

Any multi-domain operation necessarily involves the exchange of
information across domain boundaries. This is bound to represent a
significant security and confidentiality risk especially when the
child domains are controlled by different commercial concerns. PCEP
allows individual PCEs to maintain confidentiality of their domain
path information using path-keys [RFC5520], and the hierarchical PCE
architecture is specifically designed to enable as much isolation of
domain topology and capabilities information as is possible. The LSP
state in the PCRpt message must continue to maintain the internal
domain confidentiality when required.

The security consideration for PCE-Initiated LSP as per [RFC8281] is
also applicable from P-PCE to C-PCE.

Further, section 6.3 describes the use of path-key [RFC5520] for
confidentiality between C-PCE and P-PCE.

Thus securing the PCEP session (between the P-PCE and the C-PCE)
using the TCP Authentication Option (TCP-AO) [RFC5925] or Transport
Layer Security (TLS) [RFC8253] mechanisms are recommended.

5. Manageability Considerations

All manageability requirements and considerations listed in
[RFC5440], [RFC6805], [RFC8231], and [RFC8281] apply to Stateful H-
PCE defined in this document. In addition, requirements and
considerations listed in this section apply.

5.1. Control of Function and Policy

Support of the hierarchical procedure will be controlled by the
management organization responsible for each child PCE. The parent
PCE must only accept path computation requests from authorized child
PCEs. If a parent PCE receives report from an unauthorized child
PCE, the report should be dropped. All mechanism as described in
[RFC8231] and [RFC8281] continue to apply.

5.2. Information and Data Models

An implementation should allow the operator to view the stateful and
H-PCE capabilities advertised by each peer. The PCEP YANG module
[I-D.ietf-pce-pcep-yang] may be extended to include details for
stateful H-PCE deployment and operation, exact attributes to be
modeled is out of scope for this document.

5.3. Liveness Detection and Monitoring

Mechanisms defined in this document do not imply any new liveness
detection and monitoring requirements in addition to those already
listed in [RFC5440].

5.4. Verify Correct Operations

Mechanisms defined in this document do not imply any new operation
verification requirements in addition to those already listed in
[RFC5440] and [RFC8231].

5.5. Requirements On Other Protocols

Mechanisms defined in this document do not imply any new requirements
on other protocols.

5.6. Impact On Network Operations

   Mechanisms defined in [RFC5440] and [RFC8231] also apply to PCEP
   extensions defined in this document.

   The stateful H-PCE technique brings the applicability of stateful PCE
   as described in [RFC8051], for the LSP traversing multiple domains.

5.7. Error Handling between PCEs

   Error types and notifications useful for correct PCEP operation may
   be implemented for managing parent and child PCE interaction. PCEP
   Error behavior propagation, notification and error criticality level,
   are further defined in [I-D.ietf-pce-enhanced-errors].

6. Other Considerations

6.1. Applicability to Inter-Layer Traffic Engineering

   [RFC5623] describes a framework for applying the PCE-based
   architecture to inter-layer (G)MPLS traffic engineering. The H-PCE
   Stateful architecture with stateful P-PCE coordinating with the
   stateful C-PCEs of higher and lower layer is shown in the figure
   below.

```
                                        +----------+
                                        | Parent   |
                                       /| PCE      |
                                      / +----------+
                                     /     /   Stateful
                                    /     /     P-PCE
                                   /     /
                                  /     /
                  Stateful+-----+ /     /
                  C-PCE   | PCE |/     /
                  Hi      | Hi  |     /
                          +-----+    /
     +---+     +---+                /      +---+     +---+
    + LSR +--+ LSR +.......................+ LSR +--+ LSR +
    + H1  +  + H2  +              /        + H3  +  + H4  +
     +---+     +---+\        +-----+/       /+---+     +---+
                 \        | PCE |       /
                  \       | Lo  |      /
          Stateful  \     +-----+     /
          C-PCE       \              /
          Lo           \+---+     +---+/
                       + LSR +--+ LSR +
```

```
                          + L1  +  + L2  +
                           +---+     +---+
```
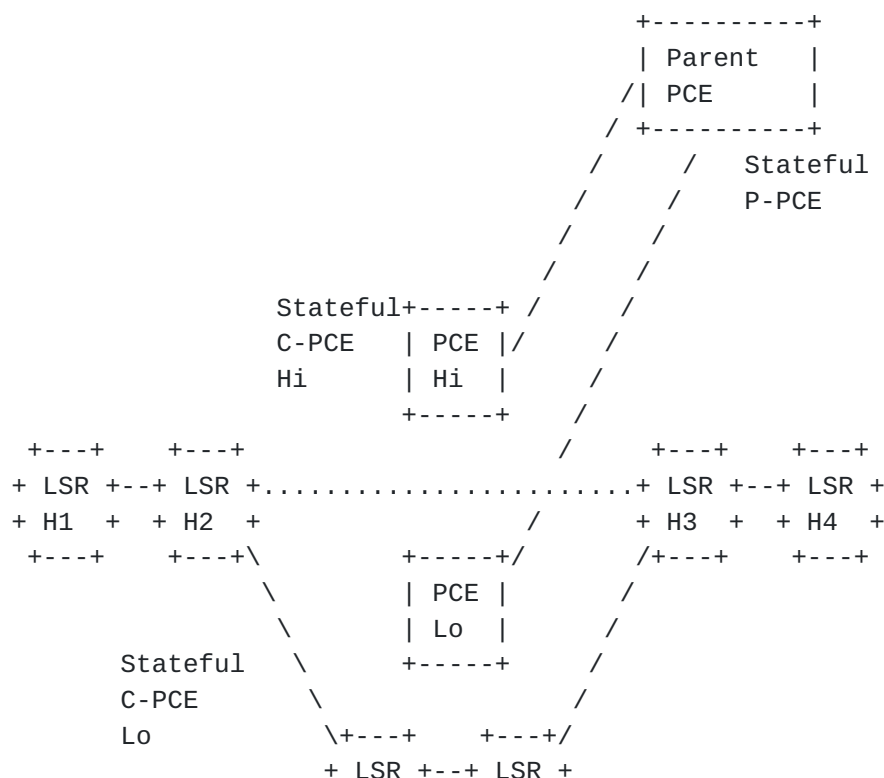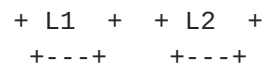
              Figure 2: Sample Inter-Layer Topology

   All procedures described in Section 3 are applicable to inter-layer
   (and therefore separate domains) path setup as well.

6.2. Scalability Considerations

   It should be noted that if all the C-PCEs would report all the LSPs
   in their domain, it could lead to scalability issues for the P-PCE.
   Thus it is recommended to only report the LSPs which are involved in
   H-PCE, i.e. the LSPs which are either delegated to the P-PCE or
   initiated by the P-PCE. Scalability considerations for PCEP as per
   [RFC8231] continue to apply for the PCEP session between child and
   parent PCE.

6.3. Confidentiality

   As described in section 4.2 of [RFC6805], information about the
   content of child domains is not shared for both scaling and
   confidentiality reasons. Along with the confidentiality during path
   computation, the child PCE could also conceal the path information, a
   C-PCE may replace a path segment with a path-key [RFC5520],
   effectively hiding the content of a segment of a path.

7. IANA Considerations

   There are no IANA considerations.

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9. References

9.1. Normative References

   [RFC4655] Farrel, A., Vasseur, J., and J. Ash, "A Path Computation
              Element (PCE)-Based Architecture", RFC 4655,
              DOI 10.17487/RFC4655, August 2006,
              <https://www.rfc-editor.org/info/rfc4655>.

   [RFC5440] Vasseur, JP., Ed. and JL. Le Roux, Ed., "Path Computation
              Element (PCE) Communication Protocol (PCEP)", RFC 5440,
              DOI 10.17487/RFC5440, March 2009,
              <http://www.rfc-editor.org/info/rfc5440>.

   [RFC5520] Bradford, R., Ed., Vasseur, JP., and A. Farrel,
              "Preserving Topology Confidentiality in Inter-Domain Path
              Computation Using a Path-Key-Based Mechanism", RFC 5520,
              DOI 10.17487/RFC5520, April 2009,
              <https://www.rfc-editor.org/info/rfc5520>.

   [RFC6805] King, D., Ed. and A. Farrel, Ed., "The Application of the
              Path Computation Element Architecture to the Determination
              of a Sequence of Domains in MPLS and GMPLS", RFC 6805, DOI
              10.17487/RFC6805, November 2012,
              <http://www.rfc-editor.org/info/rfc6805>.

   [RFC8231] Crabbe, E., Minei, I., Medved, J., and R. Varga, "Path
              Computation Element Communication Protocol (PCEP)
              Extensions for Stateful PCE", RFC 8231,
              DOI 10.17487/RFC8231, September 2017,
              <https://www.rfc-editor.org/info/rfc8231>.

   [RFC8281] Crabbe, E., Minei, I., Sivabalan, S., and R. Varga, "Path
              Computation Element Communication Protocol (PCEP)
              Extensions for PCE-Initiated LSP Setup in a Stateful PCE
              Model", RFC 8281, DOI 10.17487/RFC8281, December 2017,
              <https://www.rfc-editor.org/info/rfc8281>.

9.2. Informative References

   [RFC3209] Awduche, D., Berger, L., Gan, D., Li, T., Srinivasan, V.,
              and G. Swallow, "RSVP-TE: Extensions to RSVP for LSP
              Tunnels", RFC 3209, DOI 10.17487/RFC3209, December 2001,
              <https://www.rfc-editor.org/info/rfc3209>.

   [RFC3473] Berger, L., Ed., "Generalized Multi-Protocol Label
              Switching (GMPLS) Signaling Resource ReserVation Protocol-
              Traffic Engineering (RSVP-TE) Extensions", RFC 3473,
              DOI 10.17487/RFC3473, January 2003,
              <https://www.rfc-editor.org/info/rfc3473>.

   [RFC4726] Farrel, A., Vasseur, J., and A. Ayyangar, "A Framework for
              Inter-Domain Multiprotocol Label Switching Traffic
              Engineering", RFC 4726, DOI 10.17487/RFC4726, November
              2006, <https://www.rfc-editor.org/info/rfc4726>.

   [RFC5623] Oki, E., Takeda, T., Le Roux, JL., and A. Farrel,

                 "Framework for PCE-Based Inter-Layer MPLS and GMPLS
                 Traffic Engineering", RFC 5623, DOI 10.17487/RFC5623,
                 September 2009,
                 <https://www.rfc-editor.org/info/rfc5623>.

   [RFC5925]   Touch, J., Mankin, A., and R. Bonica, "The TCP
                 Authentication Option", RFC 5925, DOI 10.17487/RFC5925,
                 June 2010, <https://www.rfc-editor.org/info/rfc5925>.

   [RFC8051]   Zhang, X., Ed. and I. Minei, Ed., "Applicability of a
                 Stateful Path Computation Element (PCE)", RFC 8051,
                 DOI 10.17487/RFC8051, January 2017,
                 <https://www.rfc-editor.org/info/rfc8051>.

   [RFC8232]   Crabbe, E., Minei, I., Medved, J., Varga, R., Zhang, X.,
                 and D. Dhody, "Optimizations of Label Switched Path State
                 Synchronization Procedures for a Stateful PCE", RFC 8232,
                 DOI 10.17487/RFC8232, September 2017,
                 <https://www.rfc-editor.org/info/rfc8232>.

   [RFC8253]   Lopez, D., Gonzalez de Dios, O., Wu, Q., and D. Dhody,
                 "PCEPS: Usage of TLS to Provide a Secure Transport for the
                 Path Computation Element Communication Protocol (PCEP)",
                 RFC 8253, DOI 10.17487/RFC8253, October 2017,
                 <https://www.rfc-editor.org/info/rfc8253>.

   [RFC8453]   Ceccarelli, D., Ed. and Y. Lee, Ed., "Framework for
                 Abstraction and Control of TE Networks (ACTN)", RFC 8453,
                 DOI 10.17487/RFC8453, August 2018,
                 <https://www.rfc-editor.org/info/rfc8453>.

   [I-D.ietf-pce-applicability-actn]
                 Dhody, D., Lee, Y., and D. Ceccarelli, "Applicability of
                 Path Computation Element (PCE) for Abstraction and
                 Control of TE Networks (ACTN)", draft-ietf-pce-
                 applicability-actn-12 (work in progress), May 2019.

   [I-D.litkowski-pce-state-sync]
                 Litkowski, S., Sivabalan, S., and D. Dhody, "Inter
                 Stateful Path Computation Element communication
                 procedures", draft-litkowski-pce-state-sync-05 (work in
                 progress), March 2019.

   [I-D.ietf-pce-hierarchy-extensions]
                 Zhang, F., Zhao, Q., Dios, O., Casellas, R., and D. King,
                 "Extensions to Path Computation Element Communication
                 Protocol (PCEP) for Hierarchical Path Computation Elements
                 (PCE)", draft-ietf-pce-hierarchy-extensions-11 (work in

                   progress), June 2019.

     [I-D.ietf-pce-pcep-yang]
                   Dhody, D., Hardwick, J., Beeram, V., and J. Tantsura, "A
                   YANG Data Model for Path Computation Element
                   Communications Protocol (PCEP)",
                   draft-ietf-pce-pcep-yang-12 (work in progress), July 2019.

     [I-D.dugeon-pce-stateful-interdomain]
                   Dugeon, O., Meuric, J., Lee, Y., Dhody, D., and D.
                   Ceccarelli, "PCEP Extension for Stateful Inter-Domain
                   Tunnels", draft-dugeon-pce-stateful-interdomain-02 (work
                   in progress), March 2019.

     [I-D.ietf-pce-lsp-control-request]
                   Raghuram, A., Goddard, A., Yadlapalli, C., Karthik, J.,
                   Sivabalan, S., Parker, J., and M. Negi, "Ability for a
                   stateful Path Computation Element (PCE) to request and
                   obtain control of a LSP", draft-ietf-pce-lsp-control-
                   request-06 (work in progress), June 2019.

     [I-D.ietf-pce-enhanced-errors]
                   Pouyllau, et al., "Extensions to PCEP for Enhanced Errors"
                   , draft-ietf-pce-enhanced-errors-05 (work in progress),
                   February 2019.

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