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PCEP Procedures and Protocol Extensions for Using PCE as a Central
Controller (PCECC) of LSPs
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Abstract

The Path Computation Element (PCE) is a core component of Software-Defined Networking (SDN) systems.

A PCE-based Central Controller (PCECC) can simplify the processing of a distributed control plane by blending it with elements of SDN and without necessarily completely replacing it. Thus, the LSP can be calculated/set up/initiated and the label forwarding entries can also be downloaded through a centralized PCE server to each network device along the path, while leveraging the existing PCE technologies as much as possible.

This document specifies the procedures and PCEP extensions for using the PCE as the central controller for provisioning labels along the path of the static LSP.

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1. Introduction

The Path Computation Element (PCE) [RFC4655] was developed to offload the path computation function from routers in an MPLS traffic-engineered network. It can compute optimal paths for traffic across a network and can also update the paths to reflect changes in the network or traffic demands. Since then, the role and function of the PCE has grown to cover a number of other uses (such as GMPLS [RFC7025]) and to allow delegated control [RFC8231] and PCE-initiated use of network resources [RFC8281].

According to [RFC7399], Software-Defined Networking (SDN) refers to a separation between the control elements and the forwarding components so that software running in a centralized system, called a controller, can act to program the devices in the network to behave in specific ways. A required element in an SDN architecture is a component that plans how the network resources will be used and how the devices will be programmed. It is possible to view this component as performing specific computations to place traffic flows within the network given knowledge of the availability of network resources, how other forwarding devices are programmed, and the way

that other flows are routed. This is the function and purpose of a PCE, and the way that a PCE integrates into a wider network control system (including an SDN system) is presented in [RFC7491].

In early PCE implementations, where the PCE was used to derive paths for MPLS Label Switched Paths (LSPs), paths were requested by network elements (known as Path Computation Clients (PCCs)), and the results of the path computations were supplied to network elements using the Path Computation Element Communication Protocol (PCEP) [RFC5440]. This protocol was later extended to allow a PCE to send unsolicited requests to the network for LSP establishment [RFC8281].

PCE was developed to derive paths for MPLS Label Switched Paths (LSPs), which are supplied to the head end of the LSP using the Path Computation Element Communication Protocol (PCEP). But SDN has a broader applicability than signaled MPLS and GMPLS traffic-engineered (TE) networks, and the PCE may be used to determine paths in a range of use cases. PCEP has been proposed as a control protocol for use in these environments to allow the PCE to be fully enabled as a central controller.

[RFC8283] introduces the architecture for PCE as a central controller as an extension of the architecture described in [RFC4655] and assumes the continued use of PCEP as the protocol used between PCE and PCC. [RFC8283] further examines the motivations and applicability for PCEP as a Southbound Interface (SBI), and introduces the implications for the protocol. [I-D.ietf-teas-pcecc-use-cases] describes the use cases for the PCECC architecture.

A PCE-based Central Controller (PCECC) can simplify the processing of a distributed control plane by blending it with elements of SDN and without necessarily completely replacing it. Thus, the LSP can be calculated/setup/initiated and the label forwarding entries can also be downloaded through a centralized PCE server to each network device along the path while leveraging the existing PCE technologies as much as possible.

This document specifies the procedures and PCEP extensions for using the PCE as the central controller for static LSPs, where LSPs can be provisioned as explicit label instructions at each hop on the end-to-end path. Each router along the path must be told what label-forwarding instructions to program and what resources to reserve. The PCE-based controller keeps a view of the network and determines the paths of the end-to-end LSPs, and the controller uses PCEP to communicate with each router along the path of the end-to-end LSP.

While this document is focused on the procedures for the static LSPs (referred to as basic PCECC mode in Section 3), the mechanisms and protocol encodings are specified in such a way that extensions for other use cases are easy to achieve. For example, the extensions for PCECC for Segment Routing (SR) are specified in [I-D.ietf-pce-pcep-extension-pce-controller-sr] and [I-D.dhody-pce-pcep-extension-pce-controller-srv6].

1.1. Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

2. Terminology

The terminology used in this document is the same as that described in the [RFC8283].

3. Basic PCECC Mode

In this mode, LSPs are provisioned as explicit label instructions at each hop on the end-to-end path. Each router along the path must be told what label forwarding instructions to program and what resources to reserve. The controller uses PCEP to communicate with each router along the path of the end-to-end LSP.

[RFC8283] examines the motivations and applicability for PCECC and use of PCEP as an SBI. Section 3.1.2. of [RFC8283] highlights the use of PCECC for label allocation along the static LSPs and it simplifies the processing of a distributed control plane by blending it with elements of SDN and without necessarily completely replacing it. This allows the operator to introduce the advantages of SDN (such as programmability) into the network. Further Section 3.3. of [I-D.ietf-teas-pcecc-use-cases] describes some of the scenarios where the PCECC technique could be useful. Section 4 of [RFC8283] also describe the implications on the protocol when used as an SDN SBI. The operator needs to evaluate the advantages offered by PCECC against the operational and scalability needs of the PCECC.

As per Section 3.1.2. of [RFC8283], the PCE-based controller will take responsibility for managing some part of the MPLS label space for each of the routers that it controls, and may take wider responsibility for partitioning the label space for each router and allocating different parts for different uses. The PCC MUST NOT make allocations from the label space set aside for the PCE to avoid

overlap and collisions of label allocations. It is RECOMMENDED that PCE makes allocations (from the label space set aside for the PCE) for all nodes along the path. For the purpose of this document, it is assumed that the exclusive label range to be used by a PCE is known and set on both PCEP peers. A future extension could add the capability to advertise this range via a possible PCEP extension as well (see [I-D.li-pce-controlled-id-space]). The rest of the processing is similar to the existing stateful PCE mechanism.

This document also allows a case where the label space is maintained by the PCC and the labels are allocated by it. In this case, the PCE should request the allocation from PCC as described in Section 5.5.8.

4. PCEP Requirements

The following key requirements should be considered when designing the PCECC-based solution:

1. A PCEP speaker supporting this document needs to have the capability to advertise its PCECC capability to its peers.
2. A PCEP speaker need means to identify PCECC-based LSP in the PCEP messages.
3. PCEP procedures need to allow for PCC-based label allocations.
4. PCEP procedures need to provide a means to update (or clean up) label entries downloaded to the PCC.
5. PCEP procedures need to provide a means to synchronize the labels between the PCE and the PCC via PCEP messages.

5. Procedures for Using the PCE as a Central Controller (PCECC)

5.1. Stateful PCE Model

Active stateful PCE is described in [RFC8231]. PCE as a central controller (PCECC) reuses the existing active stateful PCE mechanism as much as possible to control LSPs.

5.2. New LSP Functions

Several new functions are required in PCEP to support PCECC. This document extends the existing messages to support the new functions required by PCECC:

PCInitiate: a PCEP message described in [RFC8281]. PCInitiate message is used to set up PCE-Initiated LSP based on PCECC

mechanism. It is also extended for Central Controller Instructions (CCI) (download or clean up the Label forwarding instructions in the context of this document) on all nodes along the path as described in Section 6.1.

PCRpt: a PCEP message described in [RFC8231]. PCRpt message is used to send PCECC LSP Reports. It is also extended to report the set of Central Controller Instructions (CCI) (label forwarding instructions in the context of this document) received from the PCE as described in Section 6.2. Section 5.5.6 describes the use of PCRpt message during synchronization.

PCUpd: a PCEP message described in [RFC8231]. PCUpd message is used to send PCECC LSP Updates.

The new functions defined in this document are mapped onto the PCEP messages as shown in Table 1.

Function	Message
PCECC Capability advertisement	Open
Label entry Add	PCInitiate
Label entry Clean up	PCInitiate
PCECC Initiated LSP	PCInitiate
PCECC LSP Update	PCUpd
PCECC LSP State Report	PCRpt
PCECC LSP Delegation	PCRpt
PCECC Label Report	PCRpt

Table 1: Functions mapped to the PCEP messages

5.3. New PCEP Object

This document defines a new PCEP object called CCI (Section 7.3) to specify the central controller instructions. In the scope of this document, this is limited to Label forwarding instructions. Future documents can create new CCI object-types for other types of central controller instructions. The CC-ID is the unique identifier for the central controller instructions in PCEP. The PCEP messages are extended in this document to handle the PCECC operations.

5.4. PCECC Capability Advertisement

During the PCEP Initialization Phase, PCEP Speakers (PCE or PCC) advertise their support of and willingness to use PCEP extensions for PCECC using these elements in the OPEN message:

- o A new Path Setup Type (PST) (Section 7.2) in the PATH-SETUP-TYPE-CAPABILITY TLV to indicate support for PCEP extensions for PCECC - TBD1 (Path is set up via PCECC mode)
- o A new PCECC-CAPABILITY sub-TLV (Section 7.1.1) with the L bit set to 1 inside the PATH-SETUP-TYPE-CAPABILITY TLV to indicate a willingness to use PCEP extensions for PCECC based central controller instructions for label download
- o The STATEFUL-PCE-CAPABILITY TLV ([RFC8231]) (with the I flag set [RFC8281])

The new Path Setup Type is to be listed in the PATH-SETUP-TYPE-CAPABILITY TLV by all PCEP speakers which support the PCEP extensions for PCECC in this document.

The new PCECC-CAPABILITY sub-TLV is included in PATH-SETUP-TYPE-CAPABILITY TLV in the OPEN object to indicate a willingness to use the PCEP extensions for PCECC during the established PCEP session. Using the L bit in this TLV, the PCE shows the intention to function as a PCECC server, and the PCC shows a willingness to act as a PCECC client for label download instructions (see Section 7.1.1).

If the PCECC-CAPABILITY sub-TLV is advertised and the STATEFUL-PCE-CAPABILITY TLV is not advertised, or is advertised without the I flag set, in the OPEN Object, the receiver MUST:

- o Send a PCERR message with Error-Type=19 (Invalid Operation) and Error-value=TBD4 (stateful PCE capability was not advertised)
- o Terminate the session

If a PCEP speaker receives the PATH-SETUP-TYPE-CAPABILITY TLV with the PCECC Path Setup Type but without the PCECC-CAPABILITY sub-TLV, it MUST:

- o Send a PCERR message with Error-Type 10 (Reception of an invalid object) and Error-Value TBD2 (Missing PCECC-CAPABILITY sub-TLV)
- o Terminate the PCEP session

The PCECC-CAPABILITY sub-TLV MUST NOT be used without the corresponding Path Setup Type being listed in the PATH-SETUP-TYPE-CAPABILITY TLV. If it is present without the corresponding Path Setup Type listed in the PATH-SETUP-TYPE-CAPABILITY TLV, it MUST be ignored.

If one or both speakers (PCE and PCC) have not indicated support and willingness to use the PCEP extensions for PCECC, the PCEP extensions for PCECC MUST NOT be used. If a PCECC operation is attempted when both speakers have not agreed in the OPEN messages, the receiver of the message MUST:

- o Send a PCErr message with Error-Type=19 (Invalid Operation) and Error-Value=TBD3 (Attempted PCECC operations when PCECC capability was not advertised)
- o Terminate the PCEP session

A legacy PCEP speaker (that does not recognize the PCECC Capability sub-TLV) will ignore the sub-TLV in accordance with [RFC8408] and [RFC5440]. As per [RFC8408], the legacy PCEP speaker on receipt of an unsupported PST in RP (Request Parameter) /SRP (Stateful PCE Request Parameters) Object will:

- o Send a PCErr message with Error-Type = 21 (Invalid traffic engineering path setup type) and Error-value = 1 (Unsupported path setup type)
- o Terminate the PCEP session

5.5. LSP Operations

The PCEP messages pertaining to a PCECC MUST include PATH-SETUP-TYPE TLV [RFC8408] in the SRP object [RFC8231] with PST set to TBD1 to clearly identify that PCECC LSP is intended.

5.5.1. PCE-Initiated PCECC LSP

The LSP Instantiation operation is defined in [RFC8281]. In order to set up a PCE-Initiated LSP based on the PCECC mechanism, a PCE sends PCInitiate message with PST set to TBD1 for PCECC (see Section 7.2) to the ingress PCC.

The label forwarding instructions (see Section 5.5.3) from PCECC are sent after the initial PCInitiate and PCRpt message exchange with the ingress PCC as per [RFC8281] (see Figure 1). This is done so that the PLSP-ID and other LSP identifiers can be obtained from the ingress and can be included in the label forwarding instruction in the next set of PCInitiate messages along the path as described below.

An LSP-IDENTIFIERS TLV [RFC8231] MUST be included for PCECC LSPs, it uniquely identifies the LSP in the network. Note that the fields in the LSP-IDENTIFIERS TLV are described for the RSVP-signaled LSPs but

are applicable to the PCECC LSP as well. The LSP object is included in the central controller instructions (label download Section 7.3) to identify the PCECC LSP for this instruction. The PLSP-ID is the original identifier used by the ingress PCC, so a transit/egress LSR could have multiple central controller instructions that have the same PLSP-ID. The PLSP-ID in combination with the source (in LSP-IDENTIFIERS TLV) MUST be unique. The PLSP-ID is included for maintainability reasons to ease debugging. As per [RFC8281], the LSP object could also include the SPEAKER-ENTITY-ID TLV to identify the PCE that initiated these instructions. Also, the CC-ID is unique in each PCEP session as described in Section 7.3.

On receipt of PCInitiate message for the PCECC LSP, the PCC responds with a PCRpt message with the status set to "GOING-UP" and carrying the assigned PLSP-ID (see Figure 1). The ingress PCC also sets the D (Delegate) flag (see [RFC8231]) and C (Create) flag (see [RFC8281]) in the LSP object. When the PCE receives this PCRpt message with the PLSP-ID, it assigns labels along the path; and sets up the path by sending a PCInitiate message to each node along the path of the LSP as per the PCECC technique. The CC-ID uniquely identifies the central controller instruction within a PCEP session. Each node along the path (PCC) responds with a PCRpt message to acknowledge the central controller instruction with the PCRpt messages including the central controller instruction (CCI) and the LSP objects.

The ingress node would receive one CCI object with O bit (out-label) set. The transit node(s) would receive two CCI objects with the in-label CCI without an O bit set and the out-label CCI with O bit set. The egress node would receive one CCI object without O bit set (see Figure 1). A node can determine its role based on the setting of the O bit in the CCI object(s) and the LSP-IDENTIFIERS TLV in the LSP object.

The LSP deletion operation for PCE-Initiated PCECC LSP is the same as defined in [RFC8281]. The PCE should further perform Label entry clean up operation as described in Section 5.5.3.2 for the corresponding LSP.

The PCE-Initiated PCECC LSP setup sequence is shown in Figure 1.

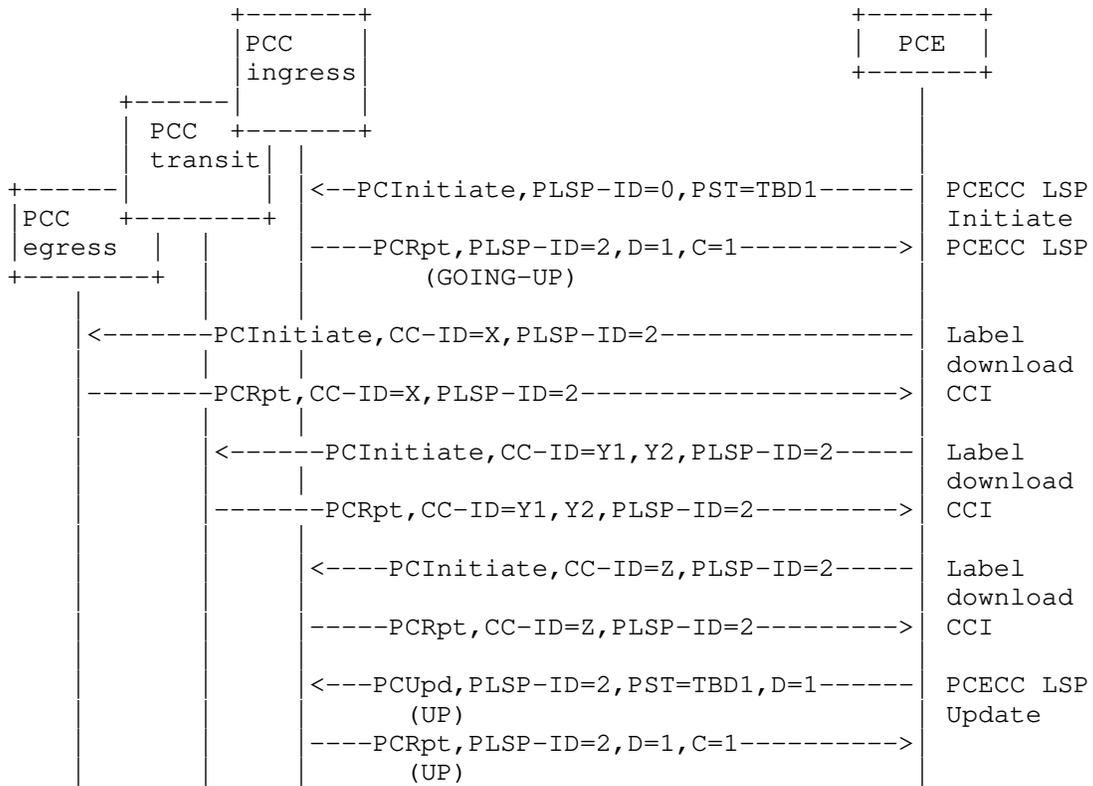


Figure 1: PCE-Initiated PCECC LSP

Once the label operations are completed, the PCE MUST send a PCUpd message to the ingress PCC. The PCUpd message is as per [RFC8231] with D flag set.

The PCECC LSPs are considered to be 'up' by default (on receipt of PCUpd message from PCE). The ingress could further choose to deploy a data plane check mechanism and report the status back to the PCE via a PCRpt message to make sure that the correct label instructions are made along the path of the PCECC LSP (and it is ready to carry traffic). The exact mechanism is out of scope of this document.

In the case where the label allocations are made by the PCC itself (see Section 5.5.8), the PCE could request an allocation to be made by the PCC, and then the PCC would send a PCRpt with the allocated label encoded in the CC-ID object as shown in Figure 2 in the configuration sequence from the egress towards the ingress along the path.

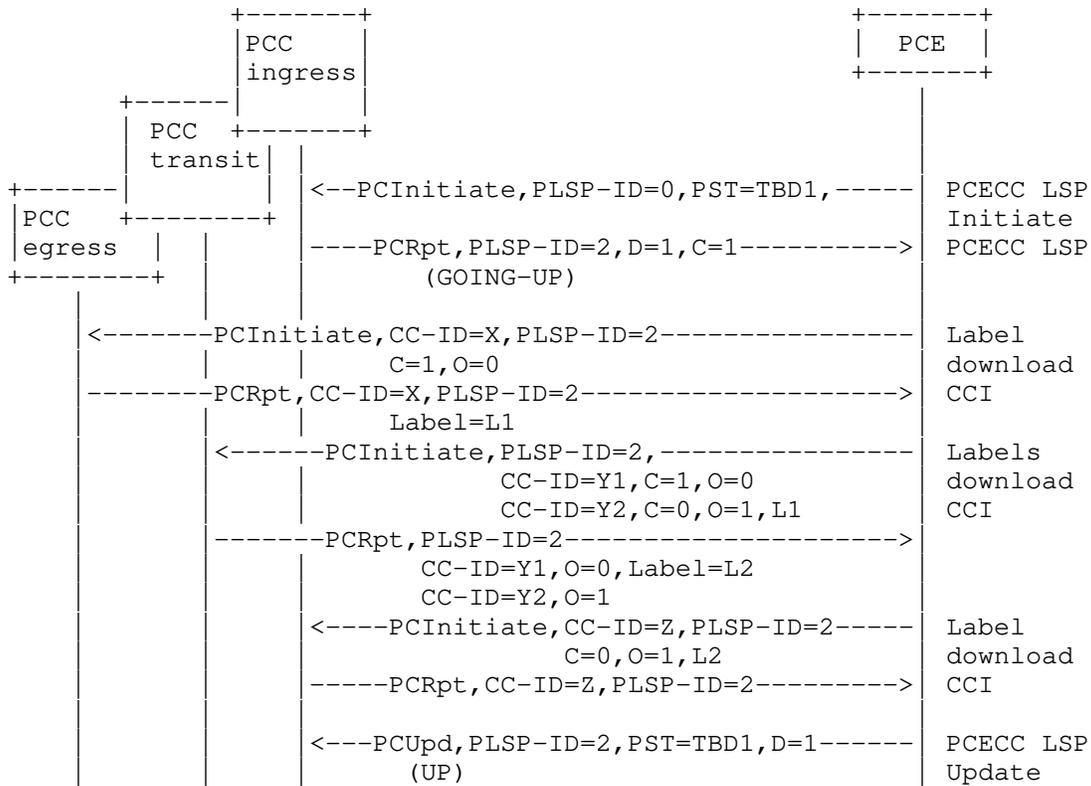


Figure 2: PCE-Initiated PCECC LSP (PCC allocation)

It should be noted that in this example, the request is made to the egress node with the C bit set in the CCI object to indicate that the label allocation needs to be done by the egress and the egress responds with the allocated label to the PCE. The PCE further inform the transit PCC without setting the C bit to 1 in the CCI object for out-label but the C bit is set to 1 for in-label so the transit node make the label allocation (for the in-label) and report to the PCE. Similarly, the C bit is unset towards the ingress to complete all the label allocation for the PCECC LSP.

5.5.2. PCC-Initiated PCECC LSP

In order to set up an LSP based on the PCECC mechanism where the LSP is configured at the PCC, a PCC MUST delegate the LSP by sending a

PCRpt message with PST set for PCECC (see Section 7.2) and D (Delegate) flag (see [RFC8231]) set in the LSP object (see Figure 3).

When a PCE receives the initial PCRpt message with D flag and PST Type set to TBD1, it SHOULD calculate the path and assigns labels along the path; and sets up the path by sending a PCInitiate message to each node along the path of the LSP as per the PCECC technique (see Figure 3). The CC-ID uniquely identifies the central controller instruction within a PCEP session. Each PCC further responds with the PCRpt messages including the central controller instruction (CCI) and the LSP objects.

Once the central controller instructions (label operations) are completed, the PCE MUST send the PCUpd message to the ingress PCC. As per [RFC8231], this PCUpd message should include the path information calculated by the PCE.

Note that the PCECC LSPs MUST be delegated to a PCE at all times.

The LSP deletion operation for PCECC LSPs is the same as defined in [RFC8231]. If the PCE receives a PCRpt message for LSP deletion then it does label clean up operation as described in Section 5.5.3.2 for the corresponding LSP.

The Basic PCECC LSP setup sequence is as shown in Figure 3.

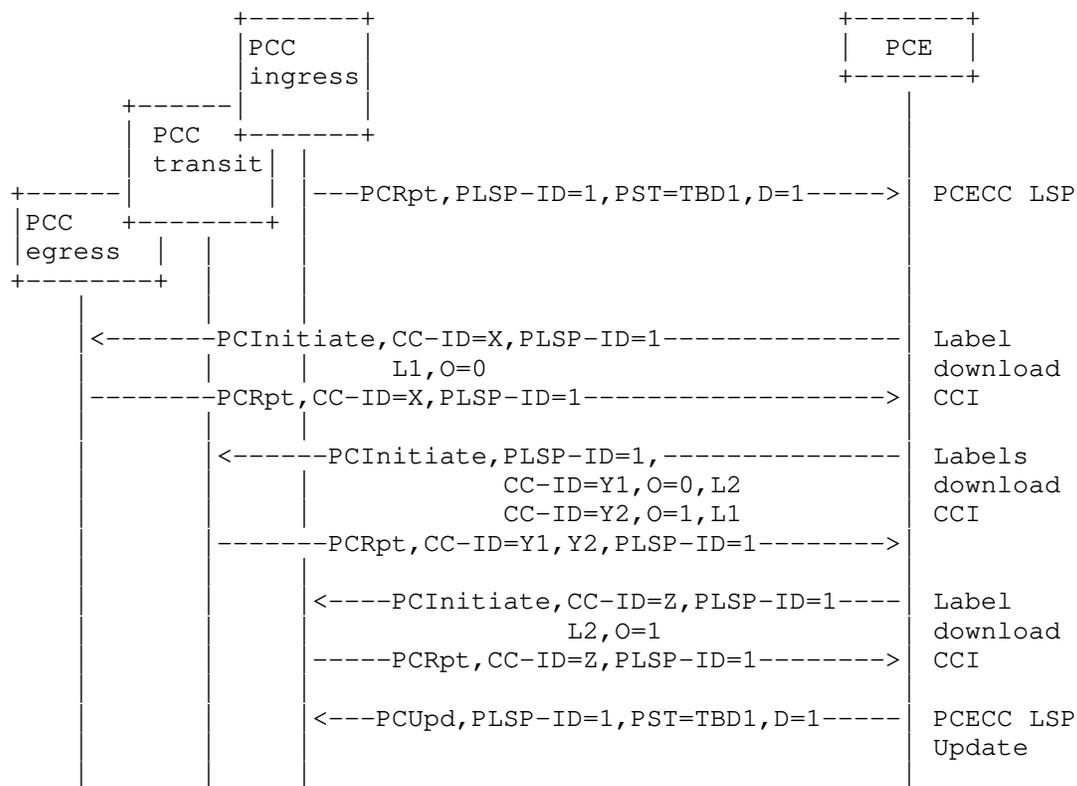
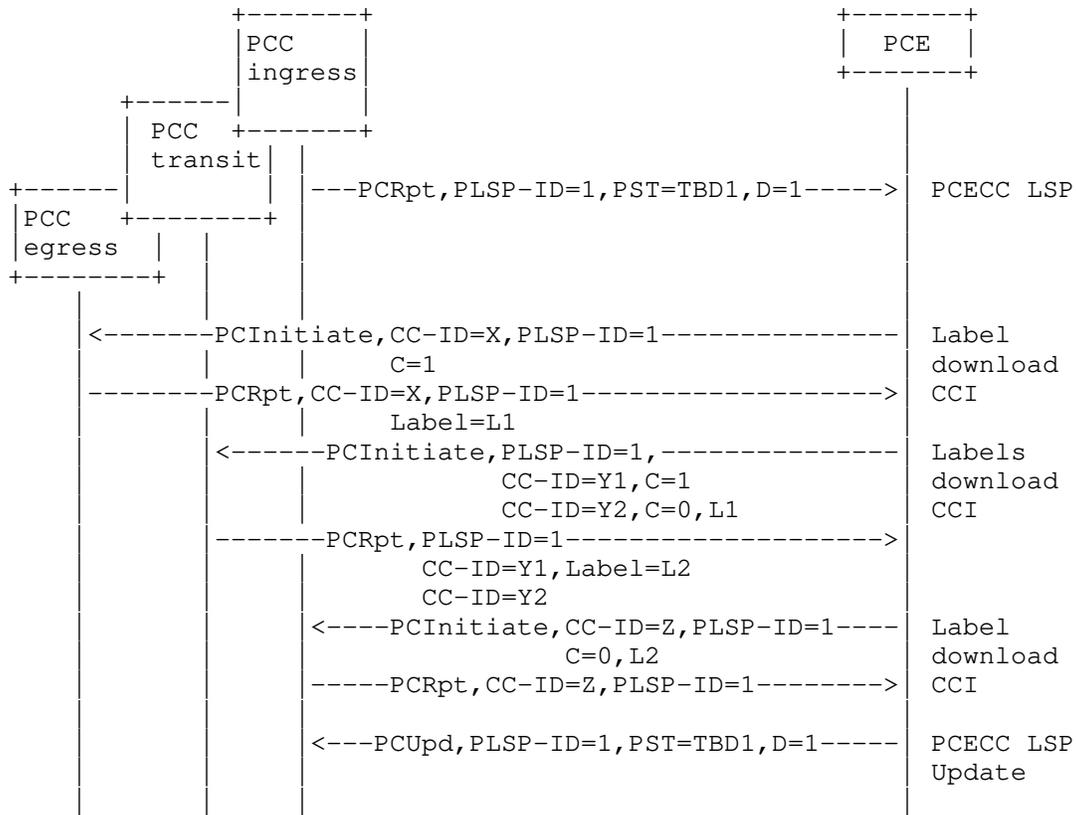


Figure 3: PCC-Initiated PCECC LSP

In the case where the label allocations are made by the PCC itself (see Section 5.5.8), the PCE could request an allocation to be made by the PCC, and then the PCC would send a PCRpt with the allocated label encoded in the CC-ID object as shown in Figure 4.



- The 0 bit is set as before (and thus not included)

Figure 4: PCC-Initiated PCECC LSP (PCC allocation)

In the case where the label allocations are made by the PCC itself (see Section 5.5.8), the procedure remains the same, with just an additional constraint on the configuration sequence.

The rest of the PCC-Initiated PCECC LSP setup operations are the same as those described in Section 5.5.1.

5.5.3. Central Controller Instructions

The new central controller instructions (CCI) for the label operations in PCEP are done via the PCInitiate message (Section 6.1), by defining a new PCEP Object for CCI operations. The local label range of each PCC is assumed to be known by both the PCC and the PCE.

5.5.3.1. Label Download CCI

In order to set up an LSP based on PCECC, the PCE sends a PCInitiate message to each node along the path to download the Label instruction as described in Section 5.5.1 and Section 5.5.2.

The CCI object MUST be included, along with the LSP object in the PCInitiate message. The LSP-IDENTIFIERS TLV MUST be included in the LSP object. The SPEAKER-ENTITY-ID TLV SHOULD be included in the LSP object.

If a node (PCC) receives a PCInitiate message which includes a Label to download, as part of CCI, that is out of the range set aside for the PCE, it MUST send a PCErr message with Error-type=TBD5 (PCECC failure) and Error-value=TBD6 (Label out of range) and MUST include the SRP object to specify the error is for the corresponding label update via PCInitiate message. If a PCC receives a PCInitiate message but fails to download the Label entry, it MUST send a PCErr message with Error-type=TBD5 (PCECC failure) and Error-value=TBD7 (instruction failed) and MUST include the SRP object to specify the error is for the corresponding label update via PCInitiate message.

A new PCEP object for central controller instructions (CCI) is defined in Section 7.3.

5.5.3.2. Label Clean up CCI

In order to delete an LSP based on PCECC, the PCE sends a central controller instructions via a PCInitiate message to each node along the path of the LSP to clean up the Label forwarding instruction.

If the PCC receives a PCInitiate message but does not recognize the label in the CCI, the PCC MUST generate a PCErr message with Error-Type 19(Invalid operation) and Error-Value=TBD8, "Unknown Label" and MUST include the SRP object to specify the error is for the corresponding label clean up (via PCInitiate message).

The R flag in the SRP object defined in [RFC8281] specifies the deletion of Label Entry in the PCInitiate message.

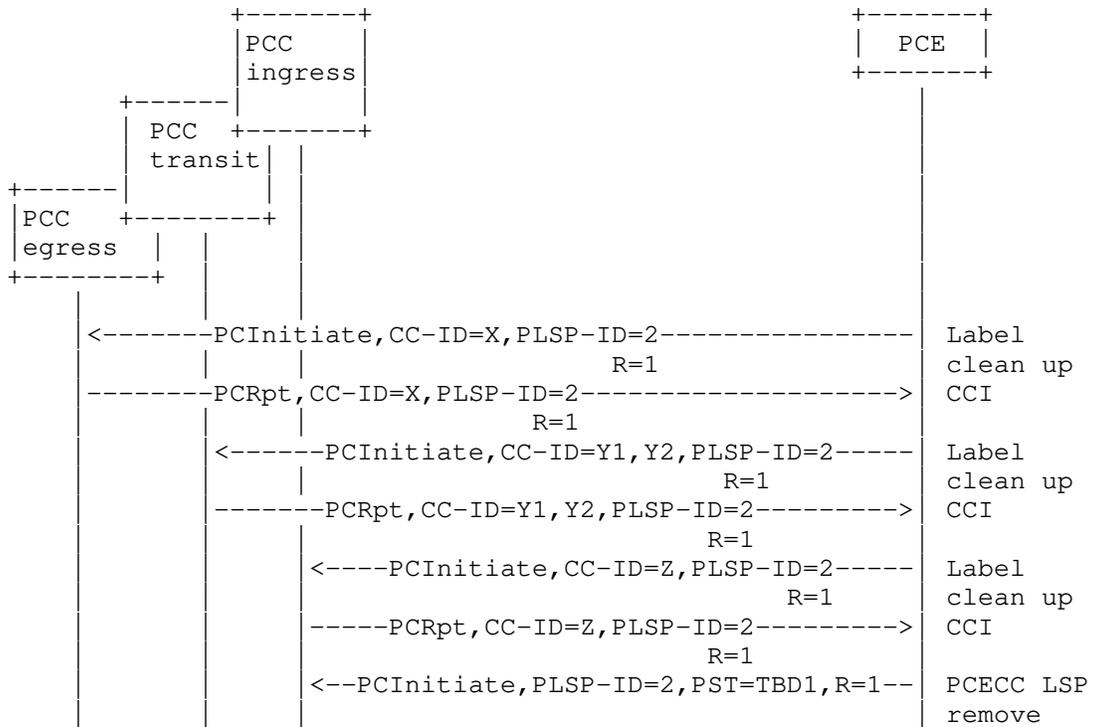


Figure 5: Label Cleanup

As per [RFC8281], following the removal of the Label forwarding instruction, the PCC MUST send a PCRpt message. The SRP object in the PCRpt MUST include the SRP-ID-number from the PCInitiate message that triggered the removal. The R flag in the SRP object MUST be set.

In the case where the label allocation is made by the PCC itself (see Section 5.5.8), the removal procedure remains the same, adding the sequence constraint.

5.5.4. PCECC LSP Update

The update is done as per the make-before-break procedures, i.e. the PCECC first updates new label instructions based on the updated path and then informs the ingress to switch traffic, before cleaning up the former instructions. New CC-IDs are used to identify the updated instructions; the identifiers in the LSP object uniquely identify the existing LSP. Once new instructions are downloaded, the PCE further updates the new path at the ingress which triggers the traffic switch

on the updated path. The ingress PCC acknowledges with a PCRpt message, on receipt of the PCRpt message, the PCE does clean up operation for the former LSP as described in Section 5.5.3.2.

The PCECC LSP Update sequence is shown in Figure 6.

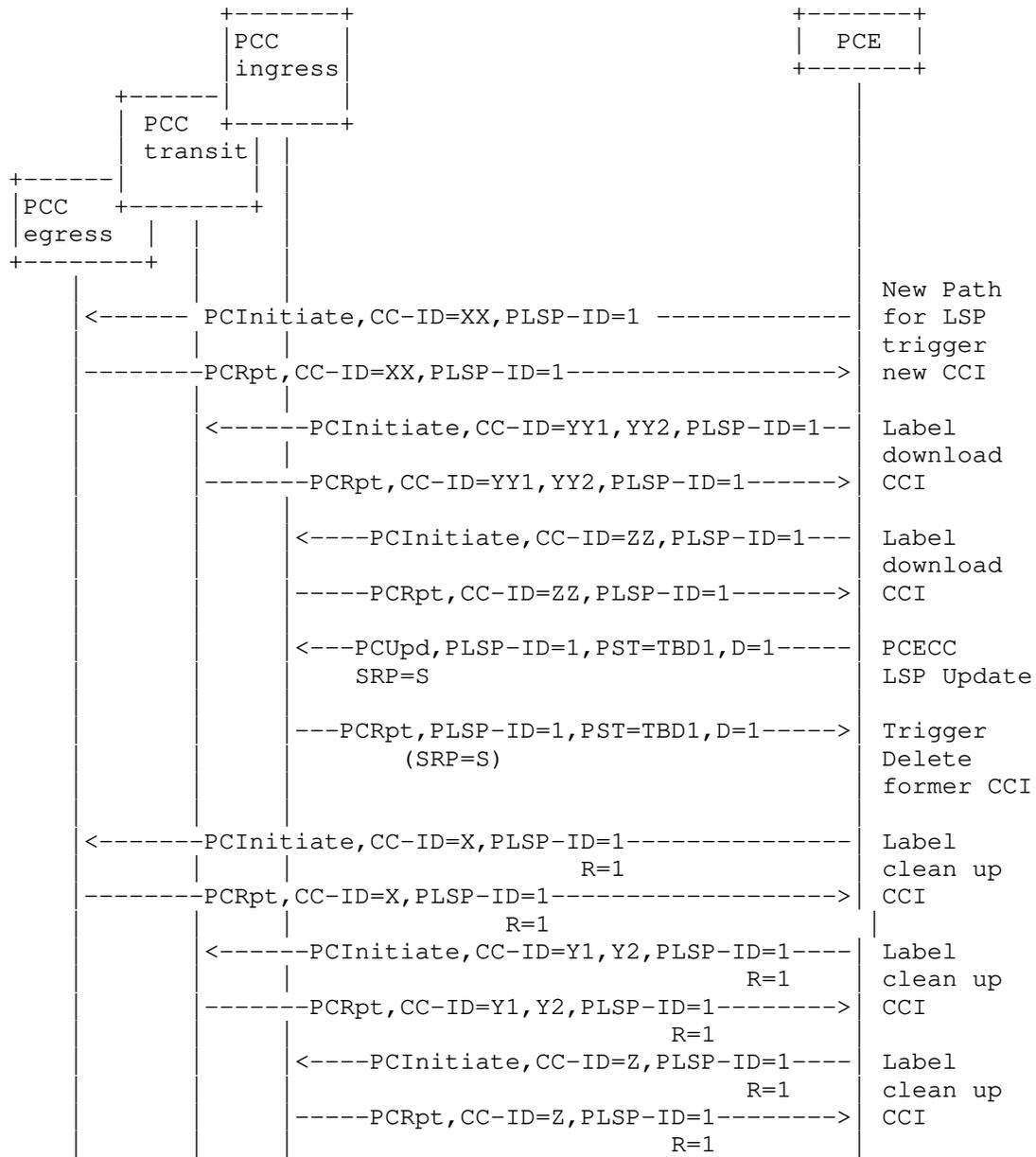


Figure 6: PCECC LSP Update

The modified PCECC LSPs are considered to be 'up' by default. The ingress could further choose to deploy a data plane check mechanism

and report the status back to the PCE via a PCRpt message. The exact mechanism is out of scope of this document.

In the case where the label allocations are made by the PCC itself (see Section 5.5.8), the procedure remains the same.

5.5.5. Re-Delegation and Clean up

As described in [RFC8281], a new PCE can gain control over an orphaned LSP. In the case of a PCECC LSP, the new PCE MUST also gain control over the central controller instructions in the same way by sending a PCInitiate message that includes the SRP, LSP, and CCI objects and carries the CC-ID and PLSP-ID identifying the instruction that it wants to take control of.

Further, as described in [RFC8281], the State Timeout Interval timer ensures that a PCE crash does not result in automatic and immediate disruption for the services using PCE-initiated LSPs. Similarly the central controller instructions are not removed immediately upon PCE failure. Instead, they are cleaned up on the expiration of this timer. This allows for network clean up without manual intervention. The PCC MUST support the removal of CCI as one of the behaviors applied on expiration of the State Timeout Interval timer.

In case of PCC-initiated PCECC LSP, the control over the orphaned LSP at the ingress PCC is taken over by the mechanism specified in [RFC8741] to request delegation. The control over the central controller instructions is described above using [RFC8281].

5.5.6. Synchronization of Central Controllers Instructions

The purpose of Central Controllers Instructions synchronization (labels in the context of this document) is to make sure that the PCE's view of CCI (Labels) matches with the PCC's Label allocation. This synchronization is performed as part of the LSP state synchronization as described in [RFC8231] and [RFC8232].

As per LSP State Synchronization [RFC8231], a PCC reports the state of its LSPs to the PCE using PCRpt messages and as per [RFC8281], PCE would initiate any missing LSPs and/or remove any LSPs that are not wanted. The same PCEP messages and procedures are also used for the Central Controllers Instructions synchronization. The PCRpt message includes the CCI and the LSP object to report the label forwarding instructions. The PCE would further remove any unwanted instructions or initiate any missing instructions.

5.5.7. PCECC LSP State Report

As mentioned before, an ingress PCC MAY choose to apply any OAM mechanism to check the status of LSP in the Data plane and MAY further send its status in a PCRpt message to the PCE.

5.5.8. PCC-Based Allocations

The PCE can request the PCC to allocate the label using the PCInitiate message. The C flag in the CCI object is set to 1 to indicate that the allocation needs to be done by the PCC. The PCC MUST try to allocate the Label and MUST report to the PCE via PCRpt or PCErr message.

If the value of the Label is 0 and the C flag is set to 1, it indicates that the PCE is requesting the allocation to be done by the PCC. If the Label is 'n' and the C flag is set to 1 in the CCI object, it indicates that the PCE requests a specific value 'n' for the Label. If the allocation is successful, the PCC MUST report via the PCRpt message with the CCI object. If the value of the Label in the CCI object is invalid, it MUST send a PCErr message with Error-Type = TBD5 ("PCECC failure") and Error Value = TBD9 ("Invalid CCI"). If it is valid but the PCC is unable to allocate it, it MUST send a PCErr message with Error-Type = TBD5 ("PCECC failure") and Error Value = TBD10 ("Unable to allocate the specified CCI").

If the PCC wishes to withdraw or modify the previously assigned label, it MUST send a PCRpt message without any Label or with the Label containing the new value respectively in the CCI object. The PCE would further trigger the Label cleanup of older label as per Section 5.5.3.2.

6. PCEP Messages

As defined in [RFC5440], a PCEP message consists of a common header followed by a variable-length body made of a set of objects that can be either mandatory or optional. An object is said to be mandatory in a PCEP message when the object must be included for the message to be considered valid. For each PCEP message type, a set of rules is defined that specify the set of objects that the message can carry. An implementation MUST form the PCEP messages using the object ordering specified in this document.

LSP-IDENTIFIERS TLV MUST be included in the LSP object for PCECC LSP.

The message formats in this document are specified using Routing Backus-Naur Form (RBNF) encoding as specified in [RFC5511].

6.1. The PCInitiate Message

The PCInitiate message [RFC8281] can be used to download or remove the labels, this document extends the message as shown below -

```
<PCInitiate Message> ::= <Common Header>
                          <PCE-initiated-lsp-list>
```

Where:

```
<Common Header> is defined in [RFC5440]
```

```
<PCE-initiated-lsp-list> ::= <PCE-initiated-lsp-request>
                              [<PCE-initiated-lsp-list>]
```

```
<PCE-initiated-lsp-request> ::=
    (<PCE-initiated-lsp-instantiation> |
     <PCE-initiated-lsp-deletion> |
     <PCE-initiated-lsp-central-control>)
```

```
<PCE-initiated-lsp-central-control> ::= <SRP>
                                          <LSP>
                                          <cci-list>
```

```
<cci-list> ::= <CCI>
                [<cci-list>]
```

Where:

```
<PCE-initiated-lsp-instantiation> and
<PCE-initiated-lsp-deletion> are as per
[RFC8281].
```

The LSP and SRP object is defined in [RFC8231].

When PCInitiate message is used for the central controller instructions (labels), the SRP, LSP, and CCI objects MUST be present. The SRP object is defined in [RFC8231] and if the SRP object is missing, the receiving PCC MUST send a PCErr message with Error-type=6 (Mandatory Object missing) and Error-value=10 (SRP object missing). The LSP object is defined in [RFC8231] and if the LSP object is missing, the receiving PCC MUST send a PCErr message with Error-type=6 (Mandatory Object missing) and Error-value=8 (LSP object missing). The CCI object is defined in Section 7.3 and if the CCI object is missing, the receiving PCC MUST send a PCErr message with Error-type=6 (Mandatory Object missing) and Error-value=TBD11 (CCI object missing). More than one CCI object MAY be included in the PCInitiate message for a transit LSR.

To clean up entries, the R (remove) bit MUST be set in the SRP object to be encoded along with the LSP and the CCI object.

The CCI object received at the ingress node MUST have the O bit (out-label) set. The CCI Object received at the egress MUST have the O bit unset. If this is not the case, PCC MUST send a PCErr message with Error-Type = TBD5 ("PCECC failure") and Error Value = TBD9 ("Invalid CCI"). Other instances of the CCI object if present, MUST be ignored.

For the P2P LSP setup via PCECC technique, at the transit LSR two CCI objects are expected for in-coming and outgoing label associated with the LSP object. If any other CCI object is included in the PCInitiate message, it MUST be ignored. If the transit LSR did not receive two CCI object with one of them having the O bit set and another with O bit unset, it MUST send a PCErr message with Error-Type = TBD5 ("PCECC failure") and Error Value = TBD9 ("Invalid CCI").

Note that, on receipt of the PCInitiate message with CCI object, the ingress, egress, or transit role of the PCC is identified via the ingress and egress IP address encoded in the LSP-IDENTIFIERS TLV.

6.2. The PCRpt Message

The PCRpt message can be used to report the labels that were allocated by the PCE, to be used during the state synchronization phase or as an acknowledgment to PCInitiate message.

```
<PCRpt Message> ::= <Common Header>
                        <state-report-list>
```

Where:

```
<state-report-list> ::= <state-report>[<state-report-list>]
```

```
<state-report> ::= (<lsp-state-report>|
                    <central-control-report>)
```

```
<lsp-state-report> ::= [<SRP>]
                        <LSP>
                        <path>
```

```
<central-control-report> ::= [<SRP>]
                              <LSP>
                              <cci-list>
```

```
<cci-list> ::= <CCI>
               [<cci-list>]
```

Where:

<path> is as per [RFC8231] and the LSP and SRP object are also defined in [RFC8231].

When PCRpt message is used to report the central controller instructions (labels), the LSP and CCI objects MUST be present. The LSP object is defined in [RFC8231] and if the LSP object is missing, the receiving PCE MUST send a PCErr message with Error-type=6 (Mandatory Object missing) and Error-value=8 (LSP object missing). The CCI object is defined in Section 7.3 and if the CCI object is missing, the receiving PCE MUST send a PCErr message with Error-type=6 (Mandatory Object missing) and Error-value=TBD11 (CCI object missing). Two CCI objects can be included in the PCRpt message for a transit LSR.

7. PCEP Objects

The PCEP objects defined in this document are compliant with the PCEP object format defined in [RFC5440].

7.1. OPEN Object

This document defines a new PST (TBD1) to be included in the PATH-SETUP-TYPE-CAPABILITY TLV in the OPEN Object. Further, a new sub-TLV for PCECC capability exchange is also defined.

7.1.1. PCECC Capability sub-TLV

The PCECC-CAPABILITY sub-TLV is an optional TLV for use in the OPEN Object in the PATH-SETUP-TYPE-CAPABILITY TLV, when the Path Setup Type list includes the PCECC Path Setup Type TBD1. A PCECC-CAPABILITY sub-TLV MUST be ignored if the PST list does not contain PST=TBD1.

Its format is shown in Figure 7.

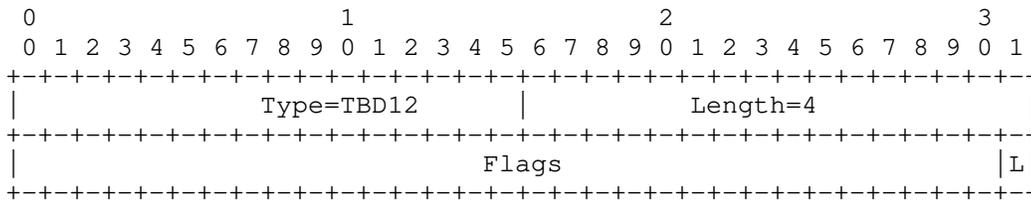


Figure 7: PCECC Capability sub-TLV

The type of the TLV is TBD12 and it has a fixed length of 4 octets.

The value comprises a single field - Flags (32 bits). Currently, the following flag bit is defined:

- o L bit (Label): if set to 1 by a PCEP speaker, the L flag indicates that the PCEP speaker support and is willing to handle the PCECC based central controller instructions for label download. The bit MUST be set to 1 by both a PCC and a PCE for the PCECC label download/report on a PCEP session.
- o Unassigned bits MUST be set to 0 on transmission and MUST be ignored on receipt.

7.2. PATH-SETUP-TYPE TLV

The PATH-SETUP-TYPE TLV is defined in [RFC8408]; this document defines a new PST value:

- o PST = TBD1: Path is set up via PCECC mode.

On a PCRpt/PCUpd/PCInitiate message, the PST=TBD1 in the PATH-SETUP-TYPE TLV in the SRP object MUST be included for a LSP set up via the PCECC-based mechanism.

7.3. CCI Object

The Central Controller Instructions (CCI) Object is used by the PCE to specify the forwarding instructions (Label information in the context of this document) to the PCC, and MAY be carried within PCInitiate or PCRpt message for label download/report.

CCI Object-Class is TBD13.

CCI Object-Type is 1 for the MPLS Label.

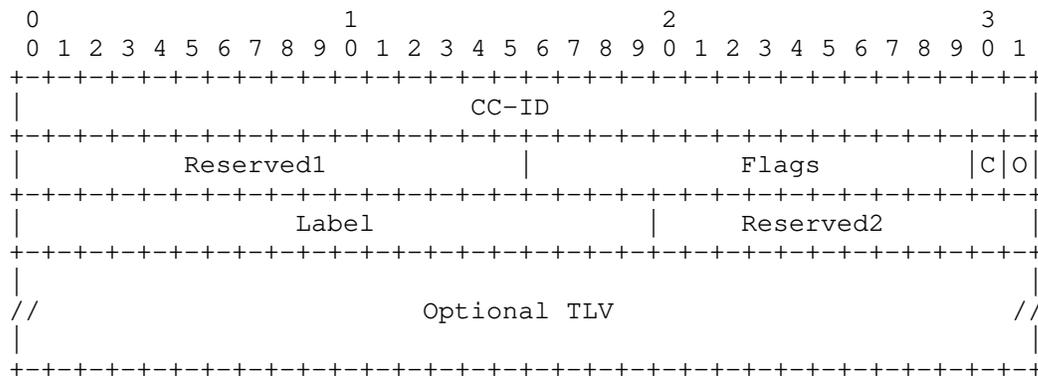


Figure 8: CCI Object

The fields in the CCI object are as follows:

CC-ID: A PCEP-specific identifier for the CCI information. A PCE creates a CC-ID for each instruction, the value is unique within the scope of the PCE and is constant for the lifetime of a PCEP session. The values 0 and 0xFFFFFFFF are reserved and MUST NOT be used. Note that [I-D.gont-numeric-ids-sec-considerations] gives advice on assigning transient numeric identifiers such as the CC-ID so as to minimize security risks.

Reserved1 (16 bit): Set to zero while sending, ignored on receive.

Flags (16 bit): A field used to carry any additional information pertaining to the CCI. Currently, the following flag bits are defined:

- * O bit (Out-label) : If the bit is set to 1, it specifies the label is the OUT label and it is mandatory to encode the next-hop information (via Address TLVs Section 7.3.1 in the CCI

object). If the bit is not set, it specifies the label is the IN label and it is optional to encode the local interface information (via Address TLVs in the CCI object).

- * C Bit (PCC Allocation): If the bit is set to 1, it indicates that the label allocation needs to be done by the PCC for this central controller instruction. A PCE sets this bit to request the PCC to make an allocation from its label space. A PCC would set this bit to indicate that it has allocated the label and report it to the PCE.
- * All unassigned bits MUST be set to zero at transmission and ignored at receipt.

Label (20-bit): The Label information.

Reserved2 (12 bit): Set to zero while sending, ignored on receive.

7.3.1. Address TLVs

[RFC8779] defines IPV4-ADDRESS, IPV6-ADDRESS, and UNNUMBERED-ENDPOINT TLVs for the use of Generalized Endpoint. The same TLVs can also be used in the CCI object to associate the next-hop information in the case of an outgoing label and local interface information in the case of an incoming label. The next-hop information encoded in these TLVs needs to be a directly connected IP address/interface information. If the PCC is not able to resolve the next-hop information, it MUST reject the CCI and respond with a PCErr message with Error-Type = TBD5 ("PCECC failure") and Error Value = TBD15 ("Invalid next-hop information").

8. Implementation Status

[Note to the RFC Editor - remove this section before publication, as well as remove the reference to RFC 7942.]

This section records the status of known implementations of the protocol defined by this specification at the time of posting of this Internet-Draft, and is based on a proposal described in [RFC7942]. The description of implementations in this section is intended to assist the IETF in its decision processes in progressing drafts to RFCs. Please note that the listing of any individual implementation here does not imply endorsement by the IETF. Furthermore, no effort has been spent to verify the information presented here that was supplied by IETF contributors. This is not intended as, and must not be construed to be, a catalog of available implementations or their features. Readers are advised to note that other implementations may exist.

According to [RFC7942], "this will allow reviewers and working groups to assign due consideration to documents that have the benefit of running code, which may serve as evidence of valuable experimentation and feedback that have made the implemented protocols more mature. It is up to the individual working groups to use this information as they see fit".

8.1. Huawei's Proof of Concept based on ONOS

The PCE function was developed in the ONOS open source platform. This extension was implemented on a private version as a proof of concept for PCECC.

- o Organization: Huawei
- o Implementation: Huawei's PoC based on ONOS
- o Description: PCEP as a southbound plugin was added to ONOS. To support PCECC, an earlier version of this I-D was implemented. Refer <https://wiki.onosproject.org/display/ONOS/PCEP+Protocol>
- o Maturity Level: Prototype
- o Coverage: Partial
- o Contact: satishk@huawei.com

9. Security Considerations

As per [RFC8283], the security considerations for a PCE-based controller is a little different from those for any other PCE system. That is, the operation relies heavily on the use and security of PCEP, so consideration should be given to the security features discussed in [RFC5440] and the additional mechanisms described in [RFC8253]. It further lists the vulnerability of a central controller architecture, such as a central point of failure, denial-of-service, and a focus for interception and modification of messages sent to individual NEs.

In PCECC operations, the PCEP sessions are also required to the internal routers and thus increasing the resources required for the session management at the PCE.

The PCECC extension builds on the existing PCEP messages and thus the security considerations described in [RFC5440], [RFC8231] and [RFC8281] continue to apply. [RFC8253] specify the support of Transport Layer Security (TLS) in PCEP, as it provides support for peer authentication, message encryption, and integrity. It further

provide mechanisms for associating peer identities with different levels of access and/or authoritative via an attribute in X.509 certificates or a local policy with a specific accept-list of X.509 certificate. This can be used to check the authority for the PCECC operations. Additional considerations are discussed in following sections.

9.1. Malicious PCE

In this extension, the PCE has complete control over the PCC to download/remove the labels and can cause the LSP's to behave inappropriately and cause a major impact to the network. As a general precaution, it is RECOMMENDED that this PCEP extension be activated on mutually-authenticated and encrypted sessions across PCEs and PCCs belonging to the same administrative authority, using TLS [RFC8253], as per the recommendations and best current practices in BCP 195 [RFC7525].

Further, an attacker may flood the PCC with PCECC related messages at a rate that exceeds either the PCC's ability to process them or the network's ability to send them, by either spoofing messages or compromising the PCE itself. [RFC8281] provides a mechanism to protect the PCC by imposing a limit. The same can be used for the PCECC operations as well.

As specified in Section 5.5.3.1, a PCC needs to check if the label in the CCI object is in the range set aside for the PCE, otherwise it MUST send a PCErr message with Error-type=TBD5 (PCECC failure) and Error-value=TBD6 (Label out of range).

9.2. Malicious PCC

The PCECC mechanism described in this document requires the PCE to keep labels (CCI) that it downloads and relies on the PCC responding (with either an acknowledgment or an error message) to requests for LSP instantiation. This is an additional attack surface by placing a requirement for the PCE to keep a CCI/label replica for each PCC. It is RECOMMENDED that PCE implementations provide a limit on resources (in this case the CCI) a single PCC can occupy. [RFC8231] provides a notification mechanism when such threshold is reached.

10. Manageability Considerations

10.1. Control of Function and Policy

A PCE or PCC implementation SHOULD allow the PCECC capability to be enabled/disabled as part of the global configuration. Section 6.1 of [RFC8664] list various controlling factors regarding path setup type.

They are also applicable to the PCECC path setup types. Further, Section 6.2 of [RFC8664] describe the migration steps when path setup type of an existing LSP is changed.

10.2. Information and Data Models

[RFC7420] describes the PCEP MIB, this MIB can be extended to get the PCECC capability status.

The PCEP YANG module [I-D.ietf-pce-pcep-yang] could be extended to enable/disable PCECC capability.

10.3. 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].

10.4. Verify Correct Operations

The operator needs the following information to verify that PCEP is operating correctly with respect to the PCECC path setup type.

- o An implementation SHOULD allow the operator to view whether the PCEP speaker sent the PCECC PST capability to its peer.
- o An implementation SHOULD allow the operator to view whether the peer sent the PCECC PST capability.
- o An implementation SHOULD allow the operator to view whether the PCECC PST is enabled on a PCEP session.
- o If one PCEP speaker advertises the PCECC PST capability, but the other does not, then the implementation SHOULD create a log to inform the operator of the capability mismatch.
- o If a PCEP speaker rejects a CCI, then it SHOULD create a log to inform the operator, giving the reason for the decision (local policy, Label issues, etc.).

10.5. Requirements On Other Protocols

PCEP extensions defined in this document do not put new requirements on other protocols.

10.6. Impact On Network Operations

PCEP extensions defined in this document do not put new requirements on network operations.

11. IANA Considerations

11.1. PATH-SETUP-TYPE-CAPABILITY Sub-TLV Type Indicators

[RFC8408] requested the creation of "PATH-SETUP-TYPE-CAPABILITY Sub-TLV Type Indicators" sub-registry. Further IANA is requested to allocate the following code-point:

Value	Meaning	Reference
TBD12	PCECC-CAPABILITY	This document

11.2. PCECC-CAPABILITY sub-TLV's Flag field

This document defines the PCECC-CAPABILITY sub-TLV and requests that IANA to create a new sub-registry to manage the value of the PCECC-CAPABILITY sub-TLV's 32-bits Flag field. New values are to be assigned by Standards Action [RFC8126]. Each bit should be tracked with the following qualities:

- o Bit number (counting from bit 0 as the most significant bit)
- o Capability description
- o Defining RFC

Currently, there is one allocation in this registry.

Bit	Name	Reference
31	Label	This document
0-30	Unassigned	This document

11.3. Path Setup Type Registry

[RFC8408] created a sub-registry within the "Path Computation Element Protocol (PCEP) Numbers" registry called "PCEP Path Setup Types". IANA is requested to allocate a new code point within this registry, as follows:

Value	Description	Reference
TBD1	Traffic engineering path is set up using PCECC mode	This document

11.4. PCEP Object

IANA is requested to allocate new code-point in the "PCEP Objects" sub-registry for the CCI object as follows:

Object-Class	Value	Name	Reference
TBD13		CCI Object-Type	This document
	0		Reserved
	1		MPLS Label

11.5. CCI Object Flag Field

IANA is requested to create a new sub-registry to manage the Flag field of the CCI object called "CCI Object Flag Field for MPLS Label". New values are to be assigned by Standards Action [RFC8126]. Each bit should be tracked with the following qualities:

- o Bit number (counting from bit 0 as the most significant bit)
- o Capability description
- o Defining RFC

Two bits to be defined for the CCI Object flag field in this document as follows:

Bit	Description	Reference
0-13	Unassigned	This document
14	C Bit - PCC allocation	This document
15	O Bit - Specifies label is out-label	This document

11.6. PCEP-Error Object

IANA is requested to allocate new error types and error values within the "PCEP-ERROR Object Error Types and Values" sub-registry of the PCEP Numbers registry for the following errors:

Error-Type	Meaning
-----	-----
6	Mandatory Object missing.
	<p style="margin-left: 40px;">Error-value = TBD11 : CCI object missing</p>
10	Reception of an invalid object.

19	Error-value = TBD2 : Invalid operation.	Missing PCECC Capability sub-TLV
	Error-value = TBD3 : Error-value = TBD4 : Error-value = TBD8 :	Attempted PCECC operations when PCECC capability was not advertised Stateful PCE capability was not advertised Unknown Label
TBD5	PCECC failure. Error-value = TBD6 : Error-value = TBD7 : Error-value = TBD9 : Error-value = TBD10 : Error-value = TBD15 :	Label out of range. Instruction failed. Invalid CCI. Unable to allocate the specified CCI. Invalid next-hop information.

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