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Stateful Path Computation Element (PCE) Protocol Extensions
for Usage with Point-to-Multipoint TE Label Switched Paths (LSPs)

Abstract

The Path Computation Element (PCE) has been identified as an appropriate technology for the determination of the paths of point-to-multipoint (P2MP) TE Label Switched Paths (LSPs). This document provides extensions required for the Path Computation Element Communication Protocol (PCEP) so as to enable the usage of a stateful PCE capability in supporting P2MP TE LSPs.

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1. Introduction

As per [RFC4655], the Path Computation Element (PCE) is an entity that is capable of computing a network path or route based on a network graph and applying computational constraints. A Path Computation Client (PCC) may make requests to a PCE for paths to be computed.

[RFC4875] describes how to set up point-to-multipoint (P2MP) Traffic Engineering Label Switched Paths (TE LSPs) for use in Multiprotocol Label Switching (MPLS) and Generalized MPLS (GMPLS) networks. [RFC5671] examines the applicability of PCE for the path computation for P2MP TE LSPs.

The PCEP is designed as a communication protocol between PCCs and PCEs for point-to-point (P2P) path computations and is defined in [RFC5440]. The extensions of PCEP to request path computation for P2MP TE LSPs are described in [RFC8306].

Stateful PCEs are shown to be helpful in many application scenarios, in both MPLS and GMPLS networks, as illustrated in [RFC8051]. These scenarios apply equally to P2P and P2MP TE LSPs. [RFC8231] provides the fundamental extensions to PCEP needed for stateful PCE to support general functionality for P2P TE LSP. [RFC8281] provides extensions to PCEP needed for stateful PCE-initiated P2P TE LSP. This document complements that work by focusing on PCEP extensions that are necessary in order for the deployment of stateful PCEs to support P2MP TE LSPs. This document describes the setup, maintenance, and teardown of PCE-initiated P2MP LSPs under the stateful PCE model.

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

Terminology used in this document is the same as terminology used in [RFC8231], [RFC8281], and [RFC8306].

3. Supporting P2MP TE LSPs for Stateful PCE

3.1. Motivation

[RFC8051] presents several use cases, demonstrating scenarios that benefit from the deployment of a stateful PCE including optimization, recovery, etc., which are equally applicable to P2MP TE LSPs. [RFC8231] defines the extensions to PCEP needed for stateful operation of P2P TE LSPs. This document complements the previous work by focusing on extensions that are necessary in order for the deployment of stateful PCEs to support P2MP TE LSPs.

In addition to that, the stateful nature of a PCE simplifies the information conveyed in PCEP messages since it is possible to refer to the LSPs via a PCEP-specific LSP identifier (PLSP-ID) ([RFC8231]). For P2MP, where the size of the message is much larger, this is an added advantage. When using a stateless PCE, a request to modify an existing P2MP tree requires that all the leaves are presented in the PCEP messages along with all the path information. But when using a

stateful PCE, the PCEP messages can use a PLSP-ID to represent all information about the LSP that has previously been exchanged in PCEP messages, and it is only necessary to encode the modifications (such as new or removed leaf nodes). The PLSP-ID provides an index into the LSP-DB at the PCE and identifies the LSP at the PCC.

In environments where the P2MP TE LSPs placement needs to change in response to application demands, it is useful to support dynamic creation and tear down of P2MP TE LSPs. The ability for a PCE to trigger the creation of P2MP TE LSPs on demand can be seamlessly integrated into a controller-based network architecture where intelligence in the controller can determine when and where to set up paths. Section 3 of [RFC8281] further describes the motivation behind the PCE-Initiation capability, which is equally applicable to P2MP TE LSPs.

3.2. Objectives

The objectives for the protocol extensions to support P2MP TE LSPs for stateful PCE are the same as the objectives described in Section 3.2 of [RFC8231].

4. Functions to Support P2MP TE LSPs for Stateful PCEs

[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 P2MP TE LSPs:

Capability Advertisement (E-C,C-E): Both the PCC and the PCE must announce during PCEP session establishment that they support Stateful PCE extensions for P2MP using mechanisms defined in Section 5.2.

LSP State Synchronization (C-E): After the session between the PCC and a stateful PCE with P2MP capability is initialized, the PCE must learn the state of a PCC's P2MP TE LSPs before it can perform path computations or update LSP attributes in a PCC.

LSP Update Request (E-C): A stateful PCE with P2MP capability requests modification of attributes on a PCC's P2MP TE LSPs.

LSP State Report (C-E): A PCC sends an LSP state report to a PCE whenever the state of a P2MP TE LSP changes.

LSP Control Delegation (C-E,E-C): A PCC grants to a PCE the right to update LSP attributes on one or more P2MP TE LSPs; the PCE becomes the authoritative source of the LSP's attributes as long as the delegation is in effect (See Section 5.7 of [RFC8231]); the PCC may withdraw the delegation or the PCE may give up the delegation at any time.

PCE-initiated LSP instantiation (E-C): A PCE sends an LSP Initiate Message to a PCC to instantiate or delete a P2MP TE LSP [RFC8281].

5. Architectural Overview of Protocol Extensions

5.1. Extension of PCEP Messages

Two new PCEP messages are defined in [RFC8231] to support stateful PCE for P2P TE LSPs. In this document, these messages are extended as follows to support P2MP TE LSPs.

Path Computation State Report (PCRpt): Each P2MP TE LSP State Report in a PCRpt message contains the actual P2MP TE LSP path attributes, the LSP status, etc. An LSP State Report carried in a PCRpt message is also used in delegation or revocation of control of a P2MP TE LSP to/from a PCE. The extension of PCRpt messages is described in Section 6.1.

Path Computation Update Request (PCUpd): Each P2MP TE LSP Update Request in a PCUpd message MUST contain all LSP parameters that a PCE wishes to set for a given P2MP TE LSP. An LSP Update Request carried in a PCUpd message is also used to return LSP delegations if at any point the PCE no longer desires control of a P2MP TE LSP. The PCUpd message is described in Section 6.2.

Further, a new PCEP message is defined in [RFC8281] to support stateful PCE instantiation of P2P TE LSPs. In this document, this message is extended as follows to support P2MP TE LSPs.

Path Computation LSP Initiate Message (PCInitiate): PCInitiate is a PCEP message sent by a PCE to a PCC to trigger the instantiation or deletion of a P2MP TE LSP. The PCInitiate message is described in Section 6.5.

The Path Computation Request (PCReq) and Path Computation Reply (PCRep) messages are also extended to support passive stateful PCE for P2P TE LSPs in [RFC8231]. In this document, these messages are extended to support P2MP TE LSPs as well.

5.2. Capability Advertisement

During the PCEP initialization phase, as per Section 7.1.1 of [RFC8231], PCEP speakers advertise Stateful capability via the STATEFUL-PCE-CAPABILITY TLV in the OPEN object. Various flags are defined for the STATEFUL-PCE-CAPABILITY TLV defined in [RFC8231] and updated in [RFC8281] and [RFC8232].

Three new flags, N (P2MP-CAPABILITY), M (P2MP-LSP-UPDATE-CAPABILITY), and P (P2MP-LSP-INSTANTIATION-CAPABILITY), are added in this document:

- N (P2MP-CAPABILITY flag - 1 bit): If set to 1 by a PCC, the N Flag indicates that the PCC is willing to send P2MP LSP State Reports whenever there's a change to the parameters or operational status of the P2MP LSP; if set to 1 by a PCE, the N Flag indicates that the PCE is interested in receiving LSP State Reports whenever there is a parameter or operational status change to the P2MP LSP. The P2MP-CAPABILITY Flag MUST be advertised by both a PCC and a PCE for the P2MP extension (as per this document) of the PCRpt messages to be allowed on a PCEP session.
- M (P2MP-LSP-UPDATE-CAPABILITY flag - 1 bit): If set to 1 by a PCC, the M Flag indicates that the PCC allows modification of P2MP LSP parameters; if set to 1 by a PCE, the M Flag indicates that the PCE is capable of updating P2MP LSP parameters. The P2MP-LSP-UPDATE-CAPABILITY Flag MUST be advertised by both a PCC and a PCE for the P2MP extension (as per this document) of the PCUpd messages to be allowed on a PCEP session.
- P (P2MP-LSP-INSTANTIATION-CAPABILITY flag - 1 bit): If set to 1 by a PCC, the P Flag indicates that the PCC allows instantiation of a P2MP LSP by a PCE. If set to 1 by a PCE, the P flag indicates that the PCE supports P2MP LSP instantiation. The P2MP-LSP-INSTANTIATION-CAPABILITY flag MUST be set by both PCC and PCE in order to support PCE-initiated P2MP LSP instantiation.

A PCEP speaker should continue to advertise the basic P2MP capability via mechanisms as described in [RFC8306].

5.3. IGP Extensions for Stateful PCE P2MP Capabilities Advertisement

When the PCC is a Label Switching Router (LSR) participating in the IGP (either OSPF or IS-IS), and PCEs are either LSRs or servers also participating in the IGP, an effective mechanism for PCE discovery within an IGP routing domain consists of utilizing IGP

advertisements. Extensions for the advertisement of PCE discovery information are defined for OSPF and for IS-IS in [RFC5088] and [RFC5089], respectively.

The PCE-CAP-FLAGS sub-TLV, defined in [RFC5089], is an optional sub-TLV used to advertise PCE capabilities. It MAY be present within the PCE Discovery (PCED) TLV carried by OSPF or IS-IS. [RFC5088] and [RFC5089] provide the description and processing rules for this sub-TLV when carried within OSPF and IS-IS, respectively.

The format of the PCE-CAP-FLAGS sub-TLV is included below for easy reference:

Type: 5

Length: Multiple of 4

Value: This contains an array of units of 32-bit flags with the most significant bit as 0. Each bit represents one PCE capability.

PCE capability bit flags are defined in [RFC5088]. This document defines new capability bits for the stateful PCE with P2MP as follows:

Bit	Capability
13	Active Stateful PCE with P2MP
14	Passive Stateful PCE with P2MP
15	PCE-Initiation with P2MP

Note that, while active, passive, or initiation stateful PCE capabilities for P2MP may be advertised during discovery, PCEP Speakers that wish to use stateful PCEP for P2MP TE LSPs MUST advertise stateful PCEP capabilities during PCEP session setup, as specified in the current document. A PCC MAY initiate stateful PCEP P2MP capability advertisement at PCEP session setup even if it did not receive any IGP PCE capability advertisements.

5.4. State Synchronization

State Synchronization operations (described in Section 5.6 of [RFC8231]) are applicable for the P2MP TE LSPs as well. The optimizations described in [RFC8232] can also be applied for P2MP TE LSPs.

5.5. LSP Delegation

LSP delegation operations (described in Section 5.7 of [RFC8231]) are applicable for P2MP TE LSPs as well.

5.6. LSP Operations

5.6.1. Passive Stateful PCE

LSP operations for passive stateful PCE (described in Section 5.8.1 of [RFC8231]) are applicable for P2MP TE LSPs as well.

The PCReq and PCRep message format for P2MP TE LSPs is described in Sections 3.4 and 3.5 of [RFC8306], respectively.

The PCReq and PCRep message for P2MP TE LSPs are extended to support encoding of the LSP object so that it is possible to refer to an LSP with a unique identifier and simplify the PCEP message exchange. For example, in case of modification of one leaf in a P2MP tree, there should be no need to carry the full P2MP tree in a PCReq message.

The extensions for the Request and Response message for passive stateful operations on P2MP TE LSPs are described in Sections 6.3 and 6.4. The extension for the Path Computation LSP State Report (PCRpt) message is described in Section 6.1.

5.6.2. Active Stateful PCE

LSP operations for active stateful PCE (described in Section 5.8.2 of [RFC8231]) are applicable for P2MP TE LSPs as well.

The extension for the Path Computation LSP Update (PCUpd) message for active stateful operations on P2MP TE LSPs is described in Section 6.2.

5.6.3. PCE-Initiated LSP

As per Section 5.1 of [RFC8281], the PCE sends a Path Computation LSP Initiate Request (PCInitiate) message to the PCC to suggest instantiation or deletion of a P2P TE LSP. This document extends the PCInitiate message to support P2MP TE LSPs (see details in Section 6.5).

The instantiation and deletion operations for P2MP TE LSPs are the same as for P2P LSPs as described in Sections 5.3 and 5.4 of [RFC8281].

5.6.3.1. P2MP TE LSPs Instantiation

The instantiation operation of P2MP TE LSPs is the same as the LSP instantiation operation defined in Section 5.3 of [RFC8281]; this includes the handling of the PLSP-ID, SYMBOLIC-PATH-NAME TLV, etc. The processing rules and use of error codes remain unchanged. The N

(P2MP) flag (Section 7.1) MUST be set in the LSP object in the PCInitiate message by the PCE to specify that the instantiation is for P2MP TE LSPs. Like the PLSP-ID (as per [RFC8281]), the P2MP-LSP-IDENTIFIERS TLV SHOULD NOT be included in the LSP object in PCInitiate messages and MUST be ignored on receipt. These identifiers are generated by the PCC on receipt of the PCInitiate message and reported via a PCRpt message to the PCE.

5.6.3.2. P2MP TE LSPs Deletion

The deletion operation of P2MP TE LSPs is the same as the LSP deletion operation defined in Section 5.4 of [RFC8281]; this entails sending an LSP Initiate Message with an LSP object carrying the PLSP-ID of the LSP to be removed as well as a Stateful PCE Request Parameter (SRP) object with the R flag set (LSP-REMOVE as per Section 5.2 of [RFC8281]). The processing rules and error codes remain unchanged.

5.6.3.3. Adding and Pruning Leaves for the P2MP TE LSP

The adding of new leaves and pruning of old leaves for the PCE-initiated P2MP TE LSP MUST be carried in a PCUpd message as per Section 6.2 for P2MP TE LSP extensions. As defined in [RFC8306], leaf type = 1 is used for adding new leaves, and leaf type = 2 is used for pruning old leaves of P2MP END-POINTS Objects.

PCC MAY use the Incremental State Update mechanism as described in [RFC4875] to signal the adding and pruning of leaves.

Section 3.10 of [RFC8306] defines the error-handling procedures when adding new leaves to or removing old leaves from the existing P2MP tree for PCReq messages. The same error handling and error codes are also applicable to the stateful PCE messages as described in this document.

5.6.3.4. P2MP TE LSPs Delegation and Cleanup

P2MP TE LSPs delegation and cleanup operations are the same as the LSP delegation and cleanup operations defined in Section 6 of [RFC8281]. The processing rules and error codes remain unchanged.

6. PCEP Message Extensions

Message formats in this section, as those in [RFC8231], [RFC8281], and [RFC5440], are presented using Routing Backus-Naur Format (RBNF) as specified in [RFC5511].

6.1. The PCRpt Message

As per Section 6.1 of [RFC8231], a PCRpt message is used to report the current state of a P2P TE LSP. This document extends the PCRpt message in reporting the status of P2MP TE LSPs.

The format of a PCRpt message is as follows:

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

Where:

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

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

Where:

```
<path> ::= <end-point-intended-path-pair-list>
           [<actual-attribute-list>
            <end-point-actual-path-pair-list>]
           [<intended-attribute-list>]
```

```
<end-point-intended-path-pair-list> ::=
        [<END-POINTS>]
        [<S2LS>]
        <intended-path>
        [<end-point-intended-path-pair-list>]
```

```
<end-point-actual-path-pair-list> ::=
        [<END-POINTS>]
        [<S2LS>]
        <actual-path>
        [<end-point-actual-path-pair-list>]
```

```
<intended-path> ::= (<ERO>|<SERO>)
                    [<intended-path>]
```

```
<actual-path> ::= (<RRO>|<SRRO>)
                  [<actual-path>]
```

<intended-attribute-list> is defined in [RFC5440] and extended by PCEP extensions.

<actual-attribute-list> consists of the actual computed and signaled values of the <BANDWIDTH> and <metric-lists> objects defined in [RFC5440].

The P2MP END-POINTS object defined in [RFC8306] is mandatory for specifying the address of P2MP leaves, grouped by leaf types.

- o New leaves to add (leaf type = 1)
- o Old leaves to remove (leaf type = 2)
- o Old leaves whose path can be modified/reoptimized (leaf type = 3)
- o Old leaves whose path must be left unchanged (leaf type = 4)

When reporting the status of a P2MP TE LSP, the destinations MUST be grouped in the END-POINTS object based on the operational status (O field in S2LS objects) and leaf type (in END-POINTS objects). This way, leaves of the same type that share the same operational status can be grouped together. For reporting the status of delegated P2MP TE LSPs, leaf type = 3 is used, whereas for nondelegated P2MP TE LSPs, leaf type = 4 is used.

For a delegated P2MP TE LSP, configuration changes are reported via a PCRpt message. For example, for adding new leaves, leaf type = 1 is used in the END-POINTS object, and for removing old leaves, leaf type = 2 is used.

Note that the compatibility with the [RFC8231] definition of <state-report> is preserved. At least one instance of <END-POINTS> MUST be present in this message for P2MP LSP.

Note that the ordering of <end-point-intended-path-pair-list>, <actual-attribute-list>, <end-point-actual-path-pair-list>, and <intended-attribute-list> is done to retain compatibility with state reports for the P2P LSPs as per [RFC8231].

During state synchronization, the PCRpt message reports the status of the full P2MP tree.

The S2LS object MUST be carried in a PCRpt message along with the END-POINTS object when an N (P2MP) flag is set in an LSP object for P2MP TE LSPs. If the S2LS object is missing, the receiving PCE MUST send a PCEP Error (PCErr) message with Error-type=6 ("Mandatory Object missing") and Error-value=13 ("S2LS object missing"). If the

END-POINTS object is missing, the receiving PCE MUST send a PCErr message with Error-type=6 ("Mandatory Object missing") and Error-value=3 ("END-POINTS object missing") (defined in [RFC5440]).

The S2LS object could be used in conjunction with the intended-path (EXPLICIT_ROUTE object or ERO) as well as the actual-path (RECORD_ROUTE object or RRO); for the same leaf, the state encoded in the S2LS object associated with the actual-path MUST be used over the intended-path.

If the E-bit (ERO-Compress bit) was set to 1 in the report, then the path will be formed by an ERO followed by a list of SECONDARY_EXPLICIT_ROUTE Objects (SEROs), or an RRO followed by a list of SECONDARY_RECORD_ROUTE Objects (SRROs).

6.2. The PCUpd Message

As per Section 6.2 of [RFC8231], a PCUpd message is used to update P2P TE LSP attributes. This document extends the PCUpd message in updating the attributes of a P2MP TE LSP.

The format of a PCUpd message is as follows:

```
<PCUpd Message> ::= <Common Header>
                    <update-request-list>
```

Where:

```
<update-request-list> ::= <update-request>
                          [<update-request-list>]
```

```
<update-request> ::= <SRP>
                    <LSP>
                    <path>
```

Where:

```
<path> ::= <end-point-path-pair-list>
          <intended-attribute-list>
```

```
<end-point-path-pair-list> ::=
    [<END-POINTS>]
    <intended-path>
    [<end-point-path-pair-list>]
```

```
<intended-path> ::= (<ERO>|<SERO>)
                    [<intended-path>]
```

<intended-attribute-list> is the attribute-list defined in [RFC5440] and extended by PCEP extensions.

Note that the compatibility with the [RFC8231] definition of <update-request> is preserved.

The PCC SHOULD use the make-before-break or sub-group-based procedures described in [RFC4875] based on a local policy decision.

The END-POINTS object MUST be carried in a PCUpd message when the N flag is set in the LSP object for a P2MP TE LSP. If the END-POINTS object is missing, the receiving PCC MUST send a PCErr message with Error-type=6 ("Mandatory Object missing") and Error-value=3 ("END-POINTS object missing") (defined in [RFC5440]).

6.3. The PCReq Message

As per Section 3.4 of [RFC8306], a PCReq message is used for a P2MP Path Computation Request. This document extends the PCReq message such that a PCC MAY include the LSP object in the PCReq message if the stateful PCE P2MP capability has been negotiated on a PCEP session between the PCC and a PCE.

The format of a PCReq message is as follows:

```
<PCReq Message> ::= <Common Header>
                    [<svec-list>]
                    <request-list>
```

where:

```
<svec-list> ::= <SVEC>
                [<OF>]
                [<metric-list>]
                [<svec-list>]
```

```
<request-list> ::= <request> [<request-list>]
```

```
<request> ::= <RP>
              <end-point-rro-pair-list>
              [<LSP>]
              [<OF>]
              [<LSPA>]
              [<BANDWIDTH>]
              [<metric-list>]
              [<IRO> | <BNC>]
              [<LOAD-BALANCING>]
```

```

<end-point-rro-pair-list> ::= <END-POINTS>
                               [<RRO-List> [<BANDWIDTH>]]
                               [<end-point-rro-pair-list>]

<RRO-List> ::= (<RRO> | <SRRO>) [<RRO-List>]
<metric-list> ::= <METRIC> [<metric-list>]

```

6.4. The PCRep Message

As per Section 3.5 of [RFC8306], a PCRep message is used for a P2MP Path Computation Reply. This document extends the PCRep message such that a PCE MAY include the LSP object in the PCRep message if the stateful PCE P2MP capability has been negotiated on a PCEP session between the PCC and a PCE.

The format of a PCRep message is as follows:

```

<PCRep Message> ::= <Common Header>
                    <response-list>

```

where:

```

<response-list> ::= <response> [<response-list>]

<response> ::= <RP>
               [<end-point-path-pair-list>]
               [<LSP>]
               [<NO-PATH>]
               [<UNREACH-DESTINATION>]
               [<attribute-list>]

<end-point-path-pair-list> ::= [<END-POINTS>]
                               <path>
                               [<end-point-path-pair-list>]

<path> ::= (<ERO> | <SERO>) [<path>]

<attribute-list> ::= [<OF>]
                    [<LSPA>]
                    [<BANDWIDTH>]
                    [<metric-list>]
                    [<IRO>]

```

6.5. The PCInitiate Message

As defined in section 5.1 of [RFC8281], a PCE sends a PCInitiate message to a PCC to recommend instantiation of a P2P TE LSP. This document extends the format of a PCInitiate message for the creation of P2MP TE LSPs, but the creation and deletion operations of P2MP TE LSPs are the same to the P2P TE LSPs.

The format of a PCInitiate message is as follows:

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

Where:

```
<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-instantiation> ::= <SRP>
                                       <LSP>
                                       <end-point-path-pair-list>
                                       [<attribute-list>]
```

```
<PCE-initiated-lsp-deletion> ::= <SRP>
                                   <LSP>
```

Where:

```
<end-point-path-pair-list> ::=
    [<END-POINTS>]
    <intended-path>
    [<end-point-path-pair-list>]
```

```
<intended-path> ::= (<ERO> | <SERO>)
                    [<intended-path>]
```

<attribute-list> is defined in [RFC5440] and extended by PCEP extensions.

The PCInitiate message with an LSP object with the N flag (P2MP) set is used to convey operation on a P2MP TE LSP. The SRP object is used to correlate between initiation requests sent by the PCE, and the error reports and state reports sent by the PCC as described in [RFC8231].

The END-POINTS object MUST be carried in a PCInitiate message when the N flag is set in an LSP object for a P2MP TE LSP. If the END-POINTS object is missing, the receiving PCC MUST send a PCErr message with Error-type=6 ("Mandatory Object missing") and Error-value=3 ("END-POINTS object missing") (defined in [RFC5440]).

6.6. Example

6.6.1. P2MP TE LSPs Update Request

An LSP Update Request message is sent by an active stateful PCE to update the P2MP TE LSPs parameters or attributes. An example of a PCUpd message for P2MP TE LSPs is described below:

```
Common Header
SRP
LSP with P2MP flag set
END-POINTS for leaf type 3
ERO list
```

In this example, a stateful PCE requests an update of the path taken to some of the leaves in a P2MP tree. The update request uses the END-POINT type 3 (modified/reoptimized). The ERO list represents the source-to-leaves path after modification. The update message does not need to encode the full P2MP tree in this case.

6.6.2. P2MP TE LSP Report

The LSP State Report message is sent by a PCC to report or delegate the P2MP TE LSP. The leaves of the P2MP TE LSP are grouped in the END-POINTS object based on the operational status and the leaf type. An example of a PCRpt message is described below for a delegated P2MP TE LSP to add new leaves to an existing P2MP TE LSP:

```
Common Header
LSP with P2MP flag set
END-POINTS for leaf type 1 (add)
S2LS (O=DOWN)
ERO list (empty)
```

An example of a PCRpt message for a P2MP TE LSP is described below to prune leaves from an existing P2MP TE LSP:

```
Common Header
LSP with P2MP flag set
END-POINTS for leaf type 2 (remove)
S2LS (O=UP)
ERO list (empty)
```

An example of a PCRpt message for a delegated P2MP TE LSP is described below to report the status of leaves in an existing P2MP TE LSP:

```

Common Header
SRP
LSP with P2MP flag set
END-POINTS for leaf type 3 (modify)
  S2LS (O=UP)
  RRO list
END-POINTS for leaf type 3 (modify)
  S2LS (O=DOWN)
  ERO list (empty)

```

In this example, the PCRpt message is in response to a PCUpd message. The PCRpt message includes the corresponding SRP object and indicates that some leaves are up (with the actual path) and some are down.

An example of a PCRpt message for a nondelegated P2MP TE LSP is described below to report status of leaves:

```

Common Header
LSP with P2MP flag set
END-POINTS for leaf type 4 (unchanged)
  S2LS (O=ACTIVE)
  RRO list
END-POINTS for leaf type 4 (unchanged)
  S2LS (O=DOWN)
  ERO list (empty)

```

6.6.3. P2MP TE LSPs Initiation Request

An LSP Initiation Request message is sent by a stateful PCE to create a P2MP TE LSP. An example of a PCInitiate message for a P2MP TE LSP is described below:

```

Common Header
SRP
LSP with P2MP flag set
END-POINTS for leaf type 1 (add)
  ERO list

```

In this example, a stateful PCE requests the creation of a P2MP TE LSP. The initiation request uses the END-POINT type 1 (new leaves). The ERO list represents the source-to-leaves path. The initiate message encodes the full P2MP tree in this case.

7. PCEP Object Extensions

The new PCEP TLVs defined in this document are in compliance with the PCEP TLV format defined in [RFC5440].

7.1. LSP Object Extension

The LSP Object is defined in Section 7.3 of [RFC8231]. It specifies the PLSP-ID to uniquely identify an LSP that is constant for the life time of a PCEP session. Similarly, for a P2MP tunnel, the PLSP-ID uniquely identifies a P2MP TE LSP. This document adds the following flags to the LSP Object:

N (P2MP flag - 1 bit): If the N flag is set to 1, it indicates that the message is for a P2MP TE LSP.

F (Fragmentation flag - 1 bit): If the F flag is unset (0), it indicates that the LSP is not fragmented or that it is the last piece of the fragmented LSP. If the F flag is set to 1, it indicates that the LSP is fragmented and that it is not the last piece of the fragmented LSP. The receiver needs to wait for additional fragments until it receives an LSP with the same PLSP-ID and with the F-bit set to 0. See Section 8 for further details.

E (ERO-compression flag - 1 bit): If the E flag is set to 1, it indicates the route is in compressed format (that is, Secondary Explicit Route Object (SERO) and Secondary Record Route Object (SRRO) objects [RFC8306] are in use).

The flags defined in this section (N, F, and E) are used in PCRpt, PCUpd, or PCInitiate messages. In the case of PCReq and PCRep messages, these flags have no meaning and thus MUST be ignored. The corresponding flags in the RP (Request Parameters) object are used as described in [RFC8306].

7.1.1. P2MP-LSP-IDENTIFIERS TLV

[RFC8231] specifies the LSP-IDENTIFIERS TLVs to be included in the LSP object. For P2MP TE LSP, this document defines P2MP-LSP-IDENTIFIERS TLVs for the LSP object. There are two P2MP-LSP-IDENTIFIERS TLVs, one for IPv4 and one for IPv6. The P2MP-LSP-IDENTIFIERS TLV MUST be included in the LSP object in a PCRpt message for P2MP TE LSPs. If the N bit is set in the LSP object in the PCRpt message but the P2MP-LSP-IDENTIFIER TLV is absent, the PCE MUST respond with a PCErr message carrying error-type 6 ("mandatory object missing") and error-value 14 ("P2MP-LSP-IDENTIFIERS TLV missing") and close the PCEP session.

The P2MP-LSP-IDENTIFIERS TLV MAY be included in the LSP object in the PCUpd message for P2MP TE LSPs. The special value of all zeros for all the fields in the value portion of the TLV is used to refer to all paths pertaining to a particular PLSP-ID. The length of the TLV remains fixed based on the IP version.

The P2MP-LSP-IDENTIFIERS TLV SHOULD NOT be used in a PCInitiate message (see Section 5.6.3.1) and MAY optionally be included in the LSP object in the PCReq and the PCRep message for P2MP TE LSP.

The format of the IPV4-P2MP-LSP-IDENTIFIERS TLV is shown in Figure 1:

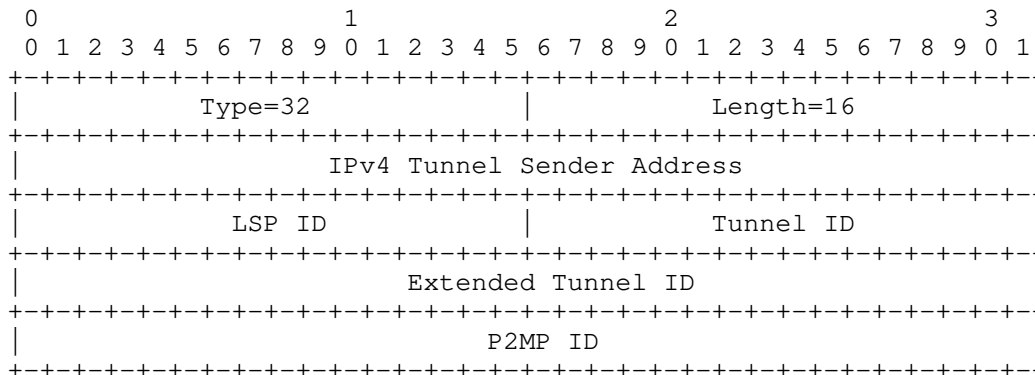


Figure 1: IPV4-P2MP-LSP-IDENTIFIERS TLV Format

The type (16 bits) of the TLV is 32. The length (16 bits) has a fixed value of 16 octets. The value contains the following fields:

IPv4 Tunnel Sender Address: Contains the sender node's IPv4 address, as defined in [RFC3209]. See Section 4.6.2.1 of [RFC3209] for the LSP_TUNNEL_IPv4 Sender Template Object.

LSP ID: Contains the 16-bit 'LSP ID' identifier defined in [RFC3209]. See Section 4.6.2.1 of [RFC3209] for the LSP_TUNNEL_IPv4 Sender Template Object.

Tunnel ID: Contains the 16-bit 'Tunnel ID' identifier defined in [RFC3209]. See Section 4.6.1.1 of [RFC3209] for the LSP_TUNNEL_IPv4 Session Object.

Extended Tunnel ID: Contains the 32-bit 'Extended Tunnel ID' identifier defined in [RFC3209]. See Section 4.6.1.1 of [RFC3209] for the LSP_TUNNEL_IPv4 Session Object.

P2MP ID: Contains the 32-bit 'P2MP ID' identifier defined in Section 19.1.1 of [RFC4875] for the P2MP LSP Tunnel IPv4 SESSION Object.

The format of the IPV6-P2MP-LSP-IDENTIFIERS TLV is shown in Figure 2:

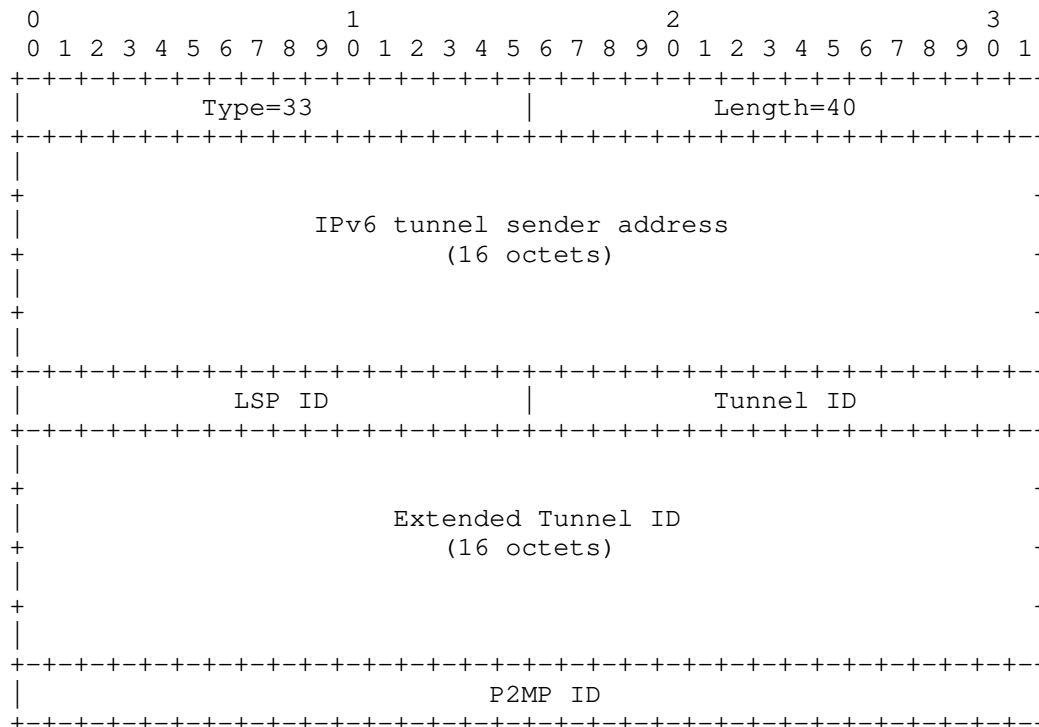


Figure 2: IPV6-P2MP-LSP-IDENTIFIERS TLV Format

The type (16 bits) of the TLV is 33. The length (16 bits) has a fixed length of 40 octets. The value contains the following fields:

IPv6 Tunnel Sender Address: Contains the sender node's IPv6 address, as defined in [RFC3209]. See Section 4.6.2.2 of [RFC3209] for the LSP_TUNNEL_IPv6 Sender Template Object.

LSP ID: Contains the 16-bit 'LSP ID' identifier defined in [RFC3209]. See Section 4.6.2.2 of [RFC3209] for the LSP_TUNNEL_IPv6 Sender Template Object.

Tunnel ID: Contains the 16-bit 'Tunnel ID' identifier defined in [RFC3209]. See Section 4.6.1.2 of [RFC3209] for the LSP_TUNNEL_IPv6 Session Object.

Extended Tunnel ID: Contains the 128-bit 'Extended Tunnel ID' identifier defined in [RFC3209]. See Section 4.6.1.2 of [RFC3209] for the LSP_TUNNEL_IPv6 Session Object.

P2MP ID: Defined above under Figure 1.

Tunnel ID: Remains constant over the lifetime of a tunnel.

7.2. S2LS Object

The S2LS (Source-to-Leaves) Object is used to report the state of one or more destinations (leaves) encoded within the END-POINTS object for a P2MP TE LSP. It MUST be carried in a PCRpt message along with an END-POINTS object when the N flag is set in an LSP object.

S2LS Object-Class is 41.

S2LS Object-Types is 1.

The format of the S2LS object is shown in the following figure:

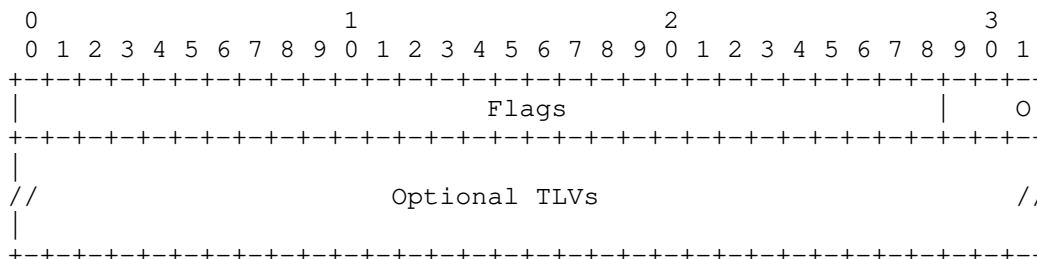


Figure 3: S2LS Object Format

Flags (32 bits): The following flag is currently defined:

O (Operational - 3 bits) The O field represents the operational status of the group of destinations. The values are as per the Operational field in the LSP object defined in Section 7.3 of [RFC8231].

Unassigned bits are reserved for future uses. They MUST be set to 0 on transmission and MUST be ignored on receipt.

When the N flag is set in an LSP object, the O field in the LSP object represents the operational status of the full P2MP TE LSP, and the O field in the S2LS object represents the operational status of a group of destinations encoded within the END-POINTS object. If there is a conflict between the O field in the LSP and the S2LS object (for

example, the O field in the LSP corresponds to down whereas the O field in the S2LS is up), the PCEP speaker MUST generate an error with error-type 10 ("Reception of an invalid object") and error-value 22 ("Mismatch of O field in S2LS and LSP object").

Future documents might define optional TLVs that could be included in the S2LS Object.

8. Message Fragmentation

The total PCEP message length, including the common header, is $(2^{16})-1$ bytes. In certain scenarios, the P2MP report and update request may not fit into a single PCEP message (e.g., initial report or update). The F flag is used in the LSP object to signal that the initial report, update, or initiate request was too large to fit into a single PCEP message and will be fragmented into multiple messages. In order to identify the single report or update, each message will use the same PLSP-ID. In order to identify that a series of PCInitiate messages represents a single Initiate, each message will use the same PLSP-ID (in this case 0) and SRP-ID-number.

The fragmentation procedure described below for report or update messages is similar to [RFC8306], which describes request and response message fragmentation.

8.1. Report Fragmentation Procedure

If the initial report is too large to fit into a single report message, the PCC will split the report over multiple messages. Each message sent to the PCE, except the last one, will have the F flag set in the LSP object to signify that the report has been fragmented into multiple messages. In order to identify that a series of report messages represents a single report, each message will use the same PLSP-ID.

The Error-Type value 18 ("P2MP Fragmentation Error") is used to report any error associated with the fragmentation of a P2MP PCEP message. A new error-value 2 indicates "Fragmented report failure" and is used if a PCE does not receive the last part of the fragmented message.

8.2. Update Fragmentation Procedure

Once the PCE computes and updates a path for some or all leaves in a P2MP TE LSP, an update message is sent to the PCC. If the update is too large to fit into a single update message, the PCE will split the update over multiple messages. Each update message sent by the PCE, except the last one, will have the F flag set in the LSP object to

signify that the update has been fragmented into multiple messages. In order to identify that a series of update messages represents a single update, each message will use the same PLSP-ID and SRP-ID-number.

The Error-Type value 18 ("P2MP Fragmentation Error") is used to report any error associated with the fragmentation of a P2MP PCEP message. A new error-value 3 indicates "Fragmented update failure" and is used if a PCC does not receive the last part of the fragmented message.

8.3. PCInitiate Fragmentation Procedure

Once the PCE initiates to set up a P2MP TE LSP, a PCInitiate message is sent to the PCC. If the initiate request is too large to fit into a single PCInitiate message, the PCE will split the initiate request over multiple messages. Each PCInitiate message sent by the PCE, except the last one, will have the F flag set in the LSP object to signify that the PCInitiate has been fragmented into multiple messages. In order to identify that a series of PCInitiate messages represents a single Initiate, each message will use the same PLSP-ID (in this case 0) and SRP-ID-number.

The Error-Type value 18 ("P2MP Fragmentation Error") is used to report any error associated with the fragmentation of a P2MP PCEP message. A new error-value 4 indicates "Fragmented instantiation failure" and is used if a PCC does not receive the last part of the fragmented message.

9. Nonsupport of P2MP TE LSPs for Stateful PCE

The PCEP extensions described in this document for stateful PCEs with P2MP capability MUST NOT be used if the PCE has not advertised its stateful capability with P2MP as per Section 5.2. If the PCC supports the extensions as per this document (understands the N (P2MP-CAPABILITY) and M (P2MP-LSP-UPDATE-CAPABILITY) flags in the LSP object) but did not advertise this capability, then upon receipt of a PCUpd message from the PCE, it SHOULD generate a PCErr with error-type 19 ("Invalid Operation"), error-value 12 ("Attempted LSP Update Request for P2MP if active stateful PCE capability for P2MP was not advertised"), and terminate the PCEP session. If the PCE supports the extensions as per this document (understands the N (P2MP-CAPABILITY) flag in the LSP object) but did not advertise this capability, then upon receipt of a PCRpt message from the PCC, it SHOULD generate a PCErr with error-type 19 ("Invalid Operation"), error-value 11 ("Attempted LSP State Report for P2MP if stateful PCE capability for P2MP was not advertised"), and it SHOULD terminate the PCEP session.

If a Stateful PCE receives a P2MP TE LSP report message and the PCE does not understand the N (P2MP-CAPABILITY) flag in the LSP object, and therefore the PCEP extensions described in this document, then the Stateful PCE would act as per Section 6.1 of [RFC8231] (and consider the PCRpt message as invalid).

The PCEP extensions described in this document for PCC or PCE with the PCE-Initiation capability for P2MP TE LSPs MUST NOT be used if the PCC or PCE has not advertised its stateful capability with Instantiation and P2MP capability as per Section 5.2. If the PCC supports the extensions as per this document (understands the P (P2MP-LSP-INSTANTIATION-CAPABILITY) flag) but did not advertise this capability, then upon receipt of a PCInitiate message from the PCE, it SHOULD generate a PCErr with error-type 19 ("Invalid Operation"), error-value 13 ("Attempted LSP Instantiation Request for P2MP if stateful PCE instantiation capability for P2MP was not advertised"), and terminate the PCEP session.

10. Manageability Considerations

All manageability requirements and considerations listed in [RFC5440], [RFC8306], [RFC8231], and [RFC8281] apply to PCEP extensions defined in this document. In addition, requirements and considerations listed in this section apply.

10.1. Control of Function and Policy

A PCE or PCC implementation MUST allow configuration of the stateful PCEP capability, the LSP Update capability, and the LSP Initiation capability for P2MP LSPs.

10.2. Information and Data Models

The PCEP YANG module [PCE-PCEP-YANG] can be extended to include advertised P2MP stateful capabilities, P2MP synchronization status, and the delegation status of a P2MP LSP, etc. The statistics module should also count data related to P2MP LSPs.

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

Mechanisms defined in this document do not imply any new operation verification requirements in addition to those already listed in [RFC5440], [RFC8306], [RFC8231], and [RFC8281].

10.5. Requirements on Other Protocols

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

10.6. Impact on Network Operations

Mechanisms defined in this document do not have any impact on network operations in addition to those already listed in [RFC5440], [RFC8306], [RFC8231], and [RFC8281].

Stateful PCE features for P2MP LSPs would help with network operations.

11. IANA Considerations

IANA has registered the code points for the protocol elements defined in this document.

11.1. PCE Capabilities in IGP Advertisements

IANA has registered the new bits in the OSPF Parameters "Path Computation Element (PCE) Capability Flags" registry, as follows:

Bit	Capability Description	Reference
13	Active Stateful PCE with P2MP	RFC 8623
14	Passive Stateful PCE with P2MP	RFC 8623
15	Stateful PCE Initiation with P2MP	RFC 8623

11.2. STATEFUL-PCE-CAPABILITY TLV

The STATEFUL-PCE-CAPABILITY TLV is defined in [RFC8231], and the "STATEFUL-PCE-CAPABILITY TLV Flag Field" subregistry was created to manage the flags in the TLV. IANA has registered the following code points in the aforementioned registry.

Bit	Description	Reference
23	P2MP-LSP-INSTANTIATION-CAPABILITY	RFC 8623
24	P2MP-LSP-UPDATE-CAPABILITY	RFC 8623
25	P2MP-CAPABILITY	RFC 8623

11.3. LSP Object

The LSP object is defined in [RFC8231], and the "LSP Object Flag Field" subregistry was created to manage the Flags field of the LSP object.

IANA has registered the following code points in the aforementioned registry.

Bit	Description	Reference
1	ERO-compression	RFC 8623
2	Fragmentation	RFC 8623
3	P2MP	RFC 8623

11.4. PCEP-ERROR Object

IANA has registered the new error values within the "PCEP-ERROR Object Error Types and Values" subregistry of the PCEP Numbers registry, as follows:

Error-Type	Meaning
6	Mandatory Object missing [RFC5440] Error-value = 13: S2LS object missing Error-value = 14: P2MP-LSP-IDENTIFIERS TLV missing
10	Reception of an invalid object [RFC5440] Error-value = 22: Mismatch of O field in S2LS and LSP object
18	P2MP Fragmentation Error [RFC8306] Error-value = 2: Fragmented Report failure Error-value = 3: Fragmented Update failure Error-value = 4: Fragmented Instantiation failure
19	Invalid Operation [RFC8231] Error-value = 11: Attempted LSP State Report for P2MP if stateful PCE capability for P2MP was not advertised Error-value = 12: Attempted LSP Update Request for P2MP if active stateful PCE capability for P2MP was not advertised Error-value = 13: Attempted LSP Instantiation Request for P2MP if stateful PCE instantiation capability for P2MP was not advertised

The reference for all new Error-values above is RFC 8623.

11.5. PCEP TLV Type Indicators

IANA has registered the following code points in the existing "PCEP TLV Type Indicators" registry as follows:

Value	Description	Reference
32	P2MP-IPV4-LSP-IDENTIFIERS	RFC 8623
33	P2MP-IPV6-LSP-IDENTIFIERS	RFC 8623

11.6. PCEP Object

IANA has registered the new object-class values and object types within the "PCEP Objects" subregistry of the PCEP Numbers registry, as follows.

Object-Class Value	Name	Reference
41	S2LS Object-Type 0: Reserved 1: S2LS	RFC 8623

11.7. S2LS Object

A new subregistry, named "S2LS Object Flag Field", has been created within the "Path Computation Element Protocol (PCEP) Numbers" registry to manage the 32-bit flag field of the S2LS object. 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

The following values are defined in this document:

Bit	Description	Reference
0-28	Unassigned	
29-31	Operational (3 bits)	RFC 8623

12. Security Considerations

The stateful operations on P2MP TE LSPs are more CPU intensive and also utilize more bandwidth on the wire (in comparison to P2P TE LSPs). If a rogue PCC were able to request unauthorized stateful PCE operations, then it may be able to mount a DoS attack against a PCE, which would disrupt the network and deny service to other PCCs. Similarly, an attacker may flood the PCC with PCUpd messages at a rate that exceeds either the PCC's ability to process them or the network's ability to signal the changes by either spoofing messages or compromising the PCE itself.

Consequently, it is important that implementations conform to the relevant security requirements as listed below:

- o As per [RFC8231], it is RECOMMENDED that these PCEP extensions only be activated on authenticated and encrypted sessions across PCEs and PCCs belonging to the same administrative authority, using Transport Layer Security (TLS) [RFC8253] as per the recommendations and best current practices in [RFC7525] (unless explicitly set aside in [RFC8253]).
- o Security considerations for path computation requests and responses are as per [RFC8306].
- o Security considerations for stateful operations (such as state report, synchronization, delegation, update, etc.) are as per [RFC8231].
- o Security considerations for the LSP instantiation mechanism are as per [RFC8231].
- o Security considerations as stated in Sections 10.1, 10.6, and 10.7 of [RFC5440] continue to apply.

13. References

13.1. Normative References

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