Standard Representation Of Domain-Sequence
draft-ietf-pce-pcep-domain-sequence-06

Abstract

   The ability to compute shortest constrained Traffic Engineering Label
   Switched Paths (TE LSPs) in Multiprotocol Label Switching (MPLS) and
   Generalized MPLS (GMPLS) networks across multiple domains has been
   identified as a key requirement. In this context, a domain is a
   collection of network elements within a common sphere of address
   management or path computational responsibility such as an Interior
   Gateway Protocol (IGP) area or an Autonomous Systems (AS). This
   document specifies a standard representation and encoding of a
   Domain-Sequence, which is defined as an ordered sequence of domains
   traversed to reach the destination domain to be used by Path
   Computation Elements (PCEs) to compute inter-domain shortest
   constrained paths across a predetermined sequence of domains . This
   document also defines new subobjects to be used to encode domain
   identifiers.

Status of This Memo

Copyright Notice

Table of Contents

1. Introduction

   A PCE may be used to compute end-to-end paths across multi-domain
   environments using a per-domain path computation technique [RFC5152].
   The so called backward recursive path computation (BRPC) mechanism
   [RFC5441] defines a PCE-based path computation procedure to compute
   inter-domain constrained (G)MPLS TE LSPs. However, both per-domain
   and BRPC techniques assume that the sequence of domains to be crossed
   from source to destination is known, either fixed by the network
   operator or obtained by other means. Also for inter-domain point-to-
   multi-point (P2MP) tree computation, [RFC7334] assumes the domain-
   tree is known in priori.

   The list of domains (domain-sequence) in a point-to-point (P2P) path
   or a point-to-multipoint (P2MP) tree is usually a constraint in the
   path computation request. A PCE determines the next PCE to forward
   the request based on the domain-sequence. In a multi-domain path
   computation, a PCC MAY indicate the sequence of domains to be
   traversed using the Include Route Object (IRO) defined in [RFC5440].

   When the sequence of domains is not known in advance, the
   Hierarchical PCE (H-PCE) [RFC6805] architecture and mechanisms can be
   used to determine the end-to-end Domain-Sequence.

   This document defines a standard way to represent and encode a
   Domain-Sequence in various deployment scenarios including P2P, P2MP
   and H-PCE.

   The Domain-Sequence (the set of domains traversed to reach the
   destination domain) is either administratively predetermined or
   discovered by some means (H-PCE) that is outside of the scope of this
   document.

[RFC5440] defines the Include Route Object (IRO) and the Explicit
Route Object (ERO); [RFC5521] defines the Exclude Route Object (XRO)
and the Explicit Exclusion Route Subobject (EXRS); The use of
Autonomous System (AS) (albeit with a 2-Byte AS number) as an
abstract node representing domain is defined in [RFC3209], this
document specifies new subobjects to include or exclude domains such
as an IGP area or an Autonomous Systems (4-Byte as per [RFC4893]).

Further, the domain identifier may simply act as delimiter to specify
where the domain boundary starts and ends.

This is a companion document to Resource ReserVation Protocol -
Traffic Engineering (RSVP-TE) extensions for the domain identifiers
[DOMAIN-SUBOBJ].

1.1. Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT",
"SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this
document are to be interpreted as described in [RFC2119].

2. Terminology

The following terminology is used in this document.

ABR: OSPF Area Border Router. Routers used to connect two IGP
   areas.

AS: Autonomous System.

ASBR: Autonomous System Boundary Router.

BN: Boundary Node, Can be an ABR or ASBR.

BRPC: Backward Recursive Path Computation

Domain: As per [RFC4655], any collection of network elements within
   a common sphere of address management or path computational
   responsibility. Examples of domains include Interior Gateway
   Protocol (IGP) areas and Autonomous Systems (ASs).

Domain-Sequence: An ordered sequence of domains traversed to reach
   the destination domain.

ERO: Explicit Route Object

H-PCE: Hierarchical PCE

   IGP: Interior Gateway Protocol. Either of the two routing
      protocols, Open Shortest Path First (OSPF) or Intermediate System
      to Intermediate System (IS-IS).

   IRO: Include Route Object

   IS-IS: Intermediate System to Intermediate System.

   OSPF: Open Shortest Path First.

   PCC: Path Computation Client: any client application requesting a
      path computation to be performed by a Path Computation Element.

   PCE: Path Computation Element. An entity (component, application,
      or network node) that is capable of computing a network path or
      route based on a network graph and applying computational
      constraints.

   P2MP: Point-to-Multipoint

   P2P: Point-to-Point

   RSVP: Resource Reservation Protocol

   TE LSP: Traffic Engineering Label Switched Path.

   XRO: Exclude Route Object

3. Detail Description

3.1. Domains

   [RFC4726] and [RFC4655] define domain as a separate administrative or
   geographic environment within the network. A domain may be further
   defined as a zone of routing or computational ability. Under these
   definitions a domain might be categorized as an AS or an IGP area.
   Each AS can be made of several IGP areas. In order to encode a
   Domain-Sequence, it is required to uniquely identify a domain in the
   Domain-Sequence. A domain can be uniquely identified by area-id or
   AS or both.

3.2. Domain-Sequence

   A domain-sequence is an ordered sequence of domains traversed to
   reach the destination domain.

   A domain-sequence can be applied as a constraint and carried in path
   computation request to PCE(s). A domain-sequence can also be the

result of a path computation. For example, in the case of H-PCE
[RFC6805] Parent PCE MAY send the Domain-Sequence as a result in a
path computation reply.

In a P2P path, the domains listed appear in the order that they are
crossed. In a P2MP path, the domain tree is represented as list of
domain sequences.

A domain-sequence enables a PCE to select the next PCE to forward the
path computation request based on the domain information.

A PCC or PCE MAY add an additional constraints covering which
Boundary Nodes (ABR or ASBR) or Border links (Inter-AS-link) MUST be
traversed while defining a Domain-Sequence.

Thus a Domain-Sequence MAY be made up of one or more of -

o AS Number

o Area ID

o Boundary Node ID

o Inter-AS-Link Address

Consequently, a Domain-Sequence can be used:

1. by a PCE in order to discover or select the next PCE in a
    collaborative path computation, such as in BRPC [RFC5441];

2. by the Parent PCE to return the Domain-Sequence when unknown,
    this can further be an input to BRPC procedure [RFC6805];

3. by a PCC (or PCE) to constraint the domains used in a H-PCE path
    computation, explicitly specifying which domains to be expanded;

4. by a PCE in per-domain path computation model [RFC5152] to
    identify the next domain(s);

3.3. Standard Representation

Domain-Sequence MAY appear in PCEP Messages, notably in -

o Include Route Object (IRO): As per [RFC5440], used to specify set
   of network elements that MUST be traversed. The subobjects in IRO
   are used to specify the domain-sequence that MUST be traversed to
   reach the destination.

o Exclude Route Object (XRO): As per [RFC5521], used to specify
   certain abstract nodes that MUST be excluded from whole path. The
   subobjects in XRO are used to specify certain domains that MUST be
   avoided to reach the destination.

o Explicit Exclusion Route Subobject (EXRS): As per [RFC5521], used
   to specify exclusion of certain abstract nodes between a specific
   pair of nodes. EXRS are a subobject inside the IRO. These
   subobjects are used to specify the domains that must be excluded
   between two abstract nodes.

o Explicit Route Object (ERO): As per [RFC5440], used to specify a
   computed path in the network. For example, in the case of H-PCE
   [RFC6805] Parent PCE MAY send the Domain-Sequence as a result in a
   path computation reply using ERO.

3.4. Include Route Object (IRO)

As per [RFC5440], IRO (Include Route Object) can be used to specify
that the computed path MUST traverse a set of specified network
elements or abstract nodes.

3.4.1. Subobjects

Some subobjects are defined in [RFC3209], [RFC3473], [RFC3477] and
[RFC4874], but new subobjects related to Domain-Sequence are needed.

The following subobject types are used in IRO.

```
          Type    Subobject
           1      IPv4 prefix
           2      IPv6 prefix
           4      Unnumbered Interface ID
           32     Autonomous system number (2 Byte)
           33     Explicit Exclusion (EXRS)
```

This document extends the above list to support 4-Byte AS numbers and
IGP Areas.

```
          Type    Subobject
           TBD1   Autonomous system number (4 Byte)
           TBD2   OSPF Area id
           TBD3   ISIS Area id
```

3.4.1.1. Autonomous system

[RFC3209] already defines 2 byte AS number.

To support 4 byte AS number as per [RFC4893] following subobject is
defined:
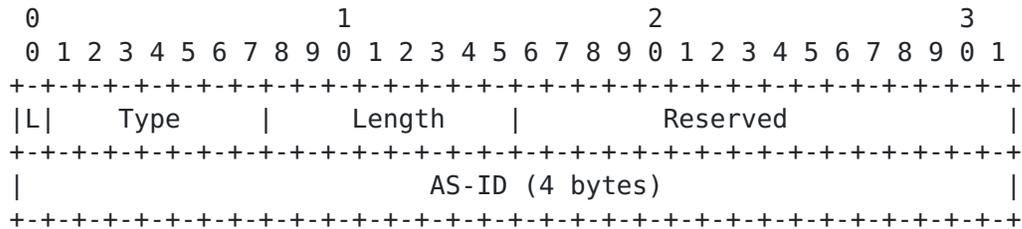
```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|L|   Type      |   Length      |           Reserved            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        AS-ID (4 bytes)                        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

L: The L bit is an attribute of the subobject as defined in [RFC3209]
   and usage in IRO subobject updated in [IRO-UPDATE].

Type: (TBD1 by IANA) indicating a 4-Byte AS Number.

Length: 8 (Total length of the subobject in bytes).

Reserved: Zero at transmission, ignored at receipt.

AS-ID: The 4-Byte AS Number. Note that if 2-Byte AS numbers are in
   use, the low order bits (16 through 31) should be used and the
   high order bits (0 through 15) should be set to zero.

3.4.1.2. IGP Area

Since the length and format of Area-id is different for OSPF and
ISIS, following two subobjects are defined:

For OSPF, the area-id is a 32 bit number. The subobject is encoded
as follows:

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|L|   Type      |   Length      |           Reserved            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                     OSPF Area Id (4 bytes)                    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
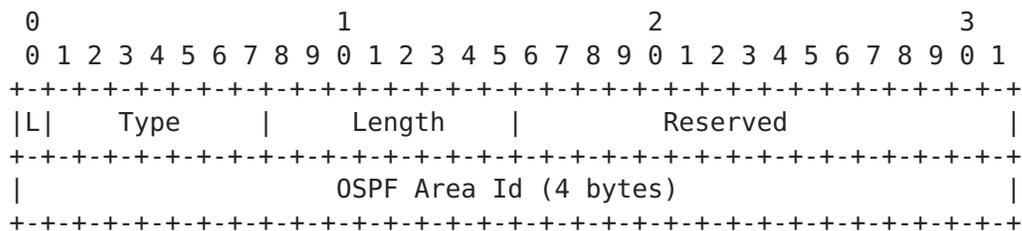
L: The L bit is an attribute of the subobject as defined in [RFC3209]
   and usage in IRO subobject updated in [IRO-UPDATE].

   Type: (TBD2 by IANA) indicating a 4-Byte OSPF Area ID.

   Length: 8 (Total length of the subobject in bytes).

   Reserved: Zero at transmission, ignored at receipt.

   OSPF Area Id: The 4-Byte OSPF Area ID.

   For IS-IS, the area-id is of variable length and thus the length of
   the Subobject is variable. The Area-id is as described in IS-IS by
   ISO standard [ISO10589]. The subobject is encoded as follows:

```
    0                   1                   2                   3
    0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |L|   Type      |    Length     |   Area-Len    |   Reserved    |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                                                               |
   //                      IS-IS Area ID                          //
   |                                                               |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
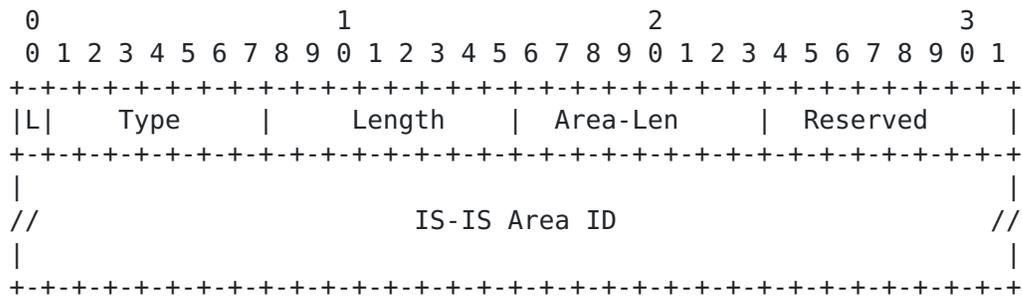
   L: The L bit is an attribute of the subobject as defined in [RFC3209]
      and usage in IRO subobject updated in [IRO-UPDATE].

   Type: (TBD3 by IANA) indicating IS-IS Area ID.

   Length: Variable. As per [RFC3209], the total length of the
      subobject in bytes, including the L, Type and Length fields. The
      Length MUST be at least 4, and MUST be a multiple of 4.

   Area-Len: Variable (Length of the actual (non-padded) IS-IS Area
      Identifier in octets; Valid values are from 2 to 11 inclusive).

   Reserved: Zero at transmission, ignored at receipt.

   IS-IS Area Id: The variable-length IS-IS area identifier. Padded
      with trailing zeroes to a four-byte boundary.

3.4.2. Update in IRO specification

   [RFC5440] describes IRO as an optional object used to specify that
   the computed path MUST traverse a set of specified network elements.
   It further state that the L bit of such sub-object has no meaning
   within an IRO. It did not mention if IRO is an ordered or un-ordered
   list of sub-objects.

An update to IRO specification [IRO-UPDATE] makes IRO as an ordered list as well as support for loose bit (L-bit).

The use IRO for domain-sequence assumes the updated specification for IRO as per [IRO-UPDATE].

3.4.3. IRO for domain-sequence

Some subobjects for IRO are defined in [RFC3209], [RFC3473], [RFC3477] and [RFC4874], further some new subobjects related to Domain-Sequence are also added in this document as mentioned in Section 3.4.

The subobjects for IPv4, IPv6 and unnumbered Interface ID can be used to specify Boundary Node (ABR/ASBR) and Inter-AS-Links. The subobjects for AS Number (2 or 4 Byte) and IGP Area is used to specify the domain identifiers in the domain-sequence.

The IRO MAY have both intra-domain (from the context of the ingress PCC) and inter-domain (domain-sequence) subobjects in a sequence in which they must be traversed in the computed path.

Thus an IRO comprising of subobjects that represents a domain-sequence may constraints or define the domains involved in an inter-domain path computation, typically involving two or more collaborative PCEs.

A Domain-Sequence can have varying degrees of granularity; it is possible to have a Domain-Sequence composed of, uniquely, AS identifiers. It is also possible to list the involved areas for a given AS.

In any case, the mapping between domains and responsible PCEs is not defined in this document. It is assumed that a PCE that needs to obtain a "next PCE" from a Domain-Sequence is able to do so (e.g. via administrative configuration, or discovery).

A PCC builds an IRO to encode the Domain-Sequence, that the cooperating PCEs should compute an inter-domain shortest constrained paths across the specified sequence of domains.

For each inclusion, the PCC clears the L-bit to indicate that the PCE is required to include the domain, or sets the L-bit to indicate that the PCC simply desires that the domain be included in the domain-sequence.

If a PCE encounters a subobject that it does not support or recognize, it MUST act according to the setting of the L-bit in the

subobject. If the L-bit is clear, the PCE MUST respond with a PCErr
with Error-Type TBD4 "Unrecognized subobject" and set the Error-Value
to the subobject type code. If the L-bit is set, the PCE MAY respond
with a PCErr as already stated or MAY ignore the subobject: this
choice is a local policy decision.

PCE MUST act according to the requirements expressed in the
subobject. That is, if the L-bit is clear, the PCE(s) MUST produce a
path that follows domain-sequence nodes in order identified by the
subobjects in the path. If the L-bit is set, the PCE(s) SHOULD
produce a path along the Domain-Sequence unless it is not possible to
construct a path complying with the other constraints expressed in
the request.

A successful path computation reported in a PCEP reply message
(PCRep) MUST include an ERO to specify the path that has been
computed as specified in [RFC5440] following the sequence of domains.

In a PCRep, PCE MAY also supply IRO (with domain sequence
information) with the NO-PATH object indicating that the set of
elements (domains) of the request's IRO prevented the PCEs from
finding a path.

The Subobject types for domains (AS and IGP Area) affect the next
domain selection as well as finding the PCE serving that domain.

Note that a particular domain in the domain-sequence can be
identified by :-

o A single IGP Area: Only the IGP (OSPF or ISIS) Area subobject is
   used to identify the next domain. (Refer Figure 1)

o A single AS: Only the AS subobject is used to identify the next
   domain. (Refer Figure 2)

o Both an AS and an IGP Area: Combination of both AS and Area are
   used to identify the next domain. In this case the order is AS
   Subobject followed by Area. (Refer Figure 3)

The Subobjects representing an internal node, a Boundary Node or an
Inter-AS-Link MAY influence the selection of the path as well.

3.5. Exclude Route Object (XRO)

The Exclude Route Object (XRO) [RFC5521] is an optional object used
to specify exclusion of certain abstract nodes or resources from the
whole path.

3.5.1. Subobjects

The following subobject types are defined to be used in XRO as
defined in [RFC3209], [RFC3477], [RFC4874], and [RFC5521].


```
             Type   Subobject
              1     IPv4 prefix
              2     IPv6 prefix
              4     Unnumbered Interface ID
              32    Autonomous system number (2 Byte)
              34    SRLG
              64    IPv4 Path Key
              65    IPv6 Path Key
```

This document extends the above list to support 4-Byte AS numbers and
IGP Areas.


```
             Type   Subobject
             TBD1   Autonomous system number (4 Byte)
             TBD2   OSPF Area id
             TBD3   ISIS Area id
```

3.5.1.1. Autonomous system

The new subobjects to support 4 byte AS and IGP (OSPF / ISIS) Area
MAY also be used in the XRO to specify exclusion of certain domains
in the path computation procedure.
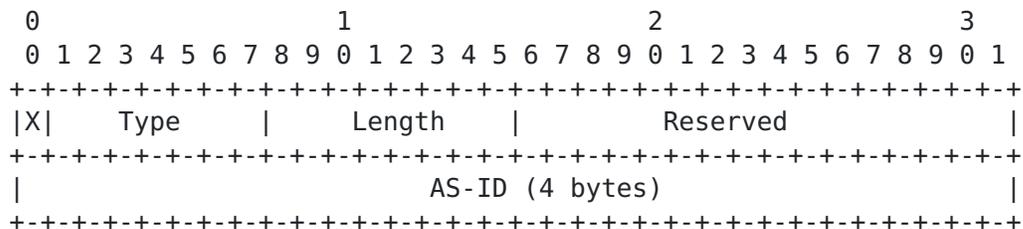
```
    0                   1                   2                   3
    0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |X|   Type     |   Length    |           Reserved               |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                     AS-ID (4 bytes)                           |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```


The X-bit indicates whether the exclusion is mandatory or desired.

0: indicates that the AS specified MUST be excluded from the path
   computed by the PCE(s).

1: indicates that the AS specified SHOULD be avoided from the inter-
   domain path computed by the PCE(s), but MAY be included subject to
   PCE policy and the absence of a viable path that meets the other
   constraints.

All other fields are consistent with the definition in Section 3.4.

3.5.1.2. IGP Area

Since the length and format of Area-id is different for OSPF and
ISIS, following two subobjects are defined:

For OSPF, the area-id is a 32 bit number. The subobject is encoded
as follows:

```
    0                   1                   2                   3
    0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |X|    Type     |    Length     |              Reserved         |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                     OSPF Area Id (4 bytes)                    |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
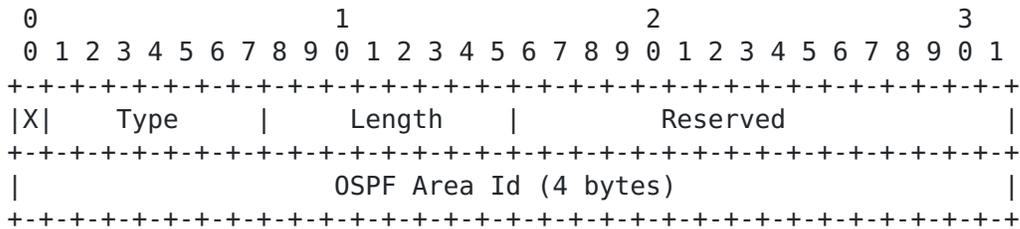
The X-bit indicates whether the exclusion is mandatory or desired.

0: indicates that the OSFF Area specified MUST be excluded from the
   path computed by the PCE(s).

1: indicates that the OSFF Area specified SHOULD be avoided from the
   inter-domain path computed by the PCE(s), but MAY be included
   subject to PCE policy and the absence of a viable path that meets
   the other constraints.

All other fields are consistent with the definition in Section 3.4.

For IS-IS, the area-id is of variable length and thus the length of
the subobject is variable. The Area-id is as described in IS-IS by
ISO standard [ISO10589]. The subobject is encoded as follows:

```
    0                   1                   2                   3
    0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |X|    Type     |    Length     |   Area-Len    |   Reserved    |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                                                               |
   //                       IS-IS Area ID                         //
   |                                                               |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
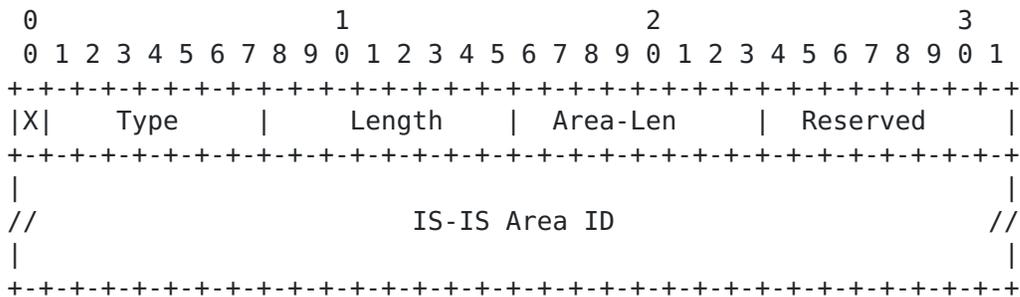
The X-bit indicates whether the exclusion is mandatory or desired.

0: indicates that the ISIS Area specified MUST be excluded from the
   path computed by the PCE(s).

1: indicates that the ISIS Area specified SHOULD be avoided from the
   inter-domain path computed by the PCE(s), but MAY be included
   subject to PCE policy and the absence of a viable path that meets
   the other constraints.

All other fields are consistent with the definition in Section 3.4.

If a PCE that supports XRO and encounters a subobject that it does
not support or recognize, it MUST act according to the setting of the
X-bit in the subobject. If the X-bit is clear, the PCE MUST respond
with a PCErr with Error-Type TBD4 "Unrecognized subobject" and set
the Error-Value to the subobject type code. If the X-bit is set, the
PCE MAY respond with a PCErr as already stated or MAY ignore the
subobject: this choice is a local policy decision.

All the other processing rules are as per [RFC5521].

3.6. Explicit Exclusion Route Subobject (EXRS)

Explicit Exclusion Route Subobject (EXRS) [RFC5521] is used to
specify exclusion of certain abstract nodes between a specific pair
of nodes.

The EXRS subobject may carry any of the subobjects defined for
inclusion in the XRO, thus the new subobjects to support 4 byte AS
and IGP (OSPF / ISIS) Area MAY also be used in the EXRS. The
meanings of the fields of the new XRO subobjects are unchanged when
the subobjects are included in an EXRS, except that scope of the
exclusion is limited to the single hop between the previous and
subsequent elements in the IRO.

All the processing rules are as per [RFC5521].

3.7. Explicit Route Object (ERO)

The Explicit Route Object (ERO) [RFC5440] is used to specify a
computed path in the network. PCEP ERO subobject types correspond to
RSVP-TE ERO subobject types as defined in [RFC3209], [RFC3473],
[RFC3477], [RFC4873], [RFC4874], and [RFC5520].

```
          Type   Subobject
           1     IPv4 prefix
           2     IPv6 prefix
           3     Label
           4     Unnumbered Interface ID
           32    Autonomous system number (2 Byte)
           33    Explicit Exclusion (EXRS)
           37    Protection
           64    IPv4 Path Key
           65    IPv6 Path Key
```

This document extends the above list to support 4-Byte AS numbers and
IGP Areas.

```
          Type   Subobject
           TBD1  Autonomous system number (4 Byte)
           TBD2  OSPF Area id
           TBD3  ISIS Area id
```

The new subobjects to support 4 byte AS and IGP (OSPF / ISIS) Area
MAY also be used in the ERO to specify an abstract node (a group of
nodes whose internal topology is opaque to the ingress node of the
LSP). Using this concept of abstraction, an explicitly routed LSP
can be specified as a sequence of domains.

In case of Hierarchical PCE [RFC6805], a Parent PCE MAY be requested
to find the domain-sequence. Refer example in Section 4.6.

The format of the new ERO subobjects is similar to new IRO
subobjects, refer Section 3.4.

4. Other Considerations

The examples in this section are for illustration purposes only; to
show how the new subobjects may be encoded.

4.1. Inter-Area Path Computation

In an inter-area path computation where the ingress and the egress
nodes belong to different IGP areas within the same AS, the Domain-
Sequence MAY be represented using a ordered list of Area subobjects.
The AS number MAY be skipped, as area information is enough to select
the next PCE.

```
+------------------+                   +------------------+
|                  |                   |                  |
|       +--+       |                   |     +--+         |
|   +--+ |  |      |                   |     |  | +--+    |
|   |  | +--+      |                   |     +--+ |  |    |
|   +--*            +                  +          +--+    |
|                  |                   |                  |
|       *--+        +                  +          +--+    |
|       |  |       |                   |          |  |    |
|       +--+       |                   |          |  |    |
|                 |+-------------------------+|   +--+    |
|                 ++++              +-++            |
|                 ||||    +--+      | ||           |
| Area 2          ++++    |  |      +-++ Area 4     |
+-----------------+|      +--+        |+-----------------+
                  |                   |
                  |      +--+         |
                  |      |  |         |
                  |  +--+ +--+        |
                  |  |  |             |
                  |  +--+             |
                  |                   |
                  |                   |
                  |                   |
                  |      +--+         |
                  |      |  |         |
                  |      +--+         |
+-----------------+|                 |+-----------------+
|                 ++-+             +-++                 |
|                 ||| |            | ||                 |
|                 ++-+  Area 0     +-++                 |
|                |+-------------------------+|  +--+    |
|       +--+     |                  |        |  |  |    |
|       |  |     |                  |        |  +--+    |
|   +--+ +--+    |                  +          +--+    |
|   |  |         +                  |          |  |    |
|   +--+         |                  +          +--+    |
|               +                  |                  |
|       +--+     |                  |     +--+         |
|       |  |     |                  |     |  |         |
|       +--+     |                  |     +--+         |
|                |                  |                  |
| Area 1         |                  | Area 5           |
+------------------+                 +------------------+
```

Figure 1: Inter-Area Path Computation

   AS Number is 100.

   This could be represented in the <IRO> as:

     +---------+ +---------+ +---------+ +---------+
     |IRO | |Sub | |Sub | |Sub |
     |Object | |Object | |Object | |Object |
     |Header | |Area 2 | |Area 0 | |Area 4 |
     | | | | | | | | | | |
     | | | | | | | | | | |
     +---------+ +---------+ +---------+ +---------+

     +---------+ +---------+ +---------+ +---------+ +---------+
     |IRO | |Sub | |Sub | |Sub | |Sub |
     |Object | |Object AS| |Object | |Object | |Object |
     |Header | |100 | |Area 2 | |Area 0 | |Area 4 |
     | | | | | | | | | | | | | |
     | | | | | | | | | | | | | |
     +---------+ +---------+ +---------+ +---------+ +---------+

   AS is optional and it MAY be skipped. PCE should be able to
   understand both notations.

4.2. Inter-AS Path Computation

   In inter-AS path computation, where ingress and egress belong to
   different AS, the Domain-Sequence is represented using an ordered
   list of AS subobjects. The Domain-Sequence MAY further include
   decomposed area information in Area subobjects.

4.2.1. Example 1

   As shown in Figure 2, where AS to be made of a single area, the area
   subobject MAY be skipped in the Domain-Sequence as AS is enough to
   uniquely identify the next domain and PCE.

```
                              +--------------------------------+
                              |AS 200                          |
                              |             +------+           |
   +------------------------+ |             |      |  +------+ |
   | AS 100                 | |             |      |  |      | |
   |                        | |             +------+  |      | |
   |         +------+ |     | +------+                |      | |
   |         |      +-+-----+-+      |                +------+ |
   |         |      | | |   | |      |                         |
   |         +------+ |     | +------+                         |
   |  +------+        |     |           +------+               |
   |  |      |        |     |           |      |               |
   |  |      |        |     |           |      |               |
   |  +------+        |     |           +------+               |
   |                  |     |                                  |
   |         +------+ |     | +------+                         |
   |         |      +-+-----+-+      |           +------+      |
   |         |      | | |   | |      |           |      |      |
   |         +------+ |     | +------+           |      |      |
   |                  |     |                    +------+      |
   |                  |     |                                  |
   |         +------+ |     |           +------+               |
   |         |      | |     |           |      |               |
   |         |PCE   | |     |           |PCE   |               |
   |         +------+ |     |           +------+               |
   |                  |     |                                  |
   +------------------------+ |                                |
                            | |                                |
                              +--------------------------------+
```
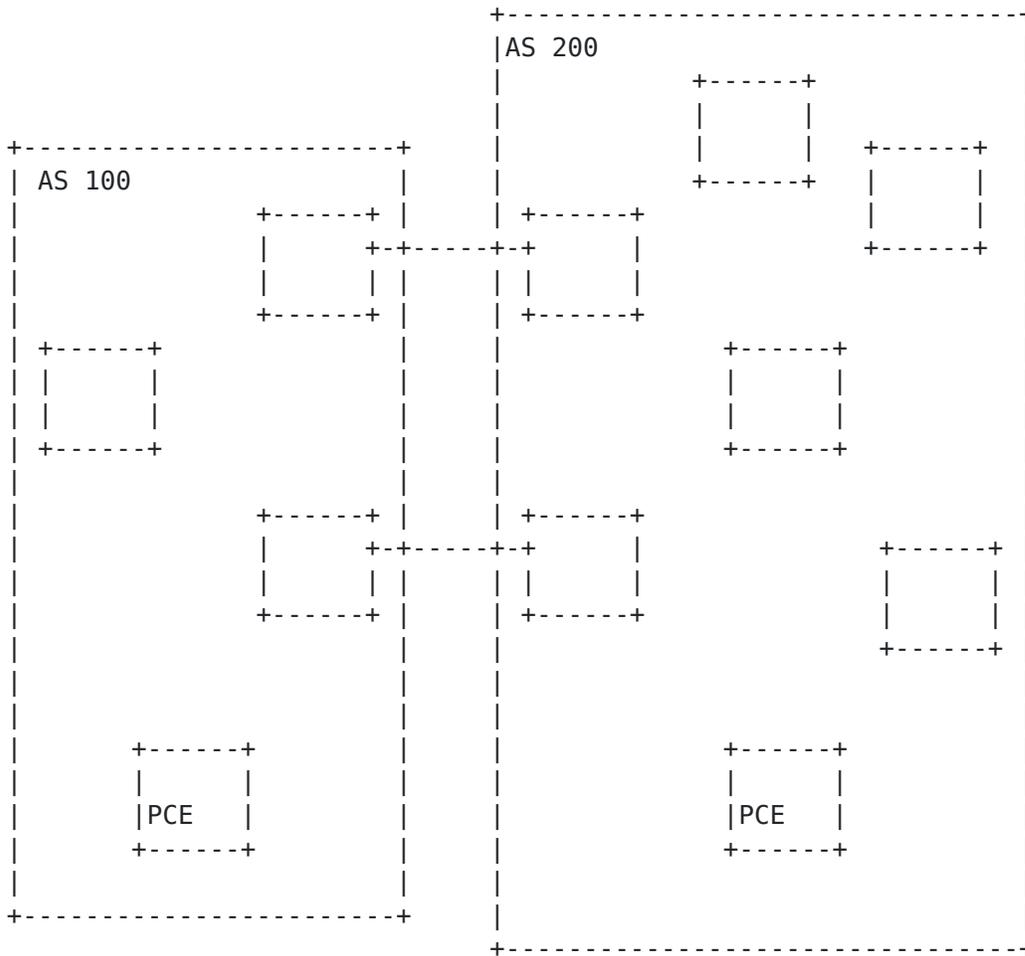
              Figure 2: Inter-AS Path Computation

   Both AS are made of Area 0.

   This could be represented in the <IRO> as:

```
+---------+  +---------+  +---------+
|IRO      |  |Sub      |  |Sub      |
|Object   |  |Object AS|  |Object AS|
|Header   |  |100      |  |200      |
|         |  |         |  |         |
|         |  |         |  |         |
+---------+  +---------+  +---------+



+---------+  +---------+  +---------+  +---------+  +---------+
|IRO      |  |Sub      |  |Sub      |  |Sub      |  |Sub      |
|Object   |  |Object AS|  |Object   |  |Object AS|  |Object   |
|Header   |  |100      |  |Area 0   |  |200      |  |Area 0   |
|         |  |         |  |         |  |         |  |         |
|         |  |         |  |         |  |         |  |         |
+---------+  +---------+  +---------+  +---------+  +---------+
```

Area subobject is optional and it MAY be skipped. PCE should be able
to understand both notations.

4.2.2. Example 2

As shown in Figure 3, where AS 200 is made up of multiple areas and
multiple domain-sequence exist, PCE MAY include both AS and Area
subobject to uniquely identify the next domain and PCE.

```
              |
              |   +-------------+              +----------------+
              |   |Area 2       |              |Area 4          |
              |   |        +--+|              |          +--+  |
              |   |        | ||              |          | |  |
              |   |  +--+   +--+|              |   +--+   +--+  |
              |   |  | |    |  |              |   | |    |  |
              |   |  *--+    |  |              |   +--+         |
              |   | /     +--+ |              |          +--+  |
              |   |/      | | ||              |          | |  |
              |   /       +--+ |              |   +--+   +--+  |
              | /|  +--+      |+-------------+|   | |    |  |
              |/ |  | |       ++-+      +-++  +--+         |
   +------------+/  |  +--+       || |     | ||             |
   |          /|  |           ++-+     +-++             |
   |         +--*||  +------------+|              |+---------------+
   |         | |||              |    +--+      |
   |         +--+||              |    | |      |
   |    +--+    ||              |    +--+      |
   |    | |     ||              |              |
   |    +--+    ||              |              |
```

```
    |           ||                  |        +--+      |
    |+--+       ||                  |        |  |      |
    ||  |       ||                  |        +--+      |
    |+--+       ||                  |                  |
    |           ||                  |        +--+      |
    |    +--+   ||   +------------+  |        |  |   |+---------------+
    |    |  |   ||   |Area 3    +-++   +--+   +-++ Area 5         |
    |    +--+   ||   |          | ||        | ||                  |
    |           ||   |          +-++        +-++                  |
    |       +--+||   |      +--+ | | Area 0      ||   +--+        |
    |       | |||   |      |  | | | +-------------+|   |  |        |
    |       +--*||   |      +--+ |             |   +--+        |
    |          \|   |           |             |      +--+      |
    |Area 1     |\  |   +--+    |             |   +--+ |  |   |
    +------------+|\ |   |  |    |             |   |  | +--+   |
                 | \|   +--+  +--+             |   +--+        |
                 |  \         |  |             |              |
                 |  |\        +--+             |      +--+     |
                 |  | \ +--+    |             |      |  |     |
                 |  |  \|  |    |             |      +--+     |
                 |  |   *--+    |             |              |
                 |  |          |             |              |
                 |  +----------+             +--------------+
                 |
                 |
       AS 100    |  AS 200
                 |
```
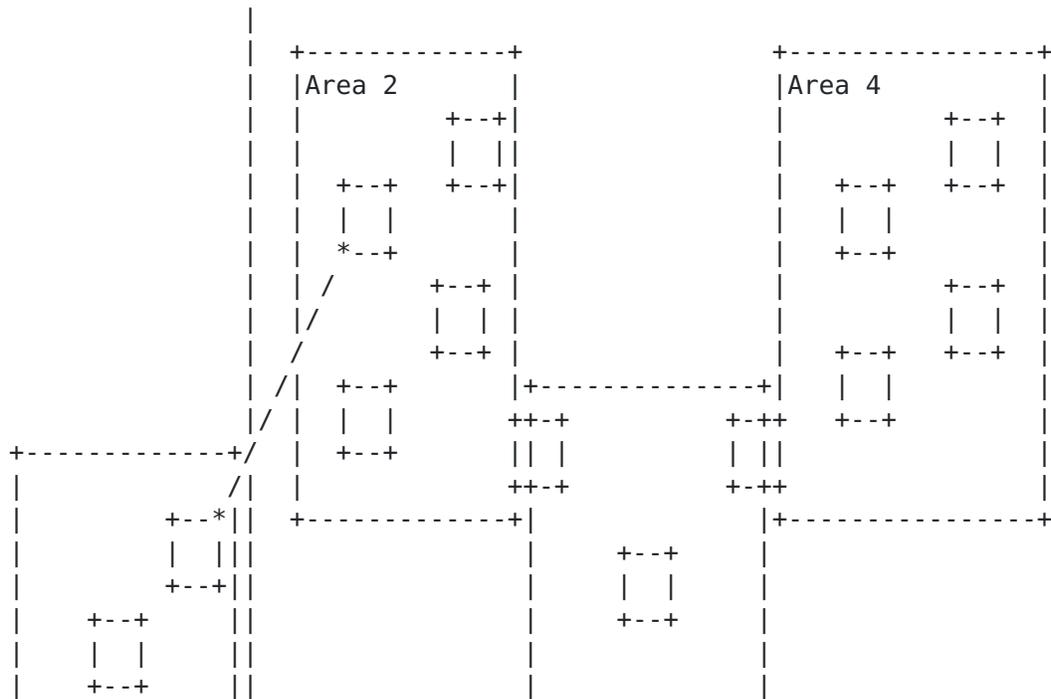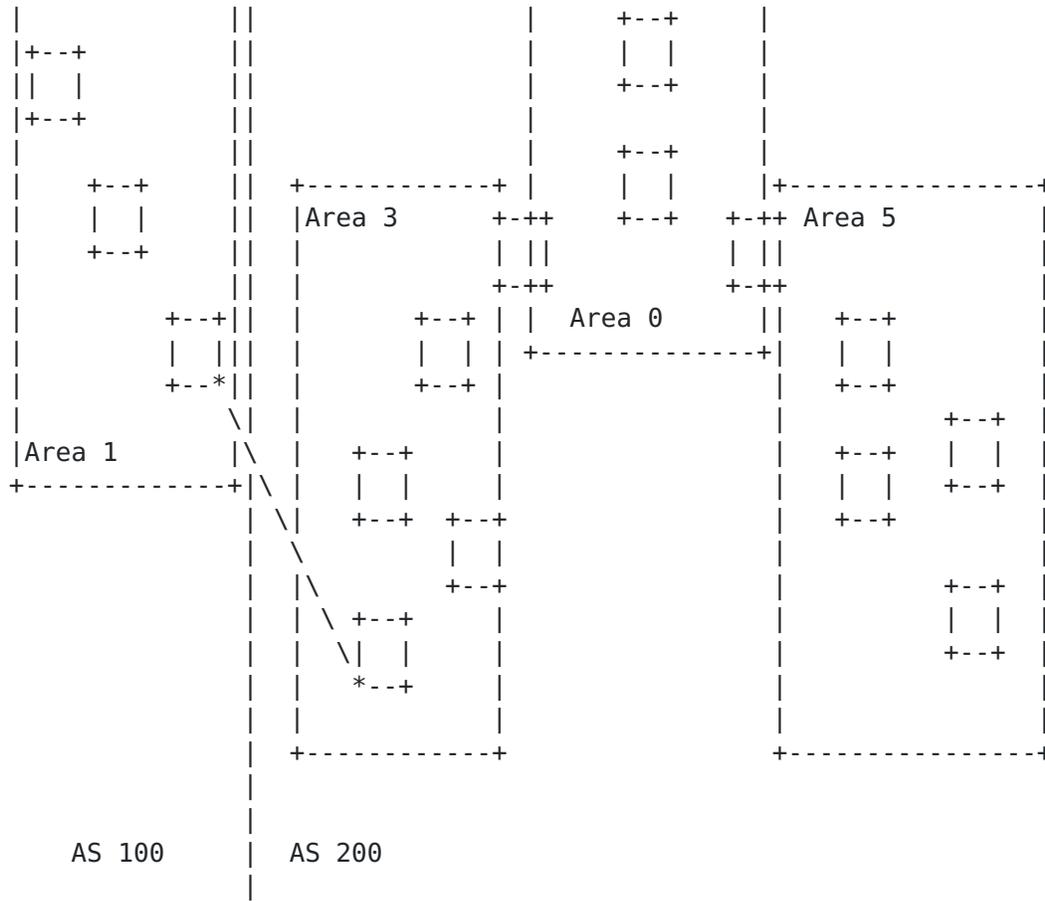
                Figure 3: Inter-AS Path Computation

   The Domain-Sequence can be carried in the IRO as shown below:


```
   +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+
   |IRO    | |Sub    | |Sub    | |Sub    | |Sub    | |Sub    | |Sub    |
   |Object | |Object | |Object | |Object | |Object | |Object | |Object |
   |Header | |AS 100 | |Area 1 | |AS 200 | |Area 3 | |Area 0 | |Area 4 |
   |       | |       | |       | |       | |       | |       | |       |
   +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+
```

   The combination of both an AS and an Area uniquely identify a domain
   in the Domain-Sequence.

   Note that an Area domain identifier always belongs to the previous AS
   that appears before it or, if no AS subobjects are present, it is
   assumed to be the current AS.

If the area information cannot be provided, PCE MAY forward the path
computation request to the next PCE based on AS alone. If multiple
PCEs are responsible, PCE MAY apply local policy to select the next
PCE.

4.3. Boundary Node and Inter-AS-Link

A PCC or PCE MAY add additional constraints covering which Boundary
Nodes (ABR or ASBR) or Border links (Inter-AS-link) MUST be traversed
while defining a Domain-Sequence. In which case the Boundary Node or
Link MAY be encoded as a part of the domain-sequence using the
existing subobjects.

Boundary Nodes (ABR / ASBR) can be encoded using the IPv4 or IPv6
prefix subobjects usually the loopback address of 32 and 128 prefix
length respectively. An Inter-AS link can be encoded using the IPv4
or IPv6 prefix subobjects or unnumbered interface subobjects.

For Figure 1, an ABR to be traversed can be specified as:

```
    +---------+ +---------+ +---------++---------+ +---------+
    |IRO      | |Sub      | |Sub      ||Sub      | |Sub      |
    |Object   | |Object   | |Object   ||Object   | |Object   |
    |Header   | |Area 2   | |IPv4     ||Area 0   | |Area 4   |
    |         | |         | |x.x.x.x  ||         | |         |
    |         | |         | |         ||         | |         |
    +---------+ +---------+ +---------++---------+ +---------+
```

For Figure 2, an inter-AS-link to be traversed can be specified as:

```
    +---------+ +---------+ +---------+ +---------+ +---------+
    |IRO      | |Sub      | |Sub      | |Sub      | |Sub      |
    |Object   | |Object AS| |Object   | |Object   | |Object AS|
    |Header   | |100      | |IPv4     | |IPv4     | |200      |
    |         | |         | |x.x.x.x  | |x.x.x.x  | |         |
    |         | |         | |         | |         | |         |
    +---------+ +---------+ +---------+ +---------+ +---------+
```

4.4. PCE Serving multiple Domains

A single PCE MAY be responsible for multiple domains; for example PCE
function deployed on an ABR. A PCE which can support 2 adjacent
domains can internally handle this situation without any impact on
the neighbouring domains.

4.5. P2MP

   In case of inter-domain P2MP path computation, (Refer [RFC7334]) the
   path domain tree is nothing but a series of Domain Sequences, as
   shown in the below figure:

      D1-D3-D6, D1-D3-D5 and D1-D2-D4.
                 D1
               / \
             D2   D3
            /   / \
          D4 D5 D6
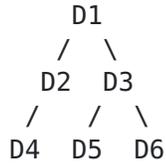
   All rules of processing as applied to P2P can be applied to P2MP as
   well.

   In case of P2MP, different destinations MAY have different Domain-
   Sequence within the domain tree, it requires domain-sequence to be
   attached per destination. (Refer [PCE-P2MP-PER-DEST])

4.6. Hierarchical PCE

   As per [RFC6805], consider a case as shown in Figure 4 consisting of
   multiple child PCEs and a parent PCE.

```
                             +--------+
                             | Parent |
                             | PCE    |
                             +--------+

+------------------+                    +------------------+
|            +--+  |                    |     +--+         |
|   +--+     |  |  |                    |     |  |         |
|   |  |     +--+  |                    |     +--+   +--+   |
|   +--*         + |                    +            |  |   |
|                  |                    |            +--+   |
|       *--+     + |                    +                   |
|       |  |     | |                    |     +--+          |
|       +--+     | |                    |     |  |          |
|                |+------------------------+| +--+          |
|              ++++                 +-++          |
|              ||||       +--+      | ||          |
| Area 2       ++++       |  |      +-++  Area 4  |
+------------------+|     +--+           |+------------------+
                   |             +--+    |
                   |     +--+    |  |    |
                   |     |  |    +--+    |
                   |     +--+            |
                   |                     |
                   |         +--+        |
                   |         |  |        |
                   |         +--+        |
+------------------+|                    |+------------------+
|              ++-+                 +-++               |
|              || |                 | ||               |
|              ++-+     Area 0      +-++               |
|                |+----------------------+|     +--+        |
|        +--+    |                    |   |  |        |
|        |  |    |                    |   +--+        |
| +--+   +--+    |                    |              |
| |  |           +                    +    +--+      |
| +--+           |                    |    |  |      |
|                +                    +    +--+      |
|       +--+     |                    |              |
|       |  |     |                    |     +--+     |
|       +--+     |                    |     |  |     |
|                |                    |     +--+     |
| Area 1         |                    | Area 5      |
+------------------+                    +------------------+
```
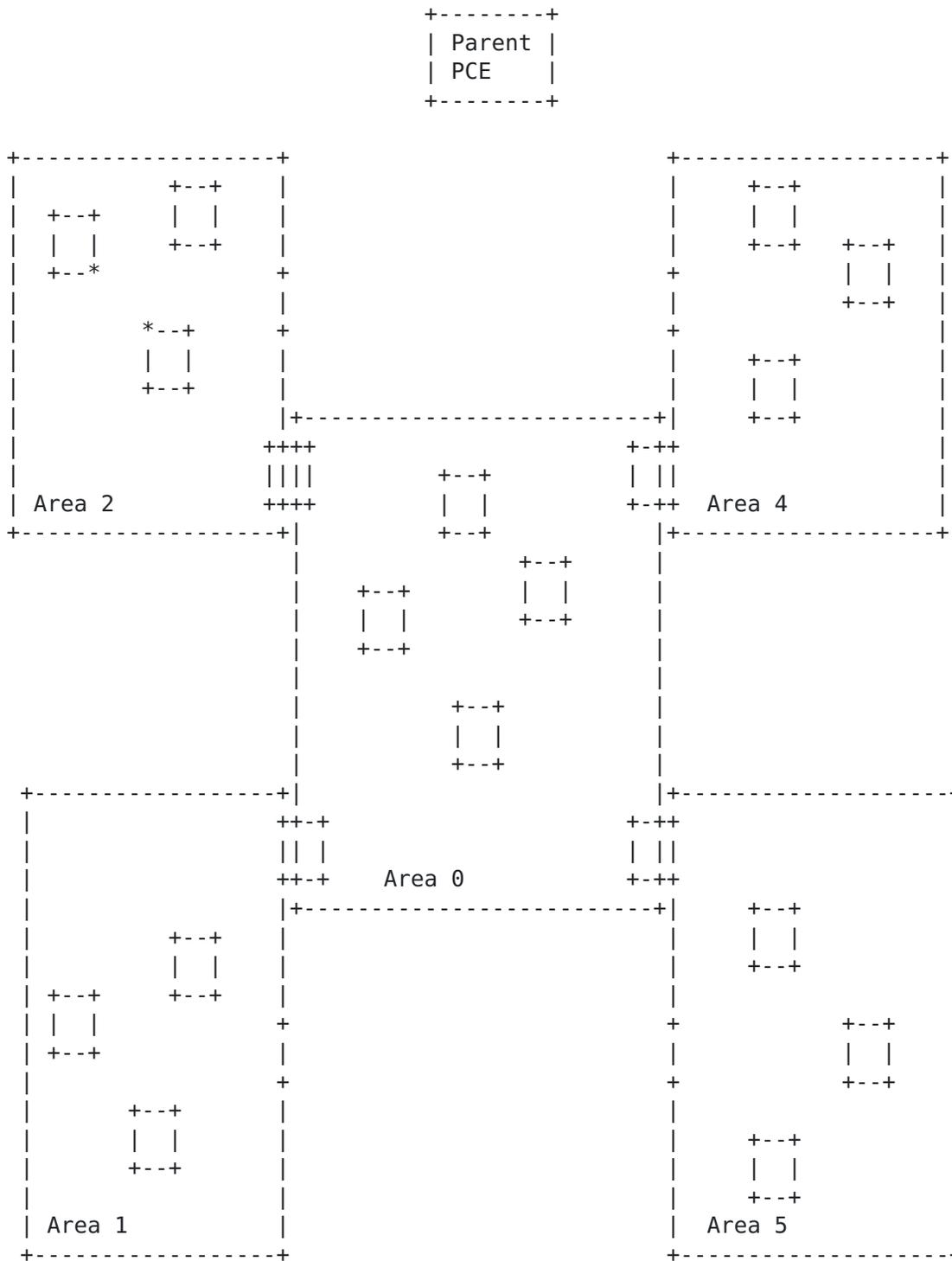
                       Figure 4: Hierarchical PCE

In H-PCE, the Ingress PCE 'PCE(1)' can request the parent PCE to
determine the Domain-Sequence and return it in the PCEP response,
using the ERO Object. The ERO can contain an ordered sequence of
subobjects such as AS and Area (OSPF/ISIS) subobjects. In this case,
the Domain-Sequence appear as:

```
+---------+ +---------+ +---------+ +---------+
|ERO      | |Sub      | |Sub      | |Sub      |
|Object   | |Object   | |Object   | |Object   |
|Header   | |Area 2   | |Area 0   | |Area 4   |
|         | |         | |         | |         |
|         | |         | |         | |         |
+---------+ +---------+ +---------+ +---------+


+---------+ +---------+ +---------+ +---------+ +---------+
|ERO      | |Sub      | |Sub      | |Sub      | |Sub      |
|Object   | |Object AS| |Object   | |Object   | |Object   |
|Header   | |100      | |Area 2   | |Area 0   | |Area 4   |
|         | |         | |         | |         | |         |
|         | |         | |         | |         | |         |
+---------+ +---------+ +---------+ +---------+ +---------+
```

4.7. Relationship to PCE Sequence

Instead of a domain-sequence, a sequence of PCEs MAY be enforced by
policy on the PCC, and this constraint can be carried in the PCReq
message (as defined in [RFC5886]).

Note that PCE-Sequence can be used along with domain-sequence in
which case PCE-Sequence SHOULD have higher precedence in selecting
the next PCE in the inter-domain path computation procedures. Note
that Domain-Sequence IRO constraints should still be checked as per
the rules of processing IRO.

4.8. Relationship to RSVP-TE

[RFC3209] already describes the notion of abstract nodes, where an
abstract node is a group of nodes whose internal topology is opaque
to the ingress node of the LSP. It further defines a subobject for
AS but with a 2-Byte AS Number.

[DOMAIN-SUBOBJ] extends the notion of abstract nodes by adding new
subobjects for IGP Areas and 4-byte AS numbers. These subobjects MAY
be included in Explicit Route Object (ERO), Exclude Route object
(XRO) or Explicit Exclusion Route Subobject (EXRS) in RSVP-TE.

In any case subobject type defined in RSVP-TE are identical to the
subobject type defined in the related documents in PCEP.

5. IANA Considerations

5.1. New Subobjects

The "PCEP Parameters" registry contains a subregistry "PCEP Objects"
with an entry for the Include Route Object (IRO), Exclude Route
Object (XRO) and Explicit Route Object (ERO). IANA is requested to
add further subobjects as follows:

```
7  ERO
10 IRO
17 XRO


Subobject Type                       Reference
TBD1      4 byte AS number           [This I.D.]
TBD2      OSPF Area ID               [This I.D.]
TBD3      IS-IS Area ID              [This I.D.]
```

5.2. Error Object Field Values

The "PCEP Parameters" registry contains a subregistry "Error Types
and Values". IANA is requested to make the following allocations
from this subregistry

```
ERROR     Meaning                       Reference
Type
TBD4      "Unrecognized subobject"      [This I.D.]
          Error-Value: type code
```

6. Security Considerations

This document specifies a standard representation of Domain-Sequence
and new subobjects, which MAY be used in inter-domain PCE scenarios
as explained in other RFC and drafts. The new subobjects and Domain-
Sequence mechanisms defined in this document allow finer and more
specific control of the path computed by a cooperating PCE(s). Such
control increases the risk if a PCEP message is intercepted,
modified, or spoofed because it allows the attacker to exert control
over the path that the PCE will compute or to make the path
computation impossible. Therefore, the security techniques described
in [RFC5440] are considered more important.

Note, however, that the Domain-Sequence mechanisms also provide the
operator with the ability to route around vulnerable parts of the
network and may be used to increase overall network security.

7. Manageability Considerations

7.1. Control of Function and Policy

Several local policy decisions should be made at the PCE. Firstly,
the exact behavior with regard to desired inclusion and exclusion of
domains must be available for examination by an operator and may be
configurable. Second, the behavior on receipt of an unrecognized
subobjects with the L or X-bit set should be configurable and must be
available for inspection. The inspection and control of these local
policy choices may be part of the PCEP MIB module.

7.2. Information and Data Models

A MIB module for management of the PCEP is being specified in a
separate document [PCEP-MIB]. That MIB module allows examination of
individual PCEP messages, in particular requests, responses and
errors. The MIB module MUST be extended to include the ability to
view the domain-sequence extensions defined in this document.

7.3. 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].

7.4. Verify Correct Operations

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

7.5. Requirements On Other Protocols

In case of per-domain path computation [RFC5152], where the full path
of an inter-domain TE LSP cannot be or is not determined at the
ingress node, and signaling message may use domain identifiers. The
Subobjects defined in this document SHOULD be supported by RSVP-TE.
[DOMAIN-SUBOBJ] extends the notion of abstract nodes by adding new
subobjects for IGP Areas and 4-byte AS numbers.

Apart from this, mechanisms defined in this document do not imply any
requirements on other protocols in addition to those already listed
in [RFC5440].

7.6. 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].

8. Acknowledgments

   We would like to thank Adrian Farrel, Pradeep Shastry, Suresh Babu,
   Quintin Zhao, Fatai Zhang, Daniel King, Oscar Gonzalez, Chen Huaimo,
   Venugopal Reddy, Reeja Paul Sandeep Boina and Avantika for their
   useful comments and suggestions.

9. References

9.1. Normative References

   [RFC2119] Bradner, S., "Key words for use in RFCs to Indicate
              Requirement Levels", BCP 14, RFC 2119, March 1997.

   [RFC5440] Vasseur, JP. and JL. Le Roux, "Path Computation Element
              (PCE) Communication Protocol (PCEP)", RFC 5440, March
              2009.

   [RFC5441] Vasseur, JP., Zhang, R., Bitar, N., and JL. Le Roux, "A
              Backward-Recursive PCE-Based Computation (BRPC) Procedure
              to Compute Shortest Constrained Inter-Domain Traffic
              Engineering Label Switched Paths", RFC 5441, April 2009.

   [RFC5521] Oki, E., Takeda, T., and A. Farrel, "Extensions to the
              Path Computation Element Communication Protocol (PCEP) for
              Route Exclusions", RFC 5521, April 2009.

   [RFC6805] King, D. and A. Farrel, "The Application of the Path
              Computation Element Architecture to the Determination of a
              Sequence of Domains in MPLS and GMPLS", RFC 6805, November
              2012.

9.2. Informative References

   [RFC3209] Awduche, D., Berger, L., Gan, D., Li, T., Srinivasan, V.,
              and G. Swallow, "RSVP-TE: Extensions to RSVP for LSP
              Tunnels", RFC 3209, December 2001.

   [RFC3473] Berger, L., "Generalized Multi-Protocol Label Switching
              (GMPLS) Signaling Resource ReserVation Protocol-Traffic
              Engineering (RSVP-TE) Extensions", RFC 3473, January 2003.

   [RFC3477] Kompella, K. and Y. Rekhter, "Signalling Unnumbered Links
              in Resource ReSerVation Protocol - Traffic Engineering
              (RSVP-TE)", RFC 3477, January 2003.

   [RFC4655] Farrel, A., Vasseur, J., and J. Ash, "A Path Computation
              Element (PCE)-Based Architecture", RFC 4655, August 2006.

   [RFC4726] Farrel, A., Vasseur, J., and A. Ayyangar, "A Framework for
              Inter-Domain Multiprotocol Label Switching Traffic
              Engineering", RFC 4726, November 2006.

   [RFC4873] Berger, L., Bryskin, I., Papadimitriou, D., and A. Farrel,
              "GMPLS Segment Recovery", RFC 4873, May 2007.

   [RFC4874] Lee, CY., Farrel, A., and S. De Cnodder, "Exclude Routes -
              Extension to Resource ReserVation Protocol-Traffic
              Engineering (RSVP-TE)", RFC 4874, April 2007.

   [RFC4893] Vohra, Q. and E. Chen, "BGP Support for Four-octet AS
              Number Space", RFC 4893, May 2007.

   [RFC5152] Vasseur, JP., Ayyangar, A., and R. Zhang, "A Per-Domain
              Path Computation Method for Establishing Inter-Domain
              Traffic Engineering (TE) Label Switched Paths (LSPs)", RFC
              5152, February 2008.

   [RFC5520] Bradford, R., Vasseur, JP., and A. Farrel, "Preserving
              Topology Confidentiality in Inter-Domain Path Computation
              Using a Path-Key-Based Mechanism", RFC 5520, April 2009.

   [RFC5886] Vasseur, JP., Le Roux, JL., and Y. Ikejiri, "A Set of
              Monitoring Tools for Path Computation Element (PCE)-Based
              Architecture", RFC 5886, June 2010.

   [RFC7334] Zhao, Q., Dhody, D., King, D., Ali, Z., and R. Casellas,
              "PCE-Based Computation Procedure to Compute Shortest
              Constrained Point-to-Multipoint (P2MP) Inter-Domain
              Traffic Engineering Label Switched Paths", RFC 7334,
              August 2014.

   [PCEP-MIB]
              Koushik, A., Emile, S., Zhao, Q., King, D., and J.
              Hardwick, "PCE communication protocol(PCEP) Management
              Information Base. (draft-ietf-pce-pcep-mib)", September
              2014.

   [PCE-P2MP-PER-DEST]
             Dhody, D., Palle, U., and V. Kondreddy, "Supporting
             explicit inclusion or exclusion of abstract nodes for a
             subset of P2MP destinations in Path Computation Element
             Communication Protocol (PCEP). (draft-dhody-pce-pcep-p2mp-
             per-destination)", September 2014.

   [DOMAIN-SUBOBJ]
             Dhody, D., Palle, U., Kondreddy, V., and R. Casellas,
             "Domain Subobjects for Resource ReserVation Protocol -
             Traffic Engineering (RSVP-TE). (draft-dhody-ccamp-rsvp-te-
             domain-subobjects)", July 2014.

   [IRO-SURVEY]
             Dhody, D., "Informal Survey into Include Route Object
             (IRO) Implementations in Path Computation Element
             communication Protocol (PCEP). (draft-dhody-pce-iro-
             survey-01)", October 2014.

   [IRO-UPDATE]
             Dhody, D., "Update to Include Route Object (IRO)
             specification in Path Computation Element communication
             Protocol (PCEP. (draft-dhody-pce-iro-update-00)", October
             2014.

   [ISO10589]
             ISO, "Intermediate system to Intermediate system routing
             information exchange protocol for use in conjunction with
             the Protocol for providing the Connectionless-mode Network
             Service (ISO 8473)", ISO/IEC 10589:2002, 1992.

Authors' Addresses

   Dhruv Dhody
   Huawei Technologies
   Leela Palace
   Bangalore, Karnataka 560008
   INDIA

   EMail: dhruv.ietf@gmail.com

   Udayasree Palle
   Huawei Technologies
   Leela Palace
   Bangalore, Karnataka 560008
   INDIA

   EMail: udayasree.palle@huawei.com

   Ramon Casellas
   CTTC
   Av. Carl Friedrich Gauss n7
   Castelldefels, Barcelona   08860
   SPAIN

   EMail: ramon.casellas@cttc.es