A Backward-Recursive PCE-Based Computation (BRPC) Procedure to Compute Shortest Constrained Inter-Domain Traffic Engineering Label Switched Paths

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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 IGP area
   or an Autonomous Systems. This document specifies a procedure
   relying on the use of multiple Path Computation Elements (PCEs) to
   compute such inter-domain shortest constrained paths across a
   predetermined sequence of domains, using a backward-recursive path
   computation technique. This technique preserves confidentiality
   across domains, which is sometimes required when domains are managed
   by different service providers.

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1. Introduction

   The requirements for inter-area and inter-AS MPLS Traffic Engineering
   (TE) have been developed by the Traffic Engineering Working Group (TE
   WG) and have been stated in [RFC4105] and [RFC4216], respectively.

   The framework for inter-domain Multiprotocol Label Switching (MPLS)
   Traffic Engineering (TE) has been provided in [RFC4726].

   [RFC5152] defines a technique for establishing an inter-domain
   Generalized MPLS (GMPLS) TE Label Switched Path (LSP) whereby the
   path is computed during the signaling process on a per-domain basis
   by the entry boundary node of each domain (each node responsible for
   triggering the computation of a section of an inter-domain TE LSP
   path is always along the path of such TE LSP). This path computation
   technique fulfills some of the requirements stated in [RFC4105] and
   [RFC4216] but not all of them. In particular, it cannot guarantee to
   find an optimal (shortest) inter-domain constrained path.
   Furthermore, it cannot be efficiently used to compute a set of inter-
   domain diversely routed TE LSPs.

   The Path Computation Element (PCE) architecture is defined in
   [RFC4655]. The aim of this document is to describe a PCE-based path
   computation procedure to compute optimal inter-domain constrained
   (G)MPLS TE LSPs.

   Qualifying a path as optimal requires some clarification. Indeed, a
   globally optimal TE LSP placement usually refers to a set of TE LSPs
   whose placements optimize the network resources with regards to a
   specified objective function (e.g., a placement that reduces the
   maximum or average network load while satisfying the TE LSP
   constraints). In this document, an optimal inter-domain constrained
   TE LSP is defined as the shortest path satisfying the set of required
   constraints that would be obtained in the absence of multiple domains
   (in other words, in a totally flat IGP network between the source and
   destination of the TE LSP). Note that this requires the use of
   consistent metric schemes in each domain (see Section 13).

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 [RFC 2119](#) [[RFC2119](#)].

2. Terminology

ABR: Area Border Routers. Routers used to connect two IGP areas
(areas in OSPF or levels in IS-IS).

ASBR: Autonomous System Border Router. Router used to connect
together ASes of the same or different service providers via one or
more inter-AS links.

Boundary Node (BN): a boundary node is either an ABR in the context
of inter-area Traffic Engineering or an ASBR in the context of
inter-AS Traffic Engineering.

Entry BN of domain(n): a BN connecting domain(n-1) to domain(n) along
a determined sequence of domains.

Exit BN of domain(n): a BN connecting domain(n) to domain(n+1) along
a determined sequence of domains.

Inter-area TE LSP: A TE LSP that crosses an IGP area boundary.

Inter-AS TE LSP: A TE LSP that crosses an AS boundary.

LSP: Label Switched Path.

LSR: Label Switching Router.

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.

PCE(i) is a PCE with the scope of domain(i).

TED: Traffic Engineering Database.

VSPT: Virtual Shortest Path Tree.

The notion of contiguous, stitched, and nested TE LSPs is defined in
[[RFC4726](#)] and will not be repeated here.

3. General Assumptions

   In the rest of this document, we make the following set of
   assumptions common to inter-area and inter-AS MPLS TE:

   o Each IGP area or Autonomous System (AS) is assumed to be Traffic
      Engineering enabled.

   o No topology or resource information is distributed between domains
      (as mandated per [RFC4105] and [RFC4216]), which is critical to
      preserve IGP/BGP scalability and confidentiality.

   o While certain constraints like bandwidth can be used across
      different domains, other TE constraints (such as resource
      affinity, color, metric, etc. [RFC2702]) could be translated at
      domain boundaries. If required, it is assumed that, at the domain
      boundary nodes, there will exist some sort of local mapping based
      on policy agreement, in order to translate such constraints across
      domain boundaries during the inter-PCE communication process.

   o Each AS can be made of several IGP areas. The path computation
      procedure described in this document applies to the case of a
      single AS made of multiple IGP areas, multiple ASes made of a
      single IGP area, or any combination of the above. For the sake of
      simplicity, each AS will be considered to be made of a single area
      in this document. The case of an inter-AS TE LSP spanning
      multiple ASes, where some of those ASes are themselves made of
      multiple IGP areas, can be easily derived from this case by
      applying the BRPC procedure described in this document,
      recursively.

   o The domain path (the set of domains traversed to reach the
      destination domain) is either administratively predetermined or
      discovered by some means that is outside of the scope of this
      document.

4. BRPC Procedure

   The BRPC procedure is a multiple-PCE path computation technique as
   described in [RFC4655]. A possible model consists of hosting the PCE
   function on boundary nodes (e.g., ABR or ASBR), but this is not
   mandated by the BRPC procedure.

   The BRPC procedure relies on communication between cooperating PCEs.
   In particular, the PCC sends a PCReq to a PCE in its domain. The
   request is forwarded between PCEs, domain-by-domain, until the PCE
   responsible for the domain containing the LSP destination is reached.
   The PCE in the destination domain creates a tree of potential paths

to the destination (the Virtual Shortest Path Tree - VSPT) and passes
this back to the previous PCE in a PCRep. Each PCE in turn adds to
the VSPT and passes it back until the PCE in the source domain uses
the VSPT to select an end-to-end path that the PCE sends to the PCC.

The BRPC procedure does not make any assumption with regards to the
nature of the inter-domain TE LSP that could be contiguous, nested,
or stitched.

Furthermore, no assumption is made on the actual path computation
algorithm in use by a PCE (e.g., it can be any variant of Constrained
Shortest Path First (CSPF) or an algorithm based on linear
programming to solve multi-constraint optimization problems).

4.1. Domain Path Selection

The PCE-based BRPC procedure applies to the computation of an optimal
constrained inter-domain TE LSP. The sequence of domains to be
traversed is either administratively predetermined or discovered by
some means that is outside of the scope of this document. The PCC
MAY indicate the sequence of domains to be traversed using the
Include Route Object (IRO) defined in [RFC5440] so that it is
available to all PCEs. Note also that a sequence of PCEs MAY be
enforced by policy on the PCC, and this constraint can be carried in
the PCEP path computation request (as defined in [PCE-MONITOR]).

The BRPC procedure guarantees to compute the optimal path across a
specific sequence of traversed domains (which constitutes an
additional constraint). In the case of an arbitrary set of meshed
domains, the BRPC procedure can be used to compute the optimal path
across each domain set in order to get the optimal constrained path
between the source and the destination of the TE LSP. The BRPC
procedure can also be used across a subset of all domain sequences,
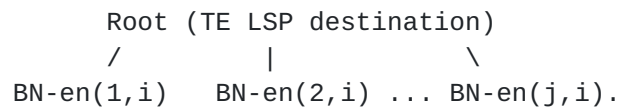and the best path among these sequences can then be selected.

4.2. Mode of Operation

Definition of VSPT(i)

In each domain i:

o There is a set of X-en(i) entry BNs noted BN-en(k,i) where
   BN-en(k,i) is the kth entry BN of domain(i).

o There is a set of X-ex(i) exit BNs noted BN-ex(k,i) where
   BN-ex(k,i) is the kth exit BN of domain(i).

VSPT(i): MP2P (multipoint-to-point) tree returned by PCE(i) to
PCE(i-1):

```
                    Root (TE LSP destination)
                   /         |              \
            BN-en(1,i)   BN-en(2,i) ... BN-en(j,i).

              where [X-en(i)] is the number of
            entry BNs in domain i and j<= [X-en(i)]
```

                        Figure 1: MP2P Tree

Each link of tree VSPT(i) represents the shortest constrained path
between BN-en(j,i) and the TE LSP destination that satisfies the set
of required constraints for the TE LSP (bandwidth, affinities, etc.).
These are path segments to reach the TE LSP destination from
BN-en(j,i).

Note that PCE(i) only considers the entry BNs of domain(i), i.e.,
only the BNs that provide connectivity from domain(i-1). In other
words, the set BN-en(k,i) is only made of those BNs that provide
connectivity from domain (i-1) to domain(i). Furthermore, some BNs
may be excluded according to policy constraints (either due to local
policy or policies signaled in the path computation request).

Step 1:
First, the PCC needs to determine the PCE capable of serving its path
computation request (this can be done with local configuration or via
IGP discovery (see [RFC5088] and [RFC5089])). The path computation
request is then relayed until reaching a PCE(n) such that the TE LSP
destination resides in the domain(n). At each step of the process,
the next PCE can either be statically configured or dynamically
discovered via IGP/BGP extensions. If no next PCE can be found or
the next-hop PCE of choice is unavailable, the procedure stops and a
path computation error is returned (see Section 9). If PCE(i-1)
discovers multiple PCEs for the adjacent domain(i), PCE(i) may select
a subset of these PCEs based on some local policies or heuristics.
The PCE selection process is outside of the scope of this document.

Step 2:
PCE(n) computes VSPT(n), the tree made of the list of shortest
constrained paths between every BN-en(j,n) and the TE LSP destination
using a suitable path computation algorithm (e.g., CSPF) and returns
the computed VSPT(n) to PCE(n-1).

Step i:
For i=n-1 to 2: PCE(i) computes VSPT(i), the tree made of the
shortest constrained paths between each BN-en(j,i) and the TE LSP
destination. It does this by considering its own TED and the
information in VSPT(i+1).

In the case of inter-AS TE LSP computation, this also requires adding
the inter-AS TE links that connect the domain(i) to the domain(i+1).

Step n:
Finally, PCE(1) computes the end-to-end shortest constrained path
from the source to the destination and returns the corresponding path
to the requesting PCC in the form of a PCRep message as defined in
[[RFC5440](#)].

Each branch of the VSPT tree (path) may be returned in the form of an
explicit path (in which case, all the hops along the path segment are
listed) or a loose path (in which case, only the BN is specified) so
as to preserve confidentiality along with the respective cost. In
the latter case, various techniques can be used in order to retrieve
the computed explicit paths on a per-domain basis during the
signaling process, thanks to the use of path keys as described in
[[PATH-KEY](#)].

A PCE that can compute the requested path for more than one
consecutive domain on the path SHOULD perform this computation for
all such domains before passing the PCRep to the previous PCE in the
sequence.

BRPC guarantees to find the optimal (shortest) constrained inter-
domain TE LSP according to a set of defined domains to be traversed.
Note that other variants of the BRPC procedure relying on the same
principles are also possible.

Note also that in case of Equal Cost Multi-Path (ECMP) paths, more
than one path could be returned to the requesting PCC.

[5](#). PCEP Protocol Extensions

The BRPC procedure requires the specification of a new flag of the RP
object carried within the PCReq message (defined in [[RFC5440](#)]) to
specify that the shortest paths satisfying the constraints from the
destination to the set of entry boundary nodes are requested (such a
set of paths forms the downstream VSPT as specified in [Section 4.2](#)).

The following new flag of the RP object is defined:

VSPT Flag

Bit Number   Name Flag
   25   VSPT

When set, the VSPT Flag indicates that the PCC requests the
computation of an inter-domain TE LSP using the BRPC procedure
defined in this document.

Because path segments computed by a downstream PCE in the context of
the BRPC procedure MUST be provided along with their respective path
costs, the C flag of the METRIC object carried within the PCReq
message MUST be set. It is the choice of the requester to
appropriately set the O bit of the RP object.

[6](#). VSPT Encoding

The VSPT is returned within a PCRep message. The encoding consists
of a non-ordered list of Explicit Route Objects (EROs) where each ERO
represents a path segment from a BN to the destination specified in
the END-POINT object of the corresponding PCReq message.

Example:
```
<---- area 1 ----><---- area 0 -----><------ area 2 ------>
                                ABR1-A-B-+
                                 |       |
                                ABR2-----D
                                 |       |
                                ABR3--C--+
```

 Figure 2: An Example of VSPT Encoding Using a Set of EROs

In the simple example shown in Figure 2, if we make the assumption
that a constrained path exists between each ABR and the destination
D, the VSPT computed by a PCE serving area 2 consists of the
following non-ordered set of EROs:

o ERO1: ABR1(TE Router ID)-A(Interface IP address)-B(Interface IP
   address)-D(TE Router ID)

o ERO2: ABR2(TE Router ID)-D(TE Router ID)

o ERO3: ABR3(TE Router ID)-C(interface IP address)-D(TE Router ID)

The PCReq message, PCRep message, PCEP END-POINT object, and ERO
object are defined in [[RFC5440](#)].

[7](#). Inter-AS TE Links

In the case of inter-AS TE LSP path computation, the BRPC procedure
requires the knowledge of the traffic engineering attributes of the
inter-AS TE links. The process by which the PCE acquires this
information is out of the scope of the BRPC procedure, which is
compliant with the PCE architecture defined in [[RFC4655](#)].

That said, a straightforward solution consists of allowing the ASBRs
to flood the TE information related to the inter-ASBR links although
no IGP TE is enabled over those links (there is no IGP adjacency over
the inter-ASBR links). This allows the PCE of a domain to get entire
TE visibility up to the set of entry ASBRs in the downstream domain
(see the IGP extensions defined in [[RFC5316](#)] and [[RFC5392](#)]).

[8](#). Usage in Conjunction with Per-Domain Path Computation

The BRPC procedure may be used to compute path segments in
conjunction with other path computation techniques (such as the per-
domain path computation technique defined in [[RFC5152](#)]) to compute
the end-to-end path. In this case, end-to-end path optimality can no
longer be guaranteed.

[9](#). BRPC Procedure Completion Failure

If the BRPC procedure cannot be completed because a PCE along the
domain does not recognize the procedure (VSPT flag of the RP object),
as stated in [[RFC5440](#)], the PCE sends a PCErr message to the upstream
PCE with an Error-Type=4 (Not supported object), Error-value=4
(Unsupported parameter). The PCE may include the parent object (RP
object) up to and including (but no further than) the unknown or
unsupported parameter. In this case where the unknown or unsupported
parameter is a bit flag (VSPT flag), the included RP object should
contain the whole bit flag field with all bits after the parameter at
issue set to zero. The corresponding path computation request is
then cancelled by the PCE without further notification.

If the BRPC procedure cannot be completed because a PCE along the
domain path recognizes but does not support the procedure, it MUST
return a PCErr message to the upstream PCE with an Error-Type "BRPC
procedure completion failure".

The PCErr message MUST be relayed to the requesting PCC.

PCEP-ERROR objects are used to report a PCEP protocol error and are
characterized by an Error-Type that specifies the type of error and
an Error-value that provides additional information about the error
type. Both the Error-Type and the Error-value are managed by IANA.

A new Error-Type is defined that relates to the BRPC procedure.

```
Error-Type        Meaning
   13             BRPC procedure completion failure
                  Error-value
                     1: BRPC procedure not supported by one or more PCEs
                        along the domain path
```

[10](#). Applicability

As discussed in [Section 3](#), the requirements for inter-area and
inter-AS MPLS Traffic Engineering have been developed by the Traffic
Engineering Working Group (TE WG) and have been stated in [[RFC4105](#)]
and [[RFC4216](#)], respectively. Among the set of requirements, both
documents indicate the need for some solution that provides the
ability to compute an optimal (shortest) constrained inter-domain TE
LSP and to compute a set of diverse inter-domain TE LSPs.

[10.1](#). Diverse End-to-End Path Computation

PCEP (see [[RFC5440](#)]) allows a PCC to request the computation of a set
of diverse TE LSPs by setting the SVEC object's flags L, N, or S to
request link, node, or SRLG (Shared Risk Link Group) diversity,
respectively. Such requests MUST be taken into account by each PCE
along the path computation chain during the VSPT computation. In the
context of the BRPC procedure, a set of diversely routed TE LSPs
between two LSRs can be computed since the path segments of the VSPT
are simultaneously computed by a given PCE. The BRPC procedure
allows for the computation of diverse paths under various objective
functions (such as minimizing the sum of the costs of the N diverse
paths, etc.).

By contrast, with a 2-step approach consisting of computing the first
path followed by computing the second path after having removed the
set of network elements traversed by the first path (if that does not
violate confidentiality preservation), one cannot guarantee that a
solution will be found even if such solution exists. Furthermore,
even if a solution is found, it may not be the most optimal one with
respect to an objective function such as minimizing the sum of the
paths' costs, bounding the path delays of both paths, and so on.
Finally, it must be noted that such a 2-step path computation
approach is usually less efficient in terms of signaling delays since
it requires that two serialized TE LSPs be set up.

[10.2](#). Path Optimality

   BRPC guarantees that the optimal (shortest) constrained inter-domain
   path will always be found, subject to policy constraints. Both in
   the case where local path computation techniques are used (such as to
   build stitched or nested TE LSPs), and in the case where a domain has
   more than one BN-en or more than one BN-ex, it is only possible to
   guarantee optimality after some network change within the domain by
   completely re-executing the BRPC procedure.

[11](#). Reoptimization of an Inter-Domain TE LSP

   The ability to reoptimize an existing inter-domain TE LSP path has
   been explicitly listed as a requirement in [[RFC4105](#)] and [[RFC4216](#)].
   In the case of a TE LSP reoptimization request, the reoptimization
   procedure defined in [[RFC5440](#)] applies when the path in use (if
   available on the head-end) is provided as part of the path
   computation request so that the PCEs involved in the reoptimization
   request can avoid double bandwidth accounting.

[12](#). Path Computation Failure

   If a PCE requires to relay a path computation request according to
   the BRPC procedure defined in this document to a downstream PCE and
   no such PCE is available, the PCE MUST send a negative path
   computation reply to the requester using a PCReq message as specified
   in [[RFC5440](#)] that contains a NO-PATH object. In such case, the
   NO-PATH object MUST carry a NO-PATH-VECTOR TLV (defined in [[RFC5440](#)])
   with the newly defined bit named "BRPC path computation chain
   unavailable" set.

   Bit number   Name Flag
      28   BRPC path computation chain unavailable

[13](#). Metric Normalization

   In the case of inter-area TE, the same IGP/TE metric scheme is
   usually adopted for all the IGP areas (e.g., based on the link-speed,
   propagation delay, or some other combination of link attributes).
   Hence, the proposed set of mechanisms always computes the shortest
   path across multiple areas that obey the required set of constraints
   with respect to a specified objective function. Conversely, in the
   case of inter-AS TE, in order for this path computation to be
   meaningful, metric normalization between ASes may be required. One
   solution to avoid IGP metric modification would be for the service
   providers to agree on a TE metric normalization scheme and use the TE

metric for TE LSP path computation (in that case, the use of the TE
metric must be requested in the PCEP path computation request) using
the METRIC object (defined in [RFC5440]).

14. Manageability Considerations

This section follows the guidance of [PCE-MANAGE].

14.1. Control of Function and Policy

The only configurable item is the support of the BRPC procedure on a
PCE. The support of the BRPC procedure by the PCE MAY be controlled
by a policy module governing the conditions under which a PCE should
participate in the BRPC procedure (origin of the requests, number of
requests per second, etc.). If the BRPC is not supported/allowed on
a PCE, it MUST send a PCErr message as specified in Section 9.

14.2. Information and Data Models

A BRPC MIB module will be specified in a separate document.

14.3. Liveness Detection and Monitoring

The BRPC procedure is a multiple-PCE path computation technique and,
as such, a set of PCEs are involved in the path computation chain.
If the path computation chain is not operational either because at
least one PCE does not support the BRPC procedure or because one of
the PCEs that must be involved in the path computation chain is not
available, procedures are defined to report such failures in Sections
9 and 12, respectively. Furthermore, a built-in diagnostic tool to
check the availability and performances of a PCE chain is defined in
[PCE-MONITOR].

14.4. Verifying Correct Operation

Verifying the correct operation of BRPC can be performed by
monitoring a set of parameters. A BRPC implementation SHOULD provide
the following parameters:

o Number of successful BRPC procedure completions on a per-PCE-peer
   basis

o Number of BRPC procedure completion failures because the VSPT flag
   was not recognized (on a per-PCE-peer basis)

o Number of BRPC procedure completion failures because the BRPC
   procedure was not supported (on a per-PCE-peer basis)

14.5. Requirements on Other Protocols and Functional Components

   The BRPC procedure does not put any new requirements on other
   protocols. That said, since the BRPC procedure relies on the PCEP
   protocol, there is a dependency between BRPC and PCEP; consequently,
   the BRPC procedure inherently makes use of the management functions
   developed for PCEP.

14.6. Impact on Network Operation

   The BRPC procedure does not have any significant impact on network
   operation: indeed, BRPC is a multiple-PCE path computation scheme as
   defined in [RFC4655] and does not differ from any other path
   computation request.

14.7. Path Computation Chain Monitoring

   [PCE-MONITOR] specifies a set of mechanisms that can be used to
   gather PCE state metrics. Because BRPC is a multiple-PCE path
   computation technique, such mechanisms could be advantageously used
   in the context of the BRPC procedure to check the liveness of the
   path computation chain, locate a faulty component, monitor the
   overall performance, and so on.

15. IANA Considerations

15.1. New Flag of the RP Object

   A new flag of the RP object (specified in [RFC5440]) is defined in
   this document. IANA maintains a registry of RP object flags in the
   "RP Object Flag Field" sub-registry of the "Path Computation Element
   Protocol (PCEP) Numbers" registry.

   IANA has allocated the following value:

Bit	Description	Reference
25	VSPT	This document

15.2. New Error-Type and Error-Value

   IANA maintains a registry of Error-Types and Error-values for use in
   PCEP messages. This is maintained as the "PCEP-ERROR Object Error
   Types and Values" sub-registry of the "Path Computation Element
   Protocol (PCEP) Numbers" registry.

A new Error-value is defined for the Error-Type "Not supported object" (type 4).

```
Error-Type     Meaning and error values                Reference
    4          Not supported object

               Error-value=4: Unsupported parameter    This document
```

A new Error-Type is defined in this document as follows:

```
Error-Type     Meaning                                 Reference
   13          BRPC procedure completion failure        This document

               Error-value=1: BRPC procedure not        This document
               supported by one or more PCEs along
               the domain path
```

15.3. New Flag of the NO-PATH-VECTOR TLV

A new flag of the NO-PATH-VECTOR TLV defined in [RFC5440]) is specified in this document.

IANA maintains a registry of flags for the NO-PATH-VECTOR TLV in the "NO-PATH-VECTOR TLV Flag Field" sub-registry of the "Path Computation Element Protocol (PCEP) Numbers" registry.

IANA has allocated the following allocation value:

```
   Bit number   Meaning                    Reference
       4         BRPC path computation      This document
                 chain unavailable
```

16. Security Considerations

The BRPC procedure relies on the use of the PCEP protocol and as such is subjected to the potential attacks listed in Section 10 of [RFC5440]. In addition to the security mechanisms described in [RFC5440] with regards to spoofing, snooping, falsification, and denial of service, an implementation MAY support a policy module governing the conditions under which a PCE should participate in the BRPC procedure.

The BRPC procedure does not increase the information exchanged between ASes and preserves topology confidentiality, in compliance with [RFC4105] and [RFC4216].

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