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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):

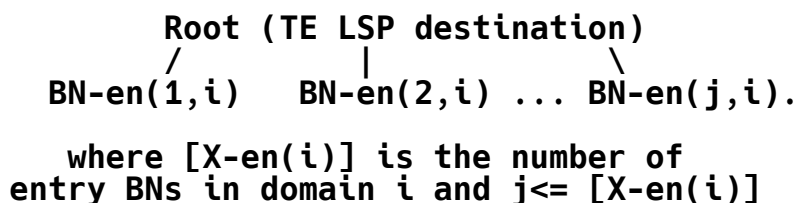


Figure 1: MP2P Tree

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 0 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 supported by one or more PCEs along the domain path	This document

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 chain unavailable	This document

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].

17. Acknowledgments

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