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Framework for PCE-Based Inter-Layer MPLS and GMPLS Traffic Engineering

Abstract

A network may comprise multiple layers. It is important to globally optimize network resource utilization, taking into account all layers rather than optimizing resource utilization at each layer independently. This allows better network efficiency to be achieved through a process that we call inter-layer traffic engineering. The Path Computation Element (PCE) can be a powerful tool to achieve inter-layer traffic engineering.

This document describes a framework for applying the PCE-based architecture to inter-layer Multiprotocol Label Switching (MPLS) and Generalized MPLS (GMPLS) traffic engineering. It provides suggestions for the deployment of PCE in support of multi-layer networks. This document also describes network models where PCE performs inter-layer traffic engineering, and the relationship between PCE and a functional component called the Virtual Network Topology Manager (VNTM).

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1. Introduction

A network may comprise multiple layers. These layers may represent separations of technologies (e.g., packet switch capable (PSC), time division multiplex (TDM), or lambda switch capable (LSC)) [RFC3945], separation of data plane switching granularity levels (e.g., PSC-1, PSC-2, VC4, or VC12) [RFC5212], or a distinction between client and server networking roles. In this multi-layer network, Label Switched Paths (LSPs) in a lower layer are used to carry higher-layer LSPs across the lower-layer network. The network topology formed by lower-layer LSPs and advertised as traffic engineering links (TE links) in the higher-layer network is called the Virtual Network Topology (VNT) [RFC5212].

It may be effective to optimize network resource utilization globally, i.e., taking into account all layers rather than optimizing resource utilization at each layer independently. This allows better network efficiency to be achieved and is what we call inter-layer traffic engineering. Inter-layer traffic engineering includes using mechanisms that allow the computation of end-to-end paths across layers (known as inter-layer path computation) and mechanisms that control and manage the Virtual Network Topology (VNT) by setting up and releasing LSPs in the lower layers [RFC5212].

Inter-layer traffic engineering is included in the scope of the Path Computation Element (PCE)-based architecture [RFC4655], and PCE can provide a suitable mechanism for resolving inter-layer path computation issues.

PCE Communication Protocol requirements for inter-layer traffic engineering are set out in [PCC-PCE].

This document describes a framework for applying the PCE-based architecture to inter-layer traffic engineering. It provides suggestions for the deployment of PCE in support of multi-layer networks. This document also describes network models where PCE performs inter-layer traffic engineering as well as describing the relationship between PCE and a functional component in charge of the control and management of the VNT, called the Virtual Network Topology Manager (VNTM).

1.1. Terminology

This document uses terminology from the PCE-based path computation architecture [RFC4655] and also common terminology from Multi-Protocol Label Switching (MPLS) [RFC3031], Generalized MPLS (GMPLS) [RFC3945], and Multi-Layer Networks [RFC5212].

2. Inter-Layer Path Computation

This section describes key topics of inter-layer path computation in MPLS and GMPLS networks.

[RFC4206] defines a way to signal a higher-layer LSP that has an explicit route and includes hops traversed by LSPs in lower layers. The computation of end-to-end paths across layers is called inter-layer path computation.

A Label Switching Router (LSR) in the higher layer might not have information on the topology of the lower layer, particularly in an overlay or augmented model deployment, and hence may not be able to compute an end-to-end path across layers.

PCE-based inter-layer path computation consists of using one or more PCEs to compute an end-to-end path across layers. This could be achieved by a single PCE path computation, where the PCE has topology information about multiple layers and can directly compute an end-to-end path across layers, considering the topology of all of the layers. Alternatively, the inter-layer path computation could be performed as a multiple PCE computation, where each member of a set of PCEs has information about the topology of one or more layers (but not all layers) and the PCEs collaborate to compute an end-to-end path.

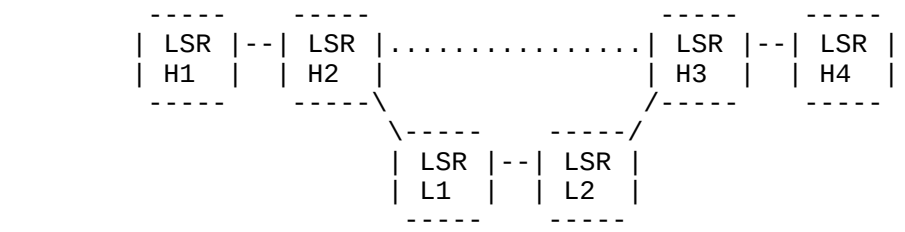

Figure 1: A Simple Example of a Multi-Layer Network

Consider, for instance, the two-layer network shown in Figure 1, where the higher-layer network (LSRs H1, H2, H3, and H4) is a packet-based IP/MPLS or GMPLS network, and the lower-layer network (LSRs, H2, L1, L2, and H3) is a GMPLS optical network. An ingress LSR in the higher-layer network (H1) tries to set up an LSP to an egress LSR (H4) also in the higher-layer network across the lower-layer network, and needs a path in the higher-layer network. However, suppose that there is no TE link in the higher-layer network between the border LSRs located on the boundary between the higher-layer and lower-layer networks (H2 and H3). Suppose also that the ingress LSR does not have topology visibility into the lower layer.

If a single-layer path computation is applied in the higher-layer, the path computation fails because of the missing TE link. On the other hand, inter-layer path computation is able to provide a route in the higher-layer (H1-H2-H3-H4) and to suggest that a lower-layer LSP be set up between the border LSRs (H2-L1-L2-H3).

Lower-layer LSPs that are advertised as TE links into the higher-layer network form a Virtual Network Topology (VNT) that can be used for routing higher-layer LSPs. Inter-layer path computation for end-to-end LSPs in the higher-layer network that span the lower-layer network may utilize the VNT, and PCE is a candidate for computing the paths of such higher-layer LSPs within the higher-layer network. Alternatively, the PCE-based path computation model can:

- Perform a single computation on behalf of the ingress LSR using information gathered from more than one layer. This mode is referred to as single PCE computation in [RFC4655].

- Compute a path on behalf of the ingress LSR through cooperation with PCEs responsible for each layer. This mode is referred to as multiple PCE computation with inter-PCE communication in [RFC4655].

- Perform separate path computations on behalf of the TE-LSP head-end and each transit border LSR that is the entry point to a new layer. This mode is referred to as multiple PCE computation (without inter-PCE communication) in [RFC4655]. This option utilizes per-layer path computation, which is performed independently by successive PCEs.

Note that when a network consists of more than two layers (e.g., MPLS over SONET over Optical Transport Network (OTN)) and a path traversing more than two layers needs to be computed, it is possible to combine multiple PCE-based path computation models. For example, the single PCE computation model could be used for computing a path across the SONET layer and the OTN layer, and the multiple PCE computation with inter-PCE communication model could be used for computing a path across the MPLS layer (computed by higher-layer PCE) and the SONET layer (computed by lower-layer PCE).

The PCE invoked by the head-end LSR computes a path that the LSR can use to signal an MPLS-TE or GMPLS LSP once the path information has been converted to an Explicit Route Object (ERO) for use in RSVP-TE signaling. There are two options.

- Option 1: Mono-Layer Path

  The PCE computes a "mono-layer" path, i.e., a path that includes only TE links from the same layer. There are two cases for this option. In the first case, the PCE computes a path that includes already established lower-layer LSPs or lower-layer LSPs to be established on demand. That is, the resulting ERO includes subobject(s) corresponding to lower-layer hierarchical LSPs expressed as the TE link identifiers of the hierarchical LSPs when advertised as TE links in the higher-layer network. The TE link may be a regular TE link that is actually established or a virtual TE link that is not established yet (see [RFC5212]). If it is a virtual TE link, this triggers a setup attempt for a new lower-layer LSP when signaling reaches the head-end of the lower-layer LSP. Note that the path of a virtual TE link is not necessarily known in advance, and this may require a further (lower-layer) path computation.

  The second case is that the PCE computes a path that includes a loose hop that spans the lower-layer network. The higher-layer path computation selects which lower-layer network to use and the entry and exit points of that lower-layer network, but does not select the path across the lower-layer network. A transit LSR that is the entry point to the lower-layer network is expected to expand the loose hop (either itself or relying on the services of a PCE). The path expansion process on the border LSR may result either in the selection of an existing lower-layer LSP or in the computation and setup of a new lower-layer LSP.

  Note that even if a PCE computes a path with a loose hop expecting that the loose hop will be expanded across the lower-layer network, the LSR (that is an entry point to the lower-layer network) may simply expand the loose hop in the same layer. If more strict control of how the LSR establishes the path is required, mechanisms such as Path Key [RFC5520] could be applied.

- Option 2: Multi-Layer Path

  The PCE computes a "multi-layer" path, i.e., a path that includes TE links from distinct layers [RFC4206]. Such a path can include the complete path of one or more lower-layer LSPs that already exist or that are not yet established. In the latter case, the signaling of the higher-layer LSP will trigger the establishment of the lower-layer LSPs.

3. Inter-Layer Path Computation Models

In Section 2, three models are defined to perform PCE-based inter-layer path computation -- namely, single PCE computation, multiple PCE computation with inter-PCE communication, and multiple PCE computation without inter-PCE communication. Single PCE computation is discussed in Section 3.1 below, and multiple PCE computation (with and without inter-PCE communication) is discussed in Section 3.2 below.

3.1. Single PCE Inter-Layer Path Computation

In this model, inter-layer path computation is performed by a single PCE that has topology visibility into all layers. Such a PCE is called a multi-layer PCE.

In Figure 2, the network is comprised of two layers. LSRs H1, H2, H3, and H4 belong to the higher layer, and LSRs H2, H3, L1, and L2 belong to the lower layer. The PCE is a multi-layer PCE that has visibility into both layers. It can perform end-to-end path computation across layers (single PCE path computation). For instance, it can compute an optimal path H1-H2-L1-L2-H3-H4 for a higher-layer LSP from H1 to H4. This path includes the path of a lower-layer LSP from H2 to H3 that is already in existence or not yet established.

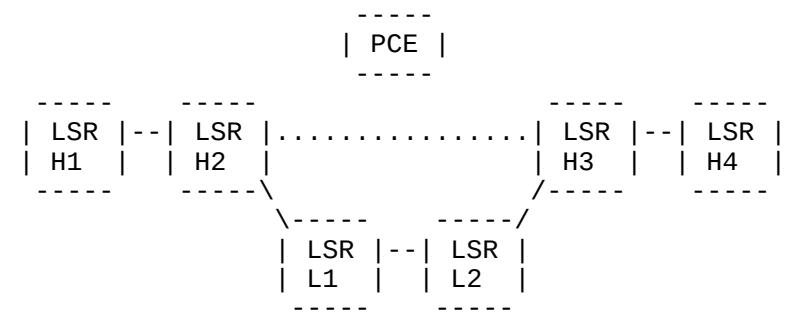

Figure 2: Single PCE Inter-Layer Path Computation

3.2. Multiple PCE Inter-Layer Path Computation

In this model, there is at least one PCE per layer, and each PCE has topology visibility restricted to its own layer. Some providers may want to keep the layer boundaries due to factors such as organizational and/or service management issues. The choice for multiple PCE computation instead of single PCE computation may also

be driven by scalability considerations, as in this mode a PCE only needs to maintain topology information for one layer (resulting in a size reduction for the Traffic Engineering Database (TED)).

These PCEs are called mono-layer PCEs. Mono-layer PCEs collaborate to compute an end-to-end optimal path across layers.

Figure 3 shows multiple PCE inter-layer computation with inter-PCE communication. There is one PCE in each layer. The PCEs from each layer collaborate to compute an end-to-end path across layers. PCE Hi is responsible for computations in the higher layer and may "consult" with PCE Lo to compute paths across the lower layer. PCE Lo is responsible for path computation in the lower layer. A simple example of cooperation between the PCEs could be as follows:

- LSR H1 sends a request to PCE Hi for a path H1-H4.

- PCE Hi selects H2 as the entry point to the lower layer and H3 as the exit point.

- PCE Hi requests a path H2-H3 from PCE Lo.

- PCE Lo returns H2-L1-L2-H3 to PCE Hi.

- PCE Hi is now able to compute the full path (H1-H2-L1-L2-H3-H4) and return it to H1.

Of course, more complex cooperation may be required if an optimal end-to-end path is desired.

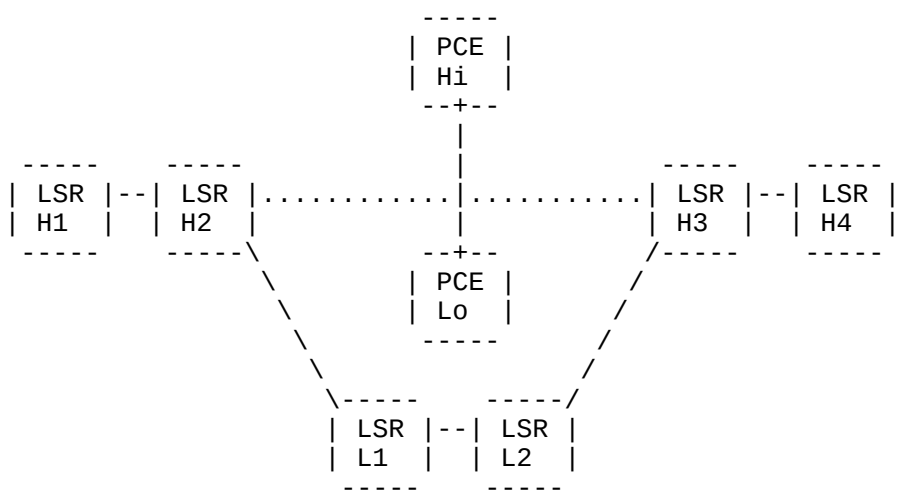

Figure 3: Multiple PCE Inter-Layer Path Computation with Inter-PCE Communication

Figure 4 shows multiple PCE inter-layer path computation without inter-PCE communication. As described in Section 2, separate path computations are performed on behalf of the TE-LSP head-end and each transit border LSR that is the entry point to a new layer.

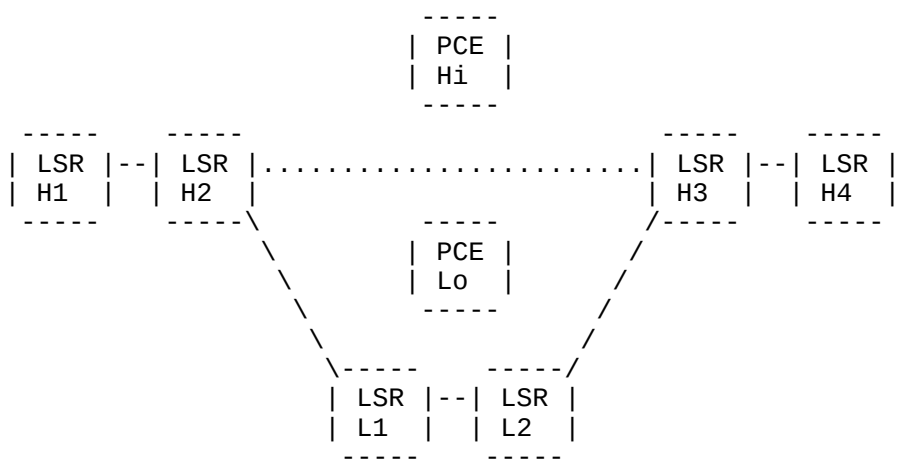

Figure 4: Multiple PCE Inter-Layer Path Computation without Inter-PCE Communication

3.3. General Observations

- Depending on implementation details, the time to perform inter-layer path computation in the single PCE inter-layer path computation model may be less than that of the multiple PCE model with cooperating mono-layer PCEs, because there is no requirement to exchange messages between cooperating PCEs.

- When TE topology for all layer networks is visible within one routing domain, the single PCE inter-layer path computation model may be adopted because a PCE is able to collect all layers' TE topologies by participating in only one routing domain.

- As the single PCE inter-layer path computation model uses more TE topology information in one computation than is used by PCEs in the multiple PCE path computation model, it requires more computation power and memory.

When there are multiple candidate layer border nodes (we may say that the higher layer is multi-homed), optimal path computation requires that all the possible paths transiting different layer border nodes or links be examined. This is relatively simple in the single PCE inter-layer path computation model because the PCE has full visibility -- the computation is similar to the computation within a single domain of a single layer. In the multiple PCE inter-layer path computation model, backward-recursive techniques described in [RFC5441] could be used by considering layers as separate domains.

4. Inter-Layer Path Control

4.1. VNT Management

As a result of mono-layer path computation, a PCE may determine that there is insufficient bandwidth available in the higher-layer network to support this or future higher-layer LSPs. The problem might be resolved if new LSPs are provisioned across the lower-layer network. Furthermore, the modification, re-organization, and new provisioning of lower-layer LSPs may enable better utilization of lower-layer network resources, given the demands of the higher-layer network. In other words, the VNT needs to be controlled or managed in cooperation with inter-layer path computation.

A VNT Manager (VNTM) is defined as a functional element that manages and controls the VNT. The PCE and VNT Manager are distinct functional elements that may or may not be collocated.

4.2. Inter-Layer Path Control Models

4.2.1. PCE-VNTM Cooperation Model

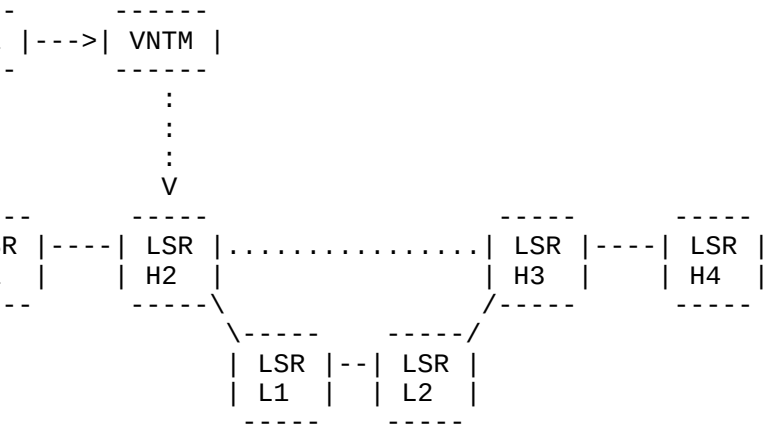

Figure 5: PCE-VNTM Cooperation Model

A multi-layer network consists of higher-layer and lower-layer networks. LSRs H1, H2, H3, and H4 belong to the higher-layer network, and LSRs H2, L1, L2, and H3 belong to the lower-layer network, as shown in Figure 5. The case of single PCE inter-layer path computation is considered here to explain the cooperation model between PCE and VNTM, but multiple PCE path computation with or without inter-PCE communication can also be applied to this model.

Consider that H1 requests the PCE to compute an inter-layer path between H1 and H4. There is no TE link in the higher layer between H2 and H3 before the path computation request, so the request fails. But the PCE may provide information to the VNT Manager responsible for the lower-layer network that may help resolve the situation for future higher-layer LSP setup.

The roles of PCE and VNTM are as follows. PCE performs inter-layer path computation and is unable to supply a path because there is no TE link between H2 and H3. The computation fails, but PCE suggests to VNTM that a lower-layer LSP (H2-H3) could be established to support future LSP requests. Messages from PCE to VNTM contain information about the higher-layer demand (from H2 to H3), and may include a suggested path in the lower layer (if the PCE has visibility into the lower-layer network). VNTM uses local policy and possibly management/configuration input to determine how to process the suggestion from PCE, and may request an ingress LSR (e.g., H2) to

establish a lower-layer LSP. VNTM or the ingress LSR (H2) may themselves use a PCE with visibility into the lower layer to compute the path of this new LSP.

When the higher-layer PCE fails to compute a path and notifies VNTM, it may wait for the lower-layer LSP to be set up and advertised as a TE link. PCE may have a timer. After TED is updated within a specified duration, PCE will know a new TE link. It could then compute the complete end-to-end path for the higher-layer LSP and return the result to the PCC. In this case, the PCC may be kept waiting for some time, and it is important that the PCC understands this. It is also important that the PCE and VNTM have an agreement that the lower-layer LSP will be set up in a timely manner, or that the PCE will be notified by the VNTM that no new LSP will become available. In any case, if the PCE decides to wait, it must operate a timeout. An example of such a cooperative procedure between PCE and VNTM is as follows, using the example network in Figure 4.

Step 1: H1 (PCC) requests PCE to compute a path between H1 and H4.

Step 2: The path computation fails because there is no TE link across the lower-layer network.

Step 3: PCE suggests to VNTM that a new TE link connecting H2 and H3 would be useful. The PCE notifies VNTM that it will be waiting for the TE link to be created. VNTM considers whether lower-layer LSPs should be established, if necessary and acceptable within VNTM’s policy constraints.

Step 4: VNTM requests an ingress LSR in the lower-layer network (e.g., H2) to establish a lower-layer LSP. The request message may include a lower-layer LSP route obtained from the PCE responsible for the lower-layer network.

Step 5: The ingress LSR signals to establish the lower-layer LSP.

Step 6: If the lower-layer LSP setup is successful, the ingress LSR notifies VNTM that the LSP is complete and supplies the tunnel information.

Step 7: The ingress LSR (H2) advertises the new LSP as a TE link in the higher-layer network routing instance.

Step 8: PCE notices the new TE link advertisement and recomputes the requested path.

Step 9: PCE replies to H1 (PCC) with a computed higher-layer LSP route. The computed path is categorized as a mono-layer path that includes the already-established lower-layer LSP as a single hop in the higher layer. The higher-layer route is specified as H1-H2-H3-H4, where all hops are strict.

Step 10: H1 initiates signaling with the computed path H2-H3-H4 to establish the higher-layer LSP.

4.2.2. Higher-Layer Signaling Trigger Model

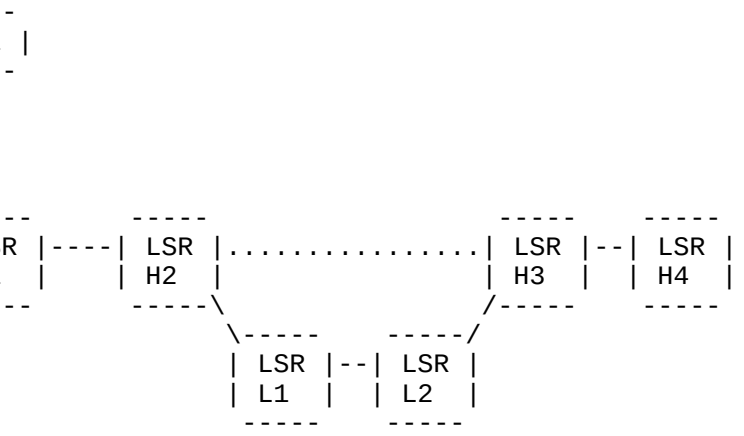

Figure 6: Higher-Layer Signaling Trigger Model

Figure 6 shows the higher-layer signaling trigger model. The case of single PCE path computation is considered to explain the higher-layer signaling trigger model here, but multiple PCE path computation with/without inter-PCE communication can also be applied to this model.

As in the case described in Section 4.2.1, consider that H1 requests PCE to compute a path between H1 and H4. There is no TE link in the higher layer between H2 and H3 before the path computation request.

PCE is unable to compute a mono-layer path, but may judge that the establishment of a lower-layer LSP between H2 and H3 would provide adequate connectivity. If the PCE has inter-layer visibility, it may return a path that includes hops in the lower layer (H1-H2-L1-L2-H3-H4), but if it has no visibility into the lower layer, it may return a path with a loose hop from H2 to H3 (H1-H2-H3(loose)-H4). The former is a multi-layer path, and the latter a mono-layer path that includes loose hops.

In the higher-layer signaling trigger model with a multi-layer path, the LSP route supplied by the PCE includes the route of a lower-layer LSP that is not yet established. A border LSR that is located at the boundary between the higher-layer and lower-layer networks (H2 in this example) receives a higher-layer signaling message, notices that the next hop is in the lower-layer network, and starts to set up the lower-layer LSP as described in [RFC4206]. Note that these actions depend on a policy being applied at the border LSR. An example procedure of the signaling trigger model with a multi-layer path is as follows.

Step 1: H1 (PCC) requests PCE to compute a path between H1 and H4. The request indicates that inter-layer path computation is allowed.

Step 2: As a result of the inter-layer path computation, PCE judges that a new lower-layer LSP needs to be established.

Step 3: PCE replies to H1 (PCC) with a computed multi-layer route including higher-layer and lower-layer LSP routes. The route may be specified as H1-H2-L1-L2-H3-H4, where all hops are strict.

Step 4: H1 initiates higher-layer signaling using the computed explicit router of H2-L1-L2-H3-H4.

Step 5: The border LSR (H2) that receives the higher-layer signaling message starts lower-layer signaling to establish a lower-layer LSP along the specified lower-layer route of H2-L1-L2-H3. That is, the border LSR recognizes the hops within the explicit route that apply to the lower-layer network, verifies with local policy that a new LSP is acceptable, and establishes the required lower-layer LSP. Note that it is possible that a suitable lower-layer LSP has already been established (or become available) between the time that the computation was performed and the moment when the higher-layer signaling message reached the border LSR. In this case, the border LSR may select such a lower-layer LSP without the need to signal a new LSP, provided that the lower-layer LSP satisfies the explicit route in the higher-layer signaling request.

Step 6: After the lower-layer LSP is established, the higher-layer signaling continues along the specified higher-layer route of H2-H3-H4 using hierarchical signaling [RFC4206].

On the other hand, in the signaling trigger model with a mono-layer path, a higher-layer LSP route includes a loose hop to traverse the lower-layer network between the two border LSRs. A border LSR that receives a higher-layer signaling message needs to determine a path for a new lower-layer LSP. It applies local policy to verify that a new LSP is acceptable and then either consults a PCE with responsibility for the lower-layer network or computes the path by itself, and initiates signaling to establish the lower-layer LSP. Again, it is possible that a suitable lower-layer LSP has already been established (or become available). In this case, the border LSR may select such a lower-layer LSP without the need to signal a new LSP, provided that the existing lower-layer LSP satisfies the explicit route in the higher-layer signaling request. Since the higher-layer signaling request used a loose hop without specifying any specifics of the path within the lower-layer network, the border LSR has greater freedom to choose a lower-layer LSP than in the previous example.

The difference between procedures of the signaling trigger model with a multi-layer path and a mono-layer path is Step 5. Step 5 of the signaling trigger model with a mono-layer path is as follows:

Step 5': The border LSR (H2) that receives the higher-layer signaling message applies local policy to verify that a new LSP is acceptable and then initiates establishment of a lower-layer LSP. It either consults a PCE with responsibility for the lower-layer network or computes the route by itself to expand the loose hop route in the higher-layer path.

Finally, note that a virtual TE link may have been advertised into the higher-layer network. This causes the PCE to return a path H1-H2-H3-H4, where all the hops are strict. But when the higher-layer signaling message reaches the layer border node H2 (that was responsible for advertising the virtual TE link), it realizes that the TE link does not exist yet, and signals the necessary LSP across the lower-layer network using its own path determination (just as for a loose hop in the higher layer) before continuing with the higher-layer signaling.

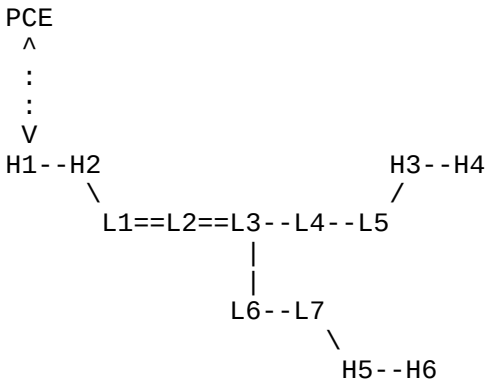

Figure 7: Example of a Multi-Layer Network

Examples of multi-layer EROs are explained using Figure 7, which shows how lower-layer LSP setup is performed in the higher-layer signaling trigger model using an ERO that can include subobjects in both the higher and lower layers. The higher-layer signaling trigger model provides several options for the ERO when it reaches the last LSR in the higher layer higher-layer network (H2).

1. The next subobject is a loose hop to H3 (mono-layer ERO).

2. The next subobject is a strict hop to L1, followed by a loose hop to H3.

3. The next subobjects are a series of hops (strict or loose) in the lower-layer network, followed by H3. For example, {L1(strict), L3(loose), L5(loose), H3(strict)}.

In the first example, the lower layer can utilize any LSP tunnel that will deliver the end-to-end LSP to H3. In the third case, the lower layer must select an LSP tunnel that traverses L3 and L5. However, this does not mean that the lower layer can or should use an LSP from L1 to L3 and another from L3 to L5.

4.2.3. NMS-VNTM Cooperation Model

In this model, NMS and VNTM cooperate to establish a lower-layer LSP. There are two flavors in this model. One is where interaction between layers in path computation is performed at the PCE level. This is called "integrated flavor". The other is where interaction between layers in path computation is achieved through NMS and VNTM cooperation, which could be a point of application of administrative, billing, and security policy. This is called "separated flavor".

o NMS-VNTM Cooperation Model (integrated flavor)

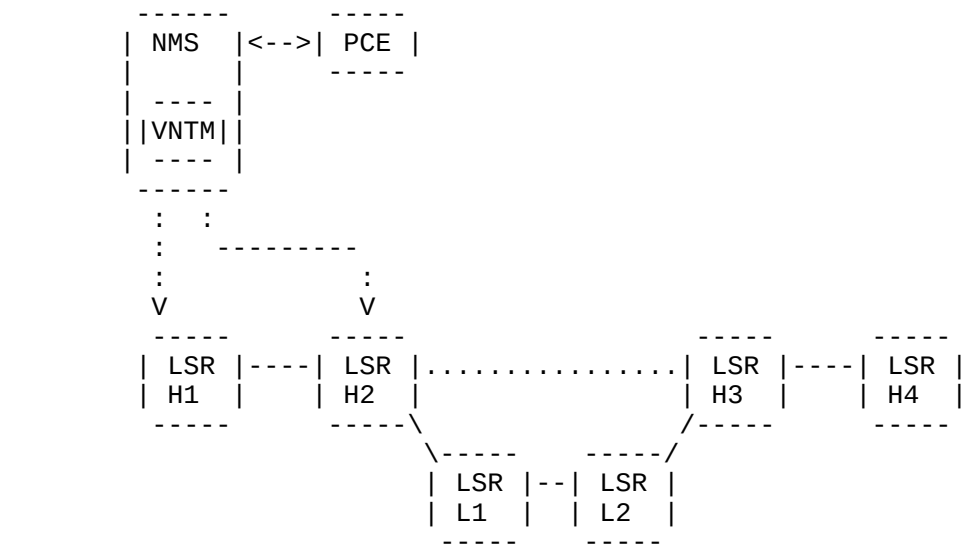

Figure 8: NMS-VNTM Cooperation Model (integrated flavor)

Figure 8 shows the NMS-VNTM cooperation model (integrated flavor). The case of single PCE path computation is considered to explain the NMS-VNTM cooperation model (integrated flavor) here, but multiple PCE path computation with inter-PCE communication can also be applied to this model. Note that multiple PCE path computation without inter-PCE communication does not fit in with this model. For this model to have meaning, the VNTM and NMS are closely coupled.

The NMS sends the path computation request to the PCE. The PCE returns the inter-layer path computation result. When the NMS receives the path computation result, the NMS works with the VNTM and sends the request to LSR H2 to set up the lower-layer LSP. VNTM uses local policy and possibly management/configuration input to determine how to process the computation result from PCE.

An example procedure of the NMS-VNTM cooperation model (integrated flavor) is as follows.

Step 1: NMS requests PCE to compute a path between H1 and H4. The request indicates that inter-layer path computation is allowed.

Step 2: PCE computes a path. The result (H1-H2-L1-L2-H3-H4) is sent back to the NMS.

Step 3: NMS discovers that a lower-layer LSP is needed. NMS works with VNTM to determine whether the new TE LSP H2-L1-L2-H3 is permitted according to policy, etc.

Step 4: VNTM requests the ingress LSR in the lower-layer network (H2) to establish a lower-layer LSP. The request message includes the lower-layer LSP route obtained from PCE.

Step 5: H2 signals to establish the lower-layer LSP.

Step 6: If the lower-layer LSP setup is successful, H2 notifies VNTM that the LSP is complete and supplies the tunnel information.

Step 7: H2 advertises the new LSP as a TE link in the higher-layer network routing instance.

Step 8: VNTM notifies NMS that the underlying lower-layer LSP has been set up, and NMS notices the new TE link advertisement.

Step 9: NMS requests H1 to set up a higher-layer LSP between H1 and H4 with the path computed in Step 2. The lower-layer links are replaced by the corresponding higher-layer TE link. Hence, the NMS sends the path H1-H2-H3-H4 to H1.

Step 10: H1 initiates signaling with the path H2-H3-H4 to establish the higher-layer LSP.

o NMS-VNTM Cooperation Model (separate flavor)

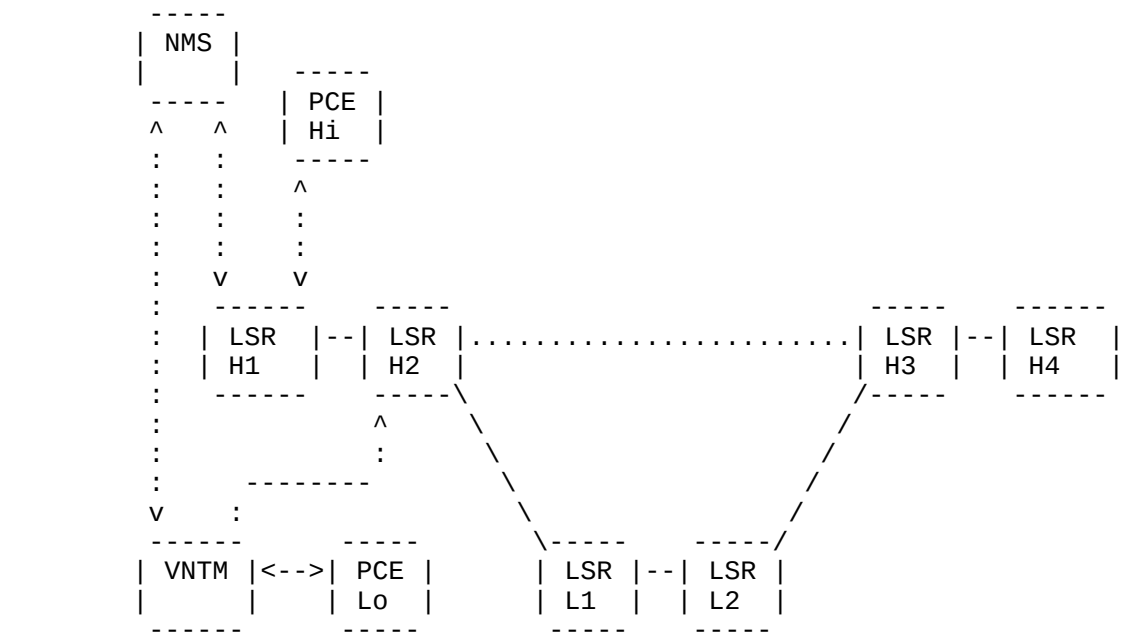

Figure 9: NMS-VNTM Cooperation Model (separate flavor)

Figure 9 shows the NMS-VNTM cooperation model (separate flavor). The NMS manages the higher layer. The case of multiple PCE computation without inter-PCE communication is used to explain the NMS-VNTM cooperation model here, but single PCE path computation could also be applied to this model. Note that multiple PCE path computation with inter-PCE communication does not fit in with this model.

The NMS requests a head-end LSR (H1 in this example) to set up a higher-layer LSP between head-end and tail-end LSRs without specifying any route. The head-end LSR, which is a PCC, requests the higher-layer PCE to compute a path between head-end and tail-end LSRs. There is no TE link in the higher-layer between border LSRs (H2 and H3 in this example). When the PCE fails to compute a path, it informs the PCC (i.e., head-end LSR), which notifies the NMS. The notification may include information about the reason for failure (such as that there is no TE link between the border LSRs or that computation constraints cannot be met).

Note that it is equally valid for the higher-layer PCE to be consulted by the NMS rather than by the head-end LSR. In this case, the result is the same -- the NMS discovers that an end-to-end LSP cannot be provisioned owing to the lack of a TE link between H2 and H3.

The NMS may now suggest (or request) to the VNTM that a lower-layer LSP between the border LSRs be established and be advertised as a TE link in the higher layer to support future higher-layer LSP requests. The communication between the NMS and the VNTM may be performed in an automatic manner or in a manual manner, and is a key interaction between layers that may also be separate administrative domains. Thus, this communication is potentially a point of application of administrative, billing, and security policy. The NMS may wait for the lower-layer LSP to be set up and advertised as a TE link, or it may reject the operator's request for the service that requires the higher-layer LSP with a suggestion that the operator try again later.

The VNTM requests the lower-layer PCE to compute a path, and then requests H2 to establish a lower-layer LSP. Alternatively, the VNTM may make a direct request to H2 for the LSP, and H2 may consult the lower-layer PCE. After the NMS is informed or notices that the lower-layer LSP has been established, it can request the head-end LSR (H1) to set up the higher-layer end-to-end LSP between H1 and H4.

Thus, cooperation between the higher layer and lower layer is performed though communication between NMS and VNTM. An example of such a procedure of the NSM-VNTM cooperation model is as follows, using the example network in Figure 6.

Step 1: NMS requests a head-end LSR (H1) to set up a higher-layer LSP between H1 and H4 without specifying any route.

Step 2: H1 (PCC) requests PCE to compute a path between H2 and H3.

Step 3: The path computation fails because there is no TE link across the lower-layer network.

Step 4: H1 (PCC) notifies NMS. The notification may include an indication that there is no TE link between H2 and H4.

Step 5: NMS suggests (or requests) to VNTM that a new TE link connecting H2 and H3 would be useful. The NMS notifies VNTM that it will be waiting for the TE link to be created. VNTM considers whether lower-layer LSPs should be established, if necessary and acceptable within VNTM's policy constraints.

Step 6: VNTM requests the lower-layer PCE for path computation.

Step 7: VNTM requests the ingress LSR in the lower-layer network (H2) to establish a lower-layer LSP. The request message includes a lower-layer LSP route obtained from the lower-layer PCE responsible for the lower-layer network.

Step 8: H2 signals the lower-layer LSP.

Step 9: If the lower-layer LSP setup is successful, H2 notifies VNTM that the LSP is complete and supplies the tunnel information.

Step 10: H2 advertises the new LSP as a TE link in the higher-layer network routing instance.

Step 11: VNTM notifies NMS that the underlying lower-layer LSP has been set up, and NMS notices the new TE link advertisement.

Step 12: NMS again requests H1 to set up a higher-layer LSP between H1 and H4.

Step 13: H1 requests the higher-layer PCE to compute a path and obtains a successful result that includes the higher-layer route that is specified as H1-H2-H3-H4, where all hops are strict.

Step 14: H1 initiates signaling with the computed path H2-H3-H4 to establish the higher-layer LSP.

4.2.4. Possible Combinations of Inter-Layer Path Computation and Inter-Layer Path Control Models

Table 1 summarizes the possible combinations of inter-layer path computation and inter-layer path control models. There are three inter-layer path computation models: the single PCE path computation model, the multiple PCE path computation with inter-PCE communication model, and the multiple PCE path computation without inter-PCE communication model. There are also four inter-layer path control models: the PCE-VNTM cooperation model, the higher-layer signaling trigger model, the NMS-VNTM cooperation model (integrated flavor), and the NMS-VNTM cooperation model (separate flavor). All the combinations between inter-layer path computation and path control models, except for the combination of the multiple PCE path computation with inter-layer PCE communication model and the NMS-VNTM cooperation model, are possible.

Table 1: Possible Combinations of Inter-Layer Path Computation and Inter-Layer Path Control Models

Path computation \ Path control	Single PCE	Multiple PCE with inter-PCE	Multiple PCE w/o inter-PCE
PCE-VNTM cooperation	Yes	Yes	Yes
Higher-layer signaling trigger	Yes	Yes	Yes
NMS-VNTM cooperation (integrated flavor)	Yes	Yes	No
NMS-VNTM cooperation (separate flavor)	No*	No	Yes

* Note that, in case of NSM-VNTM cooperation (separate flavor) and single PCE inter-layer path computation, the PCE function used by NMS and VNTM may be collocated, but it will operate on separate TEDs.

5. Choosing between Inter-Layer Path Control Models

This section compares the PCE-VNTM cooperation model, the higher-layer signaling trigger model, and the NMS-VNTM cooperation model in terms of VNTM functions, border LSR functions, higher-layer signaling time, and complexity (in terms of number of states and messages). An appropriate model may be chosen by a network operator in different deployment scenarios, taking all these considerations into account.

5.1. VNTM Functions

VNTM functions are required in both the PCE-VNTM cooperation model and the NMS-VNTM model. In the PCE-VNTM cooperation model, communications are required between PCE and VNTM and between VNTM and a border LSR. Communications between a higher-layer PCE and the VNTM are event notifications and may use Simple Network Management Protocol (SNMP) notifications from the PCE MIB modules [PCE-MIB]. Note that communications from the PCE to the VNTM do not have any acknowledgements. VNTM-LSR communication can use existing GMPLS-TE MIB modules [RFC4802].

In the NMS-VNTM cooperation model, communications are required between NMS and VNTM, between VNTM and a lower-layer PCE, and between VNTM and a border LSR. NMS-VNTM communications, which are out of scope of this document, may use proprietary or standard interfaces, some of which, for example, are standardized in TM Forum. Communications between VNTM and a lower-layer PCE use the Path Computation Element Communication Protocol (PCEP) [RFC5440]. VNTM-LSR communications are the same as in the PCE-VNTM cooperation model.

In the higher-layer signaling trigger model, no VNTM functions are required, and no such communications are required.

If VNTM functions are not supported in a multi-layer network, the higher-layer signaling trigger model has to be chosen.

The inclusion of VNTM functionality allows better coordination of cross-network LSP tunnels and application of network-wide policy that is far harder to apply in the trigger model since it requires the coordination of policy between multiple border LSRs.

Also, VNTM functions could be applied to establish LSPs (or connections) in non-MPLS/GMPLS networks, which do not have signaling capabilities, by configuring each node along the path from the VNTM.

5.2. Border LSR Functions

In the higher-layer signaling trigger model, a border LSR must have some additional functions. It needs to trigger lower-layer signaling when a higher-layer Path message suggests that lower-layer LSP setup is necessary. Note that, if virtual TE links are used, the border LSRs must be capable of triggered signaling.

If the ERO in the higher-layer Path message uses a mono-layer path or specifies a loose hop, the border LSR receiving the Path message must obtain a lower-layer route either by consulting a PCE or by using its own computation engine. If the ERO in the higher-layer Path message uses a multi-layer path, the border LSR must judge whether lower-layer signaling is needed.

In the PCE-VNTM and NMS-VNTM cooperation models, no additional function for triggered signaling is required in border LSRs except when virtual TE links are used. Therefore, if these additional functions are not supported in border LSRs, where a border LSR is controlled by VNTM to set up a lower-layer LSP, the cooperation model has to be chosen.

5.3. Complete Inter-Layer LSP Setup Time

The complete inter-layer LSP setup time includes inter-layer path computation, signaling, and the communication time between PCC and PCE, PCE and VNTM, NMS and VNTM, and VNTM and LSR. In the PCE-VNTM and the NMS-VNTM cooperation models, the additional communication steps are required compared with the higher-layer signaling trigger model. On the other hand, the cooperation model provides better control at the cost of a longer service setup time.

Note that, in terms of higher-layer signaling time, in the higher-layer signaling trigger model, the required time from when higher-layer signaling starts to when it is completed is more than that of the cooperation model except when a virtual TE link is included. This is because the former model requires lower-layer signaling to take place during the higher-layer signaling. A higher-layer ingress LSR has to wait for more time until the higher-layer signaling is completed. A higher-layer ingress LSR is required to be tolerant of longer path setup times.

5.4. Network Complexity

If the higher- and lower-layer networks have multiple interconnects, then optimal path computation for end-to-end LSPs that cross the layer boundaries is non-trivial. The higher-layer LSP must be routed to the correct layer border nodes to achieve optimality in both layers.

Where the lower-layer LSPs are advertised into the higher-layer network as TE links, the computation can be resolved in the higher-layer network. Care needs to be taken in the allocation of TE metrics (i.e., costs) to the lower-layer LSPs as they are advertised as TE links into the higher-layer network, and this might be a function for a VNT Manager component. Similarly, attention should be given to the fact that the LSPs crossing the lower-layer network might share points of common failure (e.g., they might traverse the same link in the lower-layer network) and the shared risk link groups (SRLGs) for the TE links advertised in the higher-layer must be set accordingly.

In the single PCE model, an end-to-end path can be found in a single computation because there is full visibility into both layers and all possible paths through all layer interconnects can be considered.

Where PCEs cooperate to determine a path, an iterative computation model such as [RFC5441] can be used to select an optimal path across layers.

When non-cooperating mono-layer PCEs, each of which is in a separate layer, are used with the triggered LSP model, it is not possible to determine the best border LSRs, and connectivity cannot even be guaranteed. In this case, crankback signaling techniques [RFC4920] can be used to eventually achieve connectivity, but optimality is far harder to achieve. In this model, a PCE that is requested by an ingress LSR to compute a path expects a border LSR to set up a lower-layer path triggered by high-layer signaling when there is no TE link between border LSRs.

5.5. Separation of Layer Management

Many network operators may want to provide a clear separation between the management of the different layer networks. In some cases, the lower-layer network may come from a separate commercial arm of an organization or from a different corporate body entirely. In these cases, the policy applied to the establishment of LSPs in the lower-layer network and to the advertisement of these LSPs as TE links in the higher-layer network will reflect commercial agreements and security concerns (see Section 8). Since the capacity of the LSPs in the lower-layer network are likely to be significantly larger than those in the client higher-layer network (multiplex-server model), the administrator of the lower-layer network may want to exercise caution before allowing a single small demand in the higher layer to tie up valuable resources in the lower layer.

The necessary policy points for this separation of administration and management are more easily achieved through the VNTM approach than by using triggered signaling. In effect, the VNTM is the coordination point for all lower-layer LSPs and can be closely tied to a human operator as well as to policy and billing. Such a model can also be achieved using triggered signaling.

6. Stability Considerations

Inter-layer traffic engineering needs to be managed and operated correctly to avoid introducing instability problems.

Lower-layer LSPs are likely, by the nature of the technologies used in layered networks, to be of considerably higher capacity than the higher-layer LSPs. This has the benefit of allowing multiple higher-layer LSPs to be carried across the lower-layer network in a single lower-layer LSP. However, when a new lower-layer LSP is set up to support a request for a higher-layer LSP because there is no suitable route in the higher-layer network, it may be the case that a very large LSP is established in support of a very small traffic demand. Further, if the higher-layer LSP is short-lived, the requirement for the lower-layer LSP will go away, either leaving it in place but

unused or requiring it to be torn down. This may cause excessive tie-up of unused lower-layer network resources, or may introduce instability into the lower-layer network. It is important that appropriate policy controls or configuration features are available so that demand-led establishment of lower-layer LSPs (the so-called "bandwidth on demand") is filtered according to the requirements of the lower-layer network.

When a higher-layer LSP is requested to be set up, a new lower-layer LSP may be established if there is no route with the requested bandwidth for the higher-layer LSP. After the lower-layer LSP is established, existing high-layer LSPs could be re-routed to use the newly established lower-layer LSP, if using the lower-layer LSP provides a better route than that taken by the existing LSPs. This re-routing may result in lower utilization of other lower-layer LSPs that used to carry the existing higher-layer LSPs. When the utilization of a lower-layer LSP drops below a threshold (or drops to zero), the LSP is deleted according to lower-layer network policy.

But consider that some other new higher-layer LSP may be requested at once, requiring the establishment or re-establishment of a lower-layer LSP. This, in turn, may cause higher-layer re-routing, making other lower-layer LSPs under-utilized in a cyclic manner. This behavior makes the higher-layer network unstable.

Inter-layer traffic engineering needs to avoid network instability problems. To solve the problem, network operators may have some constraints achieved through configuration or policy, where inter-layer path control actions such as re-routing and deletion of lower-layer LSPs are not easily allowed. For example, threshold parameters for the actions are determined so that hysteresis control behavior can be performed.

7. Manageability Considerations

Inter-layer MPLS or GMPLS traffic engineering must be considered in the light of administrative and management boundaries that are likely to coincide with the technology layer boundaries. That is, each layer network may possibly be under separate management control with different policies applied to the networks, and specific policy rules applied at the boundaries between the layers.

Management mechanisms are required to make sure that inter-layer traffic engineering can be applied without violating the policy and administrative operational procedures used by the network operators.

7.1. Control of Function and Policy

7.1.1. Control of Inter-Layer Computation Function

PCE implementations that are capable of supporting inter-layer computations should provide a configuration switch to allow support of inter-layer path computations to be enabled or disabled.

When a PCE is capable of, and configured for, inter-layer path computation, it should advertise this capability as described in [PCC-PCE], but this advertisement may be suppressed through a secondary configuration option.

7.1.2. Control of Per-Layer Policy

Where each layer is operated as a separate network, the operators must have control over the policies applicable to each network, and that control should be independent of the control of policies for other networks.

Where multiple layers are operated as part of the same network, the operator may have a single point of control for an integrated policy across all layers, or may have control of separate policies for each layer.

7.1.3. Control of Inter-Layer Policy

Probably the most important issue for inter-layer traffic engineering is inter-layer policy. This may cover issues such as under what circumstances a lower-layer LSP may be established to provide connectivity in the higher-layer network. Inter-layer policy may exist to protect the lower-layer (high capacity) network from very dynamic changes in micro-demand in the higher-layer network (see Section 6). It may also be used to ensure appropriate billing for the lower-layer LSPs.

Inter-layer policy should include the definition of the points of connectivity between the network layers, the inter-layer TE model to be applied (for example, the selection between the models described in this document), and the rules for path computation and LSP setup. Where inter-layer policy is defined, it must be used consistently throughout the network, and should be made available to the PCEs that perform inter-layer computation so that appropriate paths are computed. Mechanisms for providing policy information to PCEs are discussed in [RFC5394].

VNTM may provide a suitable functional component for the implementation of inter-layer policy. Use of VNTM allows the administrator of the lower-layer network to apply inter-layer policy without making that policy public to the operator of the higher-layer network. Similarly, a cooperative PCE model (with or without inter-PCE communication) allows separate application of policy during the selection of paths.

7.2. Information and Data Models

Any protocol extensions to support inter-layer computations must be accompanied by the definition of MIB objects for the control and monitoring of the protocol extensions. These MIB object definitions will conventionally be placed in a separate document from that which defines the protocol extensions. The MIB objects may be provided in the same MIB module as used for the management of the base protocol that is being extended.

Note that inter-layer PCE functions should, themselves, be manageable through MIB modules. In general, this means that the MIB modules for managing PCEs should include objects that can be used to select and report on the inter-layer behavior of each PCE. It may also be appropriate to provide statistical information that reports on the inter-layer PCE interactions.

Where there are communications between a PCE and VNTM, additional MIB modules may be necessary to manage and model these communications. On the other hand, if these communications are provided through MIB notifications, then those notifications must form part of a MIB module definition.

Policy Information Base (PIB) modules may also be appropriate to meet the requirements as described in Section 7.1 and [RFC5394].

7.3. Liveness Detection and Monitoring

Liveness detection and monitoring is required between PCEs and PCCs, and between cooperating PCEs as described in [RFC4657]. Inter-layer traffic engineering does not change this requirement.

Where there are communications between a PCE and VNTM, additional liveness detection and monitoring may be required to allow the PCE to know whether the VNTM has received its information about failed path computations and desired TE links.

When a lower-layer LSP fails (perhaps because of the failure of a lower-layer network resource) or is torn down as a result of lower-layer network policy, the consequent change should be reported to the

higher layer as a change in the VNT, although inter-layer policy may dictate that such a change is hidden from the higher layer. The higher-layer network may additionally operate data plane failure techniques over the virtual TE links in the VNT in order to monitor the liveness of the connections, but it should be noted that if the virtual TE link is advertised but not yet established as an LSP in the lower layer, such higher-layer Operations, Administration, and Management (OAM) techniques will report a failure.

7.4. Verifying Correct Operation

The correct operation of the PCE computations and interactions are described in [RFC4657], [RFC5440], etc., and does not need further discussion here.

The correct operation of inter-layer traffic engineering may be measured in several ways. First, the failure rate of higher-layer path computations owing to an absence of connectivity across the lower layer may be observed as a measure of the effectiveness of the VNT and may be reported as part of the data model described in Section 7.2. Second, the rate of change of the VNT (i.e., the rate of establishment and removal of higher-layer TE links based on lower-layer LSPs) may be seen as a measure of the correct planning of the VNT and may also form part of the data model described in Section 7.2. Third, network resource utilization in the lower layer (both in terms of resource congestion and in consideration of under-utilization of LSPs set up to support virtual TE links) can indicate whether effective inter-layer traffic engineering is being applied.

Management tools in the higher-layer network should provide a view of which TE links are provided using planned lower-layer capacity (that is, physical connectivity or permanent connections) and which TE links are dynamic and achieved through inter-layer traffic engineering. Management tools in the lower layer should provide a view of the use to which lower-layer LSPs are put, including whether they have been set up to support TE links in a VNT and, if so, for which client network.

7.5. Requirements on Other Protocols and Functional Components

There are no protocols or protocol extensions defined in this document, and so it is not appropriate to consider specific interactions with other protocols. It should be noted, however, that the objective of this document is to enable inter-layer traffic engineering for MPLS-TE and GMPLS networks, and so it is assumed that the necessary features for inter-layer operation of routing and signaling protocols are in existence or will be developed.

This document introduces roles for various network components (PCE, LSR, NMS, and VNTM). Those components are all required to play their part in order that inter-layer TE can be effective. That is, an inter-layer TE model that assumes the presence and operation of any of these functional components obviously depends on those components to fulfill their roles as described in this document.

7.6. Impact on Network Operation

The use of a PCE to compute inter-layer paths is expected to have a significant and beneficial impact on network operations. Inter-layer traffic engineering of itself may provide additional flexibility to the higher-layer network while allowing the lower-layer network to support more and varied client networks in a more efficient way. Traffic engineering across network layers allows optimal use to be made of network resources in all layers.

The use of PCE as described in this document may also have a beneficial effect on the loading of PCEs responsible for performing inter-layer path computation while facilitating a more independent operation model for the network layers.

8. Security Considerations

Inter-layer traffic engineering with PCE raises new security issues in all three inter-layer path control models.

In the cooperation model between PCE and VNTM, when the PCE determines that a new lower-layer LSP is desirable, communications are needed between the PCE and VNTM and between the VNTM and a border LSR. In this case, these communications should have security mechanisms to ensure authenticity, privacy, and integrity of the information exchanged. In particular, it is important to protect against false triggers for LSP setup in the lower-layer network, since such falsification could tie up lower-layer network resources (achieving a denial-of-service attack on the lower-layer network and on the higher-layer network that is attempting to use it) and could result in incorrect billing for services provided by the lower-layer network. Where the PCE MIB modules are used to provide the notification exchanges between the higher-layer PCE and the VNTM, SNMPv3 should be used to ensure adequate security. Additionally, the VNTM should provide configurable or dynamic policy functions so that the VNTM behavior upon receiving notification from a higher-layer PCE can be controlled.

The main security concern in the higher-layer signaling trigger model is related to confidentiality. The PCE may inform a higher-layer PCC about a multi-layer path that includes an ERO in the lower-layer

network, but the PCC may not have TE topology visibility into the lower-layer network and might not be trusted with this information. A loose hop across the lower-layer network could be used, but this decreases the benefit of multi-layer traffic engineering. A better alternative may be to mask the lower-layer path using a path key [RFC5520] that can be expanded within the lower-layer network. Consideration must also be given to filtering the recorded path information from the lower-layer -- see [RFC4208], for example.

Additionally, in the higher-layer signaling trigger model, consideration must be given to the security of signaling at the inter-layer interface, since the layers may belong to different administrative or trust domains.

The NMS-VNTM cooperation model introduces communication between the NMS and the VNTM. Both of these components belong to the management plane, and such communication is out of scope for this PCE document. Note that the NMS-VNTM cooperation model may be considered to address many security and policy concerns because the control and decision-making is placed within the sphere of influence of the operator in contrast to the more dynamic mechanisms of the other models. However, the security issues have simply moved, and will require authentication of operators and of policy.

Security issues may also exist when a single PCE is granted full visibility of TE information that applies to multiple layers. Any access to the single PCE will immediately gain access to the topology information for all network layers -- effectively, a single security breach can expose information that requires multiple breaches in other models.

Note that, as described in Section 6, inter-layer TE can cause network stability issues, and this could be leveraged to attack either the higher- or lower-layer network. Precautionary measures, such as those described in Section 7.1.3, can be applied through policy or configuration to dampen any network oscillations.

9. Acknowledgments

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