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Yimin Shen
Juniper Networks
Rahul Aggarwal
Arktan, Inc
Wim Henderickx
Alcatel-Lucent
Yuanlong Jiang
Huawei Technologies
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PW Endpoint Fast Failure Protection
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Abstract

This document specifies a fast mechanism for protecting pseudowires against egress endpoint failures, including egress attachment circuit failure, egress PE failure, multi-segment PW terminating PE failure, and multi-segment PW switching PE failure. Operating on the basis of multi-homed CE, redundant PWs, upstream label assignment and context specific label switching, the mechanism enables local repair to be performed by the router upstream adjacent to a failure. The router can restore a PW in the order of tens of milliseconds, by rerouting traffic around the failure to a protector through a pre-established bypass tunnel. Therefore, the mechanism can be used to reduce traffic loss before global repair reacts to the failure and the network converges on the topology changes due to the failure.

Table of Contents

1. Introduction

Per [RFC3985, RFC4447, RFC5659], a pseudowire (PW) or PW segment can be thought of as a connection between a pair of forwarders hosted by two PEs, carrying an emulated layer-2 service over a packet switched network (PSN). In the single-segment PW (SS-PW) case, a forwarder binds a PW to an attachment circuit (AC). In the multi-segment PW (MS-PW) case, a forwarder on a terminating PE (T-PE) binds a PW segment to an AC, while a forwarder on a switching PE (S-PE) binds one PW segment to another PW segment. In each direction between the PEs, PW packets are transported by a PSN tunnel, which is also called a transport tunnel.

In order to protect the PW service against network failures, it is necessary to protect every link and node along the entire data path. For the traffic in a given direction, this include ingress AC, ingress (T-)PE, intermediate routers of transport tunnel, S-PEs, egress (T-)PE, and egress AC. To minimize service disruption upon a failure, it is also desirable that each of these components is protected by a fast protection mechanism based on local repair. Such mechanism generally involves a bypass path that is pre-computed and pre-installed in the data plane on the router upstream adjacent to an anticipated failure. This router is referred to as a "point of local repair" (PLR). The bypass path has the property that it can guide traffic around the failure, while remaining unaffected by the topology changes resulting from the failure. When the failure occurs, the PLR can invoke the bypass path to achieve fast restoration for the service.

Today, fast protection against ingress AC failure and ingress (T-)PE failure can be achieved by using a multi-homed CE and redundant ACs, such as multi-chassis link aggregation group (MC-LAG). Fast protection against the failure of an intermediate router of transport tunnel can be achieved through RSVP fast-reroute [RFC4090] or IP/LDP fast-reroute [RFC5714, RFC5286]. However, there is no equivalent mechanism that can be used against an egress AC failure, an egress (T-)PE failure, or an S-PE failure. For these failures, service restoration has to rely on global repair or control plane repair. Global repair normally involves the ingress CE or the ingress (T-)PE switching traffic to an alternative path, based on remote failure detection via PW status notification, end-to-end OAM, etc. Control plane repair relies on control protocols to converge on the topology changes due to a failure. Compared to local repair, these mechanisms are relatively slow in reacting to a failure and restoring traffic.

This document is intended to serve the above need. It specifies a fast protection mechanism based on local repair to protect PWs against the following endpoint failures.

a. Egress AC failure.

b. Egress PE failure: Link or node failure of an egress PE of an SS-PW, or a T-PE of an MS-PW.

c. Switching PE (S-PE) failure: Link or node failure of an S-PE of an MS-PW.

The mechanism is applicable to LDP signaled PWs. It is relevant to networks with redundant PWs and multi-homed CEs. It is designed on the basis of MPLS upstream label assignment and context-specific label switching [RFC5331]. Fast protection refers to its ability to restore traffic in the order of tens of milliseconds. Compared with global repair and control plane repair, this mechanism can provide faster service restoration. However, it is intended to complement those mechanisms, rather than replacing them.

2. Specification of Requirements

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

3. Reference Models for Egress Endpoint Failures

This document refers to the following topologies to describe egress endpoint failures and protection procedures.

3.1. Single-Segment PW

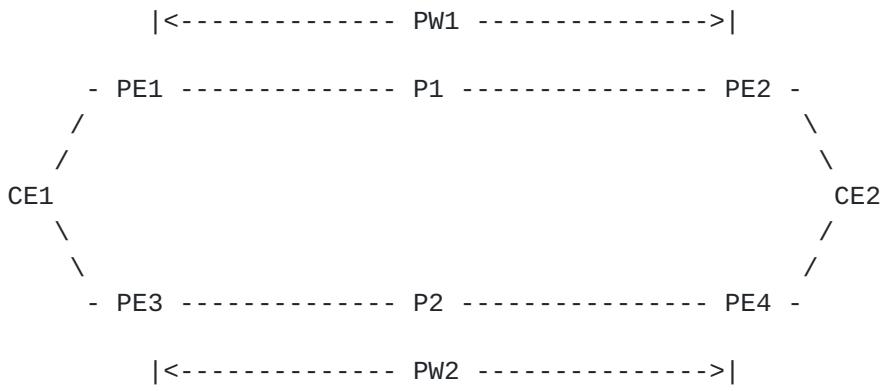


Figure 1

In Figure 1, the IP/MPLS network consists of PE and P routers. It provides a PW service between CE1 and CE2. Each CE is multi-homed via two ACs to two PEs. This forms two divergent paths between the CEs. The first path uses PW1 between PE1 and PE2, and the second path uses PW2 between PE3 and PE4. The transport tunnels of the PWs and other links between the routers are not shown in this figure for clarity.

In general, a CE may operate the ACs in two modes when sending traffic to the remote CE, i.e. active-standby mode and active-active mode.

- In the active-standby mode, the CE chooses one AC as active AC and the corresponding path as active path, and uses the other AC as standby AC and the corresponding path as standby path. The CE only sends traffic on the active AC as long as the active path is operational. The CE will only send traffic on the standby AC after it detects a failure of the active path. Note that the CE may receive traffic on the active or standby AC, depending on whether the remote CE chooses the same active path for the traffic of the reverse direction. In this document, even if both CEs choose the same active path, each CE should still anticipate receiving traffic on a standby AC, because the traffic may be redirected to the standby path by the fast protection mechanism.

- In the active-active mode, the CE treats both ACs and their corresponding paths as active, and sends traffic on both ACs in a load balance fashion. In the reverse direction, the CE may receive traffic on both ACs.

For either mode, when considering the traffic flowing in a given direction over an active path, this document views the ACs, PEs and PWs to serve primary or backup roles. In particular, the ACs, PEs and PW along this active path are primary, while those along the other path are backup. Note that in the active-active mode, the backup path is an active path by itself, carrying its own share of traffic while protecting the other active path.

For Figure 1, the following roles are assumed for the traffic going from CE1 to CE2 via PW1.

Primary ingress AC: CE1-PE1

Primary ingress PE: PE1

Primary PW: PW1

Primary egress PE: PE2

Primary egress AC: PE2-CE2

Backup ingress AC: CE1-PE3

Backup ingress PE: PE3

Backup PW: PW2

Backup egress PE: PE4

Backup egress AC: PE4-CE2

Based on this schema, this document describes egress endpoint failures and the fast protection mechanism on the per-active-path and per-direction basis. In this case, an egress AC failure refers to the failure of the AC PE2-CE2, and an egress node failure refers to the failure of PE2. The ultimate goal is that when a failure occurs, the traffic should be locally repaired, so that it can eventually reach CE2 via the backup egress PE (PE4) and the backup egress AC (PE4-CE2).

Subsequent to the local repair, either the current active path should heal after control plane converges on the new topology, or the ingress CE should switch traffic from the primary path to the backup path, depending on the failure scenario. In the latter case, the ingress CE may perform the path switchover triggered by end-to-end OAM (in-band or out-band), PW status notification, CE-PE control protocols (e.g. LACP), etc. In the active-standby mode, this will promote the standby path to new active path. In the active-active mode, it will make the other active path carry all the traffic between the two CEs. In any case, this phase of restoration falls into the control plane repair and global repair category, and hence is out of the scope of this document. The purpose of the fast protection mechanism in this document is to reduce traffic loss before this phase of restoration takes place.

Note that in Figure 1, if the traffic in the reverse direction (i.e. from CE2 to CE1) traverses the AC CE2-PE2 and PE2 as active path, the failure of PE2 and the failure of the AC PE2-CE2 will be considered as ingress failures of the traffic. If CE2 can detect the failures, it may protect the traffic by switching it to the backup path via the AC CE2-PE4 and PE4. However, this is categorized as ingress endpoint failure protection, and hence is not handled by the mechanism described in this document.

Figure 2 shows another possible scenario, where CE1 is single-homed to PE1, while CE2 remains multi-homed to PE2 and PE4. From the perspective of egress endpoint protection for the traffic going from

CE1 to CE2 over PW1, this scenario is the same as the scenario shown in Figure 1.

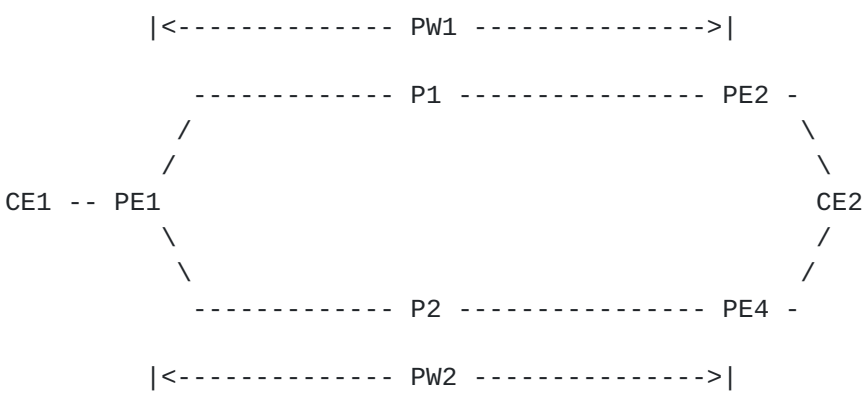


Figure 2

For clarity, primary egress AC, primary egress PE, backup egress AC, and backup egress PE may simply be referred to as primary AC, primary PE, backup AC, and backup PE, respectively, when the context of a discussion is egress endpoint.

3.2. Multi-Segment PW

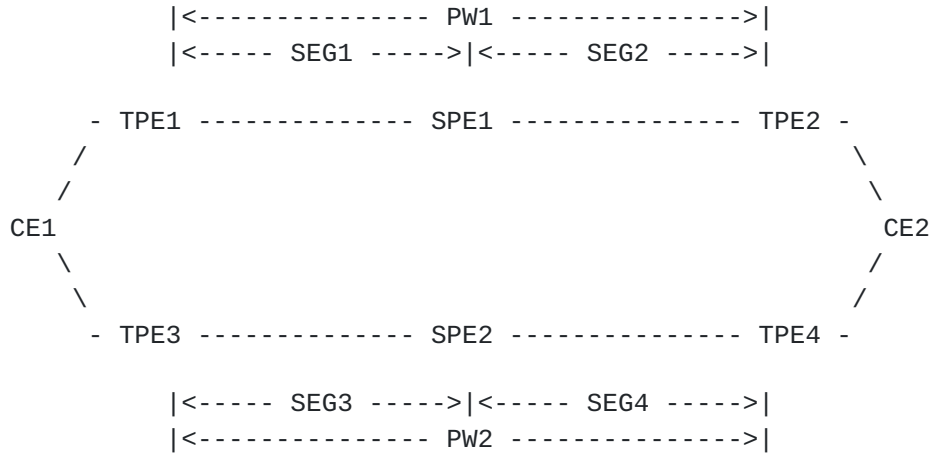


Figure 3

Figure 3 shows a topology that is similar to Figure 1 but in an MS-PW environment. PW1 and PW2 are both MS-PWs. PW1 is established between TPE1 and TPE2, and switched between segments SEG1 and SEG2 at SPE1. PW2 is established between TPE3 and TPE4, and switched between segments SEG3 and SEG4 at SPE2. CE1 is multi-homed to TPE1 and TPE3. CE2 is multi-homed to TPE2 and TPE4. The transport tunnels of the PW segments are not shown in this figure for clarity.

In this document, the following primary and backup roles are assigned for the traffic going from CE1 to CE2:

Primary ingress AC: CE1-TPE1

Primary ingress T-PE: TPE1

Primary PW: PW1

Primary S-PE: SPE1

Primary egress T-PE: TPE2

Primary egress AC: TPE2-CE2

Backup ingress AC: CE1-TPE3

Backup ingress T-PE: TPE3

Backup PW: PW2

Backup S-PE: SPE2

Backup egress T-PE: TPE4

Backup egress AC: TPE4-CE2

In this case, an egress AC failure refers to the failure of the AC TPE2-CE2. An egress node failure refers to the failure of TPE2. An S-PE failure refers to the failure of SPE1.

For consistency with the SS-PW scenario, primary T-PEs and a primary S-PEs may simply be referred to as primary PEs in this document, where specifics are not required. Similarly, backup T-PEs and backup S-PEs may be referred to as backup PEs.

4. Theory of Operation

The fast protection mechanism in this document provides three types of protection for PWs, corresponding to the three types of failures described in Section 1.

a. Egress AC protection

b. Egress (T-)PE node protection

c. S-PE node protection

4.1. Applicability

The mechanism is applicable to LDP signaled PWs in an environment where an egress CE is multi-homed to a primary PE and a backup PE and there exists a backup PW, as described in Section 3. The procedure for S-PE node protection is applicable when there exists a backup S-PE on the backup PW.

The mechanism assumes IP/MPLS transport tunnels. In a network where transport tunnels may provide ECMP to primary PEs, care should be taken to prevent misordered packet delivery during local repair. Imagine a scenario where the transport tunnel of a PW traverses a router with ECMP to a primary PE, and the ECMP include a direct link to the primary PE. Normally the router will attempt to forward PW packets in a load balance fashion over the ECMP, including this link. In this document, when the link fails, the router will treat the event as an egress PE failure, and reroute the portion of traffic on the link towards a backup PE. Meanwhile, the rest of the traffic will remain on the other ECMP branches to the primary PE. This will create a situation where the egress CE receives traffic from both the primary PE and the backup PE, which is undesirable if the PW or the flows within the PW are sensitive to packet misordering. Therefore, it is RECOMMENDED that Control Word (CW) SHOULD be used for PWs and flow labels [RFC6391] SHOULD be used for flows within a PW, whenever applicable. The goal is to ensure that the PW or a given flow SHOULD be forwarded entirely over the link in steady state, and hence be rerouted via the same path during local repair.

It is also RECOMMENDED that the mechanism SHOULD be used in conjunction with global repair and control plane repair, in such a manner that the mechanism temporarily repairs a failed path by using a bypass tunnel, and global repair and control plane repair eventually move traffic to a fully functional alternative path.

4.2. Local Repair and Protector

The fast protection ability of the mechanism comes from local repair performed by routers upstream adjacent to failures. Each of these routers is referred to as a "point of local repair" (PLR). A PLR MUST be able to detect a failure by using a rapid mechanism, such as physical layer failure detection, Bidirectional Failure Detection (BFD) [RFC5880], etc. In anticipation of the failure, the PLR MUST also pre-establish a bypass tunnel to a "protector", and pre-install a bypass route in the data plane. The bypass tunnel MUST have the property that it will not be affected by the topology changes due to the failure. Specifically, it MUST NOT traverse the primary PE or the penultimate link of the protected transport tunnel, or share any SRLG (shared risk link groups) with the penultimate link. Upon

detecting the failure, the PLR invokes the bypass route in the data plane, and reroutes PW traffic to the protector through the bypass tunnel. The protector in turn sends the traffic to the target CE. This procedure is referred to as local repair.

Different routers may serve as PLR and protector in different scenarios.

- In egress AC protection, the PLR is the primary PE, and the protector is the backup PE (Figure 4).

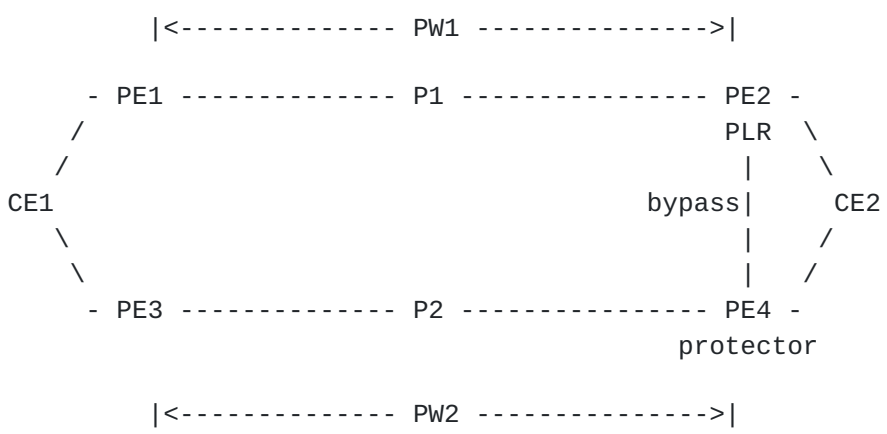


Figure 4

- In egress PE node protection, the PLR is the penultimate hop router of the transport tunnel of the primary PW, and the protector is the backup PE (Figure 5).

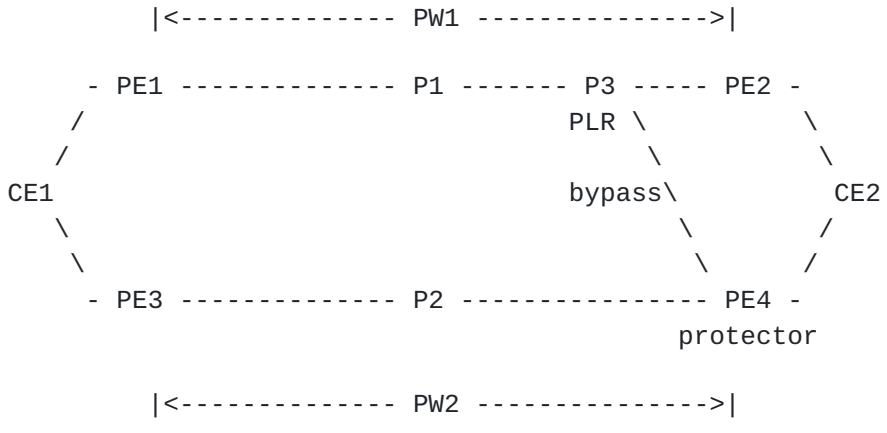


Figure 5

- In S-PE node protection, the PLR is the penultimate hop router of the transport tunnel of the primary PW segment, and the protector is the backup S-PE (Figure 6).

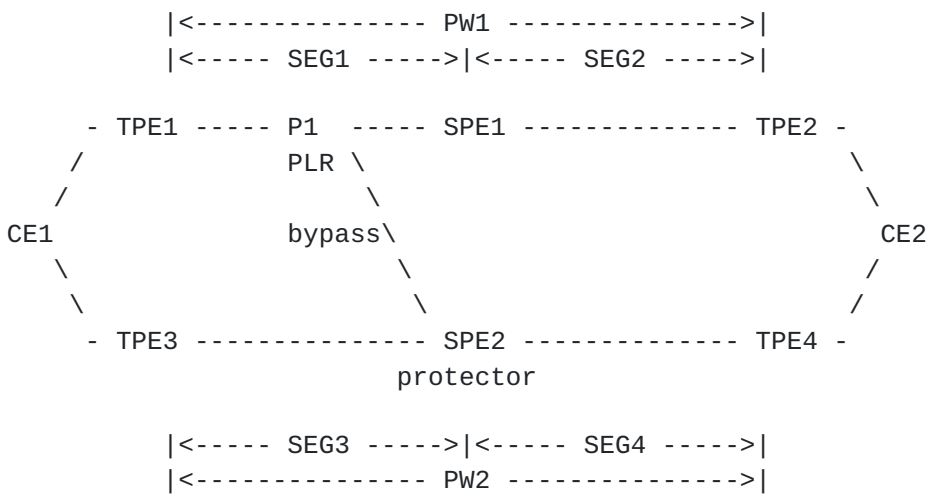


Figure 6

In egress AC protection, a PLR realizes its role based on configuration of a "context identifier" introduced in this document (Section 4.3). The PLR establishes a bypass tunnel to the protector in the same fashion as a normal PSN tunnel.

In egress PE and S-PE node protection, a PLR is a transit router on the transport tunnel, and it normally does not have knowledge of the PW(s) carried by the transport tunnel. In this document, the PLR simply computes and establishes a node protection bypass tunnel in the same fashion as the normal IP/MPLS node protection, except that with the notion of context identifier, the bypass tunnel will be established from the PLR to the protector (Section 4.6). Conversely, when the router is no longer a PLR for egress PE or S-PE node protection due to a change in network topology or the transport tunnel's path, the router should revert to the role of regular transit router, including PLR for normal IP/MPLS link or node protection.

In local repair, a PLR simply switches all the traffic received on the transport tunnel to the bypass tunnel. This requires that the protector given by the bypass tunnel MUST be intended for all the PWs carried by the transport tunnel. This is achieved by the ingress PE using a context identifier to associate a PW with the specific pair of {primary PE, protector} and map the PW to a transport tunnel destined for the same {primary PE, protector}. The ingress PE MAY map multiple PWs to the transport tunnel, if they share the {primary PE, protector} in common.

In local repair, the PLR keeps PW label intact in packets. This obviates the need for the PLR to maintain bypass routes on a per-PW basis, and allows bypass tunnel sharing between PWs. On the other

hand, this imposes a requirement on the protector that it MUST be able to forward the packets based on a PW label that is assigned by the primary PE, and ensure that the traffic MUST eventually reach the target CE. From the protector's perspective, this PW label is an upstream assigned label [RFC5331]. To achieve this, the protector MUST learn the PW label from the primary PE prior to the failure, and install proper forwarding state for the PW label in a dedicated label space associated with the primary PE. During local repair, the protector MUST perform PW label lookup in this label space.

The previous examples have shown the scenarios where the protectors are backup (T/S-)PEs. It is also possible that a protector is a dedicated router to serve such role, separate from the backup (T/S-)PE. During local repair, the PLR still reroutes traffic to the protector through a bypass tunnel. The protector then forwards the traffic to the backup (T/S-)PE, which further forwards the traffic to the target CE via a backup AC or a backup PW segment. More detail will be described in Section 4.4.

4.3. Context Identifier

A protector may protect multiple primary PEs. The protector MUST maintain a separate label space for each primary PE. Likewise, the PWs terminated on a primary PE may be protected by multiple protectors, each for a subset of the PWs. In any case, a given PW MUST be associated with one and only one pair of {primary PE, protector}.

This document introduces the notion of "context identifier" to facilitate protection establishment. A context identifier is an IPv4/v6 address assigned to each ordered pair of {primary PE, protector}. The address MUST be globally unique, or unique in the address space of the network where the primary PE and the protector reside.

4.3.1. Semantics

The semantics of a context identifier is twofold.

- A context identifier identifies a primary PE and an associated protector. It represents the primary PE as PW destination on a per protector basis. A given primary PE may be protected by multiple protectors, each for a subset of the PWs terminated on the primary PE. A distinct context identifier MUST be assigned to the primary PE and each protector.

  The ingress PE of a PW learns the context identifier of the PW's {primary PE, protector} from the primary PE via Interface_ID TLV

[RFC3471, RFC3472] in the LDP Label Mapping message of the PW. The ingress PE then sets up or resolves a transport tunnel with the context identifier, rather than a private IP address of the primary PE, as destination. This destination not only makes the transport tunnel reach the primary PE, but also conveys the identity of the protector to the PLR, which MUST use the context identifier as destination for the bypass tunnel to the protector. The ingress PE MUST map only the PWs terminated by the exact primary PE and protected by the exact protector to the transport tunnel.

- A context identifier indicates the primary PE's label space on the protector. The protector may protect PWs for multiple primary PEs. For each primary PE, it MUST maintain a separate label space to store the PW labels assigned by that primary PE. It associates a PW label with a label space via the context identifier of the {primary PE, protector}, as below.

  In addition to the normal LDP PW signaling, the primary PE MUST have a targeted LDP session with the protector, and advertise PW labels to the protector via LDP Label Mapping messages (Section 6). The primary PE MUST attach the context identifier to each message. Upon receiving the message, the protector MUST install the advertised PW label in the label space identified by the context identifier.

  When a PLR sets up or resolves a bypass tunnel to the protector, it MUST use the context identifier rather than a private IP address of the protector as destination. The protector MUST use the bypass tunnel, either the MPLS tunnel label or IP tunnel destination address, as the pointer to the corresponding label space. The protector MUST forward PW packets received on the bypass tunnel based on label lookup in that label space.

4.3.2. IGP Advertisement and Path Computation

Using a context identifier as destination for both transport tunnel and bypass tunnel requires coordination between the primary PE and the protector in IGP advertisement of the context identifier in routing domain and TE domain. The context identifier should be advertised in such a way that all the routers on the tunnels MUST be able to independently reach the following common view of paths.

- The transport tunnel MUST have the primary PE as path endpoint.

- The bypass tunnel MUST have the protector as path endpoint. In egress PE and S-PE node protection, the path MUST avoid the primary PE.

There are generally two categories of approaches to achieve the above.

- The first category does not require an ingress PE or a PLR to have knowledge of the PW egress endpoint protection schema. It does not require any IGP extension for context identifier advertisement. A context identifier is advertised by the primary PE and the protector as an address reachable via both routers. The ingress PE and the PLR can compute paths by using a normal method, such as Dijkstra, CSPF (constrained shortest path first), LFA [RFC5286] and MRT [RFC7812]. One example is to advertise a context identifier as a virtual proxy node connected to the primary PE and the protector, with the link between the proxy node and the primary PE having a more preferable IGP and TE metric than the link between the proxy node and the protector. The transport tunnel will follow the shortest path or a TE path to the primary PE, and be terminated by the primary PE. The PLR will no longer view itself as a penultimate hop of the transport tunnel, but rather two hops away from the proxy node, via the primary PE. Hence, a node protection bypass tunnel will be available via the protector to the proxy node, but actually be terminated by the protector.

- The second category requires a PLR to have knowledge of the PW egress endpoint protection schema. The primary PE advertises the context identifier as a regular IP address, while the protector advertises it by using an explicit "context identifier" object, which MUST be understood by the PLR. The "context identifier" object requires an IGP extension. In both the routing domain and the TE domain, the context identifier is only reachable via the primary PE. This ensures that the transport tunnel is terminated by the primary PE. The PLR views itself as the penultimate hop of the transport tunnel, and based on the IGP "context identifier" object, it establishes or resolves a bypass tunnel to the advertiser (i.e. the protector), while avoiding the primary PE.

The mechanism in this document intends to be flexible on the approach used by a network, as long as it satisfies the above requirements for transport tunnel path and bypass tunnel path. For any approach, the coordination between a primary PE and a protector can be achieved by configuration.

4.4. Protection Models

There are two protection models based on the location of a protector. A network MAY use either model or both.

4.4.1. Co-located Protector

In this model, the protector is a backup PE that is directly connected to the target CE via a backup AC, or it is a backup S-PE on a backup PW. That is, the protector is co-located with the backup (S-)PE. Examples of this model have been shown in Figure 4, Figure 5 and Figure 6 in Section 4.2.

In egress AC protection and egress PE node protection, when a protector receives traffic from the PLR, it forwards the traffic to the CE via the backup AC. This is shown in Figure 7, where PE2 is the PLR for egress AC failure, P3 is the PLR for PE2 failure, and PE4 (backup PE) is the protector.

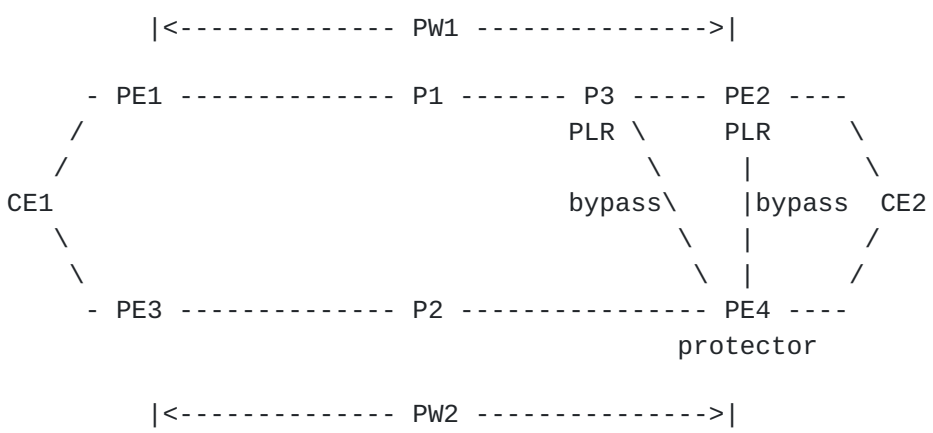


Figure 7

In S-PE node protection, when a protector receives traffic from the PLR, it forwards the traffic over the next segment of the backup PW. The T-PE of the backup PW in turn forwards the traffic to the CE via a backup AC. This is shown in Figure 8, where P1 is the PLR for SPE1 failure, and SPE2 (backup S-PE) is the protector for SPE1. SPE2 receives traffic from P1, swaps SEG1's label to SEG4's label, and forwards the traffic over a transport tunnel to TPE4.

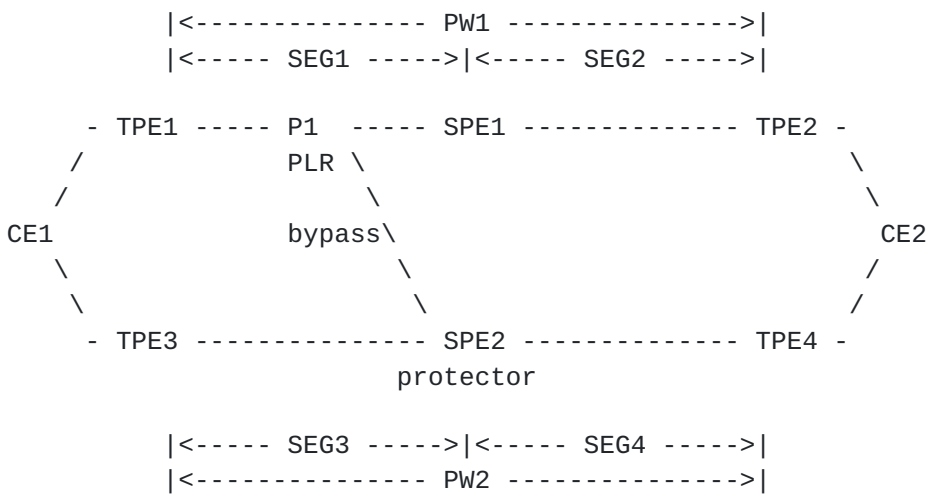


Figure 8

In the co-located protector model, the number of context identifiers needed by a network is the number of distinct {primary PE, backup PE} pairs. From the perspective of scalability, the model is suitable for networks where the number of primary PEs and the average number of backup PEs per primary PE are both relatively low.

4.4.2. Centralized Protector

In this model, the protector is a dedicated P router or PE router that serves the role. In egress AC protection and egress PE node protection, the protector may or may not be a backup PE directly connected to the target CE. In S-PE node protection, the protector may or may not be a backup S-PE on the backup PW.

In egress AC protection and egress PE node protection, if the protector is not directly connected to the CE, it forwards the traffic to a backup PE, which in turn forwards the traffic to the CE via a backup AC. This is shown in Figure 9, where the protector receives traffic from P3 (PLR for egress PE failure) or PE2 (PLR for egress AC failure), swaps PW1's label to PW2's label, and forwards the traffic via a transport tunnel to PE4 (backup PE). The protector may be protecting other PWs and other primary PEs as well, which is not shown in this figure for clarity.

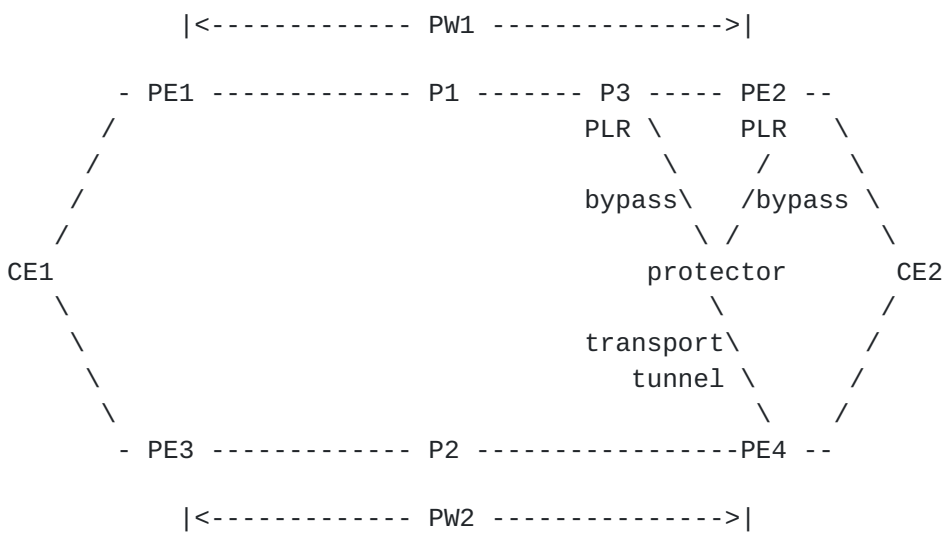


Figure 9

In S-PE node protection, if the protector is not a backup S-PE, it forwards the traffic to the backup S-PE, which in turn forwards the traffic over the next segment of the backup PW. Finally, the T-PE of the backup PW forwards the traffic to the CE via the backup AC. This is shown in Figure 10, where the protector receives traffic from P1 (PLR), swaps SEG1's label to SEG3's label, and forwards the traffic via a transport tunnel to SPE2 (backup S-PE). SPE2 in turn performs MS-PW switching from SEG3's label to SEG4's label, and forwards the traffic over a transport tunnel to TPE4 (backup T-PE). The protector may be protecting other PW segments and other primary S-PEs as well, which is not shown in this figure for clarity.

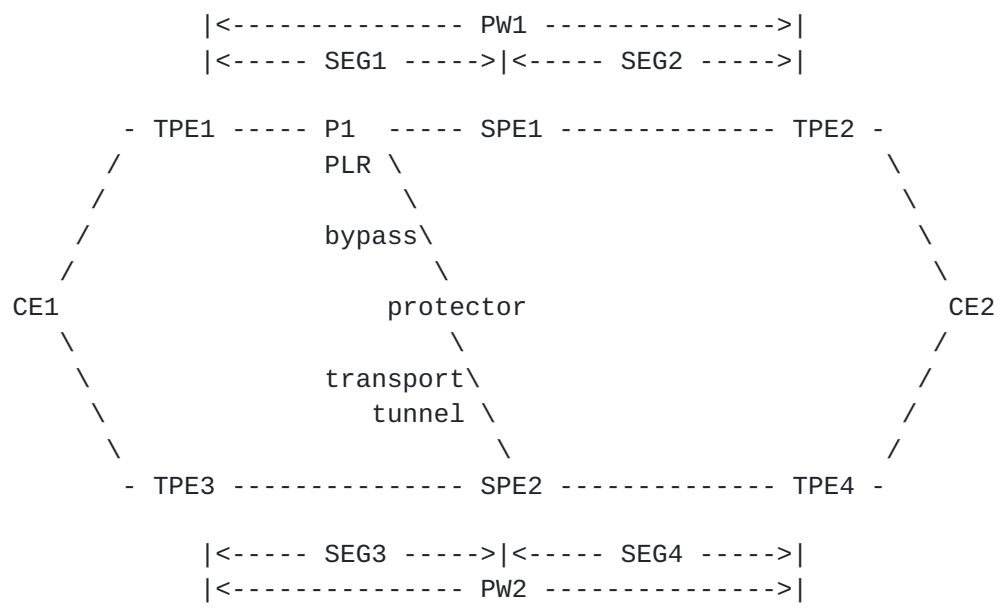


Figure 10

The centralized protector model allows multiple primary PEs to share one protector. Each primary PE may need only one protector. Therefore, the number of context identifiers needed by a network may be bound to the number of primary PEs.

4.5. Transport Tunnel

A PW is associated with a pair of {primary PE, protector}, which is represented by a unique context identifier. The ingress PE of the PW sets up or resolves a transport tunnel by using the context identifier rather than a private IP address of the primary PE as destination. This not only ensures that the PW is transported to the primary PE, but also facilitates bypass tunnel establishment at PLR, because the context identifier contains the identity of the protector as well. This is also the case for a multi-segment PW, where the ingress PE and egress PE are T/S-PEs.

An ingress PE learns the association between a PW and a context identifier from the primary PE, which MUST advertise the context identifier as a "third party next hop" via the IPv4/v6 Interface_ID TLV [RFC3471, RFC3472] in the LDP Label Mapping message of the PW.

In an ECMP scenario, a transport tunnel may have multiple penultimate hop routers. Each of them SHOULD act as a PLR independently. Also in an ECMP scenario, a penultimate hop router of a transport tunnel may have ECMP to the primary PE. At least one of the ECMP must be a direct link to the primary PE, qualifying the router as penultimate hop. The other branches of the ECMP may be direct links or indirect

paths to the primary PE. In egress PE node protection and S-PE node protection, the penultimate hop router SHOULD act as PLR for all the PWs traversing the entire ECMP.

4.6. Bypass Tunnel

A PLR may protect multiple PWs associated with one or multiple pairs of {primary PE, protector}. The PLR MUST establish a bypass tunnel to each protector for each context identifier associated with that protector. The destination of the bypass tunnel MUST be the context identifier (Section 4.3.1). Since the PLR is a transit router of the transport tunnel, it SHOULD derive the context identifier from the destination of the transport tunnel.

For examples, in Figure 7 and Figure 9, a bypass tunnel is established from PE2 (PLR for egress AC failure) to the protector, and another bypass tunnel is established from P3 (PLR for egress node failure) to the protector. In Figure 8 and Figure 10, a bypass tunnel is established from P1 (PLR for S-PE failure) to the protector.

In local repair, a PLR reroutes traffic to the protector through a bypass tunnel, with PW label intact in the packets. This normally involves pushing a label to the label stack, if the bypass tunnel is an MPLS tunnel, or pushing an IP header to the packets, if the bypass tunnel is an IP tunnel. Upon receipt of the packets, the protector forwards them based on the PW label. Specifically, the protector uses the bypass tunnel as a context to determine the primary PE's label space. If the bypass tunnel is an MPLS tunnel, the protector should have assigned a non-reserved label to the bypass tunnel, and hence this label can serve as the context. This label is also called a "context label", as it is actually bound to the context identifier. If the bypass tunnel is an IP tunnel, the context identifier should be the destination address of IP header.

To be useful for local repair, a bypass tunnel MUST have the property that it is not affected by any topology changes caused by the failure. It MUST NOT traverse the primary PE or the penultimate link of the transport tunnel, or share any SRLG with the penultimate link. It should remain effective during local repair, until the traffic is moved to an alternative path, i.e. either the same PW over a fully functional transport tunnel, or another fully functional PW.

A bypass tunnel SHOULD NOT need to be further protected against a transit link failure, transit node failure, or egress node failure.

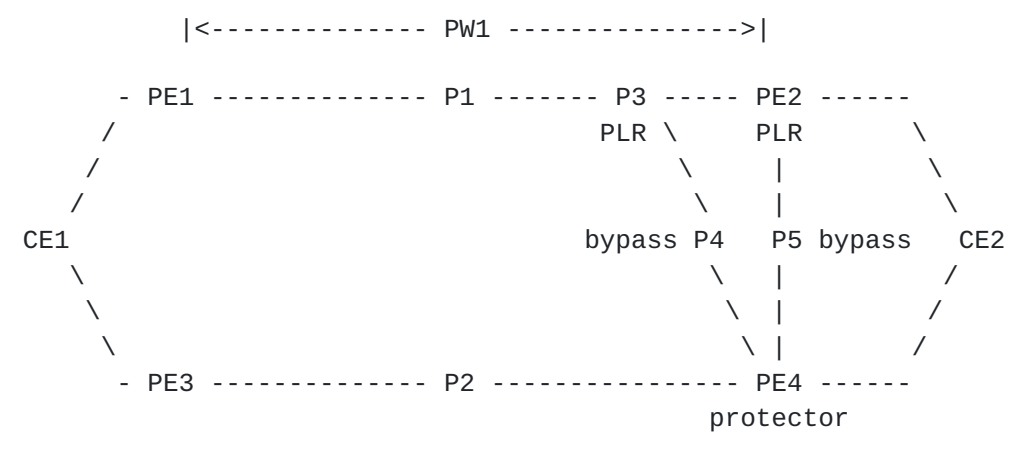
4.7. Examples of Forwarding State

This section provides some detailed examples of forwarding state on PLR, protector, and other relevant routers.

A protector learns PW labels from all the primary PEs that it protects (Section 6.2), and maintains the PW labels in separate label spaces on a per primary PE basis. In the control plane, each label space is identified by the context identifier of the corresponding {primary PE, protector}. In the forwarding plane, it is indicated by the bypass tunnel(s) destined for the context identifier.

4.7.1. Co-located Protector Model

In Figure 11, PE4 is a co-located protector that protects PW1 against egress AC failure and egress node failure. It maintains a label space for PE2, which is identified by the context identifier of {PE2, PE4}. It learns PW1's label from PE2, and installs an forwarding entry for the label in that label space. The nexthop of the forwarding entry indicates a label pop with outgoing interface pointing to the backup AC PE4-CE2.



PW1's label assigned by PE2: 100
PW2's label assigned by PE4: 200
On P3: </t>
    Incoming label of transport tunnel to PE2: 1000
    Outgoing label of transport tunnel to PE2: implicit null
    Outgoing label of bypass tunnel to PE4: 2000
On PE2:
    Outgoing label of bypass tunnel to PE4: 3000
On PE4:
    Context label (incoming label of bypass tunnels): 999

Forwarding state on P3:
label 1000 -- primary nexthop: pop, to PE2
              backup nexthop: swap 2000, to P4

Forwarding state on PE2:
label 100 -- primary nexthop: pop, to CE2
             backup nexthop: push 3000, to P5

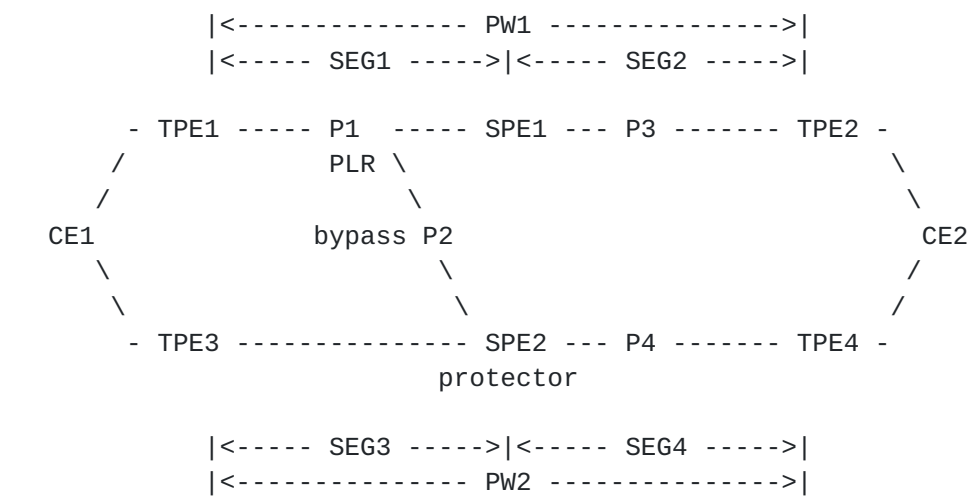
Forwarding state on PE4:
label 200 -- nexthop: pop, to CE2
label 999 -- nexthop: label table of PE2's label space

Label table of PE2's label space on PE4:
label 100 -- nexthop: pop, to CE2

Figure 11

In Figure 12, SPE2 is a co-located protector that protects PW1 against S-PE failure. It maintains a label space for SPE1, which is identified by the context identifier of {SPE1, SPE2}. It learns SEG1's label from SPE1, and installs a forwarding entry in the label space. The nexthop of the forwarding entry indicates a label swap to

SEG4's label and a label push with the label of a transport tunnel to TPE4.



SEG1's label assigned by SPE1: 100
SEG2's label assigned by TPE2: 200
SEG3's label assigned by SPE2: 300
SEG4's label assigned by TPE4: 400
On P1:
    Incoming label of transport tunnel to SPE1: 1000
    Outgoing label of transport tunnel to SPE1: implicit null
    Outgoing label of bypass tunnel to SPE2: 2000
On SPE1:
    Outgoing label of transport tunnel to TPE2: 3000
On SPE2:
    Outgoing label of transport tunnel to TPE4: 4000
    Context label (incoming label of bypass tunnel): 999

Forwarding state on P1:
label 1000 -- primary nexthop: pop, to SPE1
              backup nexthop: swap 2000, to P2

Forwarding state on SPE1:
label 100 -- nexthop: swap 200, push 3000, to P3

Forwarding state on SPE2:
label 300 -- nexthop: swap 400, push 4000, to P4
label 999 -- nexthop: label table of SPE1's label space

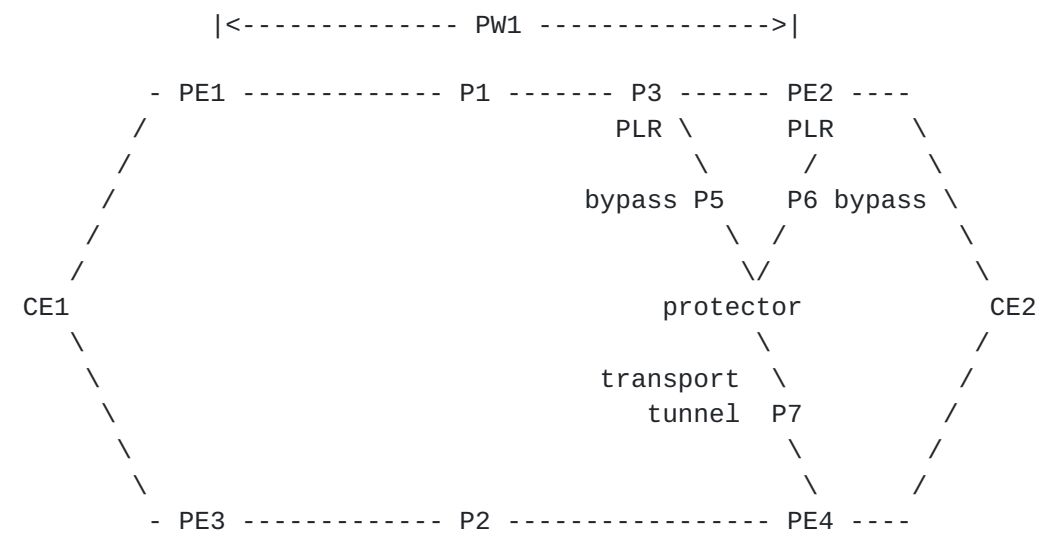
Label table of SPE1's label space on SPE2:
label 100 -- nexthop: swap 400, push 4000, to P4

Figure 12

4.7.2. Centralized Protector Model

In the centralized protector model, for each primary PW of which the protector is not a backup (S-)PE, the protector MUST also learn the label of the backup PW from the backup (S-)PE (Section 6.3). This is the backup (S-)PE that the protector will forward traffic to. The protector MUST install a forwarding entry with a label swap from the primary PW's label to the backup PW's label and a label push with the label of a transport tunnel to the backup (S-)PE.

In Figure 13, the protector is a centralized protector that protects PW1 against egress AC failure and egress node failure. It maintains a label space for PE2, which is identified by the context identifier of {PE2, protector}. It learns PW1's label from PE2, and PW2's label from PE4. It installs a forwarding entry for PW1's label in the label space. The nexthop of the forwarding entry indicates a label swap to PW2's label and a label push with the label of a transport tunnel to PE4.



PW1's label assigned by PE2: 100
PW2's label assigned by PE4: 200
On P3:
    Incoming label of transport tunnel to PE2: 1000
    Outgoing label of transport tunnel to PE2: implicit null
    Outgoing label of bypass tunnel to protector: 2000
On PE2:
    Outgoing label of bypass tunnel to protector: 3000
On protector:
    Context label (incoming label of bypass tunnels): 999
    Outgoing label of transport tunnel to PE4: 4000

Forwarding state on P3:
label 1000 -- primary nexthop: pop, to PE2
              backup nexthop: swap 2000, to P5

Forwarding state on PE2:
label 100 -- primary nexthop: pop, to CE2
             backup nexthop: push 3000, to P6

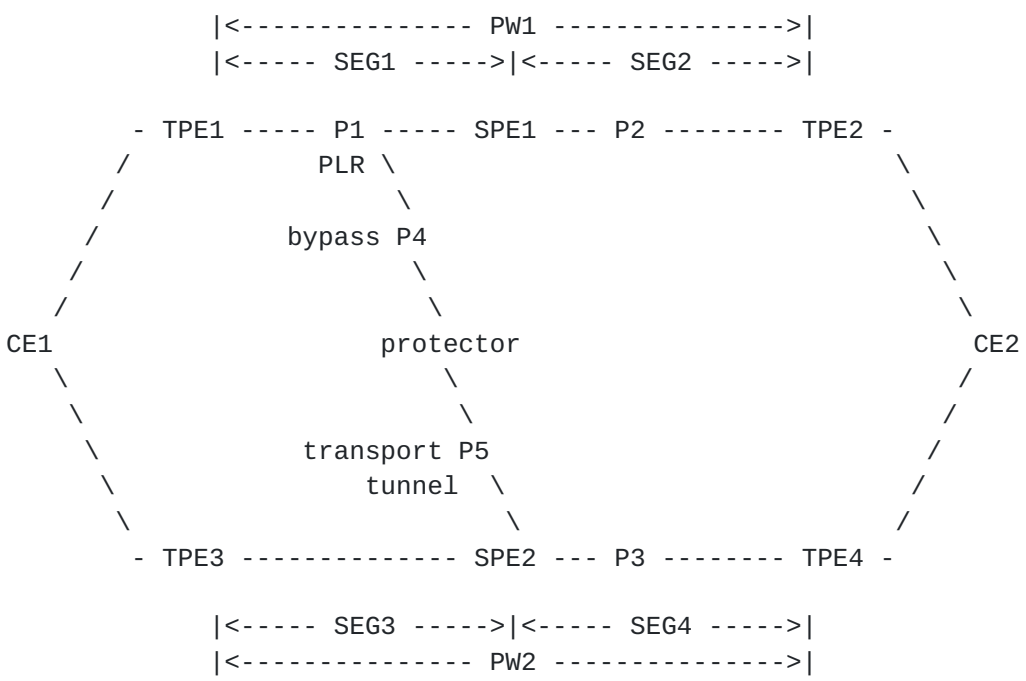
Forwarding state on PE4:
label 200 -- nexthop: pop, to CE2

Forwarding state on protector:
label 999 -- nexthop: label table of PE2's label space

Label table of PE2's label space on protector:
label 100 -- nexthop: swap 200, push 4000, to P7

Figure 13

In Figure 14, the protector is a centralized protector that protects the PW segment SEG1 of PW1 against the node failure of SPE1. It maintains a label space for SPE1, which is identified by the context identifier of {SPE1, protector}. It learns SEG1's label from SPE1, and learns SEG3's label from SPE2. It installs a forwarding entry for SEG1's label in the label space. The nexthop of the forwarding entry indicates a label swap to SEG3's label and a label push with the label of a transport tunnel to TPE4.



SEG1's label assigned by SPE1: 100
SEG2's label assigned by TPE2: 200
SEG3's label assigned by SPE2: 300
SEG4's label assigned by TPE4: 400
On P1:
    Incoming label of transport tunnel to SPE1: 1000
    Outgoing label of transport tunnel to SPE1: implicit null
    Outgoing label of bypass tunnel to protector: 2000
On SPE1:
    Outgoing label of transport tunnel to TPE2: 3000
On SPE2:
    Outgoing label of transport tunnel to TPE4: 4000
On protector:
    Context label (incoming label of bypass tunnel): 999
    Outgoing label of transport tunnel to SPE2: 5000

Forwarding state on P1:
label 1000 -- primary nexthop: pop, to SPE1
              backup nexthop: swap 2000, to P4

```
Forwarding state on SPE1:
label 100 -- nexthop: swap 200, push 3000, to P2

Forwarding state on SPE2:
label 300 -- nexthop: swap 400, push 4000, to P3

Forwarding state on protector:
label 999 -- nexthop: label table of SPE1's label space

Label table of SPE1's label space on protector:
label 100 -- nexthop: swap 300, push 5000, to P5
```

Figure 14

5. Revertive Behavior

Subsequent to local repair, there are three strategies for a network to restore traffic to a fully functional alternative path.

- Global revertive mode

  If the ingress CE is multi-homed (Figure 1), it MAY switch the traffic to the backup AC which is bound to the backup PW. Alternatively, if the ingress PE hosts a backup PW (Figure 2), the ingress PE MAY switch the traffic to the backup PW. These procedures are referred to as global repair. Possible triggers of global repair include PW status notification, VCCV, BFD, end-to-end OAM between CEs, etc.

- Control plane revertive mode

  In egress PE node protection and S-PE node protection, it is possible that the failure is limited to the link between the PLR and the primary PE, whereas the primary PE is still operational. In this case, the PLR or an upstream router on the transport tunnel MAY reroute the tunnel around the link via an alternative path to the primary PE. Thus, the transport tunnel can heal and continue to carry the PW to the primary PE. This procedure is driven by control plane convergence on the new topology, and is referred to as control plane repair.

- Local revertive mode

  The PLR MAY move traffic back to the primary PW, after the failure is resolved. In egress AC protection, upon detecting that the primary AC is restored, the PLR MAY start forwarding traffic over the AC again. Likewise, in egress PE node protection and S-PE node protection, upon detecting that the primary PE is restored,

the PLR MAY re-establish the transport tunnel to the primary PE, and move the traffic from the bypass tunnel back to the transport tunnel. These procedures are referred to as local reversion.

It is RECOMMENDED that the fast protection mechanism SHOULD be used in conjunction with the global revertive mode. Particularly in the case of egress PE and S-PE node failures, if the ingress PE or the protector loses communication with the (S-)PE for an extensive period of time, LDP session may go down. Consequently, the ingress PE may bring down the primary PW completely, or the protector may remove the forwarding entry of the primary PW label. In either case, the service will be disrupted. In other words, although the mechanism can temporarily repair traffic, control plane state may eventually expire if the failure persists. Therefore, the global revertive mode SHOULD take place in a timely manner to move traffic to a fully functional alternative path.

The control plane revertive mode may automatically happen as part of the convergence of control plane protocols. However, it is only applicable to the specific link failure scenario described above.

The local revertive mode is optional. In the circumstances where the failure is caused by resource flapping, local reversion MAY be dampened to limit potential disruption. Local revertive mode MAY be disabled completely by configuration.

6. LDP Extensions

As described in previous sections, a targeted LDP session MUST be established between each pair of primary PE and protector. The primary PE sends Label Mapping message over this session to advertise primary PW labels to the protector. In the centralized protector model, a targeted LDP session MUST also be established between a backup (S-)PE and the protector. The backup PE sends Label Mapping message over this session to advertise backup PW labels to the protector.

To facilitate the procedures, this document defines a new "Protection FEC Element" TLV. The Label Mapping messages of both the LDP sessions above MUST carry this TLV to identify a primary PW. Specifically, in the centralized protector model, the Protection FEC Element TLV advertised by a backup (S-)PE MUST match the one advertised by the primary PE, so that the protector can associate the primary PW's label with the backup PW's label, and perform a label swap. The backup (S-)PE builds such a Protection FEC Element TLV based on local configuration.

This document also defines the encoding of Capability Parameter TLV [RFC5561] for a new "Egress Protection Capability", to allow a protector to announce its capability of processing the above Protection FEC Element TLV and performing context specific label switching for PW labels.

The procedures in this section are only applicable, if the protector advertises the Egress Protection Capability, the primary PE supports the advertisement of the Protection FEC Element TLV, and in the centralized protector model, the backup PE also supports the advertisement of the Protection FEC Element TLV.

6.1. Egress Protection Capability TLV

A protector MUST advertise the Egress Protection Capability TLV in its Initialization message and Capability message, over the LDP session with a primary PE. In the centralized protector model, the protector MUST also advertise the TLV over the LDP session with a backup PE. The TLV carries one or multiple context identifiers. To the primary PE, the TLV MUST carry the context identifier of the {primary PE, protector}. In the centralized protector model, the TLV MUST carry to the backup PE multiple context identifiers, one for each {primary PE, protector} where the backup PE serves as a backup for the primary PE. This TLV MUST NOT be advertised by the primary PE or the backup PE to the protector.

The processing of the Egress Protection Capability TLV by a receiving router MUST follow the procedures defined in [RFC5561]. In particular, the router MUST advertise PW information to the protector by using the Protection FEC Element TLV, only after it has received the Egress Protection Capability TLV from the protector. It MUST validate each context identifier included in the TLV, and advertise the information of only the PWs that are associated with the context identifier. It MUST withdraw previously advertised Protection FEC TLVs, when the protector has withdrawn a previously advertised context identifier or the entire Egress Protection Capability TLV via Capability message.

The encoding of the Egress Protection Capability TLV is defined as below. It conforms to the format of Capability Parameter TLV specified in [RFC5561].

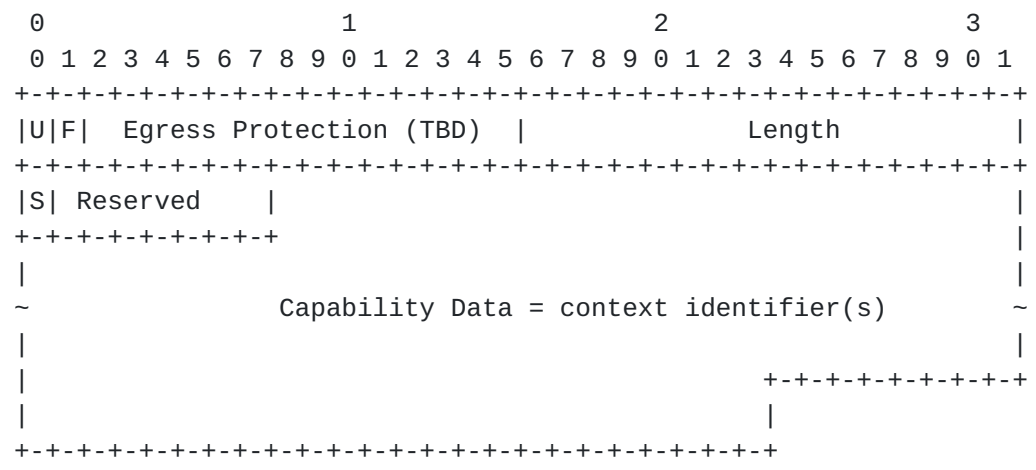


Figure 15

The U-bit MUST be set to 1 so that a receiver MUST silently ignore this TLV if unknown to it, and continue processing the rest of the message.

The F-bit MUST be set to 0 since this TLV is sent only in Initialization and Capability messages, which are not forwarded.

The TLV Code Point is TBD. It needs to be assigned by IANA.

The S-bit indicates whether the sender is advertising (S=1) or withdrawing (S=0) the capability.

The "Capability Data" is encoded with the context identifier of the {primary PE, protector}.

6.2. PW Label Distribution from Primary PE to Protector

A primary PE MUST advertise a primary PW's label to a protector by sending a Label Mapping message. The message includes a Protection FEC Element TLV (see Section 6.4 for encoding), and an Upstream-Assigned Label TLV [RFC6389] encoded with the PW's label. The combination of the Protection FEC Element TLV and the PW label represents the primary PE's forwarding state for the PW. The Label Mapping message MUST also carry an IPv4/v6 Interface_ID TLV [RFC6389, RFC3471] encoded with the context identifier of the {primary PE, protector}.

The protector that receives this Label Mapping message MUST install a forwarding entry for the PW label in the label space identified by the context identifier. The nexthop of the forwarding entry MUST ensure packets to be sent towards the target CE via a backup AC or a backup (S-)PE, depending on the protection scenario. The protector

MUST silently discard a Label Mapping message if the included context identifier is unknown to it.

6.3. PW Label Distribution from Backup PE to Protector

In the centralized protector model, a backup PE MUST advertise a backup PW's label to the protector by sending a Label Mapping message. The message includes a Protection FEC Element TLV and a Generic Label TLV encoded with the backup PW's label. This Protection FEC Element MUST be identical to the Protection FEC Element TLV that the primary PE advertises to the protector (Section 6.2). This is achieved through configuration on the backup PE. The context identifier MUST NOT be encoded in Interface_ID TLV in this message.

The protector that receives this Label Mapping message MUST associate the backup PW with the primary PW, based on the common Protection FEC Element TLV. It MUST distinguish between the Label Mapping message from the primary PE and the Label Mapping message from the backup PE based on the respective presence and absence of context identifier in Interface_ID TLV. It MUST install a forwarding entry for the primary PW's label in the label space identified by the context identifier. The nexthop of the forwarding entry MUST indicate a label swap to the backup PW's label, followed by a label push or IP header push for a transport tunnel to the backup PE.

6.4. Protection FEC Element TLV

The Protection FEC Element TLV has type 0x83. Its format is defined as below:

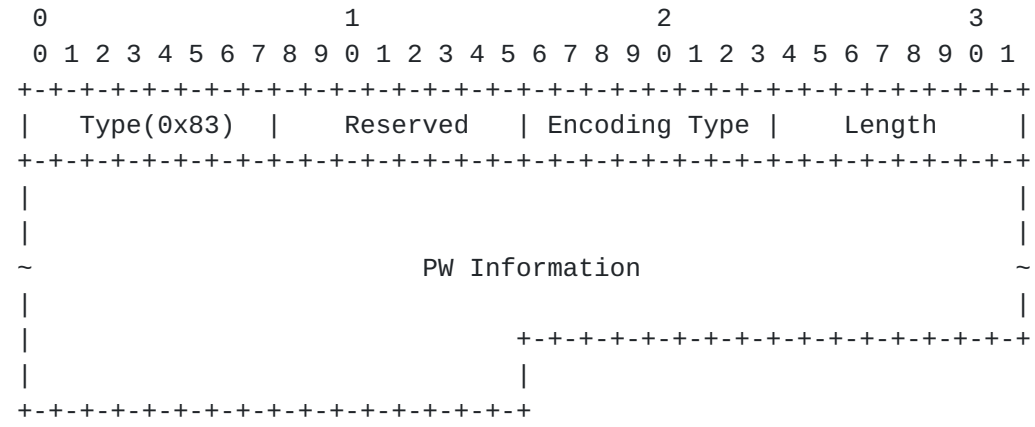


Figure 16

- Encoding Type

Type of format that PW Information field is encoded.

- Length

Length of PW Information field in octets.

- PW Information

Field of variable length that specifies a PW

For Encoding Type, 1 is defined for the PWid FEC Element format, and 2 is defined for the Generalized PWid FEC Element format [RFC4447].

6.4.1. Encoding Format for PWid

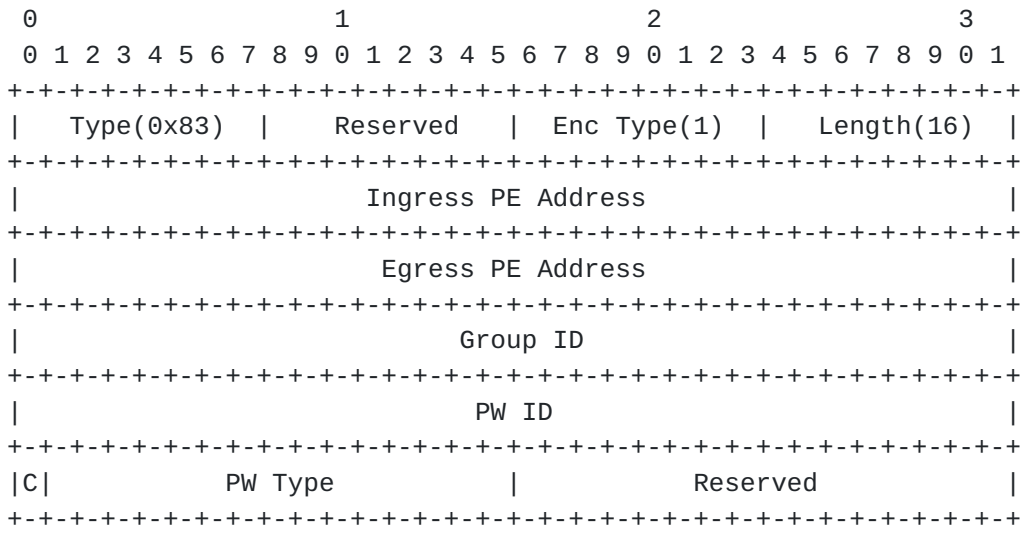


Figure 17

- Ingress PE Address

IP address of the ingress PE of PW.

- Egress PE Address

IP address of the egress PE of PW.

- Group ID

An arbitrary 32-bit value that represents a group of PWs and that is used to create groups in the PW space.

- PW ID

A non-zero 32-bit connection ID that, together with the PW Type field, identifies a particular PW.

- Control word bit (C)

A bit that flags the presence of a control word on this PW. If C = 1, control word is present; If C = 0, control word is not present.

- PW Type

A 15-bit quantity that represents the type of PW.

6.4.2. Encoding Format for Generalized PWid

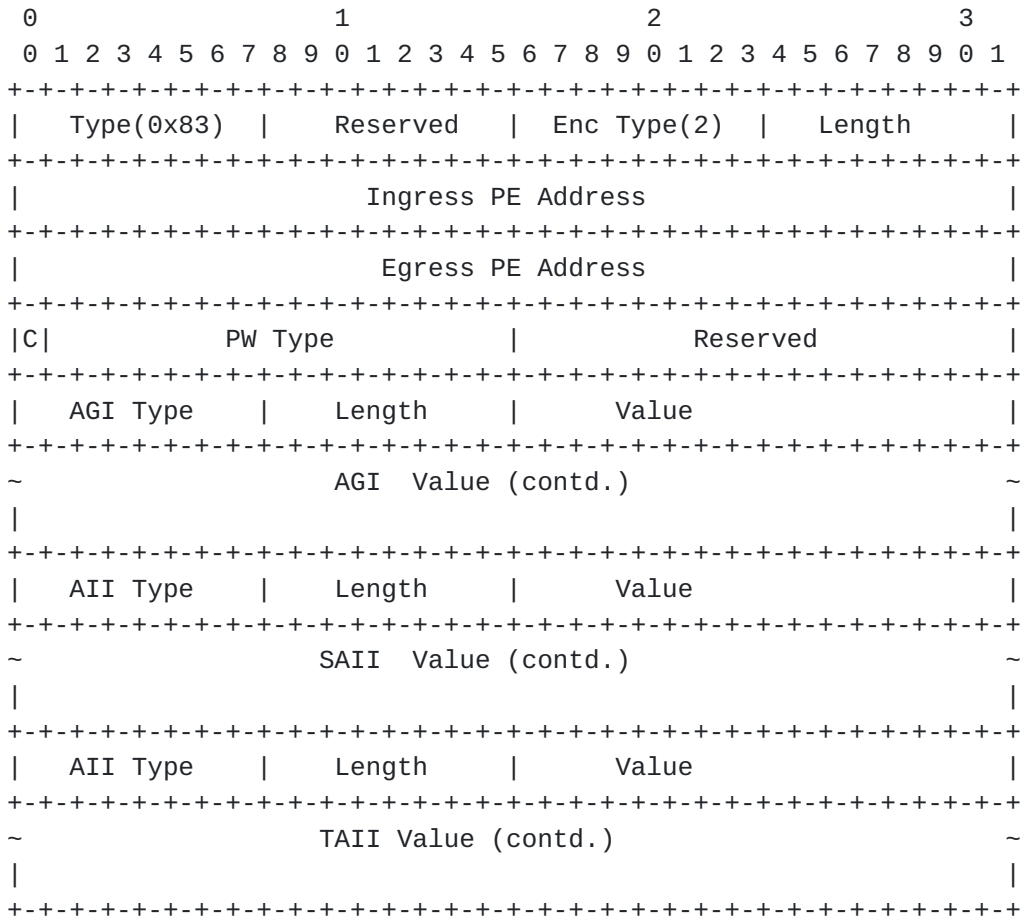


Figure 18

- Ingress PE Address

IP address of the ingress PE of PW.

- Egress PE Address

  IP address of the egress PE of PW.

- Control word bit (C)

  A bit that flags the presence of a control word on this PW. If C = 1, control word is present; If C = 0, control word is not present.

- PW Type

  A 15-bit quantity that represents the type of PW.

- AGI Type, Length, Value, AGI Value

  Attachment Group Identifier of PW.

- SAII Type, Length, Value, SAII Value

  Source Attachment Individual Identifier of PW.

- TAII Type, Length, Value, TAII Value

  Target Attachment Individual Identifier of PW.

7. IANA Considerations

This document defines the encoding of the Capability Parameter TLV for the new "Egress Protection Capability" in Section 6. This would require IANA to assign a TLV Code Point to it.

This document defines a new LDP Protection FEC Element TLV in Section 6. IANA has assigned the type value 0x83 to it.

Value	Hex	Name	Label Advertisement Discipline
131	0x83	Protection FEC Element	DU

8. Security Considerations

The security considerations discussed in [RFC5036, RFC5331, RFC3209, RFC4090] apply to this document. There is no additional consideration.

9. Acknowledgements

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Authors' Addresses

Yimin Shen
Juniper Networks
10 Technology Park Drive
Westford, MA 01886
USA

Phone: +1 9785890722
Email: yshen@juniper.net

Rahul Aggarwal
Arktan, Inc

Email: raggarwa_1@yahoo.com

Wim Henderickx
Alcatel-Lucent
Copernicuslaan 50
2018 Antwerp
Belgium

Email: wim.henderickx@alcatel-lucent.be

Yuanlong Jiang
Huawei Technologies

Email: jiangyuanlong@huawei.com