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R. Aggarwal (Editor)
Juniper Networks

Y. Kamite
NTT Communications

L. Fang
Cisco Systems, Inc

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Multicast in VPLS

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Abstract

This document describes a solution for overcoming a subset of the limitations of existing VPLS multicast solutions. It describes procedures for VPLS multicast that utilize multicast trees in the sevice provider (SP) network. One such multicast tree can be shared between multiple VPLS instances. Procedures by which a single multicast tree in the SP network can be used to carry traffic belonging only to a specified set of one or more IP multicast streams from one or more VPLSes are also described.

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1. 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].

2. Contributors

Rahul Aggarwal
Yakov Rekhter
Juniper Networks
Yuji Kamite
NTT Communications
Luyuan Fang
AT&T
Chaitanya Kodeboniya

3. Terminology

This document uses terminology described in [RFC4761] and [RFC4762].

4. Introduction

[RFC4761] and [RFC4762] describe a solution for VPLS multicast that relies on the use of P2P RSVP-TE or MP2P LDP LSPs, referred to as Ingress Replication in this document. This solution has certain limitations for certain VPLS multicast traffic profiles. For example it may result in highly non-optimal bandwidth utilization in the MPLS network when large amount of multicast traffic is to be transported

This document describes procedures for overcoming the limitations of existing VPLS multicast solutions. It describes procedures for VPLS multicast that utilize multicast trees in the Sevice Provider (SP) network. The procedures described in this document are applicable to both [RFC4761] and [RFC4762].

It provides mechanisms that allow a single multicast distribution tree in the Service Provider (SP) network to carry all the multicast traffic from one or more VPLS sites connected to a given PE, irrespective of whether these sites belong to the same or different VPLSes. Such a tree is referred to as an "Inclusive tree" and more specifically as an "Aggregate Inclusive tree" when the tree is used to carry multicast traffic from more than one VPLS.

This document also provides procedures by which a single multicast distribution tree in the SP network can be used to carry traffic belonging only to a specified set of IP multicast streams, originated in one or more VPLS sites connected to a given PE, irrespective of whether these sites belong to the same or different VPLSes. Such a tree is referred to as a "Selective tree" and more specifically as an "Aggregate Selective tree" when the IP multicast streams belong to different VPLSes. This allows multicast traffic, by default, to be carried on an Inclusive tree, while traffic from some specific multicast streams, e.g., high bandwidth streams, could be carried on one of the "Selective trees".

5. Existing Limitations of VPLS Multicast

One of the limitations of existing VPLS multicast solutions described in [RFC4761] and [RFC4762] is that they rely on ingress replication. Thus, the ingress PE replicates the multicast packet for each egress PE and sends it to the egress PE using a unicast tunnel.

Ingress Replication may be an acceptable model when the bandwidth of the multicast traffic is low or/and the number of replications performed on an average on each outgoing interface for a particular customer VPLS multicast packet is small. If this is not the case it is desirable to utilize multicast trees in the SP network to transmit VPLS multicast packets [MCAST-VPLS-REQ]. Note that unicast packets that are flooded to each of the egress PEs, before the ingress PE learns the destination MAC address of those unicast packets, MAY still use ingress replication.

6. Overview

This document describes procedures for using multicast trees in the SP network to transport VPLS multicast data packets. RSVP-TE P2MP LSPs described in [RFC4875] are an example of such multicast trees. The use of multicast trees in the SP network can be beneficial when the bandwidth of the multicast traffic is high or when it is desirable to optimize the number of copies of a multicast packet transmitted on a given link. This comes at a cost of state in the SP network to build multicast trees and overhead to maintain this state. This document describes procedures for using multicast trees for VPLS multicast when the provider tunnels are P2MP LSPs signaled by either P2MP RSVP-PE or mLDP [MLDP].

This document uses the prefix 'C' to refer to the customer control or data packets and 'P' to refer to the provider control or data packets. An IP (multicast source, multicast group) tuple is abbreviated to (S, G).

6.1. Inclusive and Selective Multicast Trees

Multicast trees used for VPLS can be of two types:

1. Inclusive trees. This option supports the use of a single multicast distribution tree, referred to as an Inclusive P-Multicast tree, in the SP network to carry all the multicast traffic from a specified set of VPLS sites connected to a given PE. There is no assumption made with respect to whether this traffic is IP encapsulated or not. A particular P-Multicast tree can be set up to

carry the traffic originated by sites belonging to a single VPLS, or to carry the traffic originated by sites belonging to different VPLSes. The ability to carry the traffic of more than one VPLS on the same tree is termed Aggregation. The tree needs to include every PE that is a member of any of the VPLSes that are using the tree. This implies that a PE may receive multicast traffic for a multicast stream even if it doesn't have any receivers that are interested in receiving traffic for that stream.

An Inclusive P-Multicast tree as defined in this document is a P2MP tree. A P2MP tree is used to carry traffic only from VPLS sites that are connected to the PE that is the root of the tree.

2. Selective trees. A Selective P-Multicast tree is used by a PE to send IP multicast traffic for one or IP more specific multicast streams, received by a PE over PE-CE interfaces that belong to the same or different VPLSes, to a subset of the PEs that belong to those VPLSes. Each of the PEs in the subset should be on the path to a receiver of one or more multicast streams that are mapped onto the tree. The ability to use the same tree for multicast streams that belong to different VPLSes is termed Aggregation. The reason for having Selective P-Multicast trees is to provide a PE the ability to create separate SP multicast trees for specific multicast streams, e.g. high bandwidth multicast streams. This allows traffic for these multicast streams to reach only those PE routers that have receivers in these streams. This avoids flooding other PE routers in the VPLS.

A SP can use both Inclusive P-Multicast trees and Selective P-Multicast trees or either of them for a given VPLS on a PE, based on local configuration. Inclusive P-Multicast trees can be used for both IP and non-IP data multicast traffic, while Selective P-Multicast trees must be used only for IP multicast data traffic. The use of Selective P-Multicast trees for non-IP multicast traffic is outside the scope of this document.

A variety of transport technologies may be used in the SP network. For inclusive P-Multicast trees, these transport technologies include point-to-multipoint LSPs created by RSVP-TE or mLDP. For selective P-Multicast trees, only unicast PE-PE tunnels (using MPLS or IP/GRE encapsulation) and P2MP LSPs are supported, and the supported P2MP LSP signaling protocols are RSVP-TE, and mLDP. Other transport technologies are outside the scope of this document.

This document also describes the data plane encapsulations for supporting the various SP multicast transport options.

6.2. BGP-Based VPLS Membership Auto-Discovery

In order to establish Inclusive P-Multicast trees for one or more VPLSes, when Aggregation is performed or when the tunneling technology is P2MP RSVP-TE, the root of the tree must be able to discover the other PEs that have membership in one or more of these VPLSes. This document uses the BGP-based procedures described in [RFC4761] and [L2VPN-SIG] for discovering the VPLS membership of all PEs.

The leaves of the Inclusive P-Multicast trees must also be able to auto-discover the identifier of the tree. This is described in section 6.4.

6.3. IP Multicast Group Membership Discovery

The setup of a Selective P-Multicast tree for one or more IP multicast (S, G)s, requires the ingress PE to learn the PEs that have receivers in one or more of these (C-S, C-G)s, in the following cases:

+ When aggregation is used OR

+ When the tunneling technology is P2MP RSVP-TE

+ If ingress replication is used and the ingress PE wants to send traffic for (C-S, C-G)s to only those PEs that are on the path to receivers to the (C-S,C-G)s.

For discovering the IP multicast group membership, this document describes procedures that allow an ingress PE to enable explicit tracking. Thus an ingress PE can request the IP multicast membership from egress PEs for one or more C-multicast streams. These procedures are described in section "Optimizing Multicast Distribution via Selective Trees".

These procedures are applicable when IGMP is used as the multicast signaling protocol between the VPLS CEs. They are also applicable when PIM as specified in [RFC4601] is used as the multicast routing protocol between the VPLS CEs and PIM join suppression is disabled on all the CEs. However these procedures do not apply when PIM is used as the multicast routing protocol between the VPLS CEs and PIM join suppression is not disabled on all the CEs. Procedures for this case are for further study.

The leaves of the Selective P-Multicast trees must also be able to

discover the identifier of the tree. This is described in section 6.4.

6.4. Advertising P-Multicast Tree to VPLS/C-Multicast Binding

This document describes procedures based on BGP VPLS Auto-Discovery (A-D) that are used by the root of an Aggregate P-Multicast tree to advertise the Inclusive or Selective P-Multicast tree binding and the de-multiplexing information to the leaves of the tree. This document uses the PMSI Tunnel attribute [BGP-MVPN] for this purpose.

Once a PE decides to bind a set of VPLSes or customer multicast groups to an Inclusive P-Multicast tree or a Selective P-Multicast tree, it needs to announce this binding to other PEs in the network. This procedure is referred to as Inclusive P-Multicast tree or Selective P-Multicast tree binding distribution and is performed using BGP.

When an Aggregated Inclusive P-Multicast tree is used by an ingress PE, this discovery implies that an ingress PE MUST announce the binding of all VPLSes bound to the Inclusive P-Multicast tree to the other PEs. The inner label assigned by the ingress PE for each VPLS MUST be included, if more than one VPLS is bound to the same P-Multicast tree. The Inclusive P-Multicast tree Identifier MUST be included.

For a Selective P-Multicast tree this discovery implies announcing all the specific <C-S, C-G> entries bound to this P-Multicast tree along with the Selective P-Multicast tree Identifier. The inner label assigned for each <C-S, C-G> MUST be included if <C-S, C-G>s from different VPLSes are bound to the same P-Multicast tree. The labels MUST be distinct on a per VPLS basis and MAY be distinct on a per <C-S, C-G> basis. The Selective P-Multicast tree Identifier MUST be included.

6.5. Aggregation

As described above the ability to carry the traffic of more than one VPLS on the same P-Multicast tree is termed 'Aggregation'. Both Inclusive and Selective P-Multicast trees support aggregation.

Aggregation enables the SP to place a bound on the amount of multicast tree forwarding and control plane state which the P routers must have. Let us call the number of VPLSes aggregated onto a single P-Multicast tree as the "Aggregation Factor". When Inclusive source P-Multicast trees are used the number of trees that a PE is the root

of is proportional to:

+ (Number of VPLSes on the PE / Aggregation Factor).

In this case the state maintained by a P router, is proportional to:

+ ((Average number of VPLSes on a PE / Aggregation Factor) * number of PEs) / (Average number of P-Multicast trees that transit a given P router)

Thus, the state does not grow linearly with the number of VPLSes.

Aggregation requires a mechanism for the egresses of the P-Multicast tree to demultiplex the multicast traffic received over the P-Multicast tree. To enable the egress nodes to perform this demultiplexing, upstream-assigned labels [RFC5331] MUST be assigned and distributed by the root of the aggregate P-multicast tree."

6.6. Inter-AS VPLS Multicast

This document supports three models of inter-AS VPLS service, option (a), (b) and (c) which are very similar conceptually to option (a), (b) and (c) specified in [RFC4364] for IP VPNs. The three options described here are also similar to the three options described in in [RFC4761], which in turn extends the concepts of [RFC4364] to inter-AS VPLS.

For option (a) and option (b) support this document specifies a model where Inter-AS VPLS service can be offered without requiring a single P-Multicast tree to span multiple ASes. There are two variants of this model and they are described in section 10.

For option (c) support this document specifies a model where Inter-AS VPLS service is offered by requiring a single P-Multicast tree to span multiple ASs. This is because in the case of option (c) the ASBRs do not exchange BGP-VPLS NLRIs or A-D routes.

7. Intra-AS Inclusive P-Multicast Tree A-D/Binding

This section specifies procedures for the intra-AS auto-discovery (A-D) of VPLS membership and the distribution of information used to instantiate P-Multicast Tunnels.

VPLS auto-discovery/binding consists of two components: intra-AS and inter-AS. The former provides VPLS auto-discovery/binding within a single AS. The latter provides VPLS auto-discovery/binding across multiple ASes. Inter-AS auto-discovery/binding is described in section 10.

VPLS auto-discovery using BGP as described in [RFC4761, RFC6074] enables a PE to learn the VPLS membership of other PEs. A PE that belongs to a particular VPLS announces a BGP Network Layer Reachability Information (NLRI) that identifies the Virtual Switch Instance (VSI). This NLRI is constructed from the <Route-Distinguisher (RD), VPLS Edge Device Identifier (VE-ID)> tuple. The NLRI defined in [RFC4761] comprises the <RD, VE-ID> tuple and label blocks for PW signaling. The VE-ID in this case is a two octet number. The NLRI defined in [RFC6074] comprises only the <RD, VE-ID> where the VE-ID is a four octet number.

The procedures for constructing Inclusive intra-AS and inter-AS trees as specified in this document require the BGP A-D NLRI to carry only the <RD, VE-ID>. Hence these procedures can be used for both BGP-VPLS and LDP-VPLS with BGP A-D.

It is to be noted that BGP A-D is an inherent feature of BGP-VPLS. However it is not an inherent feature of LDP-VPLS. Infact there are deployments and/or implementations of LDP-VPLS that require configuration to enable a PE in a particular VPLS to determine other PEs in the VPLS and exchange PW labels using FEC 128 [RFC4447]. The use of BGP A-D for LDP-VPLS [RFC6074], to enable automatic setup of PWs, requires FEC 129 [RFC4447]. However FEC 129 is not required in order to use procedures in this document for LDP-VPLS. An LDP-VPLS implementation that supports this document MUST support the BGP A-D procedures to setup P-Multicast trees, as described here, and it MAY support FEC 129 to automate the signaling of PWs.

7.1. Originating intra-AS VPLS auto-discovery routes

To participate in the VPLS auto-discovery/binding a PE router that has a given VSI of a given VPLS originates an BGP VPLS intra-AS auto-discovery route and advertises this route in Multi-Protocol (MP) I-BGP. The route is constructed as described in [RFC4761] and [RFC6074].

The route carries a single L2VPN NLRI with the RD set to the RD of the VSI, and the VE-ID set to the VE-ID of the VSI.

The route also carries one or more Rout Targets (RTs) as specified in [RFC4761] and [RFC6074].

If an Inclusive P-Multicast tree is used to instantiate the provider tunnel for VPLS multicast on the PE, the advertising PE MUST advertise the type and the identity of the P-Multicast tree in the the PMSI Tunnel attribute [BGP-MVPN]. This attribute is described in section 12.1.

A PE that uses an Inclusive P-Multicast tree to instantiate the provider tunnel MAY aggregate two or more VPLSes present on the PE onto the same tree. If the PE decides to perform aggregation after it has already advertised the intra-AS VPLS auto-discovery routes for these VPLSes, then aggregation requires the PE to re-advertise these routes. The re-advertised routes MUST be the same as the original ones, except for the PMSI Tunnel attribute. If the PE has not previously advertised intra-AS auto-discovery routes for these VPLSes, then the aggregation requires the PE to advertise (new) intra-AS auto-discovery routes for these VPLSes. The PMSI attribute in the newly advertised/re-advertised routes MUST carry the identity of the P-Multicast tree that aggregates the VPLSes, as well as an MPLS upstream-assigned label [RFC5331]. Each re-advertised route MUST have a distinct label.

Discovery of PE capabilities in terms of what tunnels types they support is outside the scope of this document. Within a given AS PEs participating in a VPLS are expected to advertise tunnel bindings whose tunnel types are supported by all other PEs that are participating in this VPLS and are part of the same AS.

7.2. Receiving intra-AS VPLS auto-discovery routes

When a PE receives a BGP Update message that carries an intra-AS A-D route such that (a) the route was originated by some other PE within the same AS as the local PE, (b) at least one of the Route Targets of the route matches one of the import Route Targets configured for a particular VSI on the local PE, (c) the BGP route selection determines that this is the best route with respect to the NLRI carried by the route, and (d) the route carries the PMSI Tunnel attribute, the PE performs the following.

If the route carries the PMSI Tunnel attribute then:

+ If the Tunnel Type in the PMSI Tunnel attribute is set to LDP P2MP LSP, the PE SHOULD join the P-Multicast tree whose identity is carried in the PMSI Tunnel attribute.

+ If the Tunnel Type in the PMSI Tunnel attribute is set to RSVP-TE P2MP LSP, the receiving PE has to establish the appropriate state to properly handle the traffic received over that LSP. The PE that originated the route MUST establish an RSVP-TE P2MP LSP with the local PE as a leaf. This LSP MAY have been established before the local PE receives the route.

+ If the PMSI Tunnel attribute does not carry a label, then all packets that are received on the P-Multicast tree, as identified by the PMSI Tunnel attribute, are forwarded using the VSIs that have at least one of its import Route Targets that matches one of the Route Targets of the received auto-discovery route.

+ If the PMSI Tunnel attribute has the Tunnel Type set to LDP P2MP LSP or RSVP-TE P2MP LSP, and the attribute also carries an MPLS label, then the egress PE MUST treat this as an upstream-assigned label, and all packets that are received on the P-Multicast tree, as identified by the PMSI Tunnel attribute, with that upstream label are forwarded using the VSIs that have at least one of its import Route Target that matches one of the Route Targets of the received intra-AS auto-discovery route.

If the local PE uses RSVP-TE P2MP LSP for sending (multicast) traffic, originated by VPLS sites connected to the PE, to the sites attached to other PEs then the local PE MUST use the Originating Router's IP address information carried in the intra-AS A-D route to add the PE, that originated the route, as a leaf node to the LSP. This MUST be done irrespective of whether the received Intra-AS A-D route carries the PMSI Tunnel attribute or not.

8. Demultiplexing P-Multicast Tree Traffic

Demultiplexing received VPLS traffic requires the receiving PE to determine the VPLS instance the packet belongs to. The egress PE can then perform a VPLS lookup to further forward the packet. It also requires the egress PE to determine the identity of the ingress PE for MAC learning, as described in section 15.

8.1. One P-Multicast Tree - One VPLS Mapping

When a P-Multicast tree is mapped to only one VPLS, determining the tree on which the packet is received is sufficient to determine the VPLS instance on which the packet is received. The tree is determined based on the tree encapsulation. If MPLS encapsulation is used, e.g.,: RSVP-TE P2MP LSPs, the outer MPLS label is used to determine the tree. Penultimate-hop-popping MUST be disabled on the MPLS LSP (RSVP-TE P2MP LSP or LDP P2MP LSP).

8.2. One P-Multicast Tree - Many VPLS Mapping

As traffic belonging to multiple VPLSes can be carried over the same tree, there is a need to identify the VPLS the packet belongs to. This is done by using an inner label that determines to the VPLS for which the packet is intended. The ingress PE uses this label as the inner label while encapsulating a customer multicast data packet. Each of the egress PEs must be able to associate this inner label with the same VPLS and use it to demultimplex the traffic received over the Aggregate Inclusive tree or the Aggregate Selective tree.

If traffic from multiple VPLSes is carried on a single tree, upstream-assigned labels [RFC5331] MUST be used. Hence the inner label is assigned by the ingress PE. When the egress PE receives a packet over an Aggregate tree, the outer encapsulation [in the case of MPLS P2MP LSPs, the outer MPLS label] specifies the label space to perform the inner label lookup. The same label space MUST be used by the egress PE for all P-Multicast trees that have the same root [RFC5331].

If the tree uses MPLS encapsulation, as in RSVP-TE P2MP LSPs, the outer MPLS label and optionally the incoming interface provides the label space of the label beneath it. This assumes that penultimate-hop-popping is disabled. The egress PE MUST NOT advertise IMPLICIT NULL or EXPLICIT NULL for that tree once its known to the egress PE that the tree is bound to one or more VPLSes. Once the label representing the tree is popped off the MPLS label stack, the next label is the demultiplexing information that allows the proper VPLS

instance to be determined.

The ingress PE informs the egress PEs about the inner label as part of the tree binding procedures described in section 12.

9. Establishing P-Multicast Trees

This document supports only P2MP P-Multicast trees wherein its possible for egress PEs to identify the ingress PE to perform MAC learning. Specific procedures are specified only for RSVP-TE P2MP LSPs and LDP P2MP LSPs. An implementation that supports this document MUST support RSVP-TE P2MP LSPs and LDP P2MP LSPs.

A P2MP tree is used to carry traffic originated in sites connected to the PE which is the root of the tree. These sites MAY belong to different VPLSes or the same VPLS.

9.1. Common Procedures

The following procedures apply to both RSVP-TE P2MP and LDP P2MP LSPs.

Demultiplexing the C-multicast data packets at the egress PE requires that the PE must be able to determine the P2MP LSP that the packets are received on. This enables the egress PE to determine the VPLS instances that the packet belongs to. To achieve this the LSP MUST be signaled with penultimate-hop-popping (PHP) off and a non-reserved MPLS label off as described in section 8. In other words an egress PE MUST NOT advertise IMPLICIT NULL or EXPLICIT NULL for a P2MP LSP that is carrying traffic for one or more VPLSes. This is because the egress PE needs to rely on the MPLS label, that it advertises to its upstream neighbor, to determine the P2MP LSP that a C-multicast data packet is received on.

The egress PE also needs to identify the ingress PE to perform MAC learning. When P2MP LSPs are used as P2MP trees, determining the P2MP LSP that the packets are received on, is sufficient to determine the ingress PE. This is because the ingress PE is the root of the P2MP LSP.

The egress PE relies on receiving the PMSI Tunnel attribute in BGP to determine the VPLS instance to P2MP LSP mapping.

9.2. RSVP-TE P2MP LSPs

This section describes procedures that are specific to the usage of RSVP-TE P2MP LSPs for instantiating a P-Multicast tree. Procedures in [RFC4875] are used to signal the P2MP LSP. The LSP is signaled as the root of the P2MP LSP discovers the leaves. The egress PEs are discovered using the procedures described in section 7. Aggregation as described in this document is supported.

9.2.1. P2MP TE LSP - VPLS Mapping

P2MP TE LSP to VPLS mapping is learned at the egress PEs using BGP based advertisements of the P2MP TE LSP - VPLS mapping. They require that the root of the tree include the P2MP TE LSP identifier as the tunnel identifier in the BGP advertisements. This identifier contains the following information elements:

- The type of the tunnel is set to RSVP-TE P2MP LSP
- RSVP-TE P2MP LSP's SESSION Object

This Tunnel Identifier is described in section 12.1.

Once the egress PE receives the P2MP TE LSP to VPLS mapping:

+ If the egress PE already has RSVP-TE state for the P2MP TE LSP, it MUST begin to assign a MPLS label from the non-reserved label range, for the P2MP TE LSP and signal this to the previous hop of the P2MP TE LSP. Further it MUST create forwarding state to forward packets received on the P2MP LSP.

+ If the egress PE does not have RSVP-TE state for the P2MP TE LSP, it MUST retain this mapping. Subsequently when the egress PE receives the RSVP-TE P2MP signaling message, it creates the RSVP-TE P2MP LSP state. It MUST then assign a MPLS label from the non-reserved label range, for the P2MP TE LSP, and signal this to the previous hop of the P2MP TE LSP.

  Note that if the signaling to set up an RSVP-TE P2MP LSP is completed before a given egress PE learns, via a PMSI Tunnel attribute, of the VPLS or set of VPLSes to which the LSP is bound, the PE MUST discard any traffic received on that LSP until the binding is received. In order for the egress PE to be able to discard such traffic it needs to know that the LSP is associated with one or more VPLSes and that the VPLS A-D route that binds the LSP to a VPLS has not yet been received. This is provided by extending [RFC4875] with [RSVP-OBB].

9.3. Receiver Initiated MPLS Trees

Receiver initiated P2MP MPLS trees signaled using LDP [mLDP] can also be used. Procedures in [MLDP] MUST be used to signal the P2MP LSP. The LSP is signaled once the leaves receive the LDP FEC for the tree from the root as described in section 7. An ingress PE is required to discover the egress PEs when aggregation is used and this is achieved using the procedures in section 7.

9.3.1. P2MP LSP - VPLS Mapping

P2MP LSP to VPLS mapping is learned at the egress PEs using BGP based advertisements of the P2MP LSP - VPLS mapping. They require that the root of the tree include the P2MP LSP identifier as the tunnel identifier in the BGP advertisements. This identifier contains the following information elements:

- The type of the tunnel is set to LDP P2MP LSP
- LDP P2MP FEC which includes an identifier generated by the root.

Each egress PE SHOULD "join" the P2MP MPLS tree by sending LDP label mapping messages for the LDP P2MP FEC, that was learned in the BGP advertisement, using procedures described in [MLDP].

9.4. Encapsulation of Aggregate P-Multicast Trees

An Aggregate Inclusive P-Multicast tree or an Aggregate Selective P-Multicast tree MUST use a MPLS encapsulation. The protocol type in the data link header is as described in [RFC5332].

10. Inter-AS Inclusive P-Multicast Tree A-D/Binding

This document supports four options of inter-AS VPLS service, option (a), (b), (c) and (e). Of these option (a), (b) and (c) are very similar conceptually to option (a), (b) and (c) specified in [RFC4364] for IP VPNs. These three options are also similar to the three options described in [RFC4761], which in turn extend the concepts of [RFC4364] to inter-AS VPLS. An implementation MUST support all three of these options. When there are multiple ways for implementing one of these options this section specifies which one is mandatory.

For option (a), (b) and (e) support this section specifies a model where inter-AS VPLS service can be offered without requiring a single P-Multicast tree to span multiple ASes. This allows individual ASes

to potentially use different P-tunneling technologies. There are two variants of this model. One that requires MAC lookup on the ASBRs and applies to option (a) and (e). The other is one that does not require MAC lookup on the ASBRs and instead builds segmented inter-AS Inclusive or Selective trees. This applies only to option (b).

For option (c) support this document specifies a model where Inter-AS VPLS service is offered by requiring a single Inclusive P-Multicast tree to span multiple ASs. This is referred to as a non-segmented P-Multicast tree. This is because in the case of option (c) the ASBRs do not exchange BGP-VPLS NLRIs or VPLS A-D routes. Selective inter-AS trees for option (c) support may be segmented or non-segmented.

10.1. VSIs on the ASBRs

When VSIs are configured on ASBRs, the ASBRs MUST perform a MAC lookup, in addition to any MPLS lookups, to determine the forwarding decision on a VPLS packet. The P-Multicast trees are confined to an AS. An ASBR on receiving a VPLS packet from another ASBR is required to perform a MAC lookup to determine how to forward the packet. Thus an ASBR is required to keep a VSI for the VPLS and MUST be configured with its own VE ID for the VPLS. The BGP VPLS A-D routes generated by PEs in an AS MUST NOT be propagated outside the AS.

10.1.1. Option (a): VSIs on the ASBRs

When VSIs are configured on ASBRs and option (a) is used then an ASBR in one AS treats an adjoining ASBR in another AS as a CE and determines the VSI for packets received from that ASBR based on the incoming ethernet interface. In option (a) the ASBRs do not exchange VPLS A-D routes.

An implementation MUST support option (a).

10.1.2. Option (e): VSIs on the ASBRs

The VSIs on the ASBRs scheme can be used such that the interconnect between the ASBRs is a PW and MPLS encapsulation is used between the ASBRs. An ASBR in one AS treats an adjoining ASBR in another AS as a CE and determines the VSI for packets received from another ASBR based on the incoming MPLS encapsulation. This is referred to as option (e). The only VPLS A-D routes that are propagated outside the AS are the ones originated by ASBRs. This MPLS PW connects the VSIs on the ASBRs and MUST be signaled using the procedures defined in [RFC4761] or [RFC4762].

The P-Multicast trees for a VPLS are confined to each AS and the VPLS auto-discovery/binding MUST follow the intra-AS procedures described in section 8. An implementation MAY support option (e).

10.2. Option (b) - Segmented Inter-AS Trees

In this model, an inter-AS P-Multicast tree, rooted at a particular PE for a particular VPLS instance, consists of a number of "segments", one per AS, which are stitched together at ASBRs. These are known as "segmented inter-AS trees". Each segment of a segmented inter-AS tree may use a different multicast transport technology. In this model, an ASBR is not required to keep a VSI for the VPLS and is not required to perform a MAC lookup in order to forward the VPLS packet. This implies that an ASBR is not required to be configured with a VE ID for the VPLS. This model is applicable to option (b). An implementation MUST support option (b) using this model.

The construction of segmented Inter-AS trees requires the BGP-VPLS A-D NLRI described in [RFC4761, RFC6074]. A BGP VPLS A-D route for a <RD, VE ID> tuple advertised outside the AS, to which the originating PE belongs, will be referred to as an inter-AS VPLS auto-discovery route (Though this route is originated by a PE as an intra-AS route and is referred to as an inter-AS route outside the AS).

In addition to this, segmented inter-AS trees require support for the PMSI Tunnel attribute described in section 12.1. They also require additional procedures in BGP to signal leaf A-D routes between ASBRs as explained in subsequent sections.

10.2.1. Segmented Inter-AS Trees VPLS Inter-AS A-D/Binding

This section specifies the procedures for inter-AS VPLS A-D/binding for segmented inter-AS trees.

An ASBR must be configured to support a particular VPLS as follows:

+ An ASBR MUST be be configured with a set of (import) Route Targets (RTs) that specifies the set of VPLSes supported by the ASBR. These Route Targets control acceptance of BGP VPLS auto-discovery routes by the ASBR. Note that instead of being configured, the ASBR MAY obtain this set of (import) Route Targets (RTs) by using Route Target Constrain [RFC4684].

+ The ASBR MUST be configured with the tunnel types for the intra-AS segments of the VPLSes supported by the ASBR, as well as (depending on the tunnel type) the information needed to create the PMSI Tunnel attribute for these tunnel types. Note that instead of being configured, the ASBR MAY derive the tunnel types from the intra-AS auto-discovery routes received by the ASBR from the PEs in its own AS.

If an ASBR is configured to support a particular VPLS, the ASBR MUST participate in the intra-AS VPLS auto-discovery/binding procedures for that VPLS within the ASBR's own AS, as defined in this document.

Moreover, in addition to the above the ASBR performs procedures specified in the next section.

10.2.2. Propagating BGP VPLS A-D routes to other ASes: Overview

An auto-discovery route for a given VPLS, originated by an ASBR within a given AS, is propagated via BGP to other ASes. The precise rules for distributing and processing the inter-AS auto-discovery routes are given in subsequent sections.

Suppose that an ASBR A receives and installs an auto-discovery route for VPLS "X" and VE ID "V" that originated at a particular PE, PE1. The BGP next hop of that received route becomes A's "upstream neighbor" on a multicast distribution tree for (X, V) that is rooted at PE1. When the auto-discovery routes have been distributed to all the necessary ASes, they define a "reverse path" from any AS that supports VPLS X and VE ID V back to PE1. For instance, if AS2 supports VPLS X, then there will be a reverse path for VPLS X and VE ID V from AS2 to AS1. This path is a sequence of ASBRs, the first of which is in AS2, and the last of which is in AS1. Each ASBR in the sequence is the BGP next hop of the previous ASBR in the sequence.

This reverse path information can be used to construct a unidirectional multicast distribution tree for VPLS X and VE ID V, containing all the ASes that support X, and having PE1 at the root. We call such a tree an "inter-AS tree". Multicast data originating in VPLS sites for VPLS X connected to PE1 will travel downstream along the tree which is rooted at PE1.

The path along an inter-AS tree is a sequence of ASBRs. It is still necessary to specify how the multicast data gets from a given ASBR to the set of ASBRs which are immediately downstream of the given ASBR along the tree. This is done by creating "segments": ASBRs in

adjacent ASes will be connected by inter-AS segments, ASBRs in the same AS will be connected by "intra-AS segments".

For a given inter-AS tree and a given AS there MUST be only one ASBR within that AS that accepts traffic flowing on that tree. Further for a given inter-AS tree and a given AS there MUST be only one ASBR in that AS that sends the traffic flowing on that tree to a particular adjacent AS. The precise rules for accomplishing this are given in subsequent sections.

An ASBR initiates creation of an intra-AS segment when the ASBR receives an inter-AS auto-discovery route from an E-BGP neighbor. Creation of the segment is completed as a result of distributing, via I-BGP, this route within the ASBR's own AS.

For a given inter-AS tunnel each of its intra-AS segments could be constructed by its own independent mechanism. Moreover, by using upstream-assigned labels within a given AS multiple intra-AS segments of different inter-AS tunnels of either the same or different VPLSes may share the same P-Multicast tree.

If the P-Multicast tree instantiating a particular segment of an inter-AS tunnel is created by a multicast control protocol that uses receiver-initiated joins (e.g, mLDP), and this P-Multicast tree does not aggregate multiple segments, then all the information needed to create that segment will be present in the inter-AS auto-discovery routes received by the ASBR from the neighboring ASBR. But if the P-Multicast tree instantiating the segment is created by a protocol that does not use receiver-initiated joins (e.g., RSVP-TE, ingress unicast replication), or if this P-Multicast tree aggregates multiple segments (irrespective of the multicast control protocol used to create the tree), then the ASBR needs to learn the leaves of the segment. These leaves are learned from A-D routes received from other PEs in the AS, for the same VPLS (i.e. same VE-ID) as the one that the segment belongs to.

The following sections specify procedures for propagation of inter-AS auto-discovery routes across ASes in order to construct inter-AS segmented trees.

10.2.2.1. Propagating Intra-AS VPLS A-D routes in E-BGP

For a given VPLS configured on an ASBR when the ASBR receives intra-AS A-D routes originated by PEs in its own AS, the ASBR MUST propagate each of these route in E-BGP. This procedure MUST be performed for each of the VPLSes configured on the ASBR. Each of these routes is constructed as follows:

+ The route carries a single BGP VPLS A-D NLRI with the RD and VE ID being the same as the NLRI in the received intra-AS A-D route.

+ The Next Hop field of the MP_REACH_NLRI attribute is set to a routable IP address of the ASBR.

+ The route carries the PMSI Tunnel attribute with the Tunnel Type set to Ingress Replication; the attribute carries no MPLS labels.

+ The route MUST carry the export Route Target used by the VPLS.

10.2.2.2. Inter-AS A-D route received via E-BGP

When an ASBR receives from one of its E-BGP neighbors a BGP Update message that carries an inter-AS auto-discovery route, if (a) at least one of the Route Targets carried in the message matches one of the import Route Targets configured on the ASBR, and (b) the ASBR determines that the received route is the best route to the destination carried in the NLRI of the route, the ASBR re-advertises this inter-AS auto-discovery route to other PEs and ASBRs within its own AS. The best route selection procedures MUST ensure that for the same destination, all ASBRs in an AS pick the same route as the best route. The best route selection procedures are specified in [RFC4761] and clarified in [MULTI-HOMING]. The best route procedures ensure that if multiple ASBRs, in an AS, receive the same inter-AS A-D route from their E-BGP neighbors, only one of these ASBRs propagates this route in I-BGP. This ASBR becomes the root of the intra-AS segment of the inter-AS tree and ensures that this is the only ASBR that accepts traffic into this AS from the inter-AS tree.

When re-advertising an inter-AS auto-discovery route the ASBR MUST set the Next Hop field of the MP_REACH_NLRI attribute to a routable IP address of the ASBR.

Depending on the type of a P-Multicast tunnel used to instantiate the intra-AS segment of the inter-AS tunnel, the PMSI Tunnel attribute of the re-advertised inter-AS auto-discovery route is constructed as follows:

+ If the ASBR uses ingress replication to instantiate the intra-AS segment of the inter-AS tunnel, the re-advertised route MUST NOT carry the PMSI Tunnel attribute.

+ If the ASBR uses a P-Multicast tree to instantiate the intra-AS segment of the inter-AS tunnel, the PMSI Tunnel attribute MUST contain the identity of the tree that is used to instantiate the segment (note that the ASBR could create the identity of the tree

prior to the actual instantiation of the segment). If in order to instantiate the segment the ASBR needs to know the leaves of the tree, then the ASBR obtains this information from the auto-discovery routes received from other PEs/ASBRs in ASBR's own AS.

+ An ASBR that uses a P-Multicast tree to instantiate the intra-AS segment of the inter-AS tunnel MAY aggregate two or more VPLSes present on the ASBR onto the same tree. If the ASBR already advertises inter-AS auto-discovery routes for these VPLSes, then aggregation requires the ASBR to re-advertise these routes. The re-advertised routes MUST be the same as the original ones, except for the PMSI Tunnel attribute. If the ASBR has not previously advertised inter-AS auto-discovery routes for these VPLSes, then the aggregation requires the ASBR to advertise (new) inter-AS auto-discovery routes for these VPLSes. The PMSI Tunnel attribute in the newly advertised/re-advertised routes MUST carry the identity of the P-Multicast tree that aggregates the VPLSes, as well as an MPLS upstream-assigned label [RFC5331]. Each re-advertised route MUST have a distinct label.

In addition the ASBR MUST send to the E-BGP neighbor, from whom it receives the inter-AS auto-discovery route, a BGP Update message that carries a "leaf auto-discovery route". The exact encoding of this route is described in section 12. This route contains the following information elements:

+ The route carries a single NLRI with the Route Key field set to the <RD, VE ID> tuple of the BGP VPLS A-D NLRI of the inter-AS auto-discovery route received from the E-BGP neighbor. The NLRI also carries the IP address of the ASBR (this MUST be a routable IP address).

+ The leaf auto-discovery route MUST include the PMSI Tunnel attribute with the Tunnel Type set to Ingress Replication, and the Tunnel Identifier set to a routable address of the advertising router. The PMSI Tunnel attribute MUST carry a downstream assigned MPLS label that is used to demultiplex the VPLS traffic received over a unicast tunnel by the advertising router.

+ The Next Hop field of the MP_REACH_NLRI attribute of the route SHOULD be set to the same IP address as the one carried in the Originating Router's IP Address field of the route.

+ To constrain the distribution scope of this route the route MUST carry the NO_ADVERTISE BGP community ([RFC1997]).

+ The ASBR constructs an IP-based Route Target extended community by placing the IP address carried in the next hop of the received Inter-AS VPLS A-D route in the Global Administrator field of the community, with the Local Administrator field of this community set to 0, and sets the Extended Communities attribute of the Leaf A-D route to that community. Note that this Route Target is the same as the ASBR Import RT of the EBGP neighbor from which the ASBR received the inter-AS VPLS A-D route.

10.2.2.3. Leaf A-D Route received via E-BGP

When an ASBR receives via E-BGP a leaf auto-discovery route, the ASBR accepts the route only if (a) at least one of the Route Targets carried in the message matches one of the import Route Targets configured on the ASBR, and (b) the ASBR determines that the received route is the best route to the destination carried in the NLRI of the route.

If the ASBR accepts the leaf auto-discovery route, the ASBR finds an existing auto-discovery route whose BGP-VPLS A-D NLRI has the same value as the <RD, VE-ID> field of the leaf auto-discovery route.

The MPLS label carried in the PMSI Tunnel attribute of the leaf auto-discovery route is used to stitch a one hop ASBR-ASBR LSP to the tail of the intra-AS tunnel segment associated with the found auto-discovery route.

10.2.2.4. Inter-AS A-D Route received via I-BGP

In the context of this section we use the term "PE/ASBR router" to denote either a PE or an ASBR router.

Note that a given inter-AS auto-discovery route is advertised within a given AS by only one ASBR as described above.

When a PE/ASBR router receives from one of its I-BGP neighbors a BGP Update message that carries an inter-AS auto-discovery route, if (a) at least one of the Route Targets carried in the message matches one of the import Route Targets configured on the PE/ASBR, and (b) the PE/ASBR determines that the received route is the best route to the destination carried in the NLRI of the route, the PE/ASBR performs the following operations. The best route determination is based as described in [RFC4761] and clarified in [MULTI-HOMING].

If the router is an ASBR then the ASBR propagates the route to its E-BGP neighbors. When propagating the route to the E-BGP neighbors the ASBR MUST set the Next Hop field of the MP_REACH_NLRI attribute to a routable IP address of the ASBR.

If the received inter-AS auto-discovery route carries the PMSI Tunnel attribute with the Tunnel Type set to LDP P2MP LSP, the PE/ASBR SHOULD join the P-Multicast tree whose identity is carried in the PMSI Tunnel attribute.

If the received inter-AS auto-discovery route carries the PMSI Tunnel attribute with the Tunnel Identifier set to RSVP-TE P2MP LSP, then the ASBR that originated the route MUST establish an RSVP-TE P2MP LSP with the local PE/ASBRas a leaf. This LSP MAY have been established before the local PE/ASBR receives the route, or MAY be established after the local PE receives the route.

If the received inter-AS auto-discovery route carries the PMSI Tunnel attribute with the Tunnel Type set to LDP P2MP LSP, or RSVP-TE P2MP LSP, but the attribute does not carry a label, then the P-Multicast tree, as identified by the PMSI Tunnel attribute, is an intra-AS LSP segment that is part of the inter-AS Tunnel for the <VPLS, VE ID> advertised by the inter-AS auto-discovery route and rooted at the PE that originated the auto-discovery route. If the PMSI Tunnel attribute carries a (upstream-assigned) label, then a combination of this tree and the label identifies the intra-AS segment. If the received router is an ASBR, this intra-AS segment may further be stitched to ASBR-ASBR inter-AS segment of the inter-AS tunnel. If the PE/ASBR has local receivers in the VPLS, packets received over the intra-AS segment must be forwarded to the local receivers using the local VSI.

10.3. Option (c): Non-Segmented Tunnels

In this model. there is a multi-hop E-BGP peering between the PEs (or a Route Reflector) in one AS and the PEs (or Route Reflector) in another AS. The PEs exchange BGP-VPLS NLRI or BGP-VPLS A-D NLRI, along with PMSI Tunnel attribute, as in the intra-AS case described in section 8. An implementation MUST support this model.

The PEs in different ASs use a non-segmented inter-AS P2MP tunnel for VPLS multicast. A non-segmented inter-AS tunnel is a single tunnel which spans AS boundaries. The tunnel technology cannot change from one point in the tunnel to the next, so all ASes through which the tunnel passes must support that technology. In essence, AS boundaries are of no significance to a non-segmented inter-AS P2MP tunnel.

This model requires no VPLS A-D routes in the control or VPLS MAC address learning in the data plane on the ASBRs. The ASBRs only need to participate in the non-segmented P2MP tunnel setup in the control plane, and do MPLS label forwarding in the data plane.

The setup of non-segmented inter-AS P2MP tunnels MAY require the P-routers in one AS to have IP reachability to the loopback addresses of the PE routers in another AS, depending on the tunneling technology chosen. If this is the case, reachability to the loopback addresses of PE routers in one AS MUST be present in the IGP in another AS.

The data forwarding in this model is the same as in the intra-AS case described in section 8.

11. Optimizing Multicast Distribution via Selective Trees

Whenever a particular multicast stream is being sent on an Inclusive P-Multicast tree, it is likely that the data of that stream is being sent to PEs that do not require it as the sites connected to these PEs may have no receivers for the stream. If a particular stream has a significant amount of traffic, it may be beneficial to move it to a Selective P-Multicast tree which has at its leaves only those PEs, connected to sites that have receivers for the multicast stream (or at least includes fewer PEs that are attached to sites with no receivers compared to an Inclusive tree).

A PE connected to the multicast source of a particular multicast stream may be performing explicit tracking i.e. it may know the PEs that have receivers in the multicast stream. Section 11.3 describes procedures that enable explicit tracking. If this is the case Selective P-Multicast trees can also be triggered on other criteria. For instance there could be a "pseudo wasted bandwidth" criteria: switching to a Selective tree would be done if the bandwidth multiplied by the number of uninterested PEs (PE that are receiving the stream but have no receivers) is above a specified threshold. The motivation is that (a) the total bandwidth wasted by many sparsely subscribed low-bandwidth groups may be large, and (b) there's no point to moving a high-bandwidth group to a Selective tree if all the PEs have receivers for it.

Switching a (C-S, C-G) stream to a Selective P-Multicast tree may require the root of the tree to determine the egress PEs that need to receive the (C-S, C-G) traffic. This is true in the following cases:

+ If the tunnel is a P2MP tree, such as a RSVP-TE P2MP Tunnel, the PE needs to know the leaves of the tree before it can instantiate the Selective tree.

+ If a PE decides to send traffic for multicast streams, belonging to different VPLSes, using one P-Multicast Selective tree, such a tree is termed an Aggregate tree with a selective mapping. The setting up of such an Aggregate tree requires the ingress PE to know all the other PEs that have receivers for multicast groups that are mapped onto the tree.

+ If ingress replication is used and the ingress PE wants to send traffic for (C-S, C-G)s to only those PEs that are on the path to receivers to the (C-S,C-G)s.

For discovering the IP multicast group membership, for the above cases, this document describes procedures that allow an ingress PE to enable explicit tracking. Thus an ingress PE can request the IP multicast membership from egress PEs for one or more C-multicast streams. These procedures are described in section 11.3.

The root of the Selective P-Multicast tree MAY decide to do explicit tracking of the IP multicast stream only after it has determined to move the stream to a Selective tree, or it MAY have been doing explicit tracking all along. This document also describes explicit tracking for a wild-card source and/or group in section 11.3, which facilitates a Selective P-Multicast tree only mode in which IP multicast streams are always carried on a Selective P-Multicast tree. In the description on Selective P-Multicast trees the notation C-S, is intended to representeither a specific source address or a wildcard. Similarly C-G is intended to represent either a specific group address or a wildcard.

The PE at the root of the tree MUST signal the leaves of the tree that the (C-S, C-G) stream is now bound to the to the Selective Tree. Note that the PE could create the identity of the P-Multicast tree prior to the actual instantiation of the tunnel.

If the Selective tree is instantiated by a RSVP-TE P2MP LSP the PE at the root of the tree MUST establish the P2MP RSVP-TE LSP to the leaves. This LSP MAY have been established before the leaves receive the Selective tree binding, or MAY be established after the leaves receives the binding. A leaf MUST not switch to the Selective tree until it receives the binding and the RSVP-TE P2MP LSP is setup to the leaf.

11.1. Protocol for Switching to Selective Trees

Selective trees provide a PE the ability to create separate P-Multicast trees for certain <C-S, C-G> streams. The source PE, that originates the Selective tree, and the egress PEs, MUST use the Selective tree for the <C-S, C-G> streams that are mapped to it. This may require the source and egress PEs to switch to the Selective tree from an Inclusive tree if they were already using an Inclusive tree for the <C-S, C-G> streams mapped to the Selective tree.

Once a source PE decides to setup an Selective tree, it MUST announce the mapping of the <C-S, C-G> streams (which may be in different VPLSes) that are mapped to the tree to the other PEs using BGP. After the egress PEs receive the announcement they setup their forwarding path to receive traffic on the Selective tree if they have one or more receivers interested in the <C-S, C-G> streams mapped to the tree. Setting up the forwarding path requires setting up the demultiplexing forwarding entries based on the top MPLS label (if there is no inner label) or the inner label (if present) as described in section 9. The egress PEs MAY perform this switch to the Selective tree once the advertisement from the ingress PE is received or wait for a preconfigured timer to do so, after receiving the advertisement, when the P2MP LSP protocol is mLDP. When the P2MP LSP protocol is P2MP RSVP-TE an egress PE MUST perform this switch to the Selective tree only after the advertisement from the ingress PE is received and the RSVP-TE P2MP LSP has been setup to the egress PE. This switch MAY be done after waiting for a preconfigured timer after these two steps have been accomplished.

A source PE MUST use the following approach to decide when to start transmitting data on the Selective tree, if it was already using an Inclusive tree. A certain pre-configured delay after advertising the <C-S, C-G> streams mapped to an Selective tree, the source PE begins to send traffic on the Selective tree. At this point it stops to send traffic for the <C-S, C-G> streams, that are mapped on the Selective tree, on the Inclusive tree. This traffic is instead transmitted on the Selective tree.

11.2. Advertising C-(S, G) Binding to a Selective Tree

The ingress PE informs all the PEs that are on the path to receivers of the (C-S, C-G) of the binding of the Selective tree to the (C-S, C-G), using BGP. The BGP announcement is done by sending update for the MCAST-VPLS address family using what is referred to as the S-PMSI A-D route. The format of the NLRI is described in section 12.1. The NLRI MUST be constructed as follows:

+ The RD MUST be set to the RD configured locally for the VPLS. This is required to uniquely identify the <C-S, C-G> as the addresses could overlap between different VPLSes. This MUST be the same RD value used in the VPLS auto-discovery process.

+ The Multicast Source field MUST contain the source address associated with the C-multicast stream, and the Multicast Source Length field is set appropriately to reflect this. If the source address is a wildcard the source address is set to 0.

+ The Multicast Group field MUST contain the group address associated with the C-multicast stream, and the Multicast Group Length field is set appropriately to reflect this. If the group address is a wildcard the group address is set to 0.

+ The Originating Router's IP Address field MUST be set to the IP address that the (local) PE places in the BGP next-hop of the BGP-VPLS A-D routes. Note that the <RD, Originating Router's IP address> tuple uniquely identifies a given VPLS.

The PE constructs the rest of the Selective A-D route as follows.

Depending on the type of a P-Multicast tree used for the P-tunnel, the PMSI tunnel attribute of the S-PMSI A-D route is constructed as follows:

+ The PMSI tunnel attribute MUST contain the identity of the P-Multicast tree (note that the PE could create the identity of the tree prior to the actual instantiation of the tree).

+ If in order to establish the P-Multicast tree the PE needs to know the leaves of the tree within its own AS, then the PE obtains this information from the Leaf A-D routes received from other PEs/ASBRs within its own AS (as other PEs/ASBRs originate Leaf A-D routes in response to receiving the S-PMSI A-D route) by setting the Leaf Information Required flag in the PMSI Tunnel attribute to 1. This enables explicit tracking for the multicast stream(s) advertised by the S-PMSI A-D route.

+ If a PE originates S-PMSI A-D routes with the Leaf Information Required flag in the PMSI Tunnel attribute set to 1, then the PE MUST be (auto)configured with an import Route Target, which controls acceptance of Leaf A-D routes by the PE. (Procedures for originating Leaf A-D routes by the PEs that receive the S-PMSI A-D route are described in section "Receiving S-PMSI A-D routes by PEs.)

This Route Target is IP address specific. The Global Administrator field of this Route Target MUST be set to the IP address carried in the Next Hop of all the S-PMSI A-D routes advertised by this PE (if the PE uses different Next Hops, then the PE MUST be (auto)configured with multiple import RTs, one per each such Next Hop). The Local Administrator field of this Route Target MUST be set to 0.

If the PE supports Route Target Constrain [RFC4684], the PE SHOULD advertise this import Route Target within its own AS using Route Target Constrains. To constrain distribution of the Route Target Constrain routes to the AS of the advertising PE these routes SHOULD carry the NO_EXPORT Community ([RFC1997]).

+ A PE MAY aggregate two or more S-PMSIs originated by the PE onto the same P-Multicast tree. If the PE already advertises S-PMSI A-D routes for these S-PMSIs, then aggregation requires the PE to re-advertise these routes. The re-advertised routes MUST be the same as the original ones, except for the PMSI tunnel attribute. If the PE has not previously advertised S-PMSI A-D routes for these S-PMSIs, then the aggregation requires the PE to advertise (new) S-PMSI A-D routes for these S-PMSIs. The PMSI Tunnel attribute in the newly advertised/re-advertised routes MUST carry the identity of the P-Multicast tree that aggregates the S-PMSIs. If at least some of the S-PMSIs aggregated onto the same P-Multicast tree belong to different VPLSes, then all these routes MUST carry an MPLS upstream assigned label [RFC5331]. If all these aggregated S-PMSIs belong to the same VPLS, then the routes MAY carry an MPLS upstream assigned label [RFC5331]. The labels MUST be distinct on a per VPLS basis, and MAY be distinct on a per route basis.

The Next Hop field of the MP_REACH_NLRI attribute of the route SHOULD be set to the same IP address as the one carried in the Originating Router's IP Address field.

By default the set of Route Targets carried by the route MUST be the same as the Route Targets carried in the BGP-VPLS A-D route originated from the VSI. The default could be modified via configuration.

11.3. Receiving S-PMSI A-D routes by PEs

Consider a PE that receives an S-PMSI A-D route. If one or more of the VSIs on the PE have their import Route Targets that contain one or more of the Route Targets carried by the received S-PMSI A-D route, then for each such VSI the PE performs the following.

Procedures for receiving an S-PMSI A-D route by a PE (both within and outside of the AS of the PE that originates the route) are the same as specified in Section "Inter-AS A-D route received via IBGP" except that (a) instead of Inter-AS I-PMSI A-D routes the procedures apply to S-PMSI A-D routes, and (b) the rules for determining whether the received S-PMSI A-D route is the best route to the destination carried in the NLRI of the route, are the same as BGP path selection rules and may be modified by policy, and (c) a PE performs procedures specified in that section only if in addition to the criteria specified in that section the following is true:

+ If as a result of multicast state snooping on the PE-CE interfaces, the PE has snooped state for at least one multicast join that matches the multicast source and group advertised in the S-PMSI A-D route. Further if the oif (outgoing interfaces) for this state contains one or more interfaces to the locally attached CEs. When the multicast signaling protocol among the CEs is IGMP, then snooping and associated procedures are defined in [RFC 4541]. The snooped state is determined using these procedures. When the multicast signaling protocol among the CEs is PIM the, procedures in RFC4541 are not sufficient to determine the snooped state. The additional details required to determine the snooped state when CE-CE protocol is PIM are for further study. When such procedures are defined it is expected that the procedures in this section will apply to the snooped state created as a result of PIM as CE-CE protocol.

The snooped state is said to "match" the S-PMSI A-D route if any of the following is true:

+ The S-PMSI A-D route carries (C-S, C-G) and the snooped state is for (C-S, C-G). OR

+ The S-PMSI A-D route carries (C-*, C-G) and (a) the snooped state is for (C-*, C-G) OR (b) the snooped state is for at least one multicast join with the multicast group address equal to C-G and there doesn't exist another S-PMSI A-D route that carries (C-S, C-G) where C-S is the source address of the snooped state.

+ The S-PMSI A-D route carries (C-S, C-*) and (a) the snooped state is for at least one multicast join with the multicast source address equal to C-S, and (b) there doesn't exist another S-PMSI A-D route that carries (C-S, C-G) where C-G is the group address of the snooped state.

+ The S-PMSI A-D route carries (C-*, C-*) and there is no other S-PMSI A-D route that matches the snooped state as per the above conditions.

Note if the above conditions are true, and if the received S-PMSI A-D route has a PMSI Tunnel attribute with the Leaf Information Required flag set to 1, then the PE originates a Leaf A-D route. The Route Key of the Leaf A-D route is set to the MCAST-VPLS NLRI of the S-PMSI A-D route. The rest of the Leaf A-D route is constructed using the same procedures as specified in section "Originating Leaf A-D route into IBGP", except that instead of originating Leaf A-D routes in response to receiving Inter-AS A-D routes the procedures apply to originating Leaf A-D routes in response to receiving S-PMSI A-D routes.

In addition to the procedures specified in Section "Inter-AS A-D route received via IBGP" the PE MUST set up its forwarding path to receive traffic, for each multicast stream in the matching snooped state, from the tunnel advertised by the S-PMSI A-D route (the PE MUST switch to the Selective tree).

When a new snooped state is created by a PE then the PE MUST first determine if there is a S-PMSI route that matches the snooped state as per the conditions described above. If such a S-PMSI route is found then the PE MUST follow the procedures described in this section, for that particular S-PMSI route.

11.4. Inter-AS Selective Tree

Inter-AS Selective trees support all three options of inter-AS VPLS service, option (a), (b) and (c), that are supported by Inter-AS Inclusive trees. They are constructed in a manner that is very similar to Inter-AS Inclusive trees.

For option (a) and option (b) support inter-AS Selective trees are constructed without requiring a single P-Multicast tree to span multiple ASes. This allows individual ASes to potentially use different P-tunneling technologies.There are two variants of this. One that requires MAC and IP multicast lookup on the ASBRs and another that does not require MAC/IP multicast lookup on the ASBRs and instead builds segmented inter-AS Selective trees.

Segmented Inter-AS Selective trees can also be used with option (c) unlike Segmented Inter-AS Inclusive trees. This is because the S-PMSI A-D routes can be exchanged via ASBRs (even though BGP VPLS A-D routes are not exchanged via ASBRs).

In the case of Option (c) an Inter-AS Selective tree may also be a non-segmented P-Multicast tree that spans multiple ASs.

11.4.1. VSIs on the ASBRs

The requirements on ASBRs, when VSIs are present on the ABSRs, include the requirements presented in section 10. The source ASBR (that receives traffic from another AS) may independently decide whether it wishes to use Selective trees or not. If it uses Selective trees the source ASBR MUST perform a MAC lookup to determine the Selective tree to forward the VPLS packet on.

11.4.1.1. VPLS Inter-AS Selective Tree A-D Binding

The mechanisms for propagating S-PMSI A-D routes are the same as the intra-AS case described in section 12.2. The BGP Selective tree A-D routes generated by PEs in an AS MUST NOT be propagated outside the AS.

11.4.2. Inter-AS Segmented Selective Trees

Inter-AS Segmented Selective trees MUST be used when option (b) is used to provide the inter-AS VPLS service. They MAY be used when option (c) is used to provide the inter-AS VPLS service.

A Segmented inter-AS Selective Tunnel is constructed similar to an inter-AS Segmented Inclusive Tunnel. Namely, such a tunnel is constructed as a concatenation of tunnel segments. There are two types of tunnel segments: an intra-AS tunnel segment (a segment that spans ASBRs within the same AS), and inter-AS tunnel segment (a segment that spans adjacent ASBRs in adjacent ASes). ASes that are spanned by a tunnel are not required to use the same tunneling mechanism to construct the tunnel - each AS may pick up a tunneling mechanism to construct the intra-AS tunnel segment of the tunnel, in its AS.

The PE that decides to set up a Selective tree, advertises the Selective tree to multicast stream binding using a S-PMSI A-D route as per procedures in section 11.2, to the routers in its own AS.

A S-PMSI A-D route advertised outside the AS, to which the originating PE belongs, will be referred to as an inter-AS Selective Tree A-D route (Although this route is originated by a PE as an intra-AS route it is referred to as an inter-AS route outside the AS).

11.4.2.1. Handling S-PMSI A-D routes by ASBRs

Procedures for handling an S-PMSI A-D route by ASBRs (both within and outside of the AS of the PE that originates the route) are the same as specified in Section "Propagating VPLS BGP A-D routes to other ASes", except that instead of Inter-AS BGP-VPLS A-D routes and the BGP-VPLS A-D NLRI these procedures apply to S-PMSI A-D routes and the S-PMSI A-D NLRI.

In addition to these procedures an ASBR advertises a Leaf A-D route in response to a S-PMSI A-D route only if:

+ The S-PMSI A-D route was received via EBGP from another ASBR and the ASBR merges the S-PMSI A-D route into an Inter-AS BGP VPLS A-D route as described in the next section. OR

+ The ASBR receives a Leaf A-D route from a downstream PE or ASBR in response to the S-PMSI A-D route, received from an upstream PE or ASBR, that the ASBR propagated inter-AS to downstream ASBRs and PEs.

+ The ASBR has snooped state from local CEs that matches the NLRI carried in the S-PMSI A-D route as per the following rules:

  i) The NLRI encodes (C-S, C-G) which is the same as the snooped (C-S, C-G) ii) The NLRI encodes (*, C-G) and there is snooped state for at least one (C-S, C-G) and there is no other matching SPMSI A-D route for (C-S, C-G) OR there is snooped state for (*, C-G) iii) The NLRI encodes (*, *) and there is snooped state for at least one (C-S, C-G) or (*, C-G) and there is no other matching SPMSI A-D route for that (C-S, C-G) or (*, C-G) respecively.

The C-multicast data traffic is sent on the Selective tree by the originating PE. When it reaches an ASBR that is on the Inter-AS segmented tree, it is delivered to local receivers, if any. It is then forwarded on any inter-AS or intra-AS segments that exist on the Inter-AS Selective Segmented tree. If the Inter-AS Segmented

Selective Tree is merged onto an Inclusive tree, as described in the next section, the data traffic is forwarded onto the Inclusive tree.

11.4.2.1.1. Merging Selective Tree into an Inclusive Tree

Consider the situation where:

+ An ASBR is receiving (or expecting to receive) inter-AS (C-S, C-G) data from upstream via a Selective tree.

+ The ASBR is sending (or expecting to send) the inter-AS (C-S, C-G) data downstream via an Inclusive tree.

This situation may arise if the upstream providers have a policy of using Selective trees but the downstream providers have a policy of using Inclusive trees. To support this situation, an ASBR MAY, under certain conditions, merge one or more upstream Selective trees into a downstream Inclusive tree. Note that this can be the case only for option (b) and not for option (c) as for option (c) the ASBRs do not have Inclusive tree state.

A Selective tree (corresponding to a particular S-PMSI A-D route) MAY be merged by a particular ASBR into an Inclusive tree (corresponding to a particular Inter-AS BGP VPLS A-D route) if and only if the following conditions all hold:

+ The S-PMSI A-D route and the Inter-AS BGP VPLS A-D route originate in the same AS. The Inter-AS BGP VPLS A-D route carries the originating AS in the AS_PATH attribute of the route. The S-PMSI A-D route carries the originating AS in the AS_PATH attribute of the route.

+ The S-PMSI A-D route and the Inter-AS BGP VPLS A-D route have exactly the same set of RTs.

An ASBR performs merging by stitching the tail end of the P-tunnel, as specified in the the PMSI Tunnel attribute of the S-PMSI A-D route received by the ASBR, to the to the head of the P-tunnel, as specified in the PMSI Tunnel attribute of the Inter-AS BGP VPLS A-D route re-advertised by the ASBR.

An ASBR that merges an S-PMSI A-D route into an Inter-AS BGP VPLS A-D route MUST NOT re-advertise the S-PMSI A-D route.

11.4.3. Inter-AS Non-Segmented Selective trees

Inter-AS Non-segmented Selective trees MAY be used in the case of option (c).

In this method, there is a multi-hop E-BGP peering between the PEs (or a Route Reflector) in one AS and the PEs (or Route Reflector) in another AS. The PEs exchange BGP Selective tree A-D routes, along with PMSI Tunnel attribute, as in the intra-AS case described in section 10.3.

The PEs in different ASs use a non-segmented Selective inter-AS P2MP tunnel for VPLS multicast.

This method requires no VPLS information (in either the control or the data plane) on the ASBRs. The ASBRs only need to participate in the non-segmented P2MP tunnel setup in the control plane, and do MPLS label forwarding in the data plane.

The data forwarding in this model is the same as in the intra-AS case described in section 9.

12. BGP Extensions

This section describes the encoding of the BGP extensions required by this document.

12.1. Inclusive Tree/Selective Tree Identifier

Inclusive P-Multicast tree and Selective P-Multicast tree advertisements carry the P-Multicast tree identifier.

This document reuses the BGP attribute, called PMSI Tunnel attribute that is defined in [BGP-MVPN].

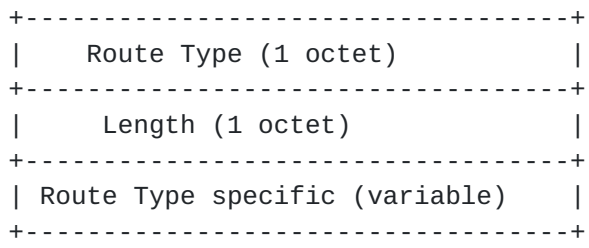
This document supports only the following Tunnel Types when PMSI Tunnel attribute is carried in VPLS A-D or VPLS S-PMSI A-D routes:

+ 0 - No tunnel information present
+ 1 - RSVP-TE P2MP LSP
+ 2 - LDP P2MP LSP
+ 6 - Ingress Replication

12.2. MCAST-VPLS NLRI

This document defines a new BGP NLRI, called the MCAST-VPLS NLRI.

Following is the format of the MCAST-VPLS NLRI:



The Route Type field defines encoding of the rest of MCAST-VPLS NLRI (Route Type specific MCAST-VPLS NLRI).

The Length field indicates the length in octets of the Route Type specific field of MCAST-VPLS NLRI.

This document defines the following Route Types for auto-discovery routes:

+ 3 - Selective Tree auto-discovery route;
+ 4 - Leaf auto-discovery route.

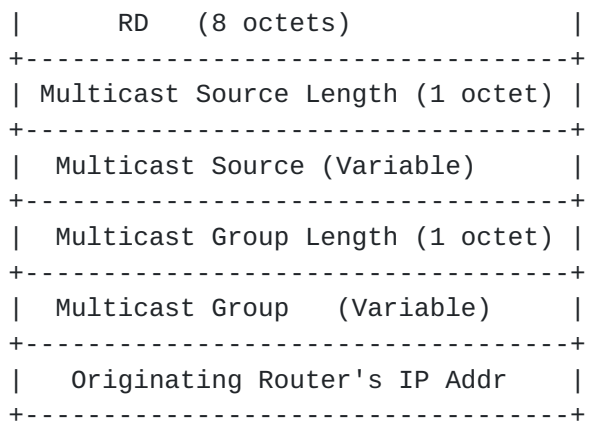
The MCAST-VPLS NLRI is carried in BGP using BGP Multiprotocol Extensions [RFC4760] with an AFI of 25 (L2VPN AFI), and an SAFI of MCAST-VPLS [To be assigned by IANA]. The NLRI field in the MP_REACH_NLRI/MP_UNREACH_NLRI attribute contains the MCAST-VPLS NLRI (encoded as specified above).

In order for two BGP speakers to exchange labeled MCAST-VPLS NLRI, they must use BGP Capabilities Advertisement to ensure that they both are capable of properly processing such NLRI. This is done as specified in [RFC4760], by using capability code 1 (multiprotocol BGP) with an AFI of 25 and an SAFI of MCAST-VPLS.

The following describes the format of the Route Type specific MCAST-VPLS NLRI for various Route Types defined in this document.

12.2.1. S-PMSI auto-discovery route

An S-PMSI A-D route type specific MCAST-VPLS NLRI consists of the following:



The RD is encoded as described in [RFC4364].

The Multicast Source field contains the C-S address i.e the address of the multicast source. If the Multicast Source field contains an IPv4 address, then the value of the Multicast Source Length field is 32. If the Multicast Source field contains an IPv6 address, then the value of the Multicast Source Length field is 128. The value of the Multicast Source Length field may be set to 0 to indicate a wildcard.

The Multicast Group field contains the C-G address i.e. the address of the multicast group. If the Multicast Group field contains an IPv4 address, then the value of the Multicast Group Length field is 32. If the Multicast Group field contains an IPv6 address, then the value of the Multicast Group Length field is 128. The Multicast Group Length field may be set to 0 to indicate a wildcard.

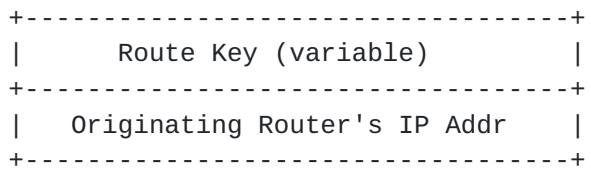
Whether the Originating Router's IP Address field carries an IPv4 or IPv6 address is determined from the value of the Length field of the MCAST-VPLS NLRI. If the Multicast Source field contains an IPv4 address and the Multicast Group field contains an IPv4 address, then the value of the Length field is 22 if the Originating Router's IP address carries an IPv4 address and 34 if it is an IPv6 address. If the Multicast Source and Multicast Group fields contain IPv6 addresses, then the value of the Length field is 46 if the Originating Router's IP address carries an IPv4 address and 58 if it is an IPv6 address. The following table summarizes the above.

Multicast Source	Multicast Group	Originating Router's IP Address	Length
IPv4	IPv4	IPv4	22
IPv4	IPv4	IPv6	34
IPv6	IPv6	IPv4	46
IPv6	IPv6	IPv6	58

Usage of Selective Tree auto-discovery routes is described in Section 11.

12.2.2. Leaf auto-discovery route

A leaf auto-discovery route type specific MCAST-VPLS NLRI consists of the following:



Whether the Originating Router's IP Address field carries an IPv4 or IPv6 address is determined from the Length field of the MCAST-VPLS NLRI and the length field of the Route Key. From these two length fields one can compute the length of the Originating Router's IP Address. If this computed length is 4 then the address is an IPv4 address and if its 16 then the address is an IPv6 address.

Usage of Leaf auto-discovery routes is described in sections "Inter-AS Inclusive P-Multicast tree A-D/Binding" and "Optimizing Multicast Distribution via Selective trees".

13. Aggregation Considerations

In general the heuristic used to decide which VPLS instances or <C-S, C-G> entries to aggregate is implementation dependent. It is also conceivable that offline tools can be used for this purpose. This section discusses some tradeoffs with respect to aggregation.

The "congruency" of aggregation is defined by the amount of overlap in the leaves of the client trees that are aggregated on a SP tree. For Aggregate Inclusive trees the congruency depends on the overlap in the membership of the VPLSes that are aggregated on the Aggregate Inclusive tree. If there is complete overlap aggregation is perfectly congruent. As the overlap between the VPLSes that are aggregated reduces, the congruency reduces.

If aggregation is done such that it is not perfectly congruent a PE may receive traffic for VPLSes to which it doesn't belong. As the amount of multicast traffic in these unwanted VPLSes increases aggregation becomes less optimal with respect to delivered traffic. Hence there is a tradeoff between reducing state and delivering unwanted traffic.

An implementation should provide knobs to control the congruency of aggregation. This will allow a SP to deploy aggregation depending on the VPLS membership and traffic profiles in its network. If different PEs or shared roots' are setting up Aggregate Inclusive trees this will also allow a SP to engineer the maximum amount of unwanted VPLSes that a particular PE may receive traffic for.

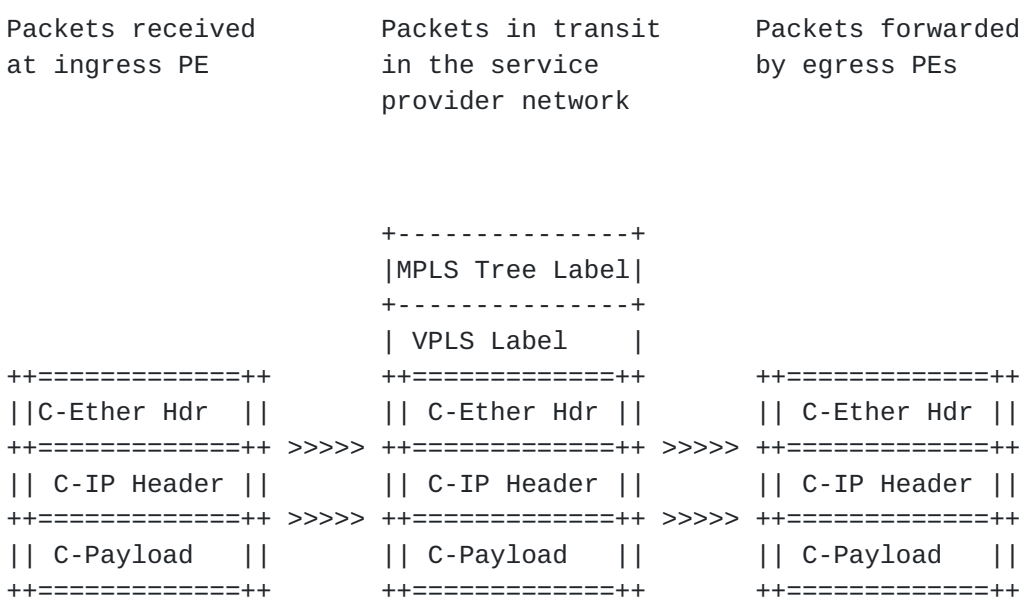
The state/bandwidth optimality trade-off can be further improved by having a versatile many-to-many association between client trees and provider trees. Thus a VPLS can be mapped to multiple Aggregate trees. The mechanisms for achieving this are for further study. Also it may be possible to use both ingress replication and an Aggregate tree for a particular VPLS. Mechanisms for achieving this are also for further study.

14. Data Forwarding

14.1. MPLS Tree Encapsulation

14.1.1. Mapping multiple VPLS instances to a P2MP LSP

The following diagram shows the progression of the VPLS multicast packet as it enters and leaves the SP network when MPLS trees are being used for multiple VPLS instances. RSVP-TE P2MP LSPs are examples of such trees.



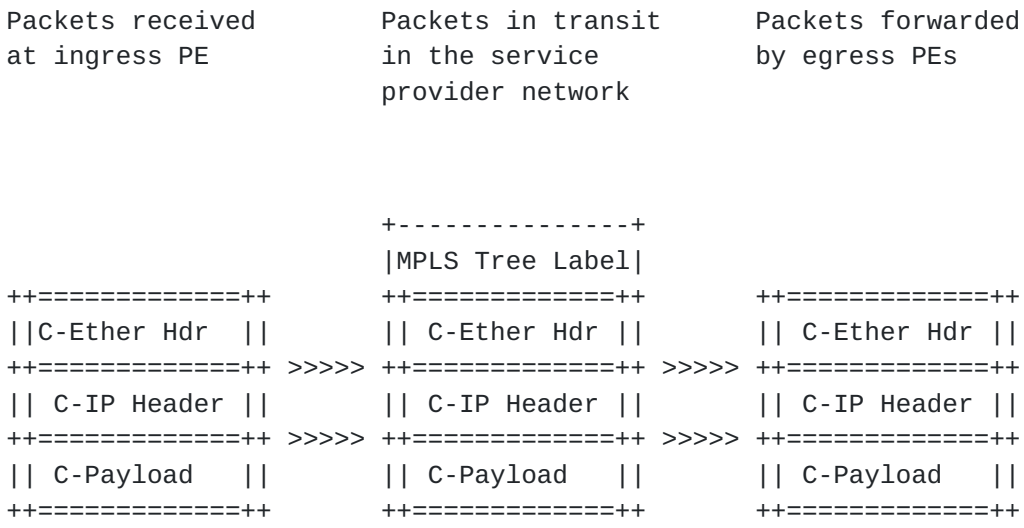
The receiver PE does a lookup on the outer MPLS tree label and

determines the MPLS forwarding table in which to lookup the inner MPLS label. This table is specific to the tree label space. The inner label is unique within the context of the root of the tree (as it is assigned by the root of the tree, without any coordination with any other nodes). Thus it is not unique across multiple roots. So, to unambiguously identify a particular VPLS one has to know the label, and the context within which that label is unique. The context is provided by the outer MPLS label [RFC5331].

The outer MPLS label is stripped. The lookup of the resulting MPLS label determines the VSI in which the receiver PE needs to do the C-multicast data packet lookup. It then strips the inner MPLS label and sends the packet to the VSI for multicast data forwarding.

14.1.2. Mapping one VPLS instance to a P2MP LSP

The following diagram shows the progression of the VPLS multicast packet as it enters and leaves the SP network when a given MPLS tree is being used for a single VPLS instance. RSVP-TE P2MP LSPs are examples of such trees.



The receiver PE does a lookup on the outer MPLS tree label and determines the VSI in which the receiver PE needs to do the C-multicast data packet lookup. It then strips the inner MPLS label and sends the packet to the VSI for multicast data forwarding.

15. VPLS Data Packet Treatment

If the destination MAC address of a VPLS packet received by a PE from a VPLS site is a multicast address, a P-Multicast tree SHOULD be used to transport the packet, if possible. If the packet is an IP multicast packet and a Selective tree exists for that multicast stream, the Selective tree MUST be used. Else if a (C-*, C-*) Selective tree exisits for the VPLS it SHOULD be used. Else if an Inclusive tree exists for the VPLS, it SHOULD be used.

If the destination MAC address of a VPLS packet is a broadcast address, it is flooded. If a (C-*, C-*) Selective tree exists for the VPLS the PE SHOULD flood over it. Else if Inclusive tree exists for the VPLS the PE SHOULD flood over it. Else the PE MUST flood over multiple PWs, based on [RFC4761] or [RFC4762].

If the destination MAC address of a packet is a unicast address and it has not been learned, the packet MUST be sent to all PEs in the VPLS. Inclusive P-Multicast trees or a Selective P-Multicast tree bound to (C-*, C-*) SHOULD be used for sending unknown unicast MAC packets to all PEs. When this is the case the receiving PEs MUST support the ability to perform MAC address learning for packets received on a multicast tree. In order to perform such learning, the receiver PE MUST be able to determine the sender PE when a VPLS packet is received on a P-Multicast tree. This further implies that the MPLS P-Multicast tree technology MUST allow the egress PE to determine the sender PE from the received MPLS packet.

When a receiver PE receives a VPLS packet with a source MAC address, that has not yet been learned, on a P-Multicast tree, the receiver PE determines the PW to the sender PE. The receiver PE then creates forwarding state in the VPLS instance with a destination MAC address being the same as the source MAC address being learned, and the PW being the PW to the sender PE.

It should be noted that when a sender PE that is sending packets destined to an unknown unicast MAC address over a P-Multicast tree learns the PW to use for forwarding packets destined to this unicast MAC address, it might immediately switch to transport such packets over this particular PW. Since the packets were initially being forwarded using a P-Multicast tree, this could lead to packet reordering. This constraint should be taken into consideration if unknown unicast frames are forwarded using a P-Multicast tree, instead of multiple PWs based on [RFC4761] or [RFC4762].

An implementation MUST support the ability to transport unknown unicast traffic over Inclusive P-Multicast trees. Further an implementation MUST support the ability to perform MAC address

learning for packets received on a P-Multicast tree.

16. Security Considerations

Security considerations discussed in [RFC4761] and [RFC4762] apply to this document. This section describes additional considerations.

As mentioned in [RFC4761], there are two aspects to achieving data privacy in a VPLS: securing the control plane and protecting the forwarding path. Compromise of the control plane could result in a PE sending multicast data belonging to some VPLS to another VPLS, or blackholing VPLS multicast data, or even sending it to an eavesdropper; none of which are acceptable from a data privacy point of view. The mechanisms in this document use BGP for the control plane. Hence techniques such as in [RFC2385] help authenticate BGP messages, making it harder to spoof updates (which can be used to divert VPLS traffic to the wrong VPLS) or withdraws (denial-of-service attacks). In the multi-AS methods (b) and (c) described in Section 11, this also means protecting the inter-AS BGP sessions, between the ASBRs, the PEs, or the Route Reflectors.

Note that [RFC2385] will not help in keeping MPLS labels, associated with P2MP LSPs or the upstream MPLS labels used for aggregation, private -- knowing the labels, one can eavesdrop on VPLS traffic. However, this requires access to the data path within a Service Provider network.

One of the requirements for protecting the data plane is that the MPLS labels are accepted only from valid interfaces. This applies both to MPLS labels associated with P2MP LSPs and also applies to the upstream assigned MPLS labels. For a PE, valid interfaces comprise links from P routers. For an ASBR, valid interfaces comprise links from P routers and links from other ASBRs in ASes that have instances of a given VPLS. It is especially important in the case of multi-AS VPLSes that one accept VPLS packets only from valid interfaces.

17. IANA Considerations

This document defines a new NLRI, called MCAST-VPLS, to be carried in BGP using multiprotocol extensions. It requires assignment of a new SAFI. This is to be assigned by IANA.

This document defines a BGP optional transitive attribute, called PMSI attribute. This is the same attribute as the one defined in [BGP-MVPN] and the code point for this attribute has already been assigned by IANA as 22 [BGP-IANA]. Hence no further action is

required from IANA regarding this attribute.

18. Acknowledgments

Many thanks to Thomas Morin for his support of this work. We would also like to thank authors of [BGP-MVPN] and [MVPN] as the details of the inter-AS segmented tree procedures in this document have benefited from those in [BGP-MVPN] and [MVPN]. We would also like to thank Wim Henderickx for his comments.

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21. Author's Address

Rahul Aggarwal

998 Lucky Avenue
Menlo Park, CA 94025

Email: raggarwa_1@yahoo.com

Yuji Kamite
NTT Communications Corporation
Tokyo Opera City Tower
3-20-2 Nishi Shinjuku, Shinjuku-ku,
Tokyo 163-1421,
Japan

Email: y.kamite@ntt.com

Luyuan Fang
Cisco Systems
300 Beaver Brook Road
BOXBOROUGH, MA 01719
USA

Email: lufang@cisco.com

Yakov Rekhter
Juniper Networks
1194 North Mathilda Ave.
Sunnyvale, CA 94089
USA

Email: yakov@juniper.net

Chaitanya Kodeboniya