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BGP Color-Aware Routing (CAR)
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Abstract

This document describes a BGP based routing solution to establish end-to-end intent-aware paths across a multi-domain transport network. The transport network can span multiple service provider and customer network domains. The BGP intent-aware paths can be used to steer traffic flows for service routes that need a specific intent. This solution is called BGP Color-Aware Routing (BGP CAR).

This document describes the routing framework and BGP extensions to enable intent-aware routing using the BGP CAR solution. The solution defines two new BGP SAFIs (BGP CAR SAFI and BGP VPN CAR SAFI) for IPv4 and IPv6. It also defines an extensible NLRI model for both SAFIs that allow multiple NLRI types to be defined for different use cases. Each type of NLRI contains key and TLV based non-key fields for efficient encoding of different per-prefix information. This specification defines two NLRI types, Color-Aware Route NLRI and IP Prefix NLRI. It defines non-key TLV types for MPLS label stack, Label Index and SRv6 SIDs. This solution also defines a new Local Color Mapping (LCM) Extended Community.

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1. Introduction

BGP Color-Aware Routing (CAR) is a BGP based routing solution to establish end-to-end intent-aware paths across a multi-domain service provider transport network. BGP CAR distributes distinct routes to a destination network endpoint, such as a PE router, for different intents or colors. Color is a non-zero 32-bit integer value associated with a network intent (low-cost, low-delay, avoid some resources, 5G network slice, etc.) as defined in Section 2.1 of [RFC9256].

BGP CAR fulfills the transport and VPN problem statement and requirements described in [I-D.hr-spring-intentaware-routing-using-color].

For this purpose, this document specifies two new BGP SAFIs, called BGP CAR SAFI (83) and VPN CAR SAFI (84) that carry infrastructure routes to set up the transport paths. Both CAR SAFI and VPN CAR SAFI apply to IPv4 Unicast and IPv6 Unicast AFIs (AFI 1 and AFI 2). The use of these SAFIs with other AFIs are outside the scope of this document.

BGP CAR SAFI can be enabled on transport devices in a provider network (underlay) to set up color-aware transport/infrastructure paths across provider networks. The multi-domain transport network

may comprise of multiple BGP ASes as well as multiple IGP domains within a single BGP AS. BGP CAR SAFI can also be enabled within a VRF on a PE router towards a peering CE router, and on devices within a customer network. VPN CAR SAFI is used for the distribution of intent-aware routes from different customers received on a PE router across the provider networks, maintaining the separation of the customer address spaces that may overlap. The BGP CAR solution thus enables intent-aware transport paths to be set up across a multi-domain network that can span customer and provider network domains.

The document also defines two BGP CAR route types for this purpose.

The BGP CAR Type-1 NLRI (E, C) enables the generation and distribution of multiple color-aware routes to the same destination IP prefix for different colors. This case arises from situations where a transport node such as a PE has a common IP address (such as a loopback) to advertise for multiple intents. The operator intends to use the common IP address as both the BGP next hop for service routes and as the transport endpoint for the data plane path. Multiple routes are needed for this same address or prefix to set up a unique path for each intent. One example is setting up multiple MPLS/SR-MPLS LSPs to an egress PE, one per intent.

The BGP CAR Type-2 NLRI (IP Prefix or E) enables the distribution of multiple color-aware routes to a transport node for the case where the operator specifies a unique network IP address block for a given intent, and the transport node gets assigned a unique IP prefix or address for each intent. An example use-case is SRv6 per-intent locators.

These BGP CAR intent-aware paths are then used by an ingress node (such as a PE) to steer traffic flows for service routes that need the specific intents. Steering may be towards a destination for all or specific traffic flows.

BGP CAR adheres to the flat routing model of BGP-IP/LU(Labeled Unicast) but extends it to support intent-awareness, thereby providing a consistent operational experience with those widely deployed transport routing technologies.

1.1. Terminology

Intent (in routing)	Any behaviors to influence routing or path selection, including any combination of the following behaviors: a) Topology path selection (e.g. minimize metric or avoid resource), b) NFV

	service insertion (e.g. service chain steering), c) per-hop behavior (e.g. a 5G slice). This is a more specific concept w.r.t. routing beyond best-effort, compared to intent as a declarative abstraction in [RFC9315].
Color	A non-zero 32-bit integer value associated with an intent (e.g. low-cost , low-delay, or avoid some resources) as defined in [RFC9256] Section 2.1. Color assignment is managed by the operator.
Colored Service Route	An egress PE (e.g. E2) colors its BGP service (e.g. VPN) route (e.g. V/v) to indicate the intent that it requests for the traffic bound to V/v. The color is encoded as a BGP Color Extended-Community [RFC9012], used as per [RFC9256], or represented by the locator part of SRv6 Service SID [RFC9252].
Color-Aware Path to (E2, C)	A path to forward packets towards E2 which satisfies the intent associated with color C. Several technologies may provide a Color-Aware Path to (E2, C): SR Policy [RFC9256], IGP Flex-Algo [RFC9350], BGP CAR [specified in this document].
Color-Aware Route (E2, C)	A distributed or signaled route that builds a color-aware path to E2 for color C.
Service Route Automated Steering on Color-Aware Path	An ingress PE (or ASBR) E1 automatically steers traffic for a C-colored service route V/v from E2 onto an (E2, C) color-aware path. If several such paths exist, a preference scheme is used to select the best path (for example, IGP Flex-Algo preferred over SR Policy preferred over BGP CAR.
Color Domain	A set of nodes which share the same Color-to-Intent mapping, typically under single administration. This set can be organized into one or multiple network domains (IGP areas/

	instances within a single BGP AS, or multiple BGP ASes). Color-to-intent mapping on nodes is set by configuration. Color re-mapping and filtering may happen at color domain boundaries. Refer to [I-D.hr-spring-intentaware-routing-using-color].
Resolution of a BGP CAR route (E, C)	An inter-domain BGP CAR route (E, C) via N is resolved on an intra-domain color-aware path (N, C) where N is the next hop of the BGP CAR route.
Resolution vs Steering	In this document, and consistent with the terminology used in the SR Policy document [RFC9256] Section 8, (Service route) steering is used to describe the mapping of the traffic for a service route onto a BGP CAR path. In contrast, the term resolution is preserved for the mapping of an inter-domain BGP CAR route on an intra-domain color-aware path.
	Service Steering: Service route maps traffic to a BGP CAR path (or other Color-Aware Path: e.g. SR Policy). If a Color-Aware Path is not available, local policy may map to traditional routing/TE path (e.g. BGP LU, RSVP-TE, IGP/LDP). The service steering concept is agnostic to the transport technology used. Section 3 describes the specific service steering mechanisms leveraged for MPLS, SR-MPLS and SRv6.
	Intra-Domain Resolution: BGP CAR route maps to intra-domain color aware path (e.g. SR Policy, IGP Flex-Algo, BGP CAR) or traditional routing/TE path (e.g. RSVP-TE, IGP/LDP, BGP-LU).
Transport Network	A network that comprises of multiple cooperating domains managed by one or more operators, and uses routing technologies such as IP, MPLS and Segment Routing to forward packets for connectivity and other services. In an SR deployment, the transport network is within a trust domain as per [RFC8402].

Transport Layer	Refers to an underlay network layer (e.g., MPLS LSPs between PEs) that gets used by an overlay or service layer (e.g., MPLS VPNs).
Transport RR	A BGP Route Reflector used to distribute transport/underlay routes within a domain or across domains.
Service RR	A BGP Route Reflector used to distribute service/ overlay routes within a domain or across domains.

Table 1

Abbreviations:

* AFI/SAFI: BGP Address-Family/Sub-Address-Family Identifiers.

* AIGP: Accumulated IGP Metric Attribute [RFC7311].

* BGP-LU: BGP Labeled Unicast SAFI [RFC8277].

* BGP-IP: BGP IPv4/IPv6 Unicast AFI/SAFIs [RFC4271], [RFC4760].

* BR: Border Router, either for an IGP Area (ABR) or a BGP Autonomous System (ASBR).

* Color-EC: BGP Color Extended-Community [RFC9012].

* E: Generic representation of a transport endpoint such as a PE, ABR or ASBR.

* LCM-EC: BGP Local Color Mapping Extended-Community.

* NLRI: Network Layer Reachability Information [RFC4271].

* P node: An intra-domain transport router.

* RR: BGP Route Reflector.

* TEA: Tunnel Encapsulation Attribute [RFC9012].

* V/v, W/w: Generic representations of a service route (indicating prefix/masklength), regardless of AFI/SAFI or actual NLRI encoding.

1.2. Illustration

Here is a brief illustration of the salient properties of the BGP CAR solution.

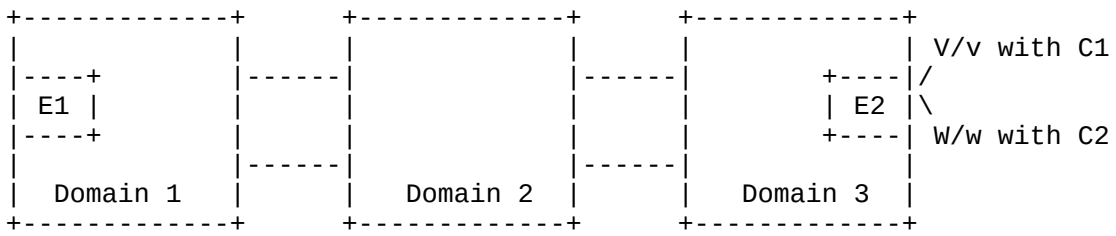


Figure 1: BGP CAR Solution Illustration

All the nodes are part of an inter-domain network under a single authority and with a consistent color-to-intent mapping:

* C1 is mapped to "low-delay"
  - Flex-Algo FA1 is mapped to "low delay" and hence to C1
* C2 is mapped to "low-delay and avoid resource R"
  - Flex-Algo FA2 is mapped to "low delay and avoid resource R" and hence C2

E1 receives two service routes from E2:

* V/v with BGP Color-EC C1
* W/w with BGP Color-EC C2

E1 has the following color-aware paths:

* (E2, C1) provided by BGP CAR with the following per-domain support:
  - Domain1: over IGP FA1
  - Domain2: over SR Policy bound to color C1
  - Domain3: over IGP FA1
* (E2, C2) provided by SR Policy

E1 automatically steers traffic for the received service routes as follows:

* V/v via (E2, C1) provided by BGP CAR

* W/w via (E2, C2) provided by SR Policy

Illustrated Properties:

* Leverage of the BGP Color-EC

  - The service routes are colored with widely used BGP Color Extended-Community [RFC9012] to request intent

* (E, C) Automated Steering

  - V/v and W/w are automatically steered on the appropriate color-aware path

* Seamless co-existence of BGP CAR and SR Policy

  - V/v is steered on BGP CAR color-aware path

  - W/w is steered on SR Policy color-aware path

* Seamless interworking of BGP CAR and SR Policy

  - V/v is steered on a BGP CAR color-aware path that is itself resolved within domain 2 onto an SR Policy bound to the color of V/v

Other properties:

* MPLS data-plane: with 300k PE’s and 5 colors, the BGP CAR solution ensures that no single node needs to support a data-plane scaling in the order of Remote PE * C (Section 5). This would otherwise exceed the MPLS data-plane.

* Control-Plane: a node should not install a (E, C) path if it’s not participating in that color-aware path.

* Incongruent Color-Intent mapping: the solution supports the signaling of a BGP CAR route across different color domains. (Section 2.8)

The key benefits of this model are:

* leverage of the BGP Color-EC [RFC9012] to color service routes

* the definition of the automated service steering: a C-colored service route V/v from E2 is steered onto a color-aware path (E2, C)

* the definition of the data model of a BGP CAR path: (E, C)

  - natural extension of BGP IP/LU data model (E)

  - consistent with SR Policy data model

* the definition of the recursive resolution of a BGP CAR route: a BGP CAR (E2, C) route via N is resolved onto the color-aware path (N, C) which may itself be provided by BGP CAR or via another color-aware routing solution (e.g., SR Policy, IGP Flex-Algo).

* Native support for multiple transport encapsulations (e.g., MPLS, SR, SRv6, IP)

1.3. Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

2. BGP CAR SAFI

2.1. Data Model

The BGP CAR data model is:

* NLRI Key: Falls into two categories, to accommodate the use-cases described in the introduction:

  - Type-1: Key is IP Prefix and Color (E, C). Color in NLRI key distinguishes a color-aware route for a common IP prefix, one per intent. Color also indicates the intent associated with the route.

  - Type-2: Key is IP Prefix (E). The unique IP prefix assigned for an intent (i.e, IP Prefix == Intent or Color) distinguishes the color-aware route. Color is not needed in NLRI key as a distinguisher.

* NLRI non-key encapsulation data: Data such as MPLS label stack, Label Index and SRv6 SID list associated with NLRI. Contained in TLVs as described in Section 2.9.2

* BGP Next Hop.

* AIGP Metric [RFC7311]: accumulates color/intent specific metric value for a CAR route across multiple BGP hops.

* Local-Color-Mapping Extended-Community (LCM-EC): Optional non-zero 32-bit Color value used to represent the intent associated with a CAR route:

  - when the CAR route propagates between different color domains.

  - when the CAR route has a unique IP prefix for an intent.

* BGP Color Extended-Community (Color-EC) [RFC9012]: Optional non-zero 32-bit Color value used to represent the intent associated with the BGP CAR next hop. It is used as per [RFC9256] for automated route resolution, when intent/color used for the next hop is different than the CAR route's intent/color.

The sections below describe the data model in detail. The sections that describe the protocol processing for CAR SAFI generally apply consistently to both route types (for instance, any operation based on color). The examples use (E, C) for simplicity.

2.2. Extensible Encoding

Extensible encoding is provided by:

* NLRI Type field: provides extensibility to add new NLRI formats for new route-types.

  NLRI (Route) Types other than Type-1 (E, C) and Type-2 (E) are outside the scope of this document.

* Key length field: specifies the key length. It allows new NLRI types to be handled opaquely, which permits transitivity of new route types through BGP speakers such as Route Reflectors.

* TLV-based encoding of non-key part of NLRI: This allows the inclusion of additional non-key fields for a prefix to support different types of transport simultaneously with efficient BGP update packing (Section 2.9).

* AIGP Attribute provides extensibility via TLVs, enabling definition of additional metric semantics for a color as needed for an intent.

2.3. BGP CAR Route Origination

A BGP CAR route may be originated locally (e.g., loopback) or through redistribution of an (E, C) color-aware path provided by another routing solution: e.g., SR Policy, IGP Flex-Algo, RSVP-TE, BGP-LU [RFC8277].

2.4. BGP CAR Route Validation

A BGP CAR path (E, C) via next hop N with encapsulation T is valid if color-aware path (N, C) exists with encapsulation T available in data-plane.

A local policy may customize the validation process:

* The color constraint in the first check may be relaxed. If N is reachable via alternate color(s) or in the default routing table, the route may be considered valid.

* The data-plane availability constraint of T may be relaxed to use an alternate encapsulation.

* A performance-measurement verification may be added to ensure that the intent associated with C is met (e.g. delay < bound).

A path that is not valid MUST NOT be considered for BGP best path selection.

2.5. BGP CAR Route Resolution

A BGP color-aware route (E2, C1) with next hop N is automatically resolved over a color-aware route (N, C1) by default. The color-aware route (N, C1) is provided by color aware mechanisms such as IGP Flex-Algo [RFC9350], SR policy [RFC9256] Section 2.2, or recursively by BGP CAR. When multiple producers of (N, C1) are available, the default preference is: IGP Flex-Algo, SR Policy, BGP CAR.

Local policy SHOULD provide additional control:

* A BGP color-aware route (E2, C1) with next hop N may be resolved over a color-aware route (N, C2): i.e., the local policy maps the resolution of C1 over a different color C2.

  - For example, in a domain where resource R is known to not be present, the inter-domain intent C1="low delay and avoid R" may be resolved over an intra-domain path of intent C2="low delay".

- Another example is: if no (N, C1) path is available and the user has allowed resolution to fallback to a C2 path.

* Route resolution may be driven by an egress node. In an SRv6 domain, an egress node selects and advertises an SRv6 SID from its locator for intent C1, with a BGP CAR route. In such a case, the ingress node resolves the received SRv6 SID over an IPv6 route for the intent-aware locator of the egress node for C1 or a summary route that covers the locator. This summary route may be provided by SRv6 Flex Algo or BGP CAR IP Prefix route itself (e.g., Appendix C.2).

* Local policy may map the CAR route to traditional mechanisms that are unaware of color or that provide best-effort, such as RSVP-TE, IGP/LDP, BGP LU/IP (e.g., Appendix A.3.2) for brownfield scenarios.

Route resolution via a different color C2 can be automated by attaching BGP Color-EC C2 to CAR route (E2, C1), leveraging Automated steering as described in Section 8.4 of Segment Routing Policy Architecture [RFC9256] for BGP CAR routes. This mechanism is illustrated in Appendix B.2. This mechanism SHOULD be supported.

For CAR route resolution, Color-EC color if present takes precedence over the route’s intent color (LCM-EC if present (Section 2.9.5), or else NLRI color).

Local policy takes precedence over the color based automated resolution specified above.

The color-aware route (N, C1) may be provided by BGP CAR itself in a hierarchical transport routing design. In such cases, based on the procedures described above, recursive resolution may occur over the same or different CAR route type. Section 7.1.2 describes a scenario where CAR (E, C) route resolves over CAR IP Prefix route.

CAR IP Prefix route is allowed to be without color for best-effort. In this case, resolution is based on BGP next hop N, or when present, a best-effort SRv6 SID advertised by node N.

A BGP CAR route may recursively resolve over a BGP route that carries TEA and follows Section 6 of [RFC9012] for validation. In this case, procedures of section 8 of [RFC9012] apply to BGP CAR routes, using color precedence as specified above for resolution.

The procedures of [RFC9012] Section 6 also apply to BGP CAR routes (AFI/SAFI = 1/83 or 2/83). For instance, a BGP CAR BR may advertise a BGP CAR route to an ingress BR or PE with a specific BGP next hop per color, with a TEA or Tunnel Encapsulation EC, as per Section 6 of [RFC9012].

BGP CAR resolution in one network domain is independent of resolution in another domain.

2.6. AIGP Metric Computation

The Accumulated IGP (AIGP) Attribute [RFC7311] is updated as the BGP CAR route propagates across the network.

The value set (or appropriately incremented) in the AIGP TLV corresponds to the metric associated with the underlying intent of the color. For example, when the color is associated with a low-latency path, the metric value is set based on the delay metric.

Information regarding the metric type used by the underlying intra-domain mechanism can also be used to set the metric value.

If BGP CAR routes traverse across a discontinuity in the transport path for a given intent, a penalty is added in accumulated IGP metric (value set by user policy). For instance, when color C1 path is not available, and route resolves via color C2 path (See Appendix A.3 for an example).

AIGP metric computation is recursive.

To avoid continuous IGP metric changes causing end to end BGP CAR route churn, an implementation should provide thresholds to trigger AIGP update.

Additional AIGP extensions may be defined to signal state for specific use-cases: Maximum SID-Depth along the BGP CAR route advertisement, Minimum MTU along the BGP CAR route advertisement. This is out of scope for this document.

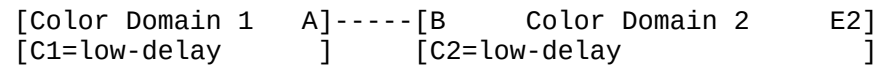
2.7. Native MultiPath Capability

The (E, C) route definition inherently provides availability of redundant paths at every BGP hop identical to BGP-LU or BGP IP. For instance, BGP CAR routes originated by two or more egress ABRs in a domain are advertised as multiple paths to ingress ABRs in the domain, where they become equal-cost or primary-backup paths. A failure of an egress ABR is detected and handled by ingress ABRs locally within the domain for faster convergence, without any

necessity to propagate the event to upstream nodes for traffic restoration.

BGP ADD-PATH [RFC7911] SHOULD be enabled for BGP CAR to signal multiple next hops through a transport RR.

2.8. BGP CAR Signaling through different Color Domains



Let us assume a BGP CAR route (E2, C2) is signaled from B to A, two border routers of respectively domain 2 and domain 1. Let us assume that these two domains do not share the same color-to-intent mapping (i.e., they belong to different color domains). Low-delay in domain 2 is color C2, while it is C1 in domain 1 (C1 <> C2).

It is not expected to be a typical scenario to have an underlay transport path (e.g., an MPLS LSP) extend across different color domains. However, the BGP CAR solution seamlessly supports this rare scenario while maintaining the separation and independence of the administrative authority in different color domains.

The solution works as described below:

* Within domain 2, the BGP CAR route is (E2, C2) via E2.

* B signals to A the BGP CAR route as (E2, C2) via B with Local-Color-Mapping-Extended-Community (LCM-EC) of color C2.

* A is aware of the intent-to-color mapping within domain 2 ("low-delay" in domain 2 is C2), as per typical coordination that exists between operators of peering domains.

* A maps C2 in LCM-EC to C1 and signals within domain 1 the received BGP CAR route as (E2, C2) via A with LCM-EC(C1).

* The nodes within the receiving domain 1 use the local color encoded in the LCM-EC for next-hop resolution and service steering.

The following procedures apply at a color domain boundary for BGP CAR routes, performed by route policy at the sending and receiving peer:

* Use local policy to control which routes are advertised to or accepted from a peer in a different color domain.

* Attach LCM-EC if not present with the route. If LCM-EC is present, then update the value to re-map the color as needed.

  - This function may be done by the advertising BGP speaker or the receiving BGP speaker as determined by the operator peering agreement, and indicated by local policy on the BGP peers.

These procedures apply to both CAR route types, in addition to all procedures specified in earlier sections. LCM-EC is described in Section 2.9.5.

Salient properties:

* The NLRI never changes, even though the color-to-intent mapping changes

* E is globally unique, which makes E-C in that order unique

* In typical expected cases, the color of the NLRI is used for resolution and steering

* In the rare case of color incongruence, the local color encoded in LCM-EC takes precedence

Operational consideratons are in Section 11. Further illustrations are provided in Appendix B.

2.9. Format and Encoding

BGP CAR leverages BGP multi-protocol extensions [RFC4760] and uses the MP_REACH_NLRI and MP_UNREACH_NLRI attributes for route updates within SAFI value 83 along with AFI 1 for IPv4 prefixes and AFI 2 for IPv6 prefixes.

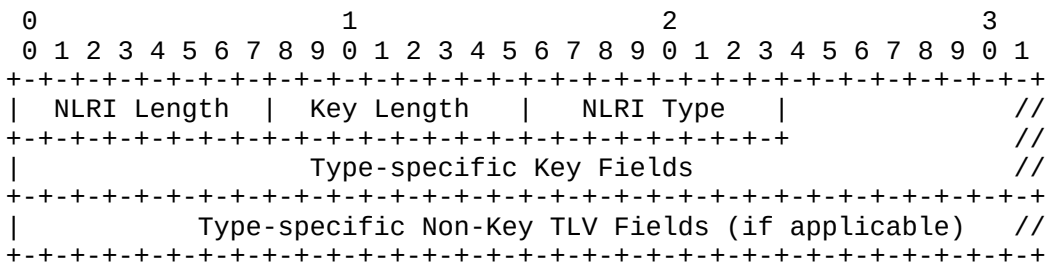
BGP speakers MUST use BGP Capabilities Advertisement to ensure support for processing of BGP CAR updates. This is done as specified in [RFC4760], by using capability code 1 (multi-protocol BGP), with AFI 1 and 2 (as required) and SAFI 83.

The Next Hop network address field in the MP_REACH_NLRI may either be an IPv4 address or an IPv6 address, independent of AFI. If the next hop length is 4, then the next hop is an IPv4 address. The next hop length may be 16 or 32 for an IPv6 next hop address, set as per section 3 of [RFC2545]. Processing of the Next Hop field is governed by standard BGP procedures as described in section 3 of [RFC4760].

The sub-sections below specify the generic encoding of the BGP CAR NLRI and non-key TLV fields followed by the encoding for specific NLRI types introduced in this document.

2.9.1. BGP CAR SAFI NLRI Format

The generic format for the BGP CAR SAFI NLRI is shown below:



where:

* NLRI Length: 1 octet field that indicates the length in octets of the NLRI excluding the NLRI Length field itself.

* Key Length: 1 octet field that indicates the length in octets of the NLRI type-specific key fields. Key length MUST be at least 2 less than the NLRI length.

* NLRI Type: 1 octet field that indicates the type of the BGP CAR NLRI.

* Type-Specific Key Fields: The exact definition of these fields depends on the NLRI type. They have length indicated by the Key Length.

* Type-Specific Non-Key TLV Fields: The fields are optional and can carry one or more non-key TLVs (of different types) depending on the NLRI type. The NLRI definition allows for encoding of specific non-key information associated with the route as part of the NLRI for efficient packing of BGP updates.

The non-key TLVs portion of the NLRI MUST be omitted while carrying it within the MP_UNREACH_NLRI when withdrawing the route advertisement.

Error handling for CAR SAFI NLRI and non-key TLVs is described in Section 2.11.

Benefits of CAR NLRI design:

The indication of the key length enables BGP Speakers to determine the key portion of the NLRI and use it along with the NLRI Type field in an opaque manner for handling of unknown or unsupported NLRI types. This can help deployed Route Reflectors (RR) to propagate NLRI types introduced in the future in a transparent manner.

The key length also helps error handling be more resilient and minimally disruptive. The use of key length in error handling is described in Section 2.11.

The ability of a route (NLRI) to carry more than one non-key TLV (of different types) provides significant benefits such as signaling multiple encapsulations simultaneously for the same route, each with a different value (label/SID etc). This enables simpler, efficient migrations with low overhead :

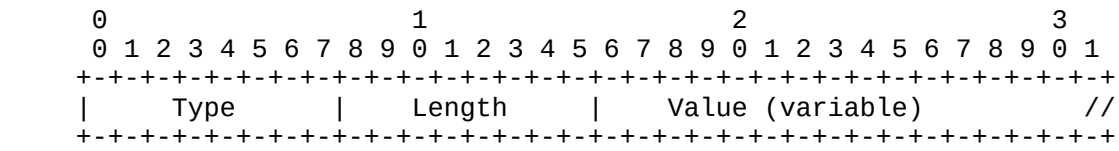
* avoids need for duplicate routes to signal different encapsulations

* avoids need for separate control planes for distribution

* preserves update packing (e.g. Appendix D)

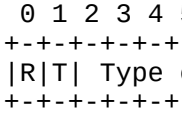
2.9.2. Type-Specific Non-Key TLV Format

The generic format for Non-Key TLVs is shown below:



where:

* Type: 1 octet that contains the type code and flags. It is encoded as shown below:



where:

- R: Bit is reserved and MUST be set to 0 and ignored on receive.

- T: Transitive bit, applicable to speakers that change the BGP CAR next hop.

o T bit set to indicate TLV is transitive. An unrecognized transitive TLV MUST be propagated by a speaker that changes the next hop.

o T bit unset to indicate TLV is non-transitive. An unrecognized non-transitive TLV MUST NOT be propagated by a speaker that changes next hop.

A speaker that does not change next hop SHOULD propagate all received TLVs.

- Type code: Remaining 6 bits contain the type of the TLV.

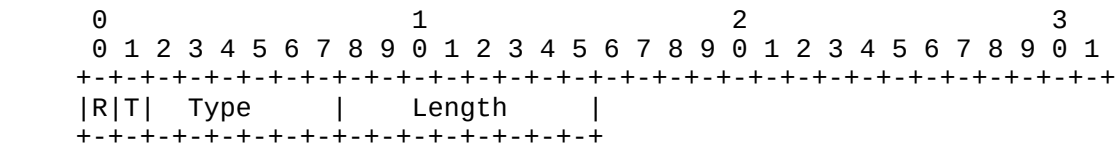
* Length: 1 octet field that contains the length of the value portion of the non-key TLV in terms of octets.

* Value: variable length field as indicated by the length field and to be interpreted as per the type field.

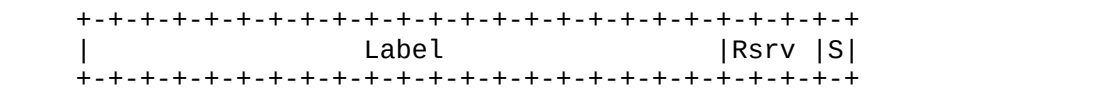
The following sub-sections specify non-key TLVs. Each NLRI type MUST list the TLVs that can be associated with it.

2.9.2.1. Label TLV

The Label TLV is used for advertisement of CAR routes along with their MPLS labels and has the following format as per Section 2.9.2:



Followed by one (or more) Labels encoded as below:



where:

* Type : Type code is 1. T bit MUST be unset.

* Length: In octets. Length is variable, MUST be a multiple of 3.

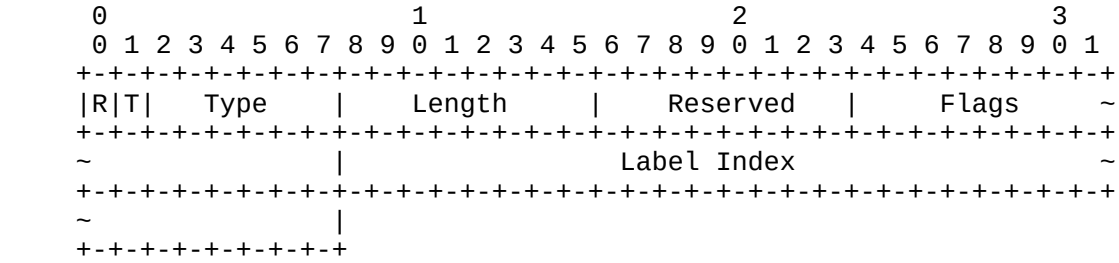
* Label Information: multiples of 3 octet fields to convey the MPLS label(s) associated with the advertised CAR route. It is used for encoding a single label or a stack of labels for usage as

described in [RFC8277]. Number of labels is derived from length field. 3-bit Rsrv and 1-bit S field SHOULD be set to zero on transmission and MUST be ignored on reception.

If a BGP transport CAR speaker sets itself as the next hop while propagating a CAR route, it allocates a local label for the type specific key, and updates the value in this TLV. It also MUST program a label cross-connect that would result in the label swap operation for the incoming label that it advertises with the label received from its best-path router(s).

2.9.2.2. Label Index TLV

The Label Index TLV is used for advertisement of Segment Routing MPLS (SR-MPLS) Segment Identifier (SID) [RFC8402] information associated with the labeled CAR routes and has the following format as per Section 2.9.2:



where:

* Type : Type code is 2. T bit MUST be set.

* Length: In octets. Length is 7.

* Reserved: 1 octet field that MUST be set to 0 and ignored on receipt.

* Flags: 2 octet field that’s defined as per the Flags field of the Label Index TLV of the BGP Prefix-SID Attribute ([RFC8669] section 3.1).

* Label Index: 4 octet field that’s defined as per the Label Index field of the Label Index TLV of the BGP Prefix-SID Attribute ([RFC8669] section 3.1).

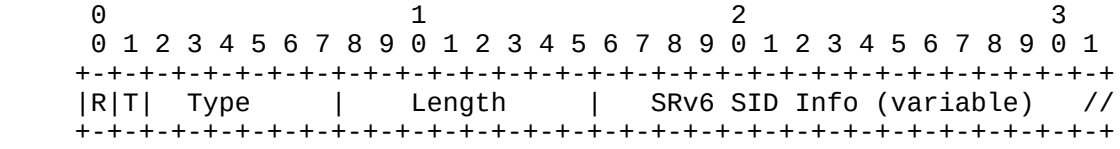
This TLV provides the equivalent functionality as Label Index TLV of [RFC8669] for Transport CAR route in SR-MPLS deployments. When a speaker allocates a local label for a received CAR route as per Section 2.9.2.1, it SHOULD use the received Label Index as a hint using procedures as specified in [RFC8669] Section 4.

The Label Index TLV provides much better packing efficiency by carrying Label Index in NLRI instead of in the BGP Prefix-SID Attribute (Appendix D).

Label Index TLV MUST NOT be carried in the Prefix-SID attribute for BGP CAR routes. If a speaker receives a CAR route with Label Index TLV in the Prefix-SID attribute, it SHOULD ignore it. The BGP Prefix-SID Attribute SHOULD NOT be sent with the labeled CAR routes if the attribute is being used only to convey the Label Index TLV.

2.9.2.3. SRv6 SID TLV

BGP Transport CAR can be also used to setup end-to-end color-aware connectivity using Segment Routing over IPv6 (SRv6) [RFC8402]. [RFC8986] specifies the SRv6 Endpoint behaviors (e.g. End PSP) which can be leveraged for BGP CAR with SRv6. The SRv6 SID TLV is used for advertisement of CAR routes along with their SRv6 SIDs and has the following format as per Section 2.9.2:



where:

* Type : Type code is 3. T bit MUST be unset.

* Length: In octets. Length is variable, MUST be either less than or equal to 16, or be a multiple of 16.

* SRv6 SID Information: field of size as indicated by the length that either carries the SRv6 SID(s) for the advertised CAR route as one of the following:

  - A single 128-bit SRv6 SID or an ordered list of 128-bit SRv6 SIDs.

  - A transposed portion (refer [RFC9252]) of the SRv6 SID that MUST be of size in multiples of one octet and less than 16.

BGP CAR SRv6 SID TLV definitions provide the following benefits:

* Native encoding of SIDs avoids robustness issue caused by overloading of MPLS label fields.

* Simple encoding to signal Unique SIDs (non-transposition), maintaining BGP update prefix packing.

* Highly efficient transposition scheme (12-14 bytes saved per NLRI), also maintaining BGP update prefix packing.

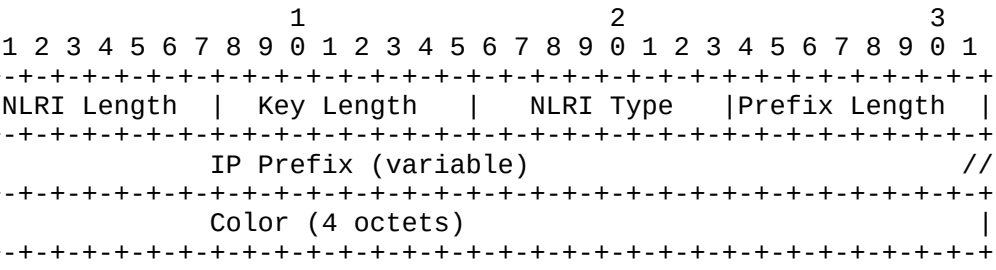
The BGP CAR route update for SRv6 encapsulation MUST include the BGP Prefix-SID attribute along with the SRv6 L3 Service TLV carrying the SRv6 SID information as specified in [RFC9252]. When using the transposition scheme of encoding for packing efficiency of BGP updates [RFC9252], transposed part of SID is carried in SRv6 SID TLV and not limited by MPLS label field size.

If a BGP transport CAR speaker sets itself as the next hop while propagating a CAR route and allocates an SRv6 SID that maps to the received SRv6 SID, it updates the value in this TLV.

Received MPLS information can map to SRv6 and vice versa. [I-D.ietf-spring-srv6-mpls-interworking] describes MPLS and SRv6 interworking procedures and extension to BGP CAR routes.

2.9.3. Color-Aware Route (E, C) NLRI Type

The Color-Aware Route NLRI Type is used for advertisement of BGP CAR color-aware routes (E, C) and has the following format:



Followed by optional Non-Key TLVs encoded as per Section 2.9.2

where:

* NLRI Length: variable

* Key Length: variable. It indicates the total length comprised of the Prefix Length field, IP Prefix field, and the Color field, as described below. For IPv4 (AFI=1), the minimum length is 5 and maximum length is 9. For IPv6 (AFI=2), the minimum length is 5 and maximum length is 21.

* NLRI Type: 1

* Type-Specific Key Fields: as below

  - Prefix Length: 1 octet field that carries the length of prefix in bits. Length MUST be less than or equal to 32 for IPv4 (AFI=1) and less than or equal to 128 for IPv6 (AFI=2).

  - IP Prefix: IPv4 or IPv6 prefix (based on the AFI). A variable size field that contains the most significant octets of the prefix. The format of this field for an IPv4 prefix is:

    0 octet for prefix length 0,

    1 octet for prefix length 1 to 8,

    2 octets for prefix length 9 to 16,

    3 octets for prefix length 17 up to 24,

    4 octets for prefix length 25 up to 32.

  - The format for this field for an IPv6 address follows the same pattern for prefix lengths of 1-128 (octets 1-16).

  - The last octet has enough trailing bits to make the end of the field fall on an octet boundary. Note that the value of the trailing bits MUST be set to zero. The size of the field MUST be less than or equal to 4 for IPv4 (AFI=1) and less than or equal to 16 for IPv6 (AFI=2).

  - Color: 4 octets that contains non-zero color value associated with the prefix.

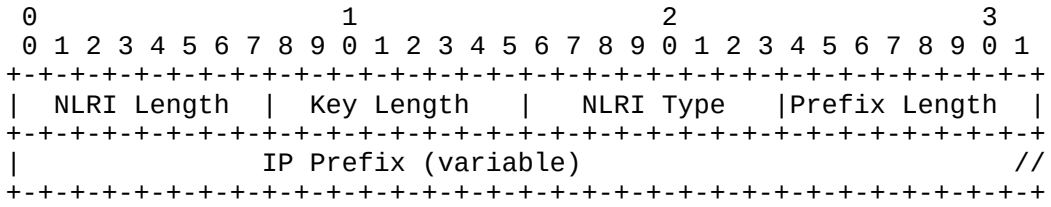
* Type-Specific Non-Key TLVs: Label TLV, Label Index TLV and SRv6 SID TLV (Section 2.9.2) may be associated with the Color-aware route NLRI type.

The prefix is unique across the administrative domains where BGP transport CAR is deployed. It is possible that the same prefix is originated by multiple BGP CAR speakers in the case of anycast addressing or multi-homing.

The Color is introduced to enable multiple route advertisements for the same prefix. The color is associated with an intent (e.g. low-latency) in originator color-domain.

2.9.4. IP Prefix (E) NLRI Type

The IP Prefix Route NLRI Type is used for advertisement of BGP CAR IP Prefix routes (E) and has the following format:



Followed by optional Non-Key TLVs encoded as per Section 2.9.2

where:

* NLRI Length: variable

* Key Length: variable. It indicates the total length comprised of the Prefix Length field and IP Prefix field as described below. For IPv4 (AFI=1), the minimum length is 1 and maximum length is 5. For IPv6 (AFI=2), the minimum length is 1 and maximum length is 17.

* NLRI Type: 2.

* Type-Specific Key Fields: as below

  - Prefix Length: 1 octet field that carries the length of prefix in bits. Length MUST be less than or equal to 32 for IPv4 (AFI=1) and less than or equal to 128 for IPv6 (AFI=2).

  - IP Prefix: IPv4 or IPv6 prefix (based on the AFI). A variable size field that contains the most significant octets of the prefix. The format of this field for an IPv4 prefix is:

    0 octet for prefix length 0,

    1 octet for prefix length 1 to 8,

    2 octets for prefix length 9 to 16,

    3 octets for prefix length 17 up to 24,

4 octets for prefix length 25 up to 32.

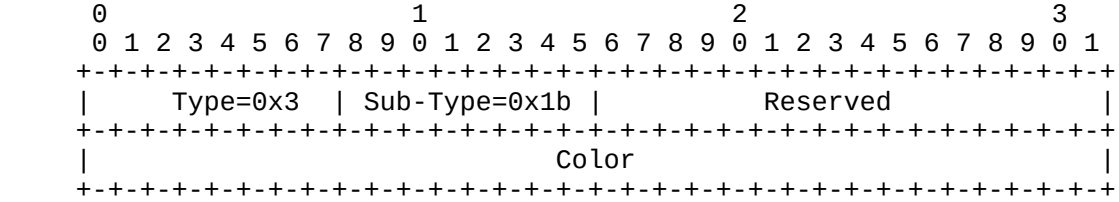
- The format for this field for an IPv6 address follows the same pattern for prefix lengths of 1-128 (octets 1-16).

- The last octet has enough trailing bits to make the end of the field fall on an octet boundary. Note that the value of the trailing bits MUST be set to zero. The size of the field MUST be less than or equal to 4 for IPv4 (AFI=1) and less than or equal to 16 for IPv6 (AFI=2).

* Type-Specific Non-Key TLVs: Label TLV, Label Index TLV and SRv6 SID TLV (Section 2.9.2) may be associated with the IP Prefix NLRI type.

2.9.5. Local-Color-Mapping (LCM) Extended-Community

This document defines a new BGP Extended-Community called "LCM". The LCM is a Transitive Opaque Extended-Community with the following encoding:



where:

* Type: 0x3.

* Sub-Type: 0x1b.

* Reserved: 2 octet of reserved field that MUST be set to zero on transmission and ignored on reception.

* Color: 4-octet field that carries the non-zero 32-bit color value.

When a CAR route crosses the originator’s color domain boundary, LCM-EC is added or updated, as specified in Section 2.8. LCM-EC conveys the local color mapping for the intent (e.g. low latency) in other (transit or destination) color domains.

For CAR IP Prefix routes, LCM-EC may also be added in the originator color domain to indicate the color associated with the IP prefix.

An implementation SHOULD NOT send more than one instance of the LCM-EC. However, if more than one instance is received, an implementation MUST disregard all instances other than the one with the numerically highest value.

If a node receives multiple BGP CAR routes (paths) for a given destination endpoint and color that have different LCM values, it is a misconfiguration in color re-mapping for one of the routes.

In this case, the LCM from the selected BGP best path SHOULD be chosen to be installed into the routing table.

A warning message SHOULD also be logged for further operator intervention.

If present, LCM-EC contains the intent of a BGP CAR route. LCM-EC Color is used instead of the Color in CAR route NLRI for procedures described in earlier sections such as route validation (Section 2.4), route resolution (Section 2.5), AIGP calculation (Section 2.6) and steering (Section 3).

The LCM-EC MAY be used for filtering of BGP CAR routes and/or for applying routing policies on the intent, when present.

2.10. LCM-EC and BGP Color-EC usage

There are 2 distinct requirements to be supported as stated in [I-D.hr-spring-intentaware-routing-using-color]:

1. Domains with different intent granularity (section 6.3.1.9)

2. Network domains under different administration, i.e., color domains (section 6.3.1.10)

Requirement 1 is the case where within the same administrative or color domain, BGP CAR routes for N end-to-end intents may need to traverse across an intermediate transit domain where only M intents are available, N >= M. For example, consider a multi-domain network is designed as Access-Core-Access. The core may have the most granular N intents, whereas the access only has fewer M intents. So, the BGP next-hop resolution for a CAR route in the access domain must be via a color-aware path for one of these M intents. As the procedures in Section 2.5 describe, and the example in Appendix B.2 illustrates, BGP Color-EC is used to automate the CAR route resolution in this case.

For requirement 2, where CAR routes traverse across different color domains, LCM-EC is used to carry the local color mapping for the NLRI color in other color domains. The related procedures are described in Section 2.8, and an example is given in Appendix B.3.

Both LCM-EC and BGP Color-EC may be present at the same time with a BGP CAR route. For example, a BGP CAR route (E, C1) from color domain D1, with LCM-EC C2 in color domain D2, may also carry Color-EC C3 and next hop N in a transit network domain within D2 where C2 is being resolved via an available intra-domain intent C3 (See the detailed example in the combination of Appendix B.2 and Appendix B.3).

In this case, as described in Section 2.5, default order of processing for resolution in presence of LCM-EC is local policy, then BGP Color-EC color, and finally LCM-EC color.

2.11. Error Handling

The error handling actions as described in [RFC7606] are applicable for handling of BGP update messages for BGP CAR SAFI. In general, as indicated in [RFC7606], the goal is to minimize the disruption of a session reset or 'AFI/SAFI disable' to the extent possible.

When the error determined allows for the router to skip the malformed NLRI(s) and continue processing of the rest of the update message, then it MUST handle such malformed NLRIs as 'Treat-as-withdraw'. In other cases, where the error in the NLRI encoding results in the inability to process the BGP update message, then the router SHOULD handle such malformed NLRIs as 'AFI/SAFI disable' when other AFI/SAFI besides BGP CAR are being advertised over the same session. Alternately, the router MUST perform 'session reset' when the session is only being used for BGP CAR SAFI.

The CAR NLRI definition encodes NLRI length and key length explicitly. The NLRI length MUST be relied upon to enable the beginning of the next NLRI field to be located. Key length MUST be relied upon to extract the key and perform 'treat-as-withdraw' for malformed information.

A sender MUST ensure that the NLRI and key lengths are number of actual bytes encoded in NLRI and key fields respectively, regardless of content being encoded.

Given NLRI length and Key length MUST be valid, failures in following checks result in 'AFI/SAFI disable' or 'session reset':

* Minimum NLRI length (must be atleast 2, as key length and NLRI type are required fields).

* Key Length MUST be at least two less than NLRI Length.

NLRI Type specific error handling:

* By default, a speaker SHOULD discard unrecognized or unsupported NLRI type and move to next NLRI.

* Key length and key errors of known NLRI type SHOULD result in discard of NLRI similar to unrecognized NLRI type. (This MUST be logged for trouble shooting).

Transparent propagation of unrecognized NLRI type:

* Key length allows unrecognized route types to transit through RR transparently without a software upgrade. The RR receiving unrecognized route types does not need to interpret the key portion of an NLRI and handles the NLRI as an opaque value of a specific length. An implementation SHOULD provide configuration that controls the RR unrecognized route type propagation behavior and possibly at the granularity of route type values allowed. This configuration option gives the operator the ability to allow specific route types to be transparently passed through RRs based on client speaker support.

* In such a case RR may reflect NLRIs with NLRI type specific key length and field errors. Clients of such RR that consume the route for installation will perform the key error handling of known NLRI type or discard unrecognized type. This prevents propagation of routes with NLRI errors any further in network.

Type-Specific Non-Key TLV handling:

* Either the length of a TLV would cause the NLRI length to be exceeded when parsing the TLV, or fewer than 2 bytes remain when beginning to parse the TLV. In either of these cases, an error condition exists and the ’treat-as-withdraw’ approach MUST be used.

* Type specific length constraints should be verified. The TLV MUST be discarded if there is an error. When discarded, an error may be logged for further analysis.

* If multiple instances of same type are encountered, all but the first instance MUST be discarded. When discarded, an error may be logged for further analysis.

* If a speaker that performs encapsulation to the BGP next hop does not receive at least one recognized forwarding information TLV with T bit unset (such as label or SRv6 SID), such NLRI is considered invalid and not eligible for best path selection. Treat-as-withdraw may be used, though it is recommended to keep the NLRI for debugging purposes.

3. Service Route Automated Steering on Color-Aware Path

An ingress PE (or ASBR) E1 automatically steers a C-colored service route V/v from E2 onto an (E2, C) color-aware path, as illustrated in (Section 1.2). If several such paths exist, a preference scheme is used to select the best path. The default preference scheme is IGP Flex-Algo first, then SR Policy, followed by BGP CAR. A configuration option may be used to adjust the default preference scheme.

An egress PE may express its intent that traffic should be steered a certain way through the transport layer by including the BGP Color-EC [RFC9012] with the relevant service routes. An ingress PE steers service traffic over a CAR (E, C) route using the service route’s next hop and BGP Color-EC.

This is consistent with the automated service route steering on SR Policy (a routing solution providing color-aware path) defined in [RFC9256]. All the steering variations described in [RFC9256] are applicable to BGP CAR color-aware path: on-demand steering, per-destination, per-flow, color-only steering. For brevity, please refer to [RFC9256] Section 8.

Appendix A provides illustrations of service route automated steering over BGP CAR (E, C) routes.

An egress PE may express its intent that traffic should be steered a certain way through the transport layer by allocating the SRv6 Service SID from a routed intent-aware locator prefix (Section 3.3 of [RFC8986]). Steering at an ingress PE is via resolution of the Service SID over a CAR Type-2 IP Prefix route. Service Steering over BGP CAR SRv6 transport is described in Section 7.

Service steering via BGP CAR routes is applicable to any BGP SAFI, including SAFIs for IPv4/IPv6 (SAFI 1), L3VPN (SAFI 128), PW, EVPN (SAFI 70), FlowSpec, and BGP-LU (SAFI 4).

4. Filtering

PE and BRs may support filtering of CAR routes. For instance, the filtering may only accept routes of locally configured colors.

Techniques such as RT-Constrain [RFC4684] may also be applied to the CAR SAFI, where Route Target (RT) Extended-Communities [RFC4360] can be used to constrain distribution and automate filtering of CAR routes. RT assignment may be via user policy, for example an RT value can be assigned to all routes of a specific color.

A PE may support on-demand installation of a CAR route based on the presence of a service route whose next-hop resolves via the CAR route.

Similarly, a PE may dynamically subscribe to receive individual CAR routes from upstream routers or route-reflectors to limit the routes that it needs to learn. On-demand subscription and automated filtering procedures for individual CAR routes are outside the scope of this document.

5. Scaling

This section analyses the key scale requirement of [I-D.hr-spring-intentaware-routing-using-color], specifically:

* No intermediate node data-plane should need to scale to (Colors * PEs).

* No node should learn and install a BGP CAR route to (E, C) if it does not install a Colored service route to E.

While the requirements and design principles generally apply to any transport, the logical analysis based on the network design in this section focuses on MPLS / SR-MPLS transport since the scaling constraints are specifically relevant to these technologies. BGP CAR SAFI is used here, but the considerations can apply to [RFC8277] or [RFC8669] used with MPLS/SR-MPLS.

Two key principles used to address the scaling requirements are a hierarchical network and routing design, and on-demand route subscription and filtering.

Figure 2 in Section 5.1 provides an ultra-scale reference topology. Section 5.1 describes this topology. Section 5.2 presents three design models to deploy BGP CAR in the reference topology, including hierarchical options. Section 5.3 analyses the logical scaling properties of each model.

Filtering techniques described in the previous section allow a PE to limit the CAR routes that it needs to learn or install. Scaling benefits of on-demand BGP subscription and filtering will be described in a separate document.

5.1. Ultra-Scale Reference Topology

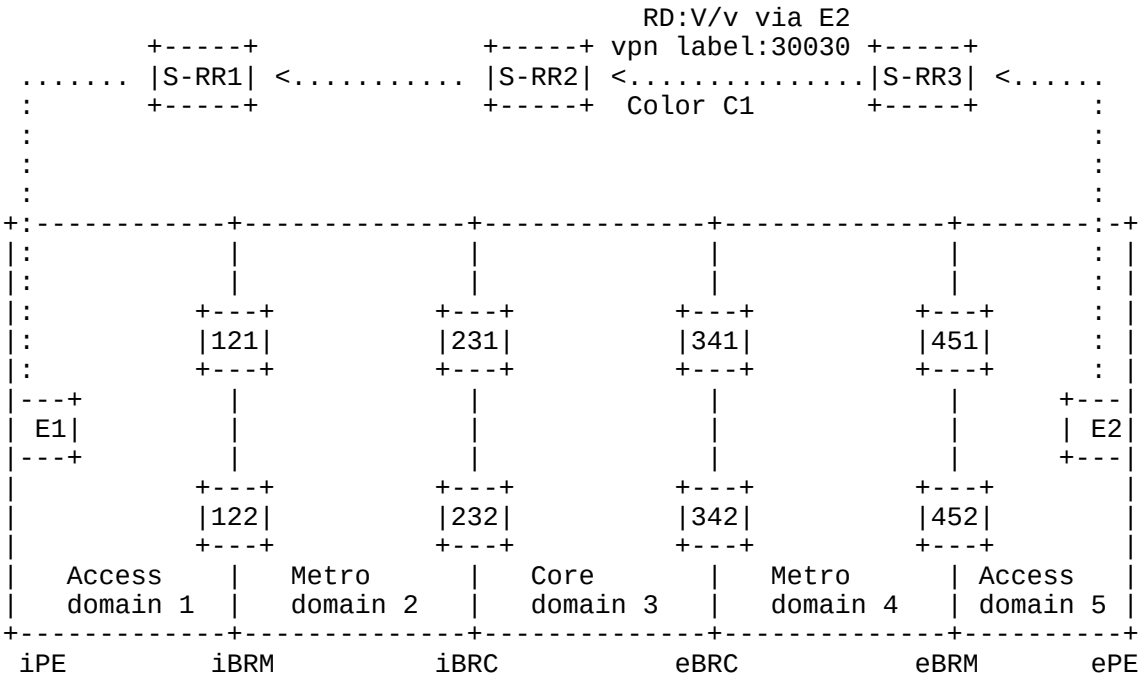


Figure 2: Ultra-Scale Reference Topology

The following description applies to the reference topology above:

* Independent IS-IS/OSPF SR instance in each domain.

* Each domain has Flex Algo 128. Prefix SID for a node is SRGB 168000 plus node number.

* A BGP CAR route (E2, C1) is advertised by egress BRM node 451. The route is sourced locally from redistribution from IGP-FA 128.

* Not shown for simplicity, node 452 will also advertise (E2, C1).

* When a transport RR is used within the domain or across domains, ADD-PATH is enabled to advertise paths from both egress BRs to it’s clients.

* Egress PE E2 advertises a VPN route RD:V/v with BGP Color extended community C1 that propagates via service RRs to ingress PE E1.

* E1 steers V/v prefix via color-aware path (E2, C1) and VPN label 30030.

5.2. Deployment Model

5.2.1. Flat

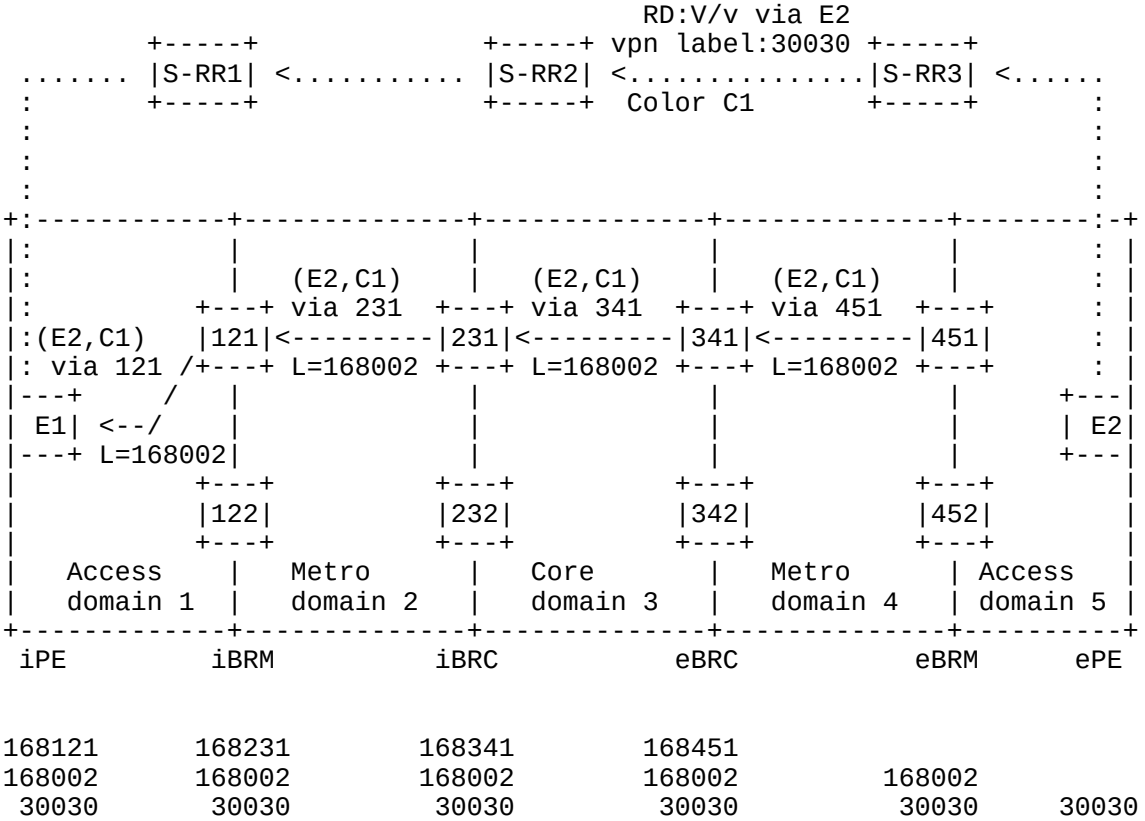


Figure 3: Flat Transport Network Design

* Node 451 advertises BGP CAR route (E2, C1) to 341, from which it goes to 231 then to 121 and finally to E1.

* Each BGP hop allocates local label and programs swap entry in forwarding for (E2, C1).

* E1 receives BGP CAR route (E2, C1) via 121 with label 168002.

  - Let’s assume E1 selects that path.

* E1 resolves BGP CAR route (E2, C1) via 121 on color-aware path (121, C1).
  - Color-aware path (121, C1) is FA128 path to 121 (label 168121).
* E1's imposition color-aware label-stack for V/v is thus
  - 30030 <=> V/v
  - 168002 <=> (E2, C1)
  - 168121 <=> (121, C1)
* Each BGP hop performs swap operation on 168002 bound to color-aware path (E2, C1).

5.2.2. Hierarchical Design with Next-Hop-Self at Ingress Domain BR

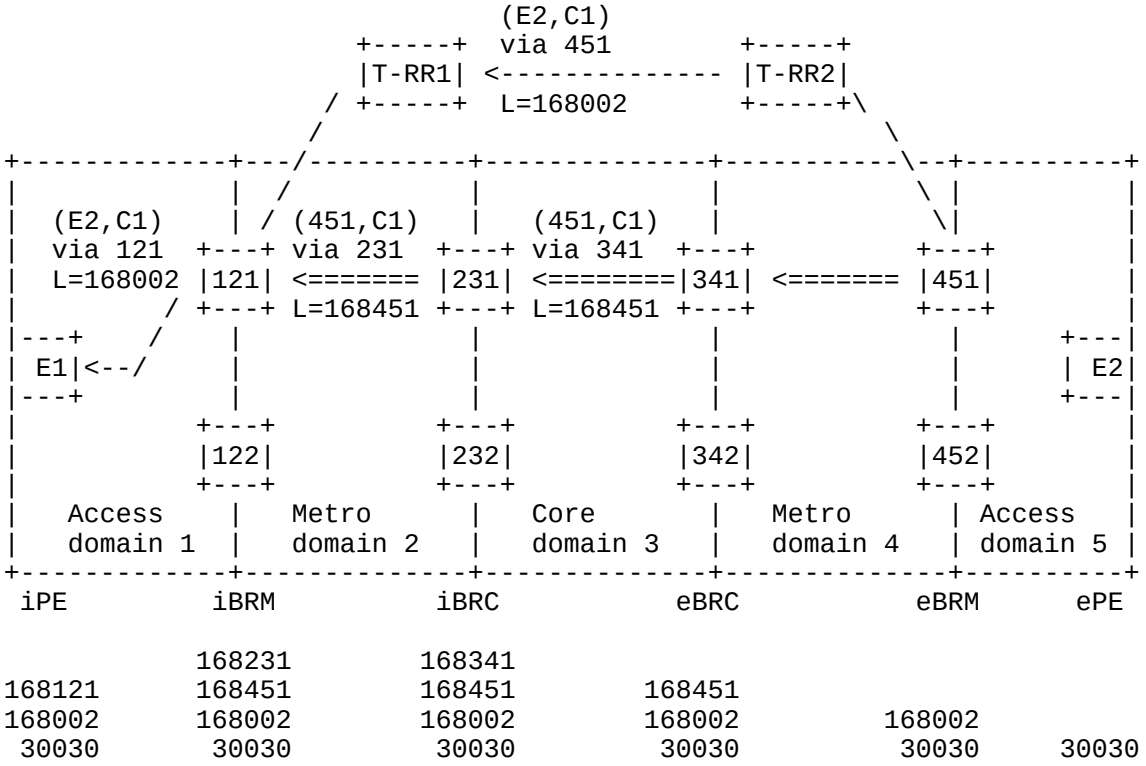


Figure 4: Hierarchical BGP transport CAR, Next-Hop-Self (NHS) at iBR

* Node 451 advertises BGP CAR route (451, C1) to 341, from which it goes to 231 and finally to 121.

* Each BGP hop allocates local label and programs swap entry in forwarding for (451, C1).

* 121 resolves received BGP CAR route (451, C1) via 231 (label 168451) on color-aware path (231, C1).

  - Color-aware path (231, C1) is FA128 path to 231 (label 168231).

* 451 advertises BGP CAR route (E2, C1) via 451 to transport RR T-RR2, which reflects it to transport RR T-RR1, which reflects it to 121.

* 121 receives BGP CAR route (E2, C1) via 451 with label 168002.

  - Let’s assume 121 selects that path.

* 121 resolves BGP CAR route (E2, C1) via 451 on color-aware path (451, C1).

  - Color-aware path (451, C1) is BGP CAR path to 451 (label 168451).

* 121 imposition of color-aware label stack for (E2, C1) is thus

  - 168002 <=> (E2, C1)

  - 168451 <=> (451, C1)

  - 168231 <=> (231, C1)

* 121 advertises (E2, C1) to E1 with next hop self (121) and label 168002

* E1 constructs same imposition color-aware label-stack for V/v via (E2, C1) as in the flat model:

  - 30030 <=> V/v

  - 168002 <=> (E2, C1)

  - 168121 <=> (121, C1)

* 121 performs swap operation on 168002 with hierarchical color-aware label stack for (E2, C1) via 451 from step 7.

* Nodes 231 and 341 perform swap operation on 168451 bound to color-aware path (451, C1).

* 451 performs swap operation on 168002 bound to color-aware path (E2, C1).

Note: E1 does not need the BGP CAR route (451, C1) in this design.

5.2.3. Hierarchical Design with Next-Hop-Unchanged at Ingress Domain BR

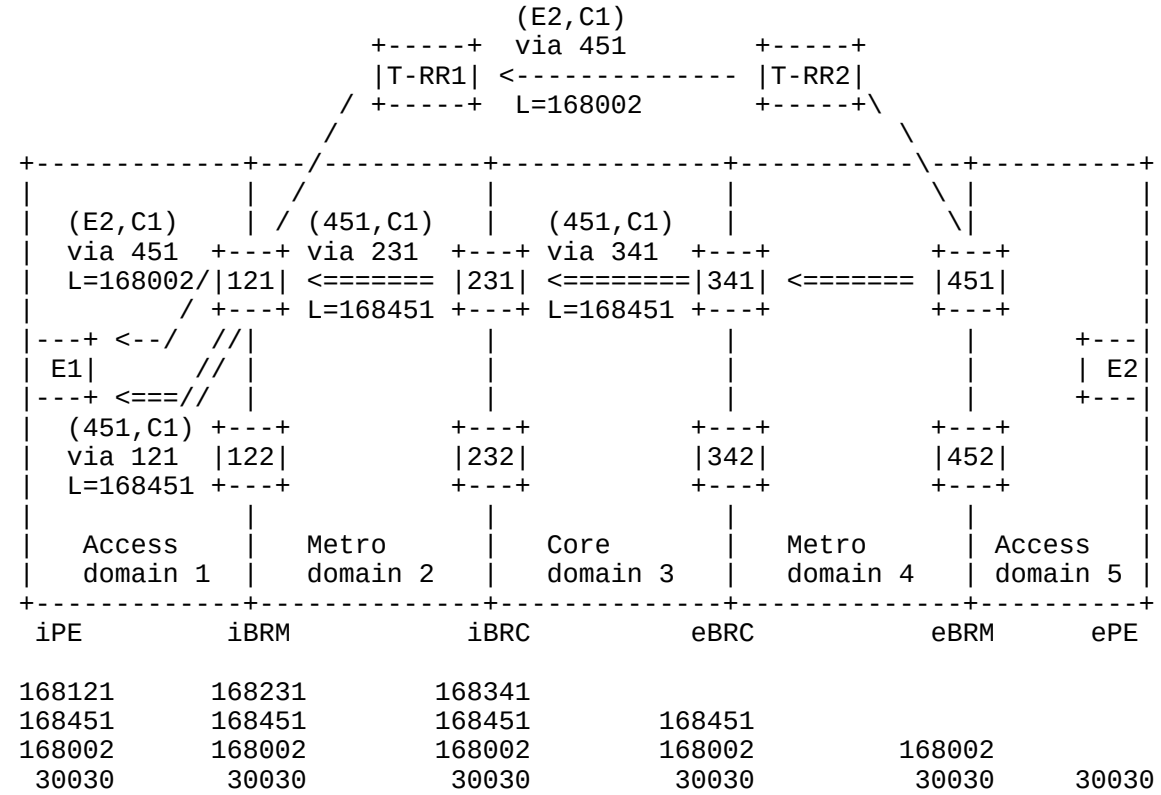


Figure 5: Hierarchical BGP transport CAR, Next-Hop-Unchanged (NHU) at iBR

* Nodes 341, 231 and 121 receive and resolve BGP CAR route (451, C1) the same as in the previous model.

* Node 121 allocates local label and programs swap entry in forwarding for (451, C1).

* 451 advertises BGP CAR route (E2, C1) to transport RR T-RR2, which reflects it to transport RR T-RR1, which reflects it to 121.

* Node 121 advertises (E2, C1) to E1 with next hop as 451; i.e., next-hop-unchanged.

* 121 also advertises (451, C1) to E1 with next hop self (121) and label 168451.

* E1 resolves BGP CAR route (451, C1) via 121 on color-aware path (121, C1).

  - Color-aware path (121, C1) is FA128 path to 121 (label 168121).

* E1 receives BGP CAR route (E2, C1) via 451 with label 168002.

  - Let’s assume E1 selects that path.

* E1 resolves BGP CAR route (E2, C1) via 451 on color-aware path (451, C1).

  - Color-aware path (451, C1) is BGP CAR path to 451 (label 168451).

* E1’s imposition color-aware label-stack for V/v is thus

  - 30030 <=> V/v

  - 168002 <=> (E2, C1)

  - 168451 <=> (451, C1)

  - 168121 <=> (121, C1)

* Nodes 121, 231 and 341 perform swap operation on 168451 bound to (451, C1).

* 451 performs swap operation on 168002 bound to color-aware path (E2, C1).

5.3. Scale Analysis

The following two tables summarize the logically analyzed scaling of the control-plane and data-plane for these three models:

	E1	121	231
FLAT	(E2,C) via (121,C)	(E2,C) via (231,C)	(E2,C) via (341,C)
H.NHS	(E2,C) via (121,C)	(E2,C) via (451,C) (451,C) via (231,C)	(451,C) via (341,C)
H.NHU	(E2,C) via (451,C) (451,C) via (121,C)	(451,C) via (231,C)	(451,C) via (341,C)

	E1	121	231
FLAT	V -> 30030 168002 168121	168002 -> 168002 168231	168002 -> 168002 168341
H.NHS	V -> 30030 168002 168121	168002 -> 168002 168451 168231	168451 -> 168451 168341
H.NHU	V -> 30030 168002 168451 168121	168451 -> 168451 168231	168451 -> 168451 168341

* The flat model is the simplest design, with a single BGP transport level. It results in the minimum label/SID stack at each BGP hop. However, it significantly increases the scale impact on the core BRs (e.g. 341), whose FIB capacity and even MPLS label space may be exceeded.

  - 341’s data-plane scales with (E2, C) where there may be 300k E’s and 5 C’s hence 1.5M entries > 1M MPLS data-plane.

* The hierarchical models avoid the need for core BRs to learn routes and install label forwarding entries for (E, C) routes.

  - Whether next hop is set to self or left unchanged at 121, 341’s data-plane scales with (451, C) where there may be thousands of 451’s and 5 C’s. Therefore, this scaling is well under the 1 million MPLS labels data-plane limit.

  - They also aid faster convergence by allowing the PE routes to be distributed via out-of-band RRs that can be scaled independent of the transport BRs.

* The next-hop-self option at ingress BRM (e.g. 121) hides the hierarchical design from the ingress PE, keeping its outgoing label programming as simple as the flat model. However, the ingress BRM requires an additional BGP transport level recursion, which coupled with load-balancing adds data-plane complexity. It needs to support a swap and push operation. It also needs to install label forwarding entries for the egress PEs that are of interest to its local ingress PEs.

* With the next-hop-unchanged option at ingress BRM (e.g. 121), only an ingress PE needs to learn and install output label entries for egress (E, C) routes. The ingress BRM only installs label forwarding entries for the egress ABR (e.g. 451). However, the ingress PE needs an additional BGP transport level recursion and pushes a BGP VPN label and two BGP transport labels. It may also need to handle load-balancing for the egress ABRs. This is the most complex data-plane option for the ingress PE.

5.4. Anycast SID

This section describes how Anycast SID complements and improves the scaling designs above.

5.4.1. Anycast SID for Transit Inter-domain Nodes

* Redundant BRs (e.g. two egress BRMs, 451 and 452) advertise BGP CAR routes for a local PE (e.g., E2) with the same SID (based on label index). Such egress BRMs may be assigned a common Anycast SID, so that the BGP next hops for these routes will also resolve via a color-aware path to the Anycast SID.

* The use of Anycast SID naturally provides fast local convergence upon failure of an egress BRM node. In addition, it decreases the recursive resolution and load-balancing complexity at an ingress BRM or PE in the hierarchical designs above.

5.4.2. Anycast SID for Transport Color Endpoints (e.g., PEs)

The common Anycast SID technique may also be used for a redundant pair of PEs that share an identical set of service (VPN) attachments.

* For example, assume a node E2’ paired with E2 above (e.g., Figure 5). Both PEs should be configured with the same static label/SID for the services (e.g., per-VRF VPN label/SID), and will advertise associated service routes with the Anycast IP as BGP next hop.

* This design provides a convergence and recursive resolution benefit on an ingress PE or ABR similar to the egress ABR case in the previous section (Section 5.4.1). However, its applicability is limited to cases where the above constraints can be met.

6. Routing Convergence

BGP CAR leverages existing well-known design techniques to provide fast convergence.

Section 2.7 describes how BGP CAR provides localized convergence within a domain for BR failures, including originating BRs, without propagating failure churn into other domains.

Anycast SID techniques described in Section 5.4 can provide further convergence optimizations for BR and PE failures deployed in redundant designs.

7. CAR SRv6

7.1. Overview

Steering services over SRv6 based intent-aware multi-domain transport paths may be categorized into two distinct cases that are described in Section 5 of [RFC9252]. Both cases are supported by BGP CAR, as described below.

7.1.1. Routed Service SID

The SRv6 Service SID that is advertised with a service route is allocated by an egress PE from a routed intent-aware locator prefix (Section 3.3 of [RFC8986]). Service steering at an ingress PE is via resolution of the Service SID signaled with the service route as described in ([RFC9252]).

The intent-aware transport path to the SRv6 locator of the egress PE is provided by underlay IP routing. Underlay IP routing can include IGP Flex-Algo [RFC9350] within a domain, and BGP CAR [this document] across multiple IGP domains or BGP ASes.

An SRv6 locator prefix is assigned for a given intent or color. The SRv6 locator may be shared with an IGP Flex-Algo, or may be assigned specific to BGP CAR for a given intent.

Distribution of SRv6 locators in BGP CAR SAFI:

* In a multi-domain network, the SRv6 locator prefix is distributed using BGP CAR SAFI to ingress PEs and ASBRs in a remote domain. The SRv6 locator prefix may be advertised in the BGP CAR SAFI from an egress PE, or redistributed into BGP CAR from an IGP-FlexAlgo at a BR. The locator prefix may also be summarized on a border node along the path and a summary route distributed to ingress PEs.

* An IP Prefix CAR route (Type-2) is defined to distribute SRv6 locator prefixes and described in Section 2.9.4 and Section 8.

* A BGP CAR advertised SRv6 locator prefix may also be used for resolution of the SRv6 service SID advertised for best-effort connectivity.

Appendix C.1 and Appendix C.2 illustrates the control and forwarding behaviors for routed SRv6 Service SID.

Section 7.2 describes the deployment options.

Section 7.3 describes operational considerations of using BGP CAR SAFI vs BGP IPv6 SAFI for inter-domain route distribution of SRv6 locators.

7.1.2. Non-routed Service SID

The SRv6 Service SID allocated by an egress PE is not routed. The service route carrying the non-routed SRv6 Service SID is advertised by the egress PE with a Color-EC C ([RFC9252] section 5). An ingress PE in a remote domain steers traffic for the received service route with Color-EC C and this SRv6 Service SID as described below.

BGP CAR distribution of (E, C) underlay route:

* The intent-aware path to the egress PE within the egress domain is provided by an SR-TE or similar policy (E, C) [RFC9256]. This (E, C) policy is distributed into the multi-domain network from egress BRs using a BGP CAR (E, C) route towards ingress PEs in other domains. This signaling is the same as for SR-MPLS as described in earlier sections.

* The (E, C) BGP CAR Type-1 route is advertised from a BR with an SRv6 transport SID allocated from an SRv6 locator assigned for the intent C. An SR-PCE or local configuration may ensure multiple BRs in the egress domain that originate the (E, C) route advertise the same SRv6 transport SID.

BGP CAR distribution of SRv6 locator underlay route:

* BGP CAR MAY also provide the underlay intent-aware inter-domain route to resolve the intent-aware SRv6 transport SID advertised with the (E, C) BGP CAR route as follows:

  - An egress domain BR has a SRv6 locator prefix that covers the SRv6 transport SID allocated by the egress BR for the (E, C) BGP CAR route.

  - The egress domain BR advertises an IP Prefix Type-2 CAR route for the SRv6 locator prefix, and the route is distributed across BGP hops in the underlay towards ingress PEs. This distribution is the same as the previous Section 7.1.1 case. The route may also be summarized in another CAR type-2 route prefix.

Service traffic steering and SRv6 transport SID resolution at ingress PE:

* An ingress PE in a remote domain resolves the received service route with Color C via the (E, C) BGP CAR route above, as described in Section 3.

* Additionally, the ingress PE resolves the SRv6 transport SID received in the BGP CAR (E, C) route via the BGP CAR IP Prefix route, similar to the SRv6 Routed Service SID resolution in Section 7.1.1.

  - Multiple (E, C) routes may resolve via a single IP Prefix CAR route.

    o Resolution of (E, C) routes over IP Prefix CAR routes is the typical resolution order as the IP Prefix route provides intent-aware reachability to the BRs that advertise the (E, C) specific routes for each egress PE. However, there can be use-cases where a IP Prefix CAR route may resolve via a (E, C) route.

* The ingress PE via the recursive resolution above builds the packet encapsulation that contains the SRv6 Service SID and the received (E, C) route’s SRv6 transport SID in the SID-list.

Appendix C.3 contains an example that illustrates the control plane distribution, recursive resolution and forwarding behaviors described above.

Note: An SR-policy may also be defined for multi-domain end to end [RFC9256], independent of BGP CAR. In that case, both BGP CAR and SR-TE inter-domain paths may be available at an ingress PE for an (E, C) route (Section 1.2).

7.2. Deployment Options For CAR SRv6 Locator Reachability Distribution and Forwarding

Since an SRv6 locator (or summary) is an IPv6 prefix, it will be installed into the IPv6 forwarding table on a BGP router (e.g., ABR or ASBR), for packet forwarding. With the use of IPv6 locator prefixes, there is no need to allocate and install per-PE SIDs on each BGP hop to forward packets.

A few options to forward packets for BGP SRv6 prefixes described in ([I-D.ietf-spring-srv6-mpls-interworking] also apply to BGP CAR. These options are described in Section 7.2.1 and Section 7.2.2.

7.2.1. Hop by Hop IPv6 Forwarding for BGP SRv6 Prefixes

This option employs hop by hop IPv6 lookup and forwarding on both BRs and P nodes in a domain along the path of propagation of BGP CAR routes. This option’s procedures include the following:

* In addition to BRs, P nodes within a domain also learn BGP CAR IP Prefix routes (for SRv6) and install them into the forwarding table.

* BGP routing is enabled on all internal nodes (iBGP) using full-mesh or an RR.

* BRs distribute external BGP SRv6 routes to internal peers including P routers, with the following conditions:

  - The external BGP Next-hop is advertised unchanged to the internal peers;

  - Internal nodes use recursive resolution via IGP at each hop to forward IPv6 packets towards the external BGP next-hop; and

  - Resolution is per intent/color (e.g., via IGP IPv6 FlexAlgo).

This design is illustrated with an example in Appendix C.1.

The benefits of this scheme are:

* Simpler design, no tunnel encapsulation is required between BRs in a domain.

* No per-PE SID allocation and installation on any BGP hop.

* This design is similar to the well-known Internet / BGP hop-by-hop IP routing model and can support large scale route distribution.

* In addition, since SRv6 locator prefixes can be summarized, this minimizes the number of routes and hence the scale requirements on P routers.

7.2.2. Encapsulation between BRs for BGP SRv6 Prefixes

In this design, IPv6 lookup and forwarding for BGP SRv6 prefixes are only done on BGP BRs. This option includes the following procedures:

* These nodes use SRv6 (or other) encapsulation to reach the BGP SRv6 next hop.
  - SRv6 outer encapsulation may be H.Encaps.Red.
  - Encapsulation is not needed for directly connected next hops, such as with eBGP single-hop sessions.

* BGP route distribution is enabled between BRs via RRs, or directly if single-hop BGP.

* An egress BR sets itself as BGP next hop, selects and advertises an appropriate encapsulation towards itself.
  - If SRv6 encapsulation, then SRv6 SID advertised from egress BR is from an SRv6 locator for the specific intent within the domain. Multiple BGP SRv6 prefixes may share a common SID, avoiding per-PE SID allocation and installation on any BGP hop.
  - If MPLS/SR-MPLS transport, the route will carry label/prefix-SID allocated by the next hop, may be shared.

* An ingress BR encapsulates SRv6 egress PE destined packets with encapsulation to BGP next hop, ie. the egress BR.

Benefits of this scheme are:

* P nodes do not need to learn or install BGP SRv6 prefixes in this (BGP-free core) design.

* No per-PE SID allocation and installation on any BGP hop.

This design is illustrated in Appendix C.2.

7.3. Operational Benefits of using CAR SAFI for SRv6 Locator Prefix Distribution

When reachability to an SRv6 SID is provided by distribution of a locator prefix via underlay routing, BGP IPv6 SAFI (AFI/SAFI=2/1) may also be used for inter-domain distribution of these IPv6 prefixes as described in [I-D.ietf-spring-srv6-mpls-interworking] (Section 7.1.2) or [I-D.ietf-idr-cpr].

Using the BGP CAR SAFI provides the following operational benefits:

* CAR SAFI is a separate BGP SAFI used for underlay transport intent-aware routing. It avoids overloading of BGP IPv6 SAFI, which also carries Internet (service) prefixes. Using CAR SAFI provides:
  - Automatic separation of SRv6 locator (transport) routes from Internet (service) routes,
    - o Preventing inadvertent leaking of routes.
    - o Avoiding need to configure specific route filters for locator routes.
  - Priority handling of infrastructure routes over service (Internet) routes.
* CAR SAFI also supports inter-domain distribution of (E, C) routes sourced from SR-Policy, in addition to SRv6 locator IPv6 prefixes.
* CAR SAFI may also be used for best-effort routes in addition to intent-aware routes as described in the next section.

Note: If infrastructure routes such as SRv6 locator routes are carried in both BGP-IP [RFC4271] / BGP-LU [RFC8277, RFC4798], and BGP CAR, Section 8 describes the path selection preference between them.

8. CAR IP Prefix Route

An IP Prefix CAR route is a route type (Type-2) that carries a routable IP prefix whose processing follows [RFC4271] and [RFC2545] semantics. IP Prefix CAR routes are installed in the default routing and forwarding table and provide longest-prefix-match forwarding. This is unlike Type-1 (E, C) routes, where it is the signaled forwarding data such as labels/SIDs that are installed in the forwarding table to create end to end paths.

IP Prefix CAR routes may be originated into BGP CAR SAFI either from an egress PE or from a BR in a domain. Type-2 routes carry infrastructure routes for both IPv4 and IPv6.

As described in Section 2.1, it is used for cases where a unique routable IP prefix is assigned for a given intent or color. It may also be used for routes providing best-effort connectivity.

A few applicable example use-cases:

* SRv6 locator prefix with color for specific intents.

* SRv6 locator prefix without color for best-effort.

* Best effort transport reachability to a PE/BR without color.

For specific intents, color may be signaled with the IP Prefix CAR route for purposes such as intent-aware SRv6 SID or BGP next-hop selection at each transit BR, color based routing policies and filtering, and intent-aware next-hop resolution (Section 2.5). These purposes are the same as with (E, C) routes. For such purposes, color associated with the CAR IP Prefix route is signaled using LCM-EC.

Reminder: LCM-EC conveys end-to-end intent/color associated with route/NLRI. When traversing network domain(s) where a different intent/color is used for next-hop resolution, BGP Color-EC may additionally be used as in Section 2.10.

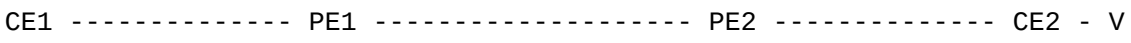
A special case of intent is best-effort which may be represented by a color and follow above procedures. But to be compatible with traditional operational usage, CAR IP Prefix route is allowed to be without color for best-effort. In this case, the routes will not carry an LCM-EC. Resolution is described in Section 2.5.

As described in Section 7.3, infrastructure prefixes are intended to be carried in CAR SAFI instead of SAFIs that also carry service routes such as BGP-IP (SAFI 1, [RFC4271]) and BGP-LU (SAFI 4, [RFC4798]). However, if such infrastructure routes are also distributed in these SAFIs, a router may receive both BGP CAR SAFI paths and IP/LU SAFI paths. By default, CAR SAFI transport path is preferred over BGP IP or BGP-LU SAFI path.

A BGP transport CAR speaker that supports packet forwarding lookup based on IPv6 prefix route (such as a BR) will set itself as next hop while advertising the route to peers. It will also install the IPv6 route into forwarding with the received next hop and/or encapsulation. If such a transit router does not support this route type, it will not install this route and will not set itself as next hop, hence will not propagate the route any further.

9. VPN CAR

This section illustrates the extension of BGP CAR to address the VPN intent-aware routing requirement stated in Section 6.1.2 of [I-D.hr-spring-intentaware-routing-using-color]. The examples use MPLS, but other transport types can also be used (e.g., SRv6).



* BGP CAR SAFI is enabled on CE1-PE1 and PE2-CE2 sessions

* BGP VPN CAR SAFI is enabled between PE1 and PE2

* Provider publishes to customer that intent ’low-delay’ is mapped to color CP on its inbound peering links

* Within its infrastructure, Provider maps intent ’low-delay’ to color CPT

* On CE1 and CE2, intent ’low-delay’ is mapped to CC

(V, CC) is a Color-Aware route originated by CE2

1. CE2 sends to PE2 : [(V, CC), Label L1] via CE2 with LCM-EC (CP)
   as per peering agreement
2. PE2 installs in VRF A: [(V, CC), L1] via CE2
   which resolves on (CE2, CP)
   or connected OIF
3 PE2 allocates VPN Label L2 and programs swap entry for (V, CC)
4. PE2 sends to PE1 : [(RD, V, CC), L2] via PE2, LCM-EC(CP)
   with regular Color-EC (CPT)
5. PE1 installs in VRF A: [(V, CC), L2] via (PE2, CPT)
   steered on (PE2, CPT)
6. PE1 allocates Label L3 and programs swap entry for (V, CC)
7. PE1 sends to CE1 : [(V, CC), L3] via PE1
   after removing LCM-EC through route-policy
8. CE1 installs : [(V, CC), L3] via PE1
   which resolves on (PE1, CC)
   or connected OIF
9. Label L3 is installed as the imposition label for (V, CC)

VPN CAR distribution for (RD, V, CC) requires a new SAFI that follows same VPN semantics as defined in [RFC4364] and also supports the distribution of routes with the CAR NLRI and associated non-key TLVs defined in Section 2.9 of this document.

Procedures defined in [RFC4364] and [RFC4659] apply to VPN CAR SAFI. Further, all CAR SAFI procedures described in Section 2 above apply to CAR SAFI enabled within a VRF. Since CE and PE are typically in different administrative domains, LCM-EC is attached to CAR routes.

VPN CAR SAFI routes follow color based steering techniques as described in Section 3 and illustrated in example above.

VPN CAR SAFI routes may also be advertised with a specific BGP next hop per color, with a TEA or Tunnel Encapsulation EC and follow the procedures of [RFC9012] Section 6.

CAR routes distributed in VPN CAR SAFI are infrastructure routes advertised by CEs in different customer VRFs on a PE. Example use-cases are intent-aware L3VPN CsC ([RFC4364] Section 9) and SRv6 over a provider network . The VPN RD distinguishes CAR routes of different customers being advertised by the PE.

9.1. Format and Encoding

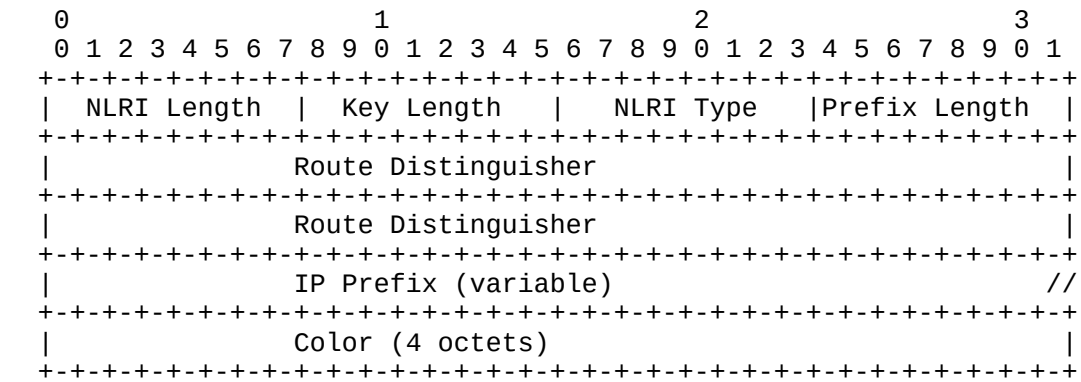
BGP VPN CAR SAFI leverages BGP multi-protocol extensions [RFC4760] and uses the MP_REACH_NLRI and MP_UNREACH_NLRI attributes for route updates within SAFI value 84 along with AFI 1 for IPv4 VPN CAR prefixes and AFI 2 for IPv6 VPN CAR prefixes.

BGP speakers MUST use BGP Capabilities Advertisement to ensure support for processing of BGP VPN CAR updates. This is done as specified in [RFC4760], by using capability code 1 (multi-protocol BGP), with AFI 1 and 2 (as required) and SAFI 84.

The Next Hop network address field in the MP_REACH_NLRI may contain either a VPN-IPv4 or a VPN-IPv6 address with 8-octet RD set to zero, independent of AFI. If the next hop length is 12, then the next hop is a VPN-IPv4 address with an RD of 0 constructed as per [RFC4364]. If the next hop length is 24 or 48, then the next hop is a VPN-IPv6 address constructed as per section 3.2.1.1 of [RFC4659].

9.1.1. VPN CAR (E, C) NLRI Type

VPN CAR Type-1 (E, C) NLRI with RD has the format shown below



Followed by optional Non-Key TLVs encoded as per Section 2.9.2

where:

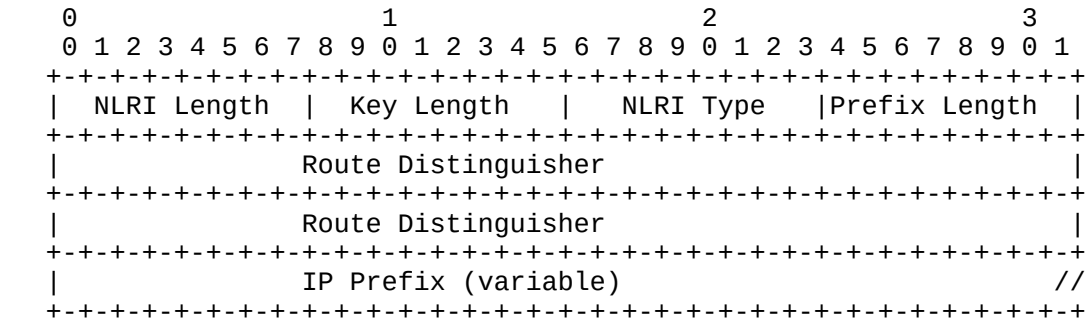
All fields are encoded as per Section 2.9.3 with the following changes:

* Key Length: This length indicates the total length comprised of the RD, Prefix Length field, IP Prefix field, and the Color field.

* Route Distinguisher: An 8-octet field encoded according to [RFC4364].

* Type-Specific Non-Key TLVs: Label TLV, Label Index TLV and SRv6 SID TLV (Section 2.9.2) may be associated with the VPN CAR (E, C) NLRI type.

9.1.2. VPN CAR IP Prefix NLRI Type



Followed by optional Non-Key TLVs encoded as per Section 2.9.2

where:

All fields are encoded as per Section 2.9.4 with the following changes:

* Key Length: This length indicates the total length comprised of the RD, Prefix Length field and IP Prefix field.

* Route Distinguisher: 8 octet field encoded according to [RFC4364].

* Type-Specific Non-Key TLVs: Label TLV, Label Index TLV and SRv6 SID TLV (Section 2.9.2) may be associated with the VPN CAR IP Prefix NLRI type.

Error handling specified in Section 2.11 also applies to VPN CAR SAFI.

10. IANA Considerations

10.1. BGP CAR SAFIs

IANA has assigned SAFI value 83 (BGP CAR) and SAFI value 84 (BGP VPN CAR) from the "SAFI Values" sub-registry under the "Subsequent Address Family Identifiers (SAFI) Parameters" registry with this document as a reference.

10.2. BGP CAR NLRI Types Registry

IANA is requested to create a "BGP CAR NLRI Types" registry in the "Border Gateway Protocol (BGP) Parameters" registry group with this document as a reference. The registry is for assignment of the one octet sized code-points for BGP CAR NLRI types and populated with the values shown below:

Type	NLRI Type	Reference
0	Reserved	[This document]
1	Color-Aware Route NLRI	[This document]
2	IP Prefix NLRI	[This document]
3-255	Unassigned	

Allocations within the registry are to be made under the "Specification Required" policy as specified in [RFC8126]) and in Section 10.4.

10.3. BGP CAR NLRI TLV Registry

IANA is requested to create a "BGP CAR NLRI TLV Types" registry in the "Border Gateway Protocol (BGP) Parameters" registry group with this document as a reference. The registry is for assignment of the 6-bits sized code-points for BGP CAR NLRI non-key TLV types and populated with the values shown below:

Type	NLRI TLV Type	Reference
0	Reserved	[This document]
1	Label TLV	[This document]
2	Label Index TLV	[This document]
3	SRv6 SID TLV	[This document]
4-64	Unassigned	

Allocations within the registry are to be made under the "Specification Required" policy as specified in [RFC8126]) and in Section 10.4.

For a new TLV to be used with existing NLRI Types, documentation of the NLRI Types must be updated.

10.4. Guidance for Designated Experts

In all cases of review by the Designated Expert (DE) described here, the DE is expected to ascertain the existence of suitable documentation (a specification) as described in [RFC8126] for BGP CAR NLRI Types Registry and BGP CAR NLRI TLV Registry.

The DE is also expected to check the clarity of purpose and use of the requested code points. Additionally, the DE must verify that any request for one of these code points has been made available for review and comment within the IETF: the DE will post the request to the IDR Working Group mailing list (or a successor mailing list designated by the IESG). The DE must ensure that any request for a code point does not conflict with work that is active or already published within the IETF.

The DE is expected to confirm that the specification satisfies the requirements for Specification Required (RFC 8126 Section 4.6). In particular, as a reminder, the specification is required to be "permanent and readily available". The DE may assume that any document in the Internet Draft or RFC repository satisfies the requirement for permanence and availability. In other cases, and in particular for any document not hosted by another standards development organization, the burden of proof of permanence falls on the applicant.

10.4.1. Additional evaluation criteria for the BGP CAR NLRI Types Registry

* Check the interoperability between new NLRI type and current NLRI types specified in this document for BGP CAR SAFIs (BGP CAR SAFI and VPN CAR SAFI), and any updates to this document.

* Check if specification indicates which non-key TLVs are applicable for the new NLRI Type.

10.4.2. Additional evaluation criteria for the BGP CAR NLRI TLV Registry

* Check the applicability of new TLV for the BGP CAR NLRI Types defined.

* Check the T bit setting for the new TLV

10.5. BGP Extended-Community Registry

IANA has assigned the sub-type 0x1b for "Local Color Mapping (LCM)" in the "Transitive Opaque Extended Community Sub-Types" registry located in the "Border Gateway Protocol (BGP) Extended Communities" registry group.

11. Manageability and Operational Considerations

Color assignments in a multi-domain network operating under a common or cooperating administrative control (i.e., a color domain) should be managed similar to transport layer IP addresses, and ensure a unique and non-conflicting color allocation across the different network domains in that color domain. This is a logical best practice in a single color or administrative domain, which is the most typical deployment scenario.

When color-aware routes propagate across a color domain boundary, there is typically no need for color assignments to be identical in both color domains, since the IP prefix is unique in the inter-domain transport network. This unique IP prefix provides a unique and non-conflicting scope for the color in an (E, C) route. Co-ordination between the operators of the color domains is needed only to enable the color to be re-mapped into a local color (carried in the LCM-EC) assigned for the same intent in the receiving color domain.

However, if networks under different administrative control establish a shared transport service between them, where the same transport service IP address is co-ordinated and shared among two (or more) color domains networks, then the color assignments associated with that shared IP address should also be co-ordinated to avoid any conflicts in either network (Appendix A.7).

It should be noted that the color assignments coordination are only necessary for routes specific to the shared service IP. Colors used for intra-domain or for inter-domain intents associated with unique IP addresses do not need any coordination.

Extended communities (LCM-EC/Color-EC) carried in BGP CAR and Service routes MUST NOT be filtered, otherwise the desired intent will not be achieved.

12. Security Considerations

This document does not change the underlying security considerations and issues inherent in the existing BGP protocol, such as those described in [RFC4271] and [RFC4272].

This document defines a new BGP SAFI and related extensions to carry color aware routes and their associated attributes. The separate SAFI is expected to be explicitly configured by an operator. It is also expected that the necessary BGP route policy filtering is configured on this new SAFI to filter routing information distributed by the routers participating in this network, at appropriate points within and at the boundaries of this network.

Also, given that this SAFI and these mechanisms can only be enabled through configuration of routers within an operator's network, standard security measures should be taken to restrict access to the management interface(s) of routers that implement these mechanisms.

Additionally, BGP sessions SHOULD be protected using TCP Authentication Option [RFC5925] and the Generalized TTL Security Mechanism [RFC5082]. BGP Origin Validation [RFC6811] and BGPsec [RFC8205] could also be used with this SAFI.

Since CAR SAFI is a separate BGP SAFI that carries transport or infrastructure routes for routers in the operator network, it provides automatic separation of infrastructure routes and the service routes that are carried in existing BGP SAFIs such as BGP IPv4/IPv6 (SAFI=1), and BGP-LU (SAFI=4) (e.g., 6PE [RFC4798]). Using CAR SAFI thus provides better security (such as protection against route leaking) than would be obtained by distributing the infrastructure routes in existing SAFIs that also carry service routes.

BGP CAR distributes label binding similar to [RFC8277] and hence its security considerations apply.

In SR deployments, BGP CAR distributes infrastructure prefixes along with their SID information for both SR-MPLS and SRv6. These deployments are within an SR Domain [RFC8402] and the security considerations of [RFC8402] apply. Additionally, security considerations related to SRv6 deployments that are discussed in section 9.3 of [RFC9252] also apply.

As [RFC4272] discusses, BGP is vulnerable to traffic-diversion attacks. This SAFI routes adds a new means by which an attacker could cause the traffic to be diverted from its normal path. Potential consequences include "hijacking" of traffic (insertion of an undesired node in the path, which allows for inspection or modification of traffic, or avoidance of security controls) or denial of service (directing traffic to a node that doesn't desire to receive it).

The restriction of the applicability of this SAFI to its intended well-defined scope and the use of techniques described above limit the likelihood of traffic diversions.

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15. References

15.1. Normative References

[RFC2119] Bradner, S., "Key words for use in RFCs to Indicate Requirement Levels", BCP 14, RFC 2119, DOI 10.17487/RFC2119, March 1997, <https://www.rfc-editor.org/info/rfc2119>.

[RFC2545] Marques, P. and F. Dupont, "Use of BGP-4 Multiprotocol Extensions for IPv6 Inter-Domain Routing", RFC 2545, DOI 10.17487/RFC2545, March 1999, <https://www.rfc-editor.org/info/rfc2545>.

[RFC4360] Sangli, S., Tappan, D., and Y. Rekhter, "BGP Extended Communities Attribute", RFC 4360, DOI 10.17487/RFC4360, February 2006, <https://www.rfc-editor.org/info/rfc4360>.

[RFC4684] Marques, P., Bonica, R., Fang, L., Martini, L., Raszuk, R., Patel, K., and J. Guichard, "Constrained Route Distribution for Border Gateway Protocol/MultiProtocol Label Switching (BGP/MPLS) Internet Protocol (IP) Virtual Private Networks (VPNs)", RFC 4684, DOI 10.17487/RFC4684, November 2006, <https://www.rfc-editor.org/info/rfc4684>.

[RFC4760] Bates, T., Chandra, R., Katz, D., and Y. Rekhter, "Multiprotocol Extensions for BGP-4", RFC 4760, DOI 10.17487/RFC4760, January 2007, <https://www.rfc-editor.org/info/rfc4760>.

[RFC7311] Mohapatra, P., Fernando, R., Rosen, E., and J. Uttaro, "The Accumulated IGP Metric Attribute for BGP", RFC 7311, DOI 10.17487/RFC7311, August 2014, <https://www.rfc-editor.org/info/rfc7311>.

[RFC7606] Chen, E., Ed., Scudder, J., Ed., Mohapatra, P., and K. Patel, "Revised Error Handling for BGP UPDATE Messages", RFC 7606, DOI 10.17487/RFC7606, August 2015, <https://www.rfc-editor.org/info/rfc7606>.

[RFC8126] Cotton, M., Leiba, B., and T. Narten, "Guidelines for Writing an IANA Considerations Section in RFCs", BCP 26, RFC 8126, DOI 10.17487/RFC8126, June 2017, <https://www.rfc-editor.org/info/rfc8126>.

[RFC8174] Leiba, B., "Ambiguity of Uppercase vs Lowercase in RFC 2119 Key Words", BCP 14, RFC 8174, DOI 10.17487/RFC8174, May 2017, <https://www.rfc-editor.org/info/rfc8174>.

[RFC8277] Rosen, E., "Using BGP to Bind MPLS Labels to Address Prefixes", RFC 8277, DOI 10.17487/RFC8277, October 2017, <https://www.rfc-editor.org/info/rfc8277>.

[RFC8402] Filsfils, C., Ed., Previdi, S., Ed., Ginsberg, L., Decraene, B., Litkowski, S., and R. Shakir, "Segment Routing Architecture", RFC 8402, DOI 10.17487/RFC8402, July 2018, <https://www.rfc-editor.org/info/rfc8402>.

[RFC8669] Previdi, S., Filsfils, C., Lindem, A., Ed., Sreekantiah, A., and H. Gredler, "Segment Routing Prefix Segment Identifier Extensions for BGP", RFC 8669, DOI 10.17487/RFC8669, December 2019, <https://www.rfc-editor.org/info/rfc8669>.

[RFC8986] Filsfils, C., Ed., Camarillo, P., Ed., Leddy, J., Voyer, D., Matsushima, S., and Z. Li, "Segment Routing over IPv6 (SRv6) Network Programming", RFC 8986, DOI 10.17487/RFC8986, February 2021, <https://www.rfc-editor.org/info/rfc8986>.

[RFC9012] Patel, K., Van de Velde, G., Sangli, S., and J. Scudder, "The BGP Tunnel Encapsulation Attribute", RFC 9012, DOI 10.17487/RFC9012, April 2021, <https://www.rfc-editor.org/info/rfc9012>.

[RFC9252] Dawra, G., Ed., Talaulikar, K., Ed., Raszuk, R., Decraene, B., Zhuang, S., and J. Rabadan, "BGP Overlay Services Based on Segment Routing over IPv6 (SRv6)", RFC 9252, DOI 10.17487/RFC9252, July 2022, <https://www.rfc-editor.org/info/rfc9252>.

[RFC9256] Filsfils, C., Talaulikar, K., Ed., Voyer, D., Bogdanov, A., and P. Mattes, "Segment Routing Policy Architecture", RFC 9256, DOI 10.17487/RFC9256, July 2022, <https://www.rfc-editor.org/info/rfc9256>.

[RFC9350] Psenak, P., Ed., Hegde, S., Filsfils, C., Talaulikar, K., and A. Gulko, "IGP Flexible Algorithm", RFC 9350, DOI 10.17487/RFC9350, February 2023, <https://www.rfc-editor.org/info/rfc9350>.

15.2. Informative References

[I-D.hr-spring-intentaware-routing-using-color] Hegde, S., Rao, D., Uttaro, J., Bogdanov, A., and L. Jalil, "Problem statement for Inter-domain Intent-aware Routing using Color", Work in Progress, Internet-Draft, draft-hr-spring-intentaware-routing-using-color-04, 31 January 2025, <https://datatracker.ietf.org/doc/html/draft-hr-spring-intentaware-routing-using-color-04>.

[I-D.ietf-idr-cpr]
Wang, H., Dong, J., Talaulikar, K., hantao, and R. Chen, "BGP Colored Prefix Routing (CPR) for SRv6 based Services", Work in Progress, Internet-Draft, draft-ietf-idr-cpr-07, 7 February 2025, <https://datatracker.ietf.org/doc/html/draft-ietf-idr-cpr-07>.

[I-D.ietf-spring-srv6-mpls-interworking]
Agrawal, S., Filsfils, C., Voyer, D., Dawra, G., Li, Z., and S. Hegde, "SRv6 and MPLS interworking", Work in Progress, Internet-Draft, draft-ietf-spring-srv6-mpls-interworking-00, 17 October 2024, <https://datatracker.ietf.org/doc/html/draft-ietf-spring-srv6-mpls-interworking-00>.

[RFC4271] Rekhter, Y., Ed., Li, T., Ed., and S. Hares, Ed., "A Border Gateway Protocol 4 (BGP-4)", RFC 4271, DOI 10.17487/RFC4271, January 2006, <https://www.rfc-editor.org/info/rfc4271>.

[RFC4272] Murphy, S., "BGP Security Vulnerabilities Analysis", RFC 4272, DOI 10.17487/RFC4272, January 2006, <https://www.rfc-editor.org/info/rfc4272>.

[RFC4364] Rosen, E. and Y. Rekhter, "BGP/MPLS IP Virtual Private Networks (VPNs)", RFC 4364, DOI 10.17487/RFC4364, February 2006, <https://www.rfc-editor.org/info/rfc4364>.

[RFC4659] De Clercq, J., Ooms, D., Carugi, M., and F. Le Faucheur, "BGP-MPLS IP Virtual Private Network (VPN) Extension for IPv6 VPN", RFC 4659, DOI 10.17487/RFC4659, September 2006, <https://www.rfc-editor.org/info/rfc4659>.

[RFC4798] De Clercq, J., Ooms, D., Prevost, S., and F. Le Faucheur, "Connecting IPv6 Islands over IPv4 MPLS Using IPv6 Provider Edge Routers (6PE)", RFC 4798, DOI 10.17487/RFC4798, February 2007, <https://www.rfc-editor.org/info/rfc4798>.

[RFC5082] Gill, V., Heasley, J., Meyer, D., Savola, P., Ed., and C. Pignataro, "The Generalized TTL Security Mechanism (GTSM)", RFC 5082, DOI 10.17487/RFC5082, October 2007, <https://www.rfc-editor.org/info/rfc5082>.

[RFC5462] Andersson, L. and R. Asati, "Multiprotocol Label Switching (MPLS) Label Stack Entry: "EXP" Field Renamed to "Traffic Class" Field", RFC 5462, DOI 10.17487/RFC5462, February 2009, <https://www.rfc-editor.org/info/rfc5462>.

[RFC5925] Touch, J., Mankin, A., and R. Bonica, "The TCP Authentication Option", RFC 5925, DOI 10.17487/RFC5925, June 2010, <https://www.rfc-editor.org/info/rfc5925>.

[RFC6811] Mohapatra, P., Scudder, J., Ward, D., Bush, R., and R. Austein, "BGP Prefix Origin Validation", RFC 6811, DOI 10.17487/RFC6811, January 2013, <https://www.rfc-editor.org/info/rfc6811>.

[RFC7911] Walton, D., Retana, A., Chen, E., and J. Scudder, "Advertisement of Multiple Paths in BGP", RFC 7911, DOI 10.17487/RFC7911, July 2016, <https://www.rfc-editor.org/info/rfc7911>.

[RFC8205] Lepinski, M., Ed. and K. Sriram, Ed., "BGPsec Protocol Specification", RFC 8205, DOI 10.17487/RFC8205, September 2017, <https://www.rfc-editor.org/info/rfc8205>.

[RFC9315] Clemm, A., Ciavaglia, L., Granville, L. Z., and J. Tantsura, "Intent-Based Networking - Concepts and Definitions", RFC 9315, DOI 10.17487/RFC9315, October 2022, <https://www.rfc-editor.org/info/rfc9315>.

Appendix A. Illustrations of Service Steering

The following sub-sections illustrate example scenarios of Colored Service Route Steering over E2E BGP CAR paths, resolving over different intra-domain mechanisms.

The examples in this section use MPLS/SR for the transport data plane. Scenarios related to SRv6 encapsulation are in a section below.

A.1. E2E BGP transport CAR intent realized using IGP Flex-Algo

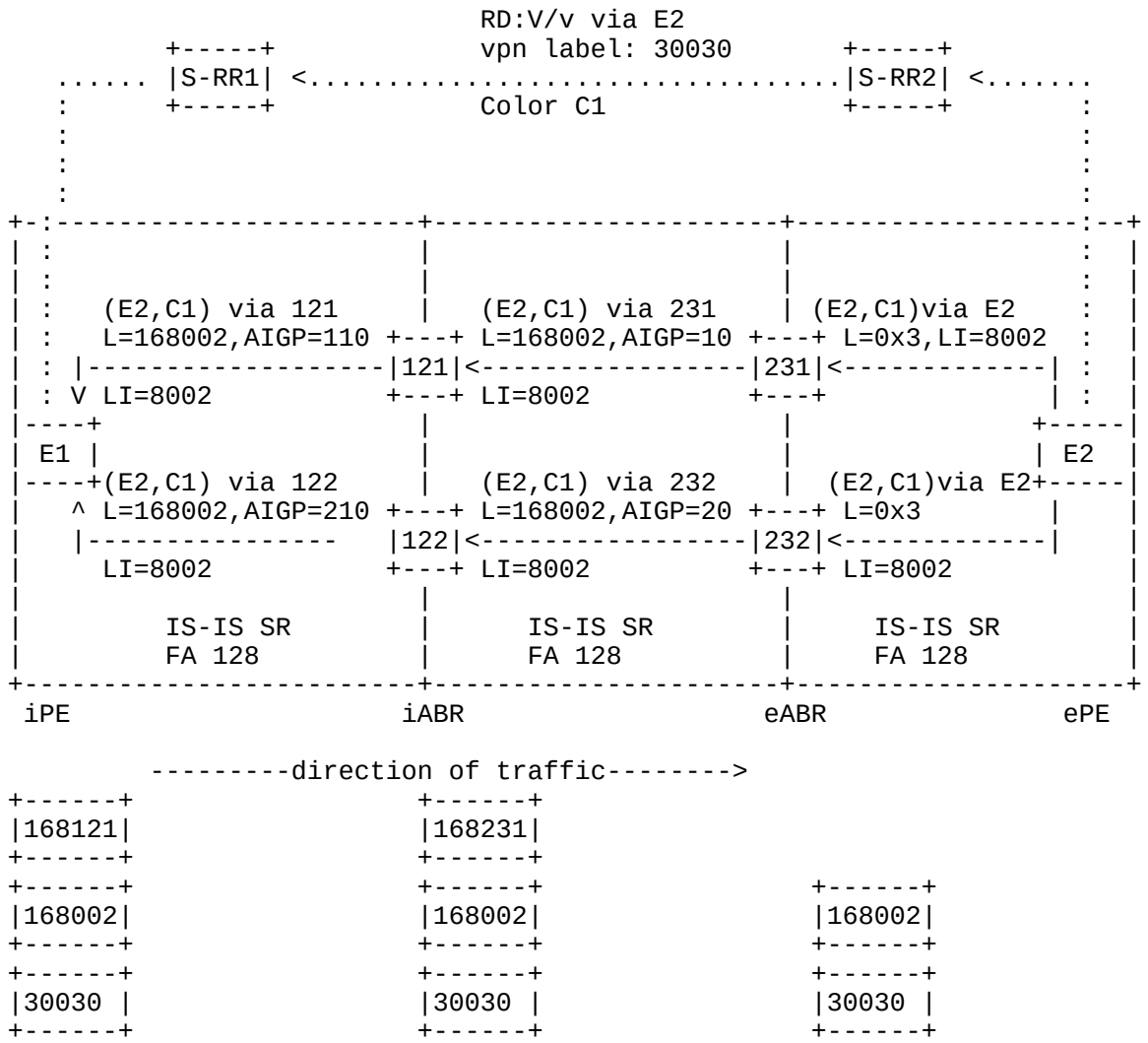


Figure 6: BGP FA Aware transport CAR path

Use case: Provide end to end intent for service flows.

* The following description applies to the reference topology above:

  - IGP FA 128 is running in each domain, and mapped to Color C1.

  - Egress PE E2 advertises a VPN route RD:V/v colored with Color-EC C1 to steer traffic to BGP transport CAR (E2, C1). VPN route propagates via service RRs to ingress PE E1.

- BGP CAR route (E2, C1) with next hop, label index and label as shown above are advertised through border routers in each domain. When a RR is used in the domain, ADD-PATH is enabled to advertise multiple available paths.

- On each BGP hop, the (E2, C1) route’s next hop is resolved over IGP FA 128 of the domain. The AIGP attribute influences BGP CAR route best path decision as per [RFC7311]. The BGP CAR label swap entry is installed that goes over FA 128 LSP to next hop providing intent in each IGP domain. The AIGP metric should be updated to reflect FA 128 metric to next hop.

- Ingress PE E1 learns CAR route (E2, C1). It steers colored VPN route RD:V/v into (E2, C1).

* Important:

  - IGP FA 128 top label provides intent within each domain.

  - BGP CAR label (e.g. 168002) carries end to end intent. Thus it stitches intent over intra-domain FA 128.

A.2. E2E BGP transport CAR intent realized using SR Policy

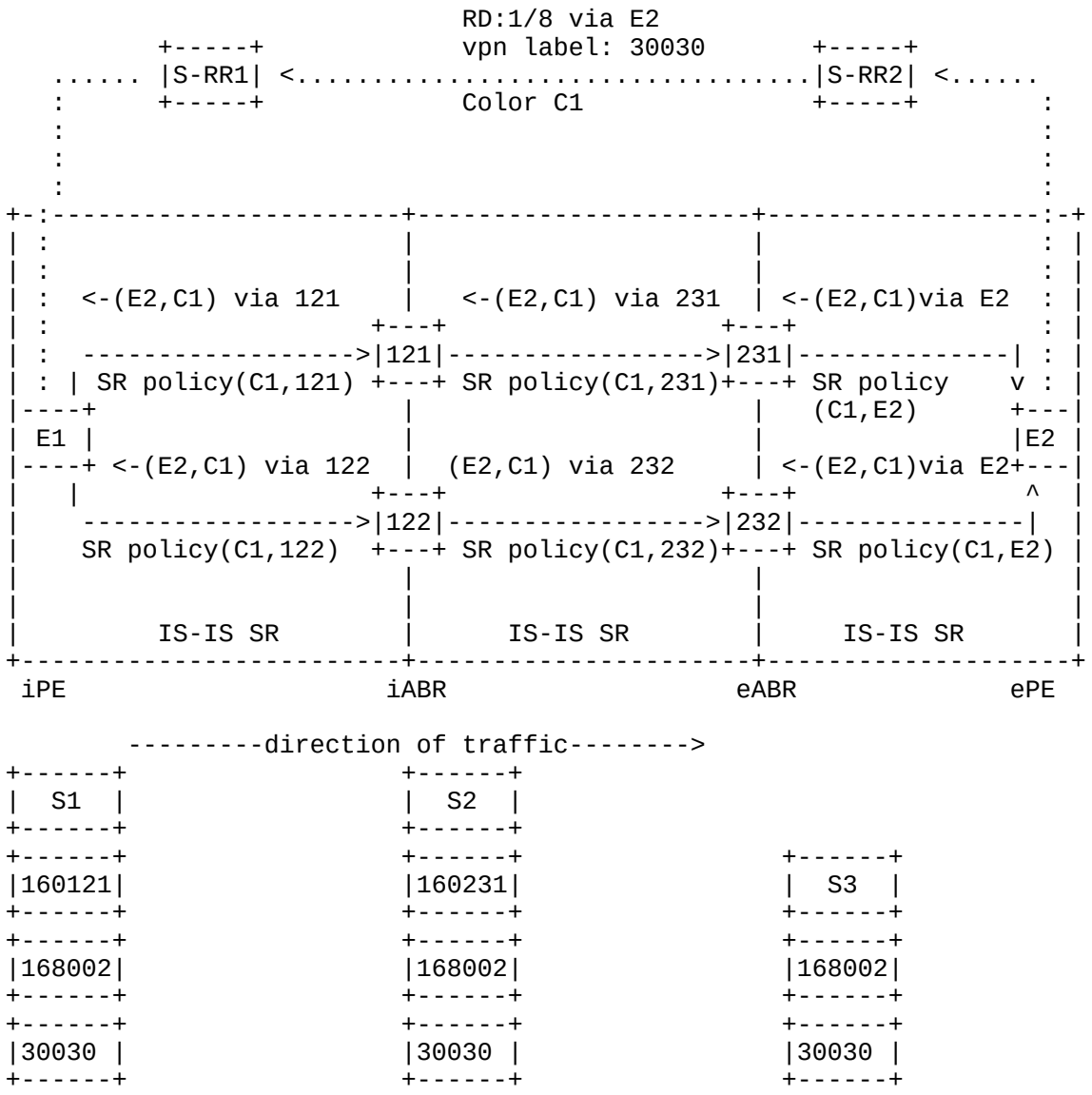


Figure 7: BGP SR policy Aware transport CAR path

Use case: Provide end to end intent for service flows.

* The following description applies to the reference topology above:

- An SR Policy provides intra-domain intent. The following are the example SID lists that are realized from SR policies in each domain and correspond to the label stack shown in Figure 7

  o SR policy (C1,121) segments <S1, 121>,

  o SR policy (C1,231) segments <S2, 231>, and

  o SR policy (C1,E2) segments <S3, E2>.

- Egress PE E2 advertises a VPN route RD:V/v colored with Color-EC C1 to steer traffic to BGP transport CAR (E2, C1). VPN route propagates via service RRs to ingress PE E1.

- BGP CAR route (E2, C1) with next hop, label index and label as shown above are advertised through border routers in each domain. When a RR is used in the domain, ADD-PATH is enabled to advertise multiple available paths.

- On each BGP hop, the CAR route (E2, C1) next hop is resolved over an SR policy (C1, next hop). BGP CAR label swap entry is installed that goes over SR policy segment list.

- Ingress PE E1 learns CAR route (E2, C1). It steers colored VPN route RD:V/v into (E2, C1).

* Important:

  - SR policy provides intent within each domain.

  - BGP CAR label (e.g. 168002) carries end to end intent. Thus it stitches intent over intra-domain SR policies.

A.3. BGP transport CAR intent realized in a section of the network

A.3.1. Provide intent for service flows only in core domain running IS-IS Flex-Algo

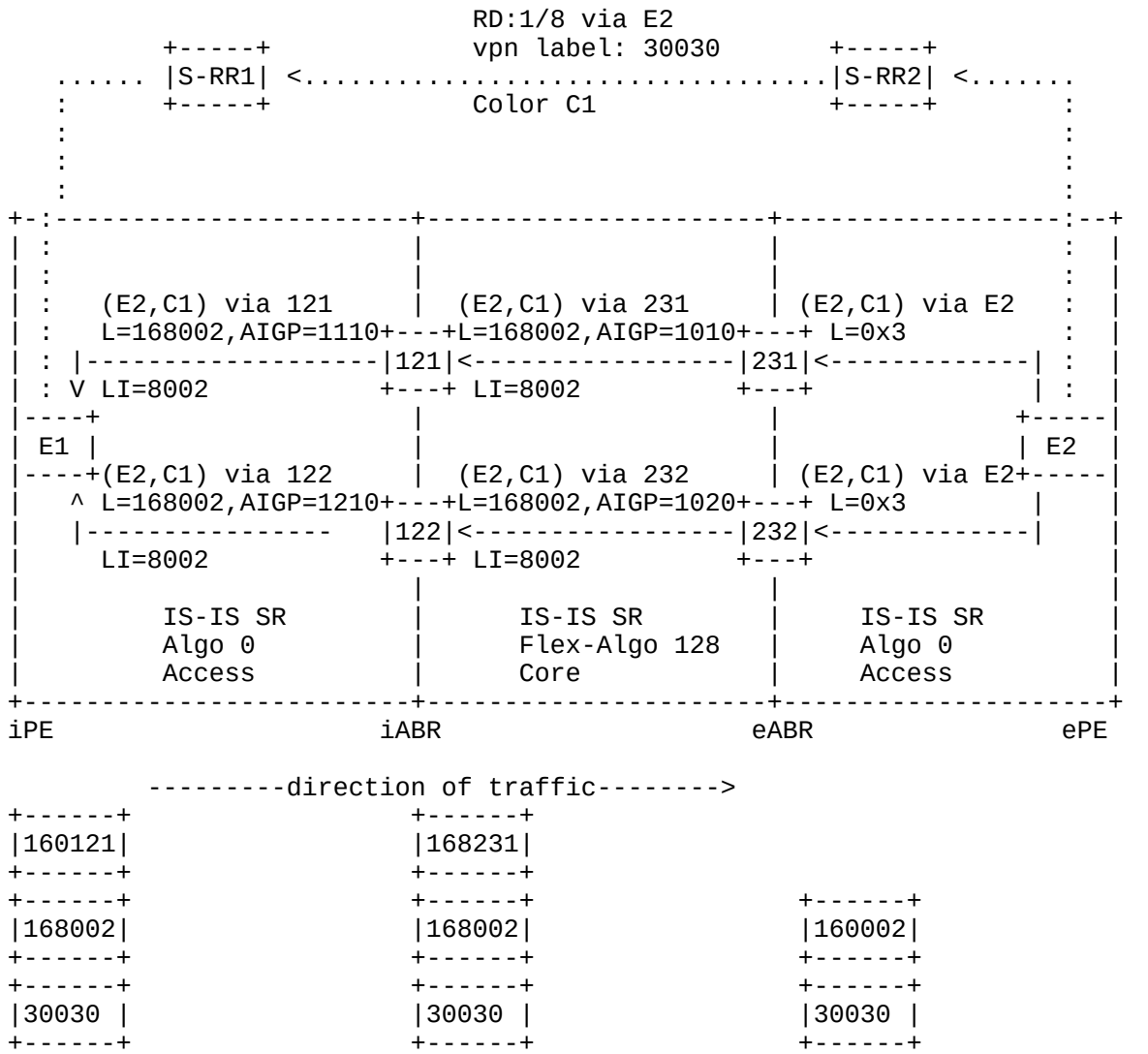


Figure 8: BGP Hybrid Flex-Algo Aware transport CAR path

* The following description applies to the reference topology above:

  - IGP FA 128 is only enabled in Core (e.g. WAN network), mapped to C1. Access network domain only has Base Algo 0.

  - Egress PE E2 advertises a VPN route RD:V/v colored with Color-EC C1 to steer traffic via BGP transport CAR (E2, C1). VPN route propagates via service RRs to ingress PE E1.

- BGP CAR route (E2, C1) with next hop, label index and label as shown above are advertised through border routers in each domain. When a RR is used in the domain, ADD-PATH is enabled to advertise multiple available paths.

- Local policy on 231 and 232 maps intent C1 to resolve CAR route next hop over IGP Base Algo 0 in right access domain. BGP CAR label swap entry is installed that goes over Base Algo 0 LSP to next hop. Updates AIGP metric to reflect Base Algo 0 metric to next hop with an additional penalty (+1000).

- On 121 and 122, CAR route (E2, C1) next hop learnt from Core domain is resolved over IGP FA 128. BGP CAR label swap entry is installed that goes over FA 128 LSP to next hop providing intent in Core IGP domain.

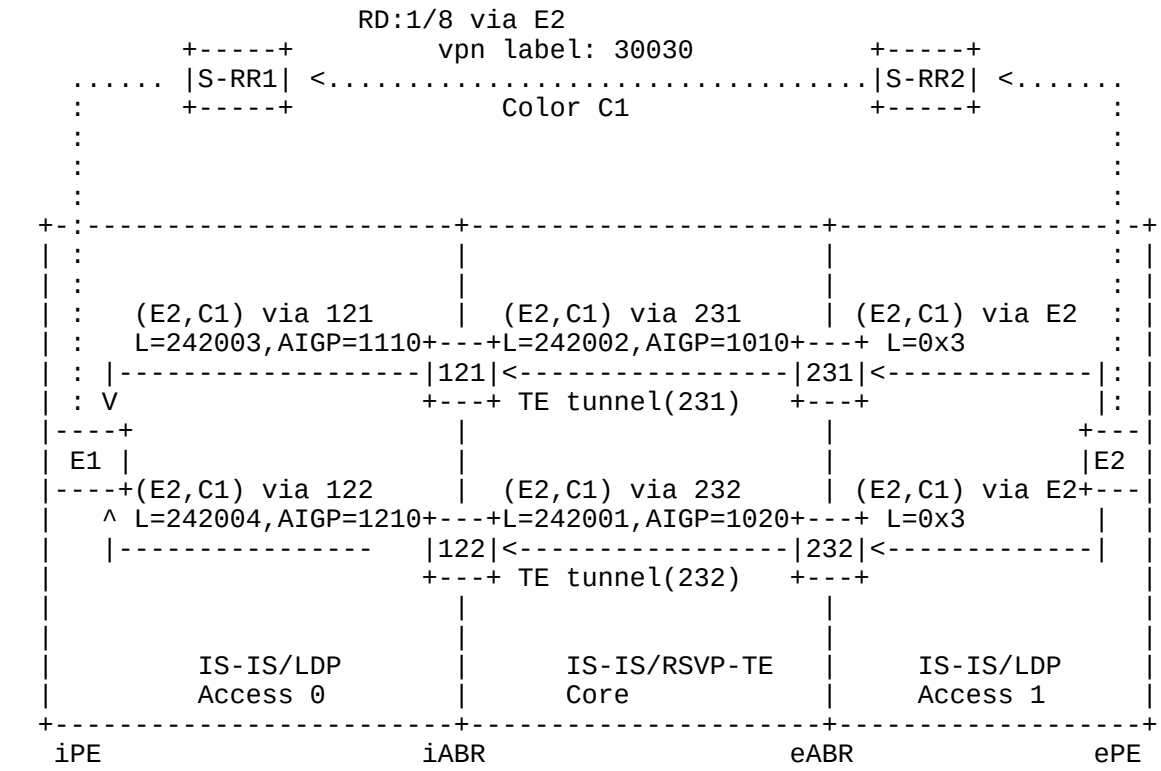
- Ingress PE E1 learns CAR route (E2, C1). It maps intent C1 to resolve CAR route next hop over IGP Base Algo 0. It steers colored VPN route RD:V/v via (E2, C1)

* Important:

  - IGP Flex-Algo 128 top label provides intent in Core domain.

  - BGP CAR label (e.g. 168002) carries intent from PEs which is realized in core domain.

A.3.2. Provide intent for service flows only in core domain over TE tunnel mesh



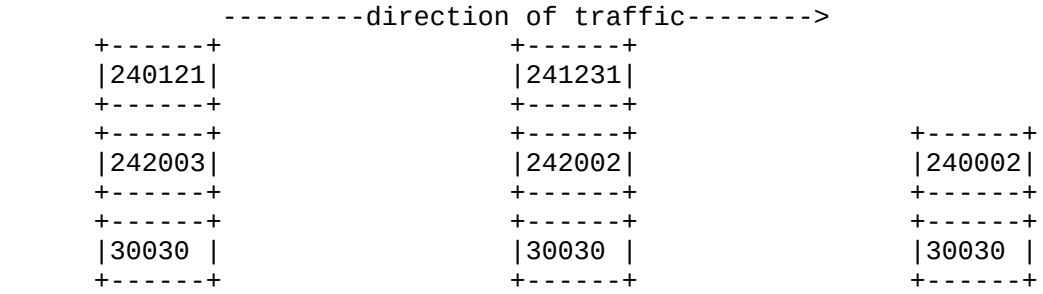


Figure 9: BGP CAR over TE tunnel mesh in core network

* The following description applies to the reference topology above:

- RSVP-TE MPLS tunnel mesh is configured only in core (e.g. WAN network). Access only has IS-IS/LDP. (Figure does not show all TE tunnels).

- Egress PE E2 advertises a VPN route RD:V/v colored with Color-EC C1 to steer traffic via BGP transport CAR (E2, C1). VPN route propagates via service RRs to ingress PE E1.

- BGP CAR route (E2, C1) with next hops and labels as shown above is advertised through border routers in each domain. When a RR is used in the domain, ADD-PATH is enabled to advertise multiple available paths.

- Local policy on 231 and 232 maps intent C1 to resolve CAR route next hop over best-effort LDP LSP in access domain 1. BGP CAR label swap entry is installed that goes over LDP LSP to next hop. AIGP metric is updated to reflect best-effort metric to next hop with an additional penalty (+1000).

- Local policy on 121 and 122 maps intent C1 to resolve CAR route next hop in Core domain over RSVP-TE tunnels. BGP CAR label swap entry is installed that goes over a TE tunnel to next hop providing intent in Core domain. AIGP metric is updated to reflect TE tunnel metric.

- Ingress PE E1 learns CAR route (E2, C1). It maps intent C1 to resolve CAR route's next hop over best-effort LDP LSP in Access domain 0. It steers colored VPN route RD:V/v via (E2, C1).

* Important:

  - RSVP-TE tunnel LSP provides intent in Core domain.

  - Dynamic BGP CAR label carries intent from PEs which is realized in core domain by resolution via RSVP-TE tunnel.

A.4. Transit network domains that do not support CAR

* In a brownfield deployment, color-aware paths between two PEs may need to go through a transit domain that does not support CAR. Examples of such a brownfield network include an MPLS LDP network with IGP best-effort, or a BGP-LU based multi-domain network. MPLS LDP network with best-effort IGP can adopt the above scheme in Section A.3. Below is the example scenario for BGP LU.

* Reference topology:

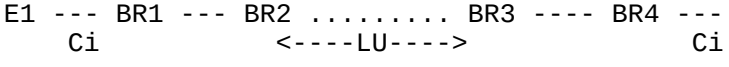


Figure 10: BGP CAR not supported in transit domain

- Network between BR2 and BR3 comprises of multiple BGP-LU hops (over IGP-LDP domains).

- E1, BR1, BR4 and E2 are enabled for BGP CAR, with Ci colors.

- BR1 and BR2 are directly connected; BR3 and BR4 are directly connected.

* BR1 and BR4 form an over-the-top peering (via RRs as needed) to exchange BGP CAR routes.

* BR1 and BR4 also form direct BGP-LU sessions to BR2 and BR3 respectively, to establish labeled paths between each other through the BGP-LU network. The sessions may be eBGP or iBGP.

* BR1 recursively resolves the BGP CAR next hop for CAR routes learnt from BR4 via the BGP-LU path to BR4.

* BR1 signals the transport discontinuity to E1 via the AIGP TLV, so that E1 can prefer other paths if available.

* BR4 does the same in the reverse direction.

* Thus, the color-awareness of the routes and hence the paths in the data plane are maintained between E1 and E2, even if the intent is not available within the BGP-LU island.

* A similar design can be used for going over network islands of other types.

A.5. Resource Avoidance using BGP CAR and IGP Flex-Algo

This example illustrates a case of resource avoidance within a domain for a multi-domain color-aware path.

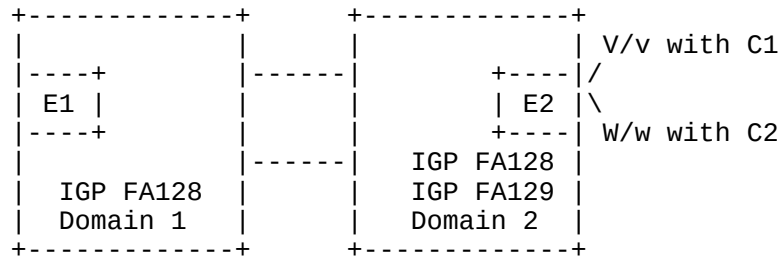


Figure 11: BGP CAR resolution over IGP FLex-Algo for resource avoidance in a domain

* C1 and C2 represent the following two unique intents in the multi-domain network:
  - C1 is mapped to "minimize IGP metric", and
  - C2 is mapped to "minimize IGP metric and avoid resource R".
* Resource R represents link(s) or node(s) to be avoided.
* Flex-Algo FA128 in Domain 2 is mapped to "minimize IGP metric" and hence to C1.
* Flex-Algo FA129 in Domain 2 is mapped to "minimize IGP metric and avoid resource R" and hence to C2.
* Flex-Algo FA128 in Domain 1 is mapped to "minimize IGP metric" i.e.,
  - There is no resource R to be avoided in Domain 1, hence both C1 and C2 are mapped to FA128.
* E1 receives the following two service routes from E2:
  - V/v with BGP Color-EC C1, and
  - W/w with BGP Color-EC C2.
* E1 has the following color-aware paths:
  - (E2, C1) provided by BGP CAR with the following per-domain resolution:
    o Domain1: over IGP FA128, and
    o Domain2: over IGP FA128.
  - (E2, C2) provided by BGP CAR with the following per-domain resolution:
    o Domain1: over IGP FA128, and
    o Domain2: over IGP FA129 (avoiding resource R).
* E1 automatically steers the received service routes as follows:
  - V/v via (E2, C1) provided by BGP CAR.
  - W/w via (E2, C2) provided by BGP CAR.

Observations:

* C1 and C2 are realized over a common intra-domain intent (FA128) in one domain and distinct intents in another domain as required.

* 32-bit Color space provides flexibility in defining a large number of intents in a multi-domain network. They may be efficiently realized by mapping to a smaller number of intra-domain intents in different domains.

A.6. Per-Flow Steering over CAR routes

This section provides an example of ingress PE per-flow steering as defined in section 8.6 of [RFC9256] onto BGP CAR routes.

The following description applies to the reference topology in Figure 6:

* Ingress PE E1 learns best-effort BGP LU route E2.

* Ingress PE E1 learns CAR route (E2, C1), C1 is mapped to "low delay".

* Ingress PE E1 learns CAR route (E2, C2), C2 is mapped to "low delay and avoid resource R".

* Ingress PE E1 is configured to instantiate an array of paths to E2 where entry 0 is the BGP LU path to next hop, color C1 is the first entry and color C2 is the second entry. The index into the array is called a Forwarding Class (FC). The index can have values 0 to 7, especially when derived from the MPLS TC bits [RFC5462].

* E1 is configured to match flows in its ingress interfaces (upon any field such as Ethernet destination/source/VLAN/TOS or IP destination/source/DSCP or transport ports etc.) and color them with an internal per-packet FC variable (0, 1 or 2 in this example).

* This array is presented as composite candidate path of SR policy (E2, C100) and acts as a container for grouping constituent paths of different colors/best-effort. This representation provides automated steering for services colored with Color-EC C100 via paths of different colors. Note that Color-EC C100 is used as indirection to the composite policy configured on ingress PE.

* Egress PE E2 advertises a VPN route RD:V/v with Color-EC C100 to steer traffic via composite SR policy (E2, C100); i.e., FC array of paths.

E1 receives three packets K, K1, and K2 on its incoming interface. These three packets matches on VPN route which recurses on E2. E1 colors these 3 packets respectively with forwarding-class 0, 1, and 2.

As a result

* E1 forwards K along the best-effort path to E2 (i.e., for MPLS data plane, it pushes the best-effort label of E2).

* E1 forwards K1 along the (E2, C1) BGP CAR route.

* E1 forwards K2 along the (E2, C2) BGP CAR route.

A.7. Advertising BGP CAR routes for shared IP addresses

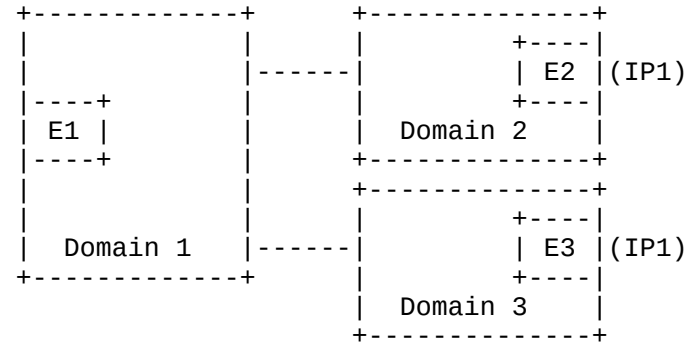


Figure 12: BGP CAR advertisements for shared IP addresses

This example describes a case where a route for the same transport IP address is originated from multiple nodes in different network domains.

One use of this scenario is an Anycast transport service, where packet encapsulation (e.g., LSP) may terminate on any one among a set of nodes. All the nodes are capable of forwarding the inner payload, typically via an IP lookup in the global table for Internet routes.

A couple of variations of the use-case are described in the example below.

One node is shown in each domain, but there will be multiple nodes in practice for redundancy.

Example-1: Anycast with forwarding to nearest

* Both E2 (in egress domain 2) and E3 (in egress domain 3) advertise Anycast (shared) IP (IP1, C1) with same label L1.

* An ingress PE E1 receives by default the best path(s) for (IP1, C1) propagated through BGP hops across the network.

* The paths to (IP1, C1) from E2 and E3 may merge at a common node along the path to E1, forming equal cost multipaths or active-backup paths at that node.

* Service route V/v is advertised from egress domains D2 and D3 with color C1 and next hop IP1.

* Traffic for V/v steered at E1 via (IP1, C1) is forwarded to either E2 or E3 (or both) as determined by routing along the network (nodes in the path).

Example-2: Anycast with egress domain visibility at ingress PE

* E2 advertises (IP1, C1) and E3 advertises (IP1, C2) CAR routes for the Anycast IP IP1. C1 and C2 are colors assigned to distinguish the egress domains originating the routes to IP1.

* An ingress PE E1 receives the best path(s) propagated through BGP hops across the network for both (IP1, C1) and (IP1, C2).

* The CAR routes (IP1, C1) and (IP1, C2) do not get merged at any intermediate node, providing E1 control over path selection and load-balancing of traffic across these two routes. Each route may itself provide multipathing or Anycast to a set of egress nodes.

* Service route V/v advertised from egress domains D2 and D3 with colors C1 and C2 respectively, but with same next hop IP1.

* E1 will resolve and steer V/v path from D2 via (IP1, C1) and path from D3 via (IP2, C2). E1 will load-balance traffic to V/v across the two paths as determined by a local load-balancing policy.

* Traffic for colored service routes steered at E1 is forwarded to either E2 or E3 (or load-balanced across both) as determined by E1.

In above example, D2 and D3 belonged to the same color or administrative domain. If D2 and D3 belong to different color domains, the domains will coordinate the assignment of colors with shared IP IP1 so that they do not cause conflicts. For instance, in Example-1:

* D2 and D3 may both use C1 for the same intent when they originate CAR route for IP1.
  - In this case, neither D2 nor D3 will reuse C1 for some other intent.
* Alternatively, D2 may use C2 and D3 may use C3 for originating a CAR route for IP1 for the same intent.
  - In this case, D2 will not use C3 for originating CAR route for IP1 for some other intent. Similarly, D3 will not use C2 for originating CAR route for IP1 for some other intent.

Appendix B. Color Mapping Illustrations

There are a variety of deployment scenarios that arise when different color mappings are used in an inter-domain environment. This section attempts to enumerate them and provide clarity into the usage of the color related protocol constructs.

B.1. Single color domain containing network domains with N:N color distribution

* All network domains (ingress, egress and all transit domains) are enabled for the same N colors.
  - A color may of course be realized by different technologies in different domains as described above.
* The N intents are both signaled end-to-end via BGP CAR routes; as well as realized in the data plane.
* Appendix A.1 is an example of this case.

B.2. Single color domain containing network domains with N:M color distribution

* Certain network domains may not be enabled for some of the colors used for end-to-end intents, but may still be required to provide transit for routes of those colors.

* When a (E, C1) route traverses a domain where color C1 is not available, the operator may decide to use a different intent of color C2 that is available in that domain to resolve the next hop and establish a path through the domain.

  - The next hop resolution may occur via paths of any intra-domain protocol or even via paths provided by BGP CAR.

  - The next hop resolution color C2 may be defined as a local policy at ingress or transit nodes of the domain.

  - It may also be automatically signaled from egress border nodes by attaching a Color-EC with value C2 to the BGP CAR routes.

* Hence, routes of N end-to-end colors may be resolved over paths from a smaller set of M colors in a transit domain, while preserving the original color-awareness end-to-end.

* Any ingress PE that installs a service (VPN) route with a color C1, must have C1 enabled locally to install IP routes to (E, C1) and resolve the service route’s next hop.

* A degenerate variation of this scenario is where a transit domain does not support any color. Appendix A.3 describes an example of this case.

Illustration for N end to end intents over fewer M intra-domain intents:

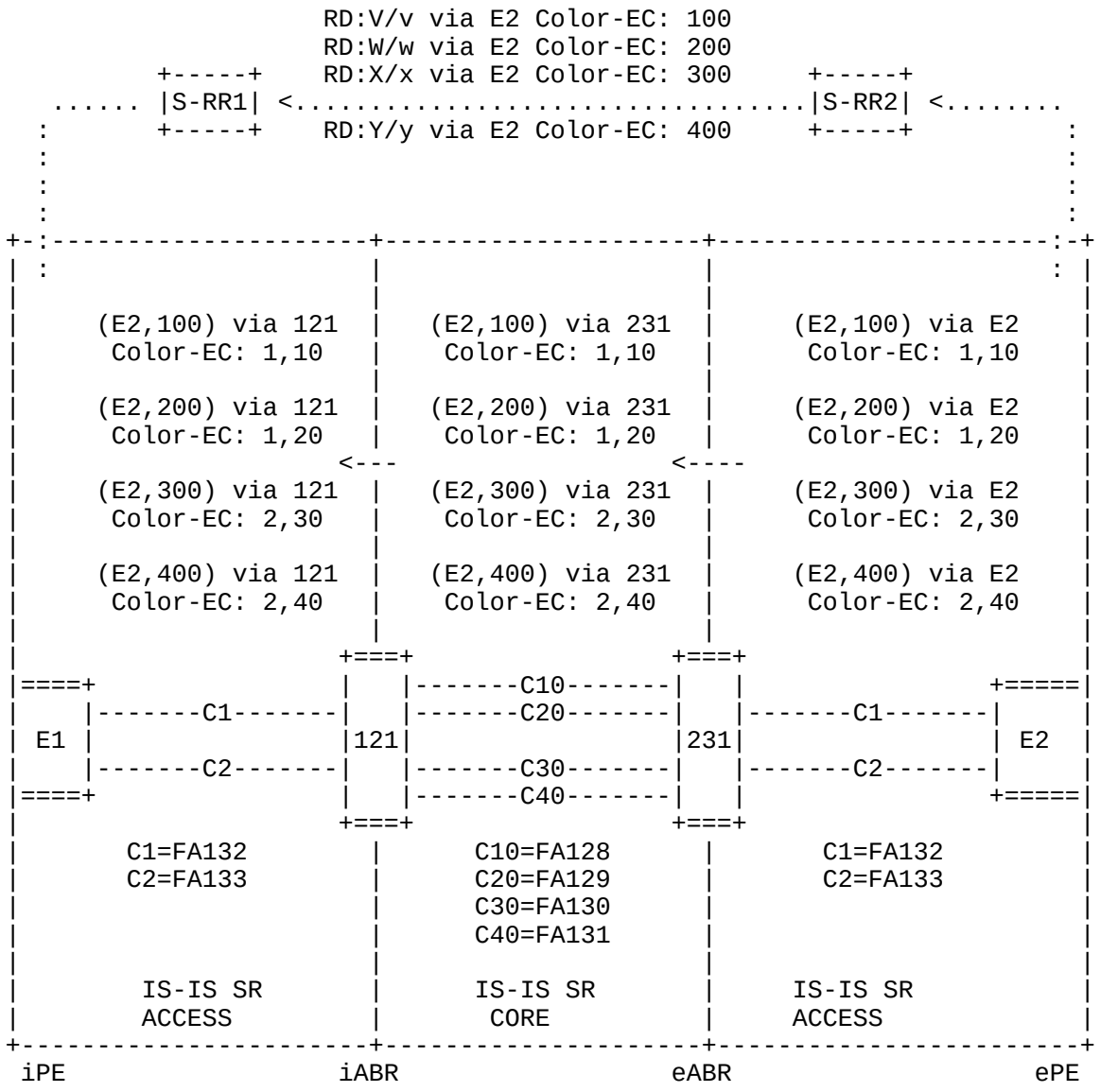


Figure 13: N:M illustration

* The following description applies to the reference topology above:

  - Core domain provides 4 intra-domain intents as described below:

    o FA128 mapped to C10,

- o FA129 mapped to C20,
- o FA130 mapped to C30, and
- o FA131 mapped to C40.

- Access domain provides following 2 intra-domain intents:
  - o FA132 mapped to C1, and
  - o FA133 mapped to C2
- Operator defines following 4 BGP CAR end to end intents as below:
  - o CAR color C100 that resolves on C1 in access and C10 in core domain,
  - o CAR color C200 that resolves on C1 in access and C20 in core domain,
  - o CAR color C300 that resolves on C2 in access and C30 in core domain, and
  - o CAR color C400 that resolves on C2 in access and C40 in core domain.
- E2 may originate BGP CAR routes with multiple BGP Color-ECs as shown above. At each hop, CAR route's next hop is resolved over the available intra-domain color. For example (E2, C100) with BGP color ECs C1, C10 resolves over C1 at ABR 231, C10 at ABR 121, and C1 at E1.
- Egress PE E2 advertises a VPN route RD:V/v colored with BGP Color-EC C100 to steer traffic through FA 132 in access and FA 128 in core. It also advertises another VPN route RD:W/w colored with BGP Color-EC C200 to steer traffic through FA 132 in access and FA 129 in core.

* Important:
  - End-to-end (BGP CAR) colors can be decoupled from intra-domain transport colors.
  - Each end-to-end BGP CAR color is a combination of various intra-domain colors or intents.

- Combination can be expressed by local policy at ABRs or by attaching multiple BGP Color-ECs at origination point of BGP CAR route.

- Service traffic is steered into suitable CAR color to use the most granular intent in a domain multiple hops away from ingress PE.

- Consistent reuse of standard color based resolution mechanism at both service and transport layers.

B.3. Multiple color domains

When the routes are distributed between domains with different color-to-intent mapping schemes, both N:N and N:M cases are possible. Although an N:M mapping is more likely to occur.

Reference topology:

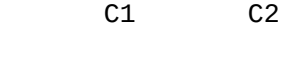


Figure 14: Multiple color domains

* C1 in D1 maps to C2 in D2 and to C3 in D3.

* BGP CAR is enabled in all three color domains.

The reference topology above is used to elaborate on the design described in Section 2.8

When the route originates in color domain D1 and gets advertised to a different color domain D2, following procedures apply:

* The NLRI of the BGP CAR route is preserved end to end, i.e., route is (E, C1).

* A BR of D1 attaches LCM-EC with value C1 when advertising to a BR in D2.

* A BR in D2 receiving (E, C1) maps C1 in received LCM-EC to local color, say C2.

  - A BR in D2 may receive (E, C1) from multiple D1 BRs which provide equal cost or primary/backup paths.

* Within D2, this LCM-EC value of C2 is used instead of the Color in CAR route NLRI (E, C1). This applies to all procedures described in the earlier section for a single color domain, such as next-hop resolution and service steering.

* A colored service route V/v originated in color domain D1 with next hop E and Color-EC C1 will also have its color extended-community value re-mapped to C2, typically at a service RR.

* On an ingress PE in D2, V/v will resolve via C2.

* When a BR in D2 advertises the route to a BR in D3, the same process repeats.

Appendix C. CAR SRv6 Illustrations

C.1. BGP CAR SRv6 locator reachability hop by hop distribution

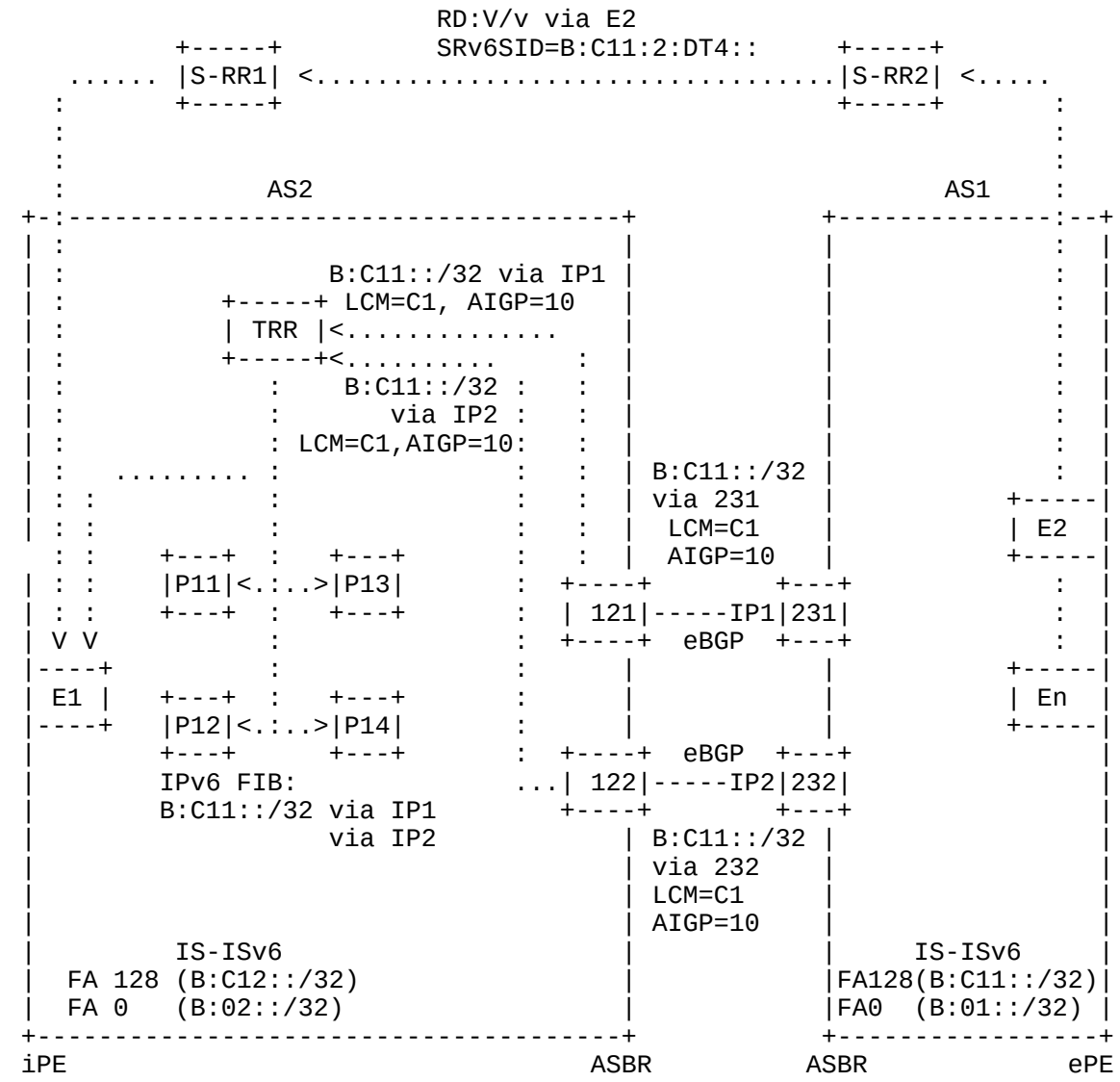


Figure 15

The topology above is an example to illustrate the BGP CAR SRv6 locator prefix route based design (Routed Service SID: Section 7.1.1), with hop by hop IPv6 routing within and between domains.

* Multi-AS network with eBGP CAR session between ASBRs.

* Transport RR (TRR) peers with P, BR and PE clients within an AS to propagate CAR prefixes. AddPath is enabled to propagate multiple paths.

* IS-IS (IGP) Flex-Algo 128 for SRv6 is running in each AS (AS may consist of multiple IGP domains), where the following steps apply:

  - Prefix B:C11::/32 summarizes Flex-Algo 128 block in AS1 for the given intent. Node locators in the egress domain are sub-allocated from the block for the given intent.

  - Similarly, Prefix B:C12::/32 summarizes Flex-Algo 128 block in AS2.

  - Per Flex-Algo external subnets for eBGP next hops IP1 and IP2 are distributed in IS-IS within AS2.

* BGP CAR prefix route B:C11::/32 with LCM C1 is originated by AS1 BRs 231 and 232 on eBGP sessions to AS2 BRs 121 and 122.

* ASBR 121 and 122 propagate the route in AS2 to all the P, ABRs and PEs through transport RR.

* Every router in AS2 resolves BGP CAR prefix B:C11::/32 next hops IP1 and IP2 in IS-ISv6 Flex-Algo 128 and programs B:C11::/32 prefix in global IPv6 forwarding table.

* AIGP attribute influences BGP CAR route best path decision.

* Egress PE E2 advertises a VPN route RD:V/v with SRv6 service SID B:C11:2:DT4::. Service SID is allocated by E2 from its locator of color C1 intent.

* Ingress PE E1 learns (via service RRs S-RR1 and S-RR2) VPN route RD:V/v with SRv6 SID B:C11:2:DT4::.

* Service traffic encapsulated with SRv6 Service SID B:C11:2:DT4:: is natively steered hop by hop along IPv6 routed path to B:C11::/32 provided by BGP CAR in AS2.

* Encapsulated service traffic is natively steered along IPv6 routed path to B:C11::/32 provided by IS-ISv6 Flex-Algo 128 in AS1.

* Design applies to multiple ASNs. BGP next hop is rewritten across a eBGP hop.

Important:

* No tunneling/encapsulation on Ingress PE and BRs for BGP CAR provided transport.

* Uses longest prefix match of SRv6 service SID to BGP CAR IP prefix. No mapping to labels/SIDs, instead use of simple IP based forwarding.

Packet forwarding

```
@E1:  IPv4 VRF V/v => H.Encaps.red <B:C11:2:DT4::> => forward based on
                                                          B:C11::/32
@P*:  IPv6 table: B:C11::/32 => forward to interface, NH
@121: IPv6 Table: B:C11::/32 => forward to interface, NH
@231: IPv6 table: B:C11:2::/48 :: => forward via IS-ISv6 FA path to E2
@231: IPv6 Table B:C11:2::/48 => forward via IS-ISv6 FA path to E2
@E2:  My SID table B:C11:2:DT4:: =>pop the outer header and lookup the
                                                    inner DA in the VRF
```

C.2. BGP CAR SRv6 locator reachability distribution with encapsulation

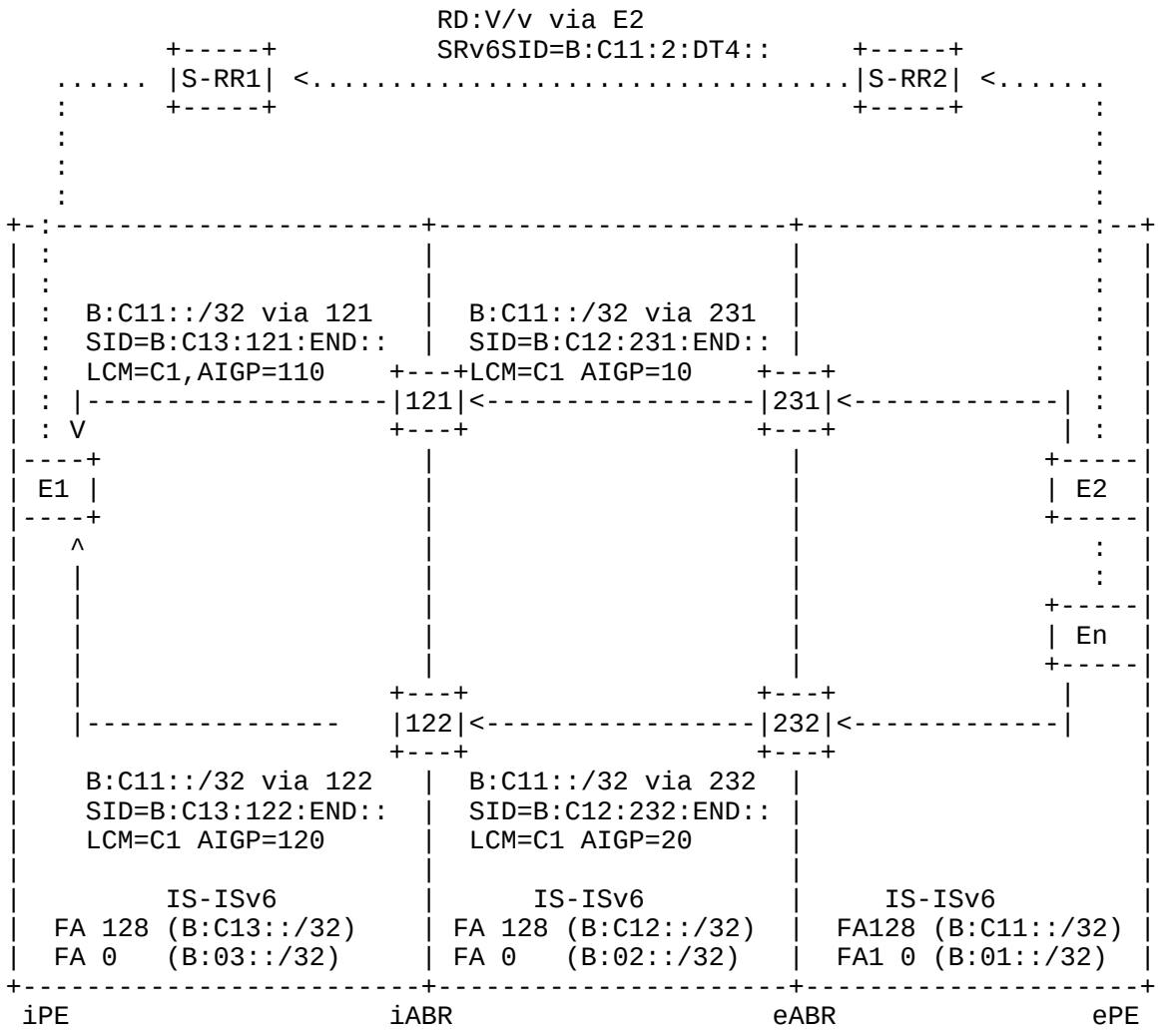


Figure 16

The topology above is an example to illustrate the BGP CAR SRv6 locator prefix route based design (Routed Service SID: Section 7.1.1), with intra-domain encapsulation. The example shown is iBGP, but also applies to eBGP (multi-AS).

* IGP Flex-Algo 128 is running in each domain, where

  - Prefix B:C11::/32 summarizes Flex-Algo 128 block in egress domain for the given intent. Node locators in the egress domain are sub-allocated from the block.

- Prefix B:C12::/32 summarizes FA128 block in transit domain.

- Prefix B:C13::/32 summarizes FA128 block in ingress domain.

* BGP CAR route B:C11::/32 is originated by ABRs 231 and 232 with LCM C1. Along the propagation path, border routers set next-hop-self and appropriately update the intra-domain encapsulation information for the C1 intent. For example, 231 and 121 signal SRv6 SID of END behavior [RFC8986] allocated from their respective locators for the C1 intent. (Note: IGP Flex-Algo is shown for intra-domain path, but SR-Policy may also provide the path as shown in Appendix C.3).

* AIGP attribute influences BGP CAR route best path decision.

* Egress PE E2 advertises a VPN route RD:V/v with SRv6 service SID B:C11:2:DT4::. Service SID is allocated by E2 from its locator of color C1 intent.

* Ingress PE E1 learns CAR route B:C11::/32 and VPN route RD:V/v with SRv6 SID B:C11:2:DT4::.

* Traffic encapsulated with SRv6 Service SID B:C11:2:DT4:: is steered along IPv6 routed path provided by BGP CAR IP prefix route to locator B:C11::/32.

Important

* Uses longest prefix match of SRv6 service SID to BGP CAR prefix. No mapping labels/SIDs, instead simple IP based forwarding.

* Originating domain PE locators of the given intent can be summarized on transit BGP hops eliminating per PE state on border routers.

Packet forwarding

```
@E1:   IPv4 VRF V/v => H.Encaps.red <B:C13:121:END::, B:C11:2:DT4::>
@121: My SID table: B:C13:121:END:: => Update DA with B:C11:2:DT4::
@121: IPv6 Table: B:C11::/32 => H.Encaps.red <B:C12:231:END::>
@231: My SID table: B:C12:231:END:: => Remove IPv6 header; Inner DA B:C11:2:DT4::
@231: IPv6 Table B:C11:2::/48 => forward via IS-ISv6 FA path to E2
@E2: My SID table B:C11:2:DT4:: =>pop the outer header and lookup the
                                  inner DA in the VRF
```

C.3. BGP CAR (E, C) route distribution for steering non-routed service SID

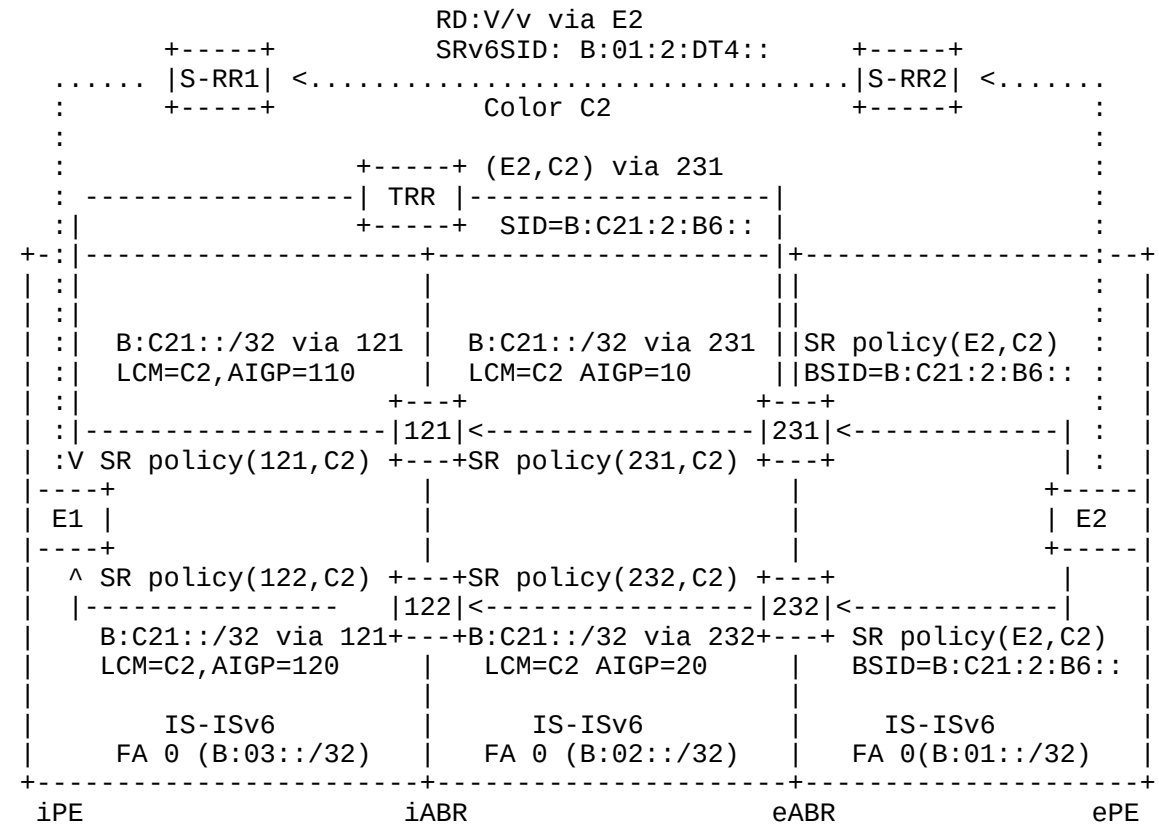


Figure 17

The topology above is an example to illustrate the BGP CAR (E, C) route based design (Section 7.1.2). The example is iBGP, but design also applies to eBGP (multi-AS).

* SR policy (E2, C2) provides given intent in egress domain.

  - SR policy (E2, C2) with segments <B:01:z:END::, B:01:2:END::> where z is the node id in egress domain.

* Egress ABRs 231 and 232 redistribute SR policy into BGP CAR Type-1 NLRI (E2, C2) to other domains, with SRv6 SID of End.B6 behavior. This route is propagated to ingress PEs through transport RR (TRR) or inline with next hop unchanged.

* The ABRs also advertise BGP CAR prefix route (B:C21::/32) summarizing locator part of SRv6 SIDs for SR policies of given intent to different PEs in egress domain. BGP CAR prefix route

propagates through border routers. At each BGP hop, BGP CAR prefix next-hop resolution triggers intra-domain transit SR policy (C2, CAR next hop). For example:

- SR policy (231, C2) with segments <B:02:y:END::, B:02:231:END::>, and

- SR policy (121, C2) with segments <B:03:x:END::, B:03:121:END::>,

- where x and y are node ids within the respective domains.

* Egress PE E2 advertises a VPN route RD:V/v with Color-EC C2.

* Ingress PE E1 steers VPN route from E2 onto BGP CAR route (E2, C2) that results in H.Encaps.red of SRv6 transport SID B:C21:2:B6:: and SRv6 service SID as last segment in IPv6 header.

* IPv6 destination B:C21:2:B6:: match on CAR prefix B:C21::/32 that steers the packet into intra-domain (intent-aware) SR Policy on ingress PE E1 and ABR 121.

* IPv6 packet destination B:C21:2:B6:: lookup in mySID table on ABR 231 or 232 results in END.B6 behavior (i.e., push of policy segments to E2).

Important

* Ingress PE steers services via (E, C) CAR route as per [RFC9256].

* In data plane (E, C) resolution results in IPv6 header destination being SRv6 SID of END.B6 behavior whose locator is of given intent on originating ABRs.

* CAR IP prefix route along the transit path provides simple LPM IPv6 forwarding along the transit BGP hops.

* CAR NLRI Type-2 prefix summarizes binding SIDs of all SR policies on originating ABR of a given intent to different PEs in egress domain. This eliminates per PE state on transit routers.

Packet forwarding

```
@E1:   IPv4 VRF V/v => H.Encaps.red <B:C21:2:B6::, B:0:E2:DT4::>
                       H.Encaps.red <SR policy (C2,121) sid list>
@121: My SID table: B:03:121:END:: => Remove outer IPv6 header; Inner DA B:C21:2:B6::
@121: IPv6 Table: B:C21::/32 => H.Encaps.red <SR Policy (C2,231) sid
                                                              list>
@231: My SID table: B:02:231:END:: => Remove outer IPv6 header; Inner DA B:C21:2:B6::

@231: MySIDtable B:C21:2:B6:: =>  H.Encaps.red <SR Policy (C2,E2) sid
                                                              list>
@E2: IPv6 Table B:0:2:DT4:: =>pop the outer header and lookup the
                               inner DA in the VRF
```

Appendix D. CAR SAFI NLRI update packing efficiency calculation

CAR SAFI NLRI encoding is optimized for update packing. It allows per route information (for example label, label index and SRv6 SID encapsulation data) to be carried in non-key TLV part of NLRI. This allows multiple NLRIs to be packed in single update message when other attributes (including LCM-EC when present) are shared. The table below shows a theoretical analysis calculated from observed BGP update message size in operational networks. It compares total BGP data on the wire for CAR SAFI and [RFC8277] style encoding in MPLS label (CASE A), SR extension with MPLS (per-prefix label index in Prefix-SID attribute) [RFC8669] (CASE B) and SRv6 SID (CASE C) cases. Scenarios considered are ideal packing (maximum number of routes packed to update message limit of 4k bytes), practical deployment case with average packing (5 routes share set of BGP path attributes and hence packed in single update message) and worst-case of no packing (each route in separate update message).

Encoding	BGP CAR NLRI	RFC-8277 style NLRI	Result
CASE A: Label (Ideal)	27.5 MB	26 MB	
(Practical)	86 MB	84 MB	No degradation from RFC8277 like encoding
(No packing)	325 MB	324 MB	
CASE B: Label & Label-index (Ideal)	42 MB	339 MB Packing not possible	CAR SAFI encoding more efficient by 88% in best case and 71% in average case over RFC8277 style encoding (which precludes packing)
(Practical)	99 MB	339 MB Packing not possible	
(No packing)	339 MB	339 MB	
CASE C: SRv6 SID (Ideal)	49 MB	378 MB	Results are similar to SR MPLS case. Transposition provides further 20% reduction in BGP data.
(Practical)	115 MB	378 MB	
(No packing)	378 MB	378 MB	

Figure 18: Summary of ideal, practical and no-packing BGP data in each case

Analysis considers 1.5 million routes (5 colors across 300k endpoints)

CASE A: BGP data exchanged for non SR MPLS case

```
    Consider 200 bytes of shared attributes
    CAR SAFI signal Label in non-key TLV part of NLRI
       Each NLRI size for AFI 1 = 12(key) + 5(label) = 17 bytes
         Ideal packing:
          number of NLRIs in 4k update size = 223 (4k-200/17)
          number of update messages of 4k size = 1.5 million/223 = 6726
          Total BGP data on wire = 6726 * 4k = ~27.5MB
         Practical packing (5 routes in update message)
          size of update message = (17 * 5) + 200 = 285
          Total BGP data on wire = 285 * 300k = ~86MB
         No-packing case (1 route per update message)
          size of update message = 17 + 200 = 217
          Total BGP data on wire = 217 * 1.5 million = ~325MB
    SAFI 128 8277 style encoding with label in NLRI
       Each NLRI size for AFI 1 = 13(key) + 3(label) = 16 bytes
         Ideal packing:
          number of NLRIs in 4k update size = 237 (4k-200/16)
          number of update messages of 4k size = 1.5 million/237 = ~6330
          Total BGP data on wire = 6330 * 4k = ~25.9MB
         Practical packing (5 routes in update message)
          size of update message = (16 * 5) + 200 = 280
          Total BGP data on wire = 280 * 300k = ~84MB
         No-packing case (1 route per update message)
          size of update message = 16 + 200 = 216
          Total BGP data on wire = 216 * 1.5 million = ~324MB

   CASE B: BGP data exchanged for SR label index
```

```
     Consider 200 bytes of shared attributes
     CAR SAFI signal Label in non-key TLV part of NLRI
        Each NLRI size for AFI 1
                         = 12(key) + 5(label) + 9(Index) = 26 bytes
          Ideal packing:
           number of NLRIs in 4k update size = 146 (4k-200/26)
           number of update messages of 4k size = 1.5 million/146 = 6726
           Total BGP data on wire = 10274 * 4k = ~42MB
          Practical packing (5 routes in update message)
           size of update message = (26 * 5) + 200 = 330
           Total BGP data on wire = 330 * 300k = ~99MB
          No-packing case (1 route per update message)
           size of update message = 26 + 200 = 226
           Total BGP data on wire = 226 * 1.5 million = ~339MB
     SAFI 128 8277 style encoding with label in NLRI
        Each NLRI size for AFI 1 = 13(key) + 3(label) = 16 bytes
          Ideal packing
           Not supported as label index is encoded in Prefix-SID
                                                          Attribute
          Practical packing (5 routes in update message)
           Not supported as label index is encoded in Prefix-SID
                                                          Attribute
          No-packing case (1 route per update message)
           size of update message = 16 + 210 = 226
           Total BGP data on wire = 216 * 1.5 million = ~339MB

   CASE C: BGP data exchanged with 128 bit single SRv6 SID
```

```
     Consider 200 bytes of shared attributes
     CAR SAFI signal Label in non-key TLV part of NLRI
        Each NLRI size for AFI 1 = 12(key) + 18(Srv6 SID) = 30 bytes
          Ideal packing:
           number of NLRIs in 4k update size = 126 (4k-200/30)
           number of update messages of 4k size = 1.5 million/126 = ~12k
           Total BGP data on wire = 12k * 4k = ~49MB
          Practical packing (5 routes in update message)
           size of update message
                         = (30 * 5) + 236 (including Prefix SID) = 386
           Total BGP data on wire = 386 * 300k = ~115MB
          No-packing case (1 route per update message)
           size of update message = 12 + 236 (SID in Prefix SID) = 252
           Total BGP data on wire = 252 * 1.5 million = ~378MB
     SAFI 128 8277 style encoding with label in NLRI (No transposition)
        Each NLRI size for AFI 1 = 13(key) + 3(label) = 16 bytes
          Ideal packing
           Not supported as label index is encoded in Prefix-SID
                                                          Attribute
          Practical packing (5 routes in update message)
           Not supported as label index is encoded in Prefix-SID
                                                          Attribute
          No-packing case (1 route per update message)
           size of update message = 16 + 236 = 252
           Total BGP data on wire = 252 * 1.5 million = ~378MB

   BGP data exchanged with SRv6 SID 4 bytes transposition into SRv6 SID
   TLV

    Consider 200 bytes of shared attributes
    CAR SAFI signal Label in non-key TLV part of NLRI
       Each NLRI size for AFI 1 = 12(key) + 6(Srv6 SID) = 18 bytes
         Ideal packing:
          number of NLRIs in 4k update size = 211 (4k-200/18)
          number of update messages of 4k size = 1.5 million/211 = ~7110
          Total BGP data on wire = 7110 * 4k = ~29MB
         Practical packing (5 routes in update message)
          size of update message
                        = (18 * 5) + 236 (including Prefix SID) = 326
          Total BGP data on wire = 326 * 300k = ~98MB
         No-packing case (1 route per update message)
          size of update message
                        = 12 + 236 (SID in Prefix-SID Attribute) = 252
          Total BGP data on wire = 252 * 1.5 million = ~378MB
```

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