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MPLS Segment Routing over IP

Abstract

MPLS Segment Routing (SR-MPLS) is a method of source routing a packet through an MPLS data plane by imposing a stack of MPLS labels on the packet to specify the path together with any packet-specific instructions to be executed on it. SR-MPLS can be leveraged to realize a source-routing mechanism across MPLS, IPv4, and IPv6 data planes by using an MPLS label stack as a source-routing instruction set while making no changes to SR-MPLS specifications and interworking with SR-MPLS implementations.

This document describes how SR-MPLS-capable routers and IP-only routers can seamlessly coexist and interoperate through the use of SR-MPLS label stacks and IP encapsulation/tunneling such as MPLS-over-UDP as defined in RFC 7510.

Status of This Memo

This is an Internet Standards Track document.

This document is a product of the Internet Engineering Task Force (IETF). It represents the consensus of the IETF community. It has received public review and has been approved for publication by the Internet Engineering Steering Group (IESG). Further information on Internet Standards is available in Section 2 of RFC 7841.

Information about the current status of this document, any errata, and how to provide feedback on it may be obtained at https://www.rfc-editor.org/info/rfc8663.

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1. Introduction

MPLS Segment Routing (SR-MPLS) [RFC8660] is a method of source routing a packet through an MPLS data plane. This is achieved by the sender imposing a stack of MPLS labels that partially or completely specify the path that the packet is to take and any instructions to be executed on the packet as it passes through the network. SR-MPLS uses an MPLS label stack to encode a sequence of source-routing instructions. This can be used to realize a source-routing mechanism that can operate across MPLS, IPv4, and IPv6 data planes. This approach makes no changes to SR-MPLS specifications and allows interworking with SR-MPLS implementations. More specifically, the source-routing instructions in a source-routed packet could be uniformly encoded as an MPLS label stack regardless of whether the underlay is IPv4, IPv6 (including Segment Routing for IPv6 (SRv6) [RFC8354]), or MPLS.

This document describes how SR-MPLS-capable routers and IP-only routers can seamlessly coexist and interoperate through the use of SR-MPLS label stacks and IP encapsulation/tunneling such as MPLS-over-UDP [RFC7510].

Section 2 describes various use cases for tunneling SR-MPLS over IP. Section 3 describes a typical application scenario and how the packet forwarding happens.

1.1. Terminology

This memo makes use of the terms defined in [RFC3031] and [RFC8660].

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. Use Cases

Tunneling SR-MPLS using IPv4 and/or IPv6 (including SRv6) tunnels is useful at least in the use cases listed below. In all cases, this can be enabled using an IP tunneling mechanism such as MPLS-over-UDP as described in [RFC7510]. The tunnel selected MUST have its remote endpoint (destination) address equal to the address of the next node capable of SR-MPLS identified as being on the SR path (i.e., the egress of the active segment). The local endpoint (source) address is set to an address of the encapsulating node. [RFC7510] gives further advice on how to set the source address if the UDP zero-checksum mode is used with MPLS-over-UDP. Using UDP as the encapsulation may be particularly beneficial because it is agnostic of the underlying transport.

* Incremental deployment of the SR-MPLS technology may be facilitated by tunneling SR-MPLS packets across parts of a network that are not SR-MPLS as shown in Figure 1. This demonstrates how islands of SR-MPLS may be connected across a legacy network. It

may be particularly useful for joining sites (such as data centers).

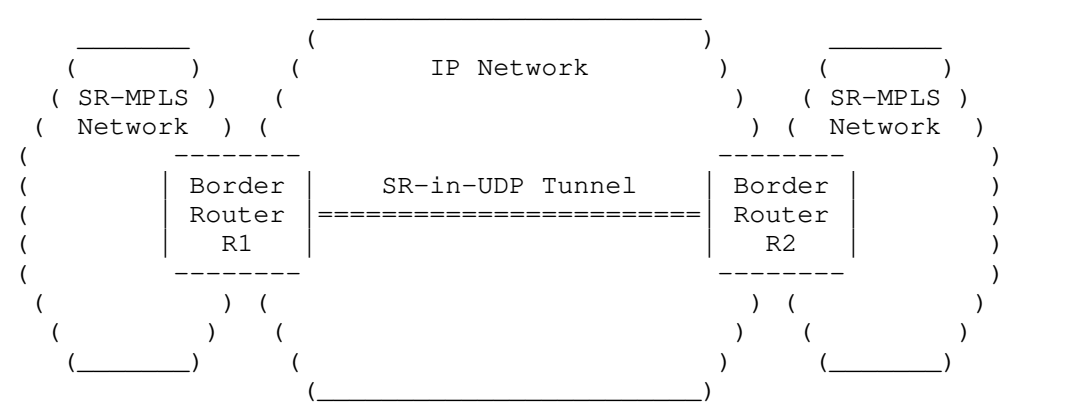
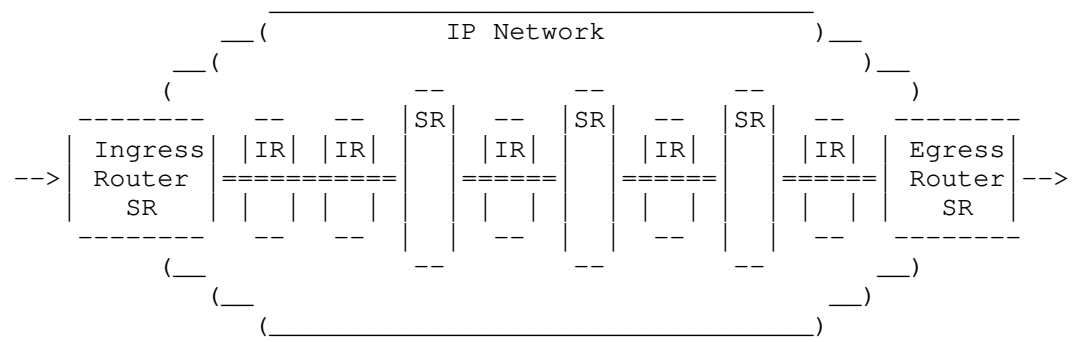


Figure 1: SR-MPLS-over-UDP to Tunnel between SR-MPLS Sites

* If the encoding of entropy [RFC6790] is desired, IP-tunneling mechanisms that allow the encoding of entropy, such as MPLS-over-UDP encapsulation [RFC7510] where the source port of the UDP header is used as an entropy field, may be used to maximize the utilization of Equal-Cost Multipath (ECMP) and/or Link Aggregation Groups (LAGs), especially when it is difficult to make use of the entropy-label mechanism. This is to be contrasted with [RFC4023] where MPLS-over-IP does not provide for an entropy mechanism. Refer to [RFC8662]) for more discussion about using entropy labels in SR-MPLS.

* Tunneling MPLS over IP provides a technology that enables Segment Routing (SR) in an IPv4 and/or IPv6 network where the routers do not support SRv6 capabilities [IPv6-SRH] and where MPLS forwarding is not an option. This is shown in Figure 2.



Key:
IR : IP-only Router
SR : SR-MPLS-capable Router
== : SR-MPLS-over-UDP Tunnel

Figure 2: SR-MPLS Enabled within an IP Network

3. Procedures of SR-MPLS-over-IP

This section describes the construction of forwarding information base (FIB) entries and the forwarding behavior that allow the deployment of SR-MPLS when some routers in the network are IP only (i.e., do not support SR-MPLS). Note that the examples in Sections 3.1.1 and 3.2 assume that OSPF or IS-IS is enabled; in fact, other mechanisms of discovery and advertisement could be used including other routing protocols (such as BGP) or a central controller.

3.1. Forwarding Entry Construction

This subsection describes how to construct the forwarding information base (FIB) entry on an SR-MPLS-capable router when some or all of the next hops along the shortest path towards a prefix Segment Identifier

(Prefix-SID) are IP-only routers. Section 3.1.1 provides a concrete example of how the process applies when using OSPF or IS-IS.

Consider router A that receives a labeled packet with top label L(E) that corresponds to the Prefix-SID SID(E) of prefix P(E) advertised by router E. Suppose the i-th next-hop router (termed NHi) along the shortest path from router A toward SID(E) is not SR-MPLS capable while both routers A and E are SR-MPLS capable. The following processing steps apply:

* Router E is SR-MPLS capable, so it advertises a Segment Routing Global Block (SRGB). The SRGB is defined in [RFC8402]. There are a number of ways that the advertisement can be achieved including IGPs, BGP, and configuration/management protocols. For example, see [DC-GATEWAY].

* When Router E advertises the Prefix-SID SID(E) of prefix P(E), it MUST also advertise the egress endpoint address and the encapsulation type of any tunnel used to reach E. This information is flooded domain wide.

* If A and E are in different routing domains, then the information MUST be flooded into both domains. How this is achieved depends on the advertisement mechanism being used. The objective is that router A knows the characteristics of router E that originated the advertisement of SID(E).

* Router A programs the FIB entry for prefix P(E) corresponding to the SID(E) according to whether a pop or swap action is advertised for the prefix. The resulting action may be:

  - pop the top label

  - swap the top label to a value equal to SID(E) plus the lower bound of the SRGB of E

Once constructed, the FIB can be used by a router to tell it how to process packets. It encapsulates the packets according to the appropriate encapsulation advertised for the segment and then sends the packets towards the next hop NHi.

3.1.1. FIB Construction Example

This section is non-normative and provides a worked example of how a FIB might be constructed using OSPF and IS-IS extensions. It is based on the process described in Section 3.1.

* Router E is SR-MPLS capable, so it advertises a Segment Routing Global Block (SRGB) using [RFC8665] or [RFC8667].

* When Router E advertises the Prefix-SID SID(E) of prefix P(E), it also advertises the encapsulation endpoint address and the tunnel type of any tunnel used to reach E using [ISIS-ENCAP] or [OSPF-ENCAP].

* If A and E are in different domains, then the information is flooded into both domains and any intervening domains.

  - The OSPF Tunnel Encapsulations TLV [OSPF-ENCAP] or the IS-IS Tunnel Encapsulation Type sub-TLV [ISIS-ENCAP] is flooded domain wide.

  - The OSPF SID/Label Range TLV [RFC8665] or the IS-IS SR-Capabilities sub-TLV [RFC8667] is advertised domain wide so that router A knows the characteristics of router E.

  - When router E advertises the prefix P(E):

    o If router E is running IS-IS, it uses the extended reachability TLV (TLVs 135, 235, 236, 237) and associates the IPv4/IPv6 or IPv4/IPv6 Source Router ID sub-TLV(s)

[RFC7794].

- o If router E is running OSPF, it uses the OSPFv2 Extended Prefix Opaque Link-State Advertisement (LSA) [RFC7684] and sets the flooding scope to Autonomous System (AS) wide.

- If router E is running IS-IS and advertises the IS-IS Router CAPABILITY TLV (TLV 242) [RFC7981], it sets the "Router ID" field to a valid value or includes an IPv6 TE Router ID sub-TLV (TLV 12), or it does both. The "S" bit (flooding scope) of the IS-IS Router CAPABILITY TLV (TLV 242) is set to "1".

* Router A programs the FIB entry for prefix P(E) corresponding to the SID(E) according to whether a pop or swap action is advertised for the prefix as follows:

  - If the No-PHP (NP) Flag in OSPF or the Persistent (P) Flag in IS-IS is clear:

    pop the top label

  - If the No-PHP (NP) Flag in OSPF or the Persistent (P) Flag in IS-IS is set:

    swap the top label to a value equal to SID(E) plus the lower bound of the SRGB of E

When forwarding the packet according to the constructed FIB entry, the router encapsulates the packet according to the encapsulation as advertised using the mechanisms described in [ISIS-ENCAP] or [OSPF-ENCAP]. It then sends the packets towards the next hop NHi.

Note that [RFC7510] specifies the use of port number 6635 to indicate that the payload of a UDP packet is MPLS, and port number 6636 for MPLS-over-UDP utilizing DTLS. However, [ISIS-ENCAP] and [OSPF-ENCAP] provide dynamic protocol mechanisms to configure the use of any Dynamic Port for a tunnel that uses UDP encapsulation. Nothing in this document prevents the use of an IGP or any other mechanism to negotiate the use of a Dynamic Port when UDP encapsulation is used for SR-MPLS, but if no such mechanism is used, then the port numbers specified in [RFC7510] are used.

3.2. Packet-Forwarding Procedures

[RFC7510] specifies an IP-based encapsulation for MPLS, i.e., MPLS-over-UDP. This approach is applicable where IP-based encapsulation for MPLS is required and further fine-grained load balancing of MPLS packets over IP networks over ECMP and/or LAGs is also required. This section provides details about the forwarding procedure when UDP encapsulation is adopted for SR-MPLS-over-IP. Other encapsulation and tunneling mechanisms can be applied using similar techniques, but for clarity, this section uses UDP encapsulation as the exemplar.

Nodes that are SR-MPLS capable can process SR-MPLS packets. Not all of the nodes in an SR-MPLS domain are SR-MPLS capable. Some nodes may be "legacy routers" that cannot handle SR-MPLS packets but can forward IP packets. A node capable of SR-MPLS MAY advertise its capabilities using the IGP as described in Section 3. There are six types of nodes in an SR-MPLS domain:

* Domain ingress nodes that receive packets and encapsulate them for transmission across the domain. Those packets may be any payload protocol including native IP packets or packets that are already MPLS encapsulated.

* Legacy transit nodes that are IP routers but that are not SR-MPLS capable (i.e., are not able to perform Segment Routing).

* Transit nodes that are SR-MPLS capable but that are not identified by a SID in the SID stack.

* Transit nodes that are SR-MPLS capable and need to perform SR-MPLS routing because they are identified by a SID in the SID stack.

* The penultimate node capable of SR-MPLS on the path that processes the last SID on the stack on behalf of the domain egress node.

* The domain egress node that forwards the payload packet for ultimate delivery.

3.2.1. Packet Forwarding with Penultimate Hop Popping

The description in this section assumes that the label associated with each Prefix-SID is advertised by the owner of the Prefix-SID as a Penultimate Hop-Popping (PHP) label. That is, if one of the IGP flooding mechanisms is used, the NP-Flag in OSPF or the P-Flag in IS-IS associated with the Prefix-SID is not set.

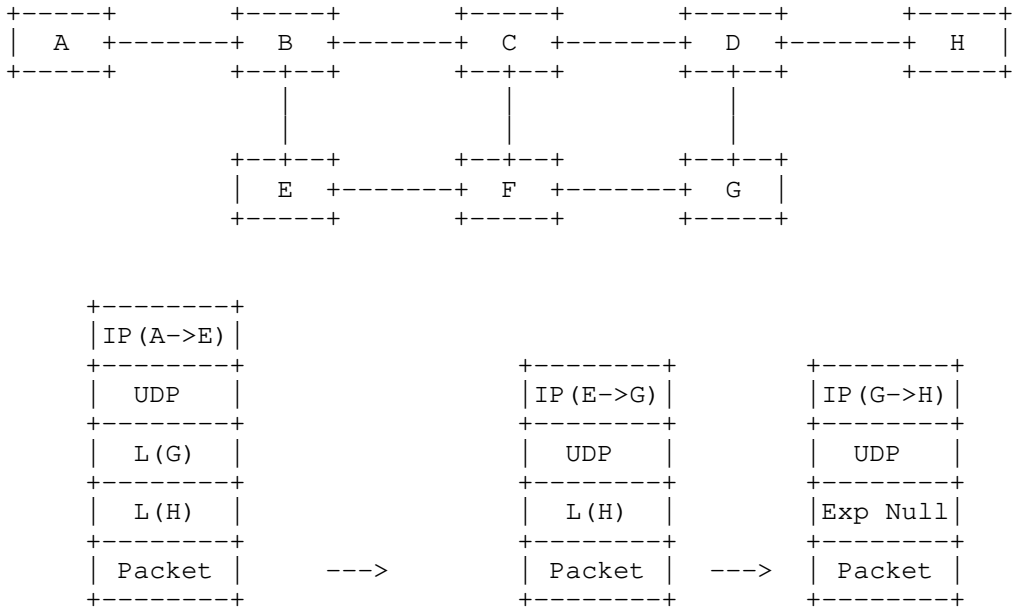


Figure 3: Packet-Forwarding Example with PHP

In the example shown in Figure 3, assume that routers A, E, G, and H are capable of SR-MPLS while the remaining routers (B, C, D, and F) are only capable of forwarding IP packets. Routers A, E, G, and H advertise their Segment Routing related information, such as via IS-IS or OSPF.

Now assume that router A (the Domain ingress) wants to send a packet to router H (the Domain egress) via the explicit path {E->G->H}. Router A will impose an MPLS label stack on the packet that corresponds to that explicit path. Since the next hop toward router E is only IP capable (B is a legacy transit node), router A replaces the top label (that indicated router E) with a UDP-based tunnel for MPLS (i.e., MPLS-over-UDP [RFC7510]) to router E and then sends the packet. In other words, router A pops the top label and then encapsulates the MPLS packet in a UDP tunnel to router E.

When the IP-encapsulated MPLS packet arrives at router E (which is a transit node capable of SR-MPLS), router E strips the IP-based tunnel header and then processes the decapsulated MPLS packet. The top label indicates that the packet must be forwarded toward router G. Since the next hop toward router G is only IP capable, router E replaces the current top label with an MPLS-over-UDP tunnel toward router G and sends it out. That is, router E pops the top label and then encapsulates the MPLS packet in a UDP tunnel to router G.

When the packet arrives at router G, router G will strip the IP-based tunnel header and then process the decapsulated MPLS packet. The top label indicates that the packet must be forwarded toward router H. Since the next hop toward router H is only IP capable (D is a legacy transit router), router G would replace the current top label with an

MPLS-over-UDP tunnel toward router H and send it out. However, since router G reaches the bottom of the label stack (G is the penultimate node capable of SR-MPLS on the path), this would leave the original packet that router A wanted to send to router H encapsulated in UDP as if it was MPLS (i.e., with a UDP header and destination port indicating MPLS) even though the original packet could have been any protocol. That is, the final SR-MPLS has been popped exposing the payload packet.

To handle this, when a router (here it is router G) pops the final SR-MPLS label, it inserts an explicit NULL label [RFC3032] before encapsulating the packet in an MPLS-over-UDP tunnel toward router H and sending it out. That is, router G pops the top label, discovers it has reached the bottom of stack, pushes an explicit NULL label, and then encapsulates the MPLS packet in a UDP tunnel to router H.

3.2.2. Packet Forwarding without Penultimate Hop Popping

Figure 4 demonstrates the packet walk in the case where the label associated with each Prefix-SID advertised by the owner of the Prefix-SID is not a Penultimate Hop-Popping (PHP) label (e.g., the NP-Flag in OSPF or the P-Flag in IS-IS associated with the Prefix-SID is set). Apart from the PHP function, the roles of the routers are unchanged from Section 3.2.1.

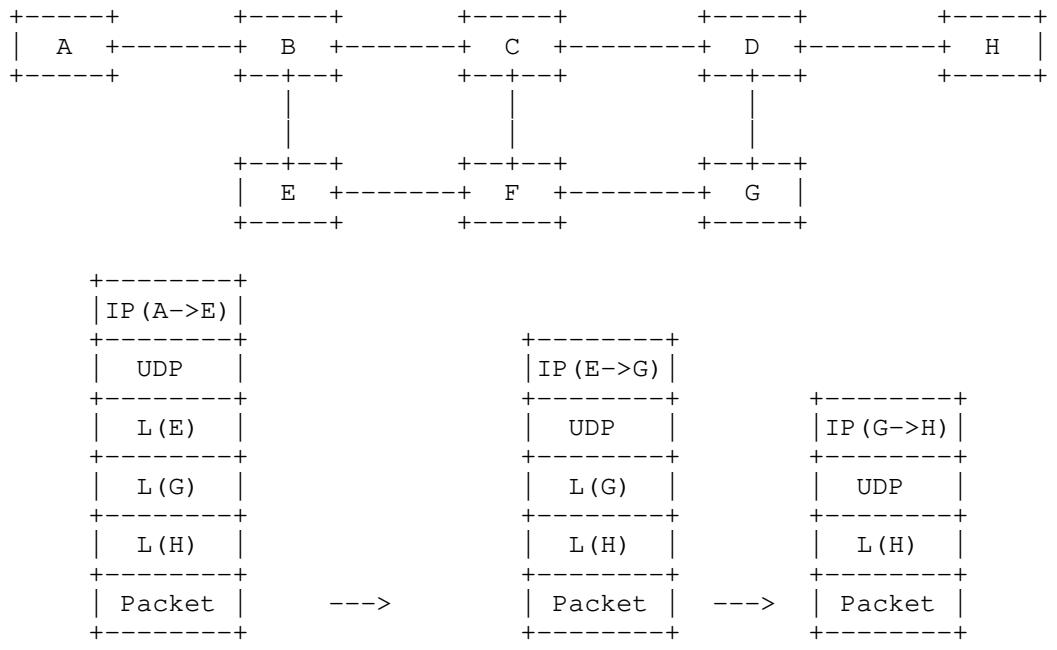


Figure 4: Packet-Forwarding Example without PHP

As can be seen from the figure, the SR-MPLS label for each segment is left in place until the end of the segment where it is popped and the next instruction is processed.

3.2.3. Additional Forwarding Procedures

Non-MPLS Interfaces: Although the description in the previous two sections is based on the use of Prefix-SIDs, tunneling SR-MPLS packets is useful when the top label of a received SR-MPLS packet indicates an Adjacency SID and the corresponding adjacent node to that Adjacency SID is not capable of MPLS forwarding but can still process SR-MPLS packets. In this scenario, the top label would be replaced by an IP tunnel toward that adjacent node and then forwarded over the corresponding link indicated by the Adjacency SID.

When to Use IP-Based Tunnels: The description in the previous two sections is based on the assumption that an MPLS-over-UDP tunnel is used when the next hop towards the next segment is not MPLS enabled. However, even in the case where the next hop towards the next segment is MPLS capable, an MPLS-over-UDP tunnel towards the

next segment could still be used instead due to local policies. For instance, in the example as described in Figure 4, assume F is now a transit node capable of SR-MPLS while all the other assumptions remain unchanged; since F is not identified by a SID in the stack and an MPLS-over-UDP tunnel is preferred to an MPLS LSP according to local policies, router E replaces the current top label with an MPLS-over-UDP tunnel toward router G and sends it out. (Note that if an MPLS LSP was preferred, the packet would be forwarded as native SR-MPLS.)

IP Header Fields: When encapsulating an MPLS packet in UDP, the resulting packet is further encapsulated in IP for transmission. IPv4 or IPv6 may be used according to the capabilities of the network. The address fields are set as described in Section 2. The other IP header fields (such as the ECN field [RFC6040], the Differentiated Services Code Point (DSCP) [RFC2983], or IPv6 Flow Label) on each UDP-encapsulated segment SHOULD be configurable according to the operator's policy; they may be copied from the header of the incoming packet; they may be promoted from the header of the payload packet; they may be set according to instructions programmed to be associated with the SID; or they may be configured dependent on the outgoing interface and payload. The TTL field setting in the encapsulating packet header is handled as described in [RFC7510], which refers to [RFC4023].

Entropy and ECMP: When encapsulating an MPLS packet with an IP tunnel header that is capable of encoding entropy (such as [RFC7510]), the corresponding entropy field (the source port in the case of a UDP tunnel) MAY be filled with an entropy value that is generated by the encapsulator to uniquely identify a flow. However, what constitutes a flow is locally determined by the encapsulator. For instance, if the MPLS label stack contains at least one entropy label and the encapsulator is capable of reading that entropy label, the entropy label value could be directly copied to the source port of the UDP header. Otherwise, the encapsulator may have to perform a hash on the whole label stack or the five-tuple of the SR-MPLS payload if the payload is determined as an IP packet. To avoid recalculating the hash or hunting for the entropy label each time the packet is encapsulated in a UDP tunnel, it MAY be desirable that the entropy value contained in the incoming packet (i.e., the UDP source port value) is retained when stripping the UDP header and is reused as the entropy value of the outgoing packet.

Congestion Considerations: Section 5 of [RFC7510] provides a detailed analysis of the implications of congestion in MPLS-over-UDP systems and builds on Section 3.1.3 of [RFC8085], which describes the congestion implications of UDP tunnels. All of those considerations apply to SR-MPLS-over-UDP tunnels as described in this document. In particular, it should be noted that the traffic carried in SR-MPLS flows is likely to be IP traffic.

4. IANA Considerations

This document has no IANA actions.

5. Security Considerations

The security consideration of [RFC8354] (which redirects the reader to [RFC5095]) and [RFC7510] apply. DTLS [RFC6347] SHOULD be used where security is needed on an SR-MPLS-over-UDP segment including when the IP segment crosses the public Internet or some other untrusted environment. [RFC8402] provides security considerations for Segment Routing, and Section 8.1 of [RFC8402] is particularly applicable to SR-MPLS.

It is difficult for an attacker to pass a raw MPLS-encoded packet into a network, and operators have considerable experience in excluding such packets at the network boundaries, for example, by excluding all packets that are revealed to be carrying an MPLS packet

as the payload of IP tunnels. Further discussion of MPLS security is found in [RFC5920].

It is easy for a network ingress node to detect any attempt to smuggle an IP packet into the network since it would see that the UDP destination port was set to MPLS, and such filtering SHOULD be applied. If, however, the mechanisms described in [RFC8665] or [RFC8667] are applied, a wider variety of UDP port numbers might be in use making port filtering harder.

SR packets not having a destination address terminating in the network would be transparently carried and would pose no different security risk to the network under consideration than any other traffic.

Where control-plane techniques are used (as described in Section 3), it is important that these protocols are adequately secured for the environment in which they are run as discussed in [RFC6862] and [RFC5920].

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