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SRv6 Implementation and Deployment Status
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Abstract

This draft provides an overview of IPv6 Segment Routing (SRv6) deployment status. It lists various SRv6 features that have been deployed in the production networks. It also provides an overview of SRv6 implementation and interoperability testing status.

Requirements Language

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

Status of This Memo

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1. Introduction

This draft provides an overview of IPv6 Segment Routing (SRv6) deployment status. It lists various SRv6 features that have been deployed in the production networks. It also provides an overview of SRv6 implementation and interoperability testing status.

2. Deployment Status

2.1. Softbank

As part of the 5G rollout, Softbank have deployed a nationwide SRv6 network.

The following SRv6 features have been deployed:

- A Segment Routing Header [RFC8754] based data plane.
- END (PSP), END.X (PSP), END.DT4, H.Encaps.Red and H.Insert.Red functions as per [RFC8986], [I-D.filsfils-spring-srv6-net-pgm-insertion].
- ISIS SRv6 extensions [I-D.ietf-isis-srv6-extensions].
- BGP VPN SRv6 extensions [I-D.ietf-bess-srv6-services].
- SRH based Topology Independent (TI-LFA) Fast Reroute mechanisms using H.Insert.Red for the O(50msec) protection against node and link, as described in [I-D.ietf-rtgwg-segment-routing-ti-lfa], [I-D.voyer-6man-extension-header-insertion].
- BGP Prefix Independent Convergence (PIC) core and edge [I-D.ietf-rtgwg-bgp-pic].
- Support for Ping and Traceroute as defined in [I-D.ietf-6man-spring-srv6-oam].

2.2. China Telecom

China Telecom (Sichuan) have deployed a multi-city SRv6 network.

The following SRv6 features have been deployed:

- A Segment Routing Header [RFC8754]. based data plane.

- END.DT4 function as per [RFC8986].

- BGP VPN SRv6 extensions [I-D.ietf-bess-srv6-services].

- BGP Prefix Independent Convergence (PIC) core and edge [I-D.ietf-rtgwg-bgp-pic].

- Support for Ping and Traceroute as defined in [I-D.ietf-6man-spring-srv6-oam].

2.3. Iliad

As part of the 5G rollout, Iliad has deployed a nationwide SRv6 network to provide a new mobile offering in Italy. This is a complete mobile IP network.

The SRv6 backbone is based on Cisco NCS 5500. All the cell site routers are Iliad's Nodebox, which are SRv6 capable and has been build in-house by the provider. In this deployment SRv6 is running on NCS 5500 and Iliad's Nodebox. I.e., the deployment includes interoperating multiple implementations of SRv6.

As of the end of 2020, the SRv6 network consists of:

- 1200 Cisco NCS 5500 routers.

- 5800 Iliad's Nodeboxes.

- The network services 6.8 million mobile subscribers (as of Q3 2020).

- The network is carrying 450 Gbps of commercial traffic at peak hours.

- It is expected to grow to more than 10000 Nodeboxes in the coming years. The SRv6 SIDs are allocated from a /40 sub-block of FC/8.

The following SRv6 features have been deployed:

- A Segment Routing Header [RFC8754]. based data plane.

- o End (PSP), End.X (PSP), End.DT4, END.DX2, H.Encaps.Red, H.Insert.Red functions as per [RFC8986] , [I-D.filsfils-spring-srv6-net-pgm-insertion].

- o BGP VPN SRv6 extensions [I-D.ietf-bess-srv6-services].

- o ISIS SRv6 extensions [I-D.ietf-isis-srv6-extensions].

- o SRH based Topology Independent (TI-LFA) Fast Reroute mechanisms using H.Insert.Red for the O(50msec) protection against node and link, as described in [I-D.ietf-rtgwg-segment-routing-ti-lfa], [I-D.voyer-6man-extension-header-insertion].

- o Support for Ping and Traceroute as defined in [I-D.ietf-6man-spring-srv6-oam].

2.4. LINE Corporation

LINE Corporation have deployed multi-tenants SRv6 network in the Data Center. The network provides per-service policy on a shared SRv6 underlay.

The following SRv6 features have been deployed:

- o A Segment Routing Header [RFC8754]. based data plane.

- o SRv6 implementation in the Linux kernel for the End.DX4, T.Encap functions as per [RFC8986].

- o Hardware support (RSS: Receive-Side Scaling) for the SRv6 packets on the NIC to get required throughput at the receiving cores.

- o SRv6 data plane aware OpenStack Neutron ML2 driver and API extension to provision tenant networks.

2.5. China Unicom

China Unicom has deployed SRv6 L3VPN over 169 backbone network from Guangzhou to Beijing to provide inter-domain CloudVPN service. The SRv6 network is based on Huawei NE40E hardware platform.

The following SRv6 features have been deployed:

- o A Segment Routing Header [RFC8754] based data plane.

- o END.DT4 function as per [I-D.filsfils-spring-srv6-network-programming].

- o BGP VPN SRv6 extensions [I-D.ietf-bess-srv6-services].

- o BGP Prefix Independent Convergence (PIC) core and edge [I-D.ietf-rtgwg-bgp-pic].

- o Support for Ping and Traceroute as defined in [I-D.ietf-6man-spring-srv6-oam].

2.6. CERNET2

CERNET2 (CERNET: China Education and Research Network) has deployed SRv6 L3VPN from Beijing to Nanjing to provide inter-domain L3VPN service for universities. CERNET2 is the largest pure IPv6 education backbone networking in the world. The SRv6 network is based on Huawei NE40E hardware platform.

The following SRv6 features have been deployed:

- o A Segment Routing Header [RFC8754] based data plane.

- o END.DT4 function as per [I-D.filsfils-spring-srv6-network-programming].

- o BGP VPN SRv6 extensions [I-D.ietf-bess-srv6-services].

- o BGP Prefix Independent Convergence (PIC) core and edge [I-D.ietf-rtgwg-bgp-pic].

- o Support for Ping and Traceroute as defined in [I-D.ietf-6man-spring-srv6-oam].

2.7. MTN Uganda Ltd.

As part of the complete mobile IP network, Uganda MTN has deployed a SRv6 network that carries all services in its backbone.

The following SRv6 features have been deployed:

- o A Segment Routing Header [RFC8754] based data plane.

- o End (PSP), End.X (PSP), End.DT4, End.DX2, End.DT2U, End.DT2M, H.Encaps, H.Insert as per [RFC8986], [I-D.filsfils-spring-srv6-net-pgm-insertion].

- o SRH based Topology Independent (TI-LFA) Fast Reroute mechanisms using H.Insert for the O(50msec) protection against node and link, as described in [I-D.ietf-rtgwg-segment-routing-ti-lfa], [I-D.voyer-6man-extension-header-insertion].

- o BGP VPN SRv6 extensions [I-D.ietf-bess-srv6-services].

- o BGP Prefix Independent Convergence (PIC) core and edge [I-D.ietf-rtgwg-bgp-pic].

- o Support for Ping and Traceroute as defined in [I-D.ietf-6man-spring-srv6-oam].

2.8. NOIA Network

NOIA Network have deployed a nationwide SRv6 network backbone. The SRv6 backbone is based on white box and cloud routers with FD.io VPP or Linux srext module installed. Details can be found at [noia-whitepaper1], [noia-whitepaper2].

The following SRv6 features have been deployed:

- o A Segment Routing Header [RFC8754] based data plane.

- o END (PSP), END.X (PSP), END.DT4, End.DT6 as per [RFC8986].

- o iOAM Proof of Transit and Trace options as per [I-D.ietf-ippm-ioam-data]

- o BFD for Multihop Paths as per [I-D.ietf-bfd-multihop].

- o SRH based Topology Independent (TI-LFA) Fast Reroute mechanisms using H.Insert for the O(50msec) protection against node and link, as described in [I-D.ietf-rtgwg-segment-routing-ti-lfa], [I-D.voyer-6man-extension-header-insertion].

2.9. Indosat Ooredoo

Indosat Ooredoo is deploying a multivendor SRv6 based 5G-ready transport network [Indosat-Ooredoo-announcement]. Indosat Ooredoo is starting its SRv6 deployment with Cisco and Huawei.

2.10. Rakuten

As part of the 5G and IoT services rollout, Rakuten is deploying L3VPN and EVPN-VPWS services over a nationwide SRv6 network using Cisco NCS540 and NCS 5500 series routers [Rakuten-announcement].

2.11. Bell Canada

As part of their MEC rollout, Bell Canada reports successful deployment of a nationwide SRv6 uSID network and interoperability

between Cisco, Arrcus and Noviflow. In this deployment, SRv6 SIDs are allocated from the ULA block [RFC4193].

The following SRv6 features have been deployed:

- A Segment Routing Header [RFC8754] based data plane.

- Compressed-SID (C-SID) with NEXT-C-SID Flavor (SRv6 uSID) [draft-ietf-spring-srv6-srh-compression].

- Traffic engineering with END (PSP), END.X (PSP), END.DT4, END.DT6 END.B6.Encaps.Red, END.B6.Encaps, H.Encaps.red and H.Insert.Red functions as per [RFC8986], [I-D.filsfils-spring-srv6-net-pgm-insertion].

- SRv6 service programming [draft-ietf-spring-sr-service-programming] using H.Encaps.Red and H.Insert.Red encapsulation as per [RFC8986], [I-D.filsfils-spring-srv6-net-pgm-insertion].

- SRv6 to MPLS interworking with End.DTM, End.DPM functions [draft-agrawal-spring-srv6-mpls-interworking].

- ISIS SRv6 extensions [I-D.ietf-isis-srv6-extensions].

- SRv6 BGP services extensions [I-D.ietf-bess-srv6-services].

- SRH based Topology Independent (TI-LFA) Fast Reroute mechanisms using H.Insert.Red for the O(50msec) protection against node and link, as described in [I-D.ietf-rtgwg-segment-routing-ti-lfa], [I-D.voyer-6man-extension-header-insertion].

- BGP Prefix Independent Convergence (PIC) core and edge [I-D.ietf-rtgwg-bgp-pic].

- Support for Ping and Traceroute as defined in [I-D.ietf-6man-spring-srv6-oam].

2.12. Additional Deployments

There are over 20 additional deployments without a public announcements. Several other deployments are in preparation.

Details to be added after the public announcements.

2.13. PSP Flavor Deployments

As noted above, SRv6 deployments at Softbank, Iliad, MTN Uganda Ltd. and NOIA Network all use PSP flavor for END and END.X behaviors as documented in [RFC8986].

2.14. Insertion Behavior Deployments

All deployments utilizing TI-LFA reported in this draft use insertion behavior as documented in [I-D.voyer-6man-extension-header-insertion].

3. Implementation Status of SRv6

The hardware and software platforms listed below are either shipping or have demonstrated support for SRv6 including [RFC8754] and [RFC8986]. This section also indicates the supported SRv6 functions and transit behaviors on open-source software

3.1. Open-source platforms

The following open source platforms supports SRv6 including [RFC8754] and [RFC8986]:

- o Linux kernel[ref-1],[ref-2]: End, End.X, End.T, End.DX2, End.DX6, End.DX4, End.DT6, End.B6, End.B6.Encaps, H.Insert, H.Encaps, H.Encaps.L2

- o Linux srext module: End, End.X, End.DX2, End.DX6, End.DX4, End.AD, End.AM

- o FD.io VPP: End, End.X, END(PSP), END.X(PSP), End.DX2, End.DX6, End.DX4, End.DT6, End.DT4, End.B6, End.B6.Encaps, End.AS, End.AD, End.AM, H.Insert, H.Encaps, H.Encaps.L2, GTP4.D, GTP4.E, GTP6.D, GTP6.D.Di, GTP6.E [ref-12]

- o P4: H.Encaps, End, End.X, Ed,d.DX4, End.DX6 [ref-16]

- o Zebra: zebra is an open source implementation as a successor of GNU Zebra and Quagga project. Zebra SRv6 implementation support all End functions defined in [RFC8986], H.Insert and H.Encaps [ref-17]. The implementation also supports FRR for BGP Prefix-SID [I-D.draft-ietf-bess-srv6-services]

3.2. Additional Routing platforms

To date, 25 publicly known hardware platforms from 10 different vendors support SRv6. Specifically, the following hardware platforms (in alphabetical order) supports SRv6 including [RFC8754] and [RFC8986]:

Arrcus:

Arrcus supports SRv6 including BGP VPN extensions [I-D.ietf-bess-srv6-services] and ISIS extensions [I-D.ietf-isis-srv6-extensions] on the following hardware platforms:

- o Arrcus Quanta (IXAE, IXA) Broadcom Jericho2-based platforms with ArcOS EFT (early field trial) code.

- o Arrcus Edgecore (AS7926) Broadcom Jericho2-based platform with ArcOS EFT (early field trial) code.

Barefoot Networks:

- o Hardware implementation in the Tofino NPU is present since May 2017.

Broadcom:

- o Hardware implementations on the Jericho, Jericho+, Qumran AX, and Qumran MX NPUs are shipping in Cisco platforms since December 2018. Also, hardware implementations on the Jericho2 NPU in Arrcus platforms are available for early field trials.

Cisco:

Cisco hardware platforms supports SRv6 since April 2017, with current status as follows:

- o Cisco ASR 9000 platform with IOS XR shipping code.

- o Cisco NCS 5500 platform with IOS XR shipping code.

- o Cisco NCS 560 platform with IOS XR shipping code.

- o Cisco NCS 540 platform with IOS XR shipping code.

- o Cisco ASR 1000 platform with IOS XE engineering code.

- o Cisco Nexus 9316D-GX platform with NX-OS shipping code.

- Cisco 93600CD-GX platform with NX-OS shipping code.

- Cisco 9364C-GX platform with NX-OS shipping code.

Huawei:

Huawei hardware platforms supports SRv6 with current status as follows:

- Huawei ATN with VRPV8 shipping code.

- Huawei CX600 with VRPV8 shipping code.

- Huawei NE40E with VRPV8 shipping code.

- Huawei ME60 with VRPV8 shipping code.

- Huawei NE5000E with VRPV8 shipping code.

- Huawei NE9000 with VRPV8 shipping code.

- Huawei NE8000 with VRPV8 shipping code.

- Huawei NG-OLT MA5800 with VRPV8 shipping code.

Kaloom:

- Implementation of SRv6 SID mobility behaviors as defined in [I-D.draft-ietf-dmm-srv6-mobile-uplane] on Barefoot Tofino based platform.

Marvell:

- Hardware implementation in the Prestera family of Ethernet switches.

Nokia:

- Hardware implementation in Nokia platform with SROS.

Intel:

- Hardware support on Intel's FPGA Programmable Acceleration Card N3000.

UTStarcom:

- Hardware implementation in UTStarcom SkyFlux UAR500.

Spirent:

- Support in Spirent TestCenter.

Ixia:

- Support in Ixia IxNetwork.

3.3. Applications

In addition to the aforementioned routing platforms, the following open-source applications have been extended to support the processing of IPv6 packets containing an SRH. For Wireshark, tcpdump, iptables and nftables, these extensions have been included in the mainstream version. Details can be found at [ref-11].

- Wireshark [ref-3]
- tcpdump [ref-4]
- iptables [ref-5], [ref-6]
- nftables [ref-7]
- Snort [ref-8]
- SEgment Routing Aware firewall (SERA) [ref-9]
- ExaBGP [ref-10]
- Contiv-VPP [ref-13]
- GoBGP [ref-14]
- GoBMP [ref-15]

3.4. PSP Flavor Implementations Status

To date, 20 publicly known routing platforms from 5 different vendors have PSP flavor implemented in hardware, including one open source platform. Specifically, The following 20 platforms (in alphabetical order) supports PSP flavor for END and END.X behaviors as documented in [RFC8986]:

- Arrcus Quanta (IXAE, IXA) Broadcom Jericho2-based platforms with ArcOS EFT (early field trial) code.

- Arrcus Edgecore (AS7926) Broadcom Jericho2-based platform with ArcOS EFT (early field trial) code.

- Cisco ASR 9000 hardware platform with IOS XR shipping code.

- Cisco NCS 5500 hardware platform with IOS XR shipping code.

- Cisco NCS 560 hardware platform with IOS XR shipping code.

- Cisco NCS 540 hardware platform with IOS XR shipping code.

- Cisco Nexus 9316D-GX hardware platform with NX-OS shipping code.

- Cisco 93600CD-GX hardware platform with NX-OS shipping code.

- Cisco 9364C-GX hardware platform with NX-OS shipping code.

- FD.io VPP Open-source platform [ref-12].

- Huawei hardware platform ATN with VRPV8 shipping code.

- Huawei hardware platform CX600 with VRPV8 shipping code.

- Huawei hardware platform NE40E with VRPV8 shipping code.

- Huawei hardware platform ME60 with VRPV8 shipping code.

- Huawei hardware platform NE5000E with VRPV8 shipping code.

- Huawei hardware platform NE9000 with VRPV8 shipping code.

- Huawei hardware platform NE8000 with VRPV8 shipping code.

- Huawei hardware platform NG-OLT MA5800 with VRPV8 shipping code.

- Juniper hardware platform MX204 as demonstrated at EANTC 2020 [EANTC-20].

- Hardware implementation in Marvell's Prestera family of Ethernet switches.

3.5. Insertion Behavior Implementations Status

The following 19 platforms (in alphabetical order) supports insertion behavior as documented in [I-D.voyer-6man-extension-header-insertion].

- Cisco ASR 9000 hardware platform with IOS XR shipping code.

- Cisco NCS 5500 hardware platform with IOS XR shipping code.
- Cisco NCS 560 hardware platform with IOS XR shipping code.
- Cisco NCS 540 hardware platform with IOS XR shipping code.
- Cisco Nexus 9316D-GX hardware platform with NX-OS shipping code.
- Cisco 93600CD-GX hardware platform with NX-OS shipping code.
- Cisco 9364C-GX hardware platform with NX-OS shipping code.
- FD.io VPP Open-source platform [ref-12].
- Huawei hardware platform ATN with VRPV8 shipping code.
- Huawei hardware platform CX600 with VRPV8 shipping code.
- Huawei hardware platform NE40E with VRPV8 shipping code.
- Huawei hardware platform ME60 with VRPV8 shipping code.
- Huawei hardware platform NE5000E with VRPV8 shipping code.
- Huawei hardware platform NE9000 with VRPV8 shipping code.
- Huawei hardware platform NE8000 with VRPV8 shipping code.
- Huawei hardware platform NG-OLT MA5800 with VRPV8 shipping code.
- Juniper hardware platform MX204 as demonstrated at EANTC 2020 [EANTC-20].
- Linux kernel [ref-1] [ref-2].
- Hardware implementation in Marvell's Prestera family of Ethernet switches.

4. Interoperability Status of SRv6

This section provides a brief inventory of publicly disclosed SRv6 interoperability testing, including SRv6 processing as described in [RFC8754] and [RFC8986] among many implementations.

Please refer to [I-D.filsfils-spring-srv6-interop] for details.

4.1. Cisco/ Nokia

There is an on-going private interop testing between Cisco IOS-XR based platform and Nokia SROS based platform. More details to be add in the future revision of the draft.

4.2. EANTC 2021

In July 2021, the European Advanced Networking Test Center (EANTC) successfully validated multiple implementations of the following SRv6 RFCs and drafts:

- A Segment Routing Header [RFC8754] based data plane
- SRv6 network programming [RFC8986]
- SRv6 BGP services extension [I-D.ietf-bess-srv6-services]
- SRv6 ISIS extensions [draft-ietf-lsr-isis-srv6-extension]
- IGP Flex Algo [draft-ietf-lsr-flex-algo]
- IS-IS Application-Specific Link Attributes [RFC8919]
- IS-IS Traffic Engineering (TE) Metric Extensions [RFC8570]
- A Two-Way Active Measurement Protocol (TWAMP) [RFC5357]
- SRH based Topology Independent (TI-LFA) Fast Reroute [draft-ietf-rtgwg-segment-routing-ti-lfa-01]

The Results from this event were published in a white paper by EANTC [EANTC-21].

The SRv6 inter-op testbed consisted of the following devices [EANTC-21]:

- Cisco NCS-5501
- Cisco NCS-540
- Cisco ASR-9901
- Huawei NetEngine 8000 M14
- Juniper MX204
- Nokia 7750 SR1

- Spirent N4U

SRv6 interoperability, including processing as described in [RFC8754] and [RFC8986], was validated for the following scenarios::

- Global IPv4 traffic using the SRv6 H.Encaps and End.DT4 behaviors.

- L3VPN for IPv4 traffic using the SRv6 H.Encaps and End.DT4 behaviors.

- Global IPv6 traffic using the SRv6 H.Encaps and End.DT6 behaviors.

- L3VPN for IPv6 traffic using the SRv6 H.Encaps and End.DT6 behaviors.

- EVPN over SRv6 for E-Line and EVPN L3VPN services.

- SRH based Topology Independent (TI-LFA) Fast Reroute mechanisms using H.Insert.Red and END(PSP) behaviors for local SRLG protection.

4.3. EANTC 2020

In March 2020, the European Advanced Networking Test Center (EANTC) successfully validated multiple implementations of the following SRv6 RFCs and drafts:

- A Segment Routing Header [RFC8754] based data plane

- SRv6 network programming [RFC8986]

- SRv6 BGP services extension [I-D.ietf-bess-srv6-services]

- SRv6 ISIS extensions [draft-bashandy-isis-srv6-extensions]

- SRH based Topology Independent (TI-LFA) Fast Reroute [draft-ietf-rtgwg-segment-routing-ti-lfa-01]

The Results from this event were published in a white paper by EANTC [EANTC-20].

The SRv6 inter-op testbed consisted of the following devices [EANTC-20]:

- Cisco 93600CD-GX

- Huawei NetEngine 8000 X4

- o Juniper MX204
- o Juniper cRPD
- o Arrcus QuantaMesh T7080-IXAE
- o Keysight Ixia IxNetwork

SRv6 interoperability, including processing as described in [RFC8754] and [RFC8986], was validated for the following scenarios:

- o L3VPN for IPv4 traffic using the SRv6 H.Encaps and End.DT4 behaviors.
- o L3VPN for IPv6 traffic using the SRv6 H.Encaps and End.DT6 behaviors.
- o The SRv6 Traffic Engineering policy using END and END(PSP) behaviors.
- o SRH based Topology Independent (TI-LFA) Fast Reroute mechanisms using H.Insert.Red and END(PSP) behaviors for link protection.
- o EVPN over SRv6 for E-Line and EVPN L3VPN services.
- o Multiple implementations of Classic (non-SRv6 capable) P nodes were tested to validate that a transit node only needs to be IPv6 capable.

4.4. EANTC 2019

In March 2019, the European Advanced Networking Test Center (EANTC) successfully validated multiple implementations of [RFC8754], [RFC8986], [I-D.ietf-bess-srv6-services], [draft-bashandy-isis-srv6-extensions], [draft-ietf-rtgwg-segment-routing-ti-lfa-01] and [draft-ietf-6man-spring-srv6-oam]. The Results from this event were showcased at the MPLS + SDN + NFV World Congress conference in April 2019 [EANTC-19].

Five different implementations of the SRv6 drafts, including [RFC8754] and [RFC8986] were used in this testing:

- o Hardware implementation in Cisco NCS 5500 router.
- o Hardware implementation in Huawei NE9000-8 router.
- o Hardware implementation in Huawei NE40E-F1A router.

- Spirent TestCenter.

- Keysight Ixia IxNetwork.

SRv6 interoperability, including processing as described in [RFC8754] and [RFC8986], was validated for the following scenarios:

- L3VPN for IPv4 traffic using the SRv6 H.Encaps and End.DT4 behaviors.

- L3VPN for IPv6 traffic using the SRv6 H.Encaps and End.DT6 behaviors.

- The testing validated the interoperability of H.Encaps and End.DT4/ End.DT6 behaviors combined with the End and End.X functions.

- SRH based Topology Independent (TI-LFA) Fast Reroute mechanisms using H.Insert.Red for link protection.

- OAM procedures (Ping and traceroute) [draft-ietf-6man-spring-srv6-oam]

Bidirectional traffic was sent between the ingress PE and Egress PE, i.e., the PEs were performing both the encapsulation (H.Encaps) and the decapsulation (END.DT4/ END.DT6) functionality, simultaneously. Multiple implementations of Classic (non-SRv6 capable) P nodes were tested to validate that a transit node only needs to be IPv6 capable.

4.5. SIGCOM 2017

The following interoperability testing scenarios were publicly showcased on August 21-24, 2017 at the SIGCOMM conference.

Five different implementations of SRv6 behaviors were used for this testing:

- Software implementation in Linux using the srext kernel module created by University of Rome, Tor Vergata, Italy.

- Software implementation in the FD.io Vector Packet Processor (VPP) virtual router.

- Hardware implementation in Barefoot Networks Tofino NPU using the P4 programming language.

- Hardware implementation in Cisco NCS 5500 router using commercially available NPU.

- Hardware implementation in Cisco ASR 1000 router using custom ASIC.

SRH interoperability including processing as described in [RFC8754] and [RFC8986] was validated in the following scenarios:

- L3VPN using the SRv6 behaviors H.Encaps and End.DX6.

- L3VPN with traffic engineering in the underlay. The testing validated the interoperability of H.Encaps and End.DX6 behaviors combined with the End and End.X functions.

- L3 VPN with traffic engineering and service chaining. This scenario validated the L3 VPN service with underlay optimization and service programming using SRH.

The results confirm consistency among SRH [RFC8754], network programming [RFC8986] and the dependent SRv6 drafts.

4.6. EANTC 2018

In March 2018, the European Advanced Networking Test Center (EANTC) successfully validated multiple implementations of [RFC8754] and [RFC8986]. The Results from this event were showcased at the MPLS + SDN + NFV World Congress conference in April 2018 [EANTC-18].

Four different implementations of the SRv6 drafts, including [RFC8754] and [RFC8986] were used in this testing:

- Hardware implementation in Cisco NCS 5500 router.

- Hardware implementation in UTStarcom UAR500.

- Spirent TestCenter.

- Ixia IxNetwork.

SRv6 interoperability, including processing as described in [RFC8754] and [RFC8986] was validated for the following scenarios:

- L3-VPN for IPv4 traffic using the SRv6 H.Encaps and End.DT4 behaviors.

- L3VPN with traffic engineering in the underlay. The testing validated the interoperability of H.Encaps and End.DT4 behaviors combined with the End and End.X functions.

- SRH based Topology Independent (TI-LFA) Fast Reroute mechanisms using H.Insert.Red.

The results confirm consistency among SRH [RFC8754], network programming [RFC8986] and the dependent SRv6 drafts.

5. Significant industry collaboration for SRv6 standardization

The work on SRv6 started in IETF in 2013 and was later published in 6man working group as [I-D.previdi-6man-segment-routing-header-00] in March 2014. The first implementation was done in 2014 [WC-2015].

5.1. Industry Collaboration for RFC8754

A significant industry group of operators, academics and vendors supported and refined the initial submission [I-D.previdi-6man-segment-routing-header-00] according to the IETF process:

- Twenty-four revisions of the document were published.

- Over 1000 emails were exchanged.

- Over 16 IETF presentations were delivered.

- Over 50 additional drafts were submitted to the IETF to specify SRv6 protocol extensions and use-cases [SRH-REF-BY]. These documents are either working group drafts or are well on their way to be adopted by their respective working group. The work spans 13 working group, including 6man, Spring, idr, bess, pce, lsr, detnet, dmm, mpls, etc. Appendix A lists IETF contribution on SRv6.

The outcome of this significant support from the operators and vendors led to the adoption of the draft by the 6man working group in December 2015.

The first last call for the SRH document was issued in March 2018.

A significant industry group of operators, academics and vendors supported and refined the idea according to the IETF process:

- 63 tickets were closed.

- Hundreds of emails have been exchanged to support the closure.

- Sixteen revisions of the document have been published to reflect the work of the group and the closure of the tickets.

After about 7 years of the above-mentioned collaboration from operators, academics and vendors led to the publication of RFC8754 in March 2020.

5.2. Industry Collaboration for SRv6 Network Programming

The same collaborative pattern is apparent as part of the standardization process SRv6 network programming [RFC8986].

The work on SRv6 Network Programming draft started in March 2017. The initial version contained the SRv6 Endpoint behaviors with PSP and USP flavors, source SR node behaviors and illustrations.

Since the inception of the idea of the SRv6 network programming, a large number of contributors, operators, vendors and academics supported and refined the document resulting in:

- 22 revisions of the document were published.
- 1360+ emails exchanged on SPRING (emails containing the draft name).
- About 66 additional drafts were submitted to the IETF that references network programming [NETPGM-REF-BY]. The work spans 12 working group(spring, 6man, idr, bess, pce, rtg, lsr, detnet, dmm, lisp, teas, bier and more).

The outcome of this significant support from the operators and vendors led to start of the Working Group last call on Dec 5, 2019.

It resulted in 27 issues addressed through 10 new revisions of the draft (6-15):

- Rev6 (Dec 11th 2019): 594 lines changed (64.6%).
- Rev7 (Dec 19th 2019): 148 lines changed (16.1%).
- Rev8 (Jan 10th 2020): 24 lines changed (2.7%).
- Rev9 (Feb 7th 2020): 25 lines changed (2.7%).
- Rev10 (Feb 23rd 2020): 101 lines changed (11.0%).
- Rev11 (Mar 2nd 2020): 23 lines of editorial changes (2.5%).
- Rev12 (Mar 4th 2020): 3 lines of editorial changes (0.3%).
- Rev13 (Mar 9th 2020): 9 lines of editorial changes (1%).

- Rev14 (Mar 16th 2020): 11 lines of editorial changes (1%).

- Rev15 (Mar 27th 2020): 11 lines of editorial changes (1%).

5.3. Academic Contributions

Academia has made significant contribution to SRv6 work. This includes both scholarly publications as well as writing open source software.

Appendix 2 provides a list of academic contributions.

6. Appendix 1

The following IETF working group documents or individual submissions references SRH RFC [RFC8754] (see [SRH-REF-BY] for the source of the information):

- draft-ietf-6man-spring-srv6-oam

- draft-ali-spring-ioam-srv6

- draft-bashandy-isis-srv6-extensions

- draft-ietf-bess-srv6-services

- draft-dawra-idr-bgpls-srv6-ext

- RFC 8986

- draft-geng-detnet-dp-sol-srv6

- draft-hu-mpls-sr-inter-domain-use-cases

- draft-ietf-dmm-srv6-mobile-uplane

- draft-li-6man-service-aware-ipv6-network

- draft-li-spring-light-weight-srv6-ioam

- draft-li-spring-srv6-path-segment

- draft-mirsky-6man-unified-id-sr

- draft-peng-spring-srv6-compatibility

- draft-xuclad-spring-sr-service-programming

o draft-bonica-6man-comp-rtg-hdr

o draft-bonica-6man-vpn-dest-opt

o draft-boutros-nvo3-geneve-applicability-for-sfc

o draft-carpenter-limited-domains

o draft-chunduri-lsr-isis-preferred-path-routing

o draft-chunduri-lsr-ospf-preferred-path-routing

o draft-dawra-idr-bgp-ls-sr-service-segments

o draft-dhody-pce-pcep-extension-pce-controller-srv6

o draft-dong-spring-sr-for-enhanced-vpn

o draft-dukes-spring-mtu-overhead-analysis

o draft-dukes-spring-sr-for-sdwan

o draft-dunbar-sr-sdwan-over-hybrid-networks

o draft-filsfils-spring-srv6-interop

o draft-filsfils-spring-srv6-net-pgm-illustration

o draft-gandhi-spring-rfc6374-srpm-udp

o draft-gandhi-spring-twamp-srpm

o draft-guichard-spring-nsh-sr

o draft-heitz-idr-msdc-fabric-autoconf

o draft-herbert-ipv4-udpencap-eh

o draft-herbert-simple-sr

o draft-homma-dmm-5gs-id-loc-coexistence

o draft-homma-nmrg-slice-gateway

o draft-ietf-idr-bgp-prefix-sid

o draft-ietf-idr-segment-routing-te-policy

- draft-ietf-intarea-gue-extensions
- draft-ietf-mpls-sr-over-ip
- draft-ietf-pce-segment-routing
- draft-ietf-pce-segment-routing-ipv6
- draft-ietf-spring-mpls-path-segment
- draft-ietf-spring-segment-routing-msdc
- draft-ietf-teas-pcecc-use-cases
- draft-li-6man-ipv6-sfc-ifit
- draft-li-idr-flowspec-srv6
- draft-li-ospf-ospfv3-srv6-extensions
- draft-li-pce-pcep-flowspec-srv6
- draft-li-tsvwg-loops-problem-opportunities
- draft-raza-spring-srv6-yang
- draft-su-bgp-trigger-segment-routing-odn
- draft-voyer-6man-extension-header-insertion
- RFC 7855
- RFC 8218
- RFC 8402

7. Appendix 2

The following is an partial list of SRv6 Contributions from Academia, including open source implementation of SRH RFC [RFC8754], network programming [RFC8986] draft and the related IETF drafts:

- o An Efficient Linux Kernel Implementation of Service Function Chaining for legacy VNFs based on IPv6 Segment Routing. Netsoft2019, https://arxiv.org/abs/1901.00936.
- o Flexible failure detection and fast reroute using eBPF and SRv6 (https://ieeexplore.ieee.org/document/8584995).
- o Zero-Loss Virtual Machine Migration with IPv6 Segment Routing (https://ieeexplore.ieee.org/document/8584942).
- o SDN Architecture and Southbound APIs for IPv6 Segment Routing Enabled Wide Area Networks, IEEE Journals & Magazine (https://doi.org/10.1109/TNSM.2018.2876251).
- o Leveraging eBPF for programmable network functions with IPv6 Segment Routing (https://doi.org/10.1145/3281411.3281426).
- o Snort demo, http://netgroup.uniroma2.it/Stefano_Salsano/papers/18-sr-snort-demo.pdf.
- o Performance of IPv6 Segment Routing in Linux Kernel, IEEE Conference Publication, (https://ieeexplore.ieee.org/document/8584976).
- o Interface Counters in Segment Routing v6: a powerful instrument for Traffic Matrix Assessment (https://doi.org/10.1109/NOF.2018.8597768).
- o Exploring various use cases for IPv6 Segment Routing (https://doi.org/10.1145/3234200.3234213).
- o SRv6Pipes: enabling in-network bytestream functions (http://hdl.handle.net/2078.1/197480).
- o SERA: SEgment Routing Aware Firewall for Service Function Chaining scenarios (http://netgroup.uniroma2.it/Stefano_Salsano/papers/18-ifip-sera-firewall-sfc.pdf).
- o Software Resolved Networks (https://doi.org/10.1145/3185467.3185471).
- o 6LB: Scalable and Application-Aware Load Balancing with Segment Routing (https://doi.org/10.1109/TNET.2018.2799242).
- o Implementation of virtual network function chaining through segment routing in a linux-based NFV infrastructure, IEEE Conference Publication, (https://doi.org/10.1109/NETSOFT.2017.8004208).
- o A Linux kernel implementation of Segment Routing with IPv6, IEEE Conference Publication(https://doi.org/10.1109/INFCOMW.2016.7562234).
- o Leveraging IPv6 Segment Routing for Service Function Chaining (http://hdl.handle.net/2078.1/168097)

8. IANA Considerations

None

9. Security Considerations

None

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12. 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>.

13. Informative References

[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>.

[RFC8754]
Filsfils, C., Previdi, S., Leddy, J., Matsushima, S., and d. daniel.voyer@bell.ca, "IPv6 Segment Routing Header (SRH)", draft-ietf-6man-segment-routing-header-16 (work in progress), February 2019.

[RFC8986]
Filsfils, C., Camarillo, P., Leddy, J., daniel.voyer@bell.ca, d., Matsushima, S., and Z. Li, "SRv6 Network Programming", RFC8986, February 2021.

[I-D.ietf-isis-srv6-extensions]
Psenak, P., Filsfils, C., Bashandy, A., Decraene, B., and Z. Hu, "IS-IS Extensions to Support Routing over IPv6 Dataplane", draft-bashandy-isis-srv6-extensions-05 (work in progress), March 2019.

[I-D.ietf-bess-srv6-services]
Dawra, G., ed., "SRv6 BGP based Overlay services", draft-ietf-bess-srv6-services (work in progress), September 2019.

[I-D.filsfils-spring-srv6-net-pgm-insertion]
Filsfils, C., et al, "SRv6 NET-PGM extension: Insertion", (work in progress), September 2019.

[I-D.voyer-6man-extension-header-insertion]

D. Voyer, Ed., Filsfils, C., et al,
"Insertion of IPv6 Segment Routing Headers in a Controlled
Domain",
(work in progress), September 2019.

[I-D.ietf-rtgwg-segment-routing-ti-lfa]
Litkowski, S., et al., "Topology Independent Fast Reroute
using Segment Routing",
draft-ietf-rtgwg-segment-routing-ti-lfa-01 (work in progress),
March 2019.

[I-D.ietf-rtgwg-bgp-pic]
Bashandy, A., et al, "BGP Prefix Independent Convergence",
draft-ietf-rtgwg-bgp-pic-08 (work in progress), Sept. 2018.

[I-D.ietf-6man-spring-srv6-oam]
Ali, Z., et al, "Operations, Administration, and Maintenance
(OAM) in Segment Routing Networks with IPv6 Data plane (SRv6),
draft-ietf-6man-spring-srv6-oam-00 (work in progress),
March 2019.

[I-D.draft-filsfils-spring-srv6-interop]
Filsfils, C., et al, "SRv6 interoperability report",
draft-filsfils-spring-srv6-interop-02 (work in progress),
March 2019.

[I-D.previdi-6man-segment-routing-header-00]
Previdi, S., Filsfils, C., et al, "IPv6 Segment Routing Header
(SRH)", draft-previdi-6man-segment-routing-header-00,
March 2014.

[EANTC-19] "MPLS+SDN+NFVVORD@PARIS2019 Interoperability Showcase",
"MPLS World Congress", Paris, 2019,
http://www.eantc.de/fileadmin/eantc/downloads/News/
2019/
EANTC-MPLSSDNNFV2019-WhitePaper-v1.2.pdf.

[ref-1] "Implementing IPv6 Segment Routing in the Linux Kernel",
July 2017, <https://doi.org/10.1145/3106328.3106329>.

[ref-2] "Reaping the Benefits of IPv6 Segment Routing", October
2017, <https://inl.info.ucl.ac.be/publications/
reaping-benefits-ipv6-segment-routing>.

[ref-3] "Add support for Segment Routing (Type 4) Extension
Header", June 2016, <https://code.wireshark.org/review/git
web?p=wireshark.git;a=commit;h=d6e9665872989c5f343fce47484
abe415d77486c>.

[ref-4] "Add support for IPv6 routing header type 4", December 2017, <https://github.com/the-tcpdump-group/tcpdump/commit/9c33608cb2fb6a64e1b76745efa530a63de08100>.

[ref-5] "[net-next,v2] netfilter: add segment routing header 'srh' match", January 2018, <https://patchwork.ozlabs.org/patch/856578/>.

[ref-6] "[iptables,v2] extensions: add support for 'srh' match", January 2018, <https://patchwork.ozlabs.org/patch/859206/> and <https://github.com/SRouting/SR-iptables/>.

[ref-7] "[nft] nftables: Adding support for segment routing header 'srh'", March 2018, <http://patchwork.ozlabs.org/patch/879061/> and <https://netfilter.org/projects/nftables/downloads.html>.

[ref-8] "IPv6 Segment Routing (SRv6) aware snort", March 2018, <https://github.com/SRouting/sr-snort>.

[ref-9] "SEgment Routing Aware firewall (SERA)", <https://github.com/SRouting/SERA>

[ref-10] "ExaBGP to support BGP-Prefix-SID for SRv6-VPN", January 2020, <https://github.com/Exa-Networks/exabgp/releases/tag/4.2.0>.

[ref-11] "SR-aware applications", <https://www.segment-routing.net/open-software/>

[ref-12] "SRv6 Mobile User Plane Plugin for VPP ", <https://github.com/FDio/vpp/tree/master/src/plugins/srv6-mobile>

[ref-13] "SRv6 (Segment Routing on IPv6) Implementation of K8s Services", May 2019, <https://github.com/contiv/vpp/blob/master/docs/setup/SRV6.md >

[ref-14] "SRv6 extensions in GoBGP (BGP implementation in Go)", <https://github.com/osrg/gobgp>

[ref-15] "SRv6 extensions in BGP Monitoring Protocol (BMP)", <https://github.com/sbezverk/gobmp>

[ref-16] "SRv6 extensions in P4", <https://github.com/netgroup/p4-srv6>

[ref-17] "SRv6 in zebra", <https://github.com/coreswitch/zebra/blob/master/docs/srv6.md>

[wc-15] "MPLS World Congress", Paris, 2015.

[EANTC-18] "MPLS+SDN+NFVVORD@PARIS2018 Interoperability Showcase", "MPLS World Congress", Paris, 2018, http://www.eantc.de/fileadmin/eantc/downloads/events/2017-2020/MPLS2018/EANTC-MPLSSDNNFV2018-WhitePaper-final.pdf.

[EANTC-20] "EANTC Multi-vendor Interoperability Test", "White Paper 2020", Paris, 2020, http://www.eantc.de/fileadmin/eantc/downloads/events/MPLS2020/EANTC-MPLSSDNNFV2020-WhitePaper.pdf

[EANTC-21] ""EANTC Multi-vendor Interoperability Test", "White Paper 2021", Paris, 2021, https://eantc.de/fileadmin/eantc/downloads/events/2021/MPLSSDNInterop/EANTC-MPLSSDNInterop-2021-WhitePaper.pdf

[SRH-REF-BY] "IETF Documents Referencing draft-ietf-6man-segment-routing-header Draft", https://datatracker.ietf.org/doc/draft-ietf-6man-segment-routing-header/referencedby/

[NETPGM-REF-BY] "IETF Documents Referencing RFC8986", https://datatracker.ietf.org/doc/draft-ietf-spring-srv6-network-programming/referencedby/

[noia-whitepaper1] "A Blockchain-backed Internet Segment Routing WAN (SR-WAN)", https://noia.network/programmable-internet-whitepaper.

[noia-whitepaper2] "Economics of Decentralized Internet Transit Exchange: Utilization of Transit Capacity", https://noia.network/tokenomics-whitepaper.

[Indosat-Ooredoo-annocement] "Bringing SRv6 and Converged SDN Transport Network to Indonesia", LinkedIn announcement by Indosat Ooredoo, https://www.linkedin.com/posts/indosatooredoo_risingupindonesia-53tahunindosatooredoo-activity-6731789039629856768-Z2YY/

[Rakuten-announcement] "Rakuten Mobile Advances Its Network for 5G and IoT Services with Cisco", https://newsroom.cisco.com/press-release-content?type=webcontent&articleId=2174308

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