SDN-Ready WAN networks: Segment Routing in MPLS-Based Environments

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***Abstract*—This article analyzes the structure, main components and operation of Segment Routing (SR) as a new way of encapsulating WAN traffic in MPLS-Based and only-BGP environments. SR is being considered the encapsulation protocol for modern Intelligent WANs. A proof-of-concept emulation in a virtualized scenario will demonstrate how SR works; and based on the results, this research could be used as a proposal for Service Providers to improve their network implementations, orienting them to topologies that will support new technological and business trends like Cloud/Fog Computing, IoT, BYOX, 5G, SDN, without changing their forwarding plane or using any signaling protocol, which leads to a better performance and effectiveness of the infrastructure, and obtaining a balance between orchestration and centralized intelligence through source-routing and underlay-overlay paradigms in an optimized IP network.**

Keywords—Segment Routing, SPRING, MPLS, eBGP, SDN, Source-Routing, Underlay-Overlay Paradigm, Proof-of-Concept Emulation.

I. INTRODUCTION

Wide Area Networks (WANs) are the fundamental axis of business connectivity, accompanying the development of organizations through the connection of Headquarters with their branches, thus, becoming the sustenance of modern and globalized businesses.

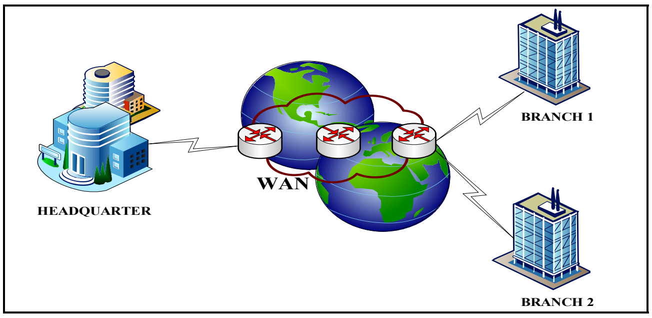

Fig. 1. Wide Area Network

Modern WANs had their beginnings in the late 60's with ARPANET, the INTERNET embryo. Later, three generations of enterprise WAN technologies were developed:

- In the mid-80s, converged networks became common, and the solution to support Voice, Video and Data was TDM-based WANs.
- In the late 80s and 90s, Frame-Relay and ATM dominated the transport converged networks.
- It was not until the early 2000s where MPLS (Multiprotocol Label Switching) saw the light as a first turning point to avoid bottlenecks in the edge of the LANs and the provider's local loops (Bob Metcalfe uses the term Teleabism to this issue), as well as managing communications efficiently and intelligently using labels without relying solely on IP addresses. In fact, this approach takes advantage of the L2 speed, with the L3 flexibility.

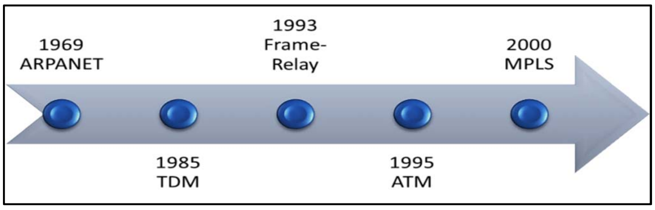

Fig. 2. WAN Evolution (until MPLS)

Cost savings and the improvement of user experience were the reasons that drove this WAN evolution; however, modern businesses and end user requirements demand much more from the network, bringing new paradigms in networking: programmability, centralized intelligence, good handling and last, but not least, efficiency in secured data flows.

II. PROBLEM STATEMENT

According to the Campus LAN and Wireless LAN Design Guide from Cisco Validated Design found in [1], there are some characteristics that a modern well-designed network must have:

- **Self-healing**: High Availability, Resiliency and Scalability.
- **Self-defending and Self-aware**: Security and total visibility.
- **Self-Optimizing**: Adapting to changing needs beyond the limits of basic standards, showing network simplification.

In addition to those characteristics, networks are facing new traffic demands and new trends are developing, highlighting the Internet of Things (IoT), Bring Your Own Everything (BYOX), 5G Mobile Connectivity, Cloud/Fog computing, dockers, teleworking, increasing video-on-demand traffic, Virtual Reality (VR), Augmented Reality apps, among others [2]. Network platforms should offer adaptable IT infrastructure that meet those business needs.

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A network modernization strategy is needed, because business transformation requires new network architectures; and Service Providers, earlier than later, should transform their networks to become SDN-ready, and with that, support client and business demands.

Segment Routing (SR) is becoming one of the mainstays to accomplish the WAN evolution required in all-IP networks, maintaining the characteristics of well-design infrastructures and reusing concepts from MPLS-LDP and Source Routing, giving a total control over the network, better scalability and better use of installed infrastructure.

III. Justification and Importance

Telecommunications and Information Technology (IT) landscapes are evolving to the Software-Defined Network (SDN) and Virtualization [3]. Segment Routing emerged as a practical and efficient solution in the WAN side to support a flexible control on steering of traffic flows, and effectively managing end-to-end traffic across the SP network, fundamental characteristics to adopt new technological paradigms mentioned in Section I and Section II.

Many SPs are considering moving to SR because it allows differentiating multiple paths to deliver applications with simplicity and scalability.

SR is not a new technology at all; in fact, it is an IP Routing concept that existed in some researches for about two decades, but its implementation is relatively new. Segment Routing is consider a variation of source routing, technique in which the source router (First-hop router) selects the best route to deliver traffic through the network in a pre-defined manner contained in the packet itself, rather than selecting it, based on the destination only (traditional approach) using dynamic routing protocols and the lowest metric found in the domain.

Segment Routing idea was proposed by Cisco Systems in November 2012 under the leadership of Clarence Filsfils [4], and the IETF (Internet Engineering Task Force) formed the SPRING (Source Packet Routing in Networking) workgroup in October 2013 to continue with the development of this technology. The RFC 8402, called Segment Routing Architecture, was developed in July 2018 [5].

The justification and importance for emulating SR technology as a Proof-of-Concept research, is to demonstrate the feasibility to deploy Segment Routing in Service Providers and hyper-scale enterprises with an already-MPLS-Based infrastructure, and prepare them to the new networking and digitized era in a seamless way.

IV. Hypothesis

The proposal of a Proof-of-Concept emulation of Segment Routing as an Overlay technology will demonstrate the connection of two-separated LAN networks (HQ and Branch) over BGP neighborships and traditional MPLS-Based infrastructure, but with the benefits of Segment-Routing, without using another signaling-labelling protocol or changing the forwarding plane of the devices.

V. Theoretical Framework

SR is an overlay (tunneling) technology that elegantly addresses the new networking requirements, because it provides highly scalable and easy solution for Traffic Engineering (TE) demands.

It can be said that traditional MPLS implementations address some of those challenges, but they have, at some point, scalability problems, because of its inherent underlay protocol complexity and rigid vendor-specific calculation for TE.

Segment Routing introduces the source-routing paradigm according to an SR policy composed by a set of instructions called segments. A segment can represent any topological or service-based instruction, which is referred to by its Segment identifier (SID) [5].

A. Segment Routing Architecture and Main Components

A host or a router, typically an edge device, acts as a steering entity in the SR domain, entity that uses the segments to know how to forward traffic. The segment is included in a Segment Routing Header (SRH) which is prepended when the packet traverses the network at the ingress node. The transit nodes in the core are not required to maintain state information of it (SR supports Equal Cost Multipath), bringing drastic gains in terms of scalability and Policy-based routing.

1) Main Components: SR Architecutre has two main components:

- **SR Data Plane**: Defines the encapsulation and encoding process of the SRH to the IP packet.
- **SR Control Plane**. Defines how nodes in the Segment Routing domain should be identified, and how the nodes should process the segments.

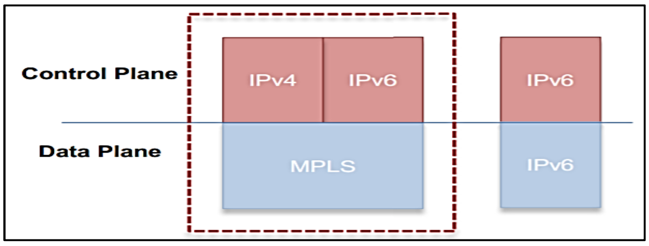

Fig. 3. Control and Data Plane in a Service Provider Device [9]

a) Segment Routing Data Plane: An SR Header contains an ordered list of segments identified by its SID. The SID could be either globally or locally significant. Globally-significant SID must be unique and is flooded throughout the Interior Gateway Protocol (IGP) Domain. On the other hand, Locally-significant SID or Adjacency SIDs allows finer grained TE and are analogous to LDP assigned labels in MPLS environments.

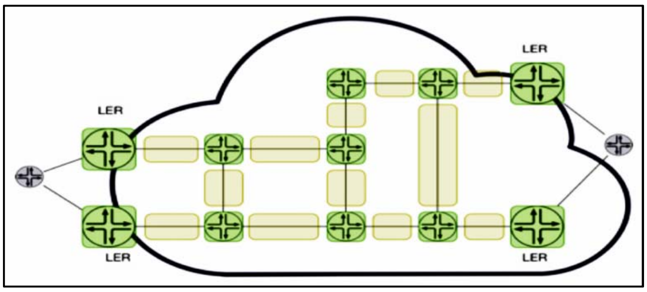

Fig. 4. SR Global SID (Dark Green) and SR Local SID (Light Green) [6]

According to [8], the four basic segment types are:

- **Node-SID**: A unique identifier for a node in an SR-Domain also called IGP-Node.

- **Adjacency-SID**: An identifier for an egress data-link with an adjacent node.
- **Service-SID**: It is an identifier for a specific service. This is a Local SID.
- **Anycast-SID**: Enables ECMP (Equal-Cost Multipathing) feature.

Same as MPLS operations, a node in a SR-Domain must perform the following three Data-plane actions:

- **Push**: Updates the segment list with a new segment, going to the top, making it the active segment.
- **Continue**: Operation that forwards the packet without any changes to the segment list.
- **Next**. Marks the next segment as the active segment.

The MPLS Operations mapped to SR operations are showed in the table below.

TABLE I. SEGMENT ROUTING OPERATIONS MAPPING TO MPLS LABEL OPERATIONS [7]

Segment Routing Ops.	MPLS Ops.
SR Header	Label Stack
Active Segment	Topmost Label
PUSH Operation	Label Push
NEXT Operation	Label POP
CONTINUE Operation	Label Swap

- **Push MPLS Operation**: Same as PUSH operation in SR.
- **Swap MPLS Operation**: Same as CONTINUE operation in SR.
- **Pop MPLS Operation**: Same as NEXT operation in SR.

For a better understanding of these operations, the next topology is shown:

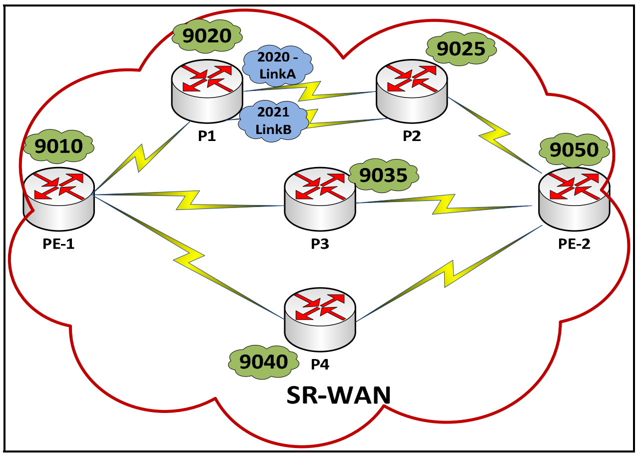

Fig. 5. SR-WAN Topology

In Figure 5, each router is assigned a unique Node-SID (IGP-SID) from SRGB (Segment Routing Global Block). For example, PE-1 is assigned a Node-SID 9010, P1 9020 and PE-2 a Node-SID 9050. Also there are two Adjacency SIDs for the links between P1 and P2 (2020 and 2021 for Link A and Link B respectively).

The path between PE-1 and PE-2 can be reached by using the SID 9050 in the SR Header. Because of the simplicity of SR, the traffic flow to PE-2 will be load-balanced over the shortest paths defined by the IGP inside the cloud.

PE-1 could enforce the path by executing a PUSH operation to set the segment list 9020, 9050 (via P1, instead of P5). If PE-1 decides to use link B instead of Link A, the segment list could be 9020, 2021, 9050. When the packet arrives to P1, it executes a NEXT operation and forwards the traffic through link A. From there, shortest path forwarding mechanism proceeds to destination. The active segment in this traffic flow is 9050.

b) Segment Routing Control Plane: The SR Control plane involves how the SID information is delivered and updated through the Segment Routing Domain.

Node-SID and Adjacency-SID are advertised in the network via Interior Gateway Protocols that support Segment Routing signaling like IS-IS (Intermediate System to Intermediate System) or OSPF (Open Shortest Path First), and via an Exterior Gateway Protocol like BGP (Border Gateway Protocol) with SR extension [11].

One of the main purposes of Control Plane is telling the ingress node how to select the path across the network. There are three methods available in SR:

- **Static (Manual) Configuration**: A static Segment Routing Tunnel is configured between SR enabled nodes. This is a temporary solution.
- **Distributed Constrained SPF (Shortest Path First) Calculation**: The ingress router calculates the SPF to a destination, under the constraint that this path matches some criteria (QoS Classification, marking or tagging, IGP-Criteria, etc.).
- **Using SDN Controller**: SR provides an environment that allows the use of SDN Controller like OpenDayLight with Path Computation Element Protocol (PCEP). This approach offers great traffic engineering capability and is one of the methods that could be investigated further in next researches.

All these methods can be run in parallel or one at a time, it depends only in the network design.

B. Segment Routing in MPLS Networks

MPLS networks use a 4-byte TAG or Label to route traffic within the MPLS Cloud instead of using IP addressing, providing a unified infrastructure capable of transport multiple protocols in its domain.

SR could be applied on the top of the MPLS network without changing the MPLS data plane.

Using this approach, the segment is encapsulated inside an MPLS Label, and with that, bringing all the simplified Traffic Engineering and all the Segment Routing benefits to MPLS infrastructure.

MPLS with Segment Routing tagging offers an Overlay Technology to deploy Transport/Transit Networks without signaling and TE protocols that causes scalability issues (Like LDP and RSVP).

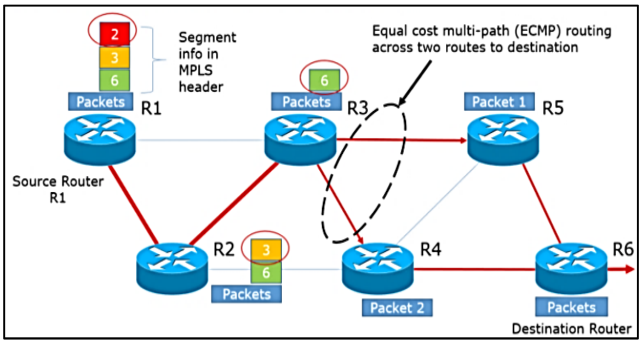

Fig. 6. SR-WAN with an MPLS-Based Infrastructure [9]

It is important to mention that according some recent researches, MPLS LFIB (Forwarding Information Base) remains constant regardless the number of paths in the Full-Mesh ISP Topology [10].

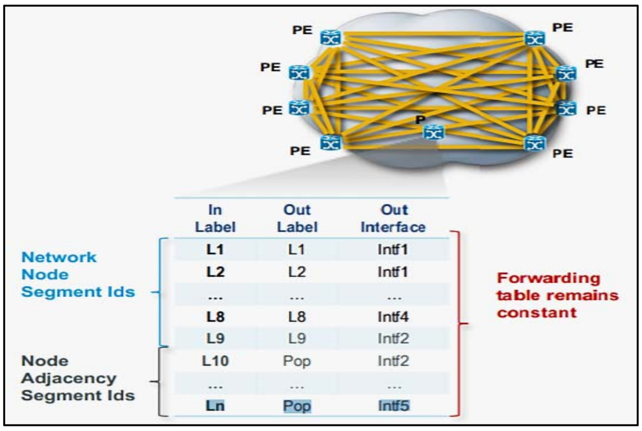

Fig. 7. MPLS FIB remains constant in SR Topology [9]

VI. Proof-of-Concept Emulation of Segment Routing in BGP and MPLS-Based Networks

In the first place, an emulation of segment routing using eBGP protocol is presented.

A. *SR Topology over BGPv4*

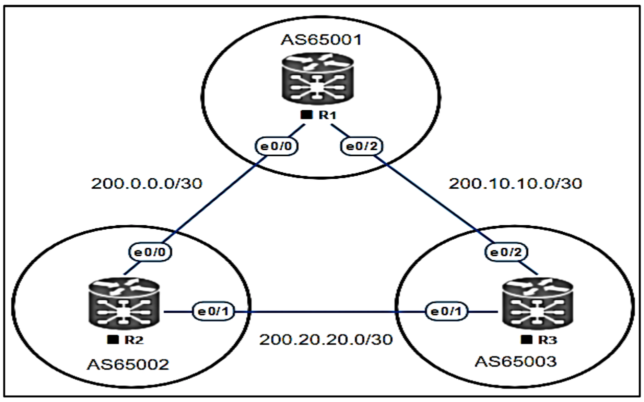

Fig. 8. SR Proof-of-Concept Topology with eBGP Neighbors

In Figure 8, Autonomous Systems (AS) 65001, 65002, and 65003 are interconnected through eBGP. In the link between each AS, there is a public network with an /30 prefix, in this case 200.0.0.0/30, 200.10.10.0/30 and 200.20.20.0/30. In addition, each router has an associated loopback interface: 10.1.1.1/32 for R1, 10.1.1.2/32 for R2 and 10.1.1.3/32 for R3.

1) *Configuring Basic Segment Routing*

For this Proof-of-Concept emulation, Cisco ASR9000 devices with IOSXR were used.

a) *eBGP configuration*

```
router bgp 65001
 bgp router-id 10.1.1.1
 address-family ipv4 unicast
 neighbor 200.0.0.2
  remote-as 65002
  address-family ipv4 unicast
    route-policy pass-all in
    route-policy pass-all out
```

Fig. 9. R1's eBGP peer configuration

b) BGP Prefix Segment Identifier Configuration: Segments are known as BGP prefix SIDs. The BGP prefix SID is global within a segment/domain routing or BGP domain. Each BGP speaker must be configured with an SRGB using the **segment-routing global-block** command.

To assign a BGP prefix SID, first create a routing policy using the **set label-index index** attribute, then associate the index to the node.

```
R1(config)# segment-routing global-block 16000 23999
R1(config)# route-policy SID($SID)
R1(config-rpl)# set label-index $SID
R1(config-rpl)# end policy
```

Fig. 10. Configuration of Segment Routing Global Block

2) *Apply the SID policy in each node:* In each node it is necessary to publish the SID policy within the BGP configuration in the address-family ipv4 unicast section.

```
R1(config)# router bgp 65001
R1(config-bgp)# bgp router-id 10.1.1.1
R1(config-bgp)# address-family ipv4 unicast
R1(config-bgp-af)#network 10.1.1.1/32 route-policy SID(1)
R1(config-bgp-af)#allocate-label all
R1(config-bgp-af)#commit
```

Fig. 11. Application of SID policy in BGP process of R1

In Figure 11, R1 was assigned the **SID 1**. R2 and R3 were assigned **SID 2** and **SID 3** respectively.

3) *Verification of label index:* Using the command **show bgp <node>,** where node is each Node's Lo IP add:

```
RP/0/0/CPU0:R1# show bgp 10.1.1.3/32
BGP routing table entry for 10.1.1.3/32
Versions:
  Process           bRIB/RIB  SendTblVer
  Last Modified: Jun 10 13:23:01.651 for 00:12:11
Paths: (2 available, best #2)
Advertised to update-groups (with more than one peer):0.2
  Path #1: Received by speaker 0
  Not advertised to any peer
  65002 65003
    200.0.0.2 from 200.0.0.2 (10.1.1.2)
   Origin IGP, localpref 100, valid, external, group-best
      Received Path ID 0, Local Path ID 0, version 0
      Origin-AS validity: not-found
      Prefix SID Attribute Size: 10
      Label Index: 3
  Path#2: Received by speaker 0
Advertised to update-groups (with more than one peer):0.2
  65003
    200.10.10.2 from 200.10.10.2 (10.1.1.3)
      Origin   IGP,   metric   0,   localpref   100,   valid,
external, best, group-best
      Received Path ID 0, Local Path ID 1, version 9
      Origin-AS validity: not-found
      Prefix SID Attribute Size: 10
      Label Index: 3
```

Fig. 12. Verification of label index in R3

ECMP (Equal Cost Multipath) is a desired behavior in a network. This characteristic allows the traffic to be forwarded from source to destination using multiple paths that have the same cost or metric, guarantying the efficiency in the topology; however, SR adopts the ECMP strategy by defining a Node-SID to be aware about ECMP using the shortest path to destination with a single label, reducing the Data Structure (Tables and Databases) size, especially in big backbone networks like in the ISP cores.

Furthermore, the forwarding table in Segment Routing is practically constant, which means, once the SIDs are configured, there is no need for tweaks, even though topology has changed, as analyzed in [9] and [12].

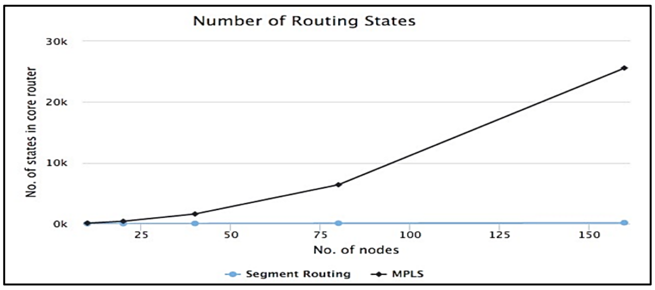

Fig. 13. MPLS vs. SR Routing States [12]

B. *SR Topology over MPLS Service Provider Cloud*

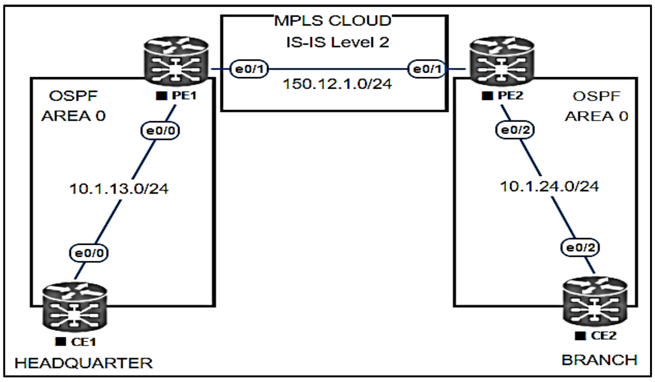

Fig. 14. SR Proof-of-Concept Topology over MPLS

In Figure 14, a Headquarter communication to its branch is made via an ISP because CE1 and CE2 do not have direct connection to each other, which is the case when the sites are separated geographically. In the local loops (CE-PE), Single-Area OSPF is the IGP deployed.

1) *MPLS Underlay Connectivty*

In this Proof-of-Concept topology, the ISP provides connectivity via an MPLS Cloud, establishing iBGP peering between Provider Edge (PE) routers. MPLS L3 VPNs is built with VRFs and, as said before, the local loop uses Single-Area OSPF.

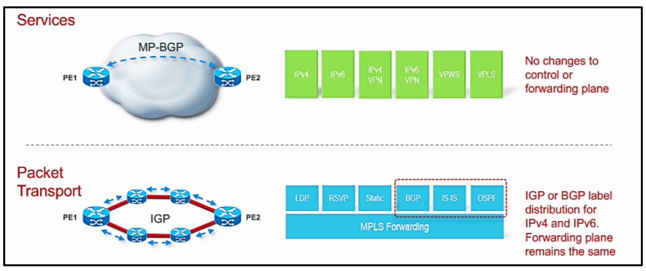

Fig. 15. MPLS Underlay Connectivity [9]

2) *IS-IS Configuration with Segment Routing.*

The IGP deployed inside the Cloud is IS-IS, and on the top of that, VPNv4 to connect the PEs.

One of the main reasons to use IS-IS is that it is not IP based, in fact, it is Connectionless Network Service (CLNS) based, meaning IS-IS runs with any L3 addressing protocol. According to IEFT Draft "IS-IS for IP Internets", IS-IS just need an extension to be used with Segment-Routing [11].

```
router isis Core
 is-type level-2-only
 net 49.0000.0000.0001.00
 address-family ipv4 unicast
  metric-style wide
  segment-routing mpls
 !
 interface Loopback0
  passive
  address-family ipv4 unicast
   prefix-sid index 1000
  !
 interface GigabitEthernet0/0/0/1
  address-family ipv4 unicast
```

Fig. 16. IS-IS and Segment Routing Configuration Sample

When SR is running, MPLS label protocols such as LDP (Label Distribution Protocol) or RSVP in Traffic Engineering implementations are not needed anymore, nevertheless, after several emulation tests, when a NO-SR-Capable node is trying to communicate with an SR-Capable node, LDP and SR tagging can interoperate with each other using an SR Mapping-server, as you can see in Figure 17.

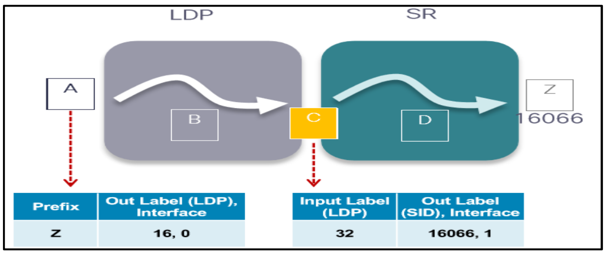

Fig. 17. LDP to SR Interoperability [9]

This behavior is verified by **show mpls interface detail** and **show cef** commands

```
RP/0/0/CPU0:PE1#show mpls int ge 0/0/0/1 detail
Thu Aug 30 04:15:48.325 UTC
Interface GigabitEthernet0/0/0/1:
        LDP labelling not enabled
        LSP labelling not enabled
        MPLS ISIS enabled
        MPLS enabled
```

Fig. 18. LDP not needed in SR topology

```
RP/0/0/CPU0:PE1#show cef  150.2.2.2 | include labels
Thu Aug 30 04:16:20.053 UTC
     local label 24004       labels imposed {24004}
```

Fig. 19. Label imposed by SR node (used instead of Transport Label)

3) *Connetiviy Test in SR Proof of Concept Topology.*

A traceroute between CEs will confirm successful connectivity between the sites.

```
HQ#traceroute 10.4.4.4 source loopback 0 numeric
Type escape sequence to abort.
Tracing the route to 10.4.4.4
VRF info: (vrf in name/id, vrf out name/id)
  1 10.1.13.1 1 msec 1 msec 0 msec
  2 150.1.12.2 [MPLS: Label 24004 Exp 0] 3 msec 3 msec
  3 10.1.24.4 3 msec *  4 msec
```

Fig. 20. Final Connetivity Test – Traceroute between CEs

VII. Related Work

Recent years have witnessed quality research about Segment Routing, including great effort in standardizing this technology, as mentioned in Section III.

Among the most relevant research works are [13], [14], and [15]. All of them, theoretically describe the protocol, as well as perform analysis of its behavior, mainly using benchmarks and testbeds obtained from emulations or through SDN and PCEP environments described in Spring-Open project, as an ONOS (Open Network Operating System) use case [16]. Another interesting scientific paper is [17], which compares SR rapid convergence mechanisms and dynamic traffic rerouting with no packet loss.

Although, the present research also defines the fundamentals, basic components, message types and operation of SR, it includes emulated proof-of-concept stages, where the interoperation with MPLS-LDP, BGP infrastructures and SR is verified using an IS-IS extension within Service Provider's cloud, taking advantage of source-routing and intelligent tunnels, but with complete and seamless interoperability between Segment Routing and current protocols for WAN routing and labeling as LDP.

This behavior leads to an adequate migration process towards pure SDN environments, without impact in Operation Expenses (OpEx) and Capital Expenses (CapEx).

VIII. Conclusions

This research went through phases of theoretical domain of the subject, conceptual analysis and a final phase of Proof-of-Concept emulations, allowing the researchers to conclude that the hypothesis stated in this paper is true. Segment Routing, as an overlay encapsulation technique on an MPLS-Ready or BGP neighborships underlay network, has been constituted as a De-facto SDN Architecture, which has an IETF Standardization, multi-vendor/open-source consensus and strong customer adoption because of its ease of implementation, without any LDP-SR interworking problems, supporting ECMP (Equal Cost Multipath), constraint-based routing, centralized admission control with existing IS-IS/OSPF extensions to advertise link attributes and making policy-based routing, multicasting and Traffic Engineering simple, automated, scalable; and of course, it is important to mention that the forwarding table remains constant regardless the number of available paths.

IX. Future Research

To complement the Segment Routing analysis and give a holistic approach to next generation WANs, the following topics should be considered in future research:

- Segment Routing in IPv6 scenarios (SRv6 Wave) [18].
- Security in Segment Routing, including Segment Routing aware security devices [19].
- SDN Controller-based Segment Routing performance.
- Intelligent Load Balancing and Traffic Engineering in Segment Routing topologies.

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