DESIGNING AND COMPARING SEAMLESS MPLS USING BGP-LU AND LDP DOD FOR LTE BACKHAUL

By

Gordon Amoako Agyemang

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Supervisor:

Noonari Juned

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CHAPTER 1

1.0 INTRODUCTION

The mobile backhaul (MBH) comprises of technologies that interconnect service providers cell site Base Stations (BTS, eNodeB) to Mobile controllers (BSC/RNC) and the core network (SGSN//MME/MGW, etc.). In the case of LTE, the MBH ties the cell site base station (eNodeB) directly to the core network (SGW and MME).
Some implementations of mobile backhaul use different technologies such TDM, SDH/SONET, ATM, Frame Relay among others to transport individual service profiles like voice and data. For example, Voice may be transported over circuit switched (connection oriented) TDM network whiles data is carried primarily over packet switched network such as Frame Relay.
The MBH must continue to support 2G, 3G and 4G-LTE services as well as newer and next-generation service such as 5G. Each service profile adds scaling complexity, management overhead thereby increasing the capital and operational expenditures to the transport network when separate transports technologies are implemented for separate services. Increasing demands for bandwidth for mobile broadband services and cloud services in addition to rising capital and operational expenditures, mobile network operators have come to realize the need to transform their MBH to IP/MPLS which offers a unified and robust transport network, high bandwidth at lower cost and flexible provisioning while providing the same service reliability and quality of service that is provided by the SONET/SDH. **[1]**

1.2 WHY MPLS

1.2.1 Service Consolidation over common transport network

Before the advent of MPLS, service providers used different transport networks to provide different services to customers. For an example, services such as voice and video which needed stringent QoS SLA were transported over ATM and Frame Relay while the Best Effort traffic were carried by IP. Maintaining different networks for different service profiles means high capital and operational expenditures.
MPLS consolidates all services over a common transport infrastructure thus reducing the cost of building and operating the network. **[2]**

1.2.2 Bandwidth Utilization and Congestion Avoidance

MPLS also provides an extensive traffic engineering to service providers which could be very difficult to achieve by traditional IP routing. In IP routing equal Cost Multiple Path (ECMP) could be used to share traffic load among different routes but only when those routes are of equal cost from the source to destination with respect to the router implementing the ECMP. Figure 1.1 illustrates a situation in which only IP routing such as OSPF is used to forward traffic in a network. All the traffic follows the same path chosen by the IGP hence causing congestion in the network whereas the bandwidth on redundant paths is not utilized **[2]**

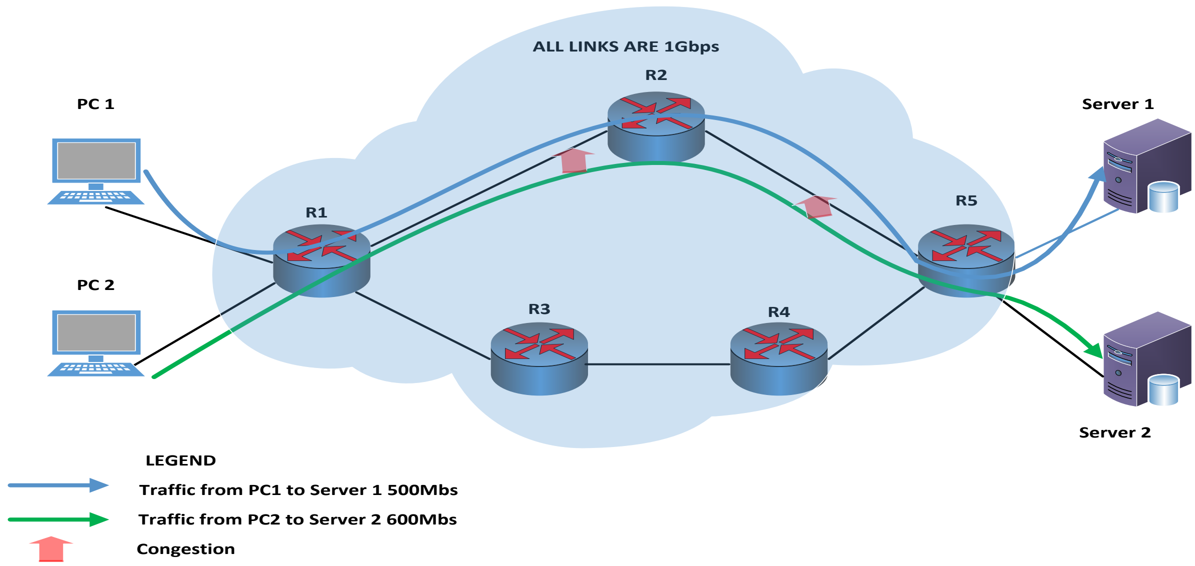


Fig 1.1 inefficient use of network bandwidth

By The Use of Resource Reservation Protocol Traffic Engineering (RSVP-TE), MPLS can forward packet through different paths other than the IGP chosen best path. MPLS-TE makes use of several constraints such as bandwidth, hops, administrative group, cost, etc. to calculate paths different from IGP best path. These could be signaled along various links in the network creating alternate paths for load balancing traffic in the network. Bandwidth utilization is therefore improved. Also, congestion which is created by all traffic following IGP best path is avoided. Fig 1.2 shows MPLS-TE used to utilize redundant bandwidth to avoid congestion in the network. **[2]**

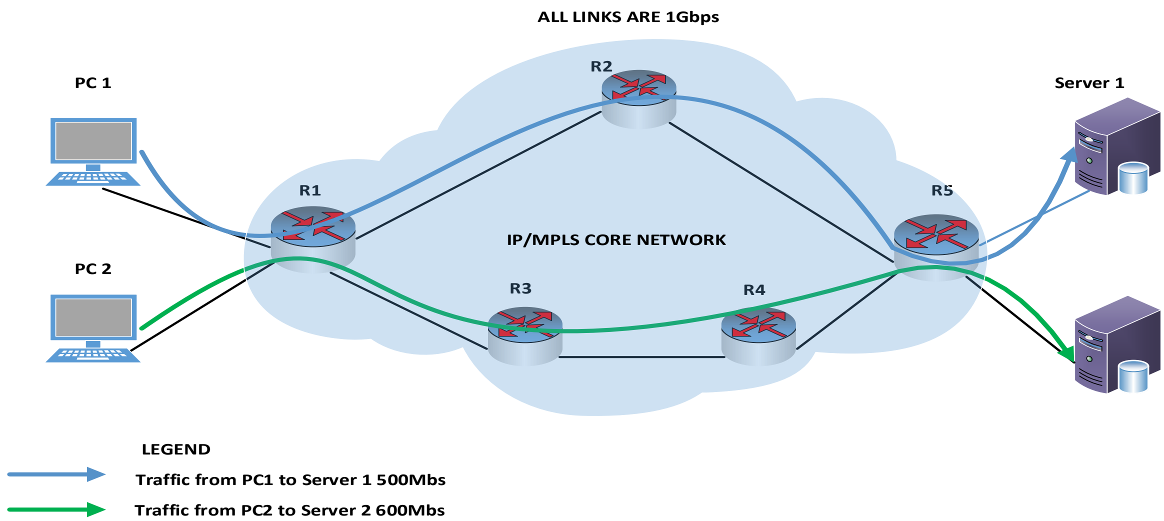


Fig 1.2 efficient utilization of network bandwidth

1.2.3 High Availability

Because of the distributed nature of IP routing protocols (i.e., each router running an instance of the protocol), it take a considerable amount of time (seconds or even minutes) for the network to converge after failure or when a new node is introduced or when a change is implemented. Sensitive traffic such as voice cannot tolerate such delays in IP routing.

MPLS has in place mechanisms such as secondary paths and Fast Reroute (FRR) that provides sub-50ms service restoration after a node or a link fails.

Secondary Path Protection – A secondary path could be signaled before (hot standby) or after the primary path fails from the head end router to the tail end route thus providing end-to-end protection. In the advent of failure, traffic is switched to the secondary path.

Fast Reroute Protection (FRR)- FFR provides a local repair to a node or link failure. Each MPLS router can signal, an MPLS path (label switched Path) that avoids a potential point of failure such the next node or next link on the primary path. The Merging Point (MP) for a link protection LSP is the next hop router on the primary LSP. Also, the merge point for a node protection LSP is the next-next hop router on the primary LSP.

Fig 1.3 show a primary path being protected by secondary path and fast Reroute. **[2]**

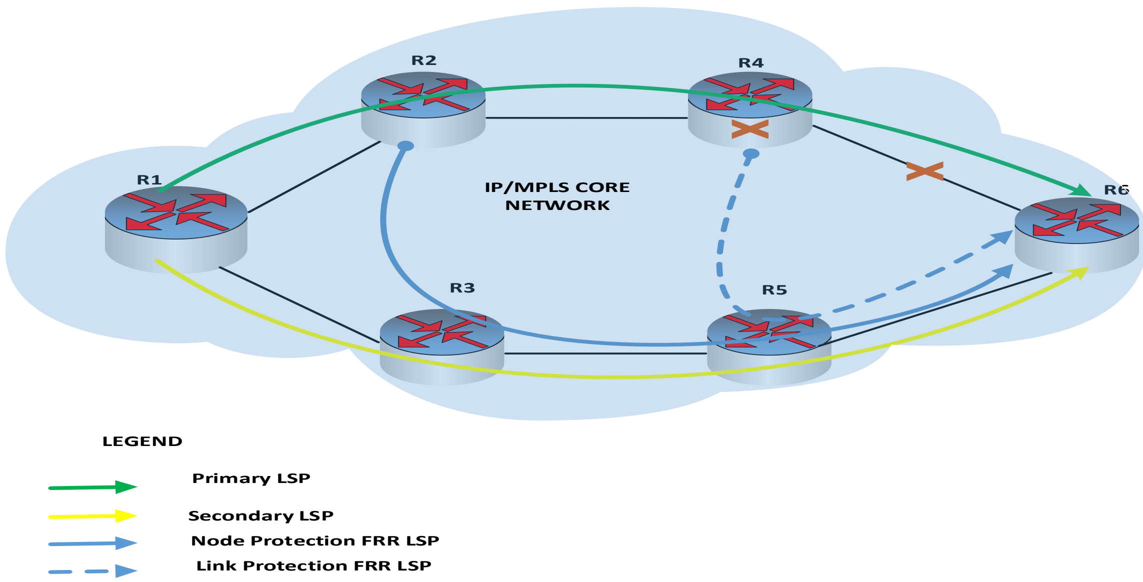


Fig 1.3 Secondary path and FRR protection of a primary path

1.2.4 BGP free core network

Suppose PC1 wants to send traffic to the external network 192,168.1.0/24. With normal IP routing, this could only happen when all the routers (R1, R2, and R3) have install FEC Z in their routing and Forwarding Information Base (FIB) tables. R2 and any other core router between R1 and R3 could be freed from installing FEC Z in their routing tables by R3 advertising FEC Z to R1 via an i-BGP session between R1 and R3. When a packet from PC1 arrives at R1, R1 encapsulates the packet with the label it received from R3. R1 then forwards the encapsulated packet to R3 over the LSP established between R1 and R3, without R2 knowing the content of the packet being carried. **[2]**

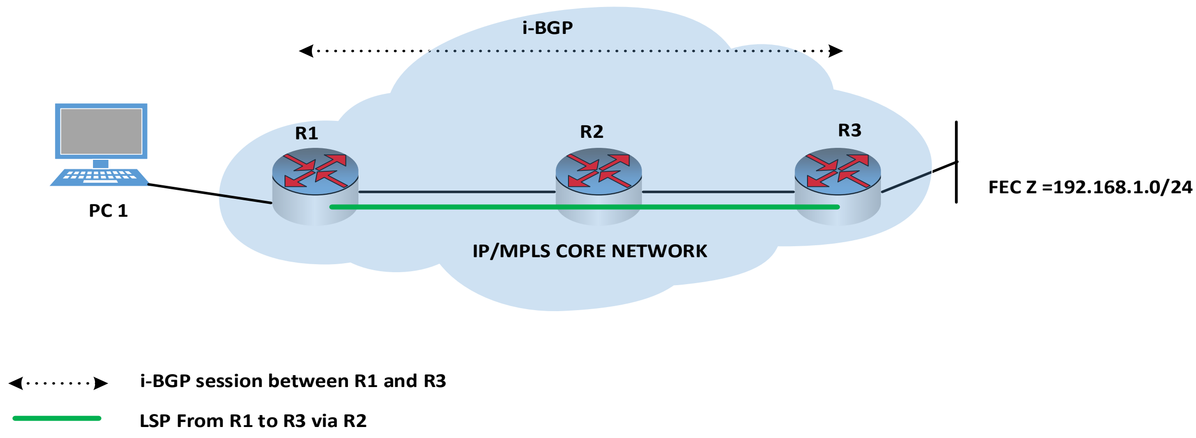


Fig 1.4 *BGP free core IP/MPLS core*

1.2.5 VPN services (L2VPN and L3VPN)

Virtual Private Network is one of the services that can be enabled over MPLS. These VPN services are categorized in three main forms:

1) Virtual Private Wire Service (VPWS) – VPWS is an emulation of pseudo-wire that provides Layer 2 point-to-point service that can be used to carry Ethernet, TDM, ATM, and Frame Relay packets. Routers in the service provider's network do not learn the MAC-address of their customers nodes. Fig.5 illustrates VPWS.

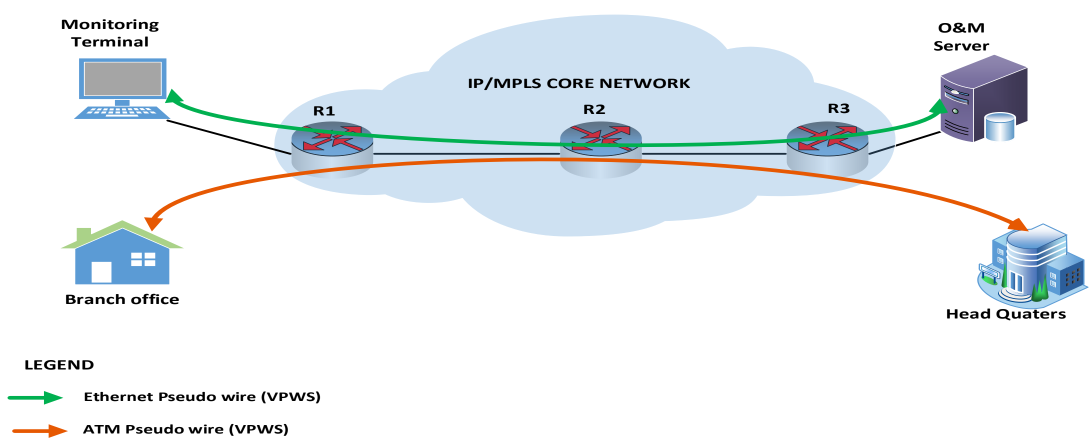


Fig 1.5 *L2VPN -point-to-point service provided by a service provider to it's customers*

2) Virtual private LAN Service (VPLS) - VPLS emulates Ethernet switch that provides point-to-multipoint Ethernet connections to their different sites. Communication between different sites is provided through MAC address learning. Also, all sites in the same VPLS services are in the same broadcast domain. VPLS supports features such as 802.1Q trunking, Q-in-Q (double tagging) and Spanning Tree Protocol (STP).

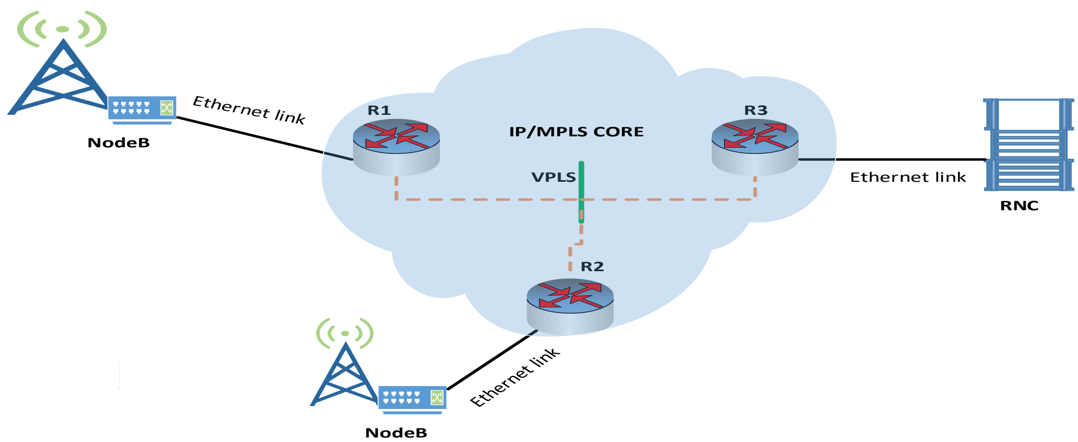


Fig 1.6 *VPLS used to connect NodeBs to RNC*

3) Virtual Private Routed Network (VPRN) or L3VPN– Provides a routed service that can be used to connect multiple customer sites while it isolates each customer's routing information from each other. Isolation between customers is achieved by creating a Virtual Routing and forwarding (VRF) instance for each VPRN customer. These create a separate routing table for each customer. This allows different customers to use the same IP subnets (overlapping IPs) without any conflict. Multiprotocol-BGP (MP-BGP) is used to distribute various customer routes in the service provider network. Before exporting the routes into MP-BGP, the routes are tagged with Route Distinguishers (RD) to make them unique. This makes it possible for MP-BGP to distribute overlapping customer routes. The Routes are also distributed along with Route Targets (RT) to identify the VPN with which a particular route belongs to at the destination. **[2]**

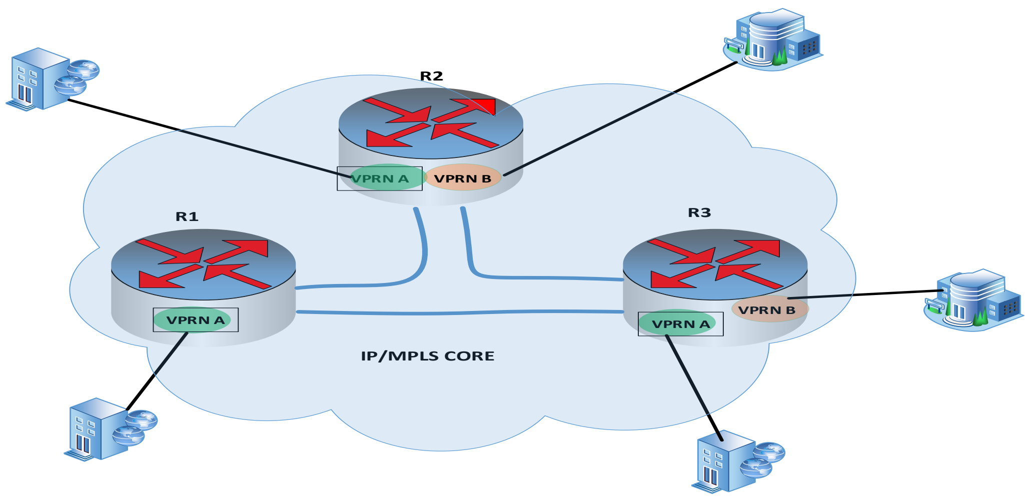


Fig 1.7 *VPRN (L3VPN) Service to customers over IP/MPLS Core Network*

1.2.6 Enhanced Switching

At the time MPLS was developed, it switched packets faster than IP merely because MPLS switching is based on a simple label lookup whiles IP Forwarding is based on longest prefix match in the routing table. Recent development in data plane IP hardware has made IP forwarding equally faster. Nonetheless MPLS still the preferred choice of packet switching in the service provider network because of its features such as traffic engineering, high availability, VPN based services, etc. **[2]**

1.3 ISSUES WITH CURRENT MPLS TRANSPORT LAYER IMPLEMENTATIONS

It is fairly straight forward to design and operate MPLS and VPN services over a flat (single) area IGP network. However, as the network grows in terms of number of routers and services, scalability issues arise. For instance, RSVP-TE enabled routers will have to maintain N*(N-1) LSP state for full mesh connectivity. Where N is the number of RSVP-TE routers.

Huge topology data base, routing tables and updates coupled with routers maintaining RSVP-TE LSP states, impose a great burden with regards to memory and processing on the routers especially the transit routers, resulting in poor performance of the network. To improve upon this scalability issues, large IP/MPLS networks are split into multiple networks (regions) - Access, Aggregation and Core networks as shown in fig. 1.8. A region maybe represented by OSPF area, IS-IS level or separate instances of OSPF and IS-IS. The IGP routing information is then confined within each region. Routing information may be allowed to crossover to other regions in a controlled manner if the need be. Inter region communication is handled by the area boarder routers via either route summarization or route leaking.

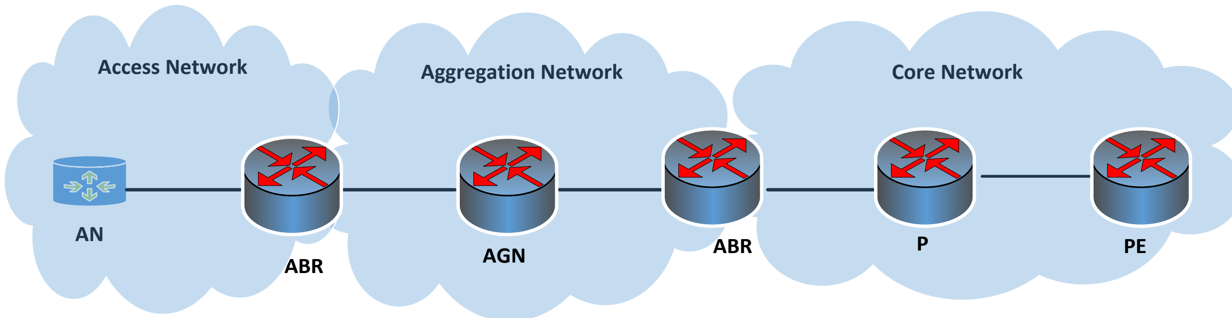


Fig. 1.8 Splitting of large network into smaller domain to enhance scalability.

Although scalability is increased by segregating the network, three major problems from the perspective of LDP and RSVP-TE LSPs crop up.

One of such issues is that Traffic engineered LSPs cannot work end-to-end across multiples areas/regions. The reason being that type 10 opaque LSAs which carries traffic engineering information cannot go beyond the area border routers. This limitation was solved by a 2-layer transport technique known as LDP-over-RSVP. LDP-over-RSVP stitches the two RSVP-TE LSP in different areas at the Border routers there by producing end-to-end RSVP-TE LSP. As illustrated in fig. 1.9 below Targeted LDP sessions is configured between the PE-ABR, ABR-ABR to signal the inner transport label. This LDP LSP established traverses regional border, and it is resolved to the outer RSVP-TE LSP to take advantage of intra-area traffic engineered LSP.

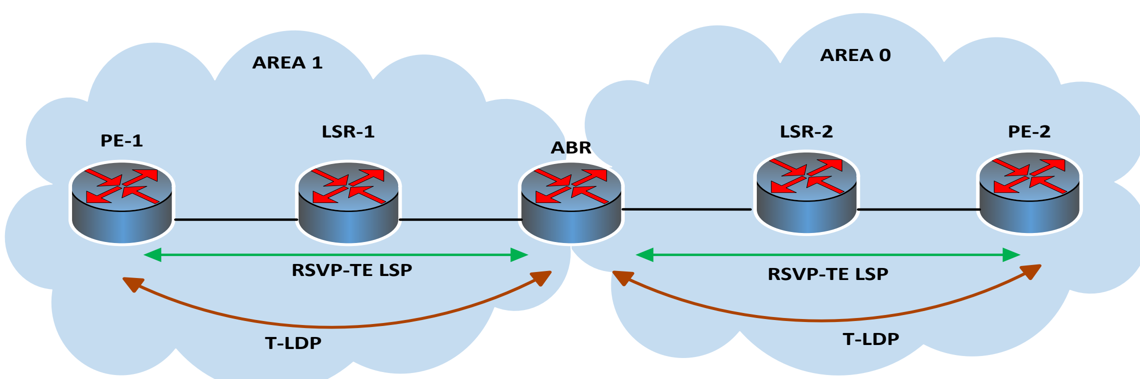


Fig. 1.9 stitching intra-area RSVP LSP to provide end-to-end LSP

Another problem introduced by multiple area design pertains to LDP LSP when prefixes are summarized into an area.

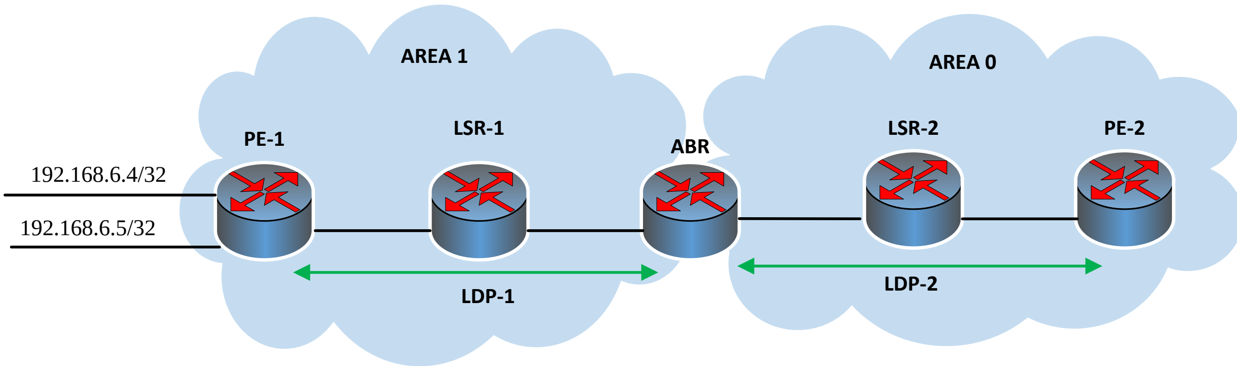


Fig.11 exact prefix match requirement for LDP LSP

When an LDP enabled router receives a label binding from its peer, by default, it looks for an exact match for the prefix in the FIB before it can resolve the LDP prefix and install it as an entry in the LFIB.
Using the fig. 1.10 above as an example, Router ABR summarizes the loopback prefixes from router PE-1 to 192.168.6.0/24 before distributing it into area 0. Routers LSR-2 and PE-2 receive LDP label bindings from Router ABR for router PE-1 loopback Prefixes (192.168.6.4/32 and 192.168.6.5/32), by default it cannot resolve and make entries in its LFIB for these prefixes as they cannot find an exact match in their FIBs. Hence LSP from router PE-1 to router PE-2 (end-to-end LSP) cannot be established.
Alcatel-Lucent implementation of LDP has a feature known as aggregate-prefix-match which serves as a workaround to this limitation. Aggregate-prefix-match overrides the default exact prefix match rule of LDP, allowing the more specific LDP prefixes to be resolved by a summarized or an aggregate prefix in the FIB. **[2]**

Another feature that tends to improve scalability in a multi-segment MPLS network is Pseudowire Stitching. **[3]** With Pseudowire Stitching one can cross-connect layer 2 VPWS services originating from a cell site router at an intermediate, not in the aggregation region/area. A single service then interconnects the cross-connected service in the aggregation region to the core region. The allows the number of cell site routers to scale in number while reducing the number service label signaling protocols (e.g. T-LDP) on the service end points between the aggregation and core regions. In other words, it reduces full mesh requirement between cell site routers and the core routers as depicted in fig. 1.11. The downside of this is that introduces service specific configuration in intermediate nodes.

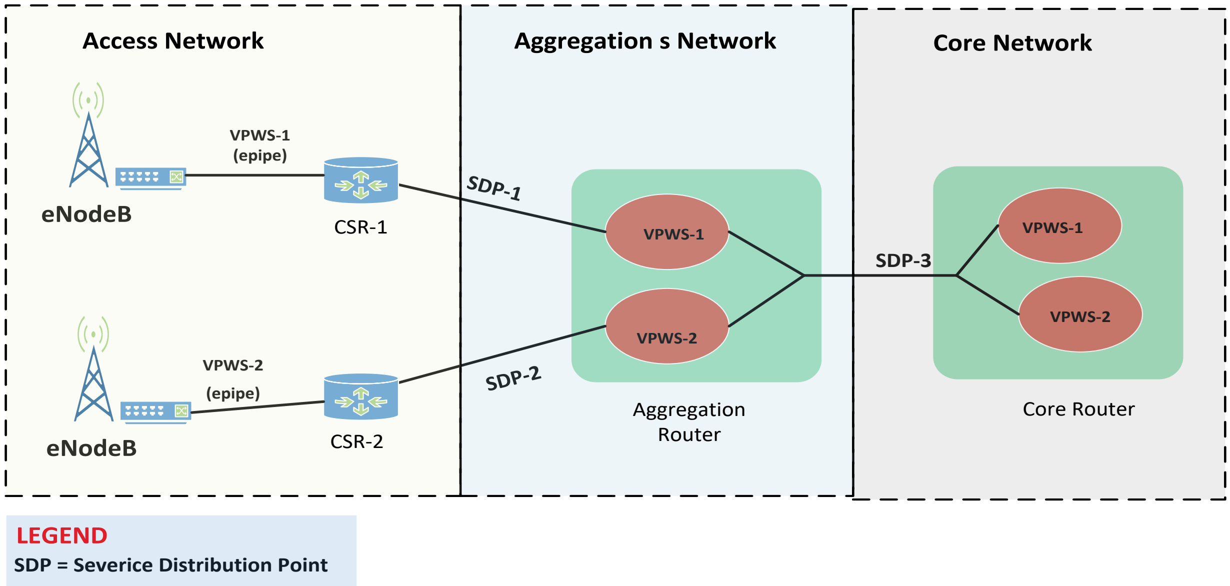


Fig 1.11 Pseudowire Switching on VPWS.

Another issue faced in Access network without Seamless MPLS is where the services from the last mile Cell Site Router (CSR-1) traverses two or more other Cell Site Routers before reaching the MPLS network as depicted in fig 1.12 below.
Delineating the services on the CSRs with VLANS leads to excessive configuration resulting in operational overheads and difficulties in troubleshooting faults.

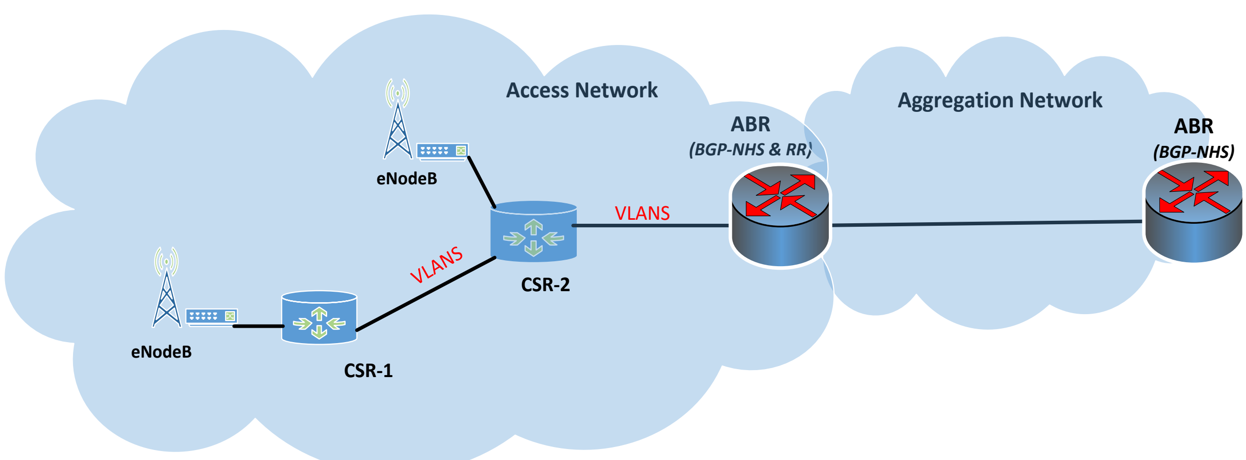


Fig 1.12 Access network without (Seamless) MPLS

AS explain above, current MPLS implementation has features such as LDP-over-RSVP-TE, LDP Extension and Pseudowire Switching and VLANS which improves scalability and provides end-to-end MPLS services. However, they do not provide the complete scalability, manageability, and resiliency required of end-to-end MPLS network. Seamless MPLS architecture aims to address these issues mention above.

1.4 SEAMLESS MPLS

In seamless MPLS network, a packet is forwarded in MPLS LSP from the moment it enters the network until the packet exits the network as illustrated in fig. 1.12 below.

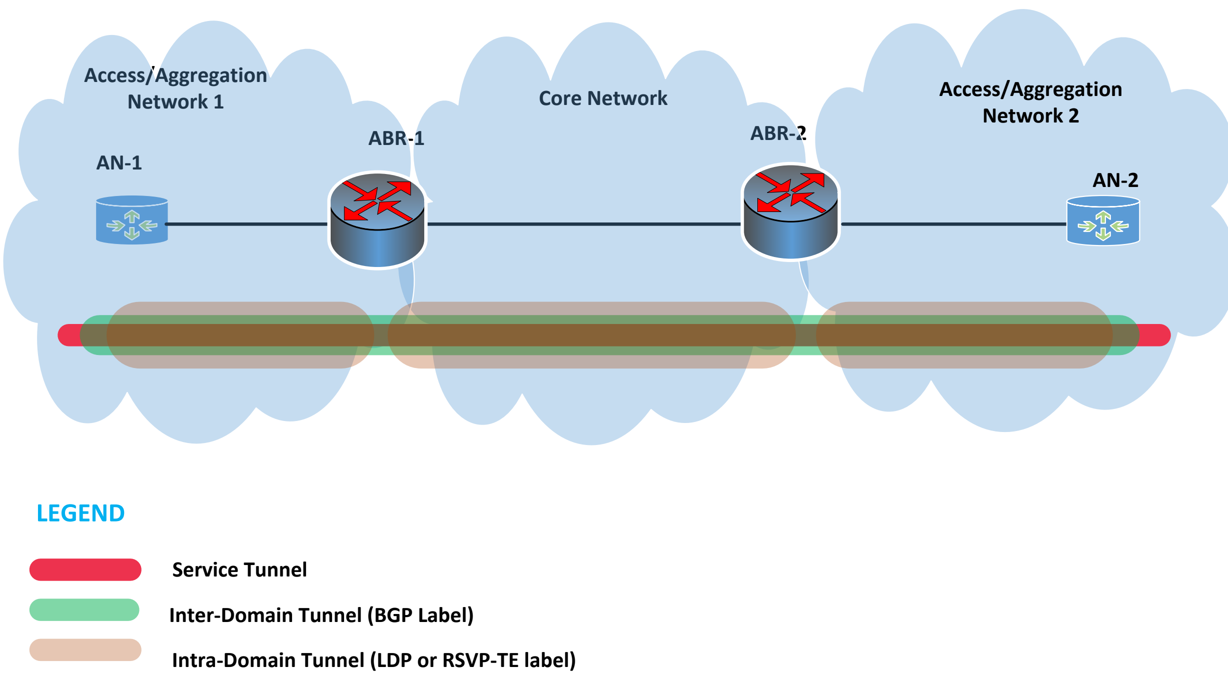


Fig 1.13 Seamless MPLS network Architecture.

1.4.1 MOTIVATIONS FOR SEAMLESS MPLS

1.4.1 .1 Single end-to-end MPLS domain

Seamless MPLS Architecture/Design creates a single MPLS domain that integrates access, aggregation and the core networks thus making operation and maintenance more efficient. As can be seen from fig 1.13, the MPLS transport layer spans across multiples areas thus joining them into a single MPLS domain. **[7]**

1.4.1 .2 No boundaries

In traditional MPLS deployments where the network is split into multiple areas, in most cases, it is required to perform service specific configurations on the border nodes to achieve optimized end-to-end inter area service. On the other hands, Seamless MPLS permits MPLS services to be created between any two points without the need for service configuration on area border router or any intermediate node as it is the case in fig 1.11 above. **[7]**

1.4.1 .3 End-to-end services decoupled from MPLS transport tunnel

With Seamless MPLS, end-to-end services can be provisioned independently from the MPLS transport tunnel, thus separating the service and transport plane. This provides network operators the flexibility to quickly provision services virtually everywhere in the network where it is required thus solving the issue seen in figure 1.12.
Also, a problem on the transport layer needs to be solved once, and the solution applies to all the services. **[7]**

1.4.1 .4 Multi-service convergence

Seamless MPLS also makes it easy to carry a wide variety of different services transported by TMD, Ethernet, IP, frame Relay, ATM on a single MPLS platform.

1.4.1 .5 Scalable Network Architecture

Seamless network architecture takes into consideration that some nodes especially those in the access region have limited capabilities. As such implementing a protocol such as LDP-DoD and static routes on these nodes and their immediate downstream routers enables the access nodes to scale in number up to thousands whiles, maintain their simplicity and low cost.
The overall nodes in Seamless MPLS network can scale to 100s of thousands**. [7]**

CHAPTER 2

Before we dive into the MPLS protocols used to design Seamless MPLS transport layer, I will like to give an overview of MPLS. In this chapter I will discuss MPLS:

1. Terminologies
2. Control Plane operations
3. Data Plane operations

2.1 INTRODUCTION TO MULTI PROTOCOL LABEL SWITCHING (MPLS)

The name MPLS intuitively spells out what the protocol does. It is a multiprotocol in the sense that it can carry payloads from varying protocol such Ethernet, Frame Relay, ATM, IPv4, IPv6, TDM and more. Label Switching Part of its name comes from the fact that MPLS transports packet by means of predefined label exchange among MPLS nodes. These exchanged labels form a transport layer known as label Switched Path (LSP) over which MPLS forwards its encapsulated traffic. These labels are signaled among MPLS routers using either of the following protocols.

i) Label Distribution Protocol (LDP)
ii) Resource Reservation Protocol- Traffic Engineering (RSVP-TE)
iii) Border Gateway Protocol Label Unicast (BGP-LU)
iv) SPRING (Source Packet Routing in Networking)

2.2 MPLS NAMING CONVENTIONS

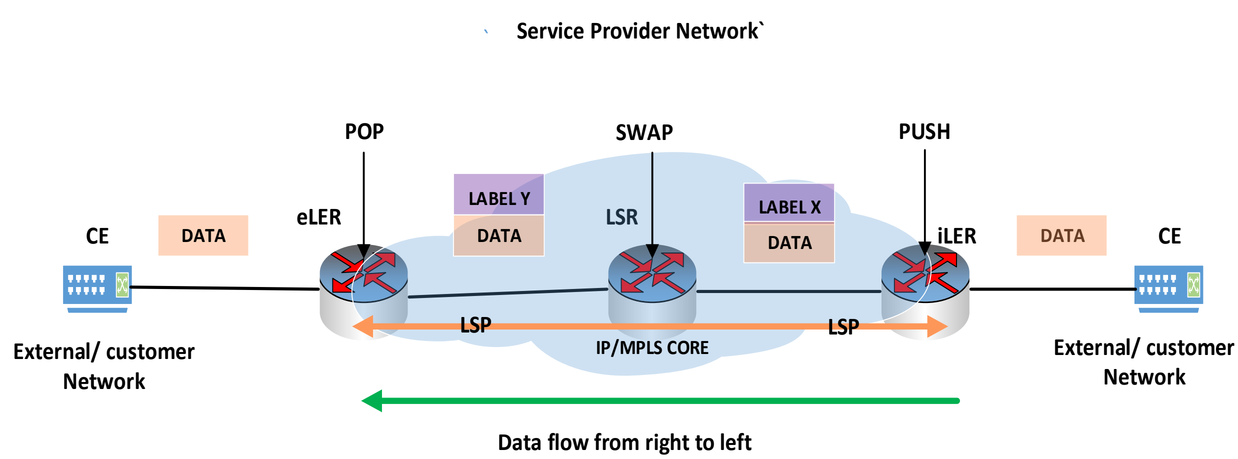


Fig 2.1 MPLS terminologies

Label Edge Router (LER) – These are routers at the edge of the service provider's network through which packets enter or leave the MPLS Network thus serving as the gateway to the MPLS network. LER connects via a link with one or more CEs and LSRs. The LER through which packets from external network enters the MPLS network is referred to as ingress Label Edge Router (iLER). The LER from which packets exits the MPLS network is also referred to as egress Label Edge Router (eLER).

Label Switched Router(LSR) – These are the routers between iLER and eLER. They do not have a direct connection with a CE.

Customer Edge Router (CE) – These routers belong to the customer and are located on the customer premises. The CE interfaces with one or more LER in order to receive the service provided by the service provider. They are oblivious of MPLS protocols and VPN services.

Label Switched Path (LSP) – This is the logical path formed by MPLS routing protocols after the exchange of labels among MPLS speaker. The path formed is unidirectional. For communication in both directions to occur LSP must be formed in both directions.

PUSH – when an unlabeled packet arrives at the iLER from a CE destined to a remote CE, the iLER encapsulates the packet in an MPLS header with a label say X. this operation by the iLER is known as PUSH. Note the unlabeled packet could also be internally generated by the iLER. The iLER the forwards the labeled packet to the appropriate LSR over an LSP.

SWAP- When an LSR receives a label packet from either iLER or another LSR it removes the label and encapsulates the packet with a new label based on the LSP it received the packet. The LSR the forwards the packet to the next LSR or the ~~an~~ eLER if it is the last LSR. The ~~is~~ operation is performed by an LSR is called **SWAP**

POP- The eLER upon receipt of a labeled packet from LSR and realizing it is the last hop removes the label and then forwards the DATA to the appropriate CE. This final removal of label by the egress router is referred to as **POP**.

2.3 MPLS HEADER STRUCTURE

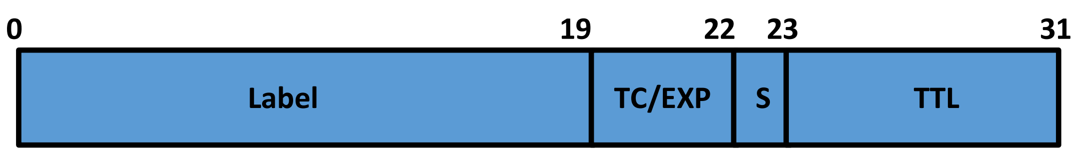


Fig 2.2 MPLS Header

MPLS header is composed of a total of 32 bits

Label- The MPLS forwarding table has the label values as an index. Packet forwarding is based on these label values. The most significant 20 significant bit of the header denotes the label given a range of 0 to 1,048,575.

S- the next 1 bit is the Stack of Bottom bit represented as S. MPLS headers can be stacked to for a hierarchy of tunnels. This makes it possible to multiplex several service tunnels on a single MPLS transport tunnel. A typical application of stacked headers is L3VPNs. The header at the bottom of the stack has the S bit set to 1 whiles those on top are set to 0. In Fig 1.10 the S bit in MPLS header N will be set to 1whiles the S bit in MPLS header from 1 to N-1 will be set to 0

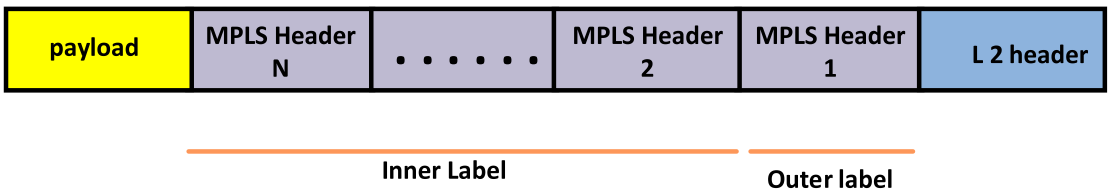


Fig 2.3 header Stack

Traffic Class (TC)- This is made of the next 3 bits given 8 possible different values. It was initially called Experimental bit (EXP). It is meant to carry Quality of Service (QoS) information. Only the TC in the topmost label is significant in QoS processing. The are two main methods used in handling the TC/EXP:

- Pipe Mode.
- Uniform Mode.

Pipe Mode

In this mode, the customer may set Differentiated Service Code Point (DSCP) value of the IP header of the packet it is sending. As the packet arrives at the iLER, by default the customer's DSCP value remains unchanged and so as it traverses through LSRs to the eLER. The TC/EXP field of the MPLS headers (both inner and top), at the iLER, are set to a certain value by the administrator who~~ich~~ may have no correlation with the customers DSCP value. These~~is~~ values~~ and~~ usu~~norm~~ally remain unchanged by LSRs. The customer DSCP value may be used to classify the packet at the iLER but has no influence on the value chosen for the TC/EXP. **[2]**

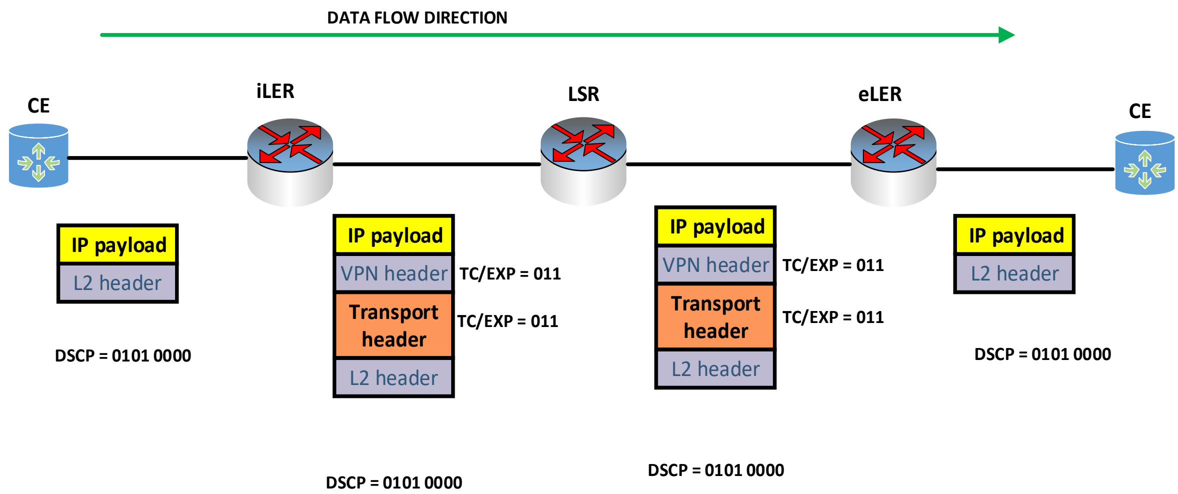


Fig 2.4 Pipe Mode TC/EXP processing. Samples principle for layer 2 packet

Uniform Mode

In uniform mode, the customer DSCP value is preserved in the MPLS network, but the first three bits are copied into the outer TC/EXP field of the MPLS header. Treatment on inner EXP values is vendor dependent. The TC field remains unchanged but the LSRs **[2]**

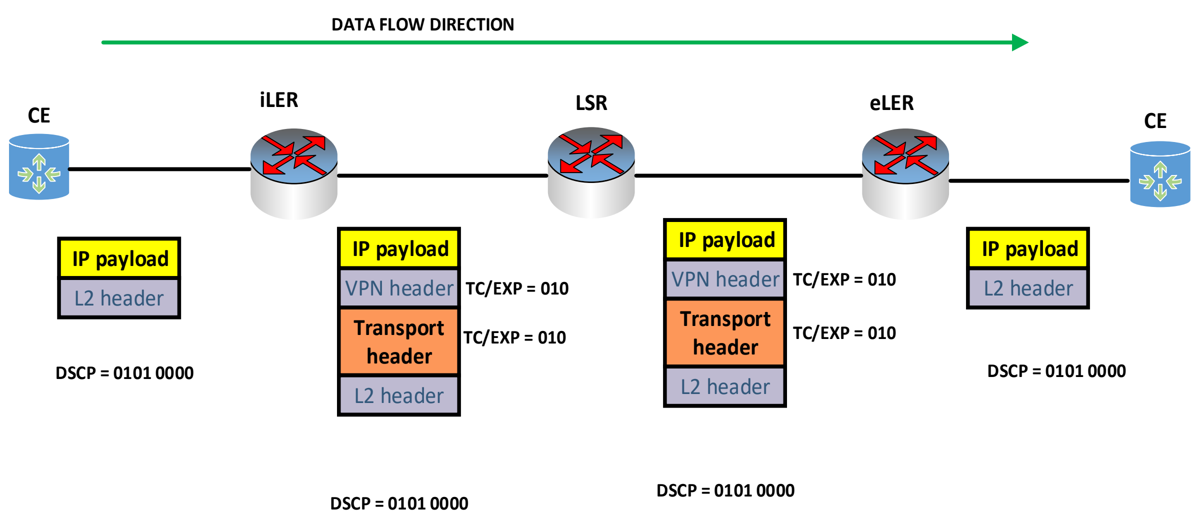


Fig 2.5 Uniform Mode TC/EXP processing. Samples principle for layer 2 packet

Time-To-Live (TTL) – This is made of the last 8 bits of the MPLS header. it takes values between 0-255. It is used for loop prevention purposes. The value in a packet is initially set to 255 and decrease by each router on receiving the packet as it travels through the network. If the value eventually reaches zero, the packet is discarded. It can also be used for path tracing. As with Traffic Class, there are two ways in processing TTL in MPLS:

- Pipe Mode.
- Uniform Mode.

Pipe Mode.

Again, in pipe mode, the TTL value set in the TTL~~C~~ field is independent of~~n~~ the TTL value in the IP header of the customer traffic. In the case of l2VPN, the customer's frame (layer header +IP payload) are encapsulated in MPLS header thus the TTL value in customer's IP header is unseen and remains unchanged by the MPLS network. The MPLS Transport and VPN header TTL are initially set to 255 at the iLER. The transport header TTL decrements at each LSR whiles the VPN header TTL remains intact as the packet is forwarded to the eLER. **[2]**

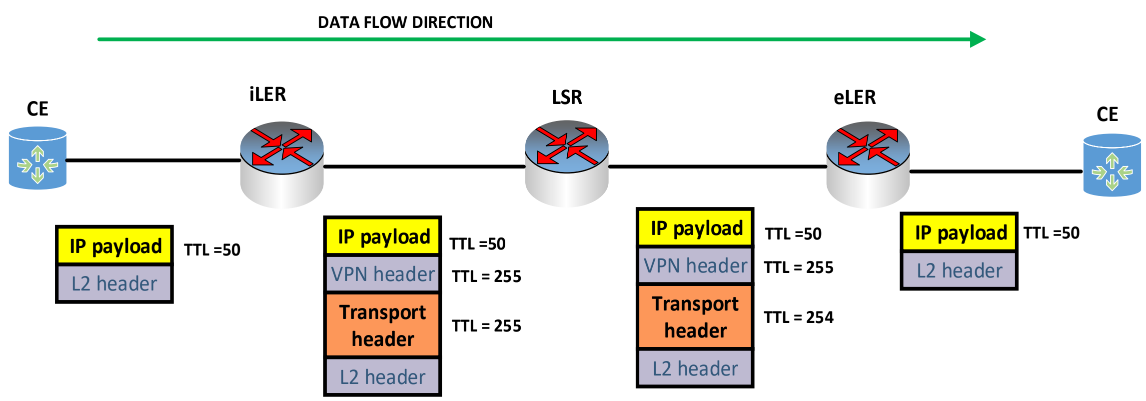


Fig 2.6 MPLS Pipe Mode TTL processing for layer two VPN (L2VPN) service

For L3VPN the, The TTL of the IP packet that is received by iLER from the customer node is decreased by one. The packet is then encapsulated in MPLS headers with the TTL field of the VPN header set to the value after decreasing the IP header TTL. The outer (transport) MPLS header TTL is set to 255. The inner TTL values remain unchanged the LSRs, but the TTL in the outer MPLS header is decreased boy one by each LSR it switched the packet. The eLER again decreases the TTL value in the IP header by one before forwarding the packet to the customer node. **[2]**

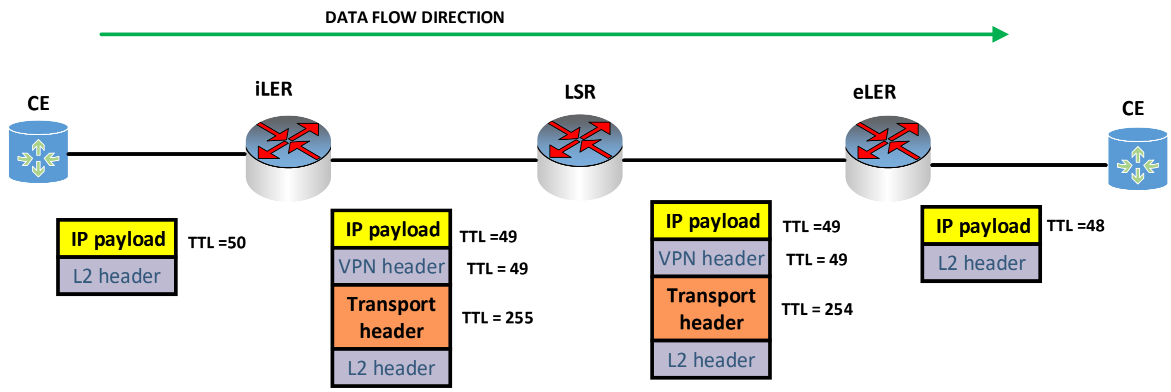


Fig 2.7 MPLS Pipe Mode TTL processing for layer three VPN (L3VPN) service

Uniform Mode.

When the iLER receives an IP packet from a customer it decreases the TTL by one then copies the resultant value onto the MPLS header TTL. The MPLS transport header TTL is decremented by one at each LSR as well as the eLER. The eLER copies the resultant MPLS TTL onto the IP TTL then forwards the packet to the customer. **[2]**

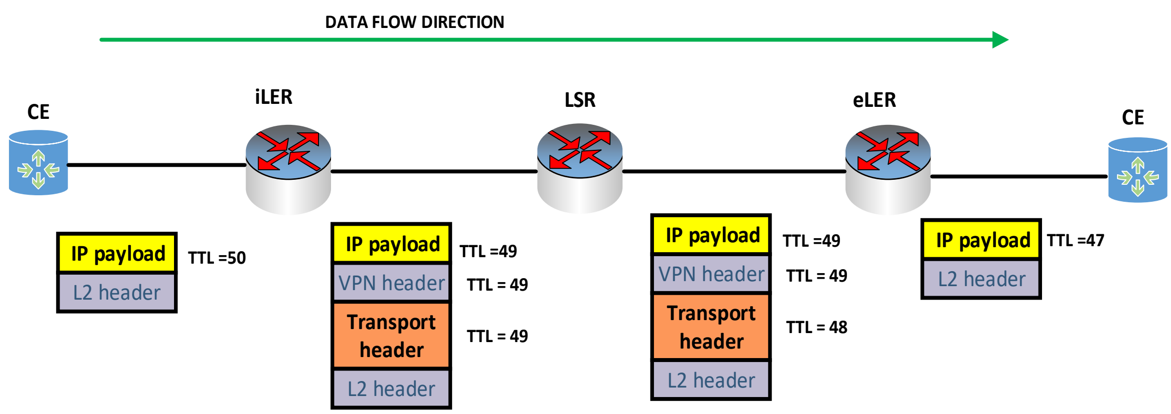


Fig 2.8 MPLS Uniform Mode TTL processing

2.4 MPLS LABEL IMPLEMENTATION

There two modes of implementing MPLS labels - Frame mode and Cell mode. MPLS label value is carried in MPLS header inserted between layer 3 header and layer 2 header. Thus this MPLS header is sometimes called shim header or layer 2.5 header. In cell mode, MPLS label information may be carried in ATM VPI/VCI cells or Frame Relay DLCI fields. [2]

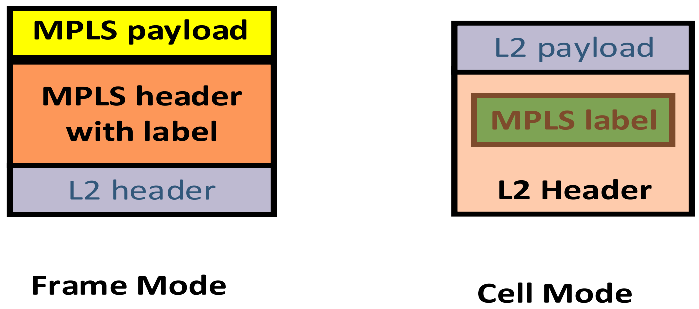


Fig 2.9 MPLS label Implementation - Frame and Cell Modes

2.5 MPLS CONTROLE PLANE OPERATIONS

MPLS Operation can be categorized into control plane and data plane. The control plane is responsible for distributing label bindings for a given FECs (Forward Equivalence Class) among MPLS speakers. The logical connection of these labels forms a label switched path (LSP) for a particular FEC. FEC classifies a group of packets such that they are forwarded along the same path with the same forwarding treatment. Simply put FEC is an IP subnet and its subnet mask.
The data plane aspect of MPLS is responsible forwarding data destined to a given FEC along the established label switched path (LSP) for the FEC.
Dynamic MPLS transport Label distribution is done mainly by the following protocols.

1) Label Distribution Protocol (LDP). LDP was developed solely for distributing MPLS label.
2) Resource Reservation Protocol-Traffic Engineering RSVP-TE. RSVP-TE existed before the advent of MPLS. It was extended distribute MPLS label thus taking advantages of its traffic engineering capabilities.
3) SPRING (Source Packet Routing in Networking).

Although these above-mentioned protocols do the actual label distribution, they rely on a Routing protocols such as IS-IS and OSPF for the distribution and maintenance of network reachability information (FECs). An MPLS router performs a label binding for a FEC after it has installed the FEC in its routing table and forwarding information Base (FIB).
3) Border Gateway Protocol- Label Unicast (BGP-LU). BGP-LU is an extension to BGP to distribute MPLS label along with the prefix it is advertising. This will form the inner layer of Seamless MPLS transport that will be discussed later in this document. The outer transport layer could be formed from LDP or RSVP-TE.

Fig 2.10 below will be used as a reference for further discussion of MPLS control and Data planes

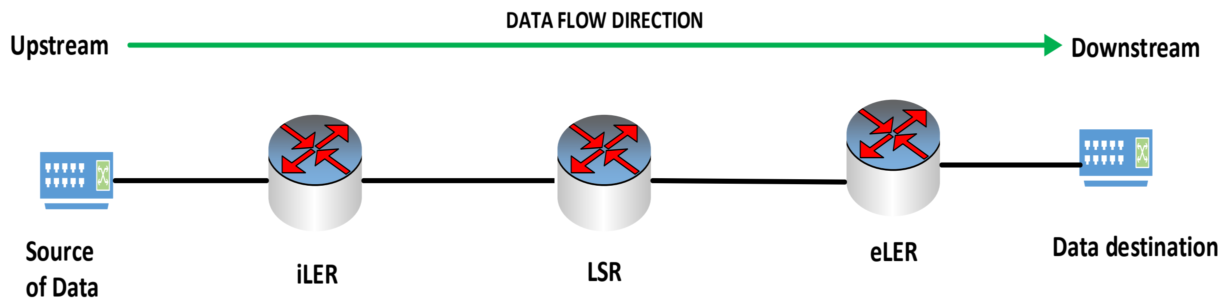


Fig 2.10 MPLS data and control plane directions

Routers which are near the source of the data are known as Upstream routers. In Fig 2.1 the iLER is an upstream router for the LSR and eLER.
Those routers closer to the data destination are called downstream routers. Likewise, LSR and eLER are downstream routers with respect to iLER.
Data flows from upstream to downstream, but MPLS labels are signaled from downstream to upstream except in special case in Multicast MPLS LSP establishment.

2.5.1 Label Distribution Modes

Multiprotocol Label Switching Architecture [RFC 3031] specifies two modes to distributes label mappings (label bindings) for prefixes in an MPLS enabled network. These modes are:

1) Downstream Unsolicited
2) Downstream on demand.

2.5.1.1 Downstream Unsolicited (DU) Mode

An LDP enabled router distributes a label binding for its known FECs to its MPLS peers without being asked to do so. It advertises FECs regardless of whether its MPLS neighbors need the FEC or not**. [2] [12]**

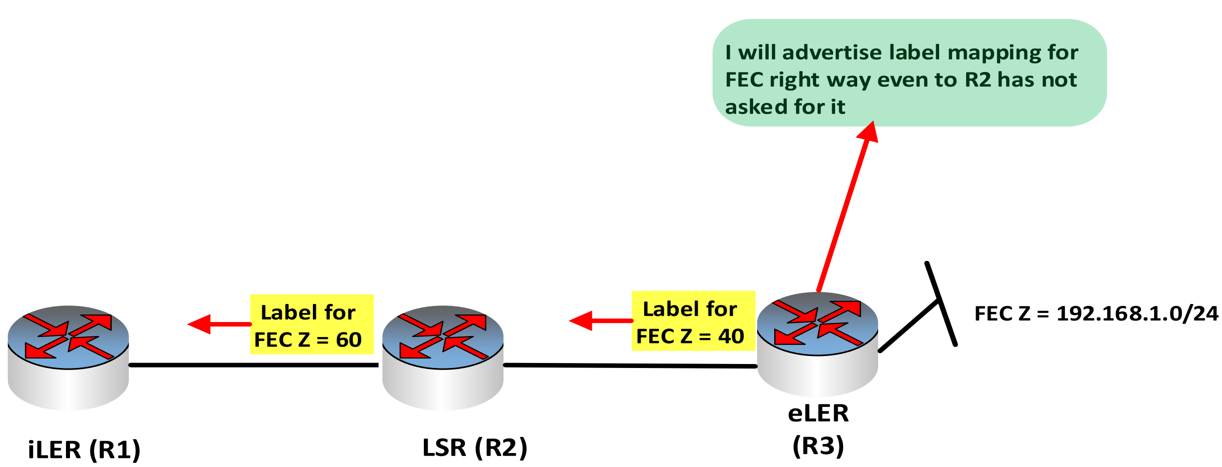


Fig 2.11 MPLS routers operating in Downstream Unsolicited (DU) Mode.

In fig 2.11 R1, R2 and R3 have be provisioned to work in LDP DU mode. After MPLS peering has been established by say LDP, R3 generates a label value of 40 for its prefix Z, allocates the label locally in its label binding table. R3 then advertises this label to R2 right away, without R2 explicitly asking for it.
R2 upon receiving this label binding from its peer R3 verifies if the FEC exists in its RIB. If it does R2 installs the label in its label binding table (FIB and LFIB).
Router R2 now knows that it needs to send MPLS packet with a label of 40 to router R3 for the destination FEC Z.
Router R2 also generates a local binding with label say 60, allocates it in its local binding table and distributes it to router R1.
Router R1 receives the label binding for router R2 verifies if the FEC exists in its RIB. If it does R2 installs the label in its label binding table (FIB and LFIB).

2.5.1.2 Downstream on Demand Mode (DoD)

An LDP enabled router distributes label bindings for FECs to its MPLS peer only if the peer explicitly requests for it. **[2] [12]**

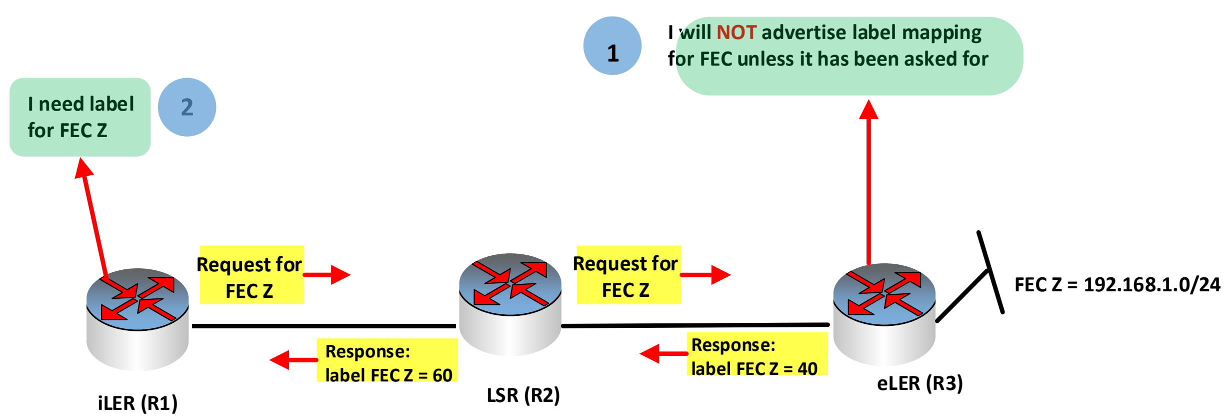


Fig 2.12 MPLS routers operating in Downstream on Demand (DoD) Mode.

In fig 2.12, R1, R2 and R3 are operating in LDP Downstream on Demand mode. R3 ~~will not~~ will not advertise a label for FEC Z unless an upstream router explicitly demands it. Assuming router R1 now need to establish a transport tunnel for FEC Z, it makes an explicit request downstream for a label binding for FEC Z.
Router R2 forwards the request to router R3 whicho is the owner of FEC Z.

Router R3 responds to the request from router R1 by adverting a label (40) mapping to

router R2.
Router R2 installs label 40 in its table, generates a local label with value 60 and advertise it to router R1.
Once router R1 receives the label binding the Label Switched Path (LSP) tunnel is formed.

2.5.2 Label Distribution Control Modes

Two modes (as specified in RFC 3031) that defines the order in which LSRs generates and distribute label mappings for prefixes (FEC) are:

1) Ordered Control
2) Independent Control

Ordered Control Mode – An LSR only distributes a label for FEC for which:

i) it i~~t~~s owner for that FEC
ii) or it has already received from its next-hop a label for that FEC

This ensures loop-free networks where LSRs only distributes labels for FECs associated with valid routes. It also makes traffic follows the desired path with specified set of properties such as paths with the specified amount of bandwidth, QoS etc

Independent Control Mode – An LSR distributes label bindings for FECs it knows about to its upstream peers without waiting to receive a label from downstream LSRs that own the FECs. **[2] [12]**
With Independent Control, LSRs May begin forwarding labeled packets before the LSP is completely established which leads to speedy convergence but may risk packet drops, loops or packets may follow an undesired path. **[2] [12]**
Another disadvantage of Independent Control mode is that, when used with LDP DoD and access static routing, would prevent the access LSRs from propagating label binding failures along the access topology. This hinders upstream LSRs from being notified about the downstream failure, therefore cannot switch to backup paths even if such alternate paths exist.

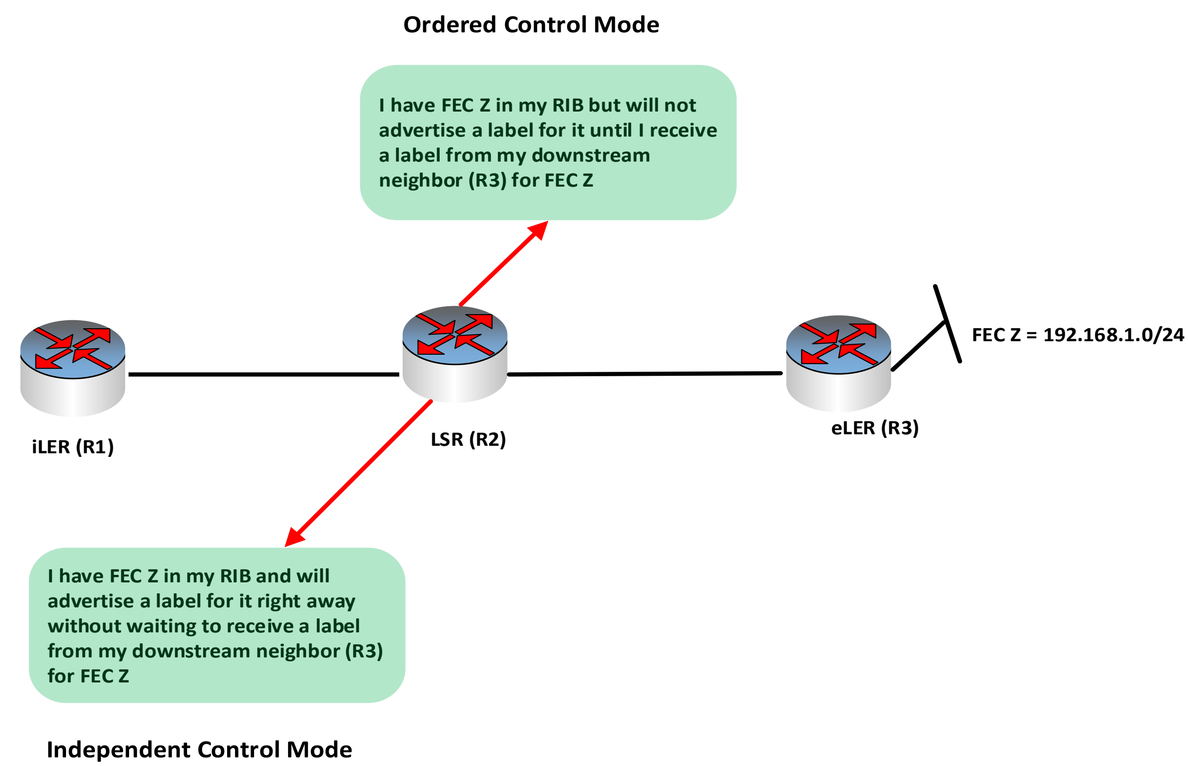


Fig 2.13 MPLS routers operating in ordered or independent control Mode.

2.5.3 Label Retention Modes

RFC 5036 following RFC 3031 defines two ways to retain the received label bindings in an LSR

These are:

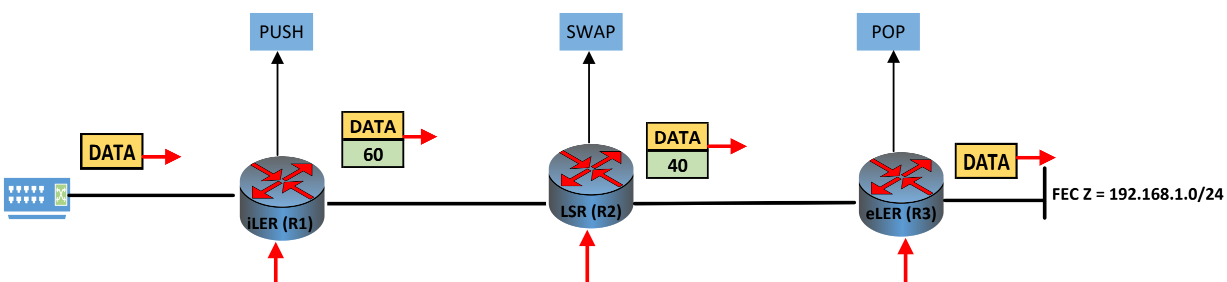
1) Conservative label retention mode – An LSR verifies the labels it receives from its peers and only stores the valid labels in its label tables (LIB). **[12]** If the LSR is operating in Downstream on Demand (DoD) mode, it will request label mappings only from the next-hop LSR per routing table, therefore preventing the LSR from requesting label mappings for any alternative (backup) routes that are not used for forwarding. Because of this the LSR cannot make use of local protection schemes that depends on the use of alternates next-hops. For example IP Loop Free Alternative Fast ReRoute (LFA FRR) and backup static routes

   Only the labels that are needed for delivering traffic are stored and maintained hence suitable for use in access LSRs where label space is limited such as in Cell Site Routers (CSRs) and DSLAMs.
   On the other hand, Conservative label retention mode is slower to react to routing changes as a new label must be received for the new route.

2) Liberal label retention mode – LSR stores and maintain all labels it receives from its peers in its LIB. **[12]** When the LSR is operating in DoD mode with liberal label retention mode, the LSR might choose to request label mappings for all known prefixes from all peer LSRs, store and maintain them for faster restoration after network failure.
The advantage of Liberal label retention mode is that; it can react quickly to routing changes because labels already exist in the LIB. The disadvantage is that it consumes router resources (memory space and CPU processing) as it retains unrequired labels.

2.6 MPLS DATA PLANE OPERATIONS

Fig 2.14 below is a conceptual view of the LFIBs of R1, R2 and R3 populated with labels distributed in either Downstream on Demand mode or Downstream Unsolicited mode. When data arrives at router R1 from a customer, Router R1 Pushes label 60 onto the unlabeled packets destined to FEC Z then forward the encapsulated packet to R2. Router R2 on receiving the packet, swaps label 60 with label 40 then forwards the packet to Router R3. Router R3 knowing that it is the egress router for packets destined to FEC Z pops (removes) the MPLS header from the packet and then forwards the unlabeled packet to the appropriate destination.



R1 Label Forwarding Table (LFIB)			
FEC	Ingress Label	Egress Label	Next Hop
Z		60	R2

R2 Label Forwarding Table (LFIB)			
FEC	Ingress Label	Egress Label	Next Hop
Z	60	40	R3

R3 Label Forwarding Table (LFIB)			
FEC	Ingress Label	Egress Label	Next Hop
Z	40		

Fig 2.14 LFIB of R1, R2, and R3

2.6.1 SPECIAL MPLS LABELS.

Label Value Zero (0) - represents IPv4 Explicit Null.
Label Value One (1) - represents router alert
Label Value Two (2) – represent IPv6 Explicit Null
Label Value Three (3)- represents Implicit Null.

2.6.1.1 Implicit Null Use case.

In Fig 2.15 if router R3 wants to save some processing resources on MPLS label lookup operations, it can ask the penultimate router (R2 in this case) to Pop only the outer MPLS transport label before sending to packet to it. Inner labels such as VPN labels are left intact by R2. R3 expresses this desire to R2 by advertising label value of 3 for FEC Z to router R2. Although R2 has 3 label as the egress label for FEC Z, it does not encapsulate the outgoing packet with MPLS label 3 since it pops the transport label.

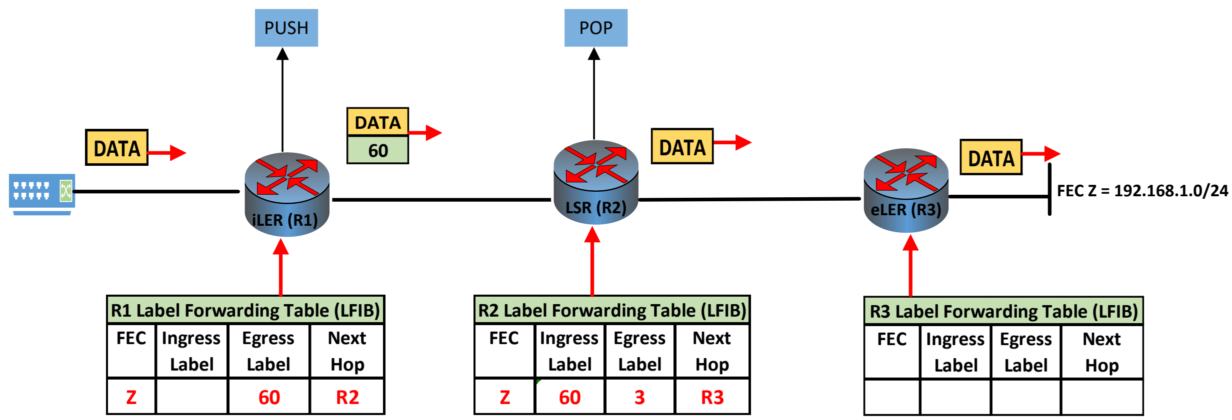


Fig 2.15 Penultimate Hop Popping

2.6.1.2 Explicit Null Use case

Penultimate hop popping on R2 save some resources on R3, nonetheless QoS information carried in the EXP field of the Transport header is lost between R2 and R3 as a consequence of R2 popping the transport label. If router R3 still wants to save processing resources, it sends to R2 explicit null label value 0 for IPv4 packets and 2 for IPv6 packet. This time R2 does not pop the outer label but rather swaps label (60) it received from R1 with label 0 so that the EXP bits remain intact. R3 on receiving a packet with label 0 immediately pops it without doing a label lookup and records the EXP bits if any for QoS processing.

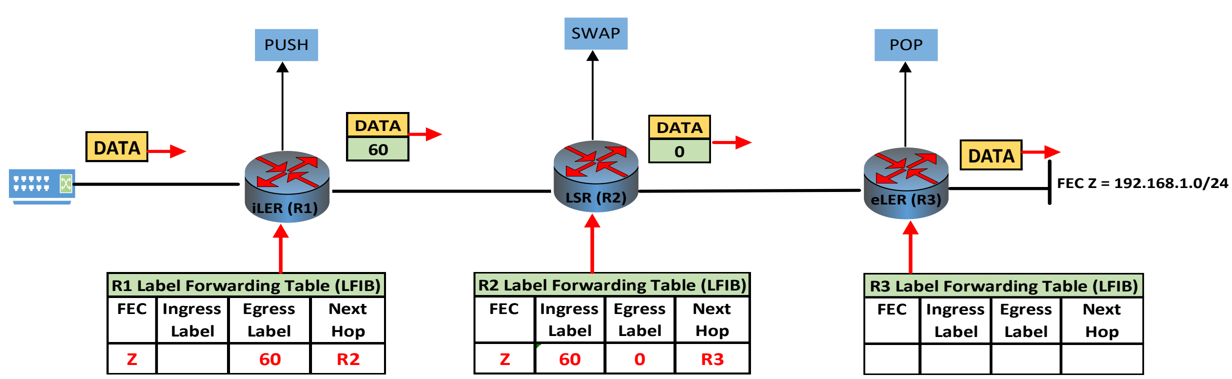


Fig 2.16 MPLS Explicit null operation

2.6.1.3 Label Value One (Router Alert)

A p~~P~~acket received with label value one (1) instructs the router to process the packet internally by its control plane. This packet is meant for operation Administration and Maintenance (OAM) purposes.

There other MPLS special label values which are not discussed in this document.

2.7 MPLS LABEL SPACE

There two ways the MPLS protocol assigns labels to FEC: Per Platform and Per Interface.
Per Platform Label Space allocates a single label per FEC per router (platform) irrespective on which interface the label is sent out of the router.
Per interface label space allocates individual labels per FEC per interface. Each outgoing interface has its own unique label. Per Interface Label space assignment consumes more resources than Per Platform Label Space assignment. Per Interface Label Space is normally used in conjunction with layer 2 protocols such ATM and Frame relay

CHAPTER 3

3.1 SEAMLESS MPLS END-TO-END TRANSPORT LAYER PROTOCOLS

This chapter will discuss two of the transport protocols that are used to implement Seamless MPLS Mobile Backhaul. These protocols are namely:

1. Label Distribution Protocol (with emphasis on Downstream on Demand mode).
2. Border Gateway Protocol Label Unicast (BGP-LU).

The Seamless MPLS transport layer could adopts of a 2-layer transport hierarchy.
The outer transport layer can be established with either LDP, RSVP-TE or SPRING to create an intra area/region MPLS LSP. This tunnel only switches MPLS packet within the area.
The inner transport layer is established with BGP-LU. This provides end-to-end LSPs between domains. BGP is chosen for this purpose because it can provide a very scalable architecture, which can support up to 100,000 routers.
This 2-layer transport hierarchy design leverage on scalability introduced by the splitting large networks into multiple smaller regions whiles at the same time offering seamless end-to-end MPLS. This allows us to confine IGP and MPLS LSP (outer transport) signaling information in their respective domains without crossing over to other regions thus improving scalability by reducing the size of MPLS states and routing/forwarding tables in routers.

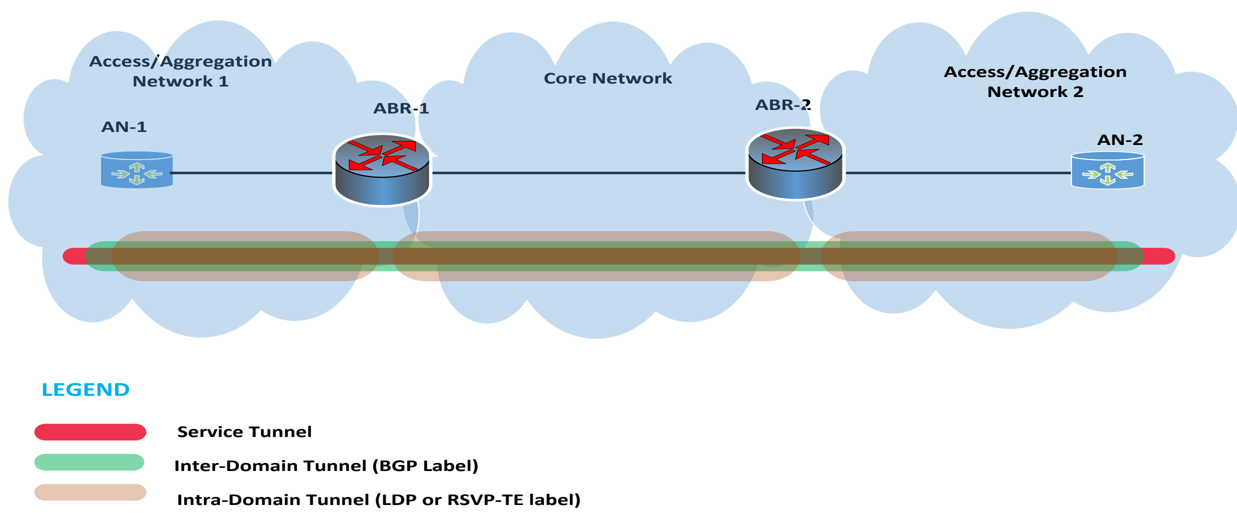


Fig. 3.1 Seamless MPLS network Architecture

3.2 LABEL DISTRIBUTION PROTOCOL (LDP) OPERATIONS

To form intra-area LDP LSP, LDP enabled routes exchange messages to become peers in order to advertise label mapping for their FEC which is usually the router ID in the form of /32 loopback address. LDP messages are comprised of:

1) Discovery messages – Hello messages sent by each LDP enabled router over transport layer protocol-UDP, to automatically discover and maintain LDP adjacency.

2) Session Messages- These massages are used to create, maintain and tear a TCP session between LDP peers. TWO LDP routers which have formed ~~a~~ neighbor relationships proceed to create a single TCP session on port 646 irrespective of the number of links between them. This ensures reliable delivery of MPLS labels. Successful TCP session makes the two routers LDP peers and is~~are~~ now ready to exchange labels. Keepalive messages are sent to ensure the TCP session is alive.
3) Advertisement Messages. These messages are used to distribute, modify and remove MPLS labels mappings for FECs over the established TCP session. An LDP router operating in Downstream on unsolicited mode will send labels to its peers without been requested for, thus forming a full mesh of LSP among all the LDP enabled routers in the network. On the other hand, if the router is operating in Downstream on Demand mode (DoD), it will wait till it receives an explicit request for the label from its peer before advertising a label mapping for a FEC in question. In DoD LSP is only formed between the requesting router and the owner of the FEC. Assuming routers R1, R2 and R3 are operating in LDP DoD mode, R3 being the downstream router and owner of the FEC (192.168.1.0/24) will not advertise a label mapping (binding) for the FEC until it receives and explicit request from an upstream router (R2 or R1).

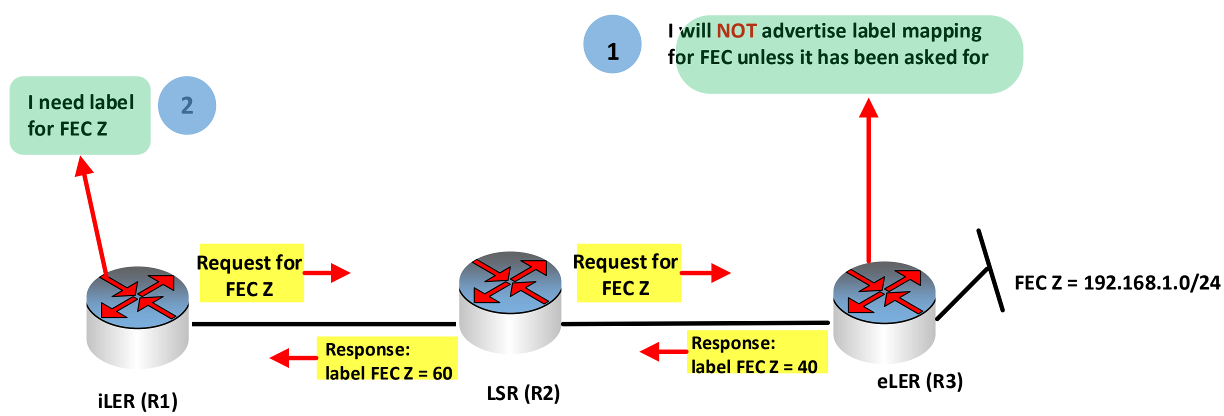


Fig. 3.2 LDP Downstream On Demand Mode (LDP DoD)

4) Notification Messages- LDP routers inform each other of errors and other events with these messages. When a router encounters error situations pertaining to LDP session probably caused an interface going down, it terminates the LDP TCP session over that interface and removes all LDP label bindings learnt via that session.

To make it easy to add features to LDP, its message structure is made of Type-Length-Value (TLV) encoding scheme.

3.2.1 Hello Message Structure

Version = 1
LDP-id = 2.2.2.2:0
Message Type: Hello(0x100)
Link Hello (Type 0)
Hello Timeout = 15s
Transport Address = 2.2.2.2
Configuration Seq.# = 1072873351

Fig 3.3 LDP Hello Message structure **[12]**

The basic components of LDP Hello messaged needed for LDP operation are LDP-Identifier (ID), Transport Address, Hello Timeout, and Configuration Sequence.

LDP-ID is a 6-byte field that uniquely identifies the LDP router and its label space. The first 4 which must be globally unique is the router ID, and the last 2 bytes denotes the label space used by a particular LDP implementation. For per platform label space the last 2 bytes are set to zero. For per interface label space the last 2 bytes contains specific values to differentiate the different LDP session over each interface. Examples 2.2.2.2:0 – for per platform label space and 2.2.2.2.4111 - for per interface label space.
Transport Address – The TCP session discussed above is formed with the peer's transport address which could be an interface or loopback IP address. Each router sends the IP address it wants the TCP session to formed with and advertises it via the hello message.
Hello, Timeout- This parameter defines the number of hello messages missed (expressed in time) before declaring the LDP adjacency down. Two routers (say R1 and R2) trying to form LDP adjacency negotiation on this value. If R1 hello message has timeout value of 20 seconds and R2 hello message has timeout value of 40 seconds, the lowest value, 20 seconds will be used by both routers as their timeout value.
Configuration Sequence – router uses this parameter to verify configuration changes in the router that sent the hello messages

3.2.2 LDP Discovery Process

LDP discovery hello messages can discover neighbors that are directly or indirectly connected at the link level.

Discovery of Directly connected neighbor is known as Basic Discovery, and the discovery of indirect neighbor is also known is Extended discovery. **[12]**

3.2.2.1 Basic Discovery

In this process LDP link hello messages are sent to all router multicast destination IP address 224.0.0.2 and UDP port 646. If a neighbor relationship gets successfully formed, periodic hello messages are sent between peers to keep the relationship alive.

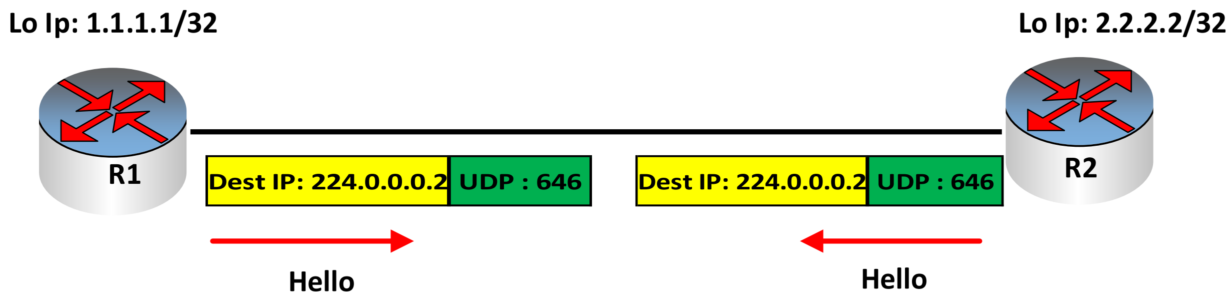


Fig 3.4 Basic (Link) LDP discovery process

3.2.2.2 Extended discovery

In this process, LDP targeted hello messages are sent to unicast destination IP address and UDP port 646. Again, periodic hello messages are sent between peers to keep the relationship alive. **[12]**
LDP must be configured with an explicit unicast IP address to use as the destination for the hello messages.

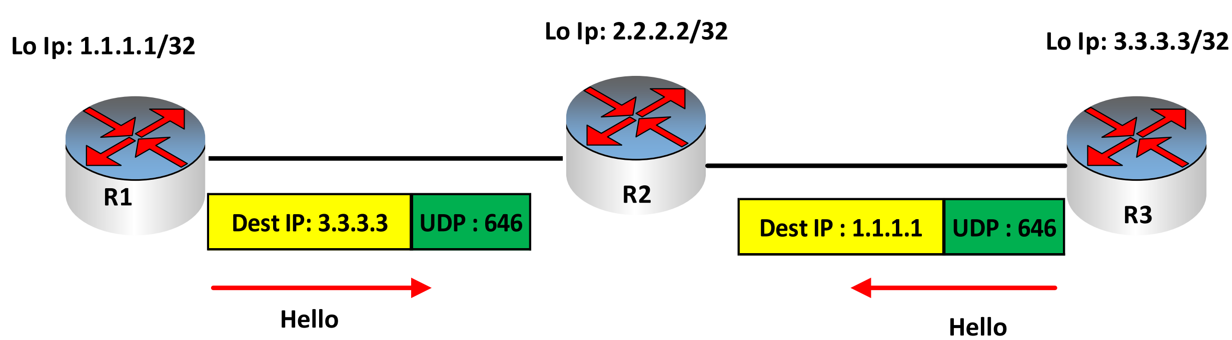


Fig 3.5 Extended (targeted) LDP discovery process

3.2.3 LDP Session Establishment

Now that LDP adjacency has been formed between a pair of routers say R1 and R2 in Fig. 3.6 below, the router (R2) with the highest transport address (2.2.2.2) initiates a

TCP connection between the pair by sending session request through init message to the transport IP and well-known TCP port 646 of its neighbor, R1 in this case. R2 chooses any available TCP port as its source port from the dynamic port range (49,152 – 65,535) stipulated by IANA. The init messages contains vital parameters such as LDP-D of both the sender and the receiver, Keep-alive timeout period and LDP version. The transport addresses here are those exchanged in the LDP hello messages. After successful establishment of the TCP connection, again the router (R2) with the highest transport IP address assumes an active role and initiates LDP session to its counterpart (R1) with the lower transport IP address. The router with the lower transport IP address then plays passive role. A session is considered successful established when a router receives a response to a Keep-alive massage it previously sent. **[2][12]**

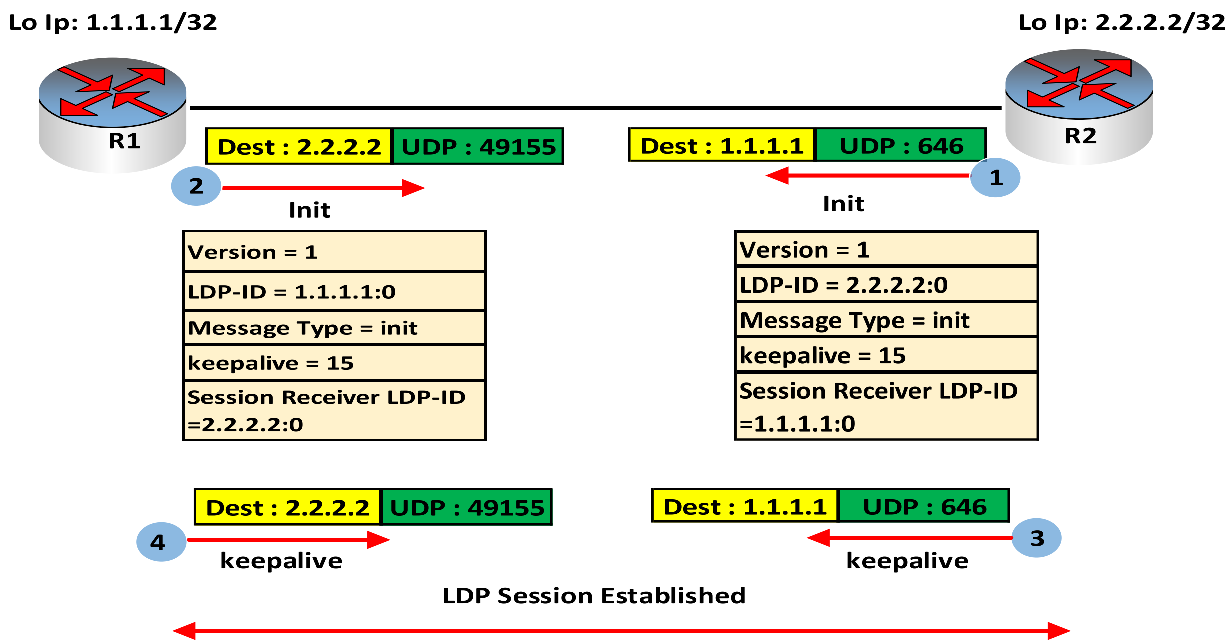


Fig. 3.6 LDP TCP session establishment.

The LDP session that is formed as result of Basic discovery is known as Link LDP Session. Link LDP Session isare formed between directly connect LDP neighbors and are used to signal hop-by-hop tunnel labels.

The LDP session that is formed as result of extended discovery is known as Targeted-LDP Session. Targeted-LDP Session isare normally created between indirectly connected LDP neighbors and are primarily used to signal layer 2 VPN service labels.

3.3 LDP DoD Label Management

3.3.1 Label Request Message Procedure

0	1 15	31
0	Label Request (0x0401)	Message length
Message ID		
FEC TLV		
Optional Parameters		

Fig 3.7 Label Request Message structure **[12]**

LDP label request message is composed of:
i) Label Request (0x0401) – this field tells the receiving router the type of the message (in this case the message type is Label Request. Other types of message are Label Abort Req (0x0404, Label Withdraw (0x0402) and Label Release (0x0403).
ii) Message length – specifies the length of the message sent.

iii) Message ID – A 32-bit value that uniquely identifies the particular request message sent. A message ID used in a particular label message request should not be used in subsequent label message requests until the LSR receives a response for the request containing a label and the message ID thus completing the label request transaction.
iv) FEC TLV- Denotes the FEC for which a label mapping (binding) is being requested for.
v) Optional Parameters- This field contains zero (0) or more Hop Count TLV or Path Vector TLV. Hop Count list the active total number of Label Switched Router hops the request massage traverses to form the LSP. Path Vector lists the LSRs along the LSP that will be created by the Labe Request Message.

The label request message is sent by an upstream router (R1) to a downstream router (R2) to request for a label mapping for a particular FEC if any of the conditions below are met:
1) If the LSR notices a new FEC in its forwarding table and has no corresponding label mapping in Label Information Base able (LFIB), and also the next hop for the FEC in question is an LDP peer.
2) If the next hop to a given FEC changes.

3) if the LSR receives label request from an upstream LDP peer and it has no corresponding label mapping in Label Information Base able (LFIB), and also the next hop for the FEC in question is an LDP peer. The scenario applies to router R2 in fig 2.x. If the router that owns the FEC receives the label request message, it must respond with a label mapping (binding) for the given FEC. If the LSR cannot fulfill the label request, it must send a notification message indicating why the label request cannot be satisfied. An LSR may fail to honor a label request message under any of the following Conditions:
1) No Route- if the router receives a label request message that contains a FEC element of which it has no route to.

2) No Label Resources – When the label resources allocate to the LSR reaches its limit it can no longer generates label bindings. When label resources become available, the LSR must make this known to the router that made label request earlier on by sending a notification message with Label Resources status code. Whiles a router waits for a notification message with Label Resources status code it must not initiates further label request massages.

3) When the LSR detects a looping label request message.

3.3.2 Label Abort Request Message

Sometime an LSR may want to abort a previously sent label message request when for instance the next hop router for FEC it has sent label request message for changes whiles it is waiting for a response. In such a situation the LSR issues a Label Abort Request Message with regards to the FEC whose label request message needs to be terminated.

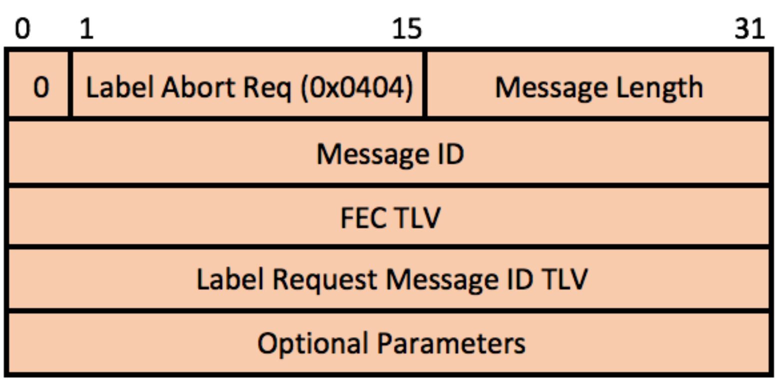


fig 3.8 Label Abort Request Message structure **[12]**

The Label Abort Request message comprises of:

i) Label Abort Request (0x0401) – this field specifies the type of the message (in this case the message type is Label Abort Request Message)
ii) Message length – specifies the length of the message sent.
iii) Message ID - A 32-bit value that uniquely identifies this particular message sent. The same message ID will not be used by the LSR until it has:

a) Acknowledgement for the abort message
b) Label binding for the label request message to be aborted
c) A notification message in response to the label request message being aborted

iv) FEC TLV – Denotes the FEC for which the Label Abort Request message is sent to abort its corresponding Label Request Message.
v) Label Request Message ID TLV- This field contains the Message ID of the Label Request message to be aborted.
vi) Optional Parameters. Label Abort Request Message has no optional parameters.

An LSR responds to Label Abort Request Message by either acknowledging or ignoring the message. LSR acknowledges Label Abort Request Message via Label Request Aborted Notification message to the sender if only it has not already responded to the Label Request message to be aborted with label binding or a Notification Message. If the LSR has already responded to the Label Request it is being asked to abort; the LSR ignores the Label Abort Request Message

3.3.3 Label Withdraw Message Procedures

An LSR will send Label Withdraw Message to its peer when a FEC is no longer valid in its RIB, or an administrator explicitly configures the LSR to no longer label switch a FEC with the label mapping being withdrawn. The peer upon receiving the label withdraw message should discard the FEC to label mapping for that particular FEC and respond with a Label Release Message.

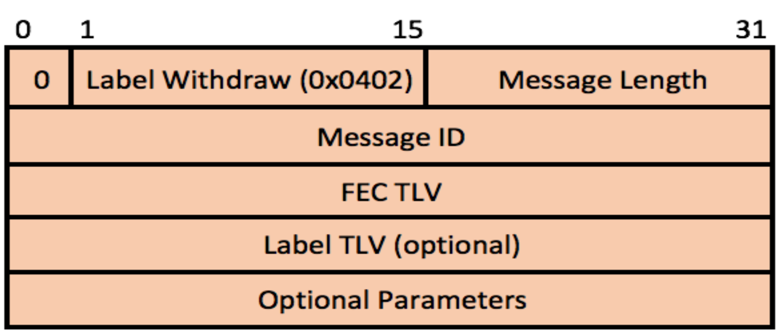


Fig 3.9 Label Withdraw Message structure **[12]**

FEC-TLV field contains the FEC for which a label is to be withdrawn.

Label-TLV if present identifies the label to be withdrawn otherwise all labels associated with the FEC specified by the FEC-TLV will be withdrawn.

3.3.4 Label Release Message Procedures

An LSR will send Label Release Message when any of the following conditions are met:

a) in response to a label withdraw message
b) When the peer that it received the FEC-label mapping from is no longer the next hop for the FEC and the LSR is operating in conservative mode.
c) Immediately it receives a FEC-Label mapping from a peer who~~ich~~ is not the next hop for the FEC, and the LSR is operating in conservative mode.

0	1 … 15	… 31
0	Label Release (0x0403)	Message Length
Message ID		
FEC TLV		
Label TLV (optional)		
Optional Parameters		

Fig 3.10 Label Release Message structure **[12]**

FEC-TLV field contain the FEC for which a label is to be released
Label-TLV if present identifies the label to be released for all FEC to which it is mapped to otherwise the LSR wishes to release all labels mappings associated with the FEC specified by the FEC-TLV.

[8]

3.3 BORDER GATEWAY PROTOCOL LABEL-UNICAST (BGP-LU)

Border Gateway Protocol (BGP) is the main protocol used today to distribute Network Layer Reachability Information (NLRI) between Autonomous Systems (AS). BGP is of two types; internal BGP (iBGP) and external BGP (eBGP). eBGP is used to distribute routing information between routers in different AS where as iBGP used to distribute routing information among within the same AS. iBGP sessions are normally established between non-directly connected peers thus making it possible to advertise network reachability information to only the routers that need them. This capability of BGP in conjunction with MPLS tunnels are used to create BGP free MPLS core networks. This enables service prodder operators to create MPLS shortcuts for IPv4/IPv6 and BGP

traffics.
BGP has also been extended making it capable of conveying multiple address family information other than just the mere IPv4 prefix/prefix-length in its update messages. An eExample of such extra information are IPv6, VPN attributes such as Route targets and VPN labels, etc. This extended version of BGP is known as Multiprotocol BGP (MP-BGP). The particular address family carried by MP-BGP specified in the Address Family Identifier (AFI) field of the Optional Parameters of BGP. A field in the Optional Capability of BGP known as Subsequent Address Family Identifier (SAFI) provides additional information about the type of the Network Layer Reachability Information. Another capability of MP-BGP that is crucial to Seamless MPLS implementation is its ability to carry MPLS label bound to the route contained in the BGP update message. This process is termed as BGP Label Unicast (BGP-LU). In BGP-LU, the BGP update message that is used to distribute a particular routing information also carries the MPLS label bound to the route itself with the SAFI set to 4**.**

3.3.1 Capability Advertisement

A BGP enabled router that has been provisioned to handle multiple routes or that uses Multiprotocol Extension to carry label binding information should use the BGP Capabilities Optional Parameter to inform its peers about this capability.

3.3.2 How BGP-LU Distribute Label Binding Information

The Network Layer Reachability Information (NLRI) carried in the BGP updates is formed as a set of one or more triplets of [length, label, prefix]. The Subsequent Address Family Identifier field of the update is set to 4 to indicate that the NLRI contains a label.

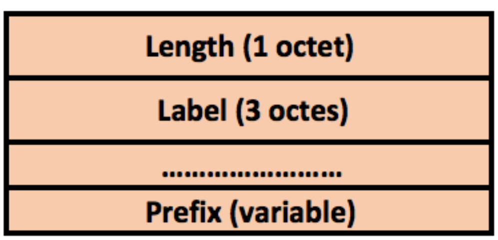


Fig 3.11 NLRI fields **[11]**

i) The Length field specifies the length in bits of the label(s) and the prefix fields combined.

ii) The label field contains the label, and it can be one or more labels depending on the number of label stacks.

iii) The Prefix field specifies address prefixes. It is followed by enough trailing bits to make the end of the field fall on an octet boundary.

The encoding above enables a single BGP update message to convey multiple routes, each with its own label.
The label(s) received for a particular route must be assigned by the next-hop LSR. When a BGP speaker redistributes the route, the label(s) mapped to that particular route must remain unchanged unless the LSR changes the value of the next hop attribute of the route to its self.

3.3.3 Label Withdrawal

A BGP Router may withdraw an already advertised route as well as the label mapping by:

i) Sending a new route and label update message with the same NLRI of the previously advertised route.
ii) Sending an update message with the withdrawn route field listing the previously advertised route.
iii) Terminating BGP session. This will withdraw all the previously advertised route.

3.3.4 Advertising Multiple Routes to a Destination

A BGP speaker can have multiple routes to the same destination if each route has a different label. In this case, if a route with a specified label is withdrawn then only the corresponding route with the corresponding label is redrawn. On the other hand, if a route is withdrawn without a label specified then only the corresponding unlabeled route will be withdrawn.

3.3.5 Forming End-to-End MPLS Transport Layer Using BGP-LU

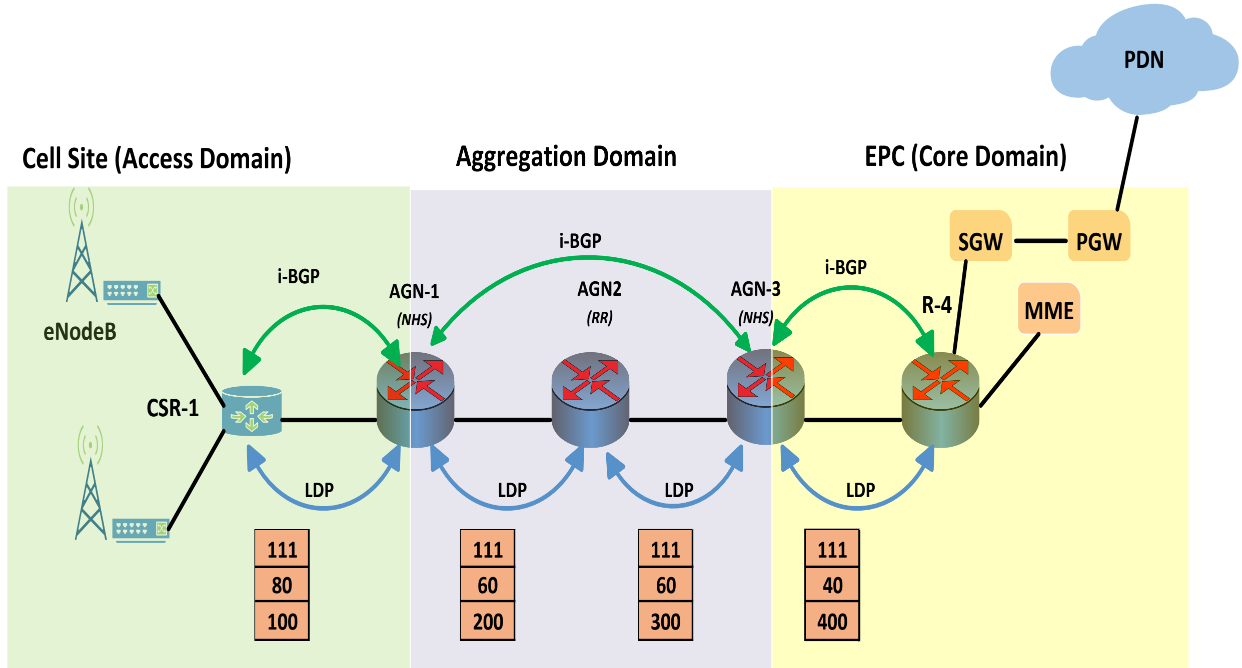


Fig 3.12 BGP-LU control and data plane operation. **[5]**

1. LDP (or RSVP) signaled LSP and i-BGP sessions are formed between the routers as shown in fig. 3.12. Also corresponding layer 2 VPN services are configured on CSR-1, and R4 carry traffic from the eNodeB to R4 and vice versa.
2. Each domain also runs a separate instance of in IGP (IS-IS or OSPF), and no prefixes in the IGP go beyond the border routers (AGN-1 and AGN-3). Again the LDP FECs are confined in their respective domains or area.
3. Router R4 distributes its loopback address (4.4.4.4/32) and label value 40 to its i-BGP peer Router R3 using BGP-LU
4. Router AGN-3 on receiving this update stores label 40 as the egress label. AGN-3 then allocates label 60 as ingress label corresponding to R4's loopback and advertises it to its other i-BGP peer router AGN-1. AGN-3 sets the BGP next hop to self. If AGN-3 receives a packet with label 60, it will swap label 60 with label 40 and forwards the packet to router R4
5. Router AGN-1 stores label 60 as the egress for MPLS packets destined to R4's, allocates label 80 as ingress label corresponding to R4's loopback and advertises it to its other i-BGP peer CSR-1. AGN-1 sets the BGP next hop to self.
6. CSR-1 receives the advertisement and stores the Label 80 as the egress label for MPLS packets destined to R4's loopback.
7. Assuming CSR-1 now has packets from the eNodeB in its VPN destined to the PDN or any element in the EPC, it first pushes the corresponding VPN label (111) on the packet. Next it pushes label 80 required to reach router R4, and lastly, it pushes a

transport label say 100 required to reach Router AGN-1. CSR-1 finally forwards the packet to AGN-1.

8. Router AGN-1on receiving the swaps the labels 80 and 100 with labels 60 and 200 respectively and forwards the packet to Router AGN-2.
9. When the packet arrives at AGN-2, it only swaps the outer label 200 with the transport label 300 required to reach router AGN-3 and forwards it to router AGN-3.
10. When router AGN-3 receives the packet, it swaps the labels 40 and 300 with labels 40 and 400 respectively and forwards the packet to Router R4

11. Router R4 being the endpoint of the MPLS tunnels pops all the MPLS labels and places the unlabeled packet into the corresponding VPN. The eventually routed to the SGW.

CHAPTER 4

4.1 SEAMLESS MPLS ARICHITECTURES DESINGS

To meet the scalable requirements of Seamless MPLS network design, the network is split into multiple access and aggregation domains and a single core domain.

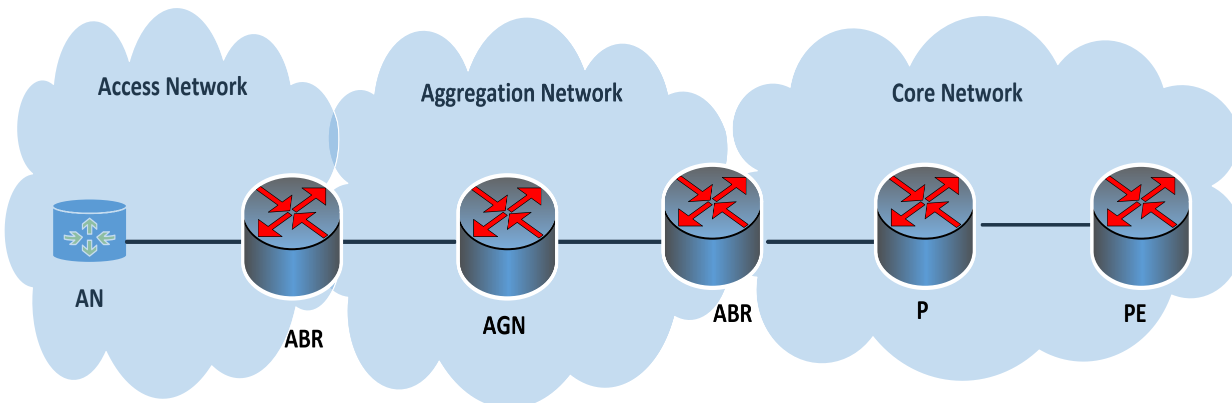


Fig. 4.1 Splitting of large network into smaller domain to enhance scalability

4.1.1 The Access Domain

The access domain serves as the interface to clients or customers. It is here that services are normally created in seamless MPLS architecture. Both Layer 3 and layer 2 services from eNodeB and other customers' equipment enters the service provider Cell site routers via Ethernet (dot1q, QinQ or null encapsulation), E1(TDM), etc. Access nodes such as cell site routers are usually far more than other nodes in the other regions. Hence their cost must be kept low as much as possible. As a result, access nodes (cell site routers) with regards to MPLS capabilities may have limited capabilities. For instance, an access node may not support BGP or may have low memory and processing power.

4.1.2 Aggregation Domain

The aggregation domain's role is to:

I. Aggregate all the traffic from the access nodes.
II. Provide the capabilities required to scale the simple access nodes connected to it.

Aggregation domains should not connect to each other but only to the core and access nodes. The Nodes in this domain must be powerful enough with regards control plane and forwarding scalability.

4.1.3 Core Domain

This domain interconnects all the aggregation domains.
The Nodes in this domain must also be powerful enough with regards control plane and forwarding scalability.

Seamless MPLS can be modeled in various ways with regards to IGP routing and MPLS label protocols. Below are some of the various models that Seamless MPLS networks.

4.2 Model 1

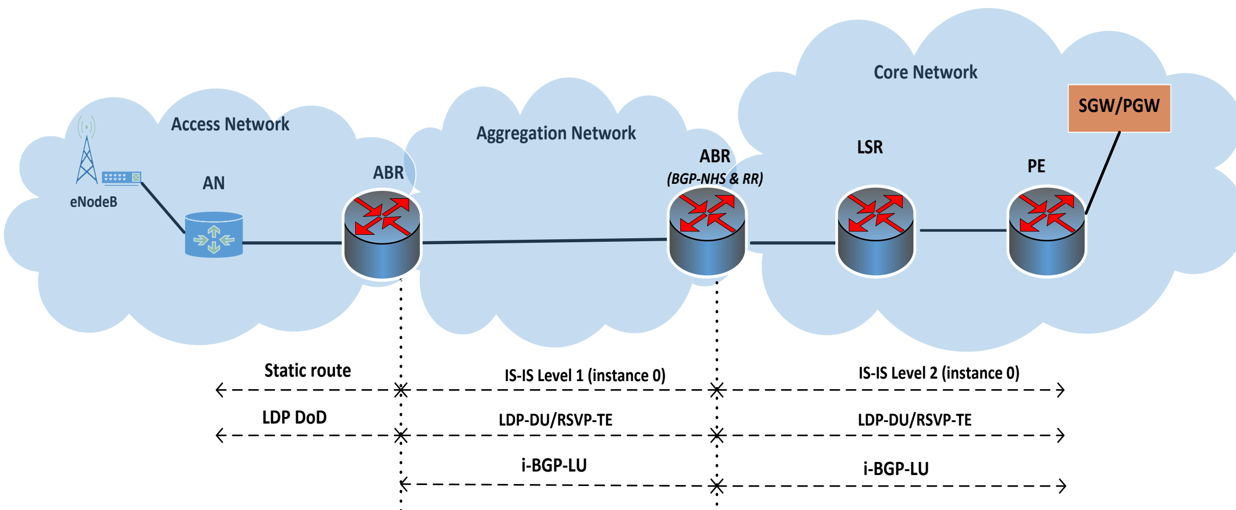


Fig 4.2 Seamless MPLS Architecture for Low-End Access Nodes

This architecture is suitable for a network where the access nodes are Low-End MPLS nodes such as DSLAMs.

4.2.1 Intra-Domain Routing

Considering the limited capabilities of some access nodes, static default route is configured from the access node to its immediate downstream router and static route from the immediate downstream router to the loopback address (/32 prefix) of the access node as illustrated in Fig 4.2 above.
Both the aggregation and core Domains operate in the same IS-IS instance with the aggregation domain mapped to IS-IS level one and the core domain mapped to IS-IS level 2. The core domain contains all the prefixes from the aggregation domains.

4.2.2 Inter-Domain Routing

Inter-domain MPLS LSP connectivity utilizes BGP-Label Unicast (RFC 3107). BGP-LU distributes inter domain routing information whiles at the same time it distributes MPLS

transport labels for the FECs it advertises. These labels form the inner End-to-End Seamless MPLS transport layer.
Also, remote Access nodes loopback addresses are leaked from IS-IS level 2 into IS-IS Level 1 (aggregation domain) if the Access nodes connected to the aggregation domain provide services to the remote Access nodes.

4.2.3 Inter-Domain MPLS LSP

Inter-domain (Aggregation and core) MPLS LSP is formed from labels distributed by BGP-LU. These labels create the inner End-to-End Seamless MPLS transport tunnel. The ABR acts as BG Next Hop (NH) for BGP routes towards the core, triggering a new label allocation that stitches the labels from a previous segment. One node may be configured as Route Reflector (RR) for the various nodes in the core domain. The aggregation domain may also host a RR.

4.2.4 Intra-Domain MPLS LSP

LDP in Downstream Unsolicited mode or RSVP-TE is used to distribute label mappings for all the loopback addresses of all the nodes in aggregation and core domains. The resulting LSP formed will be utilized as the outer Seamless MPLS transport layer.
The access node and its immediate downstream router use LDP DoD mode with Ordered label distribution control and Liberal label retention mode (for fast convergence and minimal Labels in the access nodes).
With LDP DoD, the access Node will request a label for a prefix when an MPLS session is required for that prefix. Thus, the access node installs only MPLS labels to whom it provides services.

LDP-to BGP FEC stitching (redistribution) is performed at the aggregation node (immediate downstream router). **[6]**
The AGN translates /32 FEC that it learns from LDP neighbor (AN) into BGP labeled route and redistribute it into BGP.
The AGN also translates /32 BGP labeled route that it learns from BGP neighbor into LDP FEC and redistribute it into LDP.
When the AGN receives MPLS packet from the access node, it swaps the LDP label with BGP label and pushes another label (from LDP or RSVP) on top of the BGP label to reach the BGP next-hop.
When the AGN receives MPLS packet destined to the access node, it pops the outer (from LDP or RSVP) label and swaps inner BGP label with LDP label before forwarding the packet to the access node.
LDP Extension- aggregate-prefix-match should be configured on the Access Node, to enable it resolve the static default route to the LDP FEC it receives from the PE.

4.3 Model 2

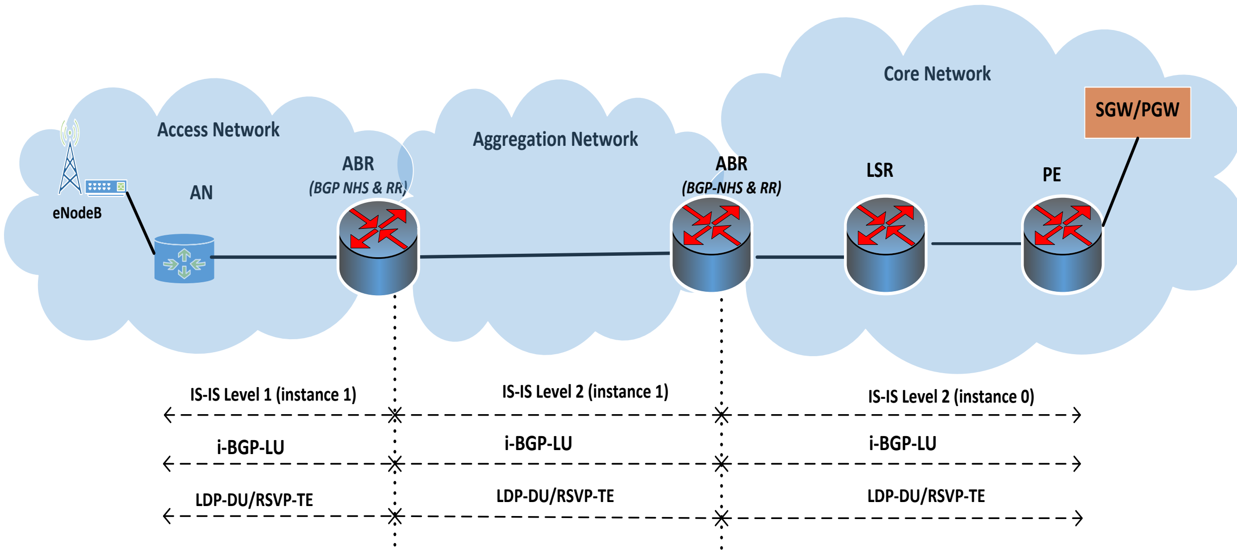


Fig 4.3 Seamless MPLS Architecture for High-End Access Nodes

[6]

4.3.1 Inter-Domain Routing

In model 2 access nodes have enough capacity to run IGP such IS-IS as well as BGP-LU. This eliminates the need to perform LDP FEC to BGP stitching at the Aggregation Nodes. The different IS-IS instances as depicted in Fig 4.3 are meant to confine intra-domain prefix advertisement. The core domain only holds core prefixes. The aggregation domain holds prefixes from all access domains that connects to it.

4.3.2 Inter-Domain MPLS LSP

Inter-domain MPLS LSP is formed from labels distributed by BGP-LU. These labels create the inner End-to-End Seamless MPLS transport layer. The AGN-1 acts as NH for BGP routes towards the aggregation domain. AGN-1 also act Route Reflector to access nodes that connect to it. Also ABR act Route Reflector to Aggregation nodes that connect to it. The ABR acts as NH for BGP routes towards the core. One of the code nodes may be configured as Route Reflector for the ABRs.

4.3.3 Intra-Domain MPLS LSP

LDP in Downstream Unsolicited mode or RSVP-TE is used to distribute label mappings for all the loopback addresses of all the nodes in their respective domains. The resulting LSP formed will be utilized as the outer Seamless MPLS transport layer.

4.4 Model 3

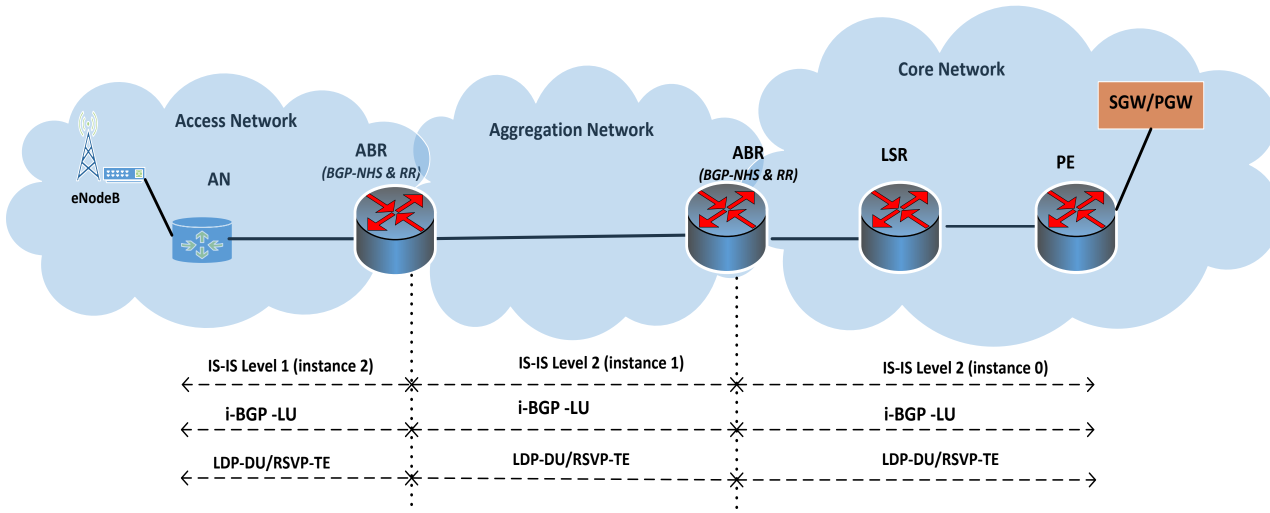


Fig 4.4 Seamless MPLS Architecture for High-End Access Nodes

The only difference between model 3 and model 2 is in the IS-IS instances implementation. Each domain is in a different IS-IS instance. The result of this is that the core domain only contains only core prefixes, aggregation domain holds only aggregation domain prefixes and access domain prefixes confined to access domain. Inter-domain and intra-domain MPLS LSP follow the same principles in model 2.

4.5 Pros and Cons of using LDP DoD in Seamless MPLS network Design

Pros

1. When LDP DoD is used in conjunction with conservative label retention mode, it conserves resource on routers because only the labels explicitly requested by the router are maintained on them.
2. Good for deploying with Cell Site Routers / DSLAMs with relatively small capacity (in terms of label space and processing power), albeit rich IP/MPLS feature set.
3. Allow network Operators extend MPLS into the Access Network with minimal CAPEX in purchasing a huge number of low end IP/MPLS Access Network Nodes.

Cons

1. LDP does not support traffic engineering. The LSP follows the IGP best path.
2. When LDP DoD is combined with conservative label retention mode, an LSR keeps only the labels for the next hop LSR. Hence reaction to routing changes become slower as new labels must be advertised for the new route hence slowing convergence. Also, the LSRs operating in LDP conservative label retention mode will

not request labels for any alternative or backup routes hence cannot leverage on local protection schemes that depend on the use of alternates next-hops such as IP Loop Free Alternative Fast ReRoute (LFA FRR) and backup static routes.

3. LDP DoD used in conjunction with Independent Control may cause the LSRs to begin forwarding labeled packets before the LSP is completely established which leads to speedy convergence but may risk packet drops, loops or packets may follow an undesired path. Another disadvantage of Independent Control mode is that, when used with LDP DoD and access static routing, would prevent the access LSRs from propagating label binding failures along the access topology. This hinders upstream LSRs from being notified of the downstream failure, therefore cannot switch to backup paths even if such alternate paths exist.

4.6 Pros and Cons of using BGP-LU in Seamless MPLS network Design

Pros

1. BGP multi-hop capability enables routers to exchange Network reachability information across areas/domain boundaries without necessarily installing those prefixes in the routing tables of all intermediates routers in a domain. Hence improving scalability by not overwhelming the routing and forwarding tables of routers that doesn't need such prefixes. This allows routers with limited service capabilities but with sufficient label stack depth to be used as transit routers.
2. BGP allows us to advertise MPLS label mapping/binding (usually /32 loopback addresses of PEs) mapped to the advertised network prefixes which provide an MPLS tunnel that enables us to forward MPLS traffic across area/region boundaries
3. It can provide very scalable Seamless MPLS architectures, supporting up to 100,000 routers.
4. BGP-LU tunneling is not restricted to any specific intra-domain MPLS transport protocol-it can be LDP, RSVP-TE or SPRING. LDP tunneling feature is tied to only RSVP-TE.

Cons

1. Requires routers which support BGP Label Unicast.
2. BGP-LU sessions require manual configuration as compared targeted LDP sessions which are created automatically as result of LDP tunneling configuration in LDP over RSVP-TE inter-domain LSP. But LDP tunneling works only with RSVP-TE
3. May Require BGP Path Attribute tuning to acquire an optimal result. For example, Accumulated IGP (AIGP) metric Path attribute needs to be enabled for optimal BGP-LU path selection between domains.

CHAPTER 5

5.1 MODEL 3 IMPLEMENTATION

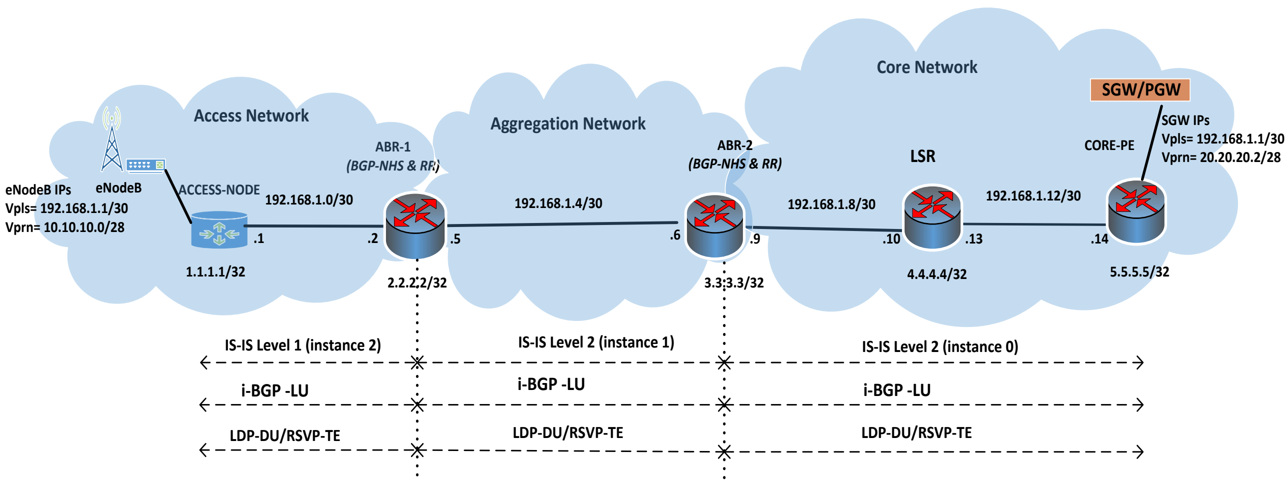


Fig 5.1 Model 3 with IP address used in the configuration below.

NOTE: I used cisco routers to simulate eNodeB and SGW to demonstrate End-to-End connectivity. All the other routers are Alcatel-Lucent (now Nokia) routers.

5.1.1 ENodeB Configuration

```
interface GigabitEthernet2/0.10
 encapsulation dot1Q 10
 ip address 192.168.1.2 255.255.255.0
!
interface GigabitEthernet2/0.20
 encapsulation dot1Q 20
 ip address 10.10.10.1 255.255.255.240
!

ip route 20.20.20.0 255.255.255.240 10.10.10.2
```

5.1.2 SGW Configuration

```
interface GigabitEthernet1/0.10
 encapsulation dot1Q 10
 ip address 192.168.1.1 255.255.255.0
!
```

```
interface GigabitEthernet1/0.20
 encapsulation dot1Q 20
 ip address 20.20.20.2 255.255.255.240
!

ip route 10.10.10.0 255.255.255.240 20.20.20.1
```

5.1.3 Access Node (AN) Configuration

```
#--------------------------------------------------
echo "Port Configuration"
#--------------------------------------------------
    port 1/1/1
        ethernet
        exit
        no shutdown
    exit
    port 1/1/2
        ethernet
            mode access
            encap-type dot1q
        exit
        no shutdown
#--------------------------------------------------
echo "Router (Network Side) Configuration"
#--------------------------------------------------
    router Base
        interface "system"
            address 1.1.1.1/32
            no shutdown
        exit
        interface "to-ABR-1"
            address 192.168.7.1/30
            description " to ABR 2"
            port 1/1/1
            no shutdown
        exit
        autonomous-system 64496
#--------------------------------------------------
echo "ISIS (Inst: 2) Configuration"
#--------------------------------------------------
        isis 2
            level-capability level-1
            area-id 49.0002
            interface "system"
                interface-type point-to-point
                no shutdown
```

```
            exit
            interface "to-ABR-1"
                interface-type point-to-point
                no shutdown
            exit
            no shutdown
        exit
#--------------------------------------------------
echo "LDP Configuration"
#--------------------------------------------------
        ldp
            interface-parameters
                interface "to-ABR-1" dual-stack
                    ipv4
                        fec-type-capability

#--------------------------------------------------
echo "Service Configuration"
#--------------------------------------------------
    service
        sdp 2 mpls create
            far-end 5.5.5.5
            bgp-tunnel
            keep-alive
                shutdown
            exit
            no shutdown
        exit
        customer 1 create
            description "Default customer"
        exit
        customer 100 create
            description "eNodeB Customer"
        exit
        vprn 15 customer 100 create
            interface "to-eNodeB" create
            exit
        exit
        vpls 10 customer 100 create
            stp
                shutdown
            exit
            sap 1/1/2:10 create
            exit
            mesh-sdp 2:10 create
                no shutdown
            exit
            no shutdown
```

```
        exit
        vprn 15 customer 100 create
            route-distinguisher 64496:15
            auto-bind-tunnel
                resolution any
            exit
            vrf-target target:64496:15
            interface "to-eNodeB" create
                address 10.10.10.2/28
                sap 1/1/2:20 create
                exit
            exit
            no shutdown
        exit
    exit

#--------------------------------------------------
echo "Policy Configuration"
#--------------------------------------------------
        policy-options
            begin
            prefix-list "SYSTEM-IP"
                prefix 1.1.1.1/32 exact
            exit
            policy-statement "EXPORT-TO-BGP"
                entry 10
                    from
                        protocol direct
                        prefix-list "SYSTEM-IP"
                    exit
                    action accept
                    exit
                exit
            exit
            commit
        exit
#--------------------------------------------------
echo "BGP Configuration"
#--------------------------------------------------
        bgp
            export "EXPORT-TO-BGP"
            group "ACCESS"
                family ipv4 vpn-ipv4
                type internal
                peer-as 64496
                neighbor 2.2.2.2
                    advertise-label ipv4
                exit
```

```
            exit
            no shutdown
        exit
    exit

# Finished SAT NOV 19 18:14:29 2016 UTC
A:ACESS-NODE#
```

5.1.4 ABR-1 Configuration

```
#--------------------------------------------------
echo "Router (Network Side) Configuration"
#--------------------------------------------------
    router Base
        interface "system"
            address 2.2.2.2/32
            no shutdown
        exit
        interface "to-ABR-2"
            address 192.168.7.5/30
            description "to ABR 3"
            port 1/1/2
            no shutdown
        exit
        interface "to-AN"
            address 192.168.7.2/30
            port 1/1/1
            no shutdown
        exit
        autonomous-system 64496
#--------------------------------------------------
echo "ISIS (Inst: 1) Configuration"
#--------------------------------------------------
        isis 1
            level-capability level-2
            interface "system"
                interface-type point-to-point
                no shutdown
            exit
            interface "to-ABR-2"
                interface-type point-to-point
                no shutdown
            exit
            no shutdown
        exit
#--------------------------------------------------
echo "ISIS (Inst: 2) Configuration"
#--------------------------------------------------
```

```
        isis 2
            level-capability level-1
            area-id 49.0002
            interface "system"
                interface-type point-to-point
                no shutdown
            exit
            interface "to-AN"
                interface-type point-to-point
                no shutdown
            exit
            no shutdown
        exit
#--------------------------------------------------
echo "LDP Configuration"
#--------------------------------------------------
        ldp
            interface-parameters
                interface "to-ABR-2" dual-stack
                    ipv4
                        fec-type-capability
                            prefix-ipv6 disable
                            p2mp-ipv6 disable
                        exit
                        no shutdown
                    exit
                    no shutdown
                exit
                interface "to-AN" dual-stack
                    ipv4
                        fec-type-capability
                            prefix-ipv6 disable
                            p2mp-ipv6 disable
                        exit
                        no shutdown

#--------------------------------------------------
echo "BGP Configuration"
#--------------------------------------------------
        bgp
            group "ACCESS"
                family ipv4 vpn-ipv4
                type internal
                cluster 2.2.2.2
                peer-as 64496
                neighbor 1.1.1.1
                    next-hop-self
                    advertise-label ipv4
```

```
            exit
        exit
        group "AGGREGATION"
            family ipv4 vpn-ipv4
            type internal
            peer-as 64496
            advertise-inactive
            neighbor 3.3.3.3
                next-hop-self
                advertise-label ipv4
            exit
        exit

# Finished FRI NOV 18 10:07:42 2016 UTC
A:ABR-1#
```

5.1.5 ABR-2 Configuration

```
#--------------------------------------------------
echo "Router (Network Side) Configuration"
#--------------------------------------------------
    router Base
        interface "system"
            address 3.3.3.3/32
            no shutdown
        exit
        interface "to-ABR-1"
            address 192.168.7.6/30
            description "to ABR-2"
            port 1/1/2
            no shutdown
        exit
        interface "to-LSR"
            address 192.168.7.9/30
            description "to LSR"
            port 1/1/3
            no shutdown
        exit
        autonomous-system 64496
#--------------------------------------------------
echo "ISIS Configuration"
#--------------------------------------------------
        isis 0
            interface "system"
                interface-type point-to-point
                no shutdown
            exit
            interface "to-LSR"
```

```
            interface-type point-to-point
            no shutdown
        exit
        no shutdown
    exit
#--------------------------------------------------
echo "ISIS (Inst: 1) Configuration"
#--------------------------------------------------
    isis 1
        level-capability level-2
        interface "system"
            interface-type point-to-point
            no shutdown
        exit
        interface "to-ABR-1"
            interface-type point-to-point
            no shutdown
        exit
        no shutdown
    exit
#--------------------------------------------------
echo "LDP Configuration"
#--------------------------------------------------
    ldp
        interface-parameters
            interface "to-ABR-1" dual-stack
                ipv4
                    fec-type-capability
                        prefix-ipv6 disable
                        p2mp-ipv6 disable
                    exit
                    no shutdown
                exit
                no shutdown
            exit
            interface "to-LSR" dual-stack
                ipv4
                    fec-type-capability
                        prefix-ipv6 disable
                        p2mp-ipv6 disable
                    exit
                    no shutdown
                exit
#--------------------------------------------------
echo "BGP Configuration"
#--------------------------------------------------
    bgp
        group "CORE"
```

```
                family ipv4 vpn-ipv4
                type internal
                cluster 3.3.3.3
                peer-as 64496
                neighbor 5.5.5.5
                    next-hop-self
                    advertise-label ipv4
                exit
            exit
            group "AGGREGATION"
                family ipv4 vpn-ipv4
                type internal
                peer-as 64496
                advertise-inactive
                neighbor 2.2.2.2
                    next-hop-self
                    advertise-label ipv4
                exit
            exit
            no shutdown
        exit
    exit

# Finished SAT NOV 19 21:16:01 2016 UTC
A:ABR-2#
```

5.1.6 LSR Configuration

```
#--------------------------------------------------
echo "Router (Network Side) Configuration"
#--------------------------------------------------
    router Base
        interface "system"
            address 4.4.4.4/32
            no shutdown
        exit
        interface "to-ABR-2"
            address 192.168.7.10/30
            description "to ABR 3"
            port 1/1/3
            no shutdown
        exit
        interface "to-PE"
            address 192.168.7.13/30
            description "to PE"
            port 1/1/2
            no shutdown
```

```
        exit
        autonomous-system 64496
#--------------------------------------------------
echo "ISIS Configuration"
#--------------------------------------------------
        isis 0
            interface "system"
                interface-type point-to-point
                no shutdown
            exit
            interface "to-ABR-2"
                interface-type point-to-point
                no shutdown
            exit
            interface "to-PE"
                interface-type point-to-point
                no shutdown
            exit
            no shutdown
        exit
#--------------------------------------------------
echo "LDP Configuration"
#--------------------------------------------------
        ldp
            interface-parameters
                interface "to-ABR-2" dual-stack
                    ipv4
                        fec-type-capability
                            prefix-ipv6 disable
                            p2mp-ipv6 disable
                        exit
                        no shutdown
                    exit
                    no shutdown
                exit
                interface "to-PE" dual-stack
                    ipv4
                        fec-type-capability

# Finished SAT NOV 19 14:45:19 2016 UTC
A:LSR#
```

5.1.7 Core PE (PE) Configuration

```
#--------------------------------------------------
echo "Port Configuration"
#--------------------------------------------------
```

```
    port 1/1/1
        ethernet
            mode access
            encap-type dot1q
        exit
        no shutdown
    exit
    port 1/1/2
        ethernet
        exit
        no shutdown
    exit

#--------------------------------------------------
echo "Router (Network Side) Configuration"
#--------------------------------------------------
    router Base
        interface "system"
            address 5.5.5.5/32
            no shutdown
        exit
        interface "to-LSR"
            address 192.168.7.14/30
            description "to LSR"
            port 1/1/2
            no shutdown
        exit
        autonomous-system 64496
#--------------------------------------------------
echo "ISIS Configuration"
#--------------------------------------------------
        isis 0
            level-capability level-2
            area-id 49.0000
            interface "system"
                interface-type point-to-point
                no shutdown
            exit
            interface "to-LSR"
                interface-type point-to-point
                no shutdown
            exit
            no shutdown
        exit
#--------------------------------------------------
echo "LDP Configuration"
#--------------------------------------------------
        ldp
```

```
            interface-parameters
                interface "to-LSR" dual-stack
                    ipv4
                        fec-type-capability
                            prefix-ipv6 disable
                            p2mp-ipv6 disable
                        exit
                        no shutdown
                    exit

#--------------------------------------------------
echo "Service Configuration"
#--------------------------------------------------
    service
        sdp 2 mpls create
            far-end 1.1.1.1
            bgp-tunnel
            keep-alive
                shutdown
            exit
            no shutdown
        exit
        customer 1 create
            description "Default customer"
        exit
        customer 100 create
            description "SGW Customer"
        exit
        vprn 15 customer 100 create
            interface "to-SGW" create
            exit
        exit
        vpls 10 customer 100 create
            stp
                shutdown
            exit
            sap 1/1/1:10 create
            exit
            mesh-sdp 2:10 create
                no shutdown
            exit
            no shutdown
        exit
        vprn 15 customer 100 create
            route-distinguisher 64496:15
            auto-bind-tunnel
                resolution any
            exit
```

```
            vrf-target target:64496:15
            interface "to-SGW" create
                address 20.20.20.1/28
                sap 1/1/1:20 create
                exit
            exit
            no shutdown
        exit

#--------------------------------------------------
echo "Policy Configuration"
#--------------------------------------------------
        policy-options
            begin
            prefix-list "SYSTEM-IP"
                prefix 5.5.5.5/32 exact
            exit
            policy-statement "EXPORT-TO-BGP"
                entry 10
                    from
                        protocol direct
                        prefix-list "SYSTEM-IP"
                    exit
                    action accept
exit
            commit
        exit
#--------------------------------------------------
echo "BGP Configuration"
#--------------------------------------------------
        bgp
            group "CORE"
                family ipv4 vpn-ipv4
                type internal
                export "EXPORT-TO-BGP"
                peer-as 64496
                neighbor 3.3.3.3
                    advertise-label ipv4
                exit
# Finished FRI NOV 18 21:09:34 2016 UTC
```

5.1.8 advertise-label ipv4 and advertise-inactive IN BGP CONFIGURATION on ABRs

```
#--------------------------------------------------
echo "BGP Configuration"
#--------------------------------------------------
```

```
bgp
    group "ACCESS"
        family ipv4 vpn-ipv4
        type internal
        cluster 2.2.2.2
        peer-as 64496
        neighbor 1.1.1.1
            next-hop-self
            advertise-label ipv4
        exit
    exit
    group "AGGREGATION"
        family ipv4 vpn-ipv4
        type internal
        peer-as 64496
        advertise-inactive
        neighbor 3.3.3.3
            next-hop-self
            advertise-label ipv4
        exit
    exit
```

The /32 system IP routes learned through BGP-LU will also learned via IS-IS. The IS-IS learned routes have lower preference than those of iBGP hence by default BGP wont advertise those routes.
advertise-inactive is added to the ABRs to force BGP advertise the /32 system IP routes learned through BGP-LU.
advertise-label ipv4 tells BGP to advertise all ipv4 in BGP-LU format (RFC 3107).

5.2 End-to-End route verification

5.2.1 Core-PE system IP learned by Access-Node

From the output below it can be seen that Access Node (AN) has learned the route to the Core PE with label 131065 advertised for the route by BGP-LU as highlighted in yellow below

A:ACESS-NODE# **show router bgp routes**

```
===============================================================
 BGP Router ID:1.1.1.1          AS:64496       Local AS:64496
===============================================================
 Legend -
 Status codes  : u - used, s - suppressed, h - history, d - decayed, * - valid
                 l - leaked, x - stale, > - best, b - backup, p - purge
```

```
 Origin codes  : i - IGP, e - EGP, ? - incomplete

===============================================================================
BGP IPv4 Routes
===============================================================================
Flag  Network                                            LocalPref   MED
      Nexthop (Router)                                   Path-Id     Label
      As-Path
-------------------------------------------------------------------------------
u*>i  5.5.5.5/32                                         100         None
      2.2.2.2                                            None        131065
      No As-Path
-------------------------------------------------------------------------------
Routes : 1
===============================================================================


A:ACESS-NODE# show router route-table

===============================================================================
Route Table (Router: Base)
===============================================================================
Dest Prefix[Flags]                            Type    Proto     Age         Pref
      Next Hop[Interface Name]                                    Metric
-------------------------------------------------------------------------------
1.1.1.1/32                                    Local   Local     00h05m53s  0
       system                                                       0
2.2.2.2/32                                    Remote  ISIS(2)   00h05m29s  15
       192.168.7.2                                                  10
5.5.5.5/32                                    Remote  BGP       00h03m28s  170
       2.2.2.2 (tunneled)                                           0
192.168.7.0/30                                Local   Local     00h05m44s  0
       to-ABR-2                                                     0
-------------------------------------------------------------------------------
No. of Routes: 4
Flags: n = Number of times nexthop is repeated
       B = BGP backup route available
       L = LFA nexthop available
       S = Sticky ECMP requested
===============================================================================
```

5.2.2 Access-Node system IP learned by Core-PE

Core PE has learned the route to the Access Node (AN) with label 131066 advertised for the by BGP-LU as highlighted in yellow below

```
A:CORE-PE# show router bgp routes
===============================================================
 BGP Router ID:5.5.5.5          AS:64496       Local AS:64496
===============================================================
 Legend -
 Status codes  : u - used, s - suppressed, h - history, d - decayed, * - valid
                 l - leaked, x - stale, > - best, b - backup, p - purge
 Origin codes  : i - IGP, e - EGP, ? - incomplete

===============================================================
BGP IPv4 Routes
===============================================================
Flag  Network                                    LocalPref   MED
      Nexthop (Router)                            Path-Id     Label
      As-Path
-------------------------------------------------------------------------------
u*>i  1.1.1.1/32                                  100        None
      3.3.3.3                                    None        131066
      No As-Path
-------------------------------------------------------------------------------
Routes : 1
===============================================================


A:CORE-PE# show router route-table

===============================================================
Route Table (Router: Base)
===============================================================
Dest Prefix[Flags]                          Type    Proto     Age        Pref
      Next Hop[Interface Name]                                  Metric
-------------------------------------------------------------------------------
1.1.1.1/32                                Remote  BGP       00h04m47s  170
       3.3.3.3 (tunneled)                                      0
3.3.3.3/32                                Remote  ISIS      00h05m31s  18
       192.168.7.13                                            20
4.4.4.4/32                                Remote  ISIS      00h05m31s  18
       192.168.7.13                                            10
5.5.5.5/32                                Local   Local     00h05m45s  0
       system                                                  0
192.168.7.8/30                            Remote  ISIS      00h05m31s  18
       192.168.7.13                                            20
192.168.7.12/30                           Local   Local     00h05m37s  0
       to-LSR                                                  0
-------------------------------------------------------------------------------
No. of Routes: 6
Flags: n = Number of times nexthop is repeated
```

```
      B = BGP backup route available
      L = LFA nexthop available
      S = Sticky ECMP requested
===============================================================
```

5.2.3 SDP, VPLS and VPRN Service Verification On Access Node And Core PE

End-to-End VPLS and VPRN service are up on both Access and Core PE nodes ready to carry packets from eNodeB to SGW and vice versa.

A:ACESS-NODE# **show service sdp**

```
===============================================================
Services: Service Destination Points
===============================================================
SdpId  AdmMTU  OprMTU  Far End       Adm  Opr       Del     LSP   Sig
-------------------------------------------------------------------------------
2      0       8910    5.5.5.5         Up   Up       MPLS    B     TLDP
-------------------------------------------------------------------------------
Number of SDPs : 1
-------------------------------------------------------------------------------
Legend: R = RSVP, L = LDP, B = BGP, M = MPLS-TP, n/a = Not Applicable
        I = SR-ISIS, O = SR-OSPF
===============================================================
```

A:CORE-PE# **show service sdp**

```
===============================================================
Services: Service Destination Points
===============================================================
SdpId  AdmMTU  OprMTU  Far End       Adm  Opr       Del     LSP   Sig
-------------------------------------------------------------------------------
2      0       8910    1.1.1.1         Up   Up       MPLS    B     TLDP
-------------------------------------------------------------------------------
Number of SDPs : 1
-------------------------------------------------------------------------------
Legend: R = RSVP, L = LDP, B = BGP, M = MPLS-TP, n/a = Not Applicable
        I = SR-ISIS, O = SR-OSPF
==============================================================
```

A:ACESS-NODE# **show service id 10 base** *(vpls service)*

```
===============================================================
Service Basic Information
===============================================================
```

```
Service Id        : 10                  Vpn Id            : 0
Service Type      : VPLS
Name              : (Not Specified)
Description       : (Not Specified)
Customer Id       : 100                 Creation Origin   : manual
Last Status Change: 11/19/2016 18:52:37
Last Mgmt Change  : 11/19/2016 18:52:28
Etree Mode        : Disabled
Admin State       : Up                  Oper State        : Up
MTU               : 1514                Def. Mesh VC Id   : 10
SAP Count         : 1                   SDP Bind Count    : 1
Snd Flush on Fail : Disabled            Host Conn Verify  : Disabled
SHCV pol IPv4     : None
Propagate MacFlush: Disabled            Per Svc Hashing   : Disabled
Allow IP Intf Bind: Disabled            Fwd-IPv4-Mcast-To*: Disabled
Def. Gateway IP   : None
Def. Gateway MAC  : None
Temp Flood Time   : Disabled            Temp Flood        : Inactive
Temp Flood Chg Cnt: 0
VSD Domain        : <none>
SPI load-balance  : Disabled
TEID load-balance : Disabled

-------------------------------------------------------------------------------
Service Access & Destination Points
-------------------------------------------------------------------------------
Identifier                        Type         AdmMTU  OprMTU  Adm  Opr
-------------------------------------------------------------------------------
sap:1/1/2:10                      q-tag        1518    1518    Up   Up
sdp:2:10 M(5.5.5.5)               Mesh         0       8910    Up   Up
===============================================================================
```

A:CORE-PE# **show service id 10 base** *(vpls service)*

```
===============================================================================
Service Basic Information
===============================================================================
Service Id        : 10                  Vpn Id            : 0
Service Type      : VPLS
Name              : (Not Specified)
Description       : (Not Specified)
Customer Id       : 100                 Creation Origin   : manual
Last Status Change: 11/18/2016 21:26:20
Last Mgmt Change  : 11/18/2016 21:26:12
Etree Mode        : Disabled
Admin State       : Up                  Oper State        : Up
```

```
MTU               : 1514              Def. Mesh VC Id   : 10
SAP Count         : 1                 SDP Bind Count    : 1
Snd Flush on Fail : Disabled          Host Conn Verify  : Disabled
SHCV pol IPv4     : None
Propagate MacFlush: Disabled          Per Svc Hashing   : Disabled
Allow IP Intf Bind: Disabled          Fwd-IPv4-Mcast-To*: Disabled
Def. Gateway IP   : None
Def. Gateway MAC  : None
Temp Flood Time   : Disabled          Temp Flood        : Inactive
Temp Flood Chg Cnt: 0
VSD Domain        : <none>
SPI load-balance  : Disabled
TEID load-balance : Disabled

-------------------------------------------------------------------------------
Service Access & Destination Points
-------------------------------------------------------------------------------
Identifier                              Type         AdmMTU  OprMTU  Adm  Opr
-------------------------------------------------------------------------------
sap:1/1/1:10                            q-tag        1518    1518    Up   Up
sdp:2:10 M(1.1.1.1)                     Mesh         0       8910    Up   Up
===============================================================================
```

A:ACESS-NODE# **show service id 15 base** *(vprn service)*

```
===============================================================================
Service Basic Information
===============================================================================
Service Id        : 15                Vpn Id            : 0
Service Type      : VPRN
Name              : (Not Specified)
Description       : (Not Specified)
Customer Id       : 100               Creation Origin   : manual
Last Status Change: 11/19/2016 18:52:28
Last Mgmt Change  : 11/19/2016 18:52:28
Admin State       : Up                Oper State        : Up

Route Dist.       : 64496:15          VPRN Type         : regular
Oper Route Dist   : 64496:15
Oper RD Type      : configured
AS Number         : None              Router Id         : 1.1.1.1
ECMP              : Enabled           ECMP Max Routes   : 1

Auto Bind Tunnel
Resolution        : any

Max IPv6 Routes   : No Limit
```

```
Ignore NH Metric  : Disabled
Hash Label        : Disabled
Vrf Target        : target:64496:15
Vrf Import        : None
Vrf Export        : None
MVPN Vrf Target   : None
MVPN Vrf Import   : None
MVPN Vrf Export   : None
Car. Sup C-VPN    : Disabled
Label mode        : vrf
BGP VPN Backup    : Disabled
BGP Export Inacti*: Disabled

SAP Count         : 1                  SDP Bind Count    : 0

-------------------------------------------------------------------------------
Service Access & Destination Points
-------------------------------------------------------------------------------
Identifier                          Type        AdmMTU  OprMTU  Adm  Opr
-------------------------------------------------------------------------------
sap:1/1/2:20                        q-tag       1518    1518    Up   Up
===============================================================================
```

A:CORE-PE# **show service id 15 base** *(vprn service)*

```
===============================================================================
Service Basic Information
===============================================================================
Service Id        : 15                 Vpn Id            : 0
Service Type      : VPRN
Name              : (Not Specified)
Description       : (Not Specified)
Customer Id       : 100                Creation Origin   : manual
Last Status Change: 11/18/2016 21:26:12
Last Mgmt Change  : 11/18/2016 21:26:12
Admin State       : Up                 Oper State        : Up

Route Dist.       : 64496:15           VPRN Type         : regular
Oper Route Dist   : 64496:15
Oper RD Type      : configured
AS Number         : None               Router Id         : 5.5.5.5
ECMP              : Enabled            ECMP Max Routes   : 1

Auto Bind Tunnel
Resolution        : any

Max IPv6 Routes   : No Limit
```

```
Ignore NH Metric  : Disabled
Hash Label        : Disabled
Vrf Target        : target:64496:15
Vrf Import        : None
Vrf Export        : None
MVPN Vrf Target   : None
MVPN Vrf Import   : None
MVPN Vrf Export   : None
Car. Sup C-VPN    : Disabled
Label mode        : vrf
BGP VPN Backup    : Disabled
BGP Export Inacti*: Disabled

SAP Count         : 1                SDP Bind Count    : 0

-------------------------------------------------------------------------------
Service Access & Destination Points
-------------------------------------------------------------------------------
Identifier                          Type       AdmMTU  OprMTU  Adm  Opr
-------------------------------------------------------------------------------
sap:1/1/1:20                        q-tag      1518    1518    Up   Up
```

5.2.4 VPRN Routing Table on Access-Node and Core PE routers

It can be seen from the output below that Access Node routing table contains the route to Core PE.

A:ACESS-NODE# **show router 15 route-table**

```
===============================================================================
Route Table (Service: 15)
===============================================================================
Dest Prefix[Flags]                            Type    Proto     Age        Pref
      Next Hop[Interface Name]                                    Metric
-------------------------------------------------------------------------------
10.10.10.0/28                                 Local   Local     00h08m25s  0
       to-eNodeB                                                    0
20.20.20.0/28                                 Remote  BGP VPN   00h05m37s  170
       5.5.5.5 (tunneled:BGP)                                       0
-------------------------------------------------------------------------------
No. of Routes: 2
Flags: n = Number of times nexthop is repeated
       B = BGP backup route available
       L = LFA nexthop available
       S = Sticky ECMP requested
===============================================================================
```

It can be seen from the output below that Core PE routing table contains the route to Access Node.

```
A:CORE-PE#  show router 15 route-table

=======================================================
Route Table (Service: 15)
=======================================================
Dest Prefix[Flags]                Type   Proto    Age        Pref
    Next Hop[Interface Name]                       Metric
-------------------------------------------------------------------------------
10.10.10.0/28                     Remote  BGP VPN   00h07m20s  170
     1.1.1.1 (tunneled:BGP)                        0
20.20.20.0/28                     Local   Local    00h08m11s  0
     to-SGW                                    0
-------------------------------------------------------------------------------
No. of Routes: 2
Flags: n = Number of times nexthop is repeated
     B = BGP backup route available
     L = LFA nexthop available
     S = Sticky ECMP requested
```

5.2.5 Ping from eNodeB to SGW for both VPLS and VPRN service

```
eNodeB#ping 192.168.1.1

Type escape sequence to abort.
Sending 5, 100-byte ICMP Echos to 192.168.1.1, timeout is 2 seconds:
!!!!!
Success rate is 100 percent (5/5), round-trip min/avg/max = 56/59/60 ms
eNodeB#
eNodeB#
eNodeB#ping 20.20.20.2

Type escape sequence to abort.
Sending 5, 100-byte ICMP Echos to 20.20.20.2, timeout is 2 seconds:
!!!!!
Success rate is 100 percent (5/5), round-trip min/avg/max = 56/58/60 ms
eNodeB#
```

5.2.6 Ping from SGW to eNodeB for both VPLS and VPRN service

```
SGW#ping 192.168.1.2
```

Type escape sequence to abort.
Sending 5, 100-byte ICMP Echos to 192.168.1.2, timeout is 2 seconds:
!!!!!
Success rate is 100 percent (5/5), round-trip min/avg/max = 56/59/60 ms
SGW#
SGW#
SGW#ping 10.10.10.1

Type escape sequence to abort.
Sending 5, 100-byte ICMP Echos to 10.10.10.1, timeout is 2 seconds:
!!!!!
Success rate is 100 percent (5/5), round-trip min/avg/max = 56/59/60 ms
SGW#

5.3 Label Stacks for Traffic from Access Node (AN) to Core PE router

The label stack displayed in the figure below if for the VPLS service. The same scenario applies to the VPRN service.

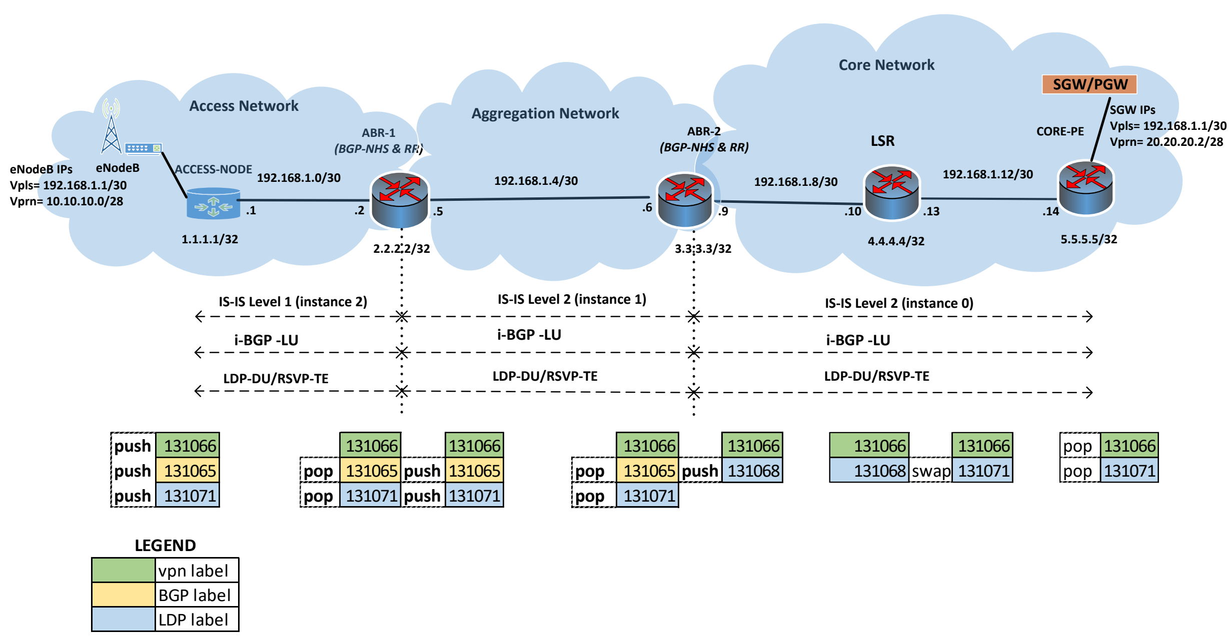


Fig 5.2 Model 3 Label Stack for traffic from Access Node to Core PE.

5.3.1 Label operations on ACCESS NODE

From the output of *show service id 10 labels* below it can be seen that VPLS service on Access Node advertise service label 131066 *(ingress label)* to Core PE and it has received label 131066 *(egress label)* from Core PE. The Access Node will push the egress label 131066 on traffic destined to SGW via Core PE.

A:ACESS-NODE# **show service id 10 labels**

```
=================================================================
Martini Service Labels
=================================================================
Svc Id     Sdp Binding        Type  I.Lbl                E.Lbl
------------------------------------------------------------------------------
10         2:10               Mesh  131066               131066
------------------------------------------------------------------------------
Number of Bound SDPs : 1
------------------------------------------------------------------------------
```

The middle transport label (**131065)** on Access Node will be pushed on top of the service label (131066) for the packet destined to Core.

A:ACESS-NODE# **show router bgp routes 5.5.5.5**

```
=================================================================
 BGP Router ID:1.1.1.1          AS:64496       Local AS:64496
=================================================================
 Legend -
 Status codes  : u - used, s - suppressed, h - history, d - decayed, * - valid
                 l - leaked, x - stale, > - best, b - backup, p - purge
 Origin codes  : i - IGP, e - EGP, ? - incomplete

================================================================
BGP IPv4 Routes
================================================================
Flag  Network                                    LocalPref   MED
      Nexthop (Router)                             Path-Id     Label
      As-Path
------------------------------------------------------------------------------
u*>i  5.5.5.5/32                                   100        None
      2.2.2.2                                    None        131065
      No As-Path
------------------------------------------------------------------------------
Routes : 1
===============================================================
```

ABR-1 (2.2.2.2) is the next hop of Access Node. Access Node pushes outer LDP transport label (131071) on the packet destined to SGW via Core PE as indicated in the output below.

A:ACESS-NODE# **show router ldp bindings active prefixes prefix 2.2.2.2/32**

```
===============================================================================
LDP Bindings (IPv4 LSR ID 1.1.1.1:0)
         (IPv6 LSR ID ::[0])
===============================================================================
Legend: U - Label In Use,  N - Label Not In Use, W - Label Withdrawn
      WP - Label Withdraw Pending, BU - Alternate For Fast Re-Route
      (S) - Static      (M) - Multi-homed Secondary Support
      (B) - BGP Next Hop (BU) - Alternate Next-hop for Fast Re-Route
      (C) - FEC resolved for class-based-forwarding
===============================================================================
LDP IPv4 Prefix Bindings (Active)
===============================================================================
Prefix                            Op           IngLbl    EgrLbl
EgrNextHop                            EgrIf/LspId
-------------------------------------------------------------------------------
2.2.2.2/32                          Push          --        131071
192.168.7.2                          1/1/1

-------------------------------------------------------------------------------
No. of IPv4 Prefix Active Bindings: 1
===============================================================================
```

5.3.2 Label operations on ABR-1

ABR-1 on receiving the traffic, pops the outer LDP label 131071. It pops the middle BGP label and pushes another BGP label 131065 which it received from ABR-2 (3.3.3.3) as it is configured as next-hop-self. The service label remains unchanged.
ABR-1 pushes LDP 131071 on top of the packet and forwards it to ABR-2.

A:ABR-1# **show router ldp bindings active prefixes prefix 2.2.2.2/32**

```
===============================================================================
LDP Bindings (IPv4 LSR ID 2.2.2.2:0)
         (IPv6 LSR ID ::[0])
===============================================================================
Legend: U - Label In Use,  N - Label Not In Use, W - Label Withdrawn
      WP - Label Withdraw Pending, BU - Alternate For Fast Re-Route
      (S) - Static      (M) - Multi-homed Secondary Support
      (B) - BGP Next Hop (BU) - Alternate Next-hop for Fast Re-Route
      (C) - FEC resolved for class-based-forwarding
===============================================================================
LDP IPv4 Prefix Bindings (Active)
===============================================================================
Prefix                            Op           IngLbl    EgrLbl
```

```
EgrNextHop                              EgrIf/LspId
-------------------------------------------------------------------------------
2.2.2.2/32                          Pop            131071     --
  --                                  --

-------------------------------------------------------------------------------
No. of IPv4 Prefix Active Bindings: 1
===============================================================================
```

```
A:ABR-1# show router tunnel-table

===============================================================================
IPv4 Tunnel Table (Router: Base)
===============================================================================
Destination       Owner     Encap TunnelId  Pref     Nexthop        Metric
-------------------------------------------------------------------------------
1.1.1.1/32        ldp       MPLS  65537     9        192.168.7.1    10
3.3.3.3/32        ldp       MPLS  65538     9        192.168.7.6    10
5.5.5.5/32        bgp       MPLS  262145    12       3.3.3.3        1000
-------------------------------------------------------------------------------
Flags: B = BGP backup route available
       E = inactive best-external BGP route
===============================================================================
```

```
A:ABR-1# show router bgp routes 5.5.5.5
===============================================================================
 BGP Router ID:2.2.2.2          AS:64496       Local AS:64496
===============================================================================
 Legend -
 Status codes  : u - used, s - suppressed, h - history, d - decayed, * - valid
                 l - leaked, x - stale, > - best, b - backup, p - purge
 Origin codes  : i - IGP, e - EGP, ? - incomplete

===============================================================================
BGP IPv4 Routes
===============================================================================
Flag  Network                                      LocalPref   MED
      Nexthop (Router)                              Path-Id     Label
      As-Path
-------------------------------------------------------------------------------
u*>i  5.5.5.5/32                                   100         None
      3.3.3.3                                      None        131065
      No As-Path
-------------------------------------------------------------------------------
Routes : 1
===============================================================================
```

A:ABR-1# **show router bgp inter-as-label**

```
===============================================================
BGP Inter-AS labels
Flags: B - entry has backup, P - entry is promoted
===============================================================
NextHop                    Received       Advertised     Label
                       Label          Label          Origin
-------------------------------------------------------------------------------
1.1.1.1                    131067         131068         Internal
3.3.3.3                    131065         131065         Internal
-------------------------------------------------------------------------------
Total Labels allocated:    2
===============================================================
```

A:ABR-1# **show router ldp bindings active prefixes prefix 3.3.3.3/32**

```
===============================================================
LDP Bindings (IPv4 LSR ID 2.2.2.2:0)
          (IPv6 LSR ID ::[0])
===============================================================
Legend: U - Label In Use,  N - Label Not In Use, W - Label Withdrawn
       WP - Label Withdraw Pending, BU - Alternate For Fast Re-Route
       (S) - Static       (M) - Multi-homed Secondary Support
       (B) - BGP Next Hop (BU) - Alternate Next-hop for Fast Re-Route
       (C) - FEC resolved for class-based-forwarding
===============================================================
LDP IPv4 Prefix Bindings (Active)
===============================================================
Prefix                             Op            IngLbl    EgrLbl
EgrNextHop                         EgrIf/LspId
-------------------------------------------------------------------------------
3.3.3.3/32                         Push          --        131071
192.168.7.6                        1/1/2

3.3.3.3/32                         Swap          131069    131071
192.168.7.6                        1/1/2

-------------------------------------------------------------------------------
No. of IPv4 Prefix Active Bindings: 2
```

5.3.3 Label operations on ABR-2

When ABR-2 receives the packet, it pops the outer label 131071 as it is the endpoint of the LDP tunnel originating from 10.10.10.2 as shown in the output of " **show router bgp inter-as-label"** above. It also the pops the middle BGP label as it is configured as next-hop-self for the BGP tunnel to 5.5.5.5. As it has LDP tunnel to 5.5.5.5 as indicated by "show router tunnel-table" output below, ABR-2 pushes LDP 131068 on top of the service label and forward it to LSR.

A:ABR-2# **show router ldp bindings active prefixes prefix 3.3.3.3/32**

```
===============================================================
LDP Bindings (IPv4 LSR ID 3.3.3.3:0)
         (IPv6 LSR ID ::[0])
===============================================================
Legend: U - Label In Use,  N - Label Not In Use, W - Label Withdrawn
      WP - Label Withdraw Pending, BU - Alternate For Fast Re-Route
      (S) - Static       (M) - Multi-homed Secondary Support
      (B) - BGP Next Hop (BU) - Alternate Next-hop for Fast Re-Route
      (C) - FEC resolved for class-based-forwarding
===============================================================
LDP IPv4 Prefix Bindings (Active)
===============================================================
Prefix                          Op          IngLbl    EgrLbl
EgrNextHop                          EgrIf/LspId
-------------------------------------------------------------------------------
3.3.3.3/32                        Pop           131071      --
  --                              --

-------------------------------------------------------------------------------
No. of IPv4 Prefix Active Bindings: 1
===============================================================
```

A:ABR-2# **show router tunnel-table**

```
===============================================================
IPv4 Tunnel Table (Router: Base)
===============================================================
Destination       Owner     Encap TunnelId  Pref     Nexthop       Metric
-------------------------------------------------------------------------------
1.1.1.1/32        bgp       MPLS  262145    12       2.2.2.2       1000
2.2.2.2/32        ldp       MPLS  65537     9        192.168.7.5   10
4.4.4.4/32        ldp       MPLS  65538     9        192.168.7.10  10
5.5.5.5/32        ldp       MPLS  65539     9        192.168.7.10  20
-------------------------------------------------------------------------------
Flags: B = BGP backup route available
     E = inactive best-external BGP route
===============================================================
```

A:ABR-2# **show router ldp bindings active prefixes prefix 5.5.5.5/32**

```
===============================================================================
LDP Bindings (IPv4 LSR ID 3.3.3.3:0)
          (IPv6 LSR ID ::[0])
===============================================================================
Legend: U - Label In Use,  N - Label Not In Use, W - Label Withdrawn
        WP - Label Withdraw Pending, BU - Alternate For Fast Re-Route
        (S) - Static       (M) - Multi-homed Secondary Support
        (B) - BGP Next Hop (BU) - Alternate Next-hop for Fast Re-Route
        (C) - FEC resolved for class-based-forwarding
===============================================================================
LDP IPv4 Prefix Bindings (Active)
===============================================================================
Prefix                                  Op            IngLbl    EgrLbl
EgrNextHop                              EgrIf/LspId
-------------------------------------------------------------------------------
5.5.5.5/32                              Push            --      131068
192.168.7.10                              1/1/3

5.5.5.5/32                              Swap          131067    131068
192.168.7.10                              1/1/3

-------------------------------------------------------------------------------
No. of IPv4 Prefix Active Bindings: 2
===============================================================================
```

5.3.4 Label operations on LSR

Router LSR has no BGP configuration. After it receives the packet, it swaps the outer LDP label 131068 with 131071 leaving the service label intact.

A:LSR# **show router ldp bindings active prefixes prefix 5.5.5.5/32**

```
===============================================================================
LDP Bindings (IPv4 LSR ID 4.4.4.4:0)
          (IPv6 LSR ID ::[0])
===============================================================================
Legend: U - Label In Use,  N - Label Not In Use, W - Label Withdrawn
        WP - Label Withdraw Pending, BU - Alternate For Fast Re-Route
        (S) - Static       (M) - Multi-homed Secondary Support
        (B) - BGP Next Hop (BU) - Alternate Next-hop for Fast Re-Route
        (C) - FEC resolved for class-based-forwarding
===============================================================================
LDP IPv4 Prefix Bindings (Active)
===============================================================================
======================
Prefix                                  Op            IngLbl    EgrLbl
```

```
EgrNextHop                        EgrIf/LspId
-----------------------------------------------------------------------------
5.5.5.5/32                        Push         --       131071
192.168.7.14                        1/1/2

5.5.5.5/32                        Swap         131068   131071
192.168.7.14                        1/1/2

-----------------------------------------------------------------------------
```

5.3.5 Label operations on CORE PE router

When router Core PE finally receives the packet, it pops both the outer LDP label *(131071)* and inner service label *(131066).* It then places the packet in the VPLS service based on the service ID. Router Core PE eventually forwards the packet to SGW.

A:CORE-PE# **show router ldp bindings active prefixes prefix 5.5.5.5/32**

```
===============================================================
LDP Bindings (IPv4 LSR ID 5.5.5.5:0)
          (IPv6 LSR ID ::[0])
===============================================================
Legend: U - Label In Use,  N - Label Not In Use, W - Label Withdrawn
        WP - Label Withdraw Pending, BU - Alternate For Fast Re-Route
        (S) - Static       (M) - Multi-homed Secondary Support
        (B) - BGP Next Hop (BU) - Alternate Next-hop for Fast Re-Route
        (C) - FEC resolved for class-based-forwarding
===============================================================
LDP IPv4 Prefix Bindings (Active)
===============================================================
Prefix                          Op           IngLbl    EgrLbl
EgrNextHop                        EgrIf/LspId
-----------------------------------------------------------------------------
5.5.5.5/32                        Pop          131071      --
  --                              --

-----------------------------------------------------------------------------
No. of IPv4 Prefix Active Bindings: 1
===============================================================
A:CORE-PE#
```

:CORE-PE# **show service id 10 labels**

```
===============================================================
Martini Service Labels
===============================================================
```

```
Svc Id     Sdp Binding        Type  I.Lbl                E.Lbl
-------------------------------------------------------------------------------
10         2:10               Mesh  131066               131066
-------------------------------------------------------------------------------
Number of Bound SDPs : 1
-------------------------------------------------------------------------------
===============================================================================
```

5.4 Operations, administration and maintenance (OAM)

5.4.1 Oam ping On ACCESS NODE

```
A:ACESS-NODE#  oam lsp-ping bgp-label prefix 5.5.5.5/32
LSP-PING 5.5.5.5/32: 80 bytes MPLS payload
Seq=1, send from intf to-ABR-2, reply from 5.5.5.5
       udp-data-len=32 ttl=255 rtt=7.22ms rc=3 (EgressRtr)

---- LSP 5.5.5.5/32 PING Statistics ----
1 packets sent, 1 packets received, 0.00% packet loss
round-trip min = 7.22ms, avg = 7.22ms, max = 7.22ms, stddev = 0.000ms
```

5.4.2 Oam trace On ACCESS NODE

```
A:ACESS-NODE#  oam lsp-trace bgp-label prefix 5.5.5.5/32
lsp-trace to 5.5.5.5/32: 0 hops min, 0 hops max, 104 byte packets
1  2.2.2.2  rtt=1.72ms rc=8(DSRtrMatchLabel) rsc=1
2  3.3.3.3  rtt=3.95ms rc=8(DSRtrMatchLabel) rsc=1
3  5.5.5.5  rtt=6.40ms rc=3(EgressRtr) rsc=1
A:ACESS-NODE#
```

5.4.3 Oam ping On Core PE

```
A:CORE-PE# oam lsp-ping bgp-label prefix 1.1.1.1/32
LSP-PING 1.1.1.1/32: 80 bytes MPLS payload
Seq=1, send from intf to-LSR, reply from 1.1.1.1
       udp-data-len=32 ttl=255 rtt=8.21ms rc=3 (EgressRtr)

---- LSP 1.1.1.1/32 PING Statistics ----
1 packets sent, 1 packets received, 0.00% packet loss
round-trip min = 8.21ms, avg = 8.21ms, max = 8.21ms, stddev = 0.000ms
```

5.4.4 Oam trace On Core PE

```
A:CORE-PE# oam lsp-trace bgp-label prefix 1.1.1.1/32
lsp-trace to 1.1.1.1/32: 0 hops min, 0 hops max, 104 byte packets
1  4.4.4.4  rtt=4.95ms rc=8(DSRtrMatchLabel)
2  3.3.3.3  rtt=6.95ms rc=8(DSRtrMatchLabel) rsc=1
3  2.2.2.2  rtt=8.80ms rc=8(DSRtrMatchLabel) rsc=1
4  1.1.1.1  rtt=5.92ms rc=3(EgressRtr) rsc=1
A:CORE-PE#
```

CHAPTER 6

6.1 MODEL 1 IMPLEMENTATION

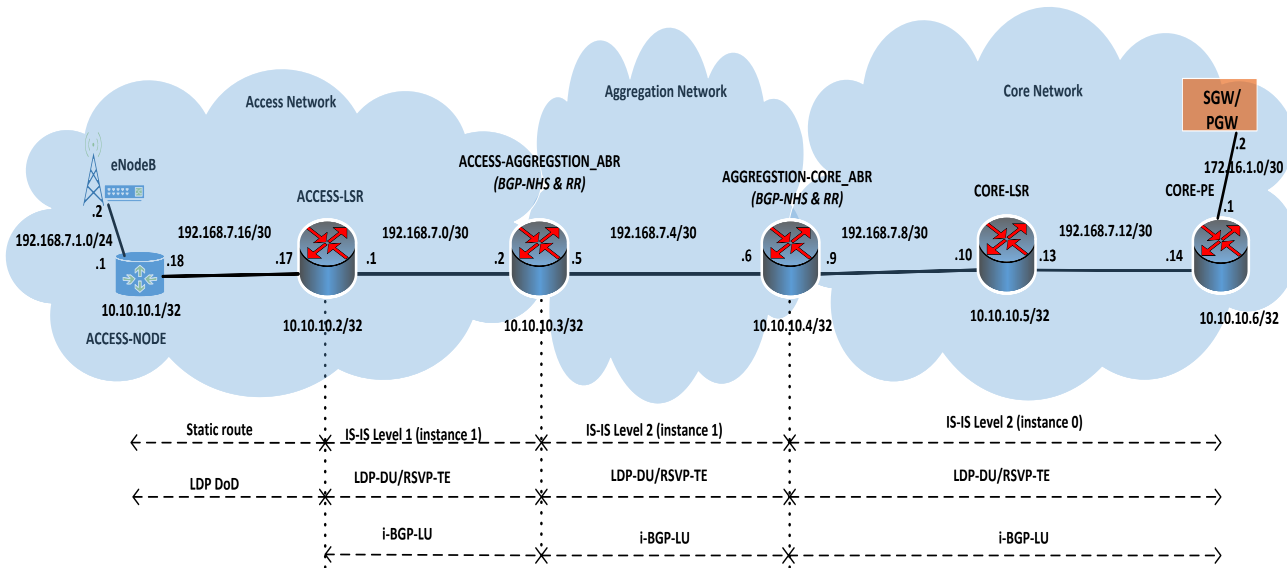


Fig 6.1 Model 1 with IP address used in the configuration below.

The access part of this architecture is suitable for low-end access nodes (cell site routers) that supports LDP and not necessarily BGP capable. The LDP tunnel originating from the Cell Site Router is stitched to the BGP-LU tunnel in the next hop router (10.10.10.2) to the Access Node.

The topology in figure 6.1 constitute the following routers.

1. The ACCESS-NODE and CORE-PE routers run Cisco IOS-XR software.
2. The router in between run Alcatel-Lucent/Nokia 7750 SR software.
3. The eNodeB and the SGW are simulated with routers running Cisco IOS software.

LDP label distribution mode between the ACCESS-NODE and ACCESS-LSR is Downstream on Demand (LDP DoD) as shown in the output below.

RP/0/0/CPU0:ACCESS-NODE#**show mpls ldp neighbor detail**
Tue Dec 13 08:49:02.152 UTC

```
Peer LDP Identifier: 10.10.10.2:0
  TCP connection: 10.10.10.2:50706 - 10.10.10.1:646
  Graceful Restart: No
  Session Holdtime: 30 sec
  State: Oper; Msgs sent/rcvd: 25/24; Downstream-on-Demand
  Up time: 00:01:32
  LDP Discovery Sources:
    IPv4: (1)
      GigabitEthernet0/0/0/0
    IPv6: (0)
  Addresses bound to this peer:
    IPv4: (3)
      10.10.10.2     192.168.7.1    192.168.7.17
    IPv6: (0)
  Peer holdtime: 30 sec; KA interval: 10 sec; Peer state: Estab
  NSR: Disabled
  Capabilities:
    Sent:
      0x508  (MP: Point-to-Multipoint (P2MP))
      0x509  (MP: Multipoint-to-Multipoint (MP2MP))
      0x50b  (Typed Wildcard FEC)
    Received:
      0x508  (MP: Point-to-Multipoint (P2MP))

RP/0/0/CPU0:ACCESS-NODE#
```

A:ACCESS-LSR# **show router ldp session detail**

```
============================================================
LDP IPv4 Sessions (Detail)
============================================================

Legend:  DoD - Downstream on Demand (for address FEC's only)
         DU  - Downstream Unsolicited
============================================================
-------------------------------------------------------------------------------
Session with Peer 10.10.10.1:0, Local 10.10.10.2:0
-------------------------------------------------------------------------------
Adjacency Type       : Link         State                : Established
Up Time              : 0d 00:04:54
Max PDU Length       : 4096         KA/Hold Time Remaining : 29
Link Adjacencies     : 1            Targeted Adjacencies   : 0
Local Address        : 10.10.10.2   Peer Address           : 10.10.10.1
```

```
Local UDP Port        : 646          Peer UDP Port         : 646
Local TCP Port        : 50706         Peer TCP Port         : 646
Local KA Timeout      : 30            Peer KA Timeout       : 180
Mesg Sent             : 140          Mesg Recv             : 130
IPv4 Pfx FEC Sent     : 1            IPv4 Pfx FEC Recv     : 1
IPv6 Pfx FEC Sent     : 0            IPv6 Pfx FEC Recv     : 0
IPv4 P2MP FEC Sent    : 0             IPv4 P2MP FEC Recv    : 0
IPv6 P2MP FEC Sent    : 0             IPv6 P2MP FEC Recv    : 0
Svc Fec128 Sent       : 0            Svc Fec128 Recv       : 0
Svc Fec129 Sent       : 0            Svc Fec129 Recv       : 0
IPv4 Addrs Sent       : 3            IPv4 Addrs Recv       : 2
IPv6 Addrs Sent       : 0            IPv6 Addrs Recv       : 0
Local GR State        : Not Capable   Peer GR State         : Not Capable
Local Nbr Liveness Time: 0            Peer Nbr Liveness Time : 0
Local Recovery Time   : 0             Peer Recovery Time    : 0
Number of Restart     : 0             Last Restart Time     : Never
Label Distribution    : DoD
Oper Fec Limit Thresho*: 0
```

6.1.1 eNodeB Configuration

```
eNodeB#show running-config
!
interface GigabitEthernet1/0
 description to-ACCESS-NODE
 ip address 192.168.1.2 255.255.255.0
!
ip route 0.0.0.0 0.0.0.0 192.168.1.1
!
eNodeB#
```

6.1.2 SGW Configuration

```
SGW#show running-config
!
interface GigabitEthernet1/0
 description to-CORE-PE
 ip address 172.16.1.2 255.255.255.0
!
ip route 0.0.0.0 0.0.0.0 172.16.1.1
!
```

6.1.3 ACCESS-NODE (Cell Site Router) Configuration

```
RP/0/0/CPU0:ACCESS-NODE#show running-config
```

```
Mon Dec 12 16:52:13.792 UTC
Building configuration...
!! IOS XR Configuration 6.1.1
!! Last configuration change at Sun Dec 11 20:04:38 2016 by gordon
!
hostname ACCESS-NODE
vrf one
 address-family ipv4 unicast
 !
!
vrf VRF-A
 address-family ipv4 unicast
  import route-target
   77:77
  !
  export route-target
   77:77
  !
 !
!
ipv4 access-list LDP-LIST
 10 permit ipv4 host 10.10.10.2 any
!
interface Loopback0
 ipv4 address 10.10.10.1 255.255.255.255
!
interface GigabitEthernet0/0/0/0
 ipv4 address 192.168.7.18 255.255.255.252
!
interface GigabitEthernet0/0/0/2
 vrf VRF-A
 ipv4 address 192.168.1.1 255.255.255.0
!
router static
 address-family ipv4 unicast
  0.0.0.0/0 192.168.7.17
  10.10.10.2/32 GigabitEthernet0/0/0/0 192.168.7.17
  10.10.10.6/32 GigabitEthernet0/0/0/0 192.168.7.17
 !
!
router bgp 64496
 address-family ipv4 unicast
  additional-paths receive
  additional-paths send
 !
 address-family vpnv4 unicast
 !
 neighbor 10.10.10.6
```

```
  remote-as 64496
  update-source Loopback0
  address-family ipv4 unicast
  !
  address-family vpnv4 unicast
  !
 !
 vrf VRF-A
  rd 77:77
  address-family ipv4 unicast
   network 192.168.1.0/24
  !
 !
!
mpls ldp
 router-id 10.10.10.1
 session downstream-on-demand with LDP-LIST
 address-family ipv4
 !
 interface GigabitEthernet0/0/0/0
  address-family ipv4
  !
end

RP/0/0/CPU0:ACCESS-NODE#
```

6.1.4 ACCESS-LSR Configuration

```
A:ACCESS-LSR# admin display-config

# Generated MON DEC 12 05:20:34 2016 UTC

#--------------------------------------------------
echo "Router (Network Side) Configuration"
#--------------------------------------------------
    router Base
        interface "ACCESS-to-AGGREGATION_ABR"
            address 192.168.7.1/30
            port 1/1/1
            no shutdown
        exit
        interface "system"
            address 10.10.10.2/32
            no shutdown
        exit
        interface "to-ACCESS-NODE"
            address 192.168.7.17/30
```

```
            port 1/1/2
            no shutdown
        exit
        autonomous-system 64496
#--------------------------------------------------
echo "Static Route Configuration"
#--------------------------------------------------
        static-route 10.10.10.1/32 next-hop 192.168.7.18
#--------------------------------------------------
echo "ISIS (Inst: 1) Configuration"
#--------------------------------------------------
        isis 1
            level-capability level-1
            area-id 49.0002
            interface "system"
                interface-type point-to-point
                no shutdown
            exit
            interface "ACCESS-to-AGGREGATION_ABR"
                level-capability level-1
                interface-type point-to-point
                no shutdown
            exit
            no shutdown
        exit
#--------------------------------------------------
echo "LDP Configuration"
#--------------------------------------------------
        ldp
            export-tunnel-table "EXPORT-BGP-to-LDP"
            session-parameters
                peer 10.10.10.1
                    dod-label-distribution
                    fec-type-capability
                        prefix-ipv6 disable
                    exit
                exit
            exit
            interface-parameters
                interface "ACCESS-to-AGGREGATION_ABR" dual-stack
                    ipv4
                        fec-type-capability
                            prefix-ipv6 disable
                            p2mp-ipv6 disable
                        exit
                        no shutdown
                    exit
                    no shutdown
```

```
                exit
                interface "to-ACCESS-NODE" dual-stack
                    ipv4
                        fec-type-capability
                            prefix-ipv6 disable
                            p2mp-ipv6 disable
                        exit
                        no shutdown

#--------------------------------------------------
echo "ISIS (Inst: 1) Configuration"
#--------------------------------------------------
        isis 1
            no shutdown
        exit
#--------------------------------------------------
echo "Policy Configuration"
#--------------------------------------------------
        policy-options
            begin
            prefix-list "CORE-PE-SYS-IP"
                prefix 10.10.10.6/32 exact
            exit
            prefix-list "ACCESS-NODE-SYS-IP"
                prefix 10.10.10.1/32 exact
            exit
            policy-statement "EXPORT-BGP-to-LDP"
                entry 10
                    from
                        protocol bgp
                        prefix-list "CORE-PE-SYS-IP"
                    exit
                    action accept
                    exit
                exit
            exit
            policy-statement "EXPORT-LDP_FEC-to-BGP"
                entry 10
                    from
                        protocol ldp
                        prefix-list "ACCESS-NODE-SYS-IP"
                    exit
                    action accept
                    exit
                exit
            exit
            commit
        exit
```

```
#--------------------------------------------------
echo "BGP Configuration"
#--------------------------------------------------
        bgp
            group "AGGREGATION"
                family ipv4 vpn-ipv4
                next-hop-self
                export "EXPORT-LDP_FEC-to-BGP"
                peer-as 64496
                local-address 10.10.10.2
                neighbor 10.10.10.3
                    advertise-label ipv4 include-ldp-prefix
                exit
            exit
            no shutdown

# Finished MON DEC 12 05:20:40 2016 UTC
A:ACCESS-LSR#
```

6.1.5 ACCESS-AGGREGATION_ABR Configuration

```
A:ACCESS-AGGREGATION_ABR# admin display-config

# Generated MON DEC 12 09:02:53 2016 UTC

#--------------------------------------------------
echo "Router (Network Side) Configuration"
#--------------------------------------------------
    router Base
        interface "system"
            address 10.10.10.3/32
            no shutdown
        exit
        interface "to-ACCESS-LSR"
            address 192.168.7.2/30
            port 1/1/1
            no shutdown
        exit
        interface "to-AGGREGATION-CORE_ABR"
            address 192.168.7.5/30
            port 1/1/2
            no shutdown
        exit
        autonomous-system 64496
#--------------------------------------------------
echo "ISIS (Inst: 1) Configuration"
#--------------------------------------------------
```

```
        isis 1
            area-id 49.0002
            interface "system"
                interface-type point-to-point
                no shutdown
            exit
            interface "to-ACCESS-LSR"
                level-capability level-1
                interface-type point-to-point
                no shutdown
            exit
            interface "to-AGGREGATION-CORE_ABR"
                interface-type point-to-point
                no shutdown
            exit
            no shutdown
        exit
#--------------------------------------------------
echo "LDP Configuration"
#--------------------------------------------------
        ldp
            interface-parameters
                interface "to-ACCESS-LSR" dual-stack
                    ipv4
                        fec-type-capability
                            prefix-ipv6 disable
                            p2mp-ipv6 disable
                        exit
                        no shutdown
                    exit
                    no shutdown
                exit
                interface "to-AGGREGATION-CORE_ABR" dual-stack
                    ipv4
                        fec-type-capability
                            prefix-ipv6 disable
                            p2mp-ipv6 disable
                        exit
                        no shutdown

#--------------------------------------------------
echo "ISIS (Inst: 1) Configuration"
#--------------------------------------------------
        isis 1
            no shutdown
        exit
#--------------------------------------------------
echo "Policy Configuration"
```

```
#--------------------------------------------------
        policy-options
            begin
            prefix-list "SYSTEM-IPs"
                prefix 10.10.10.0/24 longer
            exit
            policy-statement "EXPORT-L2-to-L1"
                entry 10
                    from
                        protocol isis
                        prefix-list "SYSTEM-IPs"
                        level 2
                    exit
                    action accept
                    exit
                exit
            exit
            commit
        exit
#--------------------------------------------------
echo "BGP Configuration"
#--------------------------------------------------
        bgp
            group "to-RR"
                family ipv4 vpn-ipv4
                next-hop-self
                peer-as 64496
                local-address 10.10.10.3
                advertise-inactive
                neighbor 10.10.10.4
                    advertise-label ipv4 include-ldp-prefix
                exit
            exit
            group "AGGREGATION"
                family ipv4 vpn-ipv4
                next-hop-self
                cluster 10.10.10.3
                peer-as 64496
                local-address 10.10.10.3
                advertise-inactive
                neighbor 10.10.10.2
                    advertise-label ipv4
                exit
            exit
            no shutdown

# Finished MON DEC 12 09:02:57 2016 UTC
A:ACCESS-AGGREGATION_ABR#
```

6.1.6 AGGREGATION-CORE_ABR Configuration

A:AGGREGATION-CORE_ABR# admin display-config

```
# Generated MON DEC 12 13:59:56 2016 UTC

#--------------------------------------------------
echo "Router (Network Side) Configuration"
#--------------------------------------------------
    router Base
        interface "system"
            address 10.10.10.4/32
            no shutdown
        exit
        interface "to-ACCESS-AGGREGATION_ABR"
            address 192.168.7.6/30
            port 1/1/2
            no shutdown
        exit
        interface "to-CORE-LSR"
            address 192.168.7.9/30
            port 1/1/1
            no shutdown
        exit
        autonomous-system 64496
#--------------------------------------------------
echo "ISIS Configuration"
#--------------------------------------------------
        isis 0
            level-capability level-2
            area-id 49.0001
            interface "system"
                interface-type point-to-point
                no shutdown
            exit
            interface "to-CORE-LSR"
                interface-type point-to-point
                no shutdown
            exit
            no shutdown
        exit
#--------------------------------------------------
echo "ISIS (Inst: 1) Configuration"
#--------------------------------------------------
        isis 1
            level-capability level-2
            area-id 49.0002
```

```
            interface "system"
                interface-type point-to-point
                no shutdown
            exit
            interface "to-ACCESS-AGGREGATION_ABR"
                interface-type point-to-point
                no shutdown
            exit
            no shutdown
        exit
#--------------------------------------------------
echo "LDP Configuration"
#--------------------------------------------------
        ldp
            interface-parameters
                interface "to-ACCESS-AGGREGATION_ABR" dual-stack
                    ipv4
                        fec-type-capability
                            prefix-ipv6 disable
                            p2mp-ipv6 disable
                        exit
                        no shutdown
                    exit
                    no shutdown
                exit
                interface "to-CORE-LSR" dual-stack
                    ipv4
                        fec-type-capability
                            prefix-ipv6 disable
                            p2mp-ipv6 disable
                        exit
                        no shutdown

#--------------------------------------------------
echo "ISIS Configuration"
#--------------------------------------------------
        isis 0
            no shutdown
        exit
#--------------------------------------------------
echo "ISIS (Inst: 1) Configuration"
#--------------------------------------------------
        isis 1
            no shutdown
        exit
#--------------------------------------------------
echo "BGP Configuration"
#--------------------------------------------------
```

```
        bgp
            group "RR-CLIENTS"
                family ipv4 vpn-ipv4
                next-hop-self
                cluster 10.10.10.4
                peer-as 64496
                local-address 10.10.10.4
                advertise-inactive
                neighbor 10.10.10.3
                    advertise-label ipv4
                exit
                neighbor 10.10.10.6
                    advertise-label ipv4 include-ldp-prefix
                exit
            exit
            no shutdown

# Finished MON DEC 12 14:00:02 2016 UTC
A:AGGREGATION-CORE_ABR#
```

6.1.7 CORE-LSR Configuration

```
A:CORE-LSR# admin display-config

# Generated MON DEC 12 15:20:30 2016 UTC

#--------------------------------------------------
echo "Router (Network Side) Configuration"
#--------------------------------------------------
    router Base
        interface "system"
            address 10.10.10.5/32
            no shutdown
        exit
        interface "to-AGGREGATION-CORE_ABR"
            address 192.168.7.10/30
            port 1/1/1
            no shutdown
        exit
        interface "to-CORE-PE"
            address 192.168.7.13/30
            port 1/1/2
            no shutdown
        exit
        autonomous-system 64496
#--------------------------------------------------
echo "ISIS Configuration"
```

```
#--------------------------------------------------
        isis 0
            level-capability level-2
            area-id 49.0001.0010.0010.0010.0005.00
            interface "system"
                interface-type point-to-point
                no shutdown
            exit
            interface "to-AGGREGATION-CORE_ABR"
                interface-type point-to-point
                no shutdown
            exit
            interface "to-CORE-PE"
                interface-type point-to-point
                no shutdown
            exit
            no shutdown
        exit
#--------------------------------------------------
echo "LDP Configuration"
#--------------------------------------------------
        ldp
            interface-parameters
                interface "to-AGGREGATION-CORE_ABR" dual-stack
                    ipv4
                        fec-type-capability
                            prefix-ipv6 disable
                            p2mp-ipv6 disable
                        exit
                        no shutdown
                    exit
                    no shutdown
                exit
                interface "to-CORE-PE" dual-stack
                    ipv4
                        fec-type-capability
                            prefix-ipv6 disable
                            p2mp-ipv6 disable
                        exit
                        no shutdown
#--------------------------------------------------
echo "ISIS Configuration"
#--------------------------------------------------
        isis 0
            no shutdown
        exit
#--------------------------------------------------
# Finished MON DEC 12 15:20:34 2016 UTC
```

A:CORE-LSR#

6.1.8 CORE-PE Configuration

```
RP/0/0/CPU0:CORE-PE#show running-config
Mon Dec 12 17:10:59.385 UTC
Building configuration...
!! IOS XR Configuration 6.1.1
!! Last configuration change at Sun Dec 11 20:10:55 2016 by gordon
!
hostname CORE-PE
vrf VRF-A
 address-family ipv4 unicast
  import route-target
   77:77
  !
  export route-target
   77:77

!
interface Loopback0
 ipv4 address 10.10.10.6 255.255.255.255
!
interface GigabitEthernet0/0/0/0
 description to-CORE-LSR
 ipv4 address 192.168.7.14 255.255.255.252
!
interface GigabitEthernet0/0/0/2
 vrf VRF-A
 ipv4 address 172.16.1.1 255.255.255.0
!
router isis 0
 is-type level-2-only
 net 49.0001.0010.0010.0010.0006.00
 address-family ipv4 unicast
 !
 interface Loopback0
  point-to-point
  address-family ipv4 unicast
  !
 !
 interface GigabitEthernet0/0/0/0
  point-to-point
  address-family ipv4 unicast
  !
 !
!
router bgp 64496
 bgp router-id 10.10.10.6
```

```
 address-family ipv4 unicast
  network 10.10.10.6/32
  allocate-label all
 !
 address-family vpnv4 unicast
 !
 neighbor 10.10.10.1
  remote-as 64496
  update-source Loopback0
  address-family ipv4 unicast
  !
  address-family vpnv4 unicast
  !
 !
 neighbor 10.10.10.4
  remote-as 64496
  update-source Loopback0
  address-family ipv4 labeled-unicast
  !
 !
 vrf VRF-A
  rd 77:77
  address-family ipv4 unicast
   label mode per-ce
   network 172.16.1.0/24
  !
 !
!
mpls ldp
 address-family ipv4
 !
 interface GigabitEthernet0/0/0/0
  address-family ipv4
  !
RP/0/0/CPU0:CORE-PE#
```

6.2 End-to-End communication verification

6.2.1 ping from eNodeB to SGW

eNodeB#**ping 172.16.1.2 source 192.168.1.2**

```
Type escape sequence to abort.
Sending 5, 100-byte ICMP Echos to 172.16.1.2, timeout is 2 seconds:
Packet sent with a source address of 192.168.1.2
!!!!!
Success rate is 100 percent (5/5), round-trip min/avg/max = 20/20/20 ms
```

eNodeB#

6.2.2 ping from SGW to eNodeB

SGW#**ping 192.168.1.2 source 172.16.1.2**

Type escape sequence to abort.
Sending 5, 100-byte ICMP Echos to 192.168.1.2, timeout is 2 seconds:
Packet sent with a source address of 172.16.1.2
!!!!!
Success rate is 100 percent (5/5), round-trip min/avg/max = 8/18/24 ms
SGW#

6.3 MPLS Control and Data Plane for Traffic from Access Node vprn (VRF-A) to Core PE vprn (VRF-A).

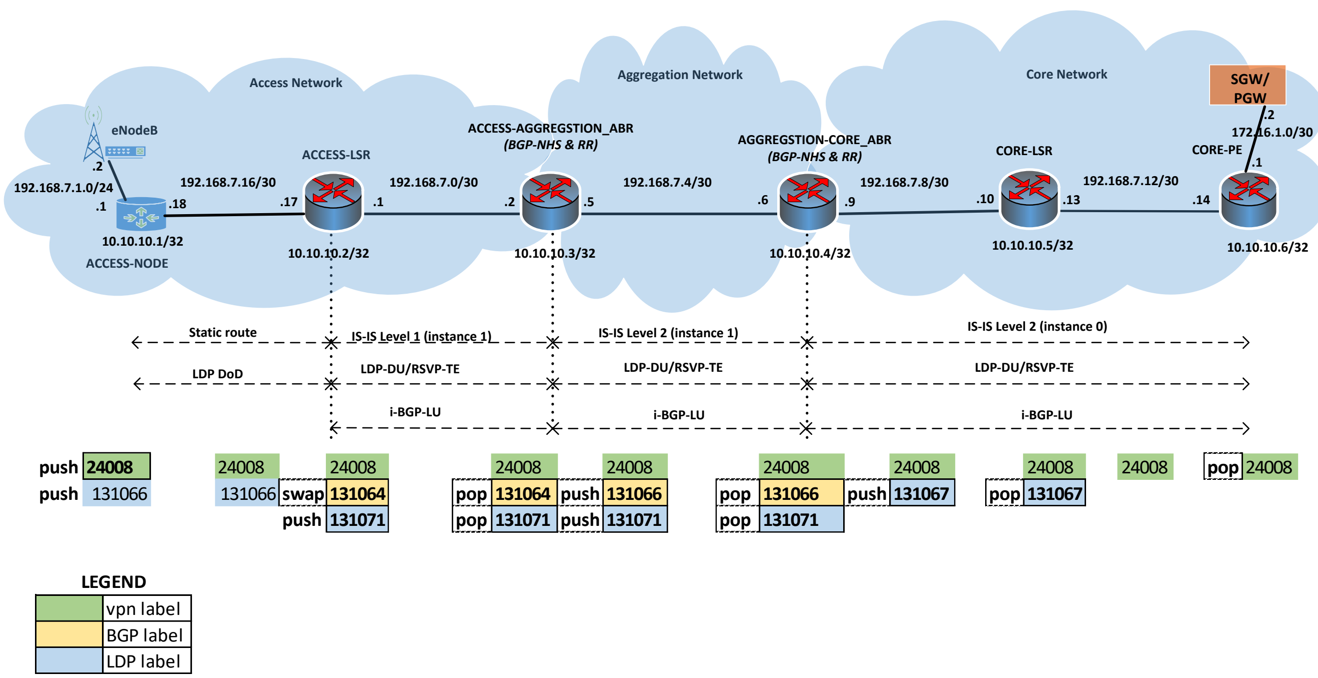


Fig 6.2 Model 1 Label Stack for traffic from Access-Node to Core-PE.

In the configuration of the topology in figure 6.2, there exist three (3) MPLS tunnels between ACCESS-LSR and CORE-PE. The inner tunnel is service tunnel; the middle tunnel is BGP-LU tunnel and the outer tunnel is LDP tunnel.

Between the ACCESS-LSR and ACCESS-NODE there exist two (2) MPLS tunnels. The inner tunnel is service tunnel and the outer tunnel is LDP tunnel.

6.3.1 Label Operations on ACCESS-NODE

6.3.1.1 Control Plane Operations

vpn service label assignment

ACCESS-NODE assigns VPN service label **24001** for vrf VRF-A and signals it to CORE-PE

```
RP/0/0/CPU0:ACCESS-NODE#show mpls forwarding labels 24001
Sun Dec 11 15:47:03.744 UTC
Local  Outgoing    Prefix             Outgoing     Next Hop        Bytes
Label  Label       or ID              Interface                    Switched
------ ----------- ------------------ ------------ --------------- ------------
24001  Aggregate   VRF-A: Per-VRF Aggr[V]   \
                                      VRF-A                        81392
RP/0/0/CPU0:ACCESS-NODE#
```

ACCESS-NODE receives VPN service label **24008** for vrf VRF-A from CORE-PE

```
RP/0/0/CPU0:ACCESS-NODE#show cef vrf VRF-A 172.16.1.2/24
Sun Dec 11 20:24:49.518 UTC
172.16.1.0/24, version 4, internal 0x5000001 0x0 (ptr 0xa145e174) [1], 0x0 (0x0), 0x208
(0xa159d168)
 Updated Dec 11 20:04:39.031
 Prefix Len 24, traffic index 0, precedence n/a, priority 3
   via 10.10.10.6/32, 3 dependencies, recursive [flags 0x6000]
    path-idx 0 NHID 0x0 [0xa16056f4 0x0]
    recursion-via-/32
    next hop VRF - 'default', table - 0xe0000000
    next hop 10.10.10.6/32 via 24002/0/21
     next hop 192.168.7.17/32 Gi0/0/0/0    labels imposed {131066 24008}
RP/0/0/CPU0:ACCESS-NODE#
```

LDP Label Assignment

For MPLS packets going to 10.10.10.6 (CORE-PE), ACCESS-NODE receives LDP label **131066** from its next hop router, ACCESS-LSR (10.10.10.2) as indicated in the output below

```
RP/0/0/CPU0:ACCESS-NODE#show mpls ldp bindings 10.10.10.6/32
Sun Dec 11 20:42:03.937 UTC
10.10.10.6/32, rev 10
        Local binding: label: 24002
        Remote bindings: (1 peers)
            Peer                Label
            -----------------   ---------
            10.10.10.2:0        131066
RP/0/0/CPU0:ACCESS-NODE#
```

6.3.1.2 DATA PLANE Operations

The ACCESS-NODE pushes the LDP label (**131066)** on top of the service label (**24008**) and forwards it to router ACCESS-LSR as shown below.

RP/0/0/CPU0:ACCESS-NODE#show cef vrf VRF-A 172.16.1.2/24
Mon Dec 12 01:23:18.961 UTC
172.16.1.0/24, version 18, internal 0x5000001 0x0 (ptr 0xa145e174) [1], 0x0 (0x0), 0x208 (0xa159d168)
 Updated Dec 12 01:17:26.006
 Prefix Len 24, traffic index 0, precedence n/a, priority 3
   via 10.10.10.6/32, 3 dependencies, recursive [flags 0x6000]
    path-idx 0 NHID 0x0 [0xa16056f4 0x0]
    recursion-via-/32
    next hop VRF - 'default', table - 0xe0000000
    next hop 10.10.10.6/32 via 24002/0/21
     next hop 192.168.7.17/32 Gi0/0/0/0   labels imposed {**131066 24008**}
RP/0/0/CPU0:ACCESS-NODE#

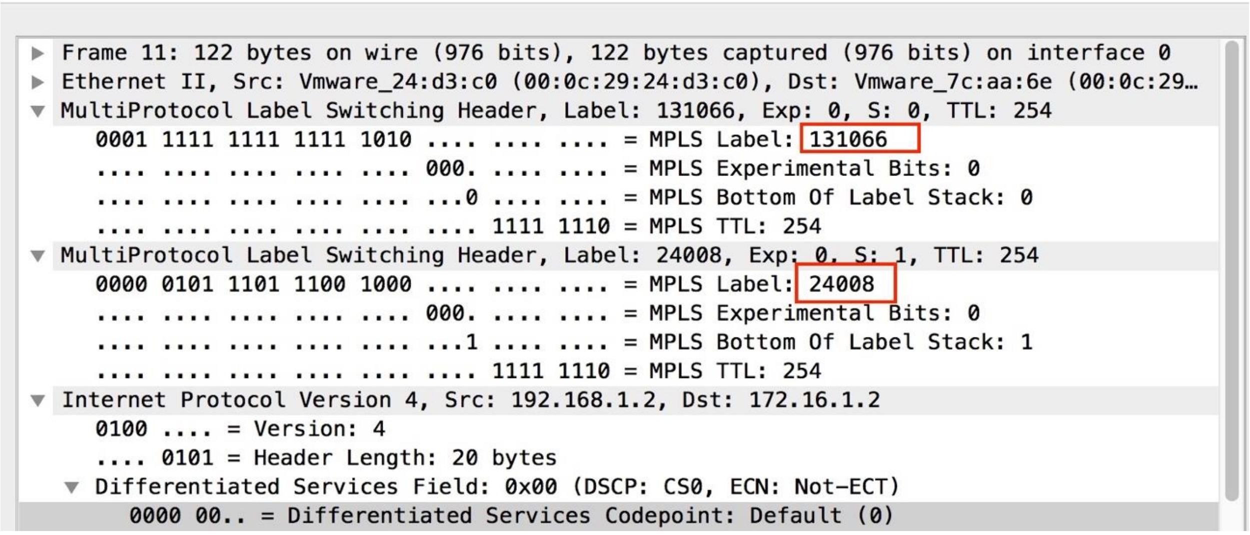


Fig 6.3 a wireshark capture showing MPLS label in the packet forwarded to 10.10.10.2

6.3.2 Labels on ACCESS-LSR

6.3.2.1 Control Plane Operations

The vpn service label **(24008)** remains unchanged on this router.

BGP-LU label assignment

ACCESS-LSR receives BGP label (**131064**) from its BGP neighbor (10.10.10.3) for the prefix 10.10.10.6/32 of which the stiches (by redistribution of BGP FEC to LDP done in the configuration above) to the LPD tunnel to the ACCESS-NODE.
It then installs BGP tunnel to CORE-PE (10.10.10.6)

A:ACCESS-LSR# **show router bgp routes 10.10.10.6/32**

```
===============================================================
 BGP Router ID:10.10.10.2       AS:64496       Local AS:64496
===============================================================
 Legend -
 Status codes  : u - used, s - suppressed, h - history, d - decayed, * - valid
                 l - leaked, x - stale, > - best, b - backup, p - purge
 Origin codes  : i - IGP, e - EGP, ? - incomplete

===============================================================
BGP IPv4 Routes
===============================================================
Flag  Network                                      LocalPref   MED
      Nexthop (Router)                              Path-Id     Label
      As-Path
-------------------------------------------------------------------------------
u*>i  10.10.10.6/32                                  100        0
      10.10.10.3                                   None        131064
```

LDP Label Assignment

ACCESS-LSR Receives LDP label (**131071**) from its next hop router 10.10.10.3 (ACCESS-AGGREGATION_ABR)

A:ACCESS-LSR# **show router ldp bindings prefixes prefix 10.10.10.3/32**

```
===============================================================
LDP Bindings (IPv4 LSR ID 10.10.10.2:0)
             (IPv6 LSR ID ::[0])
===============================================================
Legend: U - Label In Use,  N - Label Not In Use, W - Label Withdrawn
        WP - Label Withdraw Pending, BU - Alternate For Fast Re-Route
===============================================================
LDP IPv4 Prefix Bindings
===============================================================
Prefix                             IngLbl               EgrLbl
Peer                               EgrIntf/LspId
EgrNextHop
-------------------------------------------------------------------------------
```

```
10.10.10.3/32                    --                 131071
10.10.10.3:0                     1/1/1
192.168.7.2

-------------------------------------------------------------------------------
```

6.3.2.2 Data Plane Operations

When ACCESS-LSR receives a packet with LDP label **131066** from the ACCES-NODE (10.10.10.1) it swaps the LDP label **131066**l with the BGP label **131064** and then forwards it to 10.10.10.3 after pushing LDP label **131071** on top. It can verified from below that the LSPID 65538 of the of the BGP tunnel is the same as the LDP tunnel ID originating from 10.10.10.1 and terminating on this node.

A:ACCESS-LSR# **show router ldp bindings active prefixes prefix 10.10.10.6/32**

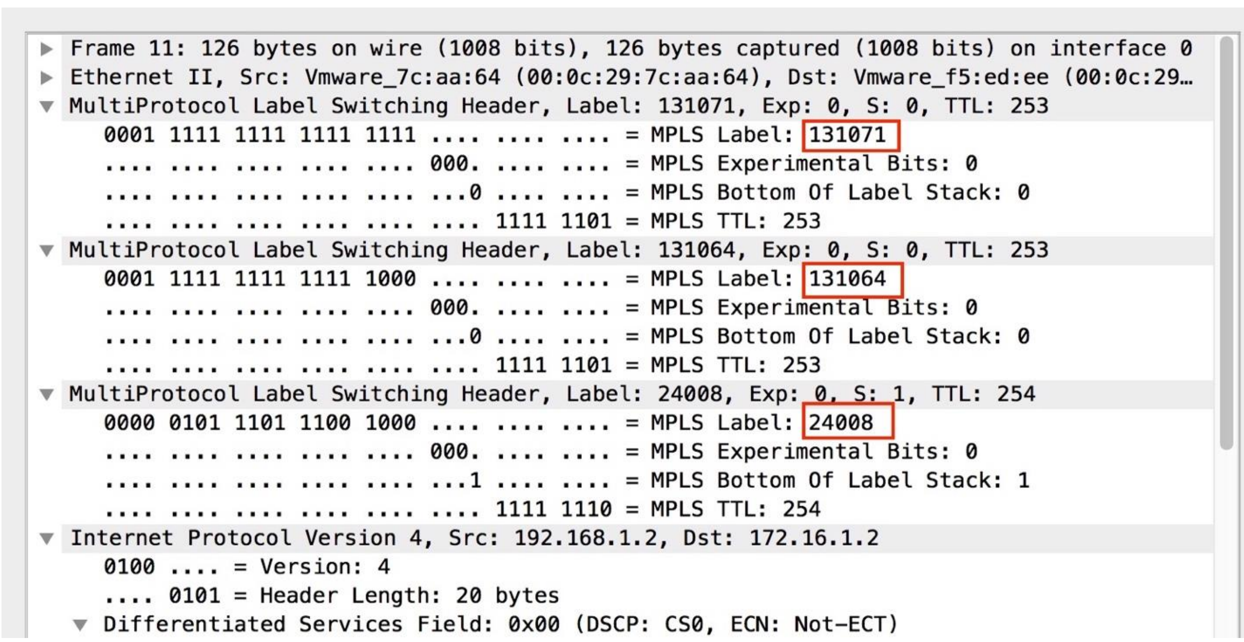
```
===============================================================================
LDP Bindings (IPv4 LSR ID 10.10.10.2:0)
          (IPv6 LSR ID ::[0])
===============================================================================
Legend: U - Label In Use,  N - Label Not In Use, W - Label Withdrawn
      WP - Label Withdraw Pending, BU - Alternate For Fast Re-Route
      (S) - Static       (M) - Multi-homed Secondary Support
      (B) - BGP Next Hop (BU) - Alternate Next-hop for Fast Re-Route
      (C) - FEC resolved for class-based-forwarding
===============================================================================
LDP IPv4 Prefix Bindings (Active)
===============================================================================
Prefix                             Op            IngLbl    EgrLbl
EgrNextHop                         EgrIf/LspId
-------------------------------------------------------------------------------
10.10.10.6/32(B)                   Swap          131066    131064
10.10.10.3                         LspId 65538

-------------------------------------------------------------------------------
```

A:ACCESS-LSR# **show router tunnel-table**

```
===============================================================================
IPv4 Tunnel Table (Router: Base)
===============================================================================
Destination      Owner    Encap TunnelId  Pref    Nexthop        Metric
-------------------------------------------------------------------------------
10.10.10.1/32    ldp      MPLS  65537     9       192.168.7.18   1
10.10.10.3/32    ldp      MPLS  65538     9       192.168.7.2    10
10.10.10.6/32    bgp      MPLS  262145    12      10.10.10.3     1000
-------------------------------------------------------------------------------
```

A:ACCESS-LSR# **show router ldp bindings active prefixes prefix 10.10.10.3/32**

```
===============================================================
LDP Bindings (IPv4 LSR ID 10.10.10.2:0)
          (IPv6 LSR ID ::[0])
===============================================================
Legend: U - Label In Use,  N - Label Not In Use, W - Label Withdrawn
      WP - Label Withdraw Pending, BU - Alternate For Fast Re-Route
      (S) - Static      (M) - Multi-homed Secondary Support
      (B) - BGP Next Hop (BU) - Alternate Next-hop for Fast Re-Route
      (C) - FEC resolved for class-based-forwarding
===============================================================
LDP IPv4 Prefix Bindings (Active)
===============================================================
Prefix                          Op          IngLbl    EgrLbl
EgrNextHop                          EgrIf/LspId
-------------------------------------------------------------------------------
10.10.10.3/32                       Push          --      131071
192.168.7.2                        1/1/1
```



```
▶ Frame 11: 126 bytes on wire (1008 bits), 126 bytes captured (1008 bits) on interface 0
▶ Ethernet II, Src: Vmware_7c:aa:64 (00:0c:29:7c:aa:64), Dst: Vmware_f5:ed:ee (00:0c:29…
▼ MultiProtocol Label Switching Header, Label: 131071, Exp: 0, S: 0, TTL: 253
    0001 1111 1111 1111 1111 .... .... .... = MPLS Label: 131071
    .... .... .... .... .... 000. .... .... = MPLS Experimental Bits: 0
    .... .... .... .... .... ...0 .... .... = MPLS Bottom Of Label Stack: 0
    .... .... .... .... .... .... 1111 1101 = MPLS TTL: 253
▼ MultiProtocol Label Switching Header, Label: 131064, Exp: 0, S: 0, TTL: 253
    0001 1111 1111 1111 1000 .... .... .... = MPLS Label: 131064
    .... .... .... .... .... 000. .... .... = MPLS Experimental Bits: 0
    .... .... .... .... .... ...0 .... .... = MPLS Bottom Of Label Stack: 0
    .... .... .... .... .... .... 1111 1101 = MPLS TTL: 253
▼ MultiProtocol Label Switching Header, Label: 24008, Exp: 0, S: 1, TTL: 254
    0000 0101 1101 1100 1000 .... .... .... = MPLS Label: 24008
    .... .... .... .... .... 000. .... .... = MPLS Experimental Bits: 0
    .... .... .... .... .... ...1 .... .... = MPLS Bottom Of Label Stack: 1
    .... .... .... .... .... .... 1111 1110 = MPLS TTL: 254
▼ Internet Protocol Version 4, Src: 192.168.1.2, Dst: 172.16.1.2
    0100 .... = Version: 4
    .... 0101 = Header Length: 20 bytes
  ▼ Differentiated Services Field: 0x00 (DSCP: CS0, ECN: Not-ECT)
```

Fig 6.4 a wireshark capture showing MPLS label in the packet forwarded to 10.10.10.3

6.3.3 Label Operations on ACCESS-AGGREGATION_ABR

6.3.3.1 Control Plane Operations

The vpn service label **(24008)** remains unchanged on this router.

BGP-LU label assignment

ACCESS-AGGREGATION_ABR receives BGP label (**131066**) from its BGP neighbor (10.10.10.4) for the prefix 10.10.10.6/32 as shown in the output below. It then installs BGP tunnel to CORE-PE (10.10.10.6).

A:ACCESS-AGGREGATION_ABR# **show router bgp routes 10.10.10.6**

```
===============================================================
 BGP Router ID:10.10.10.3       AS:64496       Local AS:64496
===============================================================
 Legend -
 Status codes  : u - used, s - suppressed, h - history, d - decayed, * - valid
                 l - leaked, x - stale, > - best, b - backup, p - purge
 Origin codes  : i - IGP, e - EGP, ? - incomplete

===============================================================
BGP IPv4 Routes
===============================================================
Flag  Network                                   LocalPref   MED
      Nexthop (Router)                           Path-Id     Label
      As-Path
-------------------------------------------------------------------------------
u*>i  10.10.10.6/32                               100        0
      10.10.10.4                                 None        131066
      No As-Path
-------------------------------------------------------------------------------
```

A:ACCESS-AGGREGATION_ABR# **show router tunnel-table**

```
===============================================================
IPv4 Tunnel Table (Router: Base)
===============================================================
Destination       Owner     Encap TunnelId  Pref     Nexthop        Metric
-------------------------------------------------------------------------------
10.10.10.1/32     bgp       MPLS  262145    12       10.10.10.2     1000
10.10.10.2/32     ldp       MPLS  65537     9        192.168.7.1    10
10.10.10.4/32     ldp       MPLS  65538     9        192.168.7.6    10
10.10.10.6/32     bgp       MPLS  262146    12       10.10.10.4     1000
-------------------------------------------------------------------------------
```

LDP label assignment

ACCESS-AGGREGATION_ABR Receives LDP label (**131071**) from its next hop router 10.10.10.4 (AGGREGATION-CORE_ABR).

A:ACCESS-AGGREGATION_ABR# **show router ldp bindings prefixes prefix 10.10.10.**4/32

```
===============================================================
LDP Bindings (IPv4 LSR ID 10.10.10.3:0)
          (IPv6 LSR ID ::[0])
===============================================================
Legend: U - Label In Use,  N - Label Not In Use, W - Label Withdrawn
      WP - Label Withdraw Pending, BU - Alternate For Fast Re-Route
===============================================================
LDP IPv4 Prefix Bindings
===============================================================
Prefix                          IngLbl              EgrLbl
Peer                            EgrIntf/LspId
EgrNextHop
------------------------------------------------------------------------------
10.10.10.4/32                       131071U                 --
10.10.10.2:0                         --
  --

10.10.10.4/32                        --                 131071
10.10.10.4:0                         1/1/2
192.168.7.6

------------------------------------------------------------------------------
```

6.3.3.2 Data Plane Operations

ACCESS-LSR LDP tunnel ends on this router as shown below from the output of " show router tunnel-table'" from ACCESS-LSR.
When ACCESS-AGGREGATION_ABR receives a packet with LDP label **131071** from the ACCES-LSR (10.10.10.2) it pops the BGP label 131064 and pushes BGP label **131066** as it is configured as the BGP next-hop. It then forwards the packet to 10.10.10.4 after popping the LDP label **131071** pushing LDP label **131071** on top as shown below.

A:ACCESS-LSR**# show router tunnel-table**

```
===============================================================
IPv4 Tunnel Table (Router: Base)
===============================================================
Destination      Owner     Encap TunnelId  Pref     Nexthop        Metric
------------------------------------------------------------------------------
```

```
10.10.10.1/32     ldp       MPLS  65537     9        192.168.7.18   1
10.10.10.3/32     ldp       MPLS  65538     9        192.168.7.2    10
10.10.10.6/32     bgp       MPLS  262145    12       10.10.10.3     1000
-------------------------------------------------------------------------------

A:ACCESS-AGGREGATION_ABR# show router bgp inter-as-label

===============================================================================
BGP Inter-AS labels
Flags: B - entry has backup, P - entry is promoted
===============================================================================
NextHop                  Received      Advertised     Label
                         Label         Label          Origin
-------------------------------------------------------------------------------
10.10.10.2               131067        131064         Internal
10.10.10.4               131066        131065         Internal
-------------------------------------------------------------------------------


A:ACCESS-AGGREGATION_ABR# show router ldp bindings active prefixes prefix 10.10.10.3/32

===============================================================================
LDP Bindings (IPv4 LSR ID 10.10.10.3:0)
             (IPv6 LSR ID ::[0])
===============================================================================
Legend: U - Label In Use,  N - Label Not In Use, W - Label Withdrawn
        WP - Label Withdraw Pending, BU - Alternate For Fast Re-Route
        (S) - Static       (M) - Multi-homed Secondary Support
        (B) - BGP Next Hop (BU) - Alternate Next-hop for Fast Re-Route
        (C) - FEC resolved for class-based-forwarding
===============================================================================
LDP IPv4 Prefix Bindings (Active)
===============================================================================
Prefix                                Op          IngLbl    EgrLbl
EgrNextHop                            EgrIf/LspId
-------------------------------------------------------------------------------
10.10.10.3/32                         Pop         131071    --
  --                                  --

-------------------------------------------------------------------------------


A:ACCESS-AGGREGATION_ABR# show router ldp bindings active prefixes prefix 10.10.10.4/32

===============================================================================
LDP Bindings (IPv4 LSR ID 10.10.10.3:0)
             (IPv6 LSR ID ::[0])
===============================================================================
```

```
Legend: U - Label In Use,  N - Label Not In Use, W - Label Withdrawn
        WP - Label Withdraw Pending, BU - Alternate For Fast Re-Route
        (S) - Static       (M) - Multi-homed Secondary Support
        (B) - BGP Next Hop (BU) - Alternate Next-hop for Fast Re-Route
        (C) - FEC resolved for class-based-forwarding
===============================================================
LDP IPv4 Prefix Bindings (Active)
===============================================================
Prefix                              Op            IngLbl    EgrLbl
EgrNextHop                              EgrIf/LspId
-------------------------------------------------------------------------------
10.10.10.4/32                           Push            --      131071
192.168.7.6                            1/1/2

10.10.10.4/32                           Swap          131070    131071
192.168.7.6                            1/1/2
```

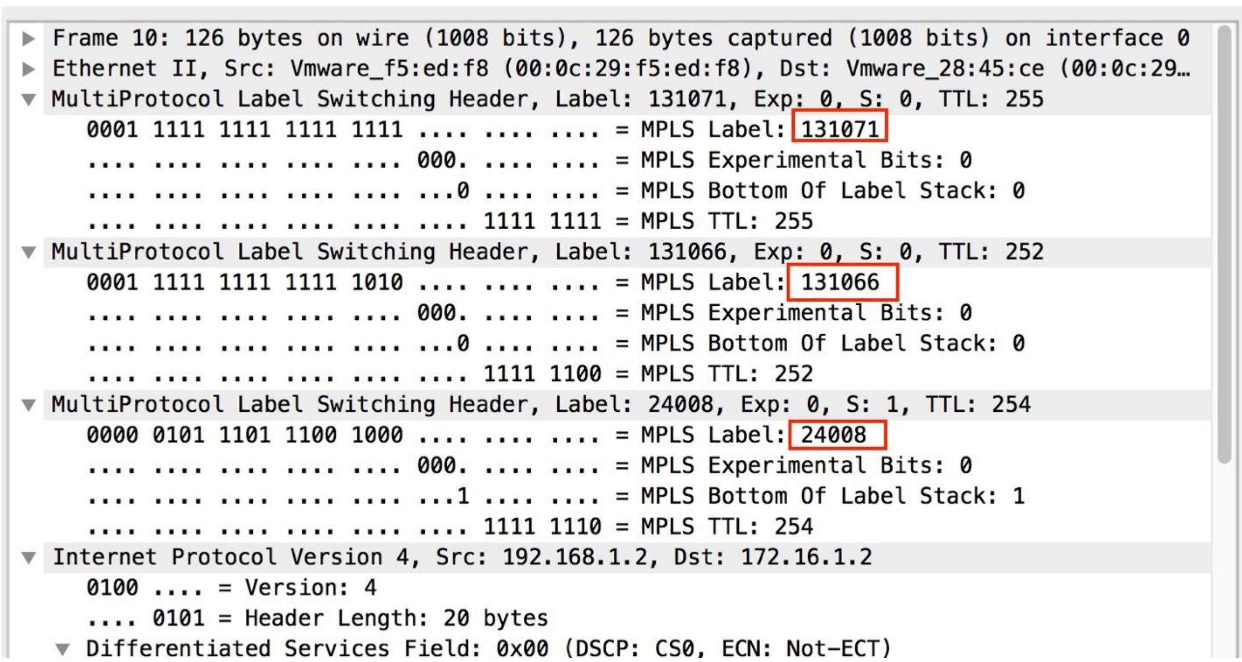


Fig 6.5 a wireshark capture showing MPLS label in the packet forwarded to 10.10.10.4

6.3.4 Label Operations on AGGREGATION-CORE_ABR (10.10.10.4)

6.3.4.1 Control Plane Operations

The vpn service label **(24008)** remains unchanged.

BGP-LU label assignment

AGGREGATION-CORE_ABR receives BGP label 3 (implicit Null) from its BGP neighbor (10.10.10.6) for the prefix 10.10.10.6/32 as show in the output below.

```
A:AGGREGATION-CORE_ABR# show router bgp routes 10.10.10.6
===============================================================
 BGP Router ID:10.10.10.4       AS:64496       Local AS:64496
===============================================================
 Legend -
 Status codes  : u - used, s - suppressed, h - history, d - decayed, * - valid
                l - leaked, x - stale, > - best, b - backup, p - purge
 Origin codes  : i - IGP, e - EGP, ? - incomplete

===============================================================
BGP IPv4 Routes
===============================================================
Flag  Network                                   LocalPref   MED
      Nexthop (Router)                           Path-Id     Label
      As-Path
-------------------------------------------------------------------------------
*i    10.10.10.6/32                              100         0
      10.10.10.6                                 None        3
      No As-Path
-------------------------------------------------------------------------------
```

LDP label assignment

AGGREGATION-CORE_ABR having LDP tunnel to 10.10.10.6 Receives LDP label (**131067**) for FEC 10.10.10.6/32 from its next hop router 10.10.10.5 (CORE-LSR).

```
A:AGGREGATION-CORE_ABR# show router ldp bindings prefixes prefix 10.10.10.6/32

===============================================================
LDP Bindings (IPv4 LSR ID 10.10.10.4:0)
             (IPv6 LSR ID ::[0])
===============================================================
Legend: U - Label In Use,  N - Label Not In Use, W - Label Withdrawn
        WP - Label Withdraw Pending, BU - Alternate For Fast Re-Route
===============================================================
LDP IPv4 Prefix Bindings
===============================================================
Prefix                            IngLbl               EgrLbl
Peer                              EgrIntf/LspId
EgrNextHop
-------------------------------------------------------------------------------
```

```
10.10.10.6/32                    131067U              --
10.10.10.3:0                      --
  --
10.10.10.6/32                    131067N             131067
10.10.10.5:0                     1/1/1
192.168.7.10

-------------------------------------------------------------------------------
```

A:AGGREGATION-CORE_ABR# **show router tunnel-table**

```
===============================================================================
IPv4 Tunnel Table (Router: Base)
===============================================================================
Destination      Owner     Encap TunnelId  Pref     Nexthop        Metric
-------------------------------------------------------------------------------
10.10.10.1/32     bgp       MPLS  262145    12      10.10.10.3      1000
10.10.10.2/32     ldp      MPLS  65538     9       192.168.7.5    20
10.10.10.3/32     ldp      MPLS  65537     9       192.168.7.5    10
10.10.10.5/32     ldp      MPLS  65539     9       192.168.7.10   10
10.10.10.6/32     ldp      MPLS  65540     9       192.168.7.10   30
-------------------------------------------------------------------------------
```

6.3.4.2 Data Plane Operations

The LDP tunnel from 10.10.10.3 end on this router so it pops the LDP label **131071.** Being the BGP next-hop router, it also pops the BGP label 131066.

A:AGGREGATION-CORE_ABR# show router ldp bindings active prefixes prefix 10.10.10.4/32

```
===============================================================================
LDP Bindings (IPv4 LSR ID 10.10.10.4:0)
             (IPv6 LSR ID ::[0])
===============================================================================
Legend: U - Label In Use,  N - Label Not In Use, W - Label Withdrawn
        WP - Label Withdraw Pending, BU - Alternate For Fast Re-Route
        (S) - Static       (M) - Multi-homed Secondary Support
        (B) - BGP Next Hop (BU) - Alternate Next-hop for Fast Re-Route
        (C) - FEC resolved for class-based-forwarding
===============================================================================
LDP IPv4 Prefix Bindings (Active)
===============================================================================
Prefix                          Op            IngLbl    EgrLbl
EgrNextHop                          EgrIf/LspId
-------------------------------------------------------------------------------
10.10.10.4/32                       Pop           131071     --
  --                              --
```

Since it received implicit null label from router 10.10.10.6 it only pushes LDP label 131067 on top of the vpn service label and forwards the packet to router 10.10.10.5 (CORE-LSR)

```
A:AGGREGATION-CORE_ABR# show router ldp bindings active prefixes prefix 10.10.10.6/32

===============================================================
LDP Bindings (IPv4 LSR ID 10.10.10.4:0)
          (IPv6 LSR ID ::[0])
===============================================================
Legend: U - Label In Use,  N - Label Not In Use, W - Label Withdrawn
       WP - Label Withdraw Pending, BU - Alternate For Fast Re-Route
       (S) - Static       (M) - Multi-homed Secondary Support
       (B) - BGP Next Hop (BU) - Alternate Next-hop for Fast Re-Route
       (C) - FEC resolved for class-based-forwarding
===============================================================
LDP IPv4 Prefix Bindings (Active)
===============================================================
Prefix                          Op           IngLbl    EgrLbl
EgrNextHop                          EgrIf/LspId
-------------------------------------------------------------------------------
10.10.10.6/32                       Push            --      131067
192.168.7.10                        1/1/1

10.10.10.6/32                       Swap         131067    131067
192.168.7.10                        1/1/1

-------------------------------------------------------------------------------
```

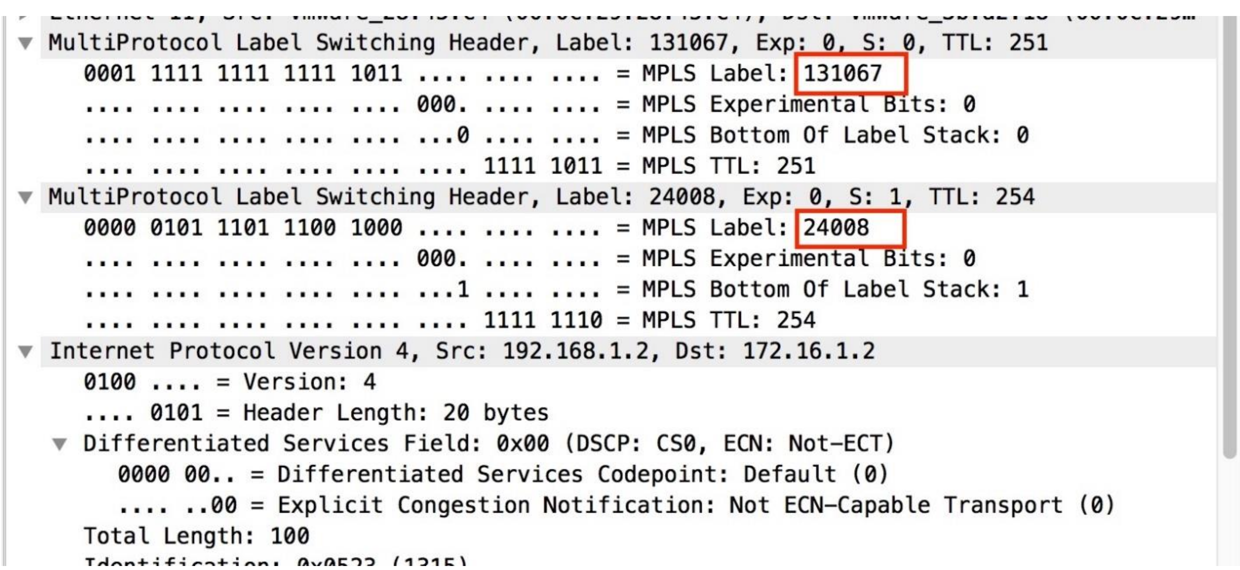


Fig 6.6 a wireshark capture showing MPLS label in the packet forwarded to 10.10.10.5

6.3.5 Label Operations on CORE-LSR (10.10.10.5)

6.3.5.1 Control Plane Operations

The vpn service label **(24008)** remains unchanged and there is no BGP enabled on this node.

LDP label assignment

CORE-LSR Receives LDP label 3 implicit null for FEC 10.10.10.6/32 from its neighbor router 10.10.10.6 (CORE-PE).

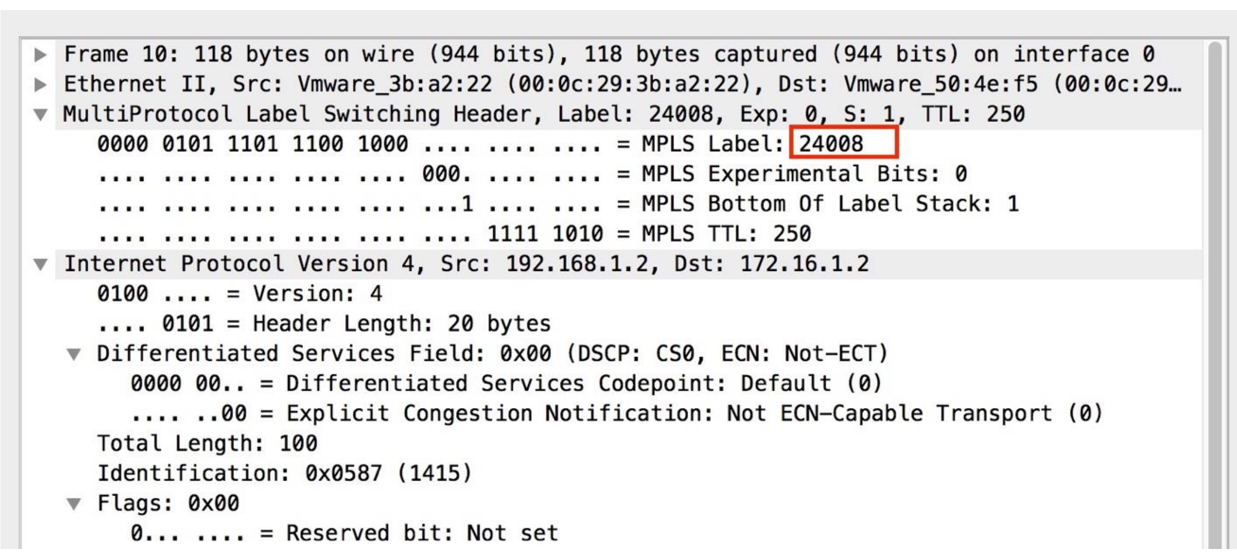
A:CORE-LSR# **show router ldp bindings prefixes prefix 10.10.10.6/32**

```
===============================================================
LDP Bindings (IPv4 LSR ID 10.10.10.5:0)
            (IPv6 LSR ID ::[0])
===============================================================
Legend: U - Label In Use,  N - Label Not In Use, W - Label Withdrawn
       WP - Label Withdraw Pending, BU - Alternate For Fast Re-Route
===============================================================
LDP IPv4 Prefix Bindings
===============================================================
Prefix                              IngLbl              EgrLbl
Peer                                EgrIntf/LspId
EgrNextHop
-------------------------------------------------------------------------------
10.10.10.6/32                           131067U             131067
10.10.10.4:0                            --
  --

10.10.10.6/32                           --                  3
10.10.10.6:0                            1/1/2
192.168.7.14

-------------------------------------------------------------------------------
```

6.3.5.2 Data Plane Operations

This router being the penultimate router, when it receives a packet from 10.10.10.4 with LDP label 131067, it pops the label and forward the packet encapsulated in only the vpn service label **24008** to CORE-PE.

```
A:CORE-LSR# show router ldp bindings active prefixes prefix 10.10.10.6/32

===============================================================
LDP Bindings (IPv4 LSR ID 10.10.10.5:0)
          (IPv6 LSR ID ::[0])
===============================================================
Legend: U - Label In Use,  N - Label Not In Use, W - Label Withdrawn
      WP - Label Withdraw Pending, BU - Alternate For Fast Re-Route
      (S) - Static       (M) - Multi-homed Secondary Support
      (B) - BGP Next Hop (BU) - Alternate Next-hop for Fast Re-Route
      (C) - FEC resolved for class-based-forwarding
===============================================================
LDP IPv4 Prefix Bindings (Active)
===============================================================
Prefix                              Op            IngLbl    EgrLbl
EgrNextHop                              EgrIf/LspId
-------------------------------------------------------------------------------
10.10.10.6/32                           Push              --      3
192.168.7.14                            1/1/2

10.10.10.6/32                           Swap          131067    3
192.168.7.14                            1/1/2

-------------------------------------------------------------------------------
```



```
▶ Frame 10: 118 bytes on wire (944 bits), 118 bytes captured (944 bits) on interface 0
▶ Ethernet II, Src: Vmware_3b:a2:22 (00:0c:29:3b:a2:22), Dst: Vmware_50:4e:f5 (00:0c:29…
▼ MultiProtocol Label Switching Header, Label: 24008, Exp: 0, S: 1, TTL: 250
    0000 0101 1101 1100 1000 .... .... .... = MPLS Label: 24008
    .... .... .... .... .... 000. .... .... = MPLS Experimental Bits: 0
    .... .... .... .... .... ...1 .... .... = MPLS Bottom Of Label Stack: 1
    .... .... .... .... .... .... 1111 1010 = MPLS TTL: 250
▼ Internet Protocol Version 4, Src: 192.168.1.2, Dst: 172.16.1.2
    0100 .... = Version: 4
    .... 0101 = Header Length: 20 bytes
  ▼ Differentiated Services Field: 0x00 (DSCP: CS0, ECN: Not-ECT)
      0000 00.. = Differentiated Services Codepoint: Default (0)
      .... ..00 = Explicit Congestion Notification: Not ECN-Capable Transport (0)
    Total Length: 100
    Identification: 0x0587 (1415)
  ▼ Flags: 0x00
      0... .... = Reserved bit: Not set
```

Fig 6.7 a wireshark capture showing MPLS label in the packet forwarded to 10.10.10.6

6.3.6 Label Operations on CORE-PE

6.3.6.1 Control Plane Operations

CORE-PE assigns VPN service label **24008** for vrf VRF-A and signals it to ACCESS-NODE

```
RP/0/0/CPU0:CORE-PE#show mpls forwarding labels 24008
Sun Dec 11 15:41:17.529 UTC
Local  Outgoing    Prefix             Outgoing     Next Hop        Bytes
Label  Label       or ID              Interface                    Switched
------ ----------- ------------------ ------------ --------------- ------------
24008  Aggregate   VRF-A: Per-VRF Aggr[V]   \
                                      VRF-A                        81212
RP/0/0/CPU0:CORE-PE#
```

LDP and BGP-LU Label Assignment

CORE-PE assigns implicit Null label (3) and for its FEC 10.10.10.6/32 as both the LDP and BGP-LU label and advertises it o 10.10.10.5 and 10.10.10.4 respectively.

6.3.6.2 Data Plane Operation

When router CORE-PE receives the packet with only the VPN label 24008, it pops it and places the unencapsulated packet in the appropriate service (VRF-A).
The packet then gets forwarded to the SGW.

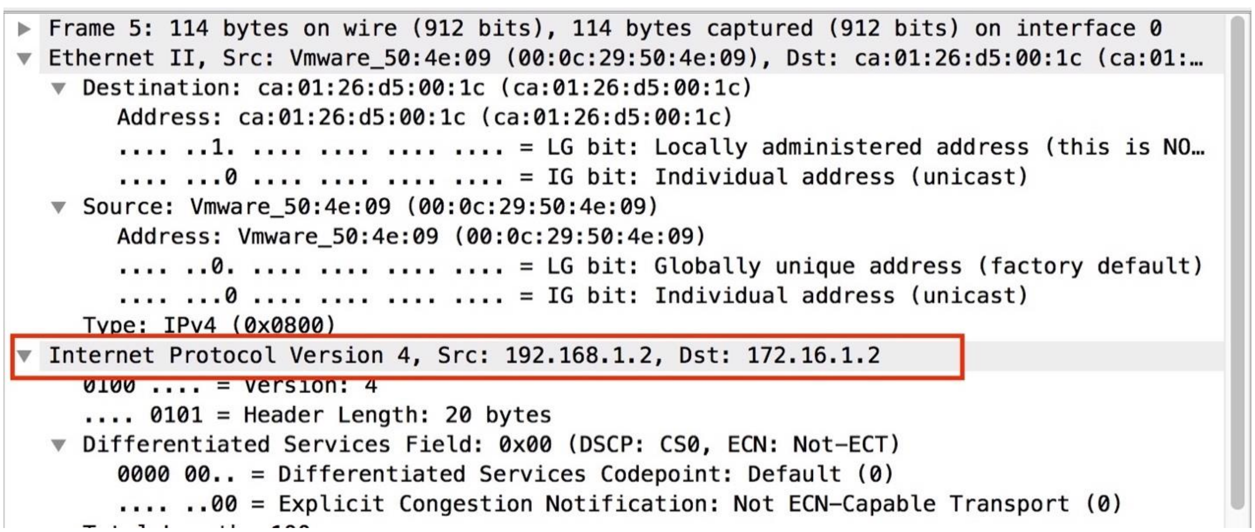


Fig 6.8 a wireshark capture showing IP packet forwarded to SGW (172.16.1.2).

CHAPTER 7

7.0 ADVANCEMENT IN THE IP INDUSTRY AND IN IETF WHICH IS APPLICABLE TO LTE BACKHAUL DESIGNS

7.1 Source Packet Routing in Networking (SPRING)

Salability is of the paramount concern in designing LTE transport. Among several ways of achieving scalability are by reducing the number of routing protocols and LSP session states in the network. MPLS capabilities of SPRING can therefore be harnessed into the LTE network especially in the access domain where low end IP/MPLS nodes reside. SPRING also known as Segment Routing does not aims at replacing existing source routing and traffic-engineering technologies but complements them by using it where removal of signaling and path state in the transport network is required.

7.2 SPRING TERMINOLOGIES

Source Routing: Path to a destination network is explicitly defined in the packet header by the source.

Segment Routing: Instructions (MPLS labels) are distributed in IGP and packets are forwarded base on the stack of these MPLS labels. Spring segments may be classified as Adjacency segment and node segment.

7.3 Adjacency Segment Advertisement and Forwarding

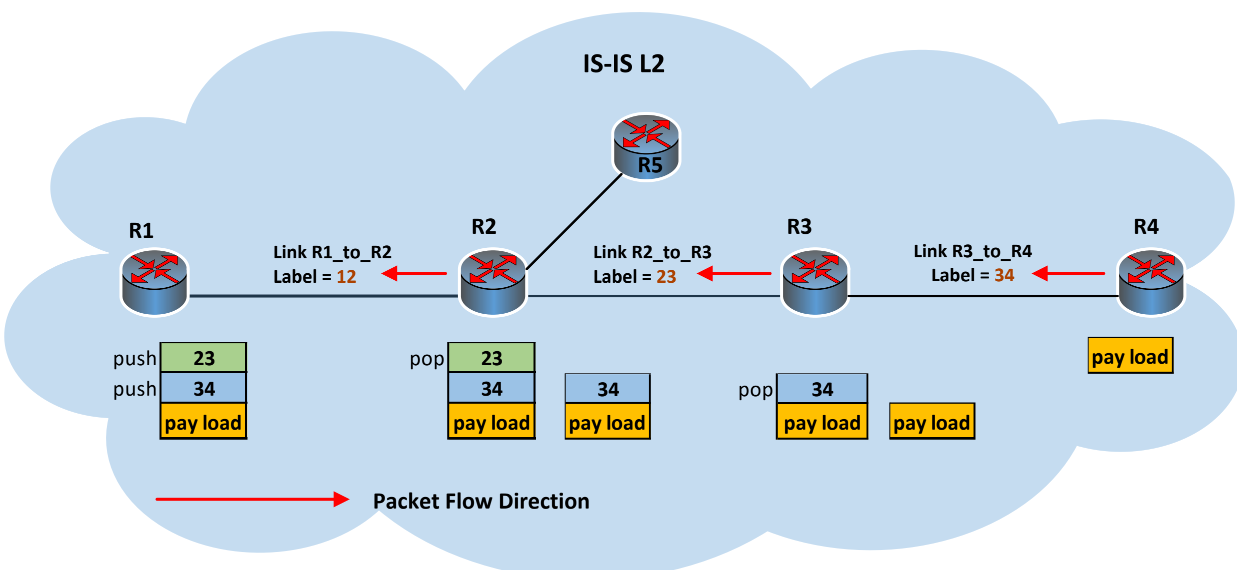


figure 7.1 SPRING Adjacency segment label advertisement and packet forwarding

With this type of advertisement, a router allocates labels for each of its links and advertise them in conjunction with the link. All routers in the domain receive the advertisement. **[9] [10] [13]**
In fig x above:
Router R4 advertises label 34 for the between link R3 and R4.
Router R3 advertises label 23 for the between link R2 and R3.
Router R2 advertises label 12 for the between link R1 and R2.

When Router needs to send packet to Router R4 it pushes the labels 23:34 on the payload.
When Router R2 receives the packet it only Pops the outer label 23 and forward the resultant packet to R3 on the link R2_to_R3.
When Router R3 receives the packet, it Pops the outer label 34 and forward the payload to R4 on the link R3_to_R4.

From the above scenario, it can be seen clearly that the forwarding path was explicitly dictated by the source router R1.

7.4 Node Segment Advertisement and Forwarding

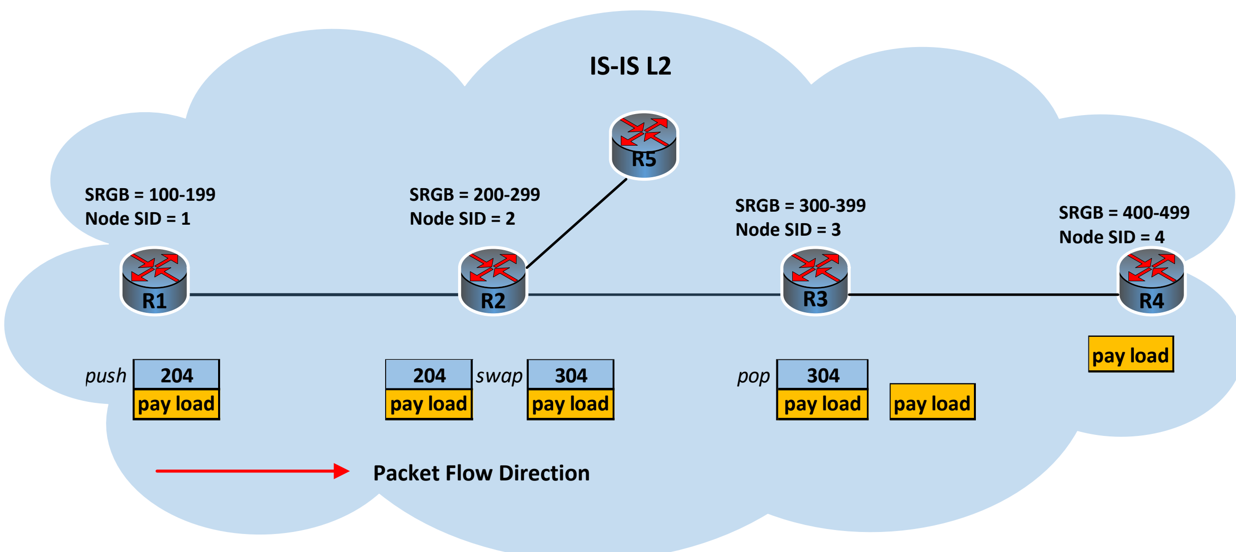


figure 7.2 SPRING Node segment label advertisement and packet forwarding

With Node segment advertisement, each router (Node) advertises a global index also known as Node Segment Identifier (Node SID) and local block known as Segment Routing Global Block (SRGB) in IGP (IS-IS or OSPF). SRGB is a locally significant MPLS label block that each MPLS router assigns to SPRING global segments.
SRGB is encodes as a Base and a Range. The Lowest label value equals to the Base. The highest label value equals to the Base + Range – 1. **[9] [10] [13]**

When Router R1 needs forward packet to Router R4:

Label Operations on Router R1

Outgoing label to R2 = R2's Label-Base + R4's Node SID = 200+4 = 204.
Router R1 pushes the label 204 on the payload and forwards it to router R2.

Label Operations on Router R2

Incoming label = R2's Label-Base + R4's Node SID = 200+4 = 204.
Outgoing label to R3 = R3's Label-Base + R4's Node SID = 300+4 = 304.

When Router R2 receives a packet with label 204 it knows it is destined to router R4.
It then swaps label 204 with label 304 and forwards the packet to router R3

Label Operations on Router R3

Incoming label = R3's Label-Base + R4's Node SID = 300+4 = 304.
Outgoing label to R4 = R4's Label-Base + R4's Node SID = 400+4 = 404.

When Router R3 receives a packet with label 304 it knows it is destined to router R4.
With Penultimate Hop Popping *(PHP)* enabled, R3 pops the label 304 and then forwards the payload to router R4.

7.5 SPRING as an alternative to LDP and RSVP-TE

1. With SPRING, MPLS labels are advertised by IGP (OSPF or IS-IS) without the use of LDP or RSVP-TE thus reducing the number of protocols running in the network.
2. SPRING naturally supports ECMP and has more scalable control plane as it does not need to keep per-LSP state.
3. SPRING facilitates troubleshooting because of its deterministic labels.

4. One instruction (label/Node SID) takes you from the source to the destination via whatever ECMP path is available between them.
5. Good for incorporating with central Controllers such as Path Computation Element (PCE). PCE aides SPRING nodes to signal TE-LSPs.

CONCLUSION

IP/MPLS is ubiquitous in today's Service Provider network because of its scalability, high availability, traffic engineering and rich VPN features set. Large IP/MPLS networks must be split into smaller domain due to the scalability constraints of the underlying IGP and RVP-TE PE-to-PE LSP states. There are several options to join the resultant smaller domains to provide end-to-end MPLS network. Among these methods are LDP over RSVP-TE and BGP-LU. The preferred method of building seamless end-to-end MPLS network is by using BGP-LU because BGP has proven to be the most scalable routing protocol and moreover BGP-LU is not protocol agnostic- it can be tunneled in LDP, RSVP-TE or SPRING.

User traffic paradigm has necessitated that service providers bring IP/MPLS VPN services closer to their customers thus extending MPLS to the Access Network. The Access Nodes (Cell site Routers) normally have limited capabilities hence the number of protocols and LSP states must be kept as low as possible. One way to achieve this is to run LDP DoD on them. The LDP LSP can then be stitched to BGP-LU tunnel at the more powerful aggregation routers to provide Seamless MPLS network.

Scalability in a domain can be more enhanced by having the IGP (OSPF or IS-IS) themselves do the label advertisement other than have LDP or RSVP run on top of IGP to do label advertisement. That is what SPRING brings on board.

REFERENCES

[1] Universal Access and Aggregation Mobile Backhaul Design Guide. Juniper Networks, 2013. pp. 17. [online]. Available: http://www.juniper.net/us/en/local/pdf/design-guides/8020018-en.pdf

[2] Alcatel-Lucent Multiprotocol Label Switching Student Guide, v2-1. Alcatel-Lucent, 2011 pp. 25, 84-110, 126-139, 202, 455

[3] Alcatel-Lucent IP MPLS Mobile Backhaul Transport Student Guide, v1.0.1. Alcatel-Lucent, 2012 pp. 65

[4] "Network Configuration," *Example Configuring the Broadband Edge as a Service NodeWithin Seamless MPLS Network Designs.* Juniper Networks, 2016. pp. 3. [online]. Available: http://www.juniper.net/techpubs/en_US/release-independent/nce/information-products/pathway-pages/nce/nce-141-bbe-solution-2.0-seamless-mpls.pdf

[5] I. Minei, J. Lucek, "MPLS Enabled Applications," *Emerging Developments and New Technologies, 3rd ed*. John Wiley & Sons, 2011. pp. 494 – 497 [online]. Available:http://stud.netgroup.uniroma2.it/~saverio/MPLSEnabledApplicationsEmergingDevelopments3e9a5.pdf

[6] "7450 Ethernet Service Switch 7750 Service Router 7950 Extensible Routing System Releases Up To 13.0.R7," *Advanced Configuration Guide - Part I* Alcatel-Lucent, 2016. pp. 516-517

[7] "Evolving to end-to-end MPLS architectures," *Nokia enables seamless, scalable, resilient MPLS networks*, Nokia 2016. [online]. Available: https://resources.alcatel-lucent.com/asset/168429

[8] A. Sanchez-Monge, K. G. Szarkowicz "Mpls in The SDN Era," *Interoperable Scenarios to Make Networks Scale to New Services* ,1st ed. O'Reilly Media, December 2016. pp. 92-104

[9] C. Bowers "Spring Technology, Applications, and Demo," Juniper Networks, Dec. 7, 2015. [online]. Available: http://ix.br/pttforum/9/slides/ixbr9-spring.pdf

[10] N. Slabakov "Spring Routing 2.0," Juniper Networks. [online]. Available: https://www.nanog.org/sites/default/files/meetings/NANOG64/1030/20150603_Slabakov_Source_Routing_2_0__v1.pdf

[11] Y. Rekhter, E. Rosen, "Carrying Label Information in BGP-4", RFC 3107, May 2001

[12] L. Andersson, I. Minei, B. Thomas, "LDP Specification", RFC 5036, October 2007

[13] S. Previdi, C. Filsfils, B. Decraene, S. Litkowski, M. Horneffer, R. Shakir “Source PacketRouting in Networking (SPRING) Problem Statement and Requirements”, RFC 7855, May 2016

[14] T. Beckhaus, B. Decraene, K. Tiruveedhula, M. Konstantynowicz, L. Martini “LDP Downstream-on-Demand in Seamless MPLS” RFC 7032, October 2013

[15] E. Rosen, A. Viswanathan, R. Callon “Multiprotocol Label Switching Architecture” RFC 3031, January 2001