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MPLS VPN
In a Service Provider Network

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Abstract

The subject of the thesis was to study the implementation of MPLS VPN solutions in a Finnish service provider environment. The thesis consists of a theoretical framework and empirical study. The study was started by collecting and using existing data and theories about the topic. The MPLS VPN solutions of a service provider were studied as a practical approach.

The thesis mainly covered the Nokia (formerly Alcatel-Lucent) environment and solutions for MPLS VPN. The primary purpose of the thesis was to compare XAMK service provider course contents, which covers MPLS VPN, with the implementation of MPLS VPN technology in a Finnish service provider environment. The mentioned course provided a decent learning environment, including theory, configuration guide, and virtual laboratory environment for exercising but only in the Cisco IOS environment. The XAMK service provider course could use the results of this thesis as an additional study source to familiarize students with the Nokia environment. A more significant impact could be made by providing a virtual environment for students to exercise, among other things, configuration examples provided by this thesis.

The study results were a simplified and handy guide of Nokia MPLS VPN solutions, mainly for junior network specialists or network specialist trainees who start working for service providers.

Keywords

MPLS, VPN, VPRN, VPLS, VPWS

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Tiivistelmä

Opinnäytetyö koostuu teoreettisesta viitekehyksestä sekä empiirisestä tutkimuksesta. Tutkimus aloitettiin keräämällä ja käyttämällä olemassa olevia tietoja ja teorioita aiheesta. Erään palvelutarjoajan MPLS VPN-ratkaisuja tutkittiin käytännönläheisenä lähestymistapana.

Opinnäytetyön aiheena oli tutkia MPLS VPN -ratkaisujen toteutusta eräässä suomalaisessa palveluntarjoajan ympäristössä. Tämän tutkimuksen päätarkoitus oli verrata XAMK:n palveluntarjoajan kurssisisältöä, jonka aiheena on pääsääntöisesti MPLS VPN teknologia Cisco IOS ympäristössä, MPLS VPN -teknologian käyttöönottoon suomalaisessa palveluntarjoajan verkossa, jossa on käytetty Nokian MPLS VPN ratkaisuja. Kurssi tarjoaa kunnollisen oppimisympäristön, mukaan lukien teoriaa, konfiguraatio oppaat, ja virtuaalinen ympäristö harjoittelua varten, mutta nämä koskee vain Cisco IOS-ympäristöä. Mainittu kurssi voisi käyttää tämän tutkimuksen tulokset opiskelijoille luettavaksi lisälähteenä tutustumaan Nokian ympäristöön. Merkittävämpi vaikutus voidaan tuoda tarjoamalla virtuaaliympäristöä, jossa opiskelijat voivat harjoitella mm. tämän tutkimuksen esittämiä konfiguraatioesimerkkejä. Lisäksi tutkimuksen tulos on yksinkertaistettu ja kätevä opas Nokian MPLS VPN -ratkaisuista, pääasiassa junior tietoliikenneasiantuntijoille tai harjoittelijoille, jotka aloittavat uransa palveluntarjoajien ympäristössä.

Asiansanat

MPLS, VPN, VPRN, VPLS, VPWS

1 Contents

2 INTRODUCTION

2.1 The background and purpose of the thesis

This study is commissioned by the South-Eastern Finland University of Applied Sciences (XAMK). The main questions this thesis will try to answer are as follows:

- How to extend XAMK service provider course material to cover also Nokia MPLS VPN solutions?
- What does a junior network specialist need to know about MPLS VPN?

The idea is to examine the implementation of MPLS VPN technology in a service provider as a practical approach and compare the implementation with the mentioned course contents. The XAMK service provider course topic is generally MPLS VPN, mainly in the Cisco IOS environment. This study aims to extend the material of the mentioned course to cover also Nokia MPLS VPN solutions. The lecturer of the service provider course of XAMK is Vesa Kankare, who also worked as a principal in this study.

Besides, the other purpose of this study is to provide a brief guide about MPLS VPN, which could be used by junior network specialists or network trainees who start their careers in a service provider environment but don not have too much knowledge about or experience working with MPLS VPN technology. This was another reason to start this study to help juniors and trainees understand the topic by providing a brief guide.

The idea of doing this study was formed after performing the XAMK service provider course and starting the career as a junior network specialist in a service provider. As mentioned earlier, the contents of the XAMK service provider course cover MPLS VPN in the Cisco IOS environment. The service provider, in which the study was done, used Nokia MPLS VPN solutions. Although MPLS VPN concepts are pretty much the same among all vendors, differences in terminology and configuration could be confusing, especially for beginners. Usually, juniors and trainees need to study Nokia MPLS VPN from the beginning to realize the difference in terminologies, technical implementations, and configurations between Nokia and Cisco solutions. Here, the idea was to integrate Nokia MPLS VPN solutions in the XAMK service provider course.

2.2 Research method

The research approach will be design-based research. According to Arthur Backer & Dolley van Eerde (2013), design-based research is worth knowing about, especially for students who will become teachers or researchers in education: Design-based research is claimed to have the potential to bridge the gap between educational practice and theory because it aims both at developing ideas about domain-specific learning and the means that are designed to support that learning. DBR thus produces useful products (e.g., educational materials) and accompanying scientific insights into how these products can be used in education.

This study was started by briefly going through the theory of MPLS as well as MPLS VPN techniques. In this part, the idea was to use the existing data from approved sources to provide a background and definition of the topic. Next, the applications of the MPLS VPN in a service provider backbone network were studied. This part was accomplished by examining the different techniques such as fiber optic, copper, and mobile connection, which use MPLS VPN technology. The provider core, provider edge, and customer edge were studied.

Several credible sources were used to complete the study alongside studying applications and deployments of MPLS VPN in the service provider network. The XAMK service provider course and Nokia documentation contents were among the most used source for this study. Additionally, there were several sessions with network specialists and solutions specialists from the service provider for using their knowledge and experiments of working with the MPLS VPN to promote the study. And finally, some labs in the virtual environment were built to put the theory into practice.

The study started in early May 2020, and the goal was to finish it before the end of the year 2020.

3 SOURCES

MPLS VPN is a topic that requires detailed explanations because many concepts and techniques need to be understood. That is why even some experts in this field struggle to gain expertise in it. Most of the MPLS VPN sources are vendor-based guides focusing on their terminology, techniques, and operating systems. Those detailed guides are usually hard to understand for newcomers in the field. Here the goal is not to underrate those detailed and comprehensive sources but to provide a simplified reference for understanding the most necessary techniques and terminologies of the topic for a beginner.

Nokia documentation was widely used for the theory part as well as configuration examples. Cisco documentation and guides were other excellent sources for this topic. The MPLS and VPN architecture book published by Cisco and the MPLS-Enabled Applications book were among other sources. The XAMK Service Provider course materials, guides, and labs were among other credible sources for this study.

4 WHAT IS MPLS?

A traditional IP packet is forwarded based on the destination IP addresses. The IP address is contained in the network layer header. The database needed for delivering information is provided either by network layer routing protocols like BGP, IS-IS, OSPF, or static routing. A router analyzes the IP packet at each hop independently in the network and forwards it based on the destination IP address (Guichard & Pepelnjak, 2009, 2009.)

Traditional IP routing has several well-known limitations, ranging from scalability issues to poor support or traffic engineering and poor integration with Layer 2 backbones already existing in large service provider networks. With the rapid growth of the Internet and the establishment of IP as the Layer 3 protocol of choice in most environments, the drawbacks of traditional IP routing have become more and more apparent (Guichard & Pepelnjak, 2009.)

Multiprotocol Label Switching is a label switching technology that provides the ability to set up connection-oriented paths over a connectionless IP network.

MPLS enables routers to forward traffic based on a simple label embedded into the packet header. In other words, the packets are identified by a label inserted into each packet. A router examines the label to determine the next hop for the packet, saving time for router address lookups to the next node when forwarding packets. MPLS is not enabled by default and must be explicitly enabled. MPLS is independent of any routing protocol but is considered multiprotocol because it works with the IP, ATM, and Frame Relay network protocols (Nokia, 2017.)

MPLS was created to combine the benefits of connectionless Layer 3 routing and forwarding with connection-oriented Layer 2 forwarding. MPLS separates the control plane, where Layer 3 protocols establish the paths used for packet forwarding and the data plane where Layer 2 label switched paths forward data packets across the MPLS infrastructure. Besides IP routing, MPLS also supports IP multicast routing and quality of service (QoS) extensions (Guichard & Pepelnjak, 2009.)

5 HISTORY OF MPLS

Internet Engineering Task Force (IETF) organized the first working group meeting for developing Multiprotocol Label Switching (MPLS) technology in 1997. Here are the significant problems that MPLS was supposed to solve:

- **Scalability of network layer routing:** Using labels to aggregate forwarding information while working in the presence of routing hierarchies.
- **Greater flexibility in delivering routing services**: Using labels to identify traffic to receive unique benefits, e.g., Quality of Services (QoS), and using labels to provide forwarding along an explicit path different from those constructed by destination-based forwarding.
- **Increasing network performance:** Using the label-swapping paradigm to optimize network performance.
- **Simplify integration of routers with cell switching based technologies:** Making a better integration of Asynchronous Transport Mode (ATM) with Internet Protocol (IP) by having a single control plane spans both ATM switch and routers (Minei & Lucek, 2011)

After initially launched, MPLS usage was extended to other applications such as Circuit Cross-Connect (CCC), ATM, and Frame Relay services over IP/MPLS infrastructure, Layer 2, and Layer 3 VPNs, and Virtual Private LAN Services (VPLS). Later, the expanding of MPLS into the access network and bringing Seamless MPLS significantly progressed this technique. MPLS was initially designed for Service providers, but later it was used mainly in the enterprise environment. MPLS is also used in some networks as an infrastructure tool to provide traffic engineering and fast-reroute capabilities. (Minei & Lucek, 2011.)

6 MPLS TERMINOLOGY

Cisco has very brief and exact definitions of some basic terms that are used with MPLS. Here are some of the most important terms that would be used in this study:

- Label Distribution Protocol (LDP): A protocol used by Label Switch Routers (LSR) to exchange label mapping information.

- Label Edge Router (LER): LER is a router in the MPLS network border that determines and applies the appropriate labels and forwards the labeled packets into the MPLS domain.

- Provider Edge (PE): The LER functions as the ingress and egress routers to the MPLS domain.

- Provider Router (P): P Routers are at the core of the service provider network. They are connected to other P routers and PE routers, but they are not connected to CE routers. P Routers only participate in label swapping in the MPLS network, but they do not participate in label pushing or popping.
- Customer Edge (CE): CE devices are not aware of the MPLS network. CES could be routers or switches that are connected to PEs.

- Label Forwarding Information Base(LFIB): Routing information used to determine the hop-by-hop path through the network.

- Label Switch Router (LSR): A router that switches the labels used to route packets through an MPLS network.

- Label Switched Paths (LSP): LSPs are defined by a signaling protocol such as LDP or BGP. LSPs are routes through the MPLS network, and they are set up based on the criteria in the Forwarding Equivalence Class (FEC).

- Forwarding Equivalence Class (FEC): A set of packets with similar characteristics might be bound to the same MPLS label. An FEC tends to correspond to a label switched path; however, an LSP might be used for multiple FECs.

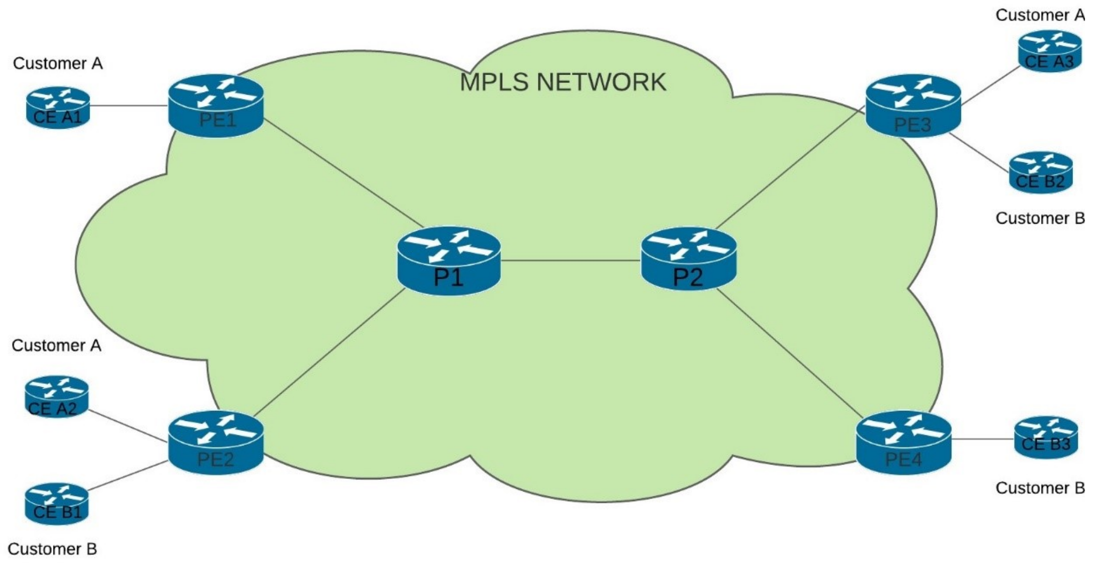


Figure 1: An MPLS architecture

There are there basic actions that could be performed with labels.

- Label Push: pushing means adding a label to a packet. The local PE routers push the labels. The local PE router is the first PE router that receives the packet from the CE.
- Label Swap: label swap means replacing a label with another one in a packet header. P routers swap the labels.
- Label Pop: it means removing the label from a packet. This is done by remote PE when it sends the packet to the remote CE.

7 MPLS-BASED VPN

Virtual Private Networks (VPNs) are private networks that use virtual tunneled connections routed through public networks. Typically the public network could be service provider network. VPNs provide connectivity between separate customer sites through virtual connections (Juniper, 2019.)

Why is the solution called a Virtual Private Network? First, it is a network because it provides connectivity between separate sites. Second, it is private because the customer requires it to have the same properties and guaranties as a private network, both in terms of network operations (addressing space, routing) and traffic forwarding. Third, it is virtual because the same physical resources and facilities could be used to provide the service to more than one customer (Minei & Lucek, 201, 2011)

VPNs can be categorized in different ways. The categorization is based on the way the routing information is exchanged in the VPN. According to Guichard & Pepelnjak, VPNs can be classified into two major categories:

- Overlay VPNs: In this model, the service provider provides only Virtual Circuits (VCs) for the customers, and routing information is exchanged directly between the customer edge (CE) devices. A VC acts as a dedicated physical link between customers' sites. If the VC is permanent, then it is called a Permanent Virtual Circuit (PVC). If the VC is established only as a temporary signaling protocol, it is called Switched Virtual Circuit (SVC). Examples of overlay VPNs are GRE and IPSec VPNs.
- Peer-to-peer VPNs: In this model, the routing information is exchanged between the customers and the service provider. Example: MPLS VPN

Both models have their benefits and back-draws. Although MPLS VPN is a peer-to-peer model, it is a combination of both models. MPLS VPN brings together the benefits of an overlay VPN such as security and isolation among the customer, using a peer-to-peer model such as simplicity.

According to Juniper, three primary types of MPLS VPNs: Layer 2 VPNs, Layer 2 circuits, and Layer 3 VPNs. In all kinds of MPLS VPNs, PE routers are responsible for performing VPN functions. P and CE router does not need to participate in performing VPN functions.

8 NOKIA TERMINOLOGY

Because different network vendors such as Cisco and Nokia use vendor-specific devices, operating systems, terms, and configurations, which are different from others, this study tried to cover at least two major network vendors' solutions widely used in service provider networks. These two are Nokia (formerly Alcatel-Lucent) and Cisco. The MPLS VPN concepts are the same in both vendors' solutions, but there are some differences in techniques and terminologies. Here, the concepts of MPLS L2 and L3 VPNs in the Nokia environment will be examined, and after that, some examples and configurations of both vendors will be provided.

8.1 Services

In the Nokia entities, a service is an entity identified by a service ID, but it can only have an optional service name. A service could refer to as a type of connectivity for the Internet or VPN services. A service could provide Layer 2 or Layer 3 connectivity between service access points (SAP) within the same router or between different routers. The SAP definition will be examined in the next sections, but briefly, it can be described as a logical place where traffic enters and exits the service. To understand the concepts better, let's see this figure:

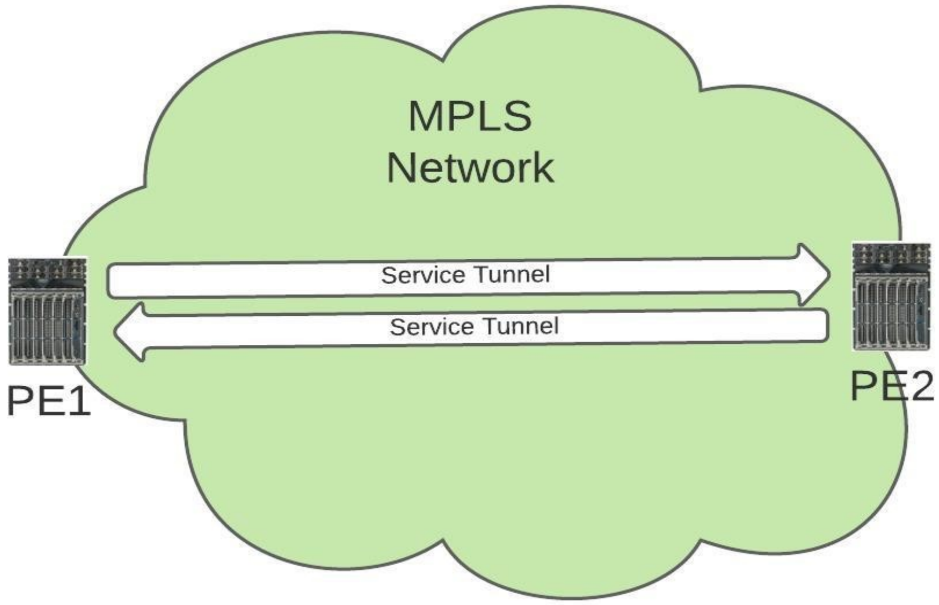


Figure 2: Nokia service tunnels

The MPLS Transport Tunnels are established between PE routers. Inside the Transport Tunnels, there could be multiple Service Tunnels. The Service Tunnels carry the customer traffics. For Layer 2 MPLS VPN (VPLS & VPWS), the Targeted LDP (TLDP) is used for establishing the Service Tunnels, but for Layer 3 MPLS VPN (VPRN), the Multiprotocol-BGP (MP-BGP) is used to establish the tunnel.

Here are the most typical Nokia services:

- Virtual Private LAN Service (VPLS)
- Virtual Private Wire Service (VPWS), also known as Virtual Leased Line (VLL)
- Ethernet Virtual Private Network (EVPN)
- Pseudowire (PW) Ports
- Virtual Private Routed Network (VPRN)
- Internet Enhanced Service (IES)

VPLS, VPWS, EVPN, and PW Ports are MPLS-based Layer 2 VPN services of Nokia, and VPRN and IES are Layer 3 services. VPLS, VPWS, PW Ports, and VPRN will be discussed in the next chapters, but other services are beyond this study’s scope.

8.2 Service Entities

In Nokia, logical service entities are used for service provisioning to provide end-to-end connectivity for customer sites. It is possible to bind several services to a single customer or a to a single LSP tunnel. Different policies such as Quality of Service (QoS) and filtering policies can be applied to a service.

According to Nokia, a basic service configuration must have the following items configures:

- a customer ID
- a service type
- a service ID
- an SAP for determining the encapsulation type and port
- an interface for assigning IP-addresses
- an associated SDP (for distributed services)

8.3 Customers

Customer is a primary service entity that is defined with a value named Customer ID. When creating a service, a customer ID must be bound with the service.

8.4 Service Access Points (SAP)

According to the Nokia definition, a Service Access Point (SAP) could be simply considered as a logical endpoint in service for entering and exiting traffic. The entering point is called ingress and exiting point egress. An SAP can be a physical port or a channel, but it also could be a logical entity within a physical port or channel. Depending on encapsulation types within a physical port or channel port, there could be multiple SAPs. If a port or channel is down, all SAPs within that port or channel would also be down.

SAPs can be configured on customer-facing ports (access ports) but not on core-facing ports. An SAP is associated with the service in which it is created, and it can provide access to different services such as VPLS, VPWS, and VPRN. All SAPs in a device must be created, and there are no default SAPs in Nokia devices.

8.4.1 SAP encapsulation types

The SAP encapsulation type is used to identify the protocol used to provide the service (Nokia, 2017.)

For Ethernet ports, there are three types of encapsulations available.

- Null: Null encapsulation means that there is only a single service for a single customer available on the port.
- Dot1q (IEEE 802.1Q): Dot1q is a standard protocol in networking that supports VLANs. Dot1q encapsulation is configurable on Ethernet and EtherChannel ports. If a port or port-channel is configured with Dot1q encapsulation type, then it can support multiple services for one or multiple customers. The encapsulation ID of the service would be the VLAN ID in the Dot1q header.
- Q-in-Q (VLAN stacking): Q-in-Q encapsulation is a technique that adds a second VLAN tag to customers' frames. The service provider uses a unique VLAN tag (outer tag) for each customer, but the customers could still use their inner tag. Using this technique, we can separate each customer's traffic from others and have multiple VLANs. Q-in-Q is supported on VPWS, VPLS, VPRN, and IES.

For identifying an SAP, a locally unique SAP ID is used, meaning that the same SAP could be used on other devices.

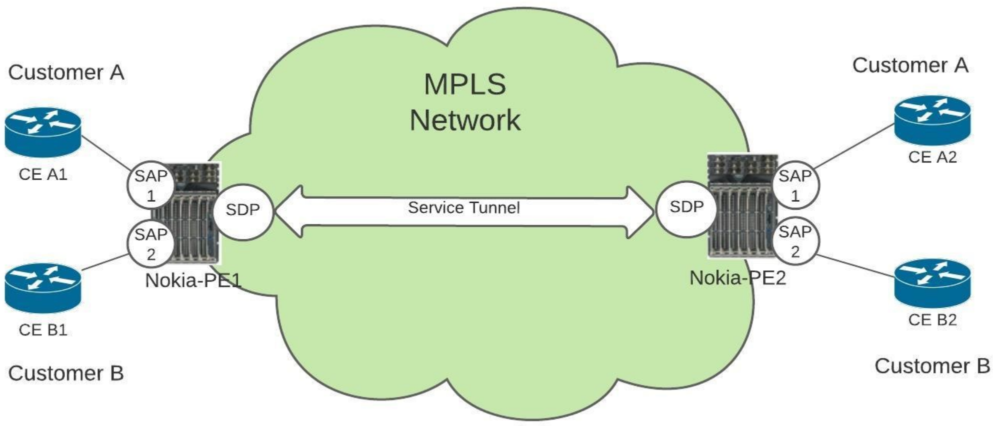


Figure 3, Nokia service entities

8.5 Service Distribution Points (SDP)

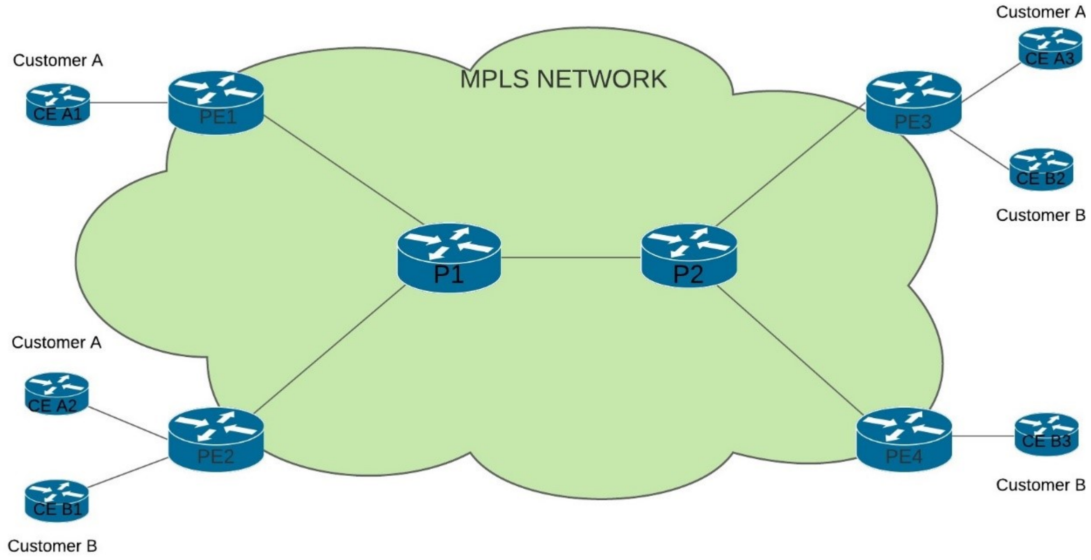
According to Nokia, SAPs are linked to the transport tunnels using a Service Distribution Point (SDP). An SDP is created to identify the endpoint of a service tunnel. After creating an SDP, it could be bind to service to create a service tunnel called a transport tunnel. The transport tunnel is a logical Label-Switched Path (LSP), which uses a signaling protocol like Label Distribution Protocol (LDP) or Resource Reservation Protocol-Traffic Engineering (RSVP-TE) for signaling. SDP uses the far-end device’s IP address to build the tunnel path. All tunnels are unidirectional, so if the far-end device needs to send traffic back to the local device, it needs to create a new tunnel.

A Distributed service is a service that is bound to an SDP. In a distributed service configuration, there are at least two SAPs (one in local node and one in remote node). An SDP could be used for binding the service to a service tunnel.

Because an SDP ID is locally unique, the same ID could also be used on other devices. An SDP can be associated with one or multiple services. Each SDP service tunnel has an ingress and egress point for the Pseudowires (PW) contained with it. We will go through Pseudowires in the next sections.

9 A BASIC MPLS VPN TOPOLOGY

In this part, the basics of MPLS backbone topology in a service provider network will be examined. There are some configuration examples but only to introduce some basic concepts. Consider the below topology:



9.1.1 Step 1: Creating IGP

This step is beyond the scope of this study, but here it is discussed briefly. Before anything else, an Interior Gateway Protocol (IGP) is enabled between backbone routers. An IGP is used for exchanging the routing information between routers within an autonomous system (AS). Intermediate system to intermediate system (IS-IS) and Open Shortest Path First (OSPF) are the typical IGP protocols among the service provider backbones.

In Nokia routers, the IGP can be checked by these commands:

- If IS-IS is enabled as IGP:
  - Show router isis adjacency
  - Show router isis database
  - Show router isis topology
  - Show router isis routes
- If OSPF is enabled as IGP:
  - Show router ospf neighbor
  - Show router ospf database
  - Show router ospf status
  - Show router ospf routes

9.2 Configuring iBGP for PE-to-PE connectivity

Service providers use internal BGP protocol for creating connectivity between PE routers in an MPLS-based backbone network. PE routers form an iBGP session that is used for many purposes. BGP could be used as a signaling protocol for L2 and L3 VPNs. The iBGP session is formed between routers belong to the same Autonomous System (AS). In MPLS VPN, PE routers exchange the VPNv4 routes via Multiprotocol BGP (MP-BGP). The concepts will be discussed in the next chapters. The configuration of iBGP between PE routers is beyond the scope of this study.

9.3 Step 2: Configuring MPLS and Enabling Label Distribution Protocol (LDP) Or Resource Reservation Protocol (RSVP)

Label Distribution Protocol (LDP) is a protocol used to distribute labels in non-traffic-engineered applications. LDP allows routers to establish label switched paths (LSPs) through a network by mapping network-layer routing information directly to data-link layer switched paths. LDP performs the label distribution only in MPLS environments. LDP operation is performed between LDP peers. LDP peers are two Label Switch Routers (LSRs). When an LDP session is created between two LSRs, they begin to learn each other’s label mappings and exchange label binding information (Nokia, 2017.)
According to Juniper, there three types of LSPs: Static LSPs, LDP-signaled LSPs, and RSVP-signaled LSPs. For static LSPs, no signaling protocol is needed, and labels are manually assigned to all participating routers. LDP-signaled LSPs are created dynamically using LDP.

Resource Reservation Protocol (RSVP) is another protocol used to distribute labels, especially in traffic-engineered applications. RSVP is a more complicated protocol than LDP and has features like allowing explicit path and bandwidth reservation for the LSPs. RSVP must be enabled on the router interfaces that participate in signaled LSPs.

There two kinds of RSVP-signaled LSPs:

- Explicit-path LSPs: in this type, all intermediate hops (strict, loose, or a combination of the two) of the LSP are created manually.
- Constrained-path LSPs: in this type, the intermediate hops of the LSPs are automatically created. The needed information is provided by the link-state routing protocols like IS-IS or OSPF.

In Nokia routers, an LDP can be enabled as follow. First, LDP must be enabled, and then

```
Configure router ldp
```

```
Configure router ldp
                  session-parameters
                           peer <far-end IP>
                           exit
                   interface-parameters
                      interface "int-name"
                      exit
                   exit
                   targeted-session
                   exit
```

Notice that targeted sessions are created for adjacency between nodes that are not directly connected.

The LDP configuration can be checked by these commands:

- Show router tunnel-table
- Show router ldp status
- Show router ldp discovery
- Show router mpls interfaces
- Show router mpls lsp

Here is an example of the configuration of RSVP:

```
Configure router mpls
         interface <interface-name>
         exit
         interface <interface-name>
         exit
```

Notice that by adding the interface under the MPLS, the interface is added automatically under the RSVP. After adding the interfaces under MPLS, it is possible to modify them under the RSVP:

```
Configure router rsvp
            interface <interface-name>
                        no shutdown
            exit
```

RSVP configuration can be check by these commands:

- Show router rsvp interface
- Show router rsvp session
- Show router rsvp neighbors

9.4 Step 3: Configuring SDP

The next step is to create SDP. SDP should be created before service creation. Multiple devices could be associated with the same SDP. An SDP-ID defines an SDP, and it must include the IP address of the far-end router.

Here is the syntax for creating SDP. Notice that MPLS encapsulation type is used in this example, but the encapsulation type could also be GRE or IP.

```
Configure service sdp <SDP-ID> mpls create
                        far-end <far-end router's IP address>
                        lsp <lsp-name>
                        path-mtu <mtu>
                        binding
                                    port <port>
                        exit
                        no shutdown
```

10 MPLS-BASED LAYER 2 VPN

In an MPLS-based layer 2 VPN, traffic is forwarded by the CE device to the PE switch in a Layer 2 format. In L2 VPN, the CE is responsible for routing the traffic, and the service provider only carries the traffic from the customer’s one site to another using the MPLS backbone. From a customer’s view, the topology is like connecting their different sites to different ports of a switch, and they seem to be in the same LAN.

In Nokia services, there are different types of MPLS-based Layer 2 VPNs, but in this study, these are discussed:

- Ethernet Virtual Private Network (EVPN)
- Virtual Private LAN Service (VPLS)
- Virtual Private Wire Service (VPWS), also know as Virtual Leased Line (VLL)

10.1 Virtual Private LAN Service (VPLS)

According to Nokia, Virtual Private LAN Service (VPLS) is a Layer 2 MPLS-based VPN multipoint-to-multipoint technology. This technology connects geographically separated customer LANs over an MPLS network. Multiple sites connected through a VPLS seem to be connected to different Layer 2 ports and seem to be in the same LAN. The VPLS requires creating a bridge domain and Virtual Forwarding Instance on each PE router in Cisco IOS XR. In the next section, some basic concepts are about VPLS will be explained.

10.1.1 Bridge Domain

VPLS uses a bridge domain to provide Layer 2 connectivity between different sites through a broadcast domain. A broadcast domain consists of virtual or physical ports. Within a bridge domain, data frames are switched based on their destination MAC addresses.

10.1.2 Virtual Forwarding Instance (VFI)

The VFI is one of the basic concepts of the VPLS. A VFI could be created on a PE router for each VPLS instance. Native bridging functions such as learning and forwarding MAC addresses could be performed by a VFI. After creating the VFI in a PE router, the PE router can establish Virtual Circuits to all other PE routers in that VPLS instance. A Virtual Switch Instance (VSI) will be created by connecting a bridge domain to a VFI (Cisco 2018.)

10.1.3 Pseudowires (PW)

VPLS services can be connected using pseudowires (PWs). PWs are used to establish a tunnel between two PE routers to transport Layer 2 protocol data units (PDU) across an MPLS network. PWs are established dynamically or statically, and they could be configured either as a mesh or a spoke SDP. In the next chapter, mesh and spoke SDP would be discussed.

10.2 Typical VPLS Network topologies

There are three basic types of VPLS topology, according to the Service Distribution Points (SDP) types:

- Hub and Spoke VPLS: In this topology, the devices are connected using a spoke SDP. This type of SDP is like a bridged port, in which the received traffic is forwarded to all other ports. The spoke SDP forwards the received traffic to all connected spoke SDPs, mesh SDPs, and SAPs.

- Full-Mesh VPLS: In a full-mesh VPLS topology, devices (PE routers) are connected using mesh SDP type. A mesh SDP is a type of SDP that forwards the received traffic to all connected spoke SDPs and SAPs, but mesh SDP doesn’t forward the traffic to other connected mesh SDPs. This is also called a split-horizon rule. In Cisco IOS XR, Virtual Forwarding Instances (VFIs) and Pseudowires (PW) are used to implement the split-horizon rule.
- Hierarchical VPLS (H-VPLS): This is an enhancement of VPLS that consists of both spoke SDPs and mesh SDPs. Let’s see this one in more detail in the next section.

In mesh and spoke SDP, VLAN tags could be added to the frames for transmitting data, and VLAN tags could be removed when receiving data. There are three types of VLAN tags: zero, one, and two. These could be considerd as the corresponding of the null, dot1q, and QinQ in SAP operations.

10.2.1 Hierarchical VPLS

In a hierarchical VPLS (H-VPLS), some drawbacks of non-hierarchical topologies are eliminated. There are some drawbacks in non-hierarchical VPLS topologies where CE devices are directly connected to the PE devices. In these topologies, the PE devices are responsible for many tasks like holding the routing and forwarding tables. This is not optimal, and these heavy tasks can cause a significant load on the device and could affect the functionality.

In a hierarchical VPLS, these problems are solved by adding additional nodes. These nodes are called the user face of Provider Edge (u-PE), also known as Access PE. The customer traffic is routed through these Access PE toward the service provider core. The Access PE device could be an Ethernet switch, and it is the first node that receives the customer traffic, but it doesn’t need to know the whole routing table.

The Access PE device transfer traffics toward the network face of Provider Edge or n-PE devices. A pseudowire (PW) is used to connect between u-PE and n-PE. The encapsulation type is Q-in-Q tagging. There are more details about pseudowires (PW) and Q-in-Q tagging in this study.

Hierarchical VPLS has many benefits over non-hierarchical VPLS, such as scalability, efficient bandwidth usage, and simple management. The hierarchical VPLS architecture is more complicated than non-hierarchical, and this could be one of the disadvantages of hierarchical VPLS.

10.3 VPLS Configuration

Let’s consider this VPLS logical topology :

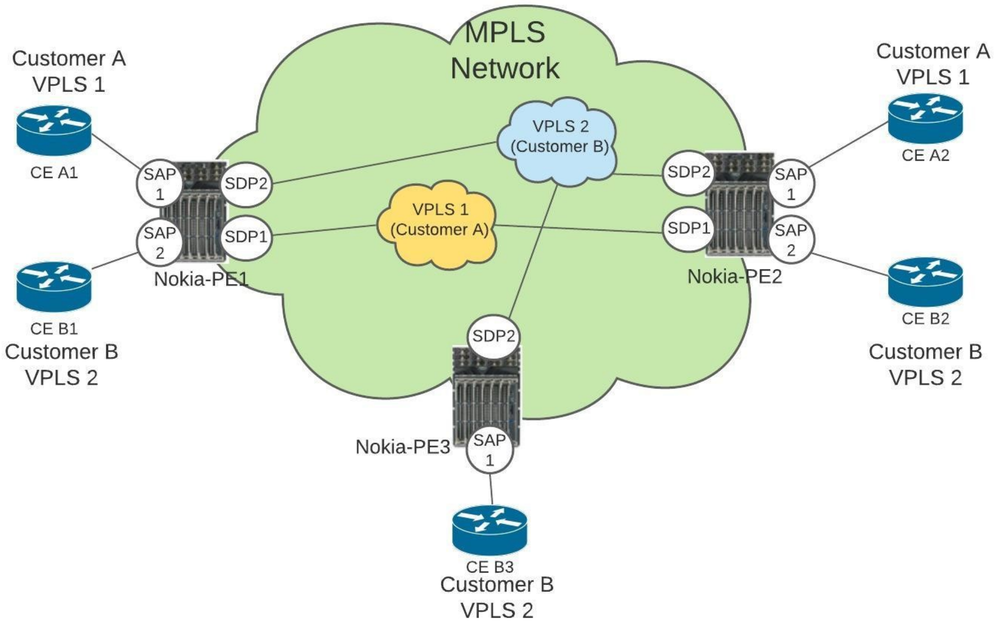


Figure 5, VPLS logical topology

In the above figure, the PE routers are considered as Access PE routers. The Access PE routers are typically connected to n-PE routers and via them to other Access PE routers. Here is an example of a basic VPLS configuration on an Access PE router. Notice that the same configuration must be done on the remote Access PE.

The first step is to create an SDP:

```
Configure service sdp <sdp-id> mpls create
                           far-end <far-end router’s IP>
                           lsp “lsp-name”
                           no shutdown
```

Then the LSP parameters could be configured:

```
Configure router mpls lsp “lsp-name”
```

```
            to “n-PE-IP”
            cspf
            primary “IGP”
            no shutdown
```

And finally, the VPLS instance could be configured:

```
Configure service vpls <vpls-id> create
            service-mtu <mtu>
            sap <sap-id> create
                      ingress
                          qos <value>
                      exit
                      egress
                          qos <value>
                       exit
             mesh-sdp <sdp-id>:vpls-id
                        no shutdown
              exit
```

These commands could check the VPLS configuration:

```
Show service service-using
Show service id <vpls-id> base
Show service id <vpls-id> sdp
Show service id <vpls-id> fdb detail
Show router ldp bindings service service-id <vpls-id> detail
```

Notice that more parameters are to be configured under the VPLS instance, but they are beyond this study’s scope.

And here is the configuration for n-PE peer:

```
Configure service sdp <sdp-id>
```

```
            far-end <IP>
            lsp “lsp-name”
            primary “IGP”
            no shutdown
```

Then creating the LSP:

```
Configure service router mpls lsp “lsp-name”
            to “Access-PE IP”
            cspf
            primary “IGP”
```

and finally, the VPLS instance configuration:

```
Configure service VPLS <vpls-id>
            service-mut <mtu>
            mesh-sdp sdp-id:vpls-id
                        no shutdown
            exit
```

Notice that here a Constrained Shortest Path First (CSPF) LSP is configured, which relies on the topology database provided by IGP. The CSPF command enables computation for constrained-path LSPs.

10.4 Virtual Private Wire Service (VPWS)

Virtual Private Wire Service (VPWS), also referred to as Virtual Leased Line (VLL), is another Layer 2 VPN service of Nokia. VPWS is a point-to-point service and can provide internetworking between different protocols like Ethernet and ATM. VPWS is a Layer 2 VPN, but there is no MAC learning service in this service. Any Transport Over MPLS (AToM) could be considered the corresponding technology of VPWS for IP/MPLS networks in the Cisco environment. There are five types of Nokia VPWSs:

- Pipe: Epipe is a point-to-point Layer 2 service of Nokia. Epipe is one of the widely used WPWS services in service provider networks because Ethernet is a widely used technology. An Epipe service can use SAPs and SDPs to build a tunnel to transfer customer data between different Ethernet protocol sites. Like other VPWS types, Epipe doesn't use MAC learning.

- Ipipe: Internetworking pipe is a VPWS VPN service between two nodes that use different technologies.
- Apipe: Asynchronous Transfer Mode (ATM) pipe is a service between two ATM SAPs.
- Fpipe: Frame-Relay pipe is VPWS VPN service between two Frame-Relay sites.
- Cpipe: Cpipe is a VPWS VPN service between two nodes that use Time Division Multiplexing (TDM) technology

In Epipe, it is possible to use encapsulations with SAPs. These encapsulations are Null, Dot1q, and Q-in-Q. (explain with details)

10.5 Creating an Epipe

In service provider networks, Epipe could provide a Layer 2 connectivity between aggregation nodes (AGN) and service termination points (ABR). The AGN could be considered as Access PE and the ABR as n-PE.

Let's consider a simple topology for configuring an Epipe:

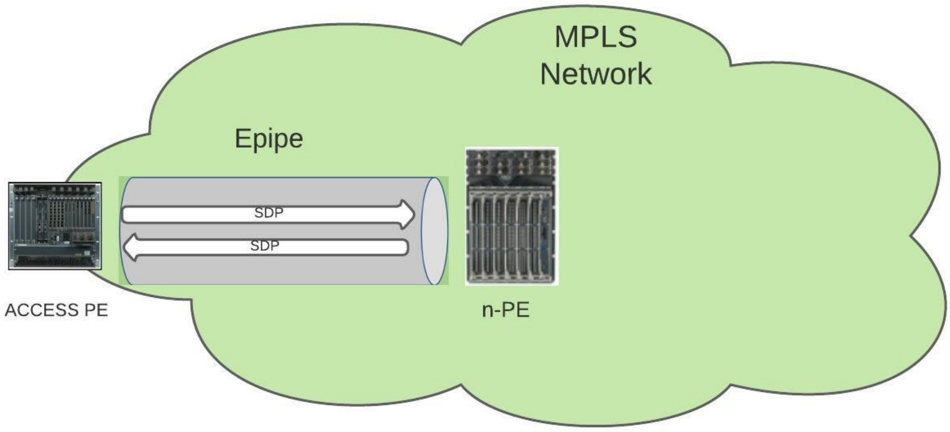


Figure 6, Epipe logical topology

Here is the syntax for creating an Epipe on the Access PE:

```
Configure service epipe <epipe-id> create
                        service-mtu <mtu>
                        sap <sap-id> create
                             no shutdown
                        sap  <sap-id>
                             no shutdown
```

After creating the Epipe and customer, the next step is to create an SDP and SDP bindings. The SDP could be mesh- or spoke-SDP. A Virtual Circuit ID (VC-ID) could also be associated with the SDP-ID to identify a virtual circuit (VC). A VC-ID, also is known as Service ID, is a logical term for identifying the service.

```
Configure service epipe <epipe-id>
                        spoke-sdp sdp-id:vc-id
                                     no shutdown
```

Notice that the VC-ID should be identical on both peers, meaning that the same value should be used on other peers. But the SDP-ID is local to the router.

These commands can be used to verify the configuration:

```
Show service id <vc-id> base
Show service id <vc-ic> sdp <sdp-id> detail
Show service sap-using sap <sap-id>
Show service sdp <sdp-id> detail
```

10.6 Ethernet Virtual Private Network (EVPN)

In this part, the EVPN will be discussed briefly. Due to the limitation of the study, we will not go through the details and configuration here.

An Ethernet VPN (EVPN) introduces a new Layer 2 VPN technology that can connect remote customer sites using a Layer 2 virtual bridge. According to Nokia, EVPN is a BGP MPLS-Based Ethernet VPN created for allowing VPLS service to be operated as IP-VPNs. EVPN has many benefits like multi-homing capabilities, simple provision, and management. The main objective of EVPN is to support MAC learning within the control plane and active-active multi-homing by creating an E-VLAN service similar to IP-VPNs. EVPN can enable integrated Layer 2 and Layer 3 services over Ethernet with multi-homing.

An E-LAN is a multipoint-to-multipoint service that connects multiple User Network Interfaces (UNI) for customers and can provide connectivity between customer sites. E-LANs are used to create multipoint L2 VPNs, transparent LAN services, and Layer 2 VPNs.

Like other types of VPNs discussed in this study, EVPN also consists of CE devices connected to PE devices. In EVPN, the data plane and control plane are separated. EVPN can be used as the control plane for different data plane encapsulations. EVPN-VXLAN, EVPN-MPLS, and PBB-EVPN are three types of EVPN. EVPN-VXLAN has mainly been used in data center EVPN applications. In EVPN-MPLS, the MPLS network is used by EVPN for creating E-LAN services. Generally, EVPN-MPLS is an evolution of VPLS services in the

WAN. The EVPN for Provider Backbone Bridging (PBB-EVPN) is a simplified EVPN that does not have the advanced features of EVPN-MPLS, but it provides very high scalability for networks. Further explanation of these technologies is beyond the scope of this study.

10.7 Pseudowire Ports (PW ports)

In this part, the Pseudowire ports concept will be discussed briefly because the details of this topic are beyond this study's scope.

According to Nokia, a PW port represents an extraction of payload carried within a tunnel. This payload is extracted onto a PW SAP within a service context (such as an Epipe, VPRN, or IES). A PW port can have a fixed connection to a physical port or switch between ports. If the PW port switches between ports, then it is called a Flex PW port.

Each port eligible to transmit traffic on a Flex PW port must be added to a PW-port-list. An MPLS-based spoke SDP can be rerouted between the ports defined in the PW port list and still be mapped to the same PW port based on the service label. Here is the instruction for provisioning an MPLS-based spoke SDP on a Flex PW port:

1. Creating a PW-port-list and adding ports to that:

   ```
   configure service system pw-port-list
           Port <port>
   ```

2. Creating PW port:

   ```
   configure pw-port <id> create
   ```

3. Configuring tunnel:

   ```
   configure sdp <id> mpls create
           far-end <IP>
           exit
   ```

4. Terminating the tunnel on a PW port via an Epipe service.

   ```
   configure epipe <id> create
   ```

```
pw-port <id>
spoke-sdp <sdp-id>:vc-id
```

11 MPLS LAYER 3 VPN

Layer 3 of the OSI model is the network layer. A VPN that operates in layer 3 through an MPLS network is called MPLS layer 3 VPN. In the MPLS Layer 3 VPN, the customer traffic is routed by the service provider routers. The service provider learns the IP addresses of CE devices and customer routes and has a wider VPN routing and forwarding (VRF) policy configuration than the Layer 2 VPN.

11.1 Virtual Routing and Forwarding (VRF)

By default, a router uses a single global routing table that contains all the directly connected networks and prefixes that it learned through static or dynamic routing protocols. Virtual Routing and Forwarding (VRF) is a technique that creates multiple virtual networks within a network entity.

In MPLS VPN architecture, VRFs are like VLAN for routers. Instead of using a single global routing, it is possible to use multiple virtual routing tables. Each VPN could have its routing and forwarding table in the router. In other words, PE routers could build a separate routing and forwarding table for each VPN (customer). This feature also allows overlapping IP-addresses between different VPNs as long as those VPNs do not have connectivity. For example, the same network address, 172.16.1.0/24, could be used by more than one VPN within a router.

A Route Distinguisher (RD) value is added to the prefixes for separating the prefixes between the VPNs. For example, consider that there are two different VPNs (customers) on a PE router. Both use the 172.16.1.0/24 network for their sites. An 8-byte field could be added to the beginning of the prefix to distinguish the routes between two VPNs. For example, 77:10 can be used for one VPN and 88:10 for another VPN. This 8-byte field could be any number, but typically service providers use some logic to define an RD. The combination of RD and prefix is called a VPNv4 route.

Another important concept related to VRFs is Route Target (RT). The RT is used to determine the import and export of routes within each VRF. Route Target could be configured as Export Route Target policy and Import Route Target policy to determine the export and import policies for each VRF. It is also possible to decide on both policies under one comment if the export and import policies are the same.

The Route Target is a useful tool for manipulating VPNv4 routes between the VPNs. RT is an 8-bytes BGP extended community value. BGP extended community is used to carry additional information with BGP. BGP extended community also carries another value named route origin, which prevents routing loops by identifying which site originated the route and therefore not advertising the route back to the originating site.

The PE routers peer with locally connected CE, but CE routers do not need to peer among themselves because routing information is exchanged via PE routers. Because RD allows overlapping of IP-address between different customers (VPRNs), at the destination PE router, the correct VPRN is identified by the Route Target (RT).

11.2 Virtual Private Routed Networks (VPRN)

VPRN is an MPLS-based Layer 3 VPN. In VPRN PE routers exchange customer routing information via Multiprotocol BGP (MP-BGP). VPRN association for each route is identified by route distinguisher (RD). RD is included in MP-BGP. After adding an RD to the prefix, a VPNv4 address is created, and it will be globally unique. The figure below shows a logical VPRN topology:

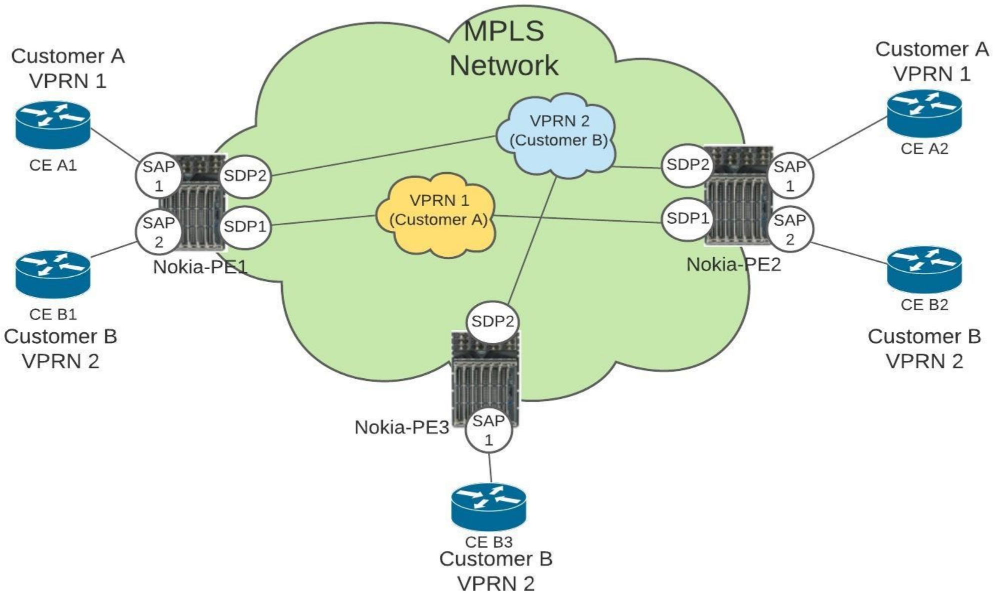


Figure 7, VPRN logical topology

VPRN uses two MPLS labels. Transport label (LSP label) and service label (VPN label). The service label is the inner one, and it will be unchanged in the service provider network. The service label is used for identifying the VPRN customer and service. The transport label is the outer one, and it will be swapped by hops when the packet traverse through the service provider network. This label is used to identify the LSP between PE routers.

11.3 Configuring VPRN

Here is a simple example of VPRN configuration on a Nokia router. Notice that many other parameters could be configured under VPRN, but those are beyond this study’s scope.

First, we need to create a BGP connectivity between PE routers:

```
Configure router bgp autonomous-system <AS-number>
Configure router bgp group <group-name>
                     family vpn-ipv4
                     peer-as <AS-number>
                     neighbor <neighbor IP>
                               local-address <local IP>
```

The same configuration must also be done on other peers.
The second step is to configure VPRN parameters and bound them with corresponding interfaces.

```
Configure service vprn <vprn-id> create
                    vrf-import “vrf-import policy”
                    vrf-export “vrf-export policy”
                    autonomous-system <BGP-AS-number>
                    route-distinguisher <RD-id>
                    type <spoke or hub>
                    auto-bind-tunnel
                              resolution-filter
                                   ldp
                                   rsvp
                              exit
```

In the above configuration example, the VRF import and export policies are created for the VPRN to determine how routes are exported from the local VRF to other VRFs and how routes are imported from other VRFs to the local VRF. The is done using the BGP extended community.

The BGP autonomous system (AS) of the service provider is configured. The type of VPRN is configured as spoke or hub, and the auto-bind-tunnel resolution-filter command configures the automatic binding of a VPRN service using tunnels to MP-BGP. Notice that LDP and RSVP tunnel types were configured here, but other tunnel types such as GRE also could be configured.

Now the interfaces could be configured:

```
Configure service vprn <vprn-id>
          interface <int-name>
              address <IP>
              exit
              ip-mtu <mtu>
```

```
sap pw-<id>:vlan-id create
            ingress
                scheduler-policy “policy”
            exit
            egress
                scheduler-policy “policy”
            exit
```

In the above example, the interface is created, and IP-address is configured. The SAP payload is extracted in a PW-port, which could be terminated via an Epipe to a physical port in an Aggregation Node device. This is explained in previous chapters. The scheduler policies could determine the ingress and egress bandwidth of the interface.

And finally, the static-routes toward the customers could be configured for each VPRN:

```
Configure service vprn <vprn-id>
        static-route-entry <customer-network> next-hop <IP>
```

12 PE-TO-CE CONNECTIVITY

In the previous chapters, MPLS VPN concepts and configuration around the backbone network have been discussed. In this part, the connectivity between backbone and customer sites (PE-to-CE) are discussed.

There are different ways to build connectivity between PE and CE devices. Different routing protocols like BGP, OSPF, IS-IS, RIP Version 2, EIGRP, and static routing could be used to build the connectivity. Regardless of which protocol was used, the customer VPN routes would be placed into the VPRN (VRF) routing table of the associated customer.

The routes learned from customers will be advertised through Multiprotocol BGP (MP-BGP) to other PE routers. The advertised routes are in VPNv4 format. If the routes are learned from the CE router via other protocols than BGP, then the routes must be redistributed into the MP-BGP. If the routes are learned via BGP from the CE router, then the redistribution is done automatically. Notice that this protocol used for CE-to-PE connectivity is external BGP (eBGP), but the protocol used for connectivity between PE routers is internal BGP (iBGP).

Here is an example of the configuration of eBGP between CE and PE routers. It is assumed that the CE router is a Cisco IOS.

First, the VRF must be configured:

```
Cisco-router# vrf definition <vrf-name>
                  rd <RD>
                  route-target import <RT>
                  route-targe export <RT>
```

Then the eBGP could be configured:

```
Cisco-router# router bgp <AS>
                no bgp default ipv4-unicast
                neighbor <PE-IP> remote-as <neighbor’s AS>
                neighbor <PE-IP> update-source loopback 0

                   address-family ipv4 vrf <vrf-name>
                   neighbor <remote-CE-IP> remote-as <neigh-
bor’s AS>
                      neighbor <remote-CE-IP> activate
                   exit -address-family

                    address-family vpnv4
```

```
          neighbor <PE-IP> activate
          neighbor <PE-IP> send-community extended
     exit-address-family
```

Notice that a separate address family must be configured under the BGP process for each VRF that receives customer's routes using eBGP. Each address family entry could have multiple BGP neighbors (customer CE routers) within the VRF.

For verifying the configuration on the CE router, these commands can be used:

```
Show ip route bgp
Show bgp neighbors
Show ip route vrf <vrf-name>
```

13 CONCLUSION

This thesis was commissioned by the South-Eastern Finland University of Applied Sciences (XAMK). Among other courses, XAMK offers a service provider course for ICT students, and the topic of the course is generally MPLS VPN. This thesis's purpose was to answer these questions:

- How to extend XAMK service provider course material to cover also Nokia MPLS VPN solutions?
- What does a junior network specialist need to know about MPLS VPN?

The goal was accomplished by studying a Finnish service provider MPLS VPN implementation and comparing the implementation with XAMK service provider course contents. The mentioned course could use the thesis results as an additional study source to familiarize students with the Nokia environment. The XAMK service provider course offers a decent learning environment, including theory, configuration guide, and virtual laboratory environment for exercising but only in the Cisco IOS environment. At the same time, Finnish service providers widely use Nokia MPLS VPN solutions. Although most of the MPLS VPN concepts are the same between Cisco and Nokia, technical implementations, terminologies, and configurations are very different. The results of this study could be used as an additional source of study by the XAMK service provider course to familiarize the students with MPLS VPN from Nokia's point of view. For example, Nokia configuration examples of MPLS VPN provided in this study could be considered correspondingly to Cisco's, which already exist in the mentioned course.

A more significant impact could be made by starting a project to provide a virtual laboratory environment for students to get their hands on configuration not only on Cisco IOS but also on the Nokia SROS environment. Besides, the configuration examples of this study could be tested in that virtual environment.

The results of this study could also be used as a brief guide of MPLS VPN in the Nokia environment by everyone interested in this topic, especially junior network specialists or network trainees who start working in service provider environments but do not have too much knowledge about MPLS VPN.

On the whole, the study could be considered as a successful one because its goals were accomplished. This study consists of theoretical frameworks and a practical approach. Credible references were used for writing the theory and also backing the findings of the practical section.

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