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MSC SYSTEMS & NETWORK ENGINEERING

Architecture of dynamic VPNs in OpenFlow

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Summary

Hello world.

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1 Introduction

Network operators today use Network Management Systems (NMSs) to get control over their devices and services that they deploy. These systems have been customized to their needs and in general perform their functionalities adequately. However, operators run into obstacles when trying to expand their business portfolio by adding new services. Which will potentially require *a)* new Application Programming Interface (API) calls to be implemented between their OSS and NMS, *b)* their NMS to be able to cope with potentially new protocols, and *c)* added expertise by engineers to define the possible feature interactions and restrictions of these protocols [1]. When these obstacles are eventually overcome the setup that will result from this implementation will be relatively static, since any change to it will require the whole process to be repeated.

To manage resources efficiently in a carrier network operators have been using Virtual Private Networks (VPNs) between customers. By differentiating traffic between VPNs they can control their traffic flow at a granular level. However, the set of interactions between different protocols and management interfaces to them are complex. The provisioning of VPNs requires expertise and a significant amount of changes to those protocols. Until recently operators were not concerned by this rigidity as their networks were in fact primarily static. However, the demand for application specific networks is growing and operators are looking for a more flexible approach in the form of Dynamic VPNs (DVPNs). DVPNs are private networks over which end-users can communicate, deployed by their common Service Provider (SP). They differ from normal VPNs in the sense that they are relatively short-lived. Using DVPNs, SPs can react more swiftly to customer requests to configure, adjust or tear down their VPNs. However, due to the aforementioned complexity DVPNs services have not been implemented on a large scale.

A potential candidate to solve the complexity of implementing DVPNs is OpenFlow [2] and Software Defined Networking (SDN). SDN is a relatively new architecture to allow for the programmability of networks. The architecture is not standardized but a generalized structure has been given in the OpenDaylight project [3]. OpenFlow is a lower level and increasingly supported API protocol towards networking devices. Implementing the SDN architecture promises *a)* CAPEX savings due to hardware being more generic and flexible, *b)* OPEX savings because of the integration of NMSs and the control interface of the devices, thereby increasing automation, and *c)* increased network agility by using the open interfaces to program network devices directly [4].

The momentum that SDN is getting might be explained by a general need for change in the networking industry. Operators primarily want to get more control over their networks, something which using the current stack of protocols is relatively complicated to get. The original OSI reference model [5] touches on the “Management Aspects” of each layer in the model, a way for management entities in the highest layer to control the behavior of lower layers. Unfortunately in the swift evolution of Transmission Control Protocol (TCP)/Internet Protocol (IP), these management interfaces are often limited or absent all together.

1.1 Research Question

It is unclear if a real-world OpenFlow and SDN implementation will actually provide any simplicity, additional flexibility or cost savings when compared to contemporary technologies [1]. And so the question arises: *“How much can operators benefit from using OpenFlow when implementing Dynamic VPNs?”* This requires research into whether DVPNs can be provisioned by current technologies and how this can be implemented in the network. Additionally, we will research the possibility of implementing DVPNs using OpenFlow. And finally we will attempt to prove the hypothesis that OpenFlow will reduce the complexity in the architecture of the management systems and the network as a whole.

1.2 Scope

The focus will primarily be on deploying Provider-provisioned VPNs (PPVPNs) at Layer 2 of the OSI-model between end-users. We have chosen to do so because these Ethernet VPNs are characterized by their trans-

parency to the end-user, who will be placed in a single broadcast domain with its peers and can thus communicate directly without configuring any sort of routing.

Previous research in [6] has proposed a very specific implementation for programmable networks to deploy on-demand VPNs but it predates the OpenFlow specification, and also omits a comparison with how this would look using contemporary technologies.

1.3 Approach

In the Section 2 we will define the conceptual design of DVPNs. This will result in a list of required features for the technologies to provide such a service. Section 3 will list the technologies available and will additionally determine their usability for implementing DVPNs when taking into account the requirements set forth in Section 2. In Section 4 we will distill the advantages and limitations of the different implementations and substantiate how they compare to each other. Finally, Section 5 summarizes the results and provides a discussion and future work on this subject.

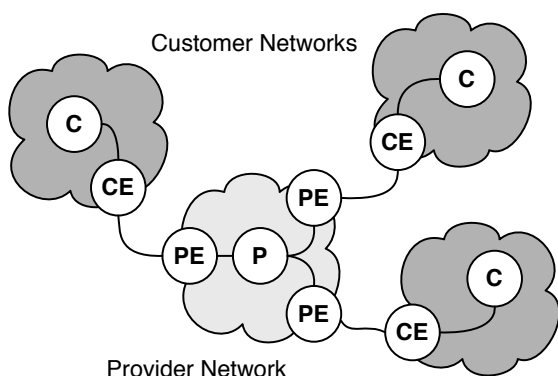
2 Dynamic VPNs

In Section 1.2 we already gave a short description of DVPNs. In this section, we will further look at the actual concept. Starting with defining what it actually provides, how it's carried over the core, the information needed to implement a VPN, from where that information is available and finally working towards a list of technical requirements that the network will need to provide.

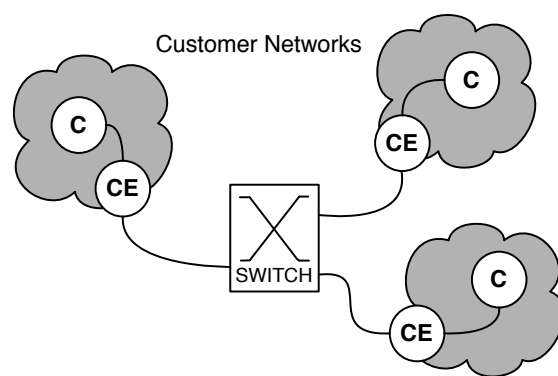
2.1 Service

To define the DVPN service, we first take a look at the concepts of non-dynamic, or static VPNs. They can be classified depending on the OSI layer which it virtualizes, the protocol that is being used and the visibility to the customer. In an IPSec VPN for example, the customer needs to setup his Customer Edge devices (CEs) at each site to actually establish the Layer 3 IP VPN. As we have already established in Section 1.2, we limit the use-case to an multi-point Ethernet Layer 2 VPN which is provisioned by the provider (PPVPN) and thus requires no action on the CE. Throughout this paper the definition of PPVPN related terms will be used as described in RFC 4026 [7] and an overview is given in Figure 1a.

What a Layer 2 PPVPN provides to the CE is a transparent connection to one or more other CEs using a single Ethernet broadcast domain. Another term to describe such a VPN service is a Virtual Private LAN Service (VPLS). It enables the interconnect of several LAN segments over a seemingly invisible carrier network. To do so, the Provider Edge device (PE) needs to keep the Customer MACs (C-MACs) ahead of the frame intact and also support the forwarding of broadcast and multicast traffic. All PEs (and of course Provider devices (Ps)) will not be visible to the CE, who will regard the other CEs as part of the VPLS as direct neighbors on the network as illustrated in Figure 1b.



(a) Terminology used to describe PPVPN devices.



(b) Appearance of VPLS from customer point-of-view.

Figure 1: Visualization of used terminology.

All these functionalities apply to VPNs as well as DVPNs. DVPNs however, also are flexible in nature. They can be configured, adapted and deconfigured within relatively short timespans. Current Layer 2 VPNs are mostly configured statically and changes in their configurations will require manual labor from the engineers. To convert them to DVPNs new tools are needed to automate this provisioning process which we will get back to in Section 2.3.

To summarize, from a service level perspective a DVPN needs to provide a network to the customer which:

1. provides a Layer 2 broadcast domain,
2. does not require configuration on the CE,
3. is transparent to CEs.

2.2 Transport

Transporting a Layer 2 frame between two CEs starts at the PE. The ingress PE learns the Source Address (SA) of the frame behind the port connected to the CE, then it needs to forward the frame to the PE where the Destination Address (DA) is present. It will need to do so while separating the traffic from other DVPNs, it has to make the traffic unique and identifiable from the rest of the VPNs transported over the network. This is done by giving the frame some sort of 'color' or 'tag' specific to the customer VPN. Additionally it should presume that P devices are not aware of the DVPN and do not learn the C-MAC addresses. This is because the network will have to scale to thousands of DVPNs and possibly millions of C-MACs divided over those DVPNs. To provide this so called MAC Scalability, only PEs should learn the C-MACs.

Forwarding from ingress PE to egress PE happens over a path of several Ps. Every PE connected to a CE member of a particular DVPN, should have one or more paths available to each and every other PE with members of that DVPN. The determination of the routes of these paths takes place through a form topology discovery. This mechanism should dynamically find all available PEs and Ps with all the connections between them and allow for the creation of paths which are not susceptible to infinite loops.

The links comprising the paths have a certain capacity which will need to be used as efficiently as possible. This means that the links comprising a path will need to have enough resources available, but that other links need not be left vacant. Also, if the required bandwidth for a DVPN exceeds the maximum capacity of one or more of the links in a single path, a second path should be installed to share the load towards the egress PE.

Continuing with the processing of the ingress customer frame, when it arrives at the ingress PE with a DA unknown to the PE, the frame will be flooded to all participating PEs. Upon arrival there, the egress PE stores the mapping of the frames SA to the ingress PE and if it knows the DA will forward out the appropriate port. Because this is a virtual broadcast domain, all Broadcast, Unknown unicast and Multicast (BUM) traffic will need to be flooded to the participating PEs. To limit the amount of BUM traffic in a single DVPN rate limits or filters will need to be in place to prevent the DVPN from being flooded with it.

Another addition to rate limiting unknown unicast traffic is by pre-populating the MAC tables of the PEs. This requires that, besides the ingress PE only learning the SA from the CE, it will also actively distribute the SA to all other PEs with members of the same DVPN. Then, instead of flooding unknown unicast frames to the PEs, the ingress PE drops the frame, knowing that the other PEs will not recognize it either. This can also be extended to limit broadcast Address Resolution Protocol (ARP) traffic if the PEs also exchange the IP address belonging to each C-MAC. When the ingress PE receives an ARP request for a certain IP address, it can look it up in its table and without flooding the frame, reply to the CE with the correct Media Access Control (MAC).

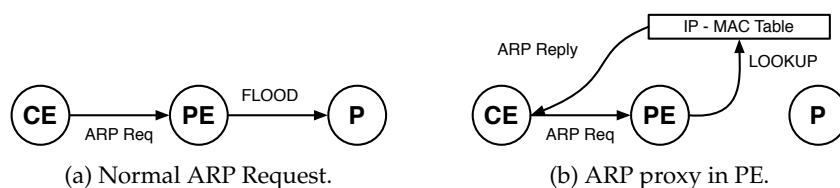


Figure 2: Processing of ARP requests at the PE.

With multiple DVPNs present on the network it can happen that one DVPN affects the available bandwidth of others. Therefore rate limits will need to be in place for the overall traffic coming in to the CE-connected ports. Policing rates of different DVPNs in the core is nearly impossible, the hardware cannot police traffic of separate DVPNs. And, because it burdens the core with another responsibility while it should only be concerned with fast forwarding, is also undesirable. However, by assigning a minimum and maximum bandwidth rate to each DVPN instance, it is possible to preprovision the paths over the network according to the required bandwidth. By also monitoring the utilization of individual links, DVPN paths can be moved away from over-provisioned links while they are in use. However, the impact on traffic when performing such a switch must be minimized and should ideally last no longer than 50 ms.

To monitor and troubleshoot large carrier networks Operations, Administration and Management (OAM) functionalities need to be supported by the network. Monitoring end-to-end activity needs to be available through automatic continuity check messages, but also by supporting 'traceroutes' through the network manually. This enables the network to react proactively to network failures by using a similar method as presented above when switching DVPNs to a different path, also known as 'fast failover.'

To sum up the requirements discussed in this section, the network needs to provide the following functionalities:

1. identify traffic from separate DVPNs by tagging,
2. scalable up to thousands of DVPNs and C-MACs,
3. topology discovery,
4. provision paths over the network,
5. efficient use of, and control over all network resources (Traffic Engineering (TE)),
6. share the load of traffic over multiple paths,
7. rate limiting or filtering of BUM traffic,
8. rate limiting of total DVPN traffic per port,
9. fast failover times (<50ms) to provide continuity to critical applications,
10. provide Operations, Administration and Management features to monitor and troubleshoot the network.

2.3 Provisioning

Before implementing a DVPN in the network, the network first has to become converged. Meaning that the topology of the complete network is known and that paths can be created over this topology.

A DVPN instance consists of multiple member ports, which are identified by their PE device and the port on that PE. The instance also contains values for its minimum and maximum available bandwidth which can be used to determine the paths that the DVPN will get assigned. When member ports reside on different PEs, a bidirectional path will need to be created through the network. The route of the path will depend on *a)* the liveness and administrative availability of the links, *b)* the administrative costs of the links, and *c)* the resources available on the links towards the PE. The exact algorithm used to choose the paths lies outside of the scope of this document. Paths are defined by the physical ports that they traverse through the network, with the PEs as the first or last in the list.

When the path between two PEs has been setup for the DVPN, it can be put in the DVPN description. More paths may be added over different routes and paths may be adjusted during the lifetime of the DVPN. This may for example be necessary when a certain link in the path fails, or when it nears its peak capacity and has to be rerouted. Individual port utilization will be monitored and when a certain link shows high utilization, the corresponding paths and DVPNs using those paths can be looked up using the information base. Also other monitoring and troubleshooting processes will profit from this information.

After the complete paths between PEs with DVPN members have been setup the traffic can start flowing. However, as has been mentioned before, the rate limiting feature will need to be applied to the ingress ports to prevent the DVPN from using up all the network's resources.

To provision DVPNs in the network, the NMS in short should be able to:

1. take input as certain ports to be placed in a DVPN,

2. determine routes that can be used for the paths,
3. monitor links and reroute paths on failure or peak capacity,
4. set the rate limits on ingress PE ports.

3 Implementation

Using the requirements set forth in Section 2 we can compile a list of contemporary technologies that can meet them and provide DVPNs. The protocols considered had to meet 2 criteria: 1) can provide Ethernet PPVPNs between multiple sites, and 2) protocol stack must be supported in hardware at time of writing.

3.1 Contemporary Technologies

3.1.1 SPB

Shortest Path Bridging (SPB) is an evolution of the original IEEE 802.1Q Virtual LAN (VLAN) standard. VLAN tags have been in use in the networking world for a long time and provide decent separation in campus networks. However, when VLAN-tagging was done at the customer network, the carrier couldn't separate the traffic from different customers anymore. This resulted in 802.1Qad or Q-in-Q which added an S-VLAN tag to separate the client VLANs from the SP VLANs in the backbone. This was usable for the Metro Ethernet networks for a while but when SPs started providing this services to more and more customers, their backbone switches could not keep up with the clients MAC addresses.

To provide the required scalability with regard to MACs in the backbone, Provider Backbone Bridging (PBB) (802.1Qay or MAC-in-MAC) was introduced. It encapsulates the whole Ethernet frame on the edge of the carrier network and forwards the frame based on the Backbone-MAC of the egress PE. It also separated client VPNs using a Service Instance Identifier (I-SID), which with 24 bits is able to supply the carrier with 16 million separate networks. The downside of PBB remained one that is common to all Layer 2 forwarding protocols: the possibility of loops. Preventing them requires Spanning Tree Protocol (STP) which will disable links to get a loop-free network. Disadvantages of STP include the relatively long convergence time and inefficient use of resources due to the disabled links. This has been solved by using IS-IS as a routing protocol to discover the network topology. After which each PE creates a Shortest Path Trees (SPTs) originating from each edge device to every other PE. This is called SPB or 802.1aq.

SPB benefits from the maturity of the Ethernet protocol by reusing protocols for OAM and Performance Measurement (PM). This allows for fast error detection and extensive troubleshooting tools by using the Institute of Electrical and Electronics Engineers (IEEE) 802.1ag and International Telecommunication Union - Technology (ITU-T) Y.1731 standards respectively. The Intermediate System-Intermediate System (IS-IS) implementation has also been adapted to rapidly detect errors however, no fast recovery function has been defined, besides complete IS-IS reconvergence. This would result in a traffic impact of several hundreds of milliseconds in large networks [8].

However, due to its Ethernet STP forwarding-based nature it lacks TE features. The paths that the VPN traffic takes are not explicitly configurable and provide limited scalability due to limited amounts of available paths (or trees in this case). As such, operators can not define constraints or explicit paths to take over the network to distribute traffic in an efficient manner. The lack of available paths also negatively affects its Equal Cost Multi Path (ECMP) functionalities. However, future, additional algorithms with multiple paths maybe introduced using extensible Equal Cost Trees (ECT) algorithms [9].

Provided that IS-IS has been configured on all provider devices, Figure 3 illustrates the interfaces needed to provision a DVPN in SPB. It excels in its simplicity by providing 'single-point provisioning'. This means that the NMS only needs to add the member CE port to a certain DVPN I-SID, after which the PE floods this binding through the IS-IS network and other PEs sharing this I-SID will install the path towards the ingress PE. The rate limiting of the CE ports is a vendor-specific feature however, and may vary per hardware platform.

3.1.2 MPLS

Multi Protocol Label Switching (MPLS) is known for its scalability and extensibility. Over the past decade additions have been made to the original specification to overcome a plethora of issues within carrier net-

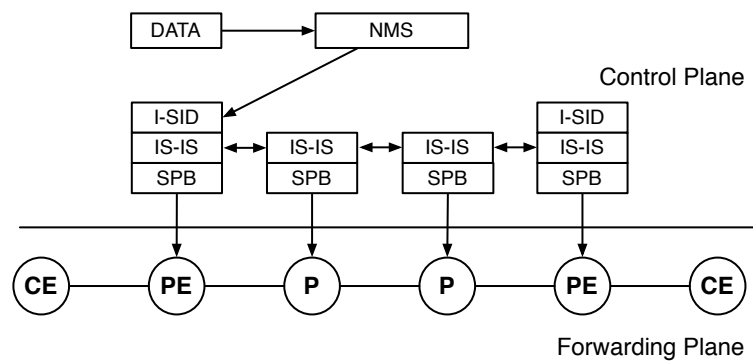


Figure 3: Provisioning a DVPN using SPB.

works. This initially started with trying to implement fast forwarding in legacy switches using labels (or tags) at the start of the frame [10]. When this issue became surmountable using new hardware, MPLS had already proven to be capable of transporting a wide arrange of protocols on the carrier backbone network, all the while also providing scalability, TE and Quality of Service (QoS) features to the operators.

MPLS itself is more a way of forwarding frames through the network, without facilitating any topology discovery, route determination, resource management, etc. These functions are left to a stack of other protocols. Without IP reachability throughout the network these protocols cannot exchange traffic and so, as a prerequisite, MPLS relies on an Interior Gateway Protocol (IGP) like Open Shortest Path First (OSPF) to discovery the topology.

The distribution of labels has to be facilitated as well, which is done using Label Distribution Protocol (LDP) and/or Resource Reservation Protocol (RSVP). These protocols run between each device in the path between two PEs and exchange the labels that they will assign to a certain path, thereby setting up a Label-switched Path (LSP). LDP does this by distributing its labels from the egress PE up towards the ingress PE based on IGP costs. RSVP, on the other hand, signals its paths from the ingress PE towards the downstream PE based on constraints, potential explicit hops or as a last resort using the IGP next hop. Label distribution is still determined from egress to ingress, but the actual path is determined at the head-end. To determine the best path to take, RSVP uses the Constrained Shortest Path First (CSPF) algorithm which can take into account link characteristics like bandwidth or Fast Reroute (FRR) support. This allows RSVP LSPs to take more well informed paths through the network and together with support for defining explicit paths, allows for granular TE features which LDP lacks. Both LDP and RSVP also allow for the use of multiple paths over the network to share traffic load towards a PE.

The aforementioned FRR feature is unique to RSVP and provides the network with fast failure recovery. It does so by preprovisioning a so-called backup LSP next to the primary LSP. When a failure is detected on the primary LSP, traffic is immediately shifted towards the standby path, yielding a sub-50ms failover. Obviously, this value also depends on the time it takes for the failure to be detected. Therefore it is important to have some sort of detection mechanism in place. One that is commonly used and integrates with OSPF is Bidirectional Forward Detection (BFD). This protocol sets up sessions between devices and triggers an alarm when the session does not behave as expected. At which point FRR kicks in.

VPNs are also provided by additional protocols. Layer 3 VPNs make use of Border Gateway Protocol (BGP) to distribute client prefixes to the edges of the carrier network. The core is only concerned with the forwarding of labels and has now knowledge of these IP prefixes. Layer 2 VPNs make use of VPLS, a service which encapsulates the entire Ethernet frame and pushes a label to it to map it to a certain separated network. Again, the core is only concerned with the labels and only the edges need to know the clients MAC addresses. When setting up a VPLS instance (a VPNs), LDP sessions are setup between all PEs part of the same VPLS instance. Consecutively, the PEs will exchange their chosen labels for that instance between each other.

The C-MACs in a VPLS instance are normally learned through the data plane. That is, when a frame comes

in from a CE, the PE learns the SA behind the corresponding port. If it doesn't know the DA, it will flood the frame to other PEs with member ports in that instance. These PEs in turn learn the SA as well behind the ingress PE. When a large number of C-MACs are present within a VPLS instance this can cause a lot of broadcast traffic, specifically ARP traffic. To solve this, the Ethernet VPN (E-VPN) standard has been proposed [11]. This technique provides MAC learning in the control plane by exchanging learned C-MACs between PEs using Multi-Protocol BGP. Additionally it may also learn the IP address associated with the C-MAC and distribute that as well. Thereby being able to act as an ARP proxy, as earlier illustrated in Figure 2b.

The different protocols all depend on each other, as illustrated in Figure 4. Each PE device runs this stack, while P devices run a subset which is shaded.

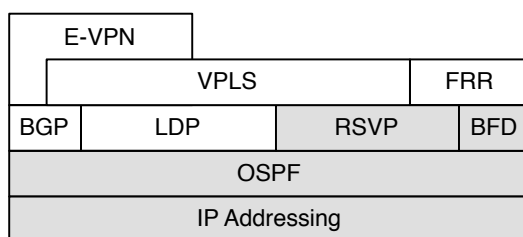


Figure 4: Dependency stack of MPLS-related technologies.

To configure a DVPN using MPLS first the participating PEs need to be configured with the new VPLS instance to which the member CE ports will be added. Next, constraints are defined by the NMS, which can be in the form of an explicit route to make a static route or by defining loose constraints based on bandwidth limits which can be used the CSPF algorithm. Using these constraints, paths are installed at each PE towards every other participating PE. These paths are then added to the VPLS instance, allowing LDP sessions to be setup between the PEs. Next, for FRR, backup LSPs need to be defined similarly to the primary LSP but over a different path, which can again be done using constraints to exclude the other links. Utilization of the links in the network has to be monitored as well and when a path has a link which is nearing capacity, new LSPs have to be provisioned and some VPLS paths move to those LSPs. And finally the ingress traffic on the CE ports need to be rate limited. This procedure again, is not standardized and is dependent on support of the hardware.

The procedure above implies that the backbone network has been setup with the following protocols and features already enabled: IP addressing, OSPF routing, MPLS forwarding, RSVP with FRR and BFD. After initial setup of the backbone network the NMS is only concerned with the PEs, as can also be seen in Figure 5.

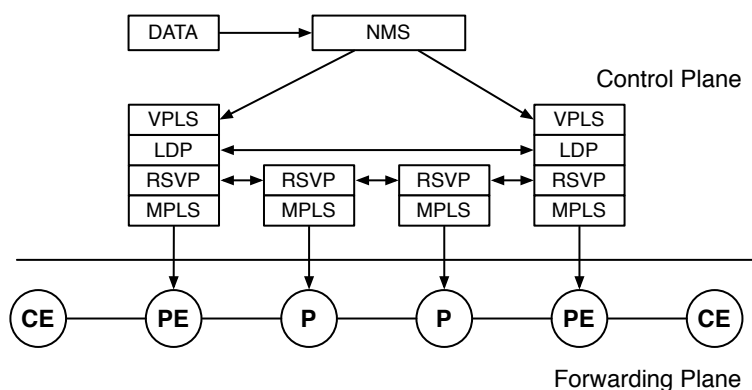


Figure 5: Provisioning a DVPN using MPLS.

3.2 OpenFlow

Section 1 gave a short introduction into what SDN and OpenFlow entail and what it promises in terms of cost savings and agility. Software Defined Networking is the general principle of designing flexible networks using open interfaces towards the hardware. OpenFlow is a subcomponent of this new principle which provides a protocol between the forwarding plane of the networking devices and a centralized controller. Essentially, taking over the role of the distributed control planes of the network devices. A general overview of the SDN architecture and OpenFlow is given in Figure 6. OpenFlow provides the controller with an API that can be used to install flow entries directly in the forwarding plane of the devices. Flow entries consist of six fields:

Match	This field contains a list of frame/packet characteristics that will need to be present to match to this entry, e.g. DA, IP source address or MPLS tags.
Priority	The precedence of this flow entry over other flow entries to which a certain frame matches.
Counters	Frames matching to this entry are counted for monitoring purposes.
Instructions	When a frame is matched using the match field, it is processed according to a list of instructions, which may include forwarding out of a port, rewriting headers and/or applying meters.
Timeouts	The time that a flow entry can be live until it is discarded.
Cookie	Value assigned by controller to identify the flow (not used to forward frames).

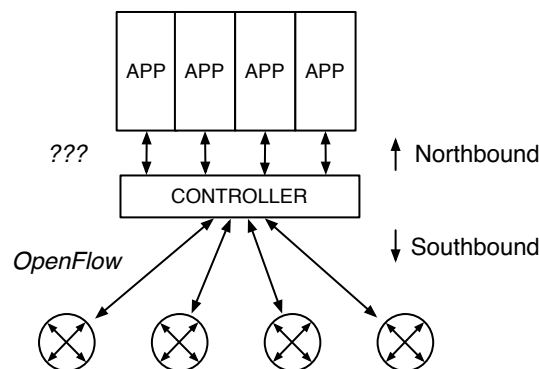


Figure 6: Architecture of SDN and OpenFlow.

Flow entries have been understandably compared to ACL entries, however it is also apparent that there are many more possibilities with regards to matching and performing actions. The frame fields that can be matched upon have changed over the lifetime of the OpenFlow specification. For example, version 1.0 could only match and/or act upon tagged traffic using a single outer-VLAN tag. Version 1.1 added matches and actions for Q-in-Q tags and MPLS labels, and version 1.3 could also match PBB tags. See Table 1 for a comparison of key features in different versions of OpenFlow spec.

Note that rate limiting on a per port basis has been available in OpenFlow since version 1.0. Additionally, version 1.3 added support for per flow rate limiting using so called ‘meters’ which can be assigned to specific flows. By doing so it becomes possible to also rate limit flows on certain aggregation ports rather than just at the ingress port of the CE.

The installation of flow entries is done by the controller, governed by the applications running on it. Applications can be written to provide functions like topology discovery, routing, etc. Moreover, without these installed applications, the network will be unable to forward any traffic. The interface between the applications and the controller is also being referred to as the ‘northbound interface’. This interface, in contrast to

	1.0	1.1	1.2	1.3
VLAN Tags	✓	✓	✓	✓
Q-in-Q Tags		✓	✓	✓
MPLS Tags		✓	✓	✓
PBB Tags				✓
Groups		✓	✓	✓
Rate limiting	✓	✓	✓	✓

Table 1: Comparison of OpenFlow versions regarding key features for DVPNs.

the southbound OpenFlow interface, has not been specified and varies between different controller implementations, limiting the portability of the network applications.

Fast failover and ECMP can be accomplished using the aforementioned port ‘groups’, which are available since version 1.1. Groups can be defined as a destination in a flow entry and contains a list of ports. The type of group defines the action of the group: ‘**all**’ sends the frame out of all ports in the group (broadcast/multicasting); ‘**select**’ outputs it to one of the ports (providing ECMP); ‘**indirect**’ is a single port group which can be used by multiple flow entries (aggregation); and ‘**fast failover**’ which choses the first *live* port out of which it will forward the frame. To support ‘fast failover’ a *liveness monitoring* technique needs to be implemented supported by the switch. This could simply be the physical link state or more intricate tools, e.g. BFD.

Implementing DVPNs using OpenFlow relies mostly on the applications running on the controller. When they are written and configured as desired, provisioning a DVPN would only require the input of the data. After which the applications and controller install flow entries into all the network devices in the DVPN path, as can be seen in Figure 7.

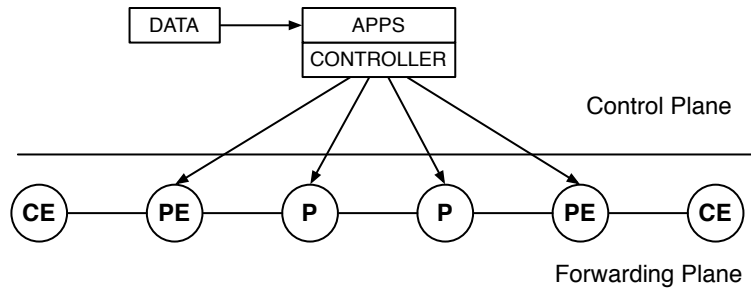


Figure 7: Provisioning a DVPN using OpenFlow.

3.2.1 DVPN Applications

To implement DVPNs, a combination of applications need to be installed on the controller that contemporary technologies solve using distributed protocols:

Topology Discovery Network devices do not require IP connectivity between each other to exchange route information. Instead, they rely on their connection to the controller to provide them with information. A topology discovery applications will instruct network devices to send out unique discovery messages which are then received by other devices, which forward the message back up to the controller. By keeping information on which packet goes in and comes out where, the application can get an overview of the network.

DVPN Provisioning The DVPN input will provide the application with at least the CE port and preferably the corresponding MAC and/or IP address. It can then instruct the path provisioning

component to setup a path between the PEs participating in the DVPN. The application is also concerned with keep the provided or dynamically learned MAC addresses up-to-date. Additionally, a flow can be installed matching on the ARP EtherType that sends the ARP request towards the controller. If the application also keeps track of the IP addresses of the CEs it can then act as an ARP proxy and reply to the requesting CE with the correct IP address.

- Path Provisioning** Using the discovered topology, paths are then setup over those routes between PEs with member CE ports in a common DVPN. To provide MAC scalability over the backbone network, the traffic will need to be tagged using either PBB or MPLS labels. In contrast with the contemporary technologies the P devices also need to be updated using the forwarding information. After all, there are no distribution protocols running between the devices.
- Traffic Engineering** The path setup procedure uses data from the DVPN input and the discovered network resources to provide the most optimal path between two PEs. Constraints for the paths taken by each DVPN can be configured by the operator and influence the route selection directly over the whole platform. Also, using input from the OAM monitoring applications paths may be preferred or deprecated based on their performance.
- OAM** The controller and applications provide a complete overview of the network but troubleshooting and monitoring still has to be done at the network level as well. Different approaches can be taken to do so, one of which could be sending out periodic keep-alive messages in the same path from the controller down to the ingress PE that the egress PE should forward back up to the controller. Another example is implementing an already defined OAM protocol in OpenFlow, as has been done in [12] which implemented Ethernet 802.1ag OAM.

The interaction between the different applications has been illustrated in Figure 8.

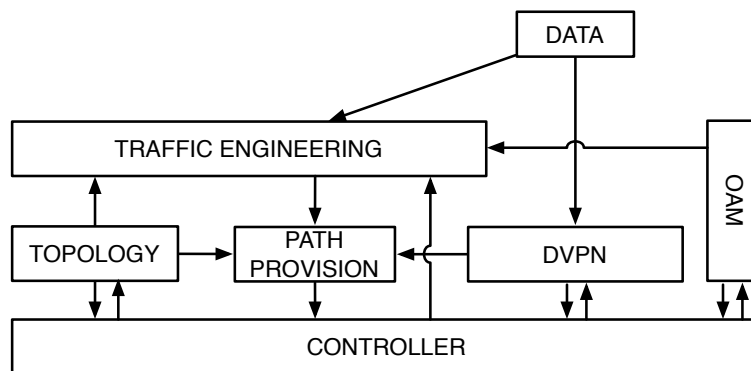


Figure 8: Interactions between applications to implement DVPNs.

Unlike contemporary technologies that require inter-device communication before any paths can be set up, the forwarding tables of OpenFlow devices are empty. The only prerequisite is that the devices all have a management connection to the controller from which they can receive their forwarding information.

4 Results

The features and limitations of the three discussed technologies in Section 3 are given in Table 2. In this section we will evaluate them against the requirements set forth in Section 2.

	SPB	MPLS	OpenFlow / SDN
Tagging of VPN Traffic	PBB	VPLS (MPLS)	PBB / MPLS
MAC Scalability	yes	yes	yes
Topology Discovery	IS-IS	OSPF	application
Path Provisioning	SPT	RSVP / LDP	application
Traffic Engineering	limited	RSVP	application
ECMP	limited	yes	yes, using Groups
BUM limiting	dependent on HW	dependent on HW	yes, using Metering
Exchange C-MACs	no	E-VPN (draft)	application
Ingress Rate Limiting	dependent on HW	dependent on HW	yes, using Queues or Metering
Fast Failover	no	FRR	yes, using Groups
OAM	802.1ag / Y.1731	LSP Ping / BFD	application
Forwarding Decision	PBB tags	MPLS labels	flow entry
BUM traffic handling	flood	flood	sent to controller

Table 2: Feature requirements available in discussed technologies.

4.1 SPB

The SPB architecture allows for a scalable carrier network supporting thousands, even millions of DVPNs using the I-SID in the PBB frame. From our theoretical implementation, it becomes evident that setting up a DVPNs requires little configuration. The I-SID only needs to be configured on the head-end PE and the IS-IS routing protocol distributes this binding to the other corresponding PEs. Another benefit is the use of Ethernet OAM standards that are mature and extensive to allow for precise monitoring and troubleshooting.

Unfortunately, the simplicity of the setup comes at a cost. The protocols has:

- limited explicit or constraints-based routing, meaning few TE features,
- limited ECMP functionality due to the infancy of the standard to support it, and
- because, failure recovery depends on IS-IS reconvergence, no fast failover.

These shortcomings are being worked on by the community, e.g. IEEE 802.1Qbp which provides extensive ECMP functions. Progress is slow however, and the overall standard will need to mature before it will be suitable for carrier implementations.

4.2 MPLS

4.3 OpenFlow

How did it do?

What are the differences?

These features are essential for implementing VPNs because the traffic flows will need to be separated upon entering the carrier network for MAC scalability.

MAC Scalability only from 1.0 onwards.

1.0 supported almost everywhere, 1.1 and 1.2 are not. 1.3 slowly coming.

The strength of these applications however, is the fact that operators can integrate their NMS and control plane even more. This allows for a more granular control over their traffic

MPLS VPNs in OpenFlow: [13]

MPLS control plane in OpenFlow: [14]

Lacks liveness monitoring

PROS/CONS

Also: access layer intelligence.

5 Conclusion

6 Future Work

Other use cases:

- multi-domain
- mobility
- smart metering

A Acronyms

ACL	Access Control List	PBB	Provider Backbone Bridging
API	Application Programming Interface	P	Provider device
ARP	Address Resolution Protocol	PE	Provider Edge device
BFD	Bidirectional Forward Detection	PM	Performance Measurement
BGP	Border Gateway Protocol	PPVPN	Provider-provisioned VPN
BUM	Broadcast, Unknown unicast and Multicast	QoS	Quality of Service
CE	Customer Edge device	RSVP	Resource Reservation Protocol
C-MAC	Customer MAC	SA	Source Address
CSPF	Constrained Shortest Path First	SDN	Software Defined Networking
DA	Destination Address	SPB	Shortest Path Bridging
DVPN	Dynamic VPN	SPT	Shortest Path Tree
ECMP	Equal Cost Multi Path	SP	Service Provider
ECT	Equal Cost Trees	STP	Spanning Tree Protocol
E-VPN	Ethernet VPN	TCP	Transmission Control Protocol
FRR	Fast Reroute	TE	Traffic Engineering
HW	Hardware	VLAN	Virtual LAN
IEEE	Institute of Electrical and Electronics Engineers	VPLS	Virtual Private LAN Service
IGP	Interior Gateway Protocol	VPN	Virtual Private Network
IP	Internet Protocol		
IS-IS	Intermediate System-Intermediate System		
ITU-T	International Telecommunication Union - Technology		
LAN	Local Area Network		
LDP	Label Distribution Protocol		
LSP	Label-switched Path		
MAC	Media Access Control		
MPLS	Multi Protocol Label Switching		
NMS	Network Management System		
OAM	Operations, Administration and Management		
OSI	Open System Interconnect		
OSPF	Open Shortest Path First		

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