Software Defined Networks, FS2022

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1 Introduction and Concepts

Traditional Networking Architecture is divided into planes, depending on the layer

.	Control Plane	Data Plane	Management Plane
Layer 2	Spanning Tree Overlays (VLANs)	Forward *Ethernet Frames*	
Layer 3	Routing Protocols Overlays (MPLS)	Forward *IP Packets*	

This results in some drawbacks such as

- – Limited decision making "intelligence"
- – Difficult administration
- – Missing overall analytics

1.1 Vision of SDN

- Hardware: cheaper
- Software: features frequent releases, decoupled from hardware
- Functionality: driven by software and controller. Aiming for a programmable network
- Simplicity: from manual to automated, from box centric to network wide, from provisioning in months to provisioning in hours
- Innovations: from closed systems to open and programmable

Virtualization of Computing needs virtualization of Network!

1.2 SDN Devices

All Information from FIB to Config can be updated via API calls (support depending: RESTCONF, NETCONF, ...)

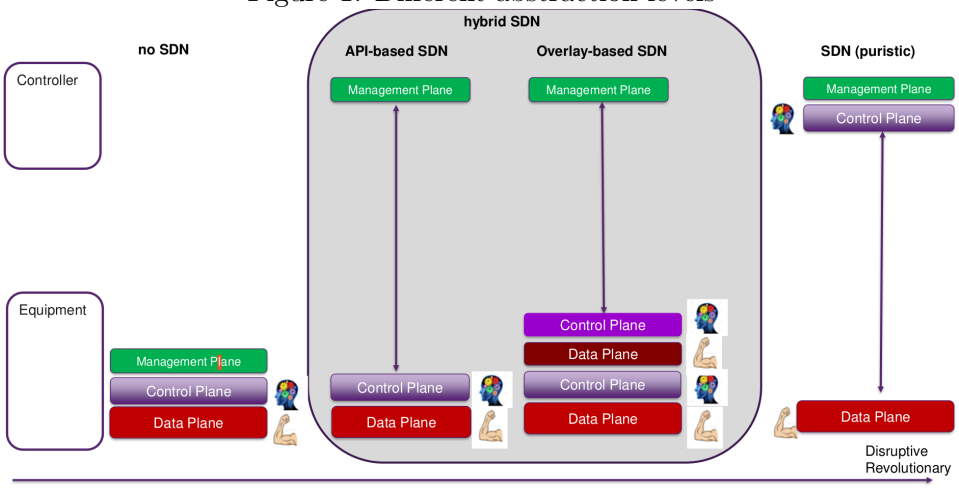
White box switches

- support OpenFlow 1.3
- Third Party OS Support

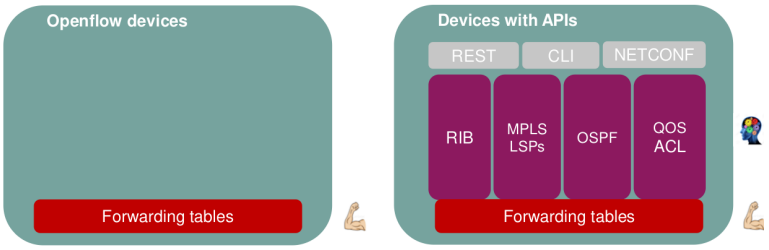
White box OS

- Open Compute Project OCP

Figure 1: Different abstraction levels



- Pica8
- Nvidia Cumulus Linuz
- opennetlinux.org
- fboss

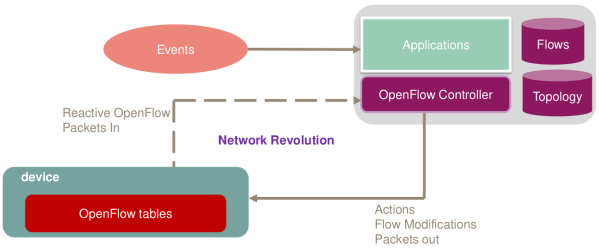


1.3 SDN Approaches

Different levels of abstraction can be applied to the topology, resulting in mainly three different SDN approaches.

1.3.1 Pure SDN

Academic approach. Only Data Plane on each device. Management and Control Plane centralized, resulting in full decoupling. OpenFlow Protocol distributes information, unknown Packets are sent to controller. Flow table is used for forwarding decisions.



Positive

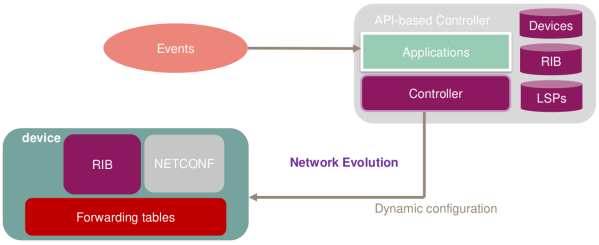
- Independent evolution and development
  - software control of the network can evolve independently from hardware
- control from high-level software program
  - debug/check behaviour more easily
  - testing/troubleshooting

Negative

- controller could be single point of failure
- no topology change without controller
- migration
- high risk

1.3.2 Hybrid SDN, API based

Data and Control Plane on each device, Management Plane centralized. Similar to snmp, ssh scripts.



Positive

- Faster provisioning of new customers and services
- Low impact in case of controller loss:
  - Provisioning delayed

Figure 2: Pure SDN schema example

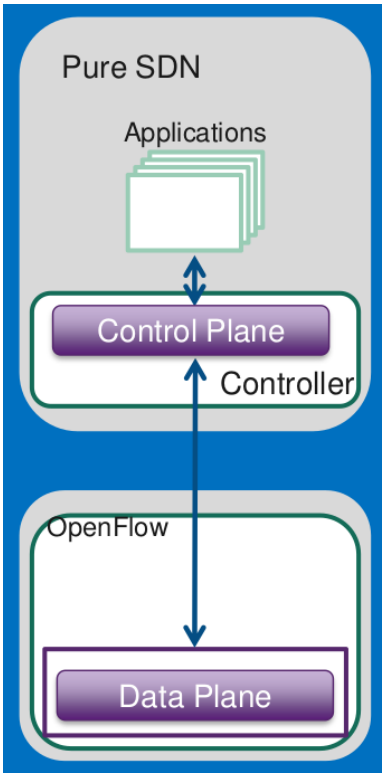
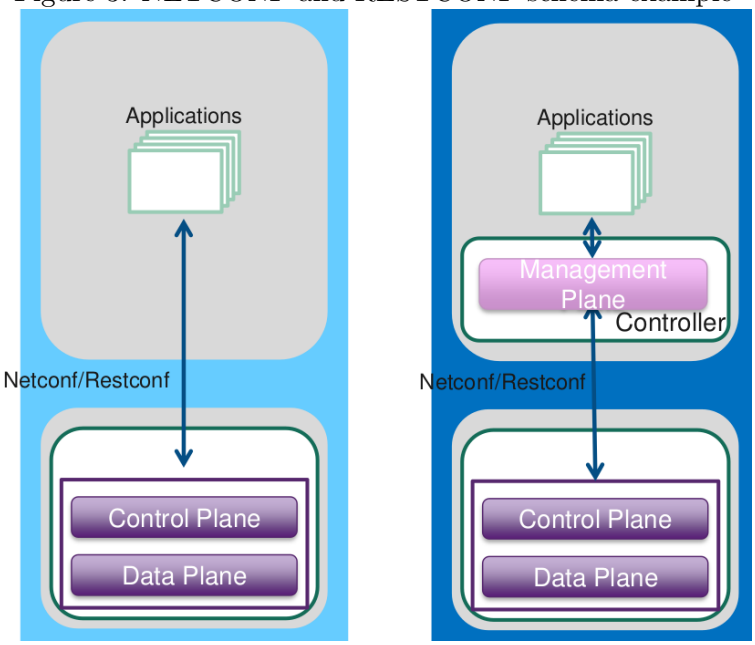


Figure 3: NETCONF and RESTCONF schema example



  - Visibility loss
  - Equivalent to any orchestration system failure
- Network partitioning: low impact
- Increased flexibility and speed

Neutral

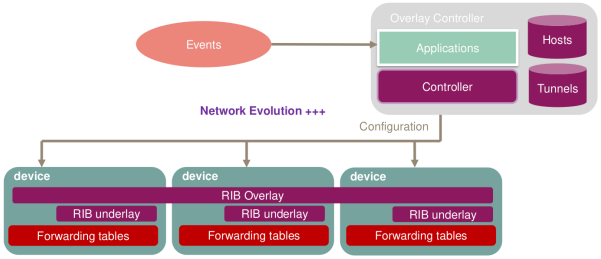
- Normal hardware cost
- No control plane change
- Transactional consistency important (all or nothing commands on devices)

Negative

- Static Management
- Not suited for multivendor environments
- software dependencies

1.3.3 Hybrid SDN, Overlay based

- Underlay Network: optimized, traditional Architecture
- Overlay Network: flexible, virtual network, centralized Management Plane
- Encapsulation necessary (VXLAN, NVGRE, IPSEC, ...)



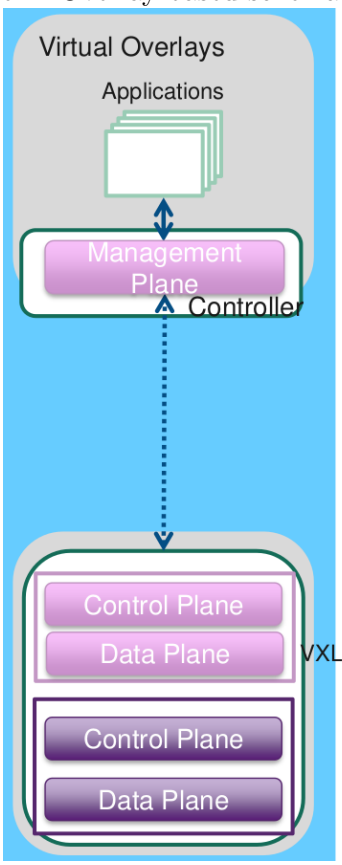
Positive

- Decoupling of services and network
  - Service provisioning in the edge elements
- No impact on the transport core

Negative

- overhead in
  - Encapsulation
  - Processing power
  - Complexity (additional control plane)
- Overlay-to-physical gateways
- End-to-end monitoring and troubleshooting

Figure 4: Overlay based schema example



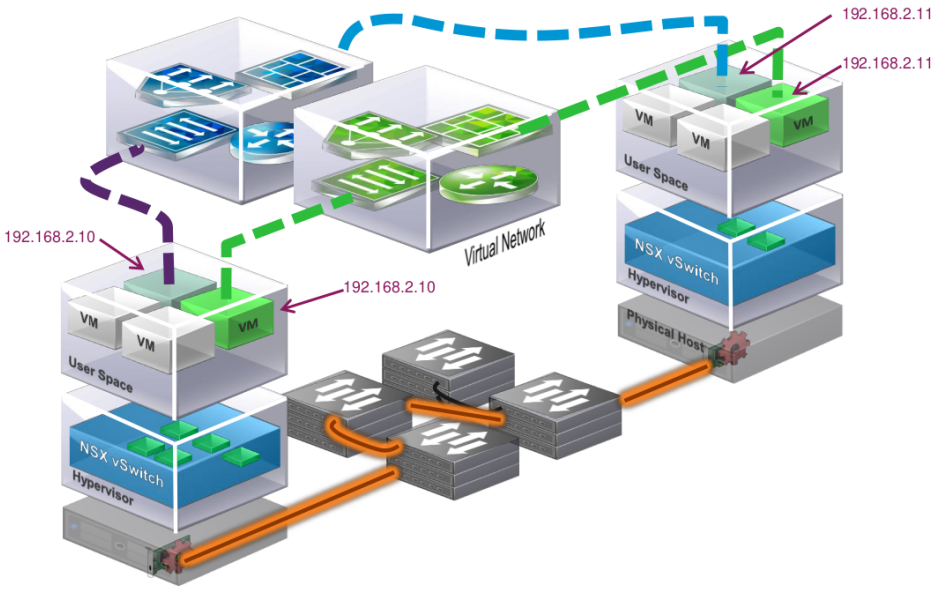


Figure 5: Datacenter example of an overlay solution

2 Segment Routing

RFC 8402: `https://datatracker.ietf.org/doc/html/rfc8402`

"Segment Routing (SR) leverages the source routing paradigm. A node steers a packet through an ordered list of instructions, called segments. A segment can represent any instruction, topological or service based. A segment can have a semantic local to an SR node or global within an SR domain. SR provides a mechanism that allows a flow to be restricted to a specific topological path, while maintaining per-flow state only at the ingress node(s) to the SR domain."

- Prefix-SIDs are
- Adjacency-SIDs are labels with the format 24NXY for the N-th adjacency from x $\rightarrow$ y
- LDP/RSVP/BGP labels are in the range [90000 - 99999]

Source Routing: The entire path is calculated as a *Segment List* by the source router, or received by a PCE (Path Computation Element). The rest of the network only executes these encoded instructions, there is no per-flow state information.

Segment: An instruction to the processing device on how to forward the packet. The Segment-ID can be encoded as an MPLS label or an IPv6 and is usually associated either with a destination prefix, a local interface or a local service. In combination, a list of segments specifies the entire path a packet is supposed to take.

Local Segment: Only the node that originates this segment understands the associated instruction.

Global Segment: Each node in the SR Domain understands the associated instruction and installs it in its forwarding table.
Default label range [16000- 23999] is called SRGB / Segment Routing Global Block.

Instruction: can be one of the following three.
PUSH – insert segment(s) at the packet head and set first as active
CONTINUE – active segment is not completed and remains active
NEXT – active segment is completed, make next item in SID list active

2.1 IGP Extensions

See also: Segment Routing IGP Control Plane on segment-routing.net

The following segment types are based on on IGP routing information. The usual topology updates with added SID information are distributed by the IGP protocol within the SR-Domain. Prefix-to-SID mapping server

SR for IS-IS supports TLV extensions of the routing protocol – additional Information transmitted via Link State Packets (LSP)

SR for OSPF is implemented by adding new Types of LSA (Link State Advertisements).

Metric-style wide must be applied for the routing protocol configuration in order to support SR capabilities.

Some sub-TLVs supported are

- SR Capability: IS-IS router Capability
- Prefix-SID: Extended IP Reachability
- Prefix-SID: IPv6 IP Reachability
- Prefix-SID: SID/Label Binding
- Adjacency-SID: Extended IS Reachability
- LAN-Adjacecny-SID: Extended IS Reachability

2.1.1 IGP Prefix Segment *(global)*

Shortest path to any known IGP network prefix. ECMP-aware. Global Segment, Label identified as 16000 + Index. Distributed by ISIS/OSPF. Prefix SID is domain-wide unique, assigned manually to the loopback address of each node. **Algorithm ID** specifies the method of choosing a path. Default is 0, shortest path.

To ensure uniqueness of Prefix-SIDs, only one can be associated with each Prefix/Algorithm combination.

Example:

```
1.1.1.1/32 prefix-SID 1001 for algorithm 0
1.1.1.1/32 prefix-SID 2001 for algorithm 1
```

A Prefix Segment can be of two different types

- Node Segment
  Associated with a /32 prefix which is a node address.
  Sets **N-Flag** in Segment ID.

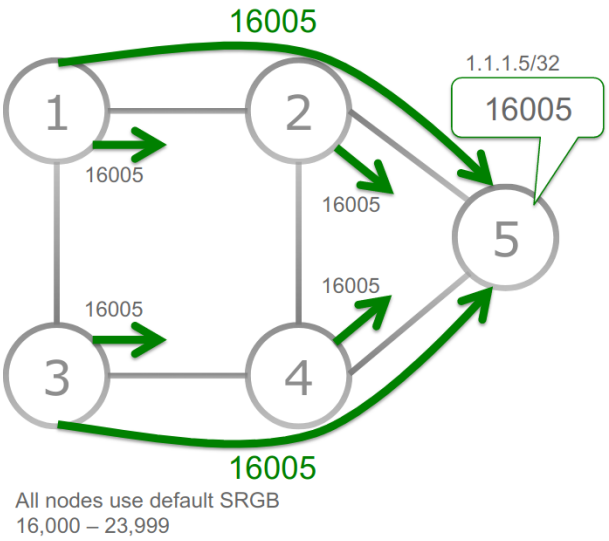


Figure 6: IGP Prefix Segment

- Anycast Segment
  Associated with an anycast prefix, which routes to the geographically closest out of a group of hosts.
  N-Flag is unset!
  Macro-Engineering: can be used to steer traffic via specific region, or make it pass some router performing special network functions.
  Offers ECMP load balancing and high availability.

2.1.2 Adjacency Segment *(local)*

Unidirectional Adjacency, traffic is steered explicitly over an interface / link. Overrides shortest path routing decisions. SID list contains node prefix first, then Adjacency-ID. Distributed by ISIS/OSPF.

- Layer-2 Adjacency can address one specific link inside a Link Aggregation Group (LAG).
- Group Adjacency

2.2 BGP Segments

- BGP Prefix Segment
  Global segment, associated with a BGP Prefix
  "steer traffic along the ECMP-aware BGP multi-path to the prefix associated with this segment"

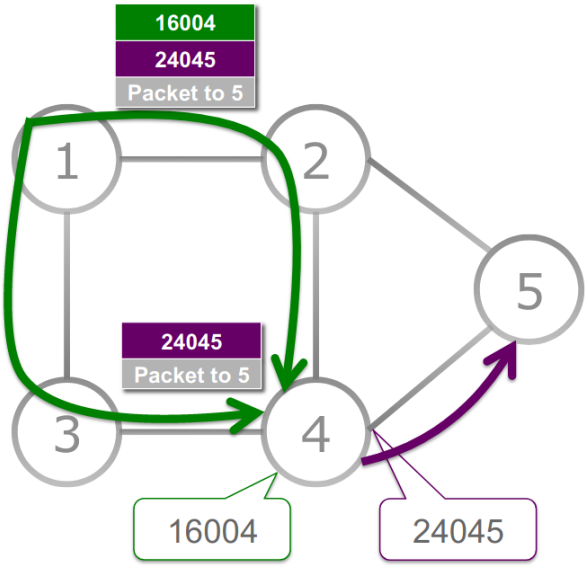


Figure 7: Combining IGP PRefix and Adjacency Segments

- BGP Anycast Segment
  Traffic steering capabilities such as *"steer traffic via spine nodes in group A"*
- BGP Peer Segment
  Associated with BGP Peering sessions to specific neighbor
  Local segments that are signaled via BGP link-state address-family
  "steer traffic to the specific BGP peer node via ECMP multi-path towards that peer router"
  Overrides the traditional BGP mechanism
- BGP Peer Adjacency Segment
  "steer traffic to the specific BGP peer node via the specified interface towards that peer router"

Combining segments can create any kind of end-to-end path.
Traffic steering only happens on source nodes to enable per-flow load balancing.
For **traffic engineering** (see 4) a policy defines the path (SID-List) to be used.

2.3 Labelling defaults

Label space of Segment Routing capable software is usually reserved, even if Segment Routing is not enabled:

- Label range [0-15] reserved for special-purposes
- Label range [16-15,999] reserved for static MPLS labels
- Label range [16,000-23,999] preserved for Segment Routing (Global Block)
- Label range [24,000-max] used for dynamic label allocation (SR Local labels)

2.4 MPLS Data Plane

MPLS data plane allows for direct mapping of key functionalities:

- $Segment \rightarrow Label$
- $SegmentList \rightarrow LabelStack$

Penultimate Hop Popping is enabled by default, Explicit-Null can be enabled if needed.

Prefix-SID label is imposed on a packet if

- Destination matches on a FEC (Forwarding Equivalence Class) with a Prefix-SID
- Downstream Neighbor is SR-Enabled
- Node is configured to prefer SR label imposition
- The matching FEC does not have an associated LDP label

MPLS services can be transported over SR-MPLS, removing the need for LDP as an additional protocol to operate.

Verification commands include

- `show cef 10.0.0.1/32`
- `show cef vrf RED 10.0.0.0/30`
- `show mpls forwarding`
- `show mpls forwarding labels 16004`

3 SRv6

IPv6 Segment Routing header: Next header field: 43 = Routing

- *Segment* $\rightarrow$ *IPv6 address*
- *Segment list* $\rightarrow$ *Address list in the SRH*

A pointer in the SRH points to the Active Segment in the list of segments encoded in the header. No segments are removed while forwarding the packet, only pointers manipulated. Active Segment is copied to the destination address field of the IP header.

- Last segment index is 0
- First segment index is *first segment*
- Active segment index is *segments left*

3.1 The SR Procedure

If source node is SR capable, the following steps are applied to a packet:

1. SR Header is created with the segment list in reversed order of the path.
2. Segment list [0] is the *last* segment
3. Segment list $[n-1]$ is the *first* segment
4. Segments left is set to $n-1$
5. First segment is set to $n-1$

In case a node in transit is not SR-enabled, plain IPv6 forwarding based on the Destination Address header field can be used. No inspection or update of the SR-header is performed.

This results in ***full interoperability*** between SRv6 and IPv6 nodes.

SR Segment Endpoints perform the following steps
IF (segments left > 0), THEN

1. Decrement Segments left by 1
2. Update DA with Segment List [Segments left]
3. Forward according to the new DA

ELSE (segments left $= 0$)

1. Remove the IP and SR header
2. Process the payload
    - Inner IP: Lookup DA and forward
    - TCP/UDP: send to socket

The final destination does not have to be SR-capable.

3.2 Segment format

SRV6 SID is a 128-bit address. Locator part routes to the node performing any possible function defined in the second part.

Optional: the function part can be split into function bits and argument bits.

3.2.1 SRv6 uSID

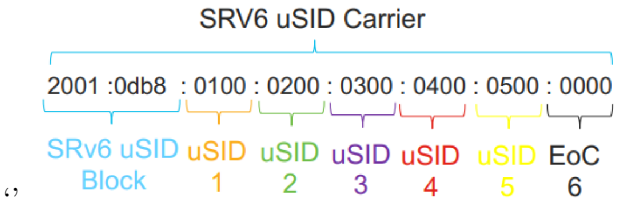
Combines several router IDs into one SRv6 SID. Completely compatible with default SRv6 SIDs.

SRv6 Locator is configured by device:

```
segment-Routing
  srv6
    locators
      locator MAIN
        micro-segment behavior unode psp-usd
        prefix fcbb:bb00:100::/48
```

ISIS configuration for SRv6:

```
router isis 1
  address-family ipv6 unicast
```



```
    segment-routing srv6
      locator MAIN
```

BGP Control Plane: per-VRF oder per-CE modes possible

```
router bgp 1
  vrf 1
    address-family ipv4 unicast
      segment-routing srv6
        locator MAIN
        alloc mode per-vrf
```

4 Traffic Engineering

Why? Simple, automated and scalable:

- no core state
- no tunnel interface
- no head-end a-priori configuration
- no head-end a-priori steering

Multi-Domain:

- SR-PCE: Path Computation Element
- Binding-SID for scale

What? SR Policies

Tuple of `(head-end, color, end-point)` uniquely identifies an SR Policy. Head-end: Router originating the SR policy (source). Color: a numerical value to differentiate multiple policies between the same pair of nodes. (Green: low-cost policy, red: low-delay policy)

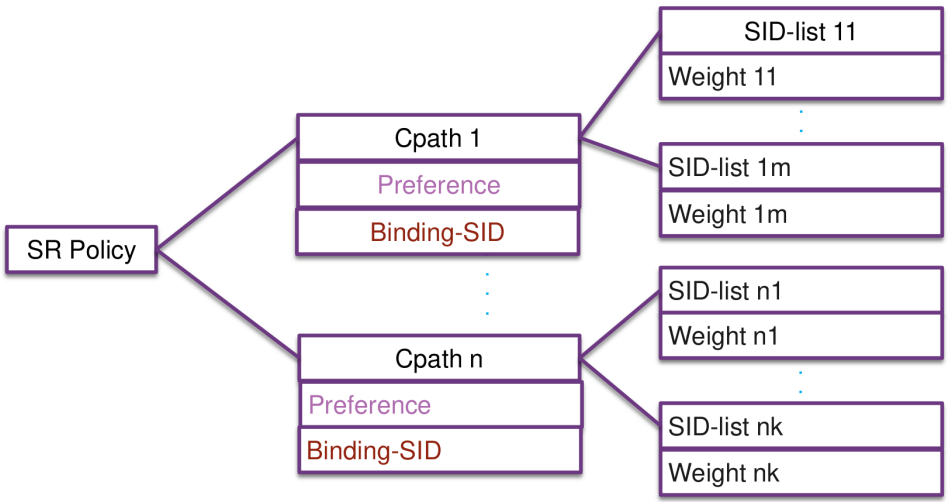


Figure 8: Structure of an SR Policy

- An SR Policy consists of 1-n candidate paths
- An SR Policy instantiates one single candidate path in RIB/FIB
- An SR Policy and all its candidate paths are associated with a single Binding-SID

- Binding SID may change at some point In time, true ID of SR Policy is its tuple
- *Binding SID installs an entry in the forwarding table to steer packets to use this policy*

A candidate path

- is either:
  - dynamic, so that it contains an optimization objective and constraints
  - explicit, so that it contains a single or a set of weighted SID lists.
- has a preference
- is valid if it is usable:
  - not empty
  - first SID is resolvable (to account for multi-domain)

Candidate Path selection happens if

- it is valid
- preference is highest

Validity of Policies is updated upon any network topology change. Traffic steered into an SR Policy path is load-shared over all SID-lists of the path → weighted ECMP based on SID List Weight

4.1 Traffic Engineering Controller

Usually, any head-end is able to compute SR-TE paths with certain optimization requirements. Still, a central view of the whole segment routing domain is necessary for several special use cases.

- Disjoint paths: two head-ends explicitly request calculation of disjoint paths from the PCE. The controller can keep track of this requirement also in case of topology changes.
- Inter-domain routing: The SR-TE database is natively multi-domain capable. Information about other SR domains is available via BGP Peering links (BGP-LS).
- Bandwidth brokering: The centralized bandwidth broker receives the bandwidth-related request from the individual routers, keeps track of the available bandwidth in the network and routes the requests accordingly.

PCC – Path Computation Client (Headend)

Any device that receives SR paths externally instead of calculating them itself. Candidate paths can be distributed via

- **PCEP:** Path Computation Element Protocol
- CLI configuration
- NETCONF / RESTCONF
- BGP

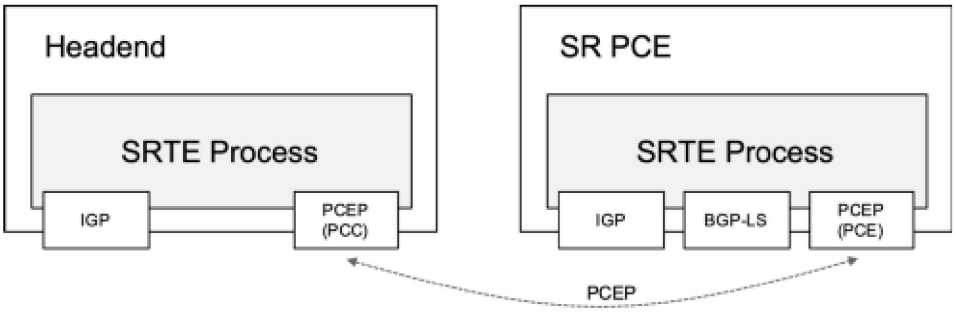


Figure 9: SRTE Headend to PCE communication

PCE – Path Computation Element

A PCE provides a path computation service to other devices (PCCs) in the network, based on provided optimization objectives and constraints. Path calculation can be initiated by the headend via stateless request/reply protocol exchange. Once the "delegation" bit is set by the headend, control of the path is then taken over by the PCE.

Path calculation can be initiated by the PCE or by an application via API.

PCE functionality can be enabled on any IOS XR device. However it is recommended to deploy separate nodes for PCE functionality to avoid the mixing of different functionality and enable better scalability.

Receives all topology information from different protocols (IS IS, OSPF, BGP LS) and combines them into the SR TE Database.

Link-delay metric is activated by default and available for policy computation.

`distribute link-state` command enables feeding SRTE DB by the routing protocol (OSPF and IS IS).

Redundancy/High Availability in PCE deployment is achieved with the following concepts:

- Primary/Secondary PCE configuration: PCE configuration on any path calculation client is either designated as primary or secondary, enabling instant failover.
- Topology learning: Using IGP / BGP information, all PCEs in the same network receive the same information about the topology present.
- SR Policy Reporting: When an SR Policy is instanciated, updated or deleted, the headend sends an **SR Policy State Report** to all its connected PCEs.
- Re-delegation behaviour: In case of failure of the primary PCE, all paths will be re-delegated to another PCE.
- PCEP Keepalive/Dead Timer: PCEP Messages (keepalive or other) are sent at least every 30 seconds.
- Reachability of the PCE is tracked in every PCCs' forwarding table (no need to wait on any timers).
- Inter-PCE State-Sync PCEP Session: An SR PCE can maintain PCEP sessions to other SR PCEs to indirectly distribute information in case some headend loses connection to one PCE.

Split-brain situation when calculating disjoint-paths: path calculation can be impossible if one path is delegated to PCE1, and it would have to be changed to calculate a disjoint path on PCE2. Creating a master/slave relationship between two PCEs solves this problem by only letting one of two PCEs calculate any disjoint path.

Northbound Interface: communicates with external applications, provides a structured endpoint to access and update topology and path information.

Southbound Interface: communicates with PCC devices, exchanging link state information and SR Paths.

4.2 LFA – Loop Free Alternate

"a directly connected neighbor that offers a repair path whose shortest path to the destination D does not traverse the protected component."

A suitable LFA does not always exist: it depends on the network topology, metrics and the component to be protected.

This is the reason LFA is usually topology dependent.

The LFA basic Loop-free condition:

$$\text{“}Dist(N, D) < Dist(N, PLR) + Dist(PLR, D)\text{”}$$

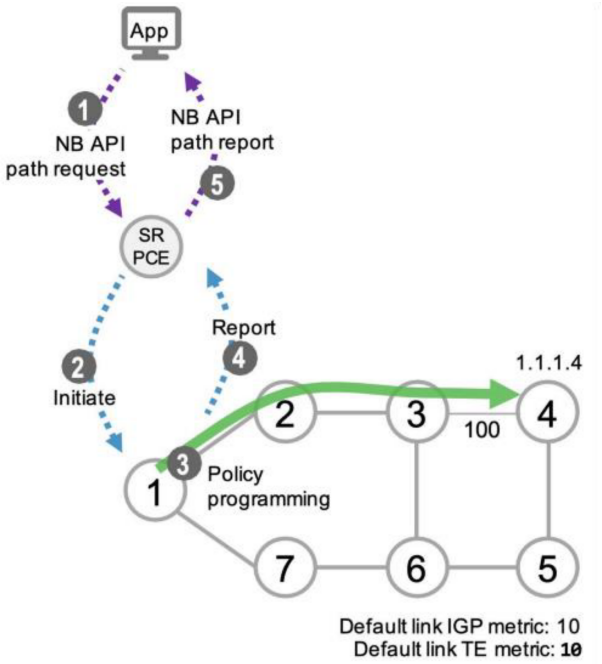


Figure 10: Basic SR TE Architecture

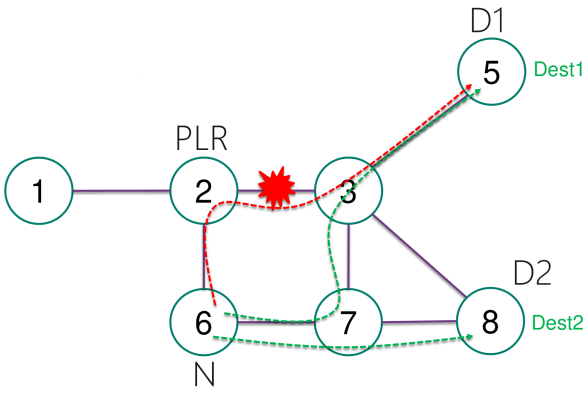


Figure 11: LFA non-ideal repair path

compares the length of the new path from the LFA (neighbor) to destination with the path from the LFA crossing the protected (failed) link.

Point of Local Repair **(PLR)**: The Node that registered a link-down event and now has to adjust its path.

N: Node that is/has designated LFA path.

4.2.1 TI-LFA: Topology Independent Loop-Free Alternate

See also TI-LFA on segment-routing.net

Offers node, link and Shared Risk Link Group SRLG protection with sub-50ms downtime. 100% Coverage in any topology. Simple to operate and understand. Automatically computed by the IGP, no other protocol required. No state outside the protecting state at the PLR, local mechanism. Optimum: Backup path follows the post-convergence path. Can be incrementally deployed Applies also to IP and LDP traffic (besides segment routing).

Path Computation: Calculate the shortest path with the outgoing link along the primary path pruned from the topology. Encode this path as a segment list to avoids microloops.

In a network with symmetric metrics, maximum two additional segments are required to form a valid repair path.

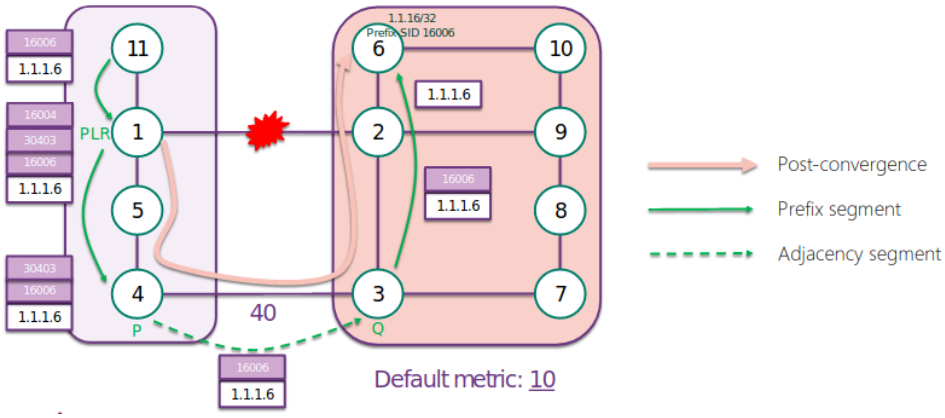


Figure 12: Repair Path using TI-LFA

Sample configuration for link protection:

```
router isis 1
  address-family ipv4 unicast
    segment-routing mpls
```

```
interface GigabitEthernet0/0/0/0
  point-to-point
  address-family ipv4 unicast
    fast-reroute per-prefix
    fast-reroute per-prefix ti-lfa

router ospf 1
  segment-routing mpls
    fast-reroute per-prefix
    fast-reroute per-prefix ti-lfa enable
```

5 Software Defined Access

The term “Fabric” describes an overlay. This is a logical topology, which virtually connects specific devices using some unspecified underlaying infrastructure. Control planes for underlay and overlay are completely separate.

Overlay transported traffic usually only “knows about” provider edge (PE) routers. Traffic routing inside the underlay network is handled by the overlay logic and also the underlay routing protocol.

Overlay can transport layer 2 or 3 traffic , using some kind of encapsulation:

- Layer 2 emulates a LAN segment, can provide different physical topologies.
  Supports: Layer 2 flooding, single subnet mobility, transports ethernet frames.
- Layer 3 abstracts IP conncectivity.
  Supports: Gateway-independent mobility, contain network failures, transport IP packets (IPv4/IPv6)

Underlay usually uses some IGP for connectivity and control plane tasks.

- OSPF
- IS IS
- Manual or automated deployment
- Low latency is important (max. 100ms)

5.1 VXLAN

VXLAN encapsulates layer 2 frames in UDP/IP, emulating a dedicated LAN network on top of a routed layer 3 network.

UDP Destination is port 4789, source port is chosen from a range of high ports to allow Equal Cost Multi-Pathing.

24-bit VXLAN segments allow for more than 16 million VNIDs, while classic VLANs are limited to 12 bit (4096 VLAN IDs).

Encapsulation of MAC in UDP can be done in hardware / at line rate.

Local Station Table - LST

Global Station Table - GST

Unknown destinations are forwarded to a spine -> Council of Oracle. The oracle (a spine node) knows everything. Because everything learned by a leaf is forwarded to the spine.

5.2 LISP

Locator Identifier Separation Protocol (Wikipedia)

Separates **EID, endpoint identities** and **RLOC, routing locators**, which an IP address usually implicitly both contains, and maps one to the other.

- Map Server / Resolver
  Control plane function
- Tunnel Router
  Ingress ITR, Egress ETR
  Registers EID of clients with Map Server encapsulates and decapsulates traffic of edge devices
- Proxy Tunnel Router PxTR
  Ingress (PITR) connects LISP- and non-LISP-domains
  Egress PETR
- Solicit Map Request
  is sent when a client location is unknown

Control Plane Register

1. Router communicates Map-Register to controller (EID, RLOC)
2. Controller builds its database

Map Request (Proxy Mode and Non-Proxy Mode)

1. Map-request for requesting a location information from the controller.
2. Non-Proxy: The request is then delegated to and will be answered by the corresponding end-router.
3. Proxy: Another request will be made to the correct router, answer will be sent by controller.
4. Request answer will be cached by the requester.

External Networks known/unknown

1. Known external networks can be listed inside the database exactly like internal hosts.
2. Unknown networks are processed as a “default route” / “not found” entry with separate destination / location.

Host Mobility

1. Known device connects with a different XTR: map entry is created.
2. Requests based on old, cached information by an ITR will be answered with "Solicit Map-Request" by the ETR that does not know the client anymore.
3. Standard Map-Request can then be sent to the correct ETR, and cache will be updated

5.3 Secure Group Tag

Topology-independent, role based access control.

Scaleable ingress tagging (SGT), egress filtering (SGACL).

Centralized policy management on DNA controller, distributed policy enforcement on all network devices.

Secure Group Tag introduces a micro level of segmentation, while VLAN and VXLAN operate on a macro level.

5.4 Cisco DNA Center

Acts as Management Controller of a campus fabric. Integrates several management systems to configure and orchestrate LAN, WLAN and WAN access.

- Fabric Control Plane
  - Different Endpoint ID Lookups are supported (IPv4, IPv6, MAC)
  - Maintanis Endpoint ID Map Registrations
  - Processes Lookup Requests by edge- and border nodes
- Fabric Edge node supplies first-hop services for users and devices that are connected to the fabric
  - Identify and Authenticate
  - Register endpoint ID with Control Plane
  - Anycast Layer 3 Gateway (provide the same gateway IP on all Edge Nodes)
  - De- and encapsulation of Data Traffic
- Fabric Border
  - Internal Border (XTR)
    Known Routes inside your company
    Communicates endpoints to outside and known subnets to inside of the fabric
    Hand-off means mapping context (VRF and SGT) between the domains

– External Border, Default (PXTR)
  Unknown Routes outside your company
  Gateway of last resort for all unknown destinations
  Exports all internal IP ranges as one summarized route to the available IGP
  Does not import external Routes Hand-off means mapping context (VRF and SGT) between the domains

5.5 Cisco ACI – Application Centric Infrastructure

"... ist eine branchendführende SDN-Lösung, die richtliniengesteuerte Automatisierung über integriertes Underlay und Overlay bietet und Richtlinienautomatisierung für VMs, Bare-Metal Server und Container anbietet."

Trend: most of the traffic does not leave the datacenter (-¿ east west traffic), while traditional 3-tier networking model is optimized for north-south traffic.
Solution: **Leaf-Spine Topology** This architecture is optimized for east-west traffic inside a datacenter, based on Clos Network from 1953.

Every Endpoint is the same distance away from any other endpoint *(deterministic)*

Leaf connect to all and only to spines, spines connect to all and only to leafs.

Scaling is easy: more bandwidth -> add spine / more ports -> add leaf

Trend: Mobility (VMotion), Layer 2 adjacency and "getting rid of spanning tree"
Solution: **VXLAN** - Creating a tunnel between all devices

Trend: Elasticity, rate of change in a datacenter network is high
Solution: Everything is / will be programmable via API!

6 AWS Cloud Networking

The following chapters describe several different technologies provided by amazon web services.

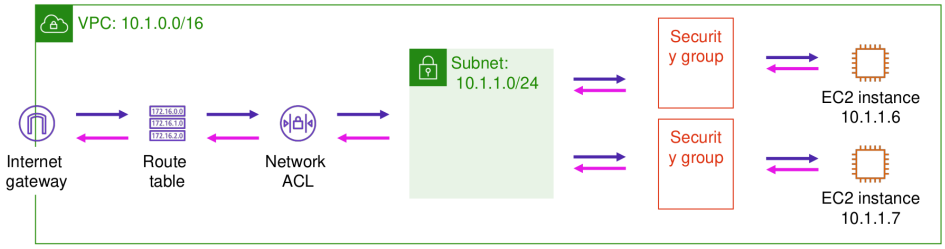


Figure 13: AWS Layered Security Example

6.1 Amazon VPC – Virtual Private Cloud

Isolated network for single workload. Placed in a single region, can span multiple availability zones (Amazon datacenters).

Contains private and public subnets for unique routing requirements. Don't overlap address space with internal networks!

Most use cases deploy multiple VPCs. Single VPC deployment can be suitable for:

- Small, single applications managed by a small team
- High Performance Computing
- Identity Management

Limit: A maximum of 5 VPCs per region per account. Multi-Account setup used for large organizations with multiple IT teams.

6.2 Internet Gateway

Used to connect public instance IP addresses to the internet. Highly available and horizontally scaleable.

Acts as default gateway for a public subnet route table.

6.3 Route Table

Every subnet must be associated with a route table. There is a default route table for every VPC.

Best practice: use a custom route table fo reach subnet.

6.4 Elastic IP Adress

Static, public IPv4 addresses. Associated to an AWS account.

Can be associated with an instance or an elastic network interface. Remapping to other instances is possible. Useful for redundancy when load balancers are not an option.

6.5 NAT Gateway

Allows IP addresses from private subnets to access the internet or other AWS services. Outbound connections are possible, but not direct inbound connections.

Acts as default gateway for private route table.

6.6 Security Groups

A security group can be described as a stateful firewall that controls inbound and outbound traffic to AWS resources. They act at the level of the instance or network interface.

Default config: Block all inbound traffic, allow all outbound traffic.

Custom security groups define Type, Protocol, Port Range, Source and Destination.

Chaining security groups allows to create a tiered architecture.

6.7 Network ACLs

Network access control lists act at the subnet level. They are stateless firewalls that require explicit rules for inbound and outbound traffic.

Custom Network ACLs are recommended for specific network security requirements only.

6.8 Bastion Host

Describes a host which is accessible from the internet to some specific users or public IPs. Once connected to this host, access ot the internal network is allowed.

This way, the internal host or instance only has to be accessible from one specific host.

7 Software Defined WAN

7.1 Introduction

Traditional WAN solutions have challenges to solve. Often MPLS circuits are used. New policies have to be applied on each device. Adding new sites is expensive. Configuration is distributed and deployed as a template. Failover is dependent on the state of a link, outages introduce latency (convergence of traditional routing protocols).

All of this hinders growth and agility.

SD-WAN aims to reduce these problems by eliminating the need for MPLS circuits, offloading user traffic to the cloud, simplify deployment and management, as well as centralize visiblity and controls.

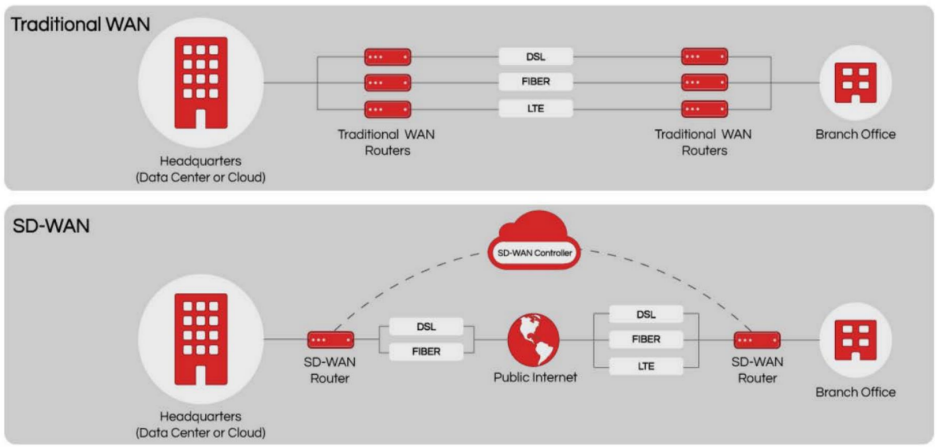


Figure 14: Traditional WAN vs. SD-WAN

7.1.1 SD-WAN vs SASE

SASE Secure Access Service Edge. Focus us on Cloud Services, datacenter is "just another branch office". Conbines the capabilities of a WAN with comprehensive security functions (secure web gateway, firewall as a service, etc.) to facilitate secure network access in cloud and mobile environments. Best practices include a zero trust approach.

SDWAN is a software-based approach to building and maintaining networks that connect geographically dispersed offices. Focus is on the datacenter.

7.1.2 Bottleneck Security

Traffic crossing the cloud is a risk. Every branch has direct internet access, split tunneling must be applied correctly. IoT / BYOD devices connected

to the cloud.

While these challenges exist, traditional security is not built for the cloud. It usually lacks in terms of performance, flexibility and scalability.

The traditional security model usually steers all traffic via some central device applying security features. This creates a bottleneck for traffic, that would otherwise not have to cross this central point.

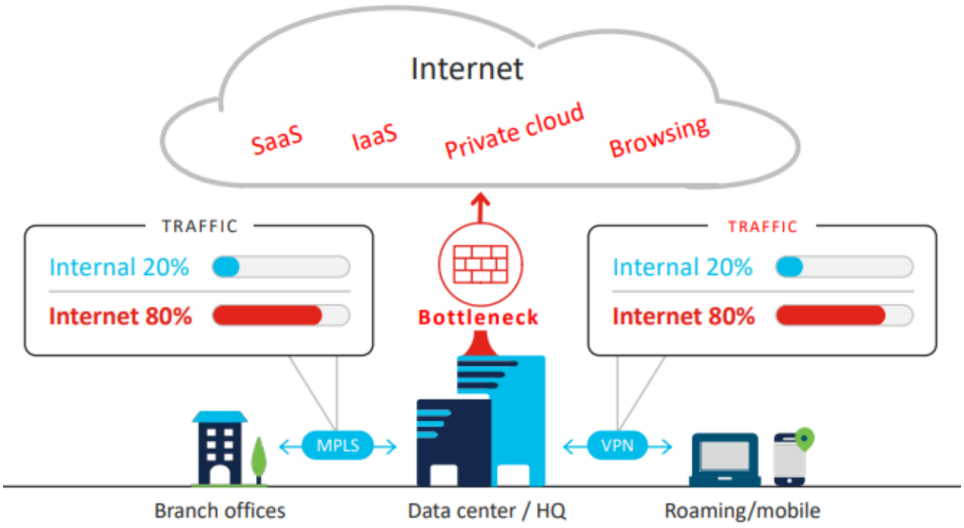


Figure 15: Central security features as bottleneck

7.1.3 SD-WAN Advantages

Cisco SD-WAN approach centralizes the management of reachability, security and application policies. It uses a single extensible control plane to manage all WAN-edge devices. Instead of having to create a full mesh connection topology between all WAN-edge devices, each device only has to be set up to connect to the controller. Everything else is automated. This dramatically lowers complexity and increases overall solution scale.

7.2 Cisco SD-WAN Components

7.2.1 vSmart

Facilitates fabric discovery. Distributes data plane and app-aware routing policies to the vEdge routers. Involved only in control plane communication, reducing the complexity. Eliminates the need for full-mesh routing on the transport side.

Highly resilient – usually several instances are deployed.

7.2.2 vEdge

WAN-Edge router, provides secure data plane with all other vEdge routers. Implements application-aware routing policies, using standards-based routing protocols (OSPF and BGP) and VRRP for first-hop redundancy. Establishes secure control plane with vSmart controllers using OMP. Exports performance statistics.

Supports zero-touch deployment and comes in physical or virtual form factor.

7.2.3 vManage

Graphical user interface, single point of management for daily operations. Provides a GUI with Role-Based Access as well as REST and NETCONF Interfaces. Centralized provisioning, troubleshooting and monitoring.

Highly resilient.

7.2.4 vBond

Only used on first connect of a newly registered device. MAC Address of vEdge device must be associated with a cisco account to ensure correct assignment.

Orchestrates control and management plane, first point of authentication. Distributes a list of vSmart and vManage controllers to all vEdge routers.

Requires a publicly reachable IP address.

7.2.5 OMP - Overlay Management Protocol

Unified control plane, TCP-based extensible control plane protocol. Runs between vEdge routers and vSmart controllers, as well as between vSmart controllers themselves. Advertises control plane context.

7.3 Dataplane Operations

Data Plane security is enforced by the creation of IPSec tunnels between all vEdge routers. Encryptino is symmetric with the SD-WAN Control plane facilitating the encryption key exchange.

IP Sec by default uses Authentication Header AH and Encapsulating Security Protocol ESP.

7.3.1 BFD - Bidirectional Forwarding Detection

Path liveliness and quality measurement detection protocol. Used to determine the quality of WAN paths and make forwarding decisions according to traffic SLA policies.

Supported Metrics are Up/Down, Loss, Latency, Jitter and IPSec tunnel maximum MTU.

Runs between vEdge and vEdge Cloud routers, inside IPSec tunnels. It is invoked automatically at tunnel establishment and cannot be disabled.

Uses hello interval, poll interval and multiplier for detection.

7.3.2 Application Visibility and Recognition

Deep Packet Inspection enables the use of detailed SLA for each application, which can be enforced using the path liveliness measures performed by the BFD protocol.

7.4 Cloud developments

- **Direct Internet Access:** Can use one or more local "DIA" exits or route traffic to the regional hub through the SD-WAN fabric and exit to the internet from there. Can be a VPN default route to ensure DIA for all traffic, or use a data policy for selective traffic DIA. NAT on the vEdge router allows only response traffic for established connections. All other traffic from the internet will be blocked.

- **Cloud Attached Compute, Cloud Gateway VPC/VNET:** vEdge cloud routers can be instantiated in Amazon VPCs or MS Azure VNETs.

7.5 SDW-WAN Overlay Routing

OMP learns and translates routing information across the VPN overlay.

Route types include

- OMP routes: Prefixes learned from site-local, similar to BGP Prefixes. Can be directly connected, static, BGP or OSPF learned routes. They advertise several attributes like TLOC, Site ID, VPN ID, Tag, Preference, Originator ID and Origin.

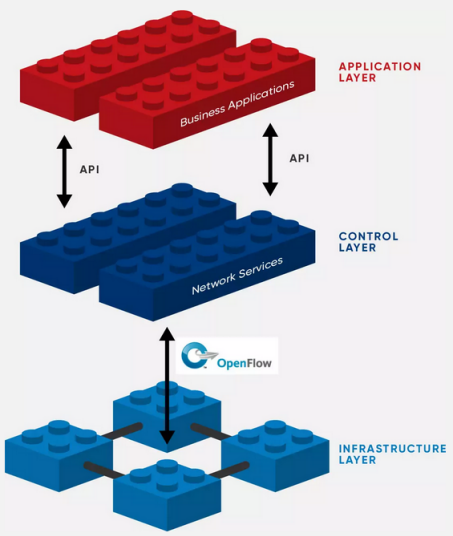
- TLOCs: Transport Locators. Ties OMP route to physical location (vEdge), similar to BGP next-hop. 3-Tuple identifier: (system-ip, color, encapsulation type).

- Service routes: ties OMP routes to an advertised network service like firewall, load balancer or IDP.

8 OpenFlow

Managed by the Open Networking Foundation.

Standard Southbound Protocol used between the SDN controller and the switch - *management only!*



OpenFlow operates as TCP Protocol (6644 / 6653) and can be secured by TLS using certificates.
Components of an OpenFlow Switch

- Flow Table(s)
- Group Table
- OpenFlow channel(s) to external controller

8.1 Controller

OpenFlow messages – for OF Channel setup between switch and controller:

HELLO	Sent by the switch, reply by the controller
FEATURE_REQUEST	Sent by controller, as supported OF capabilities
FEATURE_REPLY	Sent by switch to advertise

Controller manages *Flow Entries* in every switches flow tables (add, update, delete).

8.2 Flow Tables

Flow entry consists of

- Match fields

- Counter
- Instructions

Replaces traditional MAC/CAM table that stores hosts' hardware addresses. A flow entry is selected by IP packet matching fields, first matching entry is used ordered by priority.

- 39 fields possible to match on in OpenFlow 1.3, BUT must be supported by the hardware used
- usually in routing: most specific match

Instructions can be actions or modify pipeline processing. Possible actions are

- Forward on port
- Drop
- Flood
- Send to controller

If no match in any flow table is found: TABLE_MISS rule configuration: send to controller or drop.