yoinked from https://github.com/Nicicalu/OST-CN2-Spick

OSPF (IGP)

ECMP load balancing, fast convergence, widely used. IP Port 89 on L3 (no TCP, has own header). Uses `224.0.0.5` (all routers), `224.0.0.6` (all DR,BDR).
DR Election: Highest IF prio → if tie, highest Router ID. Priority 0 = ineligible for DR/BDR. No preemption. BDR = same rules, second best candidate
Virtual links: Cannot go through more than one area, can only run through standard non-backbone areas. (eg. not over stubby areas)

ROUTER OPERATION

– Establish neighbor adjacencies and exchange LSAs
– Build the Link-State Database (LSDB)
– Run Dijkstra's SPF algorithm:
  Intra-area change: SPF recalculation
  Inter-area change: No SPF needed – ABR handles updates
– Build the routing table from SPF results

ROUTE TYPES

O: Intra-area: Local area → Local area. Type 1 and 2 LSAs
O IA: Inter-area: Local area → Neighboring area. Via LSA 3 through backbone
O E1 or O E2: External: Local area → External (eg, BGP), from ASBR
O E1 / O N1: Cost = internal + external metrics (**def=20**)
O E2 / O N2: Cost = external metrics. Default external route for OSPF
Cost calculation: Reference Bandwidth(def=100 Mbps)/Interface Bandwidth

AREAS

AS split into **areas** with 32-bit Area ID (e.g., `0.0.0.0` = Area 0)
Backbone Area (Area 0): Core of the OSPF domain, must connect to all other areas (directly/virtual links), must be contiguous (no disjointed segments), should not contain end-user networks, summarizes topology of other areas
Non-Backbone Areas: Connect end users and local resources, All inter-area traffic must transit the backbone

ROUTER TYPES

Area Border Router (ABR): Connects two or more OSPF areas, must have 1 interface in backbone. 1 OSPF DB per Area
Internal Router (IR): All interfaces belong to the same area (non-backbone)
Backbone Router (BR): At least one interface in Area 0, Includes ABRs and routers internal to the backbone
AS Boundary Router (ASBR): Connects to external AS/Network (e.g., BGP), Advertises external routes into OSPF, can be in backbone or non-backbone

DESIGN RULES

Rule 1: Backbone (Area 0) must be contiguous – no partitions allowed
Rule 2: Every non-backbone area must connect to Area 0

LINK STATE ADVERTISEMENT (LSA) TYPES

(1) Router-LSA: ***All routers*** list directly connected links (so all outgoing interfaces with state and cost) (**intra-area**)
(2) Network-LSA: ***DR*** lists all routers and DR in broadcast/multi-access network (**intra-area**)
(3) Summary-LSA: ***ABR*** advertises networks from other areas, flooded in all the areas that are not "totally stubby" (**inter-area**)
(4) ASBR-Summary: ***ABR*** advertises path to ASBRs. ASBR sends Type 1 + external bit, ABR converts to Type 4 and floods (**inter-area**)
(5) AS-External-LSA: ***ASBR/ABR*** advertises external routes (e.g., BGP); flooded to all non-stub areas → only normal areas (**inter-area**)
(7) NSSA External: Like Type 5 but inside NSSA. Converted to Type 7 by ABR. Shown in routing table as **(O N1 or O N2)**

AREA TYPES (ALLOWED LSA TYPES)

Stubby = Blocks external LSA [No 5], Totally = Blocks inter-area LSA [No 3/4]
Default route (`0.0.0.0`) from ABR [DR ABR], Cannot contain ASBR [No ASBR]
Standard (1,2,3,4,5): [Normal
Stub Area (1,2,3): [No 4/5] [DR ABR] [No ASBR]
Totally Stubby Area (1,2): [No 3/4/5] [DR ABR] [No ASBR]
Not-So-Stubby Area (1,2,3,7): [No 4/5], no DR, allows 1 ASBR [LSA 7 → 5]
Totally NSSA (1,2,7): [No 3/4/5] [DR ABR] [LSA 7 → 5]

PACKET TYPES

(1) Hello: Usually Multicast. Discover, maintain, and verify neighbors. Forms adjacencies. Election of DR,BDR in broadcast networks. Contains network mask (sending routers' IF), Hello interval (p2p,broadcast: def=10s), Options, Priority (election), Router dead interval (def=40s), DR/BDR IP, Neighbors.
(2) Database Description (DBDD): Unicast. Exchange summaries of LSAs during adjacency formation (headers only). Contains IF Max. MTU, Options, I/M/MS bits (Initial, More, Master-slave bit), DD Seq. Num., LSA Header
(3) Link State Request (LSR): Unicast. Request specific LSAs. Contains Link State Type (router/net), Link State ID, Advertising Router (sender address)
(4) Link State Update (LSU): Multi/Unicast. **Implicit ack.** Flood new/updated LSAs. Answer to LSR (unicast). Contains Nr. of LSAs, full LSAs information.
(5) Link State Acknowledgment (LSAck): Multi/Unicast. **Explicit ack.** Confirms receipt of LSAs for reliable flooding. Acks may be grouped together.

SUB-PROTOCOLS

Hello Protocol: Neighbor discovery. Parameter negotiation. Maintain logical adjacencies on P2P, P2MP, virtual links. Elect DR/BDR on broadcast and NBMA networks. Continuously sends hello packets to maintain bidirectional connectivity; failure to receive = neighbor down (RouterDeadInterval)
Database Sync Protocol: Sync LSDB using DBD packets.

NEIGHBOR STATES

Down: Initial state, no Hello packets exchanged or after RouterDeadInterval
Init: Received Hello packet from neighbor but without its own Router ID yet
2-Way: Seen its own Router ID. DR/BRD election is taking place in NBMA
ExStart: (DBD) Bi-dir comm; highest Router-ID=master. Determine init Seq Nr
Exchange: Exchange of DBD packets (LSA headers).
Loading: Missing LSAs are requested. (LSR/LSU)
Full: Databases fully synchronized. Normal operating state

OSPF ROUTING AND ECMP

– Each router runs Dijkstra per area; link cost = metric from LSAs (1–65535)
– Routes added to RIB/FIB based on computed next hops
– ECMP: Modified Dijkstra supports Equal-Cost MultiPath if multiple paths have same cost → routes added with multiple next-hops for load balancing

PATH SELECTION

Path always has to go through backbone
1) Most specific match (CIDR)
2) Static > O > O IA > E1 > N1 > E2 > N2
3) Lowest link cost (reference bandwidth/interface bandwidth)

POSSIBLE FAILURES

– No OSPF enabled / Interface not in OSPF / Duplicate router ID
– Passive interface that has to be removed / Virtual Link badly configured
– Area ID or Area Type mismatch on neighbors
– Hello interval or Router dead interval mismatch

IS-IS (IGP)

Widely used by ISPs, Scalable, Fast failure detection & convergence, ECMP, Extendable, Less CPU intensive, Default metric of 10 on most routers
ES: End-host devices are called End Systems (ES)
IS: Routers are called Intermediate Systems (IS)

CONNECTIONLESS NETWORK SERVICES (CLNS)

CLNS: ISO Layer 3 datagram service; supports **CLNP**, **ES-IS**, **IS-IS**.
CLNP: Connectionless Network Protocol, similar to IP, used in ISO stack
ES-IS: host ↔ router discovery protocol
IS-IS: router ↔ router. Link-state routing protocol
Integrated IS-IS: Allows IP routing with IS-IS

NETWORK SERVICE ACCESS POINT (NSAP)

Variabale in length (up to 20 bytes), Identifies node, not IF. Example from IP: `192.168.1.24` → `49.0001.1921.6800.1024.00`

`49.0011.0000.0000.0003.00`
Area ID (11) | System ID (R3) | NSEL

Network Entity Title (NET): Unique router identifier. NSEL=0,Starts with 49
Authority & Format Identifier (AFI): NSAP format+authority that assigned it
Initial Domain Identifier (IDI): Variable len, identifies administrative domain
Domain Specific Part Format Identifier (DFI): Specifies format
Domain Specific Part (DSP): Var len, contains hierarchical structure of addr
NSEL (N-Selector): always `00` for routers (1b)
System ID: Unique per router (often based on lo-IP/MAC) (6b)
Area ID: Used for routing hierarchy (like OSPF areas) (AFI+IDI+DSP)

PACKET TYPES (ALL IN L1 OR L2)

All PDUs contain Header with shared common fields + specific routing-related information (Type, Length and Value (TLV)) used to extend protocol
IIH (Hello): Build,maintain adjacencies. Includes system ID, holding time, prio
  Functions: discover, build, maintain
  Interval: 10s (default); DIS sends every 3.3s on LANs
  Multiplier: Missed Hello limit → Holdtime = Interval × Multiplier(def=3)
  Multicast: [L1 `01-80-C2-00-00-14`] [L2 `01-80-C2-00-00-15`]
LSP (Link State PDU): Contains topology info including prefixes with costs; unicast on p2p or flooded throughout the area (OSPF: LSA Type 1)
CSNP (Complete SNP): Sent by DIS; lists all known LSPs (OSPF: DBD)
PSNP (Partial SNP): Used to request missing or acknowledge received LSPs

ROUTER TYPES

L1 Router: Within one area; all have same LSPDB. No inter-area routing
L2 Router: Backbone router; all have same LSPDB. Routes between areas
L1/L2 Router: Acts as both; separates LSPDBs, redistributes between levels

ADJACENCIES

Backbone must be contiguous: (L2 connection) L1 ↔ L1-L2 ↔ L2. NOTE: L1/L2 routers form both L1 **and** L2 adjacencies if they are both in the same area.
Interface MTU and auth key must be identical to become neighbors
L1: Area addresses match unless configured otherwise
L2: Alongside L1, unless router is L1 only, areas must not match

POINT-TO-POINT (NO DIS)

Initialized by receipt of ISHs, exchange p2p IIHs padded to MTU
CSNP: Sent once at adjacency startup
LSP: Advertises topology changes (link-state info)
PSNP: Acknowledges received LSPs or requests missing ones

BROADCAST/MULTI-ACCESS (DIS REQUIRED)

Not triggered by ISHs, instead broadcast IIHs with all neighbors MAC's
Designated Intermediary System (DIS): Create, update pseudonode LSPs. Flood LSPs. Simlar to DR in OSPF. No backup DIS.
DIS Election: Highest priority (0–127) (Cisco def=64) > Highest SNPA (MAC)
Preemption: Enabled → higher prio router automatically takes over DIS Role
Pseudonode: Carried out by DIS. Multiaccess links. Separate for L1,L2. Fake node IS-IS creates to represent a broadcast LAN
Passive interfaces: Advertise network prefixes without adjacency forming

PATH SELECTION

Path from L1 **always** goes through **nearest** L1/L2 (if no route leaking)
Default interface metric (m) = 10 (**Lower Metric better**)
1) Most specific match (CIDR)
2) L1 intra-area > L2 intra-area > Leaked L2 → L1 (internal m) > L1 external (external m) > L2 external (external m) > Leaked L2 → L1 (external m)
3) Lowest cost
4) Lowest system ID
5) Lowest interface

ROUTING

Summarization occurs when routers enter an IS-IS level (L1 → L2, L2 → L1).

LEVEL 1

Intra-area routing only (L1 Area like OSPF Totally Stubby Area)
L1: routers install a **default route** to nearest L1-L2 for inter-area traffic
L1-L2: Do **not** advertise L2 routes into L1 area (unless route leaking active)
  Set **Attached bit** to signal L2 connectivity to backbone
Distribution Bit: Set to 1 on L2 → L1; blocks re-advertisement L1 → L2.
Route-Leaking: injects a more specific route into L1 to improve routing

LEVEL 2

Routing between areas (***inter-area***). L1-L2 routers inject L1 routes into L2 topology. L1 routes are redistributed into L2 with L1 metric preserved in L2 LSP

IS-IS VS OSPF

Feature	*IS-IS*	*OSPF*
Layer	L2 (CLNS)	L3 (IP, Port 89)
Encapsulation	No IP, uses TLVs	IP packets
Hello Type	IIH	Hello packet
Area Model	L1/L2	Backbone + Areas
Metric	Cost (default 10)	Cost (bandwidth)
Router ID	System ID (6B)	32-bit Router ID
Adj. Types	L1, L2, L1/L2	DR/BDR, P2P
LSDB	Per level (L1/L2)	Per area
Scaling	Large-scale ISP core	Enterprise/campus
Routing Info	TLVs (flexible)	Fixed LSA types
Type	Link-State	Link-State
Shortest Path calculation	Dijkstra	Dijkstra

POSSIBLE FAILURES

– Wrong addressing (NET, Sys-ID, Area ID) / Interface type (P2P, broadcast)
– Wrongly configured L1,L1-L2,L2 routers (eg. no L1-L2 as transit)
– Auth or MTU mismatch (TLV auth → configure identical IS-IS Auth/MTU)

BGP (EGP)

Path-vector routing protocol (doesn't contain full topology). Stable, flexible, scalable. Based on TCP. Loop prevention using AS_PATH

IBGP

Routers in same AS, AD=200, more trusted (lower security overhead). AS-Path and Next-hop not modified. iBGP is needed for eBGP because otherwise external IP address might not be known inside the AS with other IGP protocols

SCALABILITY

– iBGP does not re-advertise routes between iBGP peers → full mesh required (cause no loop prevention)
– Session count = $n(n-1)/2$ (e.g., 5 routers = 10 sessions, 10 = 45)

ROUTE REFLECTORS (RR)

Solves iBGP full-mesh (***split horizon***) scaling by selective route refl. Clients only peer with RR; unaware they're clients. Only RR needs special config
Clients: iBGP neighbors that rely on the RR for route sharing
Non-clients: regular iBGP peers; still have full-mesh among themselves
ORIGINATOR_ID: stops a router from accepting its own reflected route
From non-client: RR advertises to **clients only**
From client: RR advertises to **all** (clients + non-clients)
From eBGP peer: RR advertises to **all** (clients + non-clients)

EBGP

Routers in different ASes, AD=20, stricter policy enforcement. Prepends ASN to AS-Path, modifies next-hop IP. Fails if own ASN in AS-Path. TTL=1
AS-Override: Allows reuse of same ASN across different customer sites (e.g., Swisscom); rewrites ASN to avoid loop detection
next-hop-self: Router can't install a route if the next hop address is unreachable ⇒ next-hop-self changes next hop address to own local addr by BR

AUTONOMOUS SYSTEM NUMBERS (ASN)

– Unique ID for each AS; required for Internet routing with BGP
– Private: [Legacy 16-bit 64'512-65'535] [32-bit 4'200'000'000-4'294'967'294]

PEERING / NEIGHBORS

– Two routers with a BGP TCP session (port 179) are called peers/neighbors
– Each BGP router is a **BGP speaker**
– Supports CIDR, route aggregation; decisions based on policies/rules

PATH ATTRIBUTES

Used for route control and policy enforcement
Well-known mandatory: Always present (e.g., AS-Path, Origin, Next Hop)
Well-known discretionary: Optional but recognized by all (e.g., Local Pref)
Optional transitive: Passed between ASes (e.g., Community, Aggregator)
Optional non-transitive: Not passed across ASes (e.g., MED, Weight)
NLRI: Routing table info: prefix, prefix length, and associated path attributes

MESSAGES

OPEN: Establishes session; includes version, ASN, Hold Time, BGP Identifier, optional params. **Hold Time:** Heartbeat in seconds (Cisco def=180s), reset by KEEPALIVE/UPDATE; 0 = session down. **BGP Identifier:** 32-bit Router-ID, manually set or highest loopback/active IP; used for loop prevention
KEEPALIVE: Sent every 1/3 of Hold Time; ensures neighbor liveness
UPDATE: Advertises new routes, withdraws old ones, or both; includes NLRI (prefix + path attributes); can act as KEEPALIVE
NOTIFICATION: Sent on session error (e.g. hold timer expired); terminates session immediately

NETWORK STATEMENTS

Advertise a specific network prefix to BGP peers (only the best is advertised, even if multiple exist). Must exist in the RIB so that it's imported in BGP table
Connected: next-hop: `0.0.0.0`, origin attribute: `i`, weight: 32'768 (Cisco)
Static/RP: next-hop: NH in RIB, MED: IGP metric, rest same as above

BEST PATH CALCULATION

– BGP maintains all received paths per prefix but advertises only the best one
– Best path is installed in RIB; recalculated on:
  – Next-hop reachability change
  – Redistribution change
  – Interface failure to eBGP peer
  – New/withdrawn path received
– **Influence:**
  – Outbound BGP policy → inbound traffic behavior
  – Inbound BGP policy → outbound traffic behavior

PATH SELECTION (IF PREFIXES ARE THE SAME):

1) Prefer highest **Weight** (**Cisco-specific**, local to router)
2) Prefer highest **Local Preference** (global within AS)
3) Prefer routes **originated by the router** (own), small i in path, NH `0.0.0.0`)
4) Prefer **shorter AS path** (only length is compared)
5) Prefer **lowest origin type:** IGP < EGP < Incomplete (I on origin)
6) Prefer **lowest MED** (Multi-Exit Discriminator) (also called metric)
7) Prefer **external (EBGP)** over **internal (IBGP)**
8) For iBGP: prefer path with **lowest IGP metric** to next-hop
9) For eBGP: Prefer **oldest** (more stable) path
10) Prefer **lowest BGP router ID**
11) Prefer path from **lowest neighbor IP address**

ROUTE FILTERING

– Filters control which routes are received/advertised
– Used for security, traffic shaping, memory optimization
– Tools: **prefix-list** (IP), **filter-list** (AS-path), **route-map** (flexible match/set)

STATES

State	*Action*	*Next (Success)*	*Next (Failure)*
Idle	Waiting for start event	Connect	Idle
Connect	Waiting for TCP handshake	OpenSent	Active
Active	Retrying TCP connection	OpenSent	Connect
OpenSent	Sent OPEN, waiting for OPEN	OpenConfirm	Idle
OpenConfirm	Waiting for KEEPALIVE	Established	Idle
Established	Peering active. Exchanging routes.	Established	Idle

COMMUNITIES

32b optional, transitive tag (e.g. `ASN:value`, `65000:100`). Used to mark routes for policy control across ASes. Can be added, modified, or removed at each hop

ENTERPRISE CONNECTIVITY OPTIONS

Single/Dual: denotes how many **links** there are
Multi-Homed/-Homed: denotes how many **ISPs** are connected
Single-Homed: One ISP, one link (BGP or static). Simple but no redundancy
Dual-Homed: One ISP, two links (routers). Redundancy within same provider
Multihomed: Multiple ISPs, one link. Improved redundancy and routing control, but avoid being a transit – advertise only customer-owned prefixes
Dual-Multihomed: Multiple ISPs, two links per ISP. Most redundancy

TRAFFIC ENGINEERING (TE) - INBOUND VS OUTBOUND

Local Pref: [OUT] [highest ↑] Lower local pref on backup path
Multi-Exit Discriminator (MED): [IN] [lowest ↓] Higher MED on backup path
AS-Path Prepending: [IN] [shortest ←] Add multiple own ASN on backup path
TE Limitation: AS controls [OUT], [IN] control limited - ISPs may ignore
TE with Aggregate: Prefer primary ISP with summarized routes; advertise specific prefixes on backup for failover
Transit: One ISP provides reachability to all neighboring destinations
Peering: ISPs provide each other reachability to portions of their routing table

TRANSIT VS. PEERING

Transit: ISP provides full reachability (paid relationship)
Peering: ISPs exchange selected routes; equal relationship, usually unpaid
AS Path Filtering: to avoid getting transit: ip as-path access-list 10 permit ^ $

INTERNET EXCHANGE POINT (IXP)

Facility where networks exchange traffic via BGP peering, ***routing policies*** determine which routes are advertised/accepted. Reduces transit costs, latency, and offloads upstream links

PUBLIC PEERING

Members peer via shared switch fabric and a ***route server***, which distributes routes but stays out of data path (NEXT_HOP unchanged). Simplified setup (one legal contract), minimal policy control; one BGP session to route server

PRIVATE PEERING

Direct BGP sessions between two parties (***1:1***), requires one session and legal contract per peer. May use **public or private** interconnects. Full policy control per neighbor. **Examples:** Equinix, SwissIX (non-profit)

RESOURCE PUBLIC KEY INFRASTRUCTURE (RPKI)

– Framework to validate that prefix is legitimately originated by a specific ASN
– Prevents route **hijacking** and accidental mis-originations (route **leaks**)
– RPKI validates origin only – not the AS-path

KEY COMPONENTS

Trust Anchors (TAs): Root CAs of the 5 RIRs; issue certs for resource holders
Route Origin Authorization (ROA): Digitally signed object, authorizes ASN to announce prefix (AS, prefix that AS can originate, max prefix length)
RPKI Validators: downloads+verifies+stores Validated ROA Payloads (VRPs)

RPKI VALIDATION STATES

Valid: Prefix + ASN match ROA
Invalid: Prefix found, but ASN mismatch or prefix too long
Not Found / Unknown: No matching ROA

VALIDATOR DETAILS

– Use TALs (Trust Anchor Locators) to fetch data from RIRs
– Validate cryptographic signatures (via X.509 certs with RFC 3779)
– Outputs VRPs; invalid objects are discarded
– Update frequency: >=24h (recommended), ~30–60min (practice)
– RRDP (HTTPS) to fetch RPKI repository data (RFC 8182) replacing rsync
– RPKI-RTR: used to get the validator's already-processed cache of VRPs

MONITORING

Event tracking, BGP hijack detection, Route leak detection, RPKI status check, Reachability tracking, AS path change tracking, AS path visualization

MULTICAST

Use-cases 1-to-Many: Streaming, software updates, music-on-hold
Use-cases Many-to-Many: Gaming, VR, stock data, group chat
Benefits: Efficient bandwidth, lower server/CPU load, no redundancy
Properties: UDP-based. Apps must handle drops, duplicates, out-of-order
Source: Sends to group IP; doesn't need to join
Receiver: Must explicitly join group to receive traffic

MULTICAST ADDRESS RANGES

`224.0.0.0 – 224.0.0.255`: Link-local, TTL=1 (not forwarded by routers) (IGMP)
`224.0.1.0 – 224.0.1.255`: Reserved by IANA, routable (NTP)
`232.0.0.0 – 232.255.255.255`: Source-Specific Multicast (SSM)
`235.0.0.0 – 238.255.255.255`: Globally scoped multicast (routable)
`239.0.0.0 – 239.255.255.255`: Administratively scoped (private space)

BROADCAST BASICS

L3 routes between subnets; L2 floods within same subnet
L2 (Bridging): MAC `ffff.ffff.ffff` switches flood to all ports in VLAN
L3 (Routing): `255.255.255.255`: local broadcast, not routed. Directed broadcast for specific subnet (e.g. `10.1.1.255`): can be routed if enabled

L2 MULTICAST: MAC MAPPING

1) **Get IP:** Example multicast IP address: `239.5.5.5`
2) **Convert to Binary:** `239.5.5.5` = 1110**1111**.00000101.00000101.00000101
   → Take only the last 23 bits: 0000101.00000101.00000101
3) **Map to MAC Prefix:** Fixed 0100.5E → Map last 23 bits to: 0100.5E05.0505

INTERNET GROUP MANAGEMENT PROTOCOL (IGMP)

Purpose: Manages group membership for IPv4 multicast on each segment
IGMPv1: Basic join via query-response mechanism, no explicit group leave. Router sends ***membership queries*** every 60s to `224.0.0.1`, removes group after timeout if no report received. Receiver doesn't know multicast source
IGMPv2: Adds ***Leave Group*** message. Supports ***Group-Specific Queries*** e.g. when someone leaves group ('anyone still interested in group xy?'), reducing broadcast overhead. Receiver still doesn't know who the source is
IGMPv3: Adds ***source filtering*** (Include/Exclude lists). Enables ***Source-Specific Multicast (SSM)*** – receiver requests traffic only from selected source(s), **no need for Rendezvous Point** (RP) anymore. Adds support for application-level access control and filtering. Can also be used in ASM (Any Source Multicast), but mainly with SSM. (`224.0.0.22` all IGMPv3 routers)

IGMP SNOOPING

Without snooping: multicast = broadcast on VLAN
With snooping: switch listens to IGMP messages & builds a forwarding table
Default: snooping is enabled; switch needs IGMP Querier to operate

REVERSE PATH FORWARDING (RPF)

To avoid loops, verifies that a multicast packet arrives on the interface that a unicast packet destined for the multicast source would be forwarded out of.

RENDEZVOUS POINT (RP)

Used in Shared Tree (`*,G`) setups with PIM-SM, acts as common meeting point. **RPF check** is performed toward the **RP** (not the source). Once **source is known**, routers may **switch** to a Source Tree (`S,G`). Triggered by SPT join timer expiration/RPF check confirming better route/data rate exceeding. In IPv6 RP Addr can be included in multicast 8b4b[flags]8b4b[addr]64b[pref]32b

SHARED TREE VS. SOURCE-BASED TREE

Source-Based Tree (`S,G`): Built and added to ***mroute table*** when router receives an (`S,G`) join/report from IGMP host. `S` = known source; `G` = group
Shared Tree (`*,G`): IGMP host sends ***membership report*** (IGMP Join), Router adds (`*,G`) entry to ***multicast routing table*** `*` = any/unknown

PROTOCOL INDEPENDENT MULTICAST (PIM)

Only between routers. Relies on unicast routing table (RIB) for multicast forwarding decisions and RPF. Protocol-independent.

PIM DENSE MODE (PIM-DM) – NO RP

PIM-DM relies on IGMP to learn about receivers, prevent unnecessary multicast traffic and trigger prune behavior. One router elected as IGMP querier, periodically sends IGMP query messages. Essential for IGMP snooping.
Push Model: Floods multicast to all interfaces; prunes where no receivers
(1) Flooding: Source sends traffic to multicast-enabled links using unicast RIB
(2) Distribution Tree: Initially entire network (shared tree rooted at source)
(3) Prune Messages: Routers without interested receivers send prunes upstream to remove themselves from the tree
(4) State Maintenance: Routers track source, receivers, interfaces to forward/prune per group

PIM SPARSE MODE (PIM-SM) – ASM, SSM

Pull Model: Multicast traffic only sent where requested (***explicit join***). Works with IGMP to detect interested receivers, uses unicast routing for forwarding
(1) Join/Prune: Routers send explicit join/prune messages to request or stop receiving multicast for group (`G`) to other routers
(2) Forwarding: Routers only forward multicast packets for group (`G`) on interfaces from which explicit joins were received

ANY SOURCE MULTICAST (ASM)

– Works with **IGMPv1** or **IGMPv2** → receiver does not know the source
– All routers in the multicast domain must know the RP location
1) Receiver sends ***IGMP Join*** (`*,G`) to next hop, which determines the RP for the group and sends a PIM Join (`,G`) towards RP, following RPF path
2) Shared tree (`*,G`) established, inforning RP that receiver is interested
3) The source starts sending multicast traffic to its first-hop router (FHR).
4) FHR encaps. multicast packets into PIM Register msgs, unicast to RP
5) RP sends a PIM Join (`S,G`) towards source (FHR), following RPF path towards source. Simultaneously, RP sends `Register-Stop` to FHR.
6) After receiving `Register-Stop`, FHR stops encapsulation and forwards multicast traffic natively along the (`S,G`) path.
7) The RP forwards multicast traffic down the shared tree towards the LHR. At each hop, routers perform RPF checks
8) LHR receives multicast traffic, performs RPF check towards the source
9) If a more optimal path to the source exists, the LHR sends a PIM Join (`S,G`) directly towards the source, following the RPF path.
10) After SPT (`S,G`) established, traffic flows directly from source to LHR. LHR sends PIM Prune (`*,G`) towards RP to remove itself from shared tree

SOURCE SPECIFIC MULTICAST (SSM)

– Receiver subscribes using **IGMPv3**, providing both source (`S`) and group (`G`) to the first-hop router (**explicit join**)
– No RP required → **PIM-SSM builds only (`S,G`)** Shortest Path Trees (SPT)
– **No shared tree** (`*,G`) model used; SSM is source-directed
– IANA reserved ***`232.0.0.0/8`*** for SSM in IPv4
– Join msgs forwarded hop-by-hop toward source to establish forwarding path
– Uses unicast routing table (RPF) to maintain loop-free delivery

PIM SPARSE-DENSE MODE

PIM Sparse Mode: Pull model – multicast traffic is forwarded only on request
PIM Dense Mode: Push model – traffic is flooded everywhere, then pruned
Sparse-Dense: Supports both per multicast group, depends on RP availability

PIM DENSE MODE VS. PIM SPARSE MODE USE-CASES

DM: Small/tightly scoped networks where most devices need multicast
SM: Large-scale/distributed env where multicast receivers are few/spread out

NETWORK DESIGN

Pillars: Scalability, Speed, Availability, Security, Manageability → overall cost

AVAILABILITY

MTTD: Mean Time To Detect
MTTI: Mean Time To Identify
MTTR: Mean Time To Repair
MTTRS: MTT Restore Service
MTBF: Mean Time Between Failures
MTTBSI: MTB Service Incidents
MTBF combined: $\left(\sum_{n=1} 1/\text{MTBF}_n\right)^{-1}$
MTBF parallel: $\sum_{n=1} \text{MTBF}_n/n$
Availability: $\text{MTBF}/(\text{MTBF}+\text{MTTR})$
Better Av: MTTR → 0 ∧ MTBF → ∞

REDUNDANCY

Adds reliability, increases MTBF but increases MTTR (complexity)
Backup Paths: Duplicate devices/links on primary path, build extra links for redundancy, consider backup link capacity, consider failover speed
Load Balancing: ECMP, EtherChannel, Port-Channel

TOPOLOGY

Star (flexible → office), Ring (cheap → city), Bus, Tree, Full Mesh

HIERARCHICAL DESIGN

Core: L3, Highspeed backbone, no policy, scalable/redundant, no security
Distribution: L3, policy control, HSRP/VRRP, loop protect., small fault domain
Access: L2, Connect end devices, high port count, port security, QoS marking
Switch stacking: Merging physical switches into one large logical switch
Collapsed Core: Combines Core + Distribution (small/medium networks)

FLAT DESIGN

Any-to-any; small networks, MPLS/LAN setups, lacks scalability and control

FABRIC DESIGN (EMERGING TECHNOLOGIES)

Modern design using ***Underlay*** (transport, e.g. IP, MPLS) / ***Overlay*** (logical virtual topology, e.g. EVPN) with ***Software-Defined Networking*** (SDN) and ***Software-Defined Access*** (SDA)

ENTERPRISE CAMPUS

– 1000s of users, multiple buildings, one physical location, one company
– Multiple interconnected LANs, connected via Ethernet and Wireless
– Flat design for client access, Hierarchical design for the rest (per building)
– EVPN, MPLS are used to reduce size of L2 domain

FIRST HOP REDUNDANCY PROTOCOLS (FHRP)

Ensures default gateway is always reachable, PCs can only have one. Enables fast failover during router failure
Virtual Router Redundancy Protocol (VRRP): Shared virtual IP, real MACs per router, Master router handles forwarding, rest as backup
Hot Standby Router Protocol (HSRP): (Cisco) Shared virtual IP + virtual MAC, One active, others in "hot standby" → faster
Gateway Load Balancing Protocol (GLBP): (Cisco) HSRP + Load balancing + redundancy. **Active Virtual Gateway (AVG):** Answers ARP and sends virtual MACs of AVFs. **Active Virtual Forwarder (AVF):** Forwards traffic

DATA CENTER

Parameters	*Tier 1*	*Tier 2*	*Tier 3*	*Tier 4*
Uptime guarantee	99.671%	99.741%	99.982%	99.995%
Downtime per year	<28.8 hours	<22 hours	<1.6 hours	<26.3 minutes
Price	$	$$	$$$	$$$$
Compartmentalization	No	No	No	Yes

DESIGNS

Top of Rack (ToR): switches per rack. less cabling, easy expansions/exchanges per 'rack', scalable glass fiber, ideal for high service density. more switches, more ports, more L2 Srv-2-Srv traffic, more STP
End of Row (EoR): switches per row. less switches, higher utilization of ports, switches all at one place, better L2 availability between racks. more cabling

TRAFFIC DIRECTIONS

North–South: Between external networks (client-server, in/out DC)
East–West: Within DC (e.g., server-server, storage)

THREE-TIER ARCHITECTURE

– Access → Aggregation → Core (like Hierarchical)
– Optimized for North-South traffic, Not ideal for East-West (VMs, containers)

LEAF-SPINE ARCHITECTURE

– Two-tier: Leaf switches (access) connect to Spines (core)
– High performance, low latency, Scalable, ideal for East–West traffic

WAN

Connects remote LANs via SPs for data/voice/video; key needs: bandwidth, control, design, resilience, mgmt. **Requirements:**
Bandwidth: Plan for normal load, peak usage, reserved capacity for VoIP
Control/Security: Reliance on the provider ⇒ encryption and segmentation
Availability: Use redundancy, diverse paths, SLAs to reduce outage impact
Management:
  In-band: Manage devices over the production WAN
  Out-of-band: Use separate management path for recovery/emergencies

PRIVATE WAN

Point-to-Point: Leased L2 line (Ethernet); monthly fee; private circuit; fast
Dark Fiber: Physical fiber lease; costly; ISPs prefer selling lambdas
Coarse Wavelength Division Multiplexing (CWDM): x16, cheaper, 120km, passive MUX, use mirrors to aggregate/separate signals (analog)
Dense Wavelength Division Multiplexing (DWDM): x80, 10GB/s, 1000km, active MUX, more precise, uses software ("smarter"), wideband
Connection-oriented: Predefined path, packet IDs (ATM, Frame Relay)
Connectionless: No setup; full address in each packet (Ethernet, MPLS VPN)
Circuit-Switched: Requires signaling protocol to establish e2e circuit
Packet-Switched: Expects network to know how to forward packets

PUBLIC WAN

Site-to-Site VPN: Fixed locations, devices locked to IP addr
Remote Access VPN: Changing locations, devices not locked to IP addr
Software-Defined WAN (SDWAN): connects LANs across large distances using controlling software that works with a variety of networking hardware.

MULTI PROTOCOL LABEL SWITCHING (MPLS)

– Advantage of eBGP at PE-CE: No mutual redistrib., same routing process
– Control plane (e.g. OSPF) → to learn labels
– iBGP to exchange NLRI (RD,RT,IPv4 Pref.,NextHop&VPN Lbl) between PE
– Traffic encrypted flowing over MPLS L3VPN backbone. (e.g. Bank)

Label Switched Router (LSR): Forwards labeled packets
Label Switched Path (LSP): Pre-determined path across MPLS network
Unicast Reverse Path Forwarding (uRPF): checks source of each packet & verifies that source is in routing table
imp-null: networks are directly connected, no more label switching
Virtual Private Wire Service (VPWS): Pseudowire (PW); No MAC learning at PE level; P2P L2 VPN, allows two sites to connect as if directly linked
Virtual Private LAN Service (VPLS): Emulates LAN segment across MPLS backbone, provides multipoint L2 connectivity; MAC learning at the PE level

CONFIG

1) RIB entry to 10.3.3.0/24 lists a next-hop IP address of 192.168.12.2
2) PE1 compares that info to the list of interface IPs on each peer and finds neigh with IP 192.168.12.2. The LDP ID (LID) of this peer is 2.2.2.2
3) PE1 notes that for 10.3.3.0, LIB contains one local and two remote labels
4) Among the known labels, one was learned from 2.2.2.2, with label 22

```
PE1# show ip route | inc 10.3.3.0
O    10.3.3.0 [90/2835456] via 192.168.12.2, 00:05:08, Serial0/0/1
PE1#
PE1# show mpls ldp bindings 10.3.3.0 24
  lib entry: 10.3.3.0/24, rev 28
    local binding: label: 25
    remote binding: lsr: 2.2.2.2:0, label: 22
    remote binding: lsr: 4.4.4.4:0, label: 86
PE1#
PE1# show mpls ldp nei
Peer LDP Ident: 2.2.2.2:0; Local LDP Ident 1.1.1.1:0
    TCP connection: 2.2.2.2.34326 - 1.1.1.1.646
    State: Oper; Msgs sent/rcvd: 37/33; Downstream
    Up time: 00:12:52
    LDP discovery sources:
      Serial0/0/1, Src IP addr: 192.168.12.2
    Addresses bound to peer LDP Ident:
      192.168.12.2   2.2.2.2   192.168.24.4   192.168.23.2
```

ROUTER TYPES

Customer Edge (CE): No knowledge of MPLS, no labels; connected to PE
Provider Edge (PE): On edge of MPLS net; runs iBGP and LDP; uses VRFs
Provider or Core (P): Inside MPLS VPN, no CE connection; forwards labels

DATABASES, PLANES

Control Plane: Builds routing/label tables (RIB, LIB)
Data Plane: Forwards packets (FIB, LFIB); pushes/swaps/pops labels
Cisco Express Forwarding (CEF): (Cisco) LFIB without labels? RIB → FIB?
Routing Information Base (RIB): Learned prefixes from routing protocols
Forwarding IB (FIB): Built from RIB; only best routes for forwarding
Label IB (LIB): All label mappings; No BGP prefixes; 1 label per prefix
Label Forwarding IB (LFIB): Built from LIB; used for actual forwarding decisions. (L)FIB only contains currently best LSP (decision: Routing Protocol)

MPLS HEADER

4-byte header before IP. With MPLS VPN, there will be a stack of two headers
Label (20b): actual MPLS label
EXP (3b): QoS/CoS, Now called Traffic Class (TC)
S-bit (1b): Bottom of label stack indicator, 1 = True = last label before IP header
TTL (8b): time-to-live (equal to IP TTL)

TTL

– Ingress PE decrements IP TTL field & copies IP TTL field into new MPLS TTL
– P routers decrements MPLS TTL
– Egress PE decrements MPLS TTL, pops final MPLS header, copies IP TTL
– If provider doesn't want to expose MPLS network: disable ***MPLS TTL propagation*** on PE, PE sets MPLS TTL=255, egress PE leaves original IP TTL unchanged ⇒ network appears as single router hop from TTL perspective

LABEL DISTRIBUTION PROTOCOL (LDP) - CONTROL PLANE

– Distributes labels to neighbors, triggerd by new IP route in FIB
– ***Hello messages*** sent via UDP (Port 646) to 224.0.0.2 to discover neighbors
– TCP (646) connection used to exchange label bindings (prefix to local lbl)
– Routers advertise all local bindings after TCP session is up
– Label mapping used to build LIB → LFIB
– LDP router ID must be reachable (via routing table)
– Each router manages local labels independently
– Relies on underlying routing protocol for best route & loop prevention

MPLS L3 DATA PLANE

Outer label: Transport label (LDP); identifies LSP between ingress/egress PE
Inner label: VPN label (MP-BGP); identifies customer VRF
Push: Ingress PE; classify and label packets
Swap: P router; replaces label, forwards based on new label
Pop: Egress PE removes label; sends original packet to CE
Penultimate Hop Popping (PHP): penultimate router removes the outer MPLS label before forwarding to egress PE, default enabled, ISPs disable it

VIRTUAL ROUTING AND FORWARDING (VRF) TABLES

– Virtual router inside a PE. Maintains isolated RIB + FIB and separate routing process per CE (VPN isolation)
– Exists per MPLS-aware PE router; one per attached customer

ROUTE DISTINGUISHER (RD) VS. ROUTE TARGET (RT)

Route Distinguisher (RD): ***Uniquely identifies*** VPN routes (per VRF) – allows same IP prefix to be used in different VPNs. Can be IPv4 or ASN. Forms ***VPNv4*** NLRI (**MP-BGP**): ***RD:IPv4 prefix*** (12 bytes: RD 8b, IP 4b)
Route Target (RT): Controls **route import/export** between VRFs. Used as ***extended BGP community path attributes***. Typically in the form ***ASN:nn*** or ***IP:nn***, e.g., 65000:100, 1.1.1.1:10
How RTs Work: Route is tagged with an RT when advertised by BGP. Other VRFs import the route if the RT matches their import policy. Allows overlapping or shared connectivity between tenants (e.g., shared services).

OVERLAY TECHNOLOGIES

Overlay network (virtual) sits on top of the ***underlay network*** (physical).
Generic Routing Encapsulation (GRE): Encapsulates data packets, unencrypted, P2P. Enables usage of unsupported protocols. Carries passenger protocol/original packet inside carrier/transport IP header routed by underlay

SEGMENT ROUTING (SR)

Source routing: Sender defines full path using Segment (= Instruction) List
Segment Identifier (SID): Each SID = 1 instruction (e.g., forward via ECMP, specific iface, or to a service)
Segment List: Ordered SID list carried in packet header; defines full route
State in packet: No per-flow state, intermediate nodes follow SID instructions
No new control plane: Uses existing protocols (OSPF, IS-IS, BGP) with extensions; no LDP or RSVP-TE needed
Data plane: Can operate over MPLS or IPv6
Simple but powerful: Enables TE, fast reroute, policy routing

SEGMENT LIST OPERATIONS

Push: Insert SIDs into packet; set active SID (top of list)
Continue: Active SID not yet completed; keep processing it
Next: Current SID completed; activate next SID in list

SEGMENT SIGNIFICANCE

Global Segments: Known and supported by all SR nodes in the domain, Installed in forwarding tables across the network (e.g. "Forward packet according to shortest path to Node1"). Defined in the SR Global Block (SRGB) and should be consistent across all nodes
Local Segments: Defined and installed only on originating node, Not forwarded by others, but must be understood network-wide (e.g. "Forward packet on interface to Node2"). Defined in the SR Local Block (SRLB) and are specific to the local SR node.

CONTROL PLANE SEGMENT TYPES

IGP Prefix Segment: Global SID tied to IGP prefix (multi-hop); all nodes install forwarding entries. "steer traffic along ECMP-aware shortest path"
IGP Node Segment: Global SID for a specific node (shortest-path forwarding)
IGP Anycast Segment: Global SID for a group of nodes; traffic sent to nearest
IGP Adjacency Segment: Local SID; direct link to neighbor
L2 Adjacency SID: Local SID for Layer-2 segment (e.g., Ethernet link)
Combining Segments: End-to-end paths can mix IGP and BGP segments. Traffic to BGP Anycast → more ECMP in data centers

SR-MPLS

– Reuses existing MPLS data plane – no hardware change needed
– Segments = MPLS labels; Segment List = label stack (top = active)
– Segments distributed via IGP/BGP; no LDP necessary (but possible)
– Supports both IPv4 and IPv6 networks
– PUSH=PUSH, CONTINUE=SWAP, NEXT=POP

BENEFITS OF SEGMENT ROUTING

Benefits: Simplification (removes protocols, simple operations, admin and mgmt), enhanced Traffig eng. (Delay, Bandwidth, Packet Loss, TE metric, Controller, Source-Node), Seamless deployment, Robust
Source Routing: Balances distributed intel with centralized optimization
Traffic Engineering (TE): Optimizes network performance by analyzing and controlling data flow to reduce congestion and improve QoS

DRAWBACKS OF TRADITIONAL NETWORKS

Control Plane: LDP/RSVP-TE adds complexity
Scalability: Per-flow/path limits growth; LSP, signaling overhead increase fast

VIRTUAL EXTENSIBLE LOCAL AREA NETWORK (VXLAN)

Data plane technology which encapsulates Ethernet frames in UDP datagrams to tunnel layer 2 frames over a layer 3 network. The underlay network is unaware of the overlay.
Issues of L2: STP, Max amount of VLANs (4094), Large MAC Address tables
VXLAN: Tunnels Ethernet (Layer 2) over IP using MAC-in-UDP encapsulation (Port 4789). For flexible and scalable network segmentation.
VXLAN Network Identifier (VNID): 24-bit identifier (up to 16 million segments) that defines the VXLAN broadcast domain.
Virtual Tunnel Endpoint (VTEP): Device (switch, router, or host) responsible for encapsulating/de-encapsulating VXLAN traffic.
Network Virtual Interface (NVE): Logical interface on a VTEP used for VXLAN tunnel operations.

FRAME FORMAT

– Original Ethernet frame → VXLAN Header → UDP → Outer IP Header
– The VXLAN header contains the 24-bit VNID and flags.
– Outer headers allow Layer 2 frames to traverse IP underlay networks.

VIRTUAL NETWORK IDENTIFIER (VNI)

– 24-bit VXLAN Network Identifier uniquely defines VXLAN segments.
– Replaces traditional VLAN IDs (12-bit)
– Used by VTEPs to map traffic into corresponding Layer 2 domains.

VXLAN TUNNEL ENDPOINT (VTEP)

Connects the overlay (VXLAN) and underlay (IP) networks. A VTEP can have multiple VNI interfaces, but they associate with the same VTEP IP interface.
Software VTEP: Located on hypervisors using virtual switches.
Hardware VTEP: Located on routers/switches with ASICs for performance.
VTEP IP Interface: Connects to the underlay network, handles encapsulation.
VNI Interface: Virtual interface per segment (like SVI); handles segregation of Layer 2 domains.

MAC ADDRESS LEARNING

Each VTEP maintains a VXLAN mapping table linking destination MAC addresses to remote VTEP IPs.
Data plane: reactive, Flood and learn, MAC learned from incoming traffic, BUM via ingress replication or multicast underlay, No control-plane needed
Control plane: proactive. MP-BGP EVPN/MAC-to-VTEP advertised via BGP, No flooding needed for known MACs, ARP suppression, silent-host handling
Flood and learn: Host H1 sends ARP request, switches learn H1's MAC → ARP request is flooded to H2. → H2 responds; switches learn H2's MAC.
Static VXLAN: Manual MAC-to-VTEP mappings. Sends copy of BUM traffic to all participating VTEPs. Doesn't scale well; BUM traffic is inefficient.
Multicast VXLAN: VTEPs join multicast groups per VNI. Scales better, offloads BUM replication. 20+ VTEPs = too much traffic, doesn't scale well
MP-BGP EVPN: Modern solution using BGP as control plane. Dynamically learns MAC/IP info.

ETHERNET VIRTUAL PRIVATE NETWORK (EVPN)

Overcome flood-and-learn limitations, doesn't rely on data plane learning, utilizes robust control plane MP-BGP, works with different encapsulation techniques (VXLAN, MPLS), excellent scalability, L2 and L3 Support.

LAYER 2

L2 bridging across L3 networks
BGP Control Plane: Distributes MAC info (no flooding → efficiency)
VXLAN Overlay: Encapsulates L2 in L3 UDP (data plane)
Multi-Tenancy: via VNI segmentation
Redundancy: All-active multihoming, ECMP, fast convergence

USE CASES

– Multi-tenant datacenter interconnects (DCI)
– Extending L2 over WAN between remote sites
– Scalable, segmented L2 fabrics

AUTODISCOVERY VIA ROUTE REFLECTORS

– RR reflects EVPN routes to other PEs
– RR doesn't participate in EVPN or pseudowires
– RR needs only ***address-family l2vpn evpn***
– L2VPN RIB stores endpoint/VFI info for control plane
– ***BGP_UPDATE*** from spines contain ***ORIGINATOR_ID*** (origin leaf)

HOST DETECTION

– Host connects to VTEP → MAC learned locally
– VTEP advertises MAC + L2VNI via BGP EVPN
– MAC learning follows normal Ethernet semantics

INGRESS_REPLICATION (IR)

Forwarding BUM traffic. When Multicast underlay network is not used, IR handles multi-destination traffic (ARP → unicast). Ingress device replicates BUM packets, sends them as separate unicast to egress devices.

EARLY ARP TERMINATION (ARP SUPPRESSION)

– Avoids flooding ARP requests
– VTEP queries control plane for MAC/IP/VNI mapping
– If known → direct unicast (no broadcast)

Silent Host Flow (Fallback)
– If IP/MAC unknown → ARP sent via **ingress replication**
– Replicated ARP request goes to remote VTEPs
– Only correct host responds → update reflected to all VTEPs
– Future traffic uses updated BGP mapping

LAYER 3

By adding L3 features, data routing efficiency + smooth connections improve

EVPN ROUTE TYPES

(1) Ethernet Auto-Discovery Route (3) Inclusive Multicast Route (4) Ethernet Segment Route (6) Selective Multicast Ethernet Tag Route (7) IGMP Join Synch Route (8) IGMP Leave Synch Route
Type 2 – Host Advertisement: Advertises host MAC (mandatory), optionally IP, along with L2VNI and optionally L3VNI. Used for MAC learning, ARP suppression, and host mobility. Sent when host connects to VTEP.

[2]: Route Type [0]: Eth. Segment ID [0]: Eth. Tag ID [48]: MAC Addr len [a2b9.4605.948d]: MAC [32]: IP Addr len [10.1.1.1]: IP

RT: L2VNI (VLAN) RT: L3VNI (VRF) Overlay Encapsulation: 8 - VXLAN L2VNI L3VNI Router MAC of Remote VTEP Remote VTEP IP

```
LEAF-5# show bgp l2vpn evpn 10.1.1.1
BGP routing table information for VRF default, address family L2VPN EVPN
Route Distinguisher: 10.0.0.3:32777
BGP routing table entry for [2]:[0]:[0]:[48]:[a2b9.4605.948d]:[32]:[10.1.1.1]/272, version 424
Paths: (2 available, best #1)
Flags: (0x000202) on xmit-list, is not in l2rib/evpn, is not in HW

  Advertised path-id 1
  Path type: internal, path is valid, is best path, no labeled nexthop
  AS-Path: NONE, path sourced internal to AS
    10.0.1.101 (metric 81) from 10.0.0.1 (10.0.0.1)
      Origin IGP, MED not set, localpref 100, weight 0
      Received label 100010 100999
      Extcommunity: RT:64500:100010 RT:64500:100999 ENCAP:8
            Router MAC:0200.0a00.0165
      Originator: 10.0.0.3 Cluster list: 10.0.0.1
```

Type 5 – Subnet Advertisement: Advertises IP prefix + prefix length with L3VNI. Used for inter-subnet routing. VTEP redistributes connected/static/dynamic IP routes. Additional attributes: L3VNI, extended communities.

[5]: Route Type [0]: Eth. Segment ID [0]: Eth. Tag ID [24]: IP Pref. len [198.51.100.0]: IP Prefix [0.0.0.0]: GW IP

L3VNI RT: L3VNI (VLAN) Overlay Encapsulation: 8 - VXLAN Router MAC of Remote VTEP Remote VTEP IP

```
LEAF-5# show bgp l2vpn evpn route-type 5
BGP routing table information for VRF default, address family L2VPN EVPN
Route Distinguisher: 192.0.2.3:3
BGP routing table entry for [5]:[0]:[0]:[24]:[198.51.100.0]:[0.0.0.0]/224, version 6421
Paths: (2 available, best #2)
Flags: (0x000002) on xmit-list, is not in l2rib/evpn, is not in HW

  Advertised path-id 1
  Path type: internal, path is valid, not best reason: Neighbor Address, no labeled nexthop
  AS-Path: NONE, path sourced internal to AS
    203.0.113.1 (metric 81) from 192.0.2.12 (192.0.2.2)
      Origin incomplete, MED 0, localpref 100, weight 0
      Received label 10001
      Extcommunity: RT:65000:10001 ENCAP:8 Router MAC:00ad.e688.1b08
      Originator: 192.0.2.3 Cluster list: 192.0.2.2
```

HOST DETECTION

– Host sends ARP/ND to local VTEP
– VTEP learns MAC/L2VNI and IP/L3VNI
– Info is advertised in EVPN (control plane)

HOST DELETION & MOVE

Host Deletion: When a host detaches, its ARP (default: 1500s) and MAC entry (default: 1800s) time out on the VTEP. Upon aging, the VTEP withdraws the host's MAC/L2VNI and IP/L3VNI advertisements.
Host Move: When a host moves to a new VTEP, the new VTEP advertises updated reachability with a higher move sequence number. The old VTEP withdraws its entry, completing the migration.

VIRTUAL ROUTING AND FORWARDING (VRF)

– Supports independent policies per tenant
– Key for scaling and multi-customer separation

DISTRIBUTED ANYCAST GATEWAY (DAG)

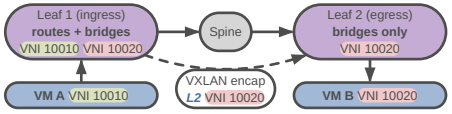
– Same gateway IP+MAC on all VTEPs
– Enables local default gateway for hosts in MPLS network with IRB
– Supports mobility + optimal forwarding across BGP EVPN fabric

INTEGRATED ROUTING AND BRIDGING (IRB)

– Enables inter-VLAN routing inside EVPN
– Avoids central gateway → no "traffic tromboning"

ASYMMETRIC IRB (L2)

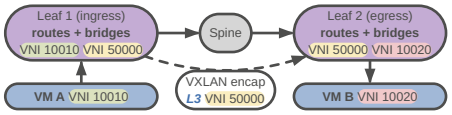
– Routing only on ingress, bridging on egress
– VXLAN uses destination VNI in both directions
– One L2 VNI per VLAN/Subnet
– Simple config, but requires all VLANs/VNIs on all VTEPs (scaling issues)



1) VM A → Leaf 1 in VNI 10010 (frame to anycast gateway)
2) Leaf 1 routes locally: VNI 10010 → VNI 10020 (L3 lookup, MAC rewrite)
3) Leaf 1 encapsulates with destination L2 VNI 10020 → spine → Leaf 2
4) Leaf 2 decapsulates and bridges in VNI 10020 to VM B – no routing

SYMMETRIC IRB (L2 + L3)

– Routing/bridging on ingress + egress VTEPs
– Uses L3 Transit VNI (same in both directions), One L3 VNI per VRF (Tenant)
– Scales well; clean separation of MAC and IP
– Requires L3 connectivity between all source/destination VTEPs for Type 2 routing (Done by configuring Type 5 routing)



1) VM A → Leaf 1 in VNI 10010 (frame to anycast gateway)
2) Leaf 1 routes locally into the L3 VNI (tenant VRF transit)
3) Encapsulation carries the L3 VNI 50000 → Leaf 2
4) Leaf 2 decapsulates, looks up dest IP in the VRF, routes into VNI 10020
5) Leaf 2 bridges to VM B in its local subnet

MULTIPROTOCOL BGP (MP-BGP)

Adress Family Identifier (AFI): Category of information being carried
Subsequent AFI (SAFI): Narrows down the specific type within that category
EVPN NLRI: Uses MP-BGP with specific AFI/SAFI. Supports multiple route types and attributes, unsupported routes are dropped by BGP

– Enables protocol-based VTEP discovery and host reachability via control-plane learning. Reduces flooding by replacing data-plane learning
– Extends BGP with multiprotocol capabilities (AFI/SAFI)
– Uses ***MP_REACH_NLRI*** and ***MP_UNREACH_NLRI*** for route advertisement and withdrawal (advertises VPNv4 between PEs in MPLS)
– Uses the ***VPNv4*** NLRI to distinguish between duplicate IPv4 prefixes

BGP CONTROL PLANE

– PEs learn MACs from local CEs (data plane)
– MACs advertised via BGP (control plane)
– Uses Route Distinguishers and MPLS labels
– Remote PEs update L2 RIB/FIB with MAC and next-hop info
– Enables seamless L2 across IP/MPLS backbone

CDN

Origin Server: Central content source (original files), usually in a datacenter
Edge / CDN Server: Also called ***Point of Presence (POP)***. Geographically distributed, caches content
Embedded PoP: Deployed directly inside ISP's local network
DNS Infrastructure: Directs users to optimal edge server (e.g. Geo-Routing)

KEY BENEFITS

Latency Reduction: Nearby edge servers reduce round-trip time
Availability: Failover and redundancy in case of node failure
Scalability: Handles traffic spikes via load balancing
Cost Optimization: Reduces backend and transit load on origin
DDoS Protection: Edge servers absorb attacks → not all traffic on one server
Global Load Reduction: Less long-distance traffic across the Internet

REQUEST ROUTING TECHNIQUES

– Decides which edge server should serve a client request
– Goal: Best performance (e.g. proximity, load, responsiveness)

DNS-BASED GEO-ROUTING

– Each edge has a unique IP
– DNS server picks closest/optimal edge server based on:
  – Resolver IP location (not user! → can cause wrong choice)
  – GeoIP DBs (MaxMind, IP2Location), load, latency, business rules
– **EDNS(0) and Client Subnet Extension (ECS):**
  – Resolver includes part of client IP in DNS request (e.g. /24 subnet)
  – Authoritative DNS makes better decision based on actual client region
  – Improves accuracy without revealing full IP, increases caching complexity

ANYCAST WITH BGP

– Same IP (e.g. 7.7.7.7) advertised from multiple locations
– BGP routing decides which path is "best" (AS-path, local pref, etc.)
– No DNS logic or per-client decision – pure BGP convergence
– **Pros:** Fast failover, simple, no app logic needed
– **Cons:** Less control, BGP ≠ best latency, route flapping risk

MANAGING TRAFFIC

Anycast: Modify BGP attributes/withdraw IP prefix. Not precise
Software: Shifting via Encapsulation tunnels (GRE)

LOAD BALANCING

Load balancing device: Efficient, reliable, High cost, single point of failure
ECMP: ToR router balances traffic. Simple, cheap, Adding/removing server changes hashing pool, re-hashing breaks TCP connections fix: GRE tunnel

HTTP CACHING & HEADERS

Caching is controlled via HTTP headers between clients, proxies, and servers
Cache-Control: Main directive (***no-cache***, ***no-store***, ***max-age***, ***must-revalidate***, etc.)
Expires: Absolute expiration time (older method, replaced by ***Cache-Control***)
ETag: Validator tag (version/hash), used with ***If-None-Match***
Last-Modified: Timestamp used with ***If-Modified-Since*** for revalidation
Age: Time (in seconds) since response was fetched from origin
Validation: Client uses ***ETag*** or ***Last-Modified***; server → 304 if unchanged

QOS

Internet is best effort: No guarantees, no QoS; all traffic treated equally (net neutrality); simple, scalable, but no delivery/order assurance or prioritization
Quality of Experience (QoE): Perceived service quality from user perspective
Route Pinning: Keeps flow on a fixed path to prevent oscillation (don't switch immediately to "better" path)
Routing-based: Path selection; QoS-aware routing; Choose best path
Node-based: Packet treatment; Congestion mgmt; queuing/scheduling/policing/shaping; "What happens to packets at each hop?"
PAK-Priority: System queue (routers) that prioritizes routing protocol packets

4-Class Model	*8-Class Model*	*12-Class Model*
Real Time	Voice	Voice
	Interactive Video	Real-Time Interactive
		Multimedia Conferencing
	Streaming Video	Broadcast Video
		Multimedia Streaming
Signaling or Control	Signaling	Signaling
	Network Control	Network Control
		Network Management
Critical Data	Critical Data	Transactional Data
		Bulk Data
Best Effort	Best Effort	Best Effort
	Scavenger	Scavenger

NETWORK PERFORMANCE METRICS

Bandwidth [Gbit/s]: Maximum transfer capacity of a link (width of pipe)
Throughput [Gbit/s]: Successfully delivered data (water that reached dest)
Latency / Delay [ms]: Time for packets to travel src → dest (length of pipe)
  End-to-End Delay: Total time sender to receiver
  One-Way Delay: From first bit sent to last bit received
  Components: **Transmission delay** (time to push onto link), **Processing delay** (lookup, queuing), **Propagation delay** (physical travel time)
Jitter [ms]: Variation in delay between packets, caused by re-routing/queuing (Voip<30ms), Calc: highest - lowest delay. Doesn't impact TCP
Packet Loss Ratio (PLR) [%]: Dropped packets due to congestion or errors

QUEUING

Incoming buffer: Usually only transit, cannot be filled up in case of a CPU overload: leads to drops
Outgoing buffer: Filled up with packets waiting for transmission, queue management is focused on the outgoing buffer

ALGORITHMS

First-In First-Out (FIFO): Basic, no prioritization
Priority Queuing (PQ): Multiple queues, serve highest first; others may starve
Round-Robin (RR): One packet per queue in turn (fair, but ignores priority)
Weighted Fair Queuing (WFQ): RR with weights, *n* packets per queue
Class-Based WFQ (CBWFQ): WFQ with user-defined classes (logical queues), queue limits, max bandwidth guaranteed or max % of bandwidth
Low Latency Queuing (LLQ): Adds strict priority queue (priority class) to CBWFQ for delay-sensitive traffic (e.g. voice) (based on IP Precedence, DSCP, src, port, protocol…)

QUEUE MANAGEMENT

Tail Drop: Drops packets when queue full; huge interruption of traffic → same as no connectivity
TCP Global Sync: Many TCP flows back off and restart simultaneously (AIMD) → link underutilization
TCP Starvation: TCP slows down after drops (congestion control), UDP doesn't → queues filled with UDP, TCP squeezed out
Random Early Detection (RED): Random early drops before full queue to prevent global sync and TCP collapse. Dropped TCP segments cause TCP sessions to reduce their windows sizes
Weighted RED (WRED): RED + DSCP/EXP-based drop logic, prioritizes higher-marked traffic, max thresh → all packets dropped

POLICING VS. SHAPING

Policing (Inbound mostly): Drops packets that exceed configured rate limits
Shaping (Outbound): Buffers packets to smooth traffic bursts

QOS MODELS

BEST_EFFORT

No guarantees, all traffic treated equally (follow Internet neutrality)

INTEGRATED SERVICES (INTSERV)

– End-to-end QoS (guaranteed for specific apps)
– Per-flow resource reservation
– Precise but not scalable (uses RSVP)
– App informs network of traffic traits, requests service before sending data

DIFFERENTIATED SERVICES (DIFFSERV)

– Scalable approach using marking, No hard guarantees, Cost-effective
– Divides traffic into classes based on business requirements
– Routers are configured with policy on how to prioritize classes

Marking (DSCP)
Differentiated Services Code Point (DSCP): 6-bit field in the IP header used to classify and manage network traffic
L3 Marking: ToS byte → DSCP (6 bits) + IP Precedence (3 bits) [overlapping]
  DSCP: (6-bit in IP header) marks packets for QoS; classifies traffic
L2 Marking: Dot1q header → 802.1p/CoS bits
EXP: (3-bit in MPLS label) serves same purpose within MPLS networks; often mapped from DSCP.

Behavior (PHB)
Per-Hop behavior (PHB): Defines what routers actually do
  Class Selector (CS): Compat with old IP Precedence, simple prio levels
  Assured Forwarding (AF): Multiple classes + drop priorities
  Expedited Forwarding (EF): Very high prio, e.g. VoIP

MODULAR QOS CLI (MQC)

Class Map: Define traffic classes (e.g., match voice or video)
Policy Map: Define actions for each class (e.g., limit, shape, priority)
Service Policy: Apply policies to interfaces or directions (in/out)

OTHER INFOS

AD: Inter-protocol choice (e.g., OSPF vs RIP) → lower wins.
Cost/Metric: Intra-protocol choice (e.g., OSPF path A vs B) → lower wins.
Routing Preference Order (across protocols):
  – Most specific prefix
  – Lowest Administrative Distance
  – Static default route
Administrative Distances: (Smallest Administrative Distance wins)

Protocol	*Distance*
Connected	0
Static (Interface)	1
Static (Next Hop)	1
BGP External	20
EIGRP Internal	90
OSPF	110
ISIS	115
RIP v1/v2	120
EIGRP External	170
BGP Internal	200