Cloud and Datacenter Networking

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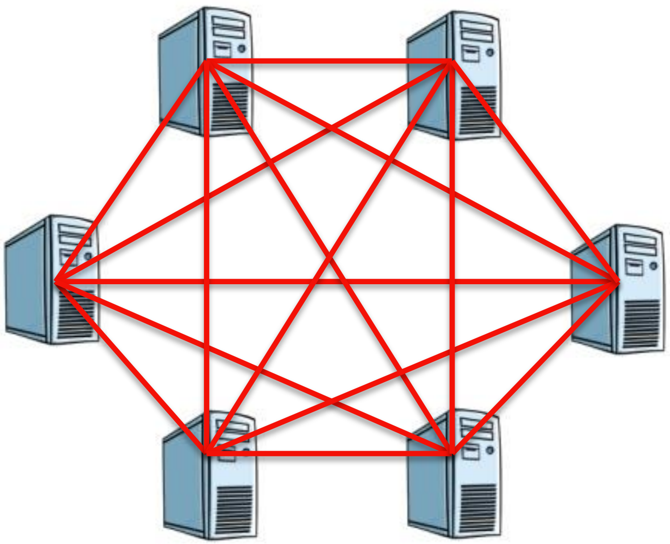
Datacenter networking infrastructure
Part I

Lesson outline

- Switched Ethernet basic concepts
- Gigabit Ethernet standard evolution
- A datacenter's networking infrastructure
- Organization and topology of a datacenter network
- Link aggregation
- VLANs

Connecting N hosts: full mesh

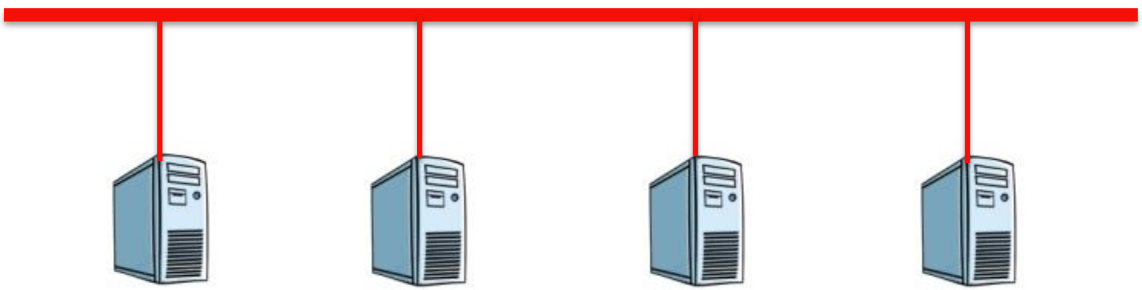
- Advantages
  - In case of full-duplex NICs, $N \cdot (N-1)$ simultaneous transmissions are possible
- Disadvantages
  - # NICs = $N \cdot (N-1)$ proportional to N^2
  - # bidirectional links = $(N \cdot (N-1)/2)$ proportional to N^2
  - Cabling is expensive
  - Costly and not scalable



Full mesh

Connecting N hosts: bus

- Advantage over full mesh
  - Cheaper: 1 NIC per host
  - Simpler and cheaper cabling
- Disadvantages
  - Transmission capacity is shared among N hosts
  - Medium Access Control (CSMA/CD) is needed to regulate access to the shared bus
  - Cabling a star topology would be simpler in a building



CSMA/CD

- CSMA – *Carrier Sense Multiple Access*
- CS: Listen before transmitting
  - If a device detects a signal from another device, it waits for a specified amount of time before attempting to transmit
  - When there is no traffic detected, a device transmits its message
  - While this transmission is occurring, the device continues to listen for traffic or collisions on the LAN
  - After the message is sent, the device returns to its default listening mode
- CD – *Collision Detection*
  - When a device is in listening mode, it can detect when a collision occurs on the shared media, because all devices can detect an increase in the amplitude of the signal above the normal level
  - When a collision occurs, the other devices in listening mode, as well as all the transmitting devices, detect the increase in the signal amplitude

CSMA/CD: Carrier Sense Multiple Access

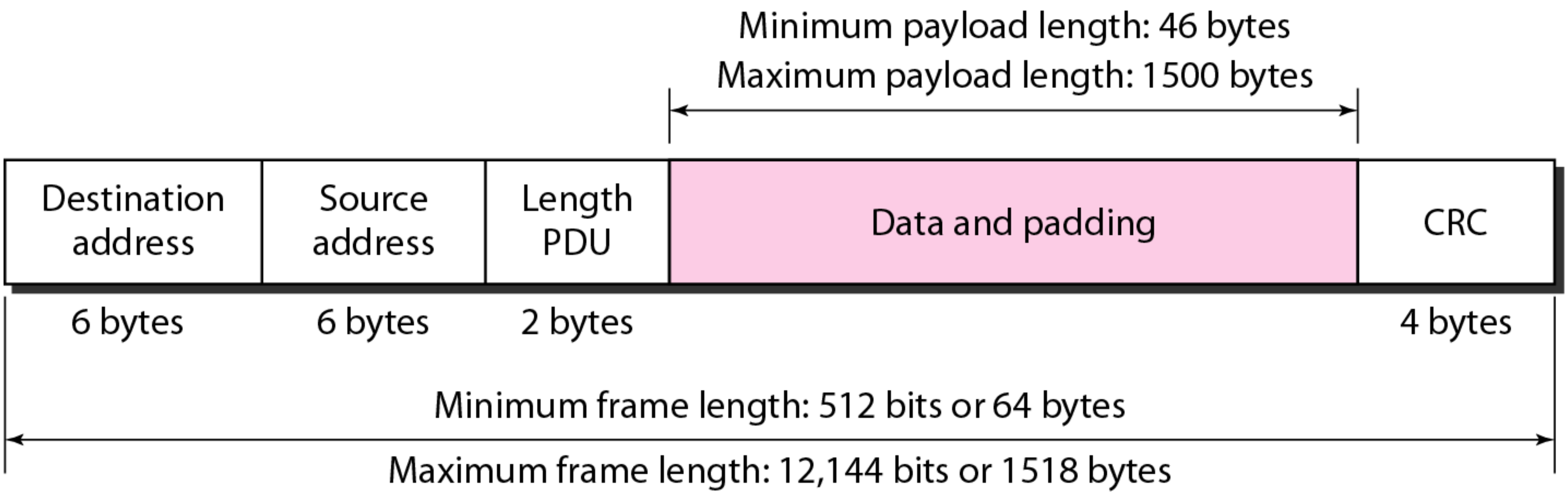
- CS: Listen before transmitting
  - If a device detects a signal from another device, it waits for a specified amount of time before attempting to transmit
  - When there is no traffic detected, a device transmits its frame
  - After the frame is sent, the device returns to its default listening mode
- CD – *Collision Detection*
  - During a frame transmission, the device continues to listen for collisions
  - When a device is in listening mode, it can detect when a collision occurs on the shared media, because all devices can detect an increase in the amplitude of the signal above the normal level
- Jam Signal
  - When a collision is detected, the transmitting devices send out a jamming signal
  - The jamming signal notifies the other devices of a collision, so that they invoke an exponential backoff algorithm
  - This backoff algorithm causes transmitting devices to stop transmitting for a random amount of time, so that the devices that were involved in the collision have a chance that they do not try to send traffic again at the same time

Ethernet frame format

IEEE 802.3						
7	1	6	6	2	46 to 1500	4
Preamble	Start of Frame Delimiter	Destination Address	Source Address	Length/ Type	802.2 Header and Data	Frame Check Sequence

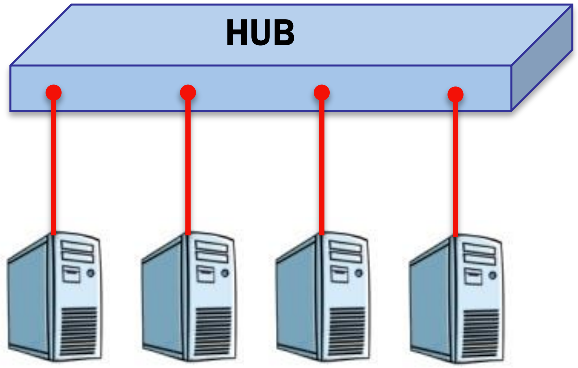
- Destination MAC Address (6 bytes) is the identifier for the intended recipient
  - The address in the frame is compared to the MAC address in the device
  - If there is a match, the device accepts the frame
  - Special destination address FF:FF:FF:FF:FF:FF for broadcast
  - Special destination addresses for LAN multicast
- Source MAC Address Field (6 bytes) identifies the frame's originating NIC
- Length/Type Field (2 bytes)
  - If this field's value ≥ $0x0600=1536_{10}$, the contents of the Data Field are decoded according to the protocol indicated (works as Type field)
  - If this field's value < 0x0600 then the value represents the length of the data in the frame (works as Length field)

Ethernet frame: min and max length



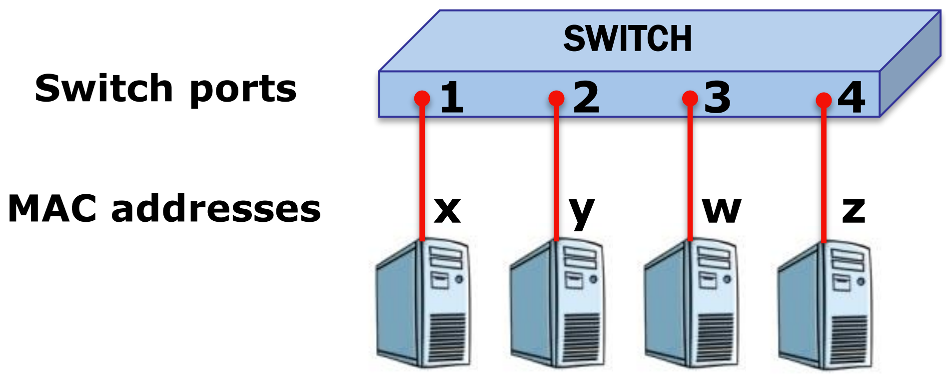
Connecting N hosts: hub

- An Ethernet hub retransmits a frame to all the ports but the one on which the frame entered the hub
- Each host compete for the shared capacity with the other N-1 hosts attached to the hub, as for the bus topology
- Advantage over bus
  - Simpler and cheaper cabling w.r.t. the bus topology (UTP cables)



Connecting N hosts: switch

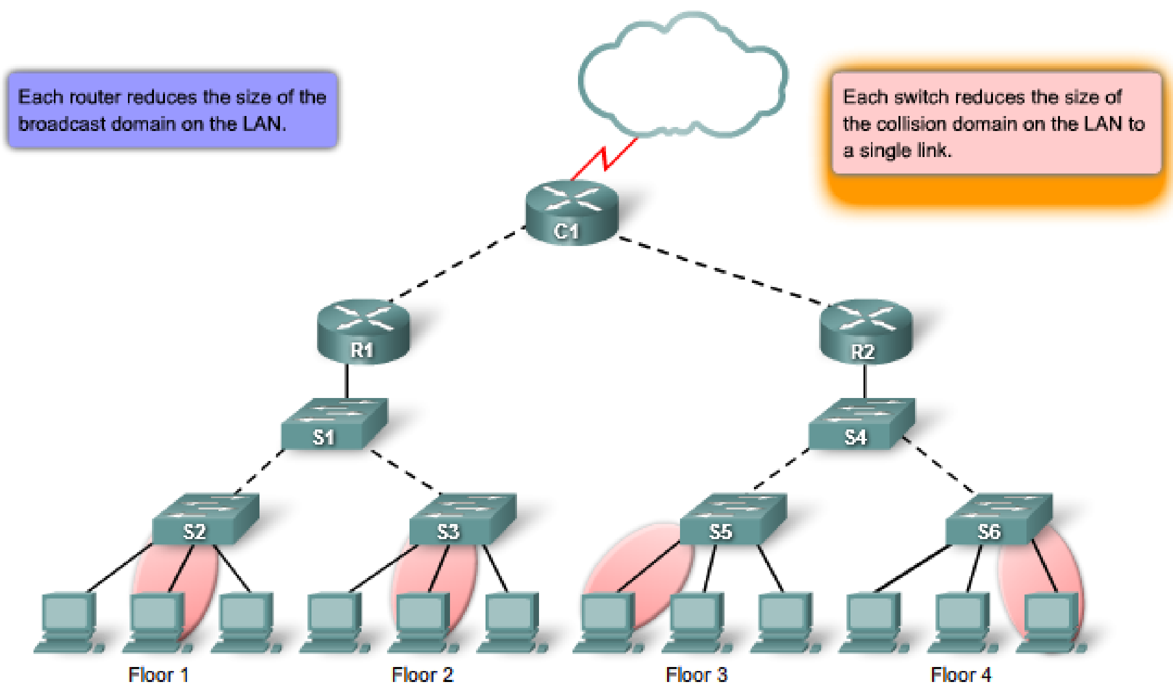
- A switch determines how to handle incoming frames by using its *MAC address table*
- A switch builds its MAC address table by recording the source MAC addresses of the nodes connected to each of its ports (*learning*)
- Once a specific node's MAC address is associated to a specific switch port in the MAC address table, the switch knows where (i.e. on which port) to send subsequent frames destined for that specific MAC address
- Before a switch learns the port on which a given MAC address is reachable, the switch transmits a frame destined for that unknown MAC address to all the ports but the one on which the frame entered the switch



MAC address	port
x	1
y	2
w	3
z	4

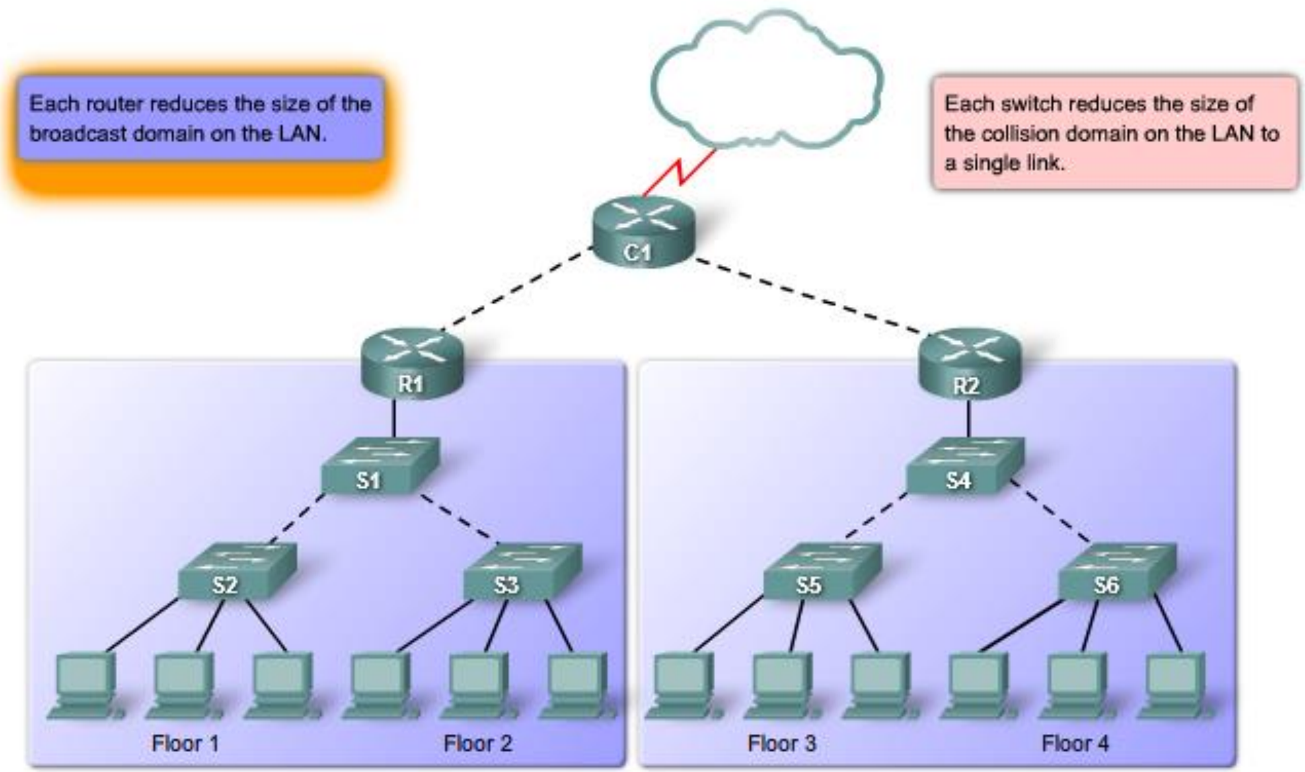
Switches and collision domains

- In store-and-forward switching, when the switch receives the frame, it stores the data in buffers until the complete frame has been received
- In a switched network, collision domains shrink to single links
- If the links between switches and hosts are full-duplex, no collisions may occur
- During the storage process, the switch also performs an error check using the Cyclic Redundancy Check (CRC) trailer portion of the frame



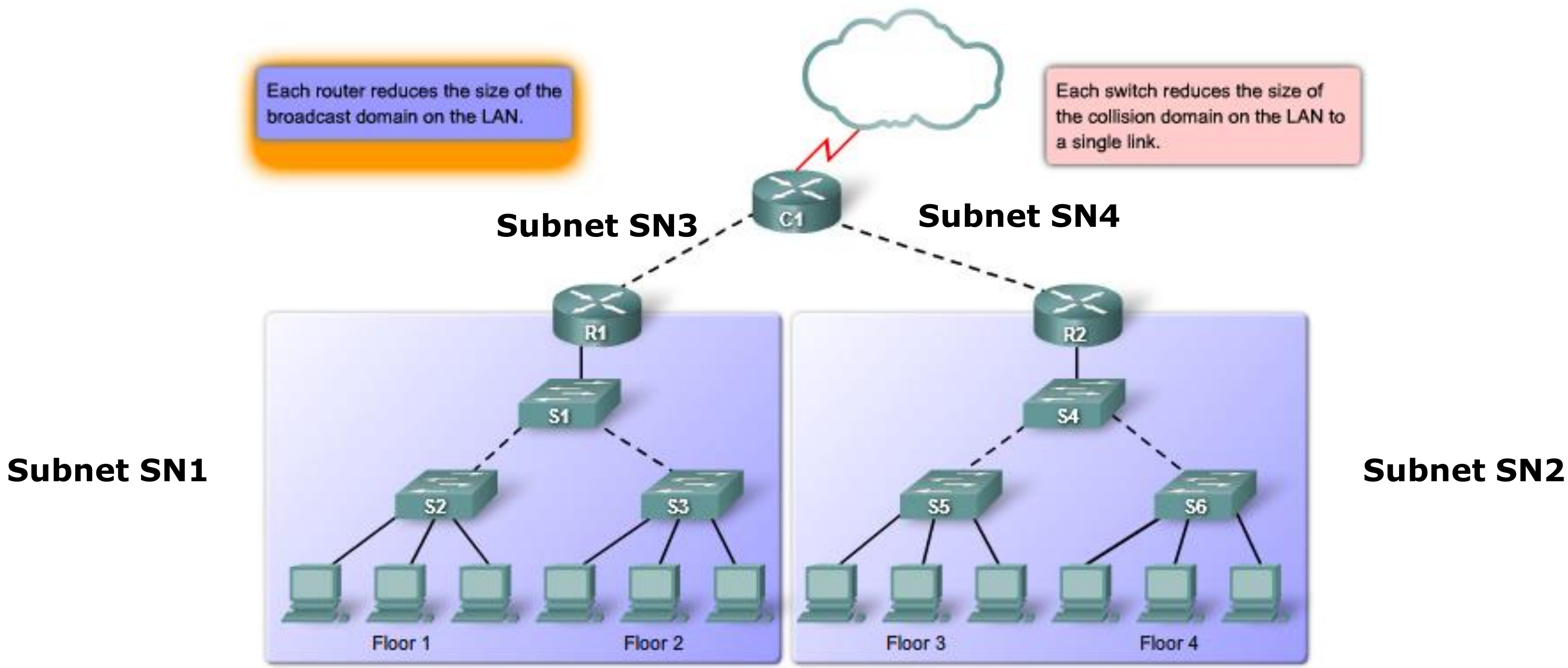
Switches and broadcast domains

- Although switches filter most frames based on MAC addresses, they do not filter broadcast frames
- A collection of interconnected switches forms <u>a single broadcast domain</u>



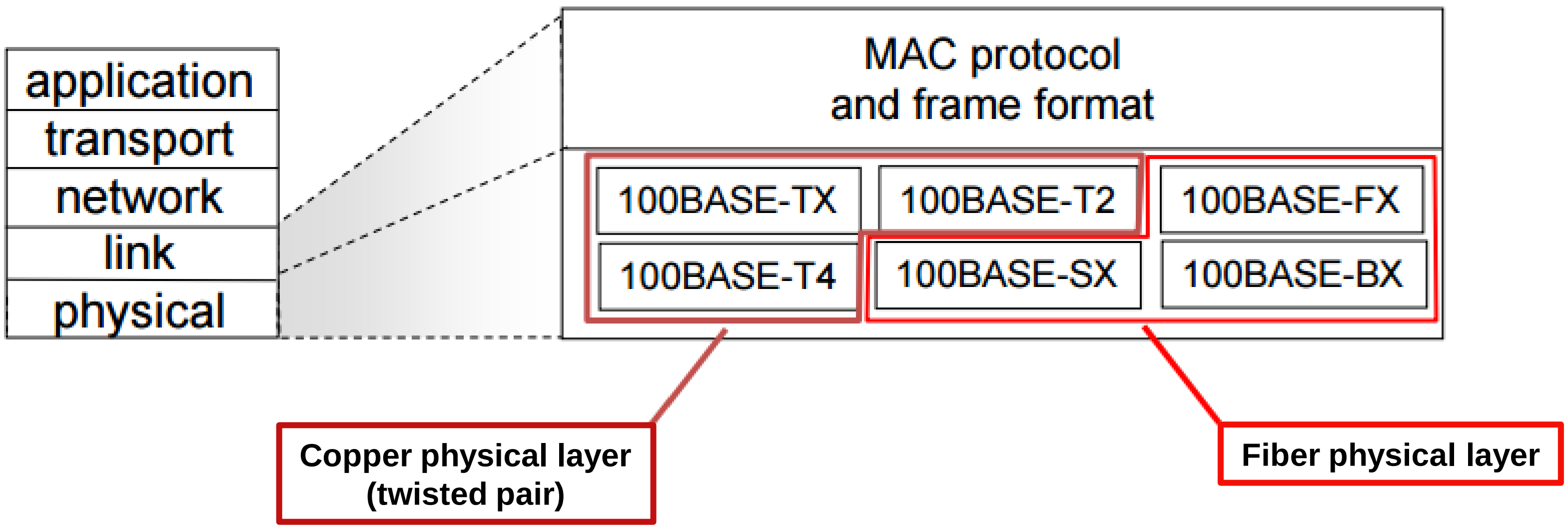
Routers and IP subnets

- To partition a large network in multiple isolated broadcast domains, routers are needed
  - Routers split a network in multiple IP subnets
  - A broadcast transmission does not cross the IP subnet boundary
  - Approach possible only if IP subnets are physically separated as in the picture below
    - Subnet SN1 on the left, SN2 on the right

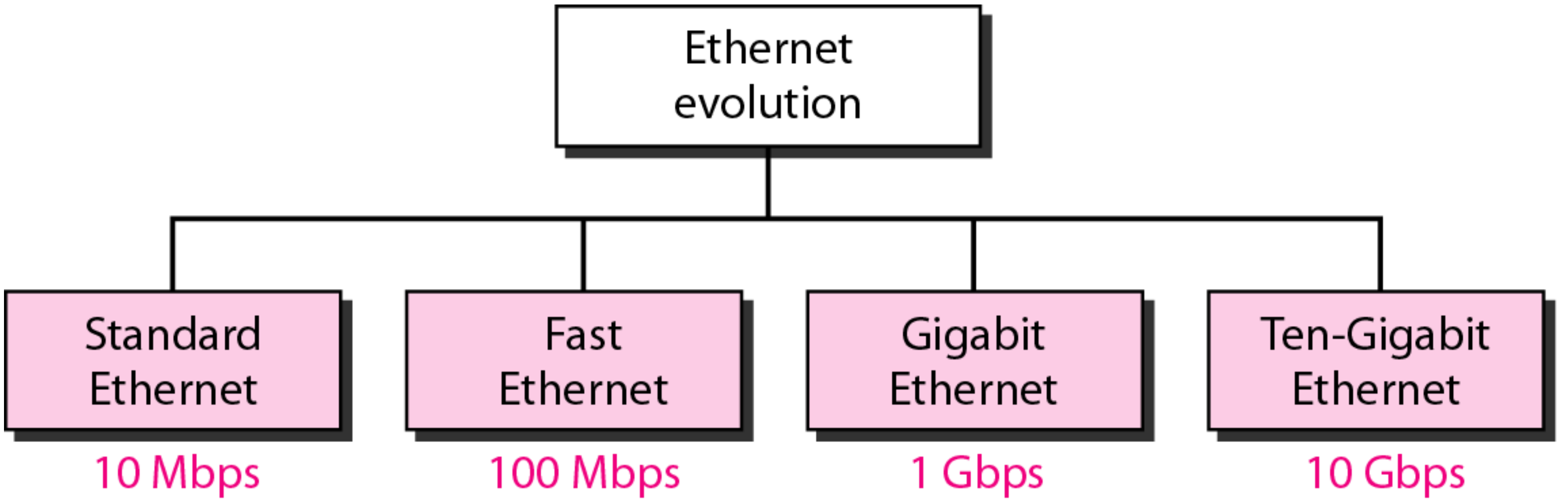


IEEE 802.3 Ethernet standards: link and physical layers

- IEEE 802.3 is actually a collection of many different standards
  - common MAC protocol and frame format
  - different speeds: 2 Mbps, 10 Mbps, 100 Mbps,1Gbps, 10Gbps, 40Gbps, 100Gbps
  - different physical layer media: fiber, cable



Ethernet technology evolution

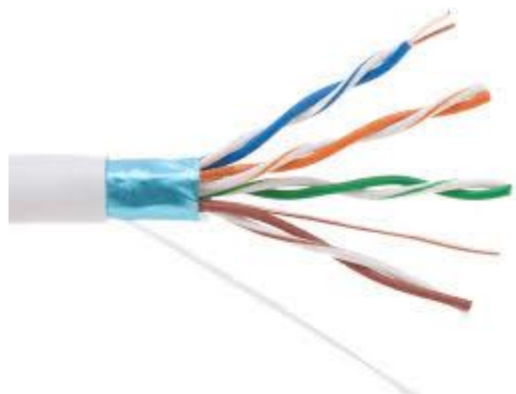


Ethernet transmission media: copper wires

- UTP (Unshielded Twisted Pair)

UTP cable with RJ-45 connector

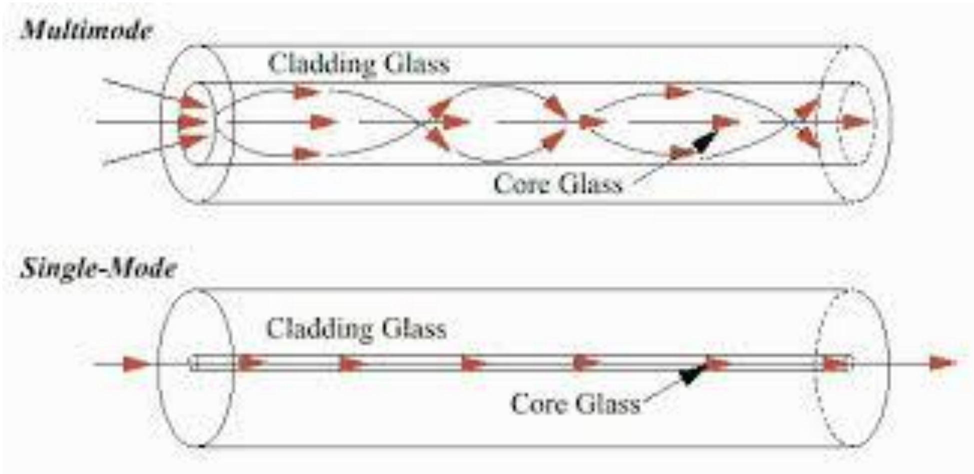
- FTP (Foiled Twisted Pair)

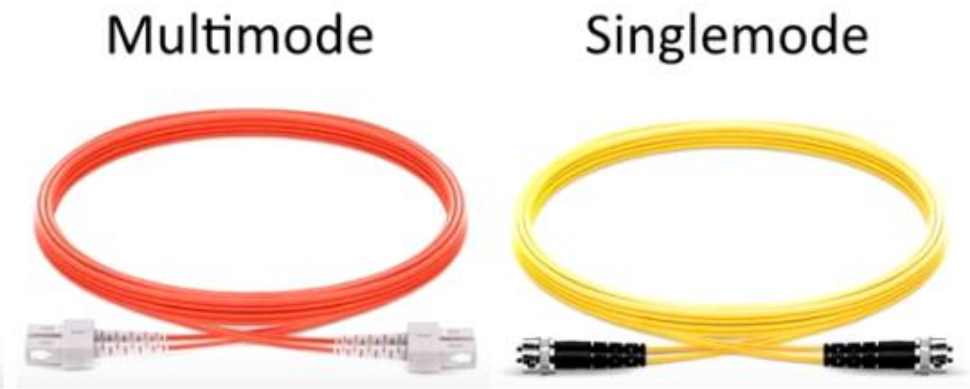


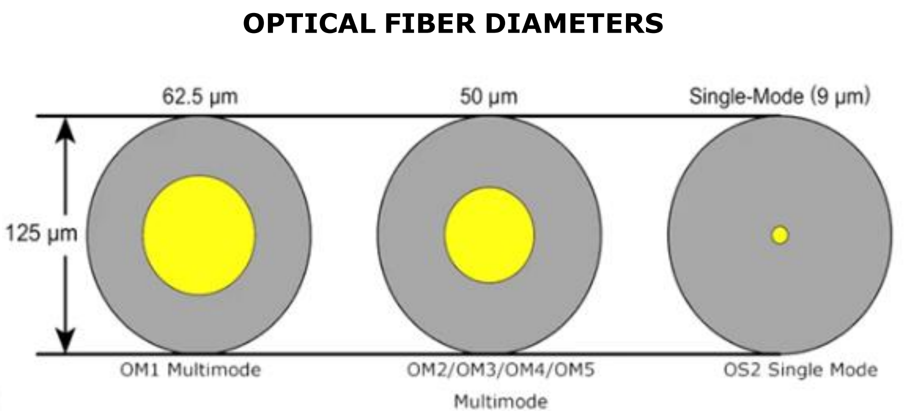
FTP cable with RJ-45 connector

- Multi-Mode Optical Fiber

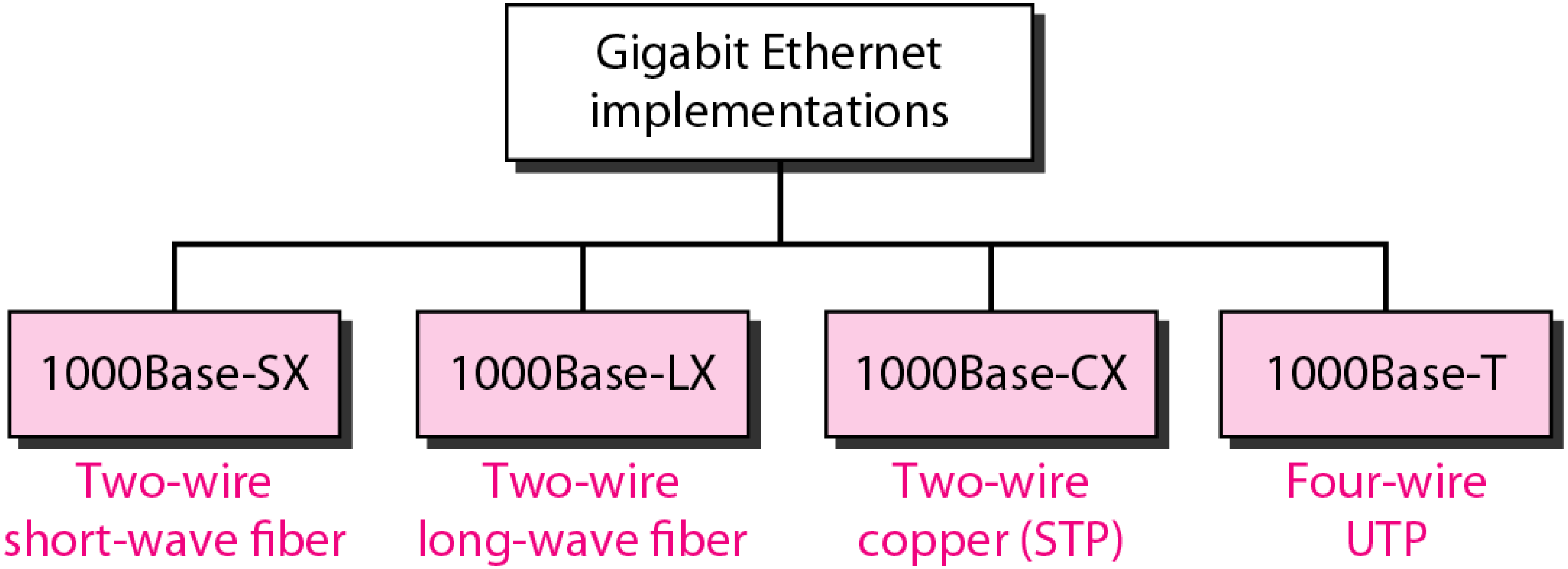
- Single Mode Optical Fiber







Gigabit Ethernet implementations and media



Characteristics	*1000Base-SX*	*1000Base-LX*	*1000Base-CX*	*1000Base-T*
Media	Fiber short-wave	Fiber long-wave	STP	Cat 5 UTP
Number of wires	2	2	2	4
Maximum length	550 m	5000 m	25 m	100 m
Block encoding	8B/10B	8B/10B	8B/10B	
Line encoding	NRZ	NRZ	NRZ	4D-PAM5

10-Gigabit Ethernet implementations and media

- IEEE 802.3ae standard for fiber optic cables
- IEEE 802.3ak for twinaxial copper cables
- IEEE 802.3an for UTP cat 6A and cat7 cables

- How does 10GbE compare to other varieties of Ethernet?
  - Frame format is the same, allowing interoperability between all varieties of legacy, fast, gigabit, and 10 Gigabit, with no reframing or protocol conversions
  - Bit time is now 0.1 ns - all other time variables scale accordingly
  - Only full-duplex fiber connections are used, CSMA/CD is not necessary

10 Gigabit Ethernet over Fiber: IEEE802.3ae

- Ratified in June 2002, the IEEE802.3ae LAN standard was developed to update the preexisting IEEE802.3 standard for 10GbE fiber transmission
- With the new standard, new media types were defined for LAN, metropolitan area network (MAN) and wide area network (WAN) connectivity
  - 10GBASE-SR (*Short Reach*) – uses the lowest cost optics (850nm) to support 10GbE transmission over standard multimode fiber for distances up to 300 meters
    10GBASE-SR is often the standard of choice to use inside the datacenters where fiber is already deployed and widely used
  - 10GBASE-LR (*Long Reach*) – uses higher cost optics (1310nm) and requires more complex alignment of the optics to support single-mode fiber up to 10 km
  - 10GBASE-LRM (*Long Reach Multimode*) – operating at 1310 nm, can span up to 220 meters with a multimode fiber using a technology called EDC (*Electronic Dispersion Compensation*)
    10GBase-LRM is targeted for those customers who have older fiber already in place but need extra reach for their network
  - 10GBASE-ER (*Extended reach*) – uses the most expensive optics (1550nm) and single-mode fiber for a link length up to 40 km
  - 10GBASE-SW, 10GBASE-LW, 10GBASE-EW – defined for use with a WAN PHY, these standards were defined to operate at the same baud rate as OC-192/STM-64 SONET/SDH equipment
  - 10GBASE-LX4 – supports traditional FDDI grade multimode fiber for distances up to 300 meters using Coarse Wavelength Division Multiplexing (CWDM), which lowers the transmission rate of each wavelength to 3.125Gbaud; the LX4 standard also supports single-mode fiber for up to 10 Km

10 Gigabit Ethernet over Copper: IEEE 802.3ak & 802.3an

- IEEE802.3ak is a low-cost 10GbE solution intended for copper cabling with short distance connectivity that makes it ideal for wiring closet and data center connectivity
  - Approved in 2004
  - Also known as 10GBASE-CX4
  - The CX4 standard transmits 10GbE over four channels using twin-axial cables derived from Infiniband connectors and cable
- IEEE802.3an is the latest proposed 10GbE standard for use with unshielded twisted-pair (UTP) style cabling
  - Approved in 2006
  - Also known as 10GBASE-T
  - At least Category 6A (Cat 6A) or Category 7 (Cat 7) UTP cables are required

Transceivers

- Transceivers are hot-swappable devices used to connect a variety of physical media to Ethernet switches and NICs
- Transceivers are also referred to as *Medium Attachment Units* (MAUs)
- Gigabit Ethernet has two types of transceivers:
  - Gigabit Interface Connector (GBIC)
  - Small Form Factor Pluggable (SFP) or “mini-GBIC”

A switch with 4 SFP ports

- 10Gb Ethernet (10 GbE) has several defined transceiver types:
  - XENPAK – mainly used in LAN switches; the first 10GbE pluggable transceivers on the market to support the 802.3ae standard transmission optics; these transceivers also support the 802.3ak copper standard to connect CX4 cables
  - XPAK – used primarily in Network Interface Cards (NIC) and Host Bus Adapter (HBA)
  - X2 – smaller form factor (about 2/3 the size of the XENPAK)
  - XFP –the closest in size to SFP
  - SFP+ - an enhanced version of SFP that supports data rates up to 16 Gbit/s and can be used for both 8 Gbit/s Fibre Channel and 10Gb Ethernet for both copper and optical cables
- 40Gb Ethernet (40 GbE) uses the following transceiver types:
  - QSFP/QSFP+ – allows data rates of 4x10 Gbit/s for Ethernet, Fibre Channel, InfiniBand and SONET/SDH links providing four channels of data in one pluggable interface


XFP transceiver


Direct-Attach Active Optical Cable with SFP+ Connectors


QSFP to 4 SFP+ Breakout Cable

Twinaxial cabling or "Twinax"

- A type of cable similar to coaxial cable, but with two inner conductors instead of one
- Applied in SFP+ Direct-Attach Copper (10GSFP+Cu), a popular choice for 10G Ethernet
- On SFP+ it is possible transmit at 10 Gigabits/second full duplex over 5 m distances
- Twinax with SFP+ offers 15 to 25 times lower transceiver latency than current 10GBASE-T Cat 6/Cat 6a/Cat 7 cabling systems: 0.1 μs versus 1.5 to 2.5 μs
- The power draw of Twinax with SFP+ is around 0.1 watts, which is also much less than 4–8 watts for 10GBASE-T
- 40GBASE-CR4 and 100GBASE-CR10 physical layers using 7 m twin-axial cable are being developed as part of 100 Gbit Ethernet specifications by IEEE 802.3bj workgroup

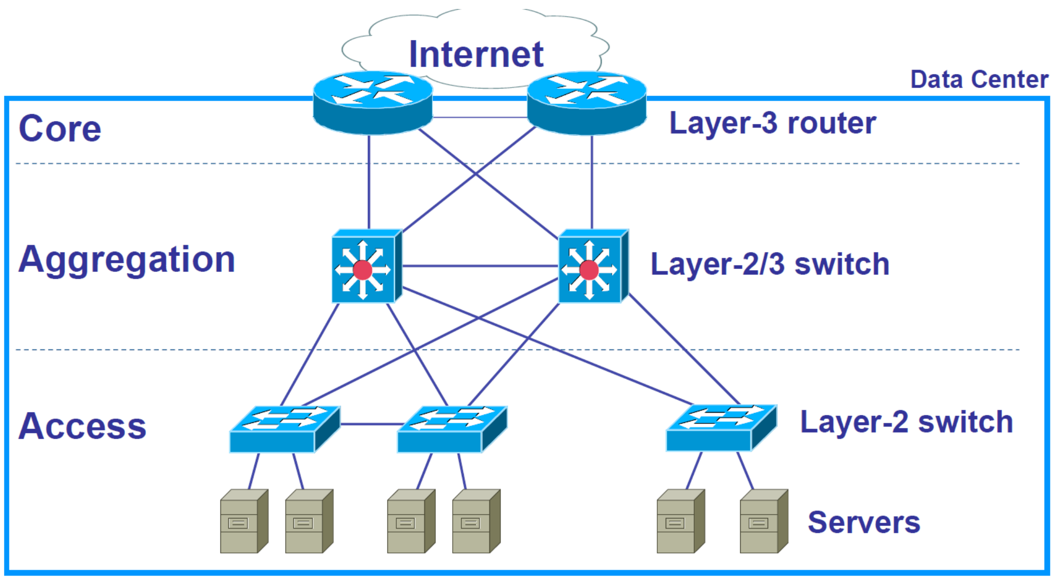
Direct Attach Twinax Copper (DAC) with SFP+ Connectors

Datacenter netwoking: infrastructures and equipments

- *A datacenter's networking infratructure allows servers to communicate among them, access shared storage resources as well as to communicate to the rest of the world through the Internet*
- As for any networking infrastructure, it comprises:
  - Active equipments
  - A cabling infrastructure (cables, pathways, patch panels, etc.)
- Active equipments include:
  - L2 switches
  - Routers and L3 switches
  - Firewalls and other special-purpose devices (load balancers, IDS, etc.)
- Moreover, a DC usually comprises storage devices and a specialize networking infrastructure (SAN) used to connect servers with storage equipments
  - Fibre Channel
- *High Performance Computing* HPC datacenters usually include a low-latency communications infrastructure to better support parallel computing
  - InfiniBand

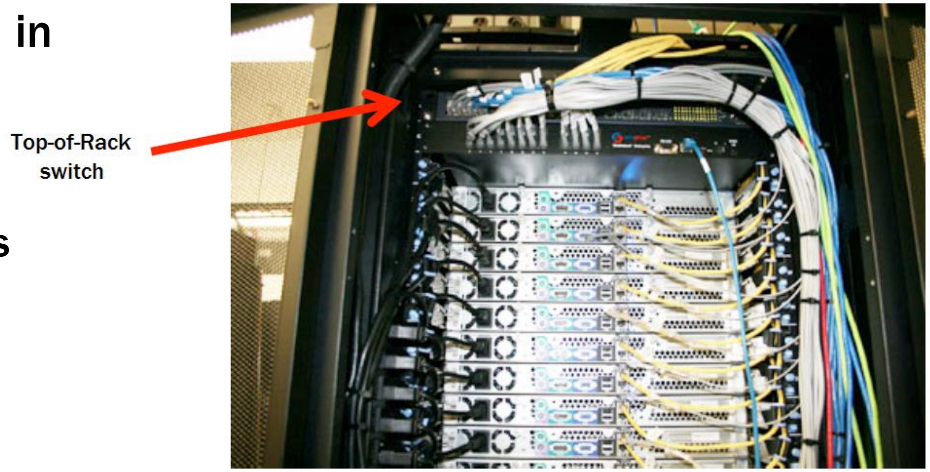
DC networking architecture: 3-tier model

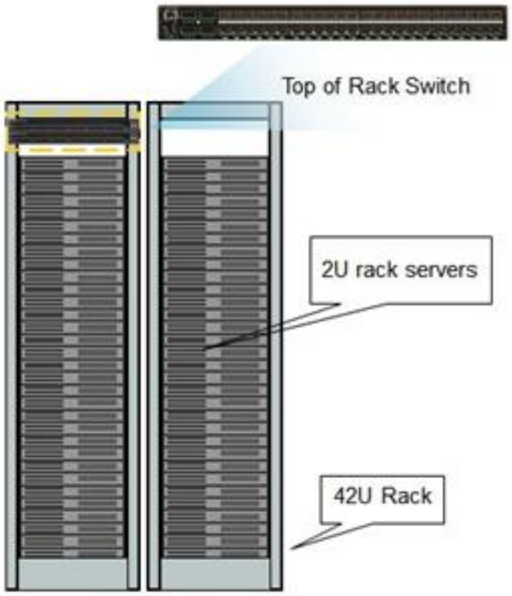
- In a DC, servers are physically organized in racks for a more efficient space utilization and for ease of management
- The datacenter networking infrastructure is designed according to a hierarchical architecture
- Servers' NICs (*network interface cards*) (2/4 NICs per server) are connected to a first layer infrastructure called *access layer*
- *Access layer's switches*, in turn, are connected to a second layer infrastructure, called *aggregation layer*
- The whole DC is connected to the Internet through a third layer infrastructure, called *core layer*, typically operating at layer 3 (*IP routing*)



Access layer: Top of Rack switch

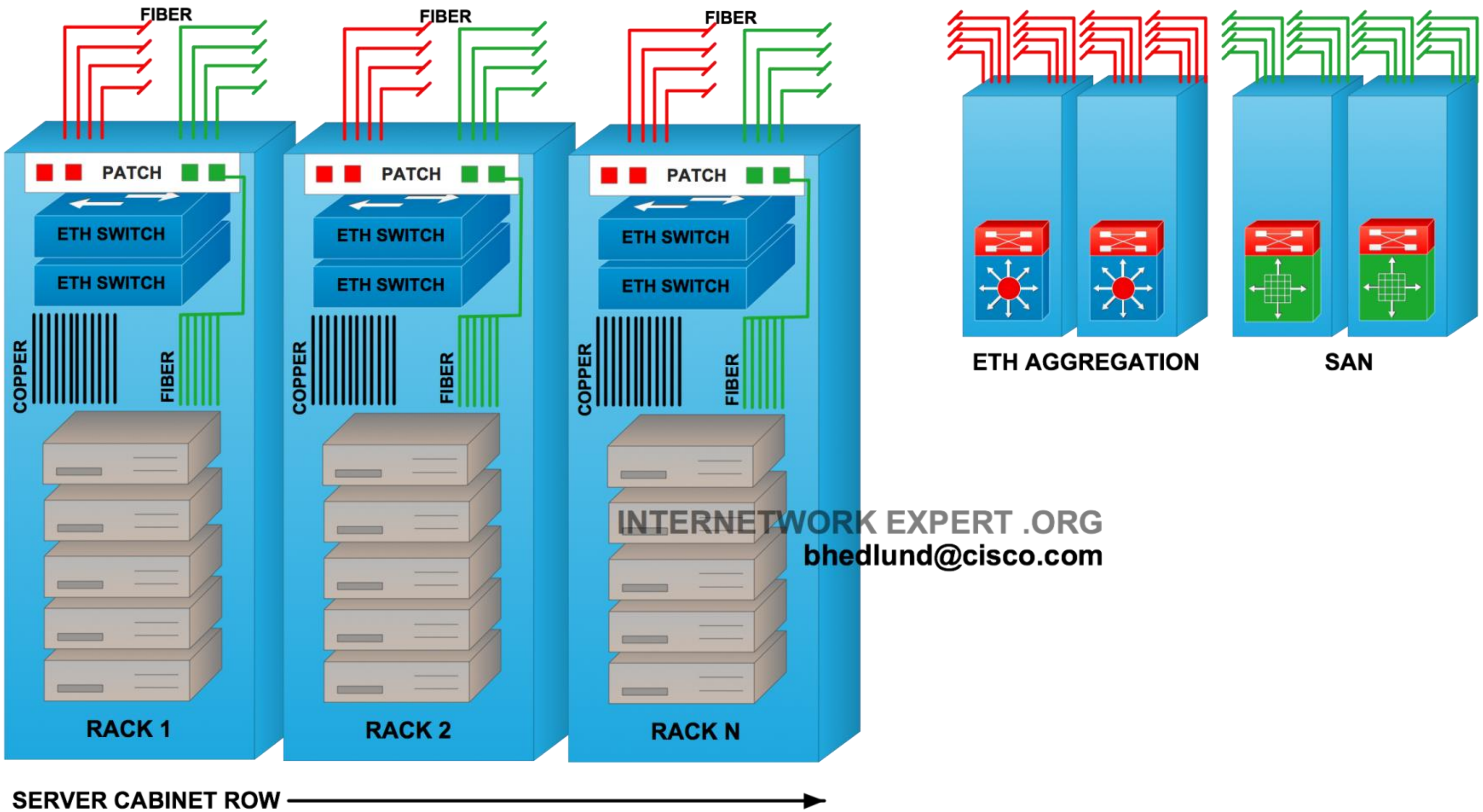
- The DC's *access layer* is typically formed by one or two Top-of-Rack (ToR) Ethernet switches located in each rack
  - N server / rack
    - N≈20 (≈40) for 2U servers (or 1U) and 42U racks
  - 2 NIC Ethernet / server
  - 1 or 2 48-ports switch + uplink in each rack
  - Until 2015:
    - 1 GbE server connectivity, 10 GbE uplink
  - Recent tren:
    - 10 GbE server connectivity, 40 GbE uplink
- Remote management NICs are also to be taken into account
  - HP iLO, Dell DRAC, etc.
  - 1 remote management NIC per server
  - 1 switch dedicated to management connections





Top of Rack (or In-Rack) design

- Switches do not need to be necessarily in top part of the rack
  - Sometimes a convenient location is in the middle of the rack
- Copper (e.g. UTP) cabling for in-rack connections
- Fibers to connect racks to aggregation layer switches and to SAN



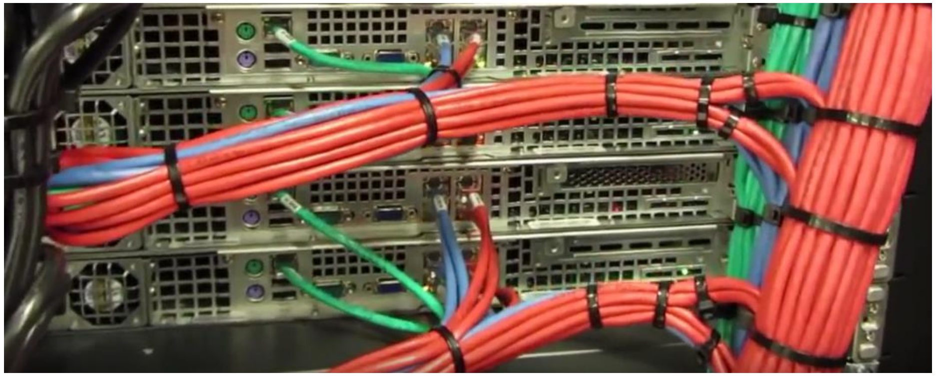
Brad Hedlund. *Top of Rack vs End of Row Data Center Designs*. http://bradhedlund.com

In-Rack switches: cabling

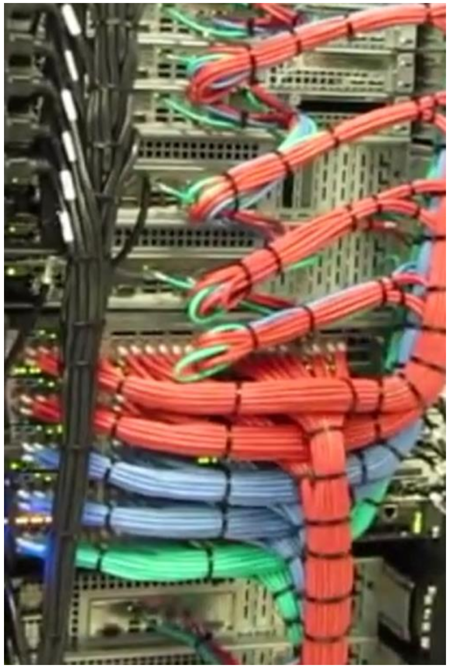
A few pictures showing racks with in-rack switches and servers connections (unstructured cabling)

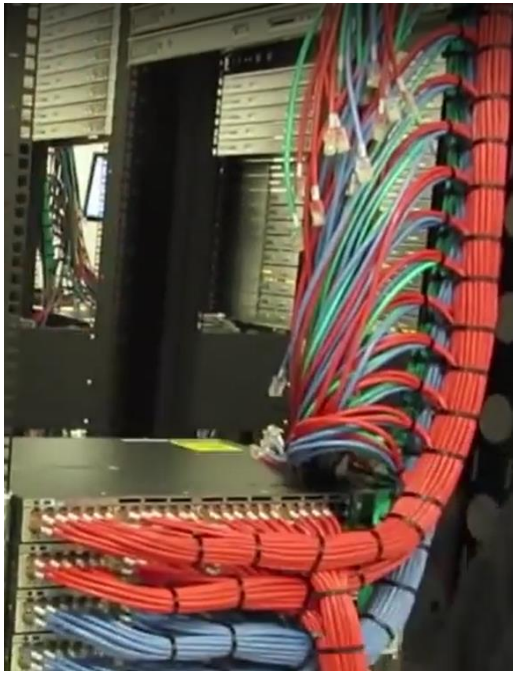
Each server has several connections:

- Dual data connections
- Dual connections to storage SAN
- Remote management



- ➢ Switches are mounted in the middle of the rack
- ➢ Cables are bundled and tied together

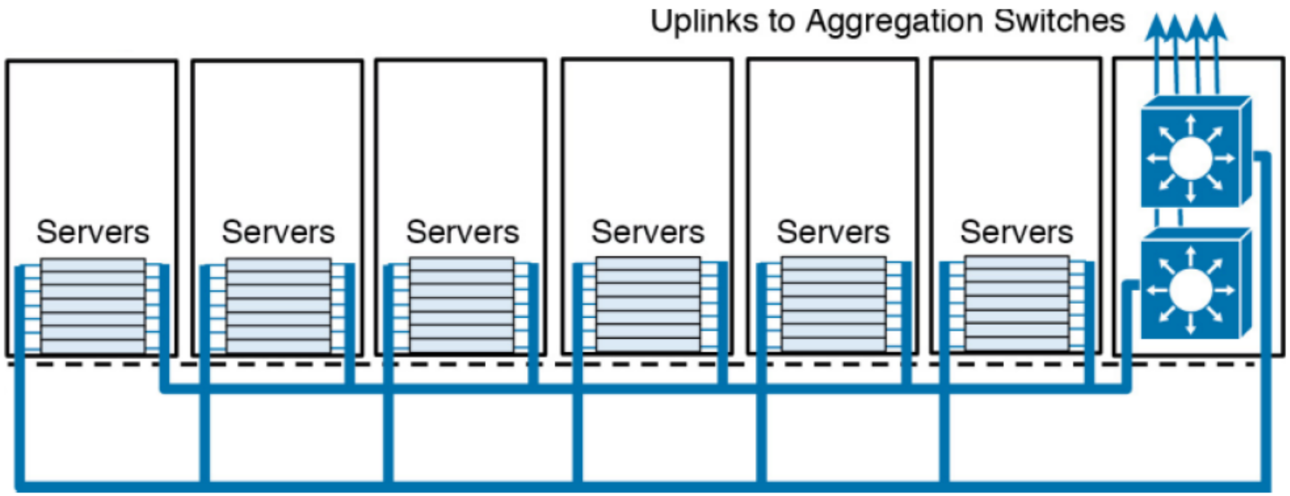




Source: Softlayer Amsterdam DC video tour

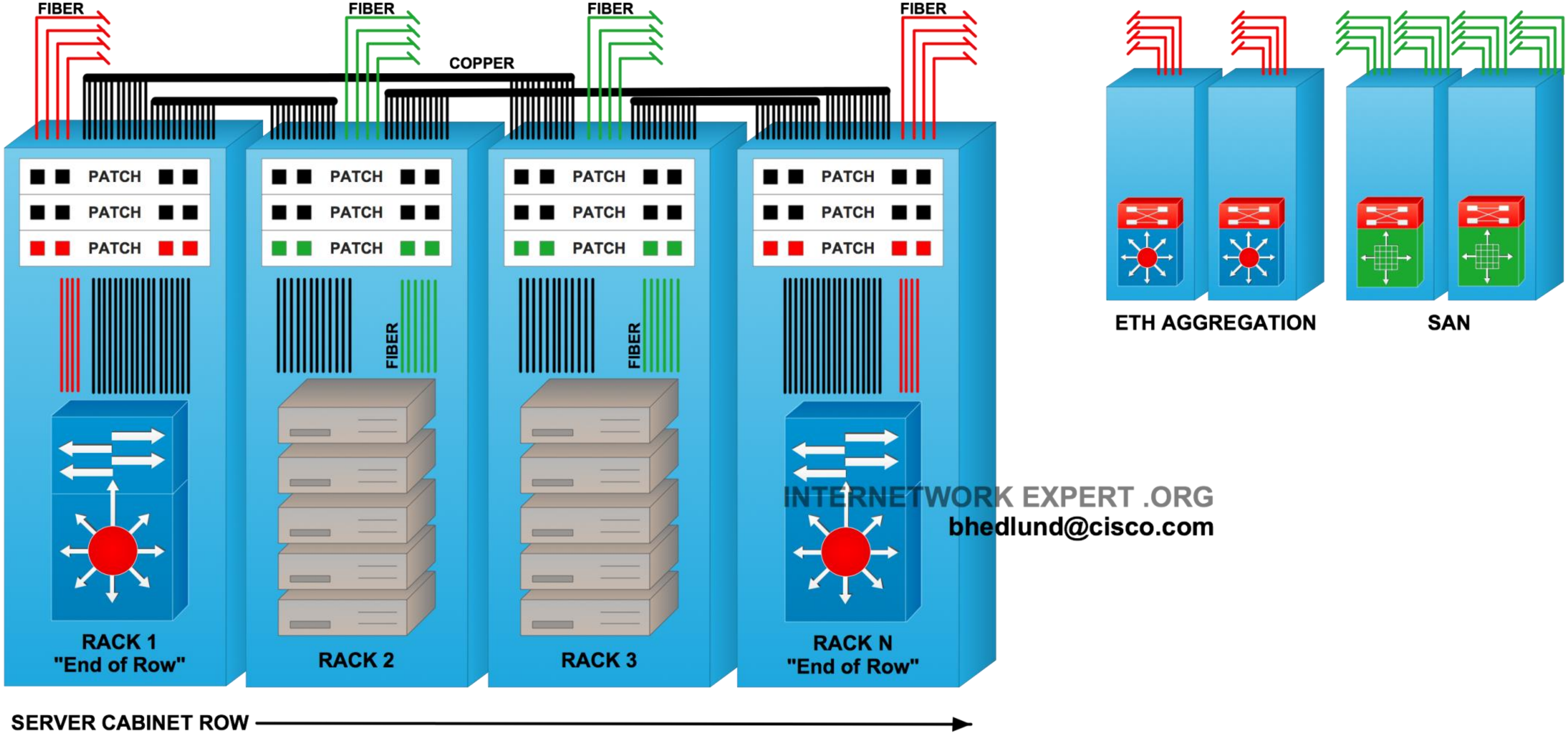
Access layer: End-of-Row or Middle-of-Row

- The *access layer,* alternatively to a ToR arrangement, may be organized by sharing two bigger switches between all the servers of a row of racks
- These two shared access switches are usually mounted in a rack of their own, physically located either at one end of a row of racks (*End-of-Row,* EoR) or at the center of a row of racks (*Middle-of-Row*, MoR)
- Advantages:
  - Network devices located in a separate rack → easier management and maintenance
  - Power and control subsystems are shared → greater energy efficiency
- Disadvantages:
  - Longer links
  - Access switches with a greater number of port → more expensive



End-of-Row design

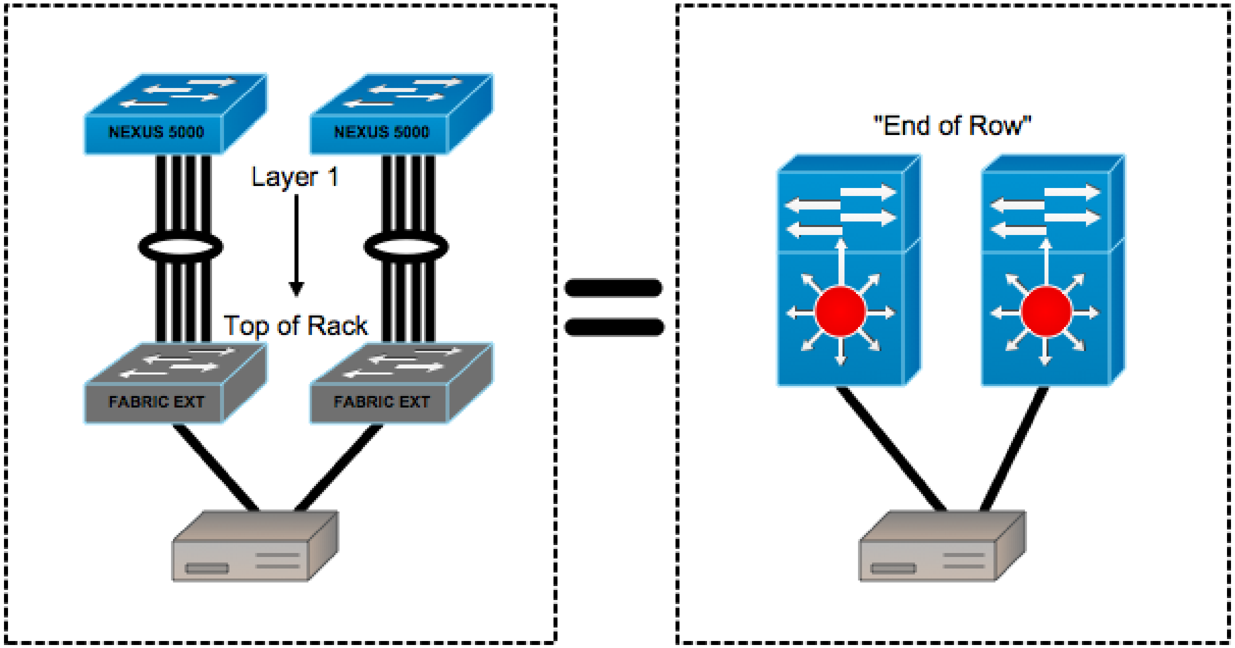
- When an End-of-Row design is used, structured cabling is preferred
- Both copper and fibers used for inter-rack cabling



Brad Hedlund. *Top of Rack vs End of Row Data Center Designs*. http://bradhedlund.com

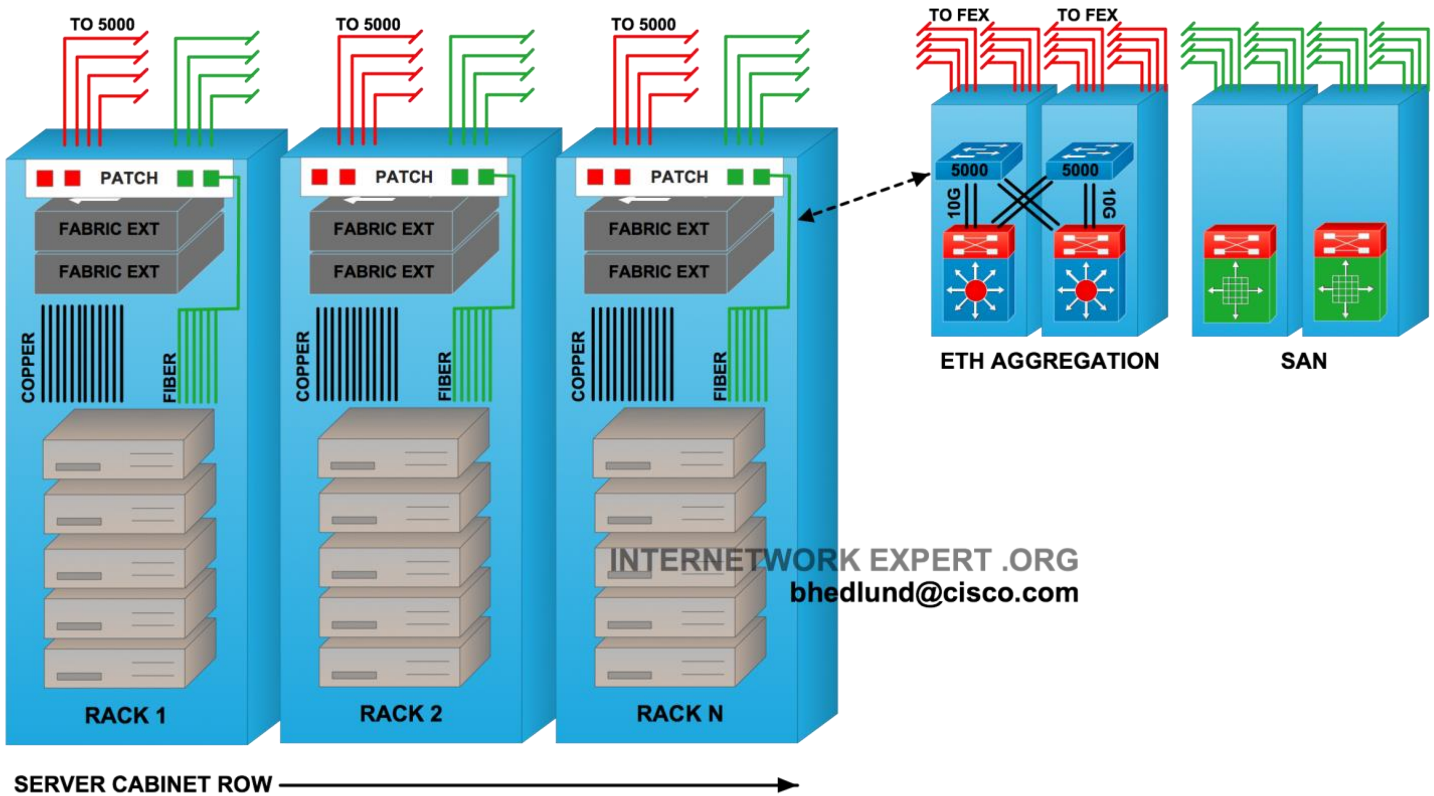
Access layer: mixed solutions with Fabric Extender (1)

- Some network device vendors recommend solutions in which the access layer is built by combining in-rack switches (*Fabric Extenders*) with End-of-Row switches



Access layer: mixed solutions with Fabric Extender (2)

- In such arrangement, in-rack switches are managed as “extensions” (*line-cards*) of the EoR switch
  - Configuration only needed in EoR switches → faster and easier to manage



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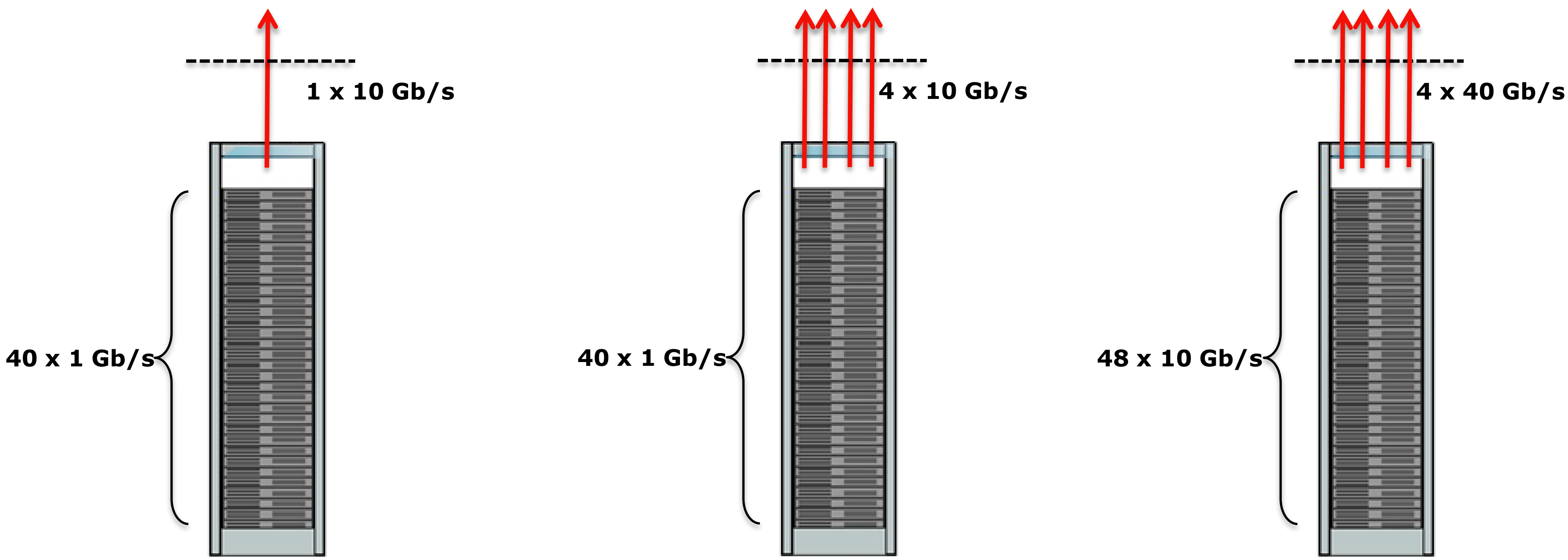
Access layer organization and cabling

- The way access layer is organized has an impact on rack and DC cabling
- In a Top-of-Rack arrangement, servers are usually directly connected to access switches, without intermediate patch panels (*unstructured cabling*)
- In End-of-Row and Middle-of-Row arrangement, *structured cabling* solutions are typically preferred, with patch panels decoupling servers from inter-rack connections to access layer switches

Access-aggregation uplink: oversubscription

- Access layer switches connected to the rest of DC (*aggregation layer*) through a number of uplink connections (typically based on optical fibers)
- The ratio between the aggregated capacity of server links and the capacity of uplink links is usually referred to as *oversubscription ratio*
- Some examples for a ToR-based access layer:

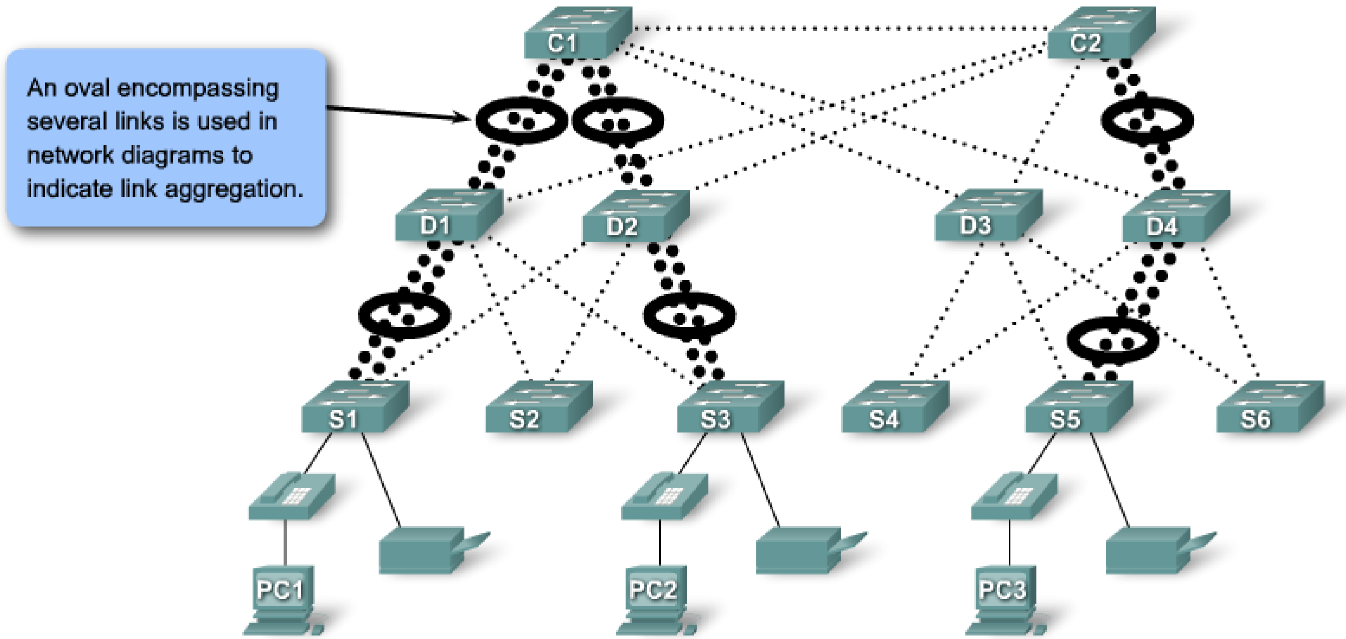


Oversubscription ratio = 40:10 = 4:1 | **Oversubscription ratio = 40:40 = 1:1** | **Oversubscription ratio = 480:160 = 3:1**

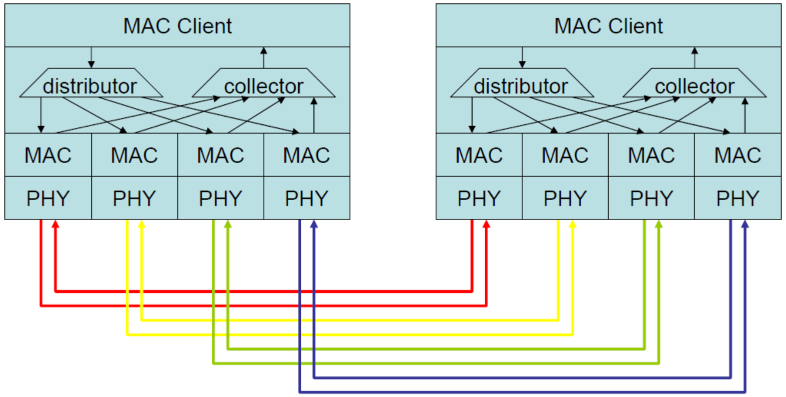
Bandwidth aggregation

- In order to reduce the oversubscription ratio, it is common to connect two switches with bunches of parallel links
- <u>Beware</u>: multiple parallel links form loops !
- Loop-avoidance techniques, such as STP, disable all links but one in a bundle
- To effectively use the aggregated bandwidth, special techniques are needed
  - E.g. Cisco's EtherChannel or the IEEE 802.3ad standard

Bandwidth aggregation is normally implemented by combining several parallel links between two switches into one logical link.



IEEE 802.3ad Link Aggregation



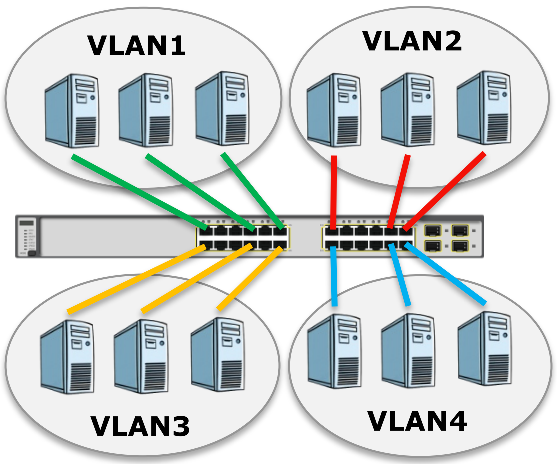
- LAG is performed above the MAC
- LAG assumes all links are:
  - full duplex
  - point to point
  - same data rate
- Traffic is distributed packet by packet
- All packets associated with a given “conversation” are transmitted on the same link to prevent mis-ordering
- Does not change packet format
- Does not add significant latency
- Does not increase the bandwidth for a single conversation
- Achieves high utilization only when carrying multiple simultaneous conversations

IEEE 802.1ax: Link Aggregation Control Protocol LACP

- LACP provides a method to control the bundling of several physical ports together to form a single logical channel
- LACP allows a network device to negotiate an automatic bundling of links by sending LACP packets to the peer (directly connected device that also implements LACP)
- Maximum number of bundled ports allowed in the port channel: 1 to 8
- LACP packets are sent with multicast group MAC address 01:80:c2:00:00:02
- During LACP detection period LACP packets are transmitted every second
- Keep alive mechanism for link member: (default: slow = 30s, fast=1s)
- Advantages deriving from LACP over static configuration
  - Failover occurs automatically
  - Dynamic configuration: the device can confirm that the configuration at the other end can handle link aggregation
- CISCO's switches support both LACP and the proprietary *Port Aggregation Protocol* (PAgP)

VLANs

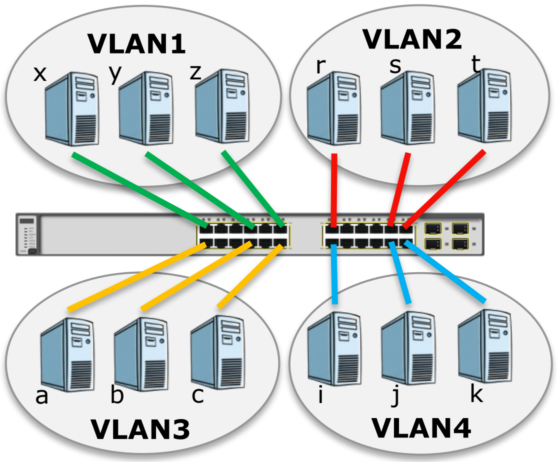
- VLANs create separate broadcast domains within the same switch
  - Needed if multiple IP subnets need to coexist in the same switch
  - A router is needed to route traffic between VLANs
- In a single switch network, VLANs are typically assigned to ports by the admin



- Each switch port could be assigned to a different VLAN
- Ports assigned to the same VLAN share broadcasts
- Ports that do not belong to the same VLAN do not share broadcasts
- The default VLAN for every port in the switch is the “native VLAN”
  - The native VLAN is always VLAN 1 and may not be deleted
- All other ports on the switch may be reassigned to alternate VLANs

VLAN bridging tables

- Implementing VLANs on a switch causes the following to occur
  - The switch maintains a separate *bridging table* for each VLAN
  - If a frame comes in on a port in VLAN x, the switch searches the bridging table for VLAN x
  - When a frame is received, the switch adds the source address to the bridging table if it is currently unknown
  - The destination is checked so a forwarding decision can be made
  - For learning and forwarding the search is made against the address table for that VLAN only



VLAN1 bridging table

MAC address	port
x	1
y	7
z	11

VLAN2 bridging table

MAC address	port
r	13
s	21
t	23

VLAN3 bridging table

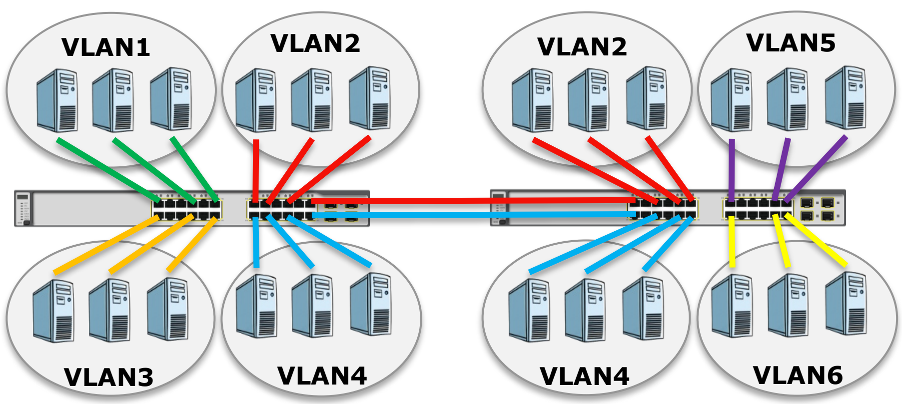
MAC address	port
a	2
b	8
c	12

VLAN4 bridging table

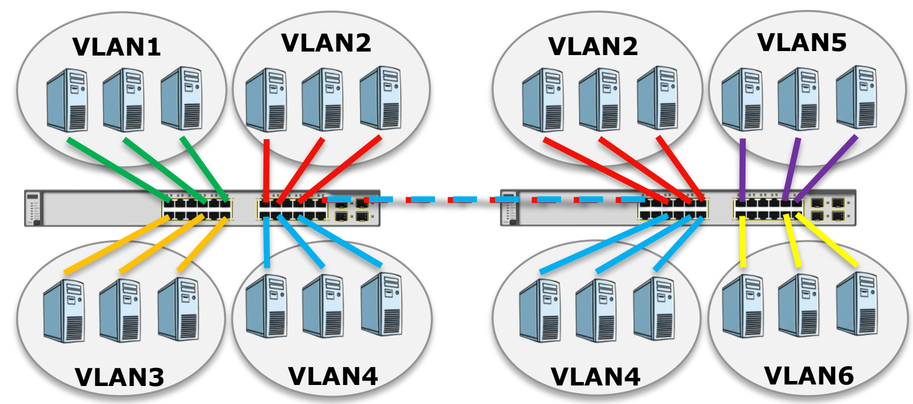
MAC address	port
i	14
j	22
k	24

VLANs spanning multiple switches

- Problem: how to extend multiple VLANs over two distinct switches ?
- Solution #1
  - one link connecting the two switches for each VLAN that needs to be extended
  - costly and inefficient
- Solution #2 – *port trunking*
  - a single link (*trunk*) connects the two switches and carries traffic for all the VLANs that live in both switches
  - To associate each frame to the corresponding VLAN, a special tag is required in the frame header (*VLAN tagging*)
- In general, a *trunk* is a link carrying traffic for several VLANs and a switch may have several trunking ports



Two pairs of ports dedicated to extend VLANs, one for VLAN2 and another for VLAN4



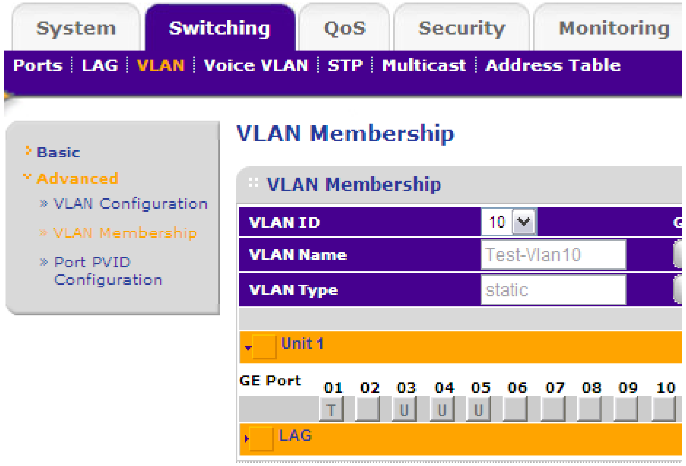
VLANs extended by means of port trunking

VLAN tagging

- VLAN Tagging is used when a link connecting two different switches needs to carry traffic for more than one VLAN
- A unique packet identifier is added within each header to designate the VLAN membership of each packet
- When a packet enters a trunk port with a given VLAN ID:
  - VLAN ID is removed from the packet
  - Packet is forwarded to the appropriate port based on the VLAN ID and destination MAC address
  - If the destination MAC address is FF:FF:FF:FF:FF:FF, the packet is forwarded to all the VLAN ports
- 2 major methods of VLAN tagging: Cisco proprietary Inter-Switch Link (ISL) and IEEE 802.1Q
- IEEE 802.1Q inserts VLAN ID (12 bits) in a new header field

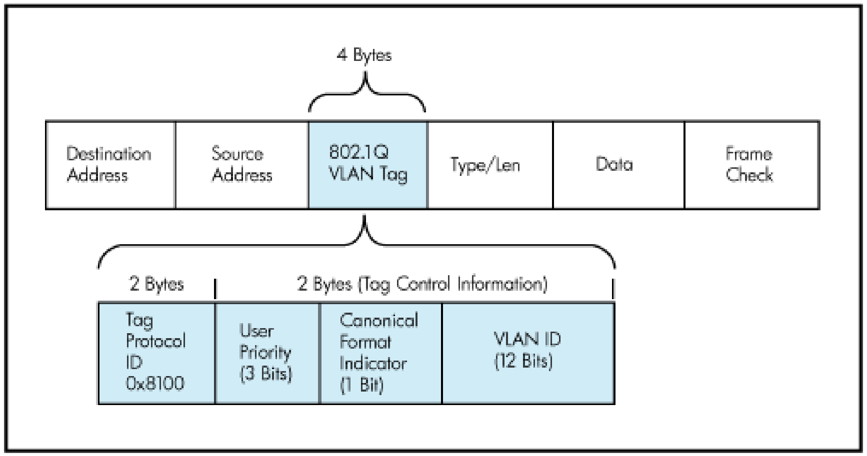
Port 01 is configured as a trunk port for VLAN 10 (T stands for Tagged)

Ports 03, 04 and 05 are statically associated to VLAN 10 without any tagging (U stands for Untagged)



IEEE 802.1Q header

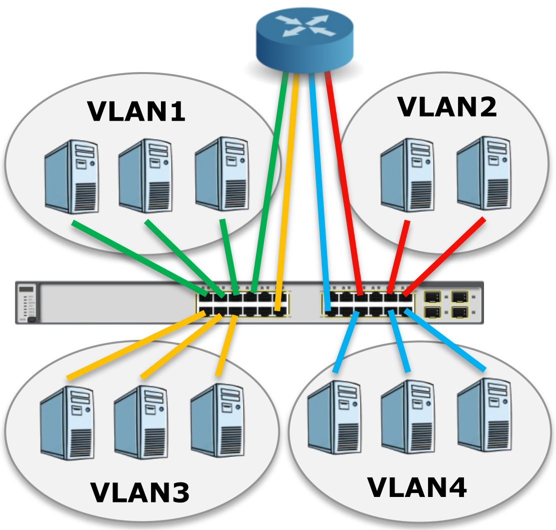
- IEEE 802.1Q adds a 4-byte header field:
- 2-byte tag protocol identifier (TPID) with a fixed value of 0x8100
- 2-byte tag control information (TCI) containing the following elements:
  - Three-bit user priority (8 priority levels, 0 thru 7)
  - One-bit canonical format (CFI indicator), 0 = canonical, 1 = noncanonical, to signal bit order in the encapsulated frame (see IETF RFC2469)
  - Twelve-bit VLAN identifier (VID) - Uniquely identifies the VLAN to which the frame belongs
    - defining 4,096 VLANs, with 0 and 4095 reserved values

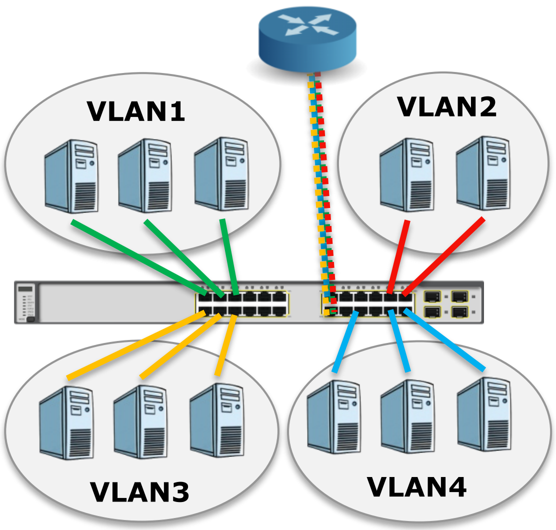


Inter-VLAN routing

- When a node in one VLAN needs to communicate with a node in another VLAN, a router is necessary to route the traffic between VLANs
  - Without the routing device, inter-VLAN traffic would not be possible
- The routing function may be external or internal to the switch
  - In the latter case, the switch itself acts as a router (so called *multilayer switches* or L3 switches)
- External router
  - Approach #1: the router is connected to the switch by one link per VLAN
  - Approach #2: the router is connected to the switch by one trunk link for all the VLANs
    - Also known as "router on a stick"
    - Possible only if the router supports sub-interfaces
      to divide a single physical interface into multiple logical interfaces

Router connected
by as many links
as the VLANs
to be connected



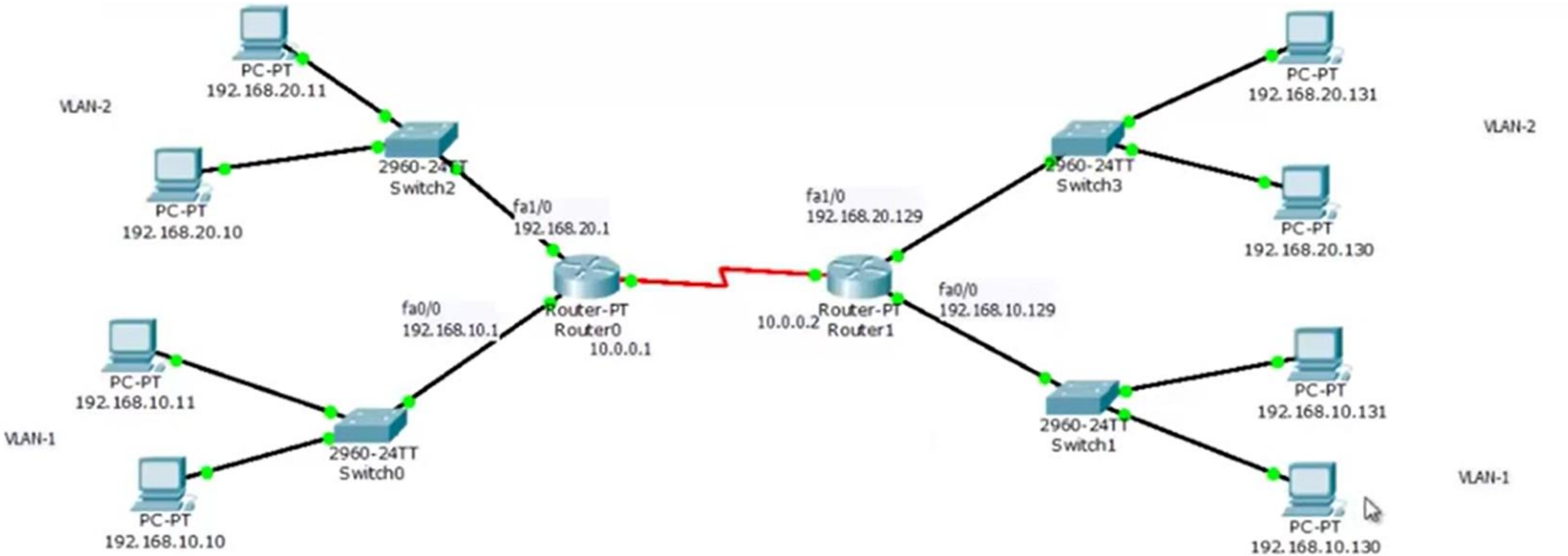


Router-on-a-stick

Router connected
by one trunk link
for all the VLANs

Inter-VLAN routing across different switches

- This scenario is an enteprise network, does not fit a datacenter
- Two VLANs, spread across two distinct switches connected by routers
- In fact, these are four VLANs, each associated to a /25 subnet
- Communication between host 192.168.20.10 (on the left) and 192.168.10.10 (on the left) is routed by Router0
- Communication between host 192.168.10.11 (on the left) and 192.168.10.130 (on the right) is routed by Router0 and Router1



Multilayer switches in a datacenter

- A multilayer switch is able to perform both kinds of packet forwarding: *bridging* at Layer 2 and *routing* at Layer 3
- Layer 3 routing in an aggregation switch can be used to route traffic among different VLANs without the need for an external router by means of so-called “Virtual Switch Interfaces” (SVIs)
  - An SVI should be configured with the VLAN’s default gateway IP address
- In a typical datacenter networks, aggregation layer switches are multilayer switches
- If one needs to exchange traffic among 2 servers (or 2 VMs) associated to 2 different VLANs, this machine-to-machine traffic would traverse the network hierarchy up to the aggregation switch even though the communicating hosts (or VMs) are physically located in the same rack