

Advanced Computer Networking (ACN)

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Protocol mechanisms

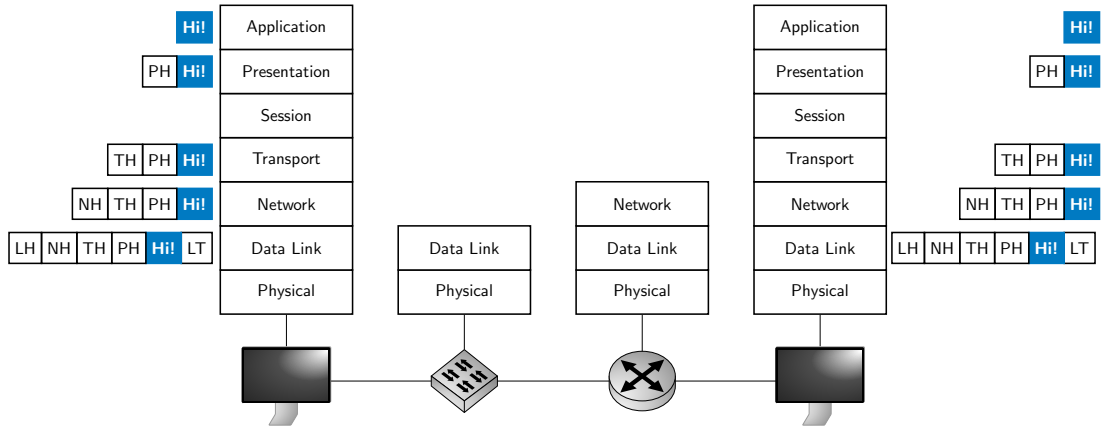
Contents

All or some of the following:

- Addressing/naming: manage identifiers
- Fragmentation: divide large message into smaller chunks to fit lower layer
- Re-sequencing: reorder out-of-sequence protocol data units (PDUs)
- Error control: detection and correction of errors and losses
 - retransmission; forward error correction
- Flow control: avoid flooding/overwhelming of receiver
- Congestion control: avoid flooding of slower network nodes/links
- Resource allocation: administer bandwidth, buffers, CPU among contenders
- Multiplexing: combine several higher-layer sessions into one “channel”
- Compression: reduce data rate by encoding
- Privacy, authentication: security policy (against listening/exploitation)

Protocol mechanisms

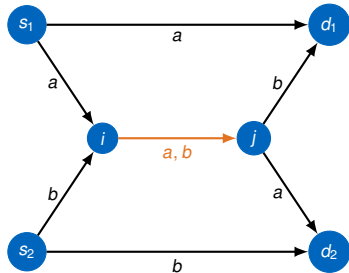
Protocol layering



Protocol mechanisms

Forwarding/routing vs. network coding

Nodes d_1 and d_2 should receive messages a, b

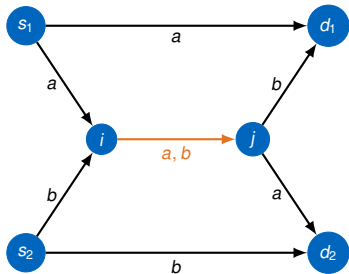


- Forwarding and routing
- Only one packet can be transmitted via a single link at the same time
- Bottleneck at link between i and j

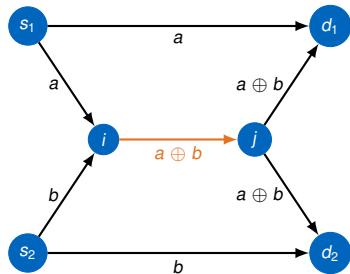
Protocol mechanisms

Forwarding/routing vs. network coding

Nodes d_1 and d_2 should receive messages a, b



- Forwarding and routing
- Only one packet can be transmitted via a single link at the same time
- Bottleneck at link between i and j



- Network coding
- Transmits a single, modified packet $a \oplus b$ between i and j (no bottleneck!)
- d_1 and d_2 can reconstruct original packets from the two received packets respectively

Protocol mechanisms

Forwarding/routing vs. network coding

Advanced protocol mechanisms

- **Network Coding**

- A different type of routing
- Nodes in a network combine packets possibly from different sources and generate groups of encoded packets
- Network coding allows to achieve the maximum possible information flow in a network
- Covered in specific lecture Network Coding (IN2315)
- Outgoing packets are arbitrary combinations of previously received packets
- Coding, i.e. combining packets, may happen on any node in the network (in contrast to FEC)

- **Traditional routing and forwarding**

- Routing determines best paths from source to destination
- Packets are forwarded by switches and routers along one of these paths
- Packet payloads remain unaltered

Protocol mechanisms

Protocol layering

Observation

- Certain protocol mechanisms of one layer also used in other layer
- Examples:
 - layer 4 mechanism (e.g., TCP ACKs & retransmissions) as also used in layer 2 (e.g., WLAN retransmissions)
 - routing in layer 3, but with certain technologies (ATM, MPLS) also below

Protocol mechanisms

Protocol layering

Observation

- Certain protocol mechanisms of one layer also used in other layer
- Examples:
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 - routing in layer 3, but with certain technologies (ATM, MPLS) also below

True definition of a layer n protocol (by Radia Perlman)

- Anything designed by a committee whose charter is to design a layer n protocol

Protocol mechanisms

Layering considered harmful?

Benefits of layering

- Need layers to manage complexity
 - don't want to reinvent Ethernet-specific protocol for each application
- Common functionality
 - "ideal" network

but:

- Layer N may duplicate lower layer functionality (e.g. error recovery)
- Different layers may need same information
- Layer N may need to peek into layer N+x

Link-Layer Protocols

Protocol mechanisms

Link Layer

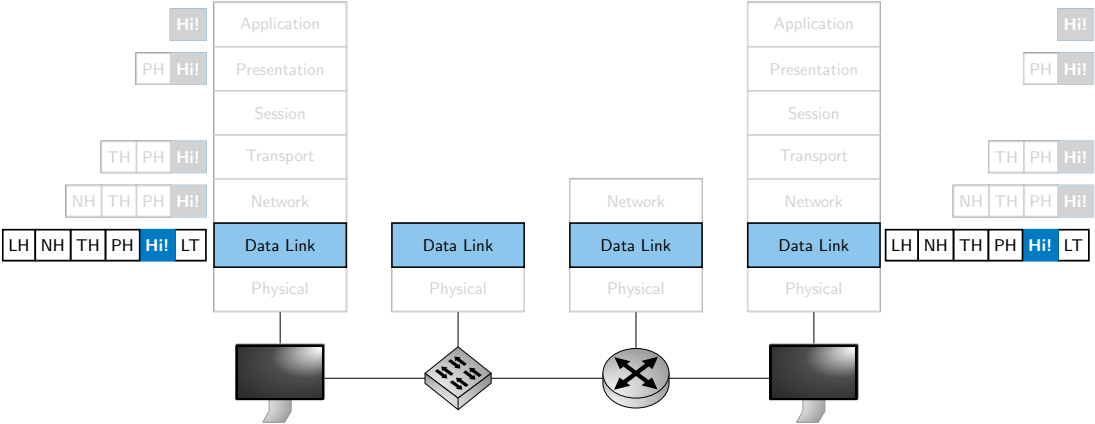
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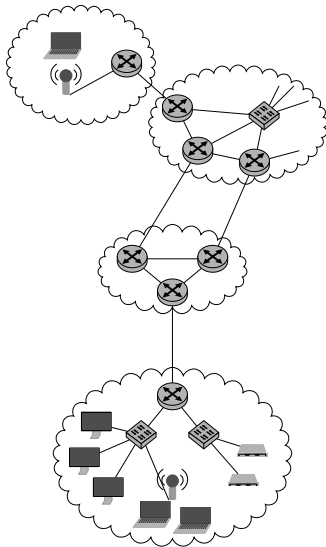


Link Layer

Link layer terminology

- Hosts and routers are nodes
- Communication channels that connect adjacent nodes along communication path are links
 - wired links
 - wireless links
 - LANs
- Layer-2 protocol data unit is called frame
- Layer-3 protocol data unit is called packet, or datagram.
"A datagram can be broken into smaller pieces called fragments, each of which is sent as a separate Internet datagram."- RFC 791 §2.3.

The **data link layer** has the responsibility of transferring a datagram from one node to an adjacent node over a link.



Framing, link access

- Encapsulate datagram into frame, adding header, trailer
- Channel access if shared medium
- “MAC” addresses used in frame headers to identify source and destination node
 - different from IP address!
 - Question: *Why are there different addresses at L2 and L3?*

Reliable delivery between adjacent nodes

- Rarely used on low bit-error rate links (fiber, some twisted pair)
- Wireless links: high error rates
 - ▶ L2 retransmission scheme, e.g., in wireless LAN (IEEE 802.11)
 - Question: *Why both link-level and end-to-end reliability?*

Link Layer Services Continued

Flow control

- Pacing between adjacent sending and receiving nodes

Error detection

- Errors caused by signal attenuation, noise
- Receiver detects presence of errors:
 - signals sender for retransmission or drops frame

Error correction

- Receiver identifies and corrects error(s)
 - Error correcting codes: correcting bit errors without retransmission
 - Terminology “error correction” may include retransmissions

Half-duplex and full-duplex

- With half duplex, nodes at both ends of link can transmit, but not at same time

Link Layer

Two types of "links"

Point-to-point

- point-to-point link between Ethernet switch and host
- PPP for dial-up access

Broadcast (shared wire or medium)

- old-fashioned Ethernet
- upstream HFC (Hybrid Fiber Coax)
- 802.11 wireless LAN

Link Layer

Multiple access protocols

Situation

- Single shared broadcast channel
- Two or more simultaneous transmissions by nodes: interference
 - **Collision** if node receives two or more signals at the same time

Definition of a **Multiple access protocol**:

- Distributed algorithm that determines how nodes share channel, i.e., determine when node can transmit
- Communication about channel sharing uses channel itself, i.e., no out-of-band channel for coordination

Link Layer

MAC Protocols: A Taxonomy (Three broad classes)

Channel Partitioning

- Divide channel into smaller “pieces” (time slots, frequency, code)
- Allocate piece to node for exclusive use

Random Access

- Channel not divided, allow collisions, “recover” from collisions
- Examples of random access MAC protocols:
 - ALOHA, slotted ALOHA
 - CSMA, CSMA/CD, CSMA/CA

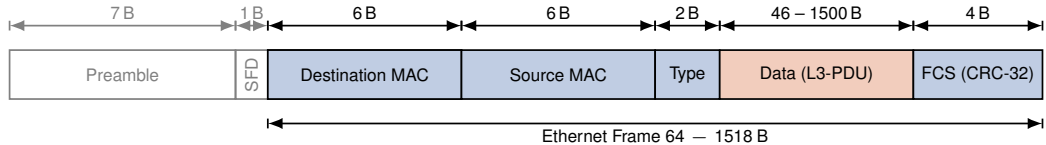
“Taking turns”

- Nodes take turns, nodes with more to send can take longer turns
- Polling from central site, token passing
- Bluetooth, FDDI, IBM Token Ring

Link Layer

Ethernet frame structure

Sending adapter encapsulates IP datagram (or other network layer protocol packet) in **Ethernet frames**

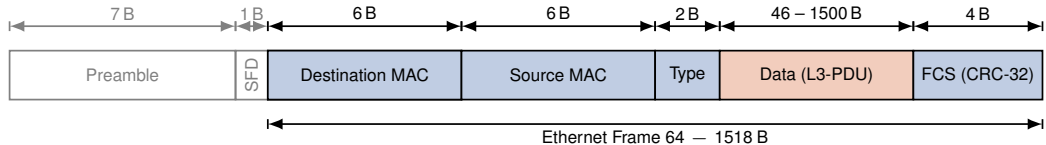


- Ethernet packet (physical layer):
 - IPG Inter packet gap, minimum idle period between two packets
 - Preamble Preamble (7 byte: 1010101010...)
 - SFD Start-of-frame delimiter (10101011)

Link Layer

Ethernet frame structure

Sending adapter encapsulates IP datagram (or other network layer protocol packet) in **Ethernet frames**



- Ethernet frame (data link layer):
 - Dst MAC Destination Address
 - Src MAC Source Address
 - Type/Length Ethernet II frame format:
 - Protocol type of payload (e.g. IP, ARP, ...)
 - Ethernet I and IEEE 802.3 frame format (rarely used today):*
 - Length of payload in byte
 - Data Data
 - PAD Padding (if data length is less than 46 byte)
 - FCS Frame Check Sequence: CRC-32

Link Layer

For comparison: IPv4 datagram [1]

Offset	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
0 B	Version				IHL				TOS								Total Length															
4 B	Identification												Flags				Fragment Offset															
8 B	TTL				Protocol				Header Checksum																							
12 B	Source Address																															
16 B	Destination Address																															
20 B	Options / Padding (optional)																															

Link Layer MAC addresses

32 bit IPv4 address

- Network layer address
- used to get datagram to destination IP subnet

MAC / LAN / physical / Ethernet address

- Function: **transmit frame from one interface to another physically-connected interface (same network)**
- 48 bit MAC address (for most LANs)
 - burned in network adapter ROM or configurable in software

Protocol mechanisms

Link Layer

Ethernet

MAC addresses

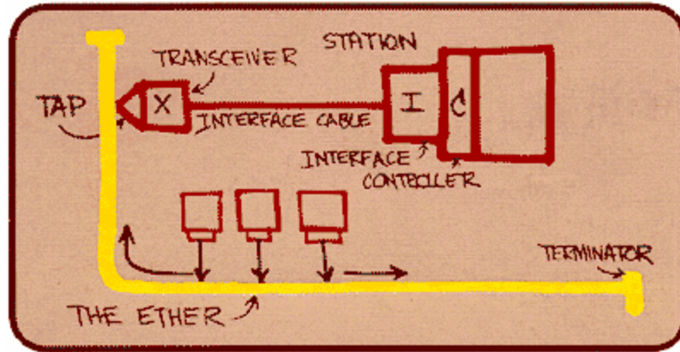
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Bibliography

Ethernet Overview

- Most common wired LAN technology
- Cheap network cards (NICs)
- First widely used LAN technology
- Simpler and cheaper than Token ring / ATM / MPLS
- Kept up with speed race: 10 Mbps - 800 Gbps (next: 1.6 Tbps Ethernet)

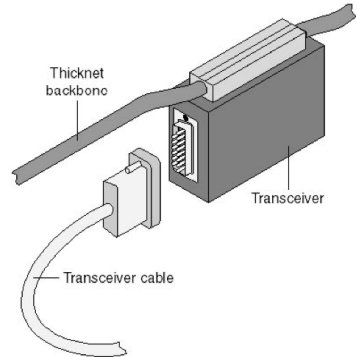
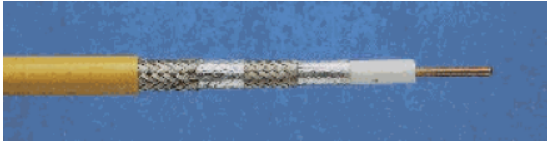


Metcalfe's Ethernet sketch (1976)

Ethernet

10BASE5 - Thick Ethernet (IEEE 802.3, standardized 1983)

- Single bus system of thick coax cable (yellow)
- 10BASE5: 10 Mbit/s
- Segments of 500 m, can be coupled with repeaters (max. 5 segments)
- Transceiver (transmitter & receiver) MAU (medium attachment unit) with carrier sensing function
- Transceiver cable max. 50 m



Ethernet

10BASE2 - Thin Ethernet (IEEE 802.3a, standardized 1985)

- Single bus system of thinner coax cables (cheaper and more flexible)
- 10BASE2: 10 Mbit/s
- Segments of max. 185 m (max. 5 segments)
- Transceiver can be part of Ethernet adapter



Figure 1: T-piece



Figure 2: BNC terminator

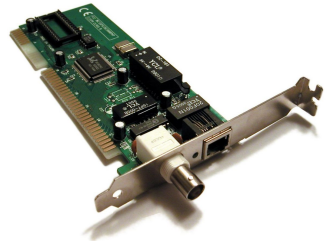


Figure 3: NIC with BNC connector

Ethernet

Bus vs. Star

Logical bus topology (10BASE5, 10BASE2):

- All nodes are part of a common collision domain
- Defect bus wire splits network in two parts

Star topology (newer standards):

- Active switch in center
- Each “spoke” runs a (separate) Ethernet protocol, therefore a defect wire disconnects only one host

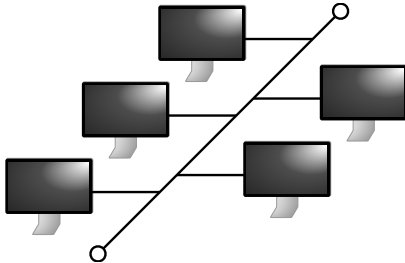


Figure 4: Bus topology

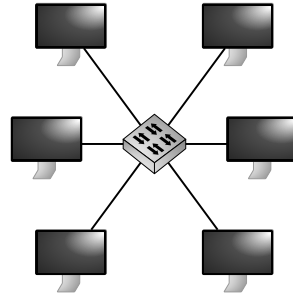


Figure 5: Star topology

Ethernet

10BASE-T - Twisted Pair (IEEE 802.3i, standardized 1990)

- Uses star topology (hubs or switches) to connect devices
- CAT-3 or CAT-5 cables (uses two pairs of twisted wires)
- Reuses standardized connectors and wiring of telephone networks
- 10BASE-T: 10 Mbit/s
- Segments of max. 100 m (max. 5 segments)

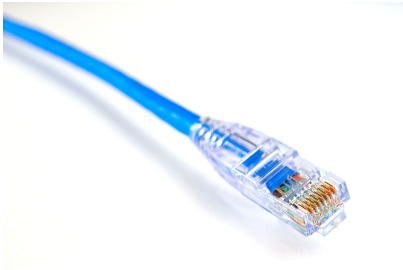


Figure 6: 8P8C connector (also known as RJ45)

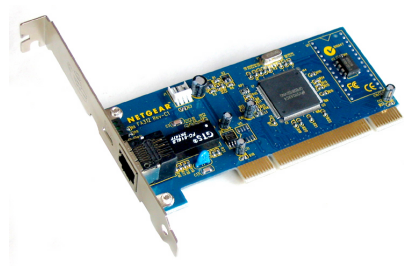


Figure 7: NIC with RJ45 connector

Ethernet

RJ45-based Ethernet Standards

100BASE-TX - Fast Ethernet (IEEE 802.3u, standardized 1995)

- CAT-5 cables or better (uses two pairs of twisted wires)
- 100BASE-TX: 100 Mbit/s

1000BASE-T - Gigabit Ethernet (IEEE 802.3ab, standardized 1999)

- CAT-5 cables or better (uses four pairs of twisted wires)

10GBASE-T - 10 Gigabit Ethernet (IEEE 802.3an, standardized 2006)

- standardized in 2006
- CAT-6a cables or better

2.5GBASE-T / 5GBASE-T (IEEE 802.3bz, standardized 2016)

- works fine on most CAT-5 installations

Ethernet

RJ45-based Ethernet

Advantages

- robustness
- cheap, existing wiring

Disadvantages

- short cable lengths
- high energy consumption (for 10G)

NIC	Offload	Media	Idle Power (W)		
			3.3v	12v	Total
Intel(Base-T)	No	Base-T	6.0	15.2	21.2
Solarflare(Base-T)	No	Base-T	1.0	17.0	18.0
Broadcom(Fibre)	Yes	Fibre	5.9	7.2	13.1
Solarflare(Fibre)	No	Fibre	2.6	3.1	5.7

(a) 10G Ethernet [2]

NIC	Media	Throughput (Gbps)		Active Power (W)
		Theoretical	Actual	
Intel 1G	Base-T	2	1.7	1.9
Broadcom Multiport(2x1G)	Base-T	4	3.3	7.0
Intel Multiport(2x1G)	Base-T	4	3.3	3.6
Intel Multiport(4x1G)	Base-T	8	5.7	12.5

(b) 1G Ethernet [2]

[2] R. Sohan et al., "Characterizing 10 gbps network interface energy consumption," in *IEEE Local Computer Network Conference*, IEEE, 2010, pp. 268–271

Ethernet

Other Ethernet standards

Many different Ethernet standards

- Sharing a common MAC protocol and frame format
- Different bandwidths: 10M, 100M, 1G, 2.5G, 5G, 10G, 25G, 40G, 100G, 200G/400G (standardized in 2018), 800G (standardized in 2024)
- Different physical layer media, such as:
 - twisted pair (xBASE-T)
 - twinaxial cabling (twinax)
 - unshielded twisted-pair (xBASE-T1)
 - multimode optical fiber (short range)
 - singlemode optical fiber (long range)
 - backplane
 - chip-to-chip interfaces on NIC

Ethernet

Supporting different physical media

Pluggable transceiver module

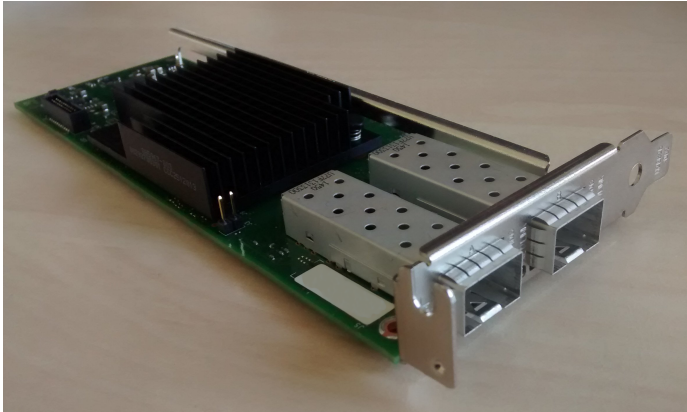


Figure 9: NIC with two slots for pluggable transceivers

Ethernet

Modern transceiver modules

- SFP (small form-factor pluggable) modules
- Most common standard for switchable transceivers
- Different generations (SFP for 1 GbE, SFP+ for 10 GbE, ...)
- SFP modules are very common for professional equipment

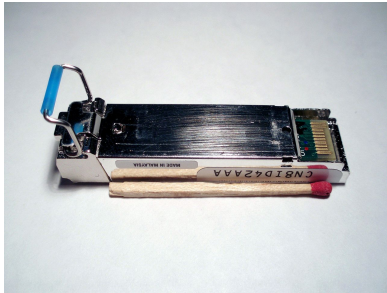


Figure 10: SFP module



Figure 11: Direct-Attach Copper (DAC) twinaxial cable with integrated SFP modules (cheap, used for low range connections ≤ 15 m)

Ethernet

Limitations of layer 2

Could Ethernet scale up to a very large (global) network?

Ethernet

Limitations of layer 2

Could Ethernet scale up to a very large (global) network?

Scalability problems:

- Flat addresses
- No hop count (so loops may lead to disaster)
- Missing additional protocols (such as ICMP)
- Perhaps missing features:
 - Fragmentation
 - Error messages
 - Congestion feedback

Protocol mechanisms

Link Layer

Ethernet

MAC addresses

Layer 2 switching

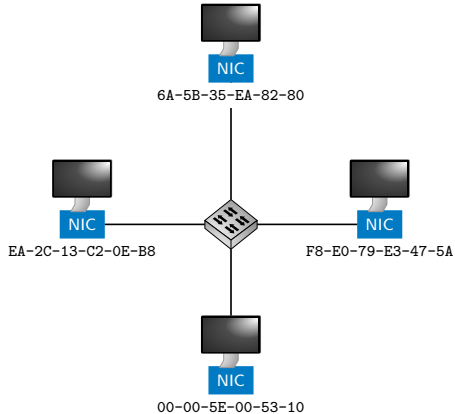
Spanning tree

Bibliography

MAC addresses

Example Network

Each adapter on a LAN has a unique MAC address



MAC addresses

MAC address layout

- Human-friendly notation for MAC addresses
 - six groups of two hex digits, separated by “-” or “:”, in transmission order, e.g., 0C-C4-11-6F-E3-98
- Multicast and broadcast
 - Broadcast address: FF-FF-FF-FF-FF-FF
 - Multicast address: least-significant bit of first byte has value “1”
- Organizationally Unique Identifier (OUI): company ID
 - manufacturer purchases portion of MAC address space from IEEE Registration Authority (assuring uniqueness)
 - OUI: First 3 bytes of address in transmission order
 - OUI enforced: 2nd least significant bit of first byte has value “0”,
 - otherwise: locally administered MAC address
- Locally administered MAC addresses:
 - Similar to private address blocks on layer 3
 - E.g. used for VMs
- MAC address: flat address portability (+ implication on privacy)
 - can move LAN card from one LAN to another
- IP address: hierarchical address NOT portable
 - address depends on IP subnet to which node is attached

MAC addresses

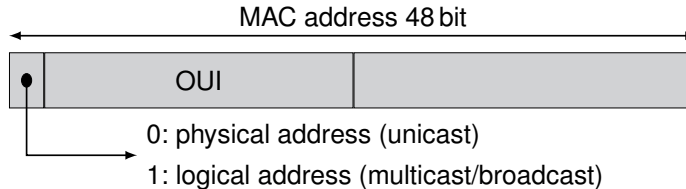
Bit-reversed representation of MAC address

- Corresponds to convention of transmitting least-significant-bit of each byte first in serial data communications (transmission of LAN addresses over the wire)
- Also known as “canonical form”, “LSB format” or “Ethernet format” (LSB: Least Significant Bit):
 - First bit of each byte on the wire maps to least significant (i.e., right-most) bit of each byte in memory (cf. RFC 2469)
- Token Ring (IEEE 802.5) and FDDI (IEEE 802.6) do **not** use canonical form, but instead: most-significant bit first

MAC addresses

MAC addressing modes

- General address types (L2 and L3): Unicast, Multicast, Broadcast, Anycast
- Terminology to distinguish destination MAC addresses
 - Physical addresses: identify specific MAC adapters
 - Logical addresses: identify logical group of MAC destinations



- LAN broadcast address: FF-FF-FF-FF-FF-FF
- Transmission of multicast frames
 - sender transmits frame with multicast destination address
- Reception of multicast frames
 - NICs can be configured to capture frames whose destination address is:
 - their unicast address, **or**
 - one of a set of multicast addresses

MAC addresses

Addresses and naming

Addresses are defined across three layers

1./2. Physical / link level

- Medium Access Control (MAC)

3. Network/IP level

- IP addresses
↔ mapping to domain names

4. Transport/application level

- Ports
↔ mapping to services
 - Standardized, well-known ports
 - Dynamic mapping

Protocol mechanisms

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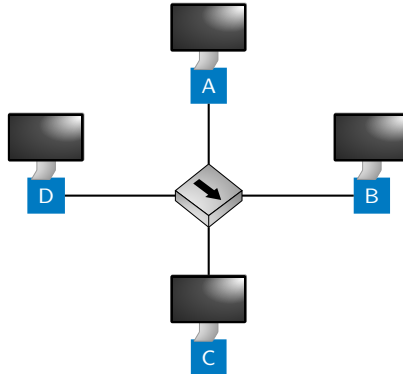
Bibliography

Layer 2 switching

Hub

Physical-layer ("dumb") repeaters:

- Bits arriving on one link go out on all other links at same rate
- Frames from all nodes connected to hub can collide with each other
- No frame buffering
- No collision detection at hub: host NICs detect collisions



Layer 2 switching

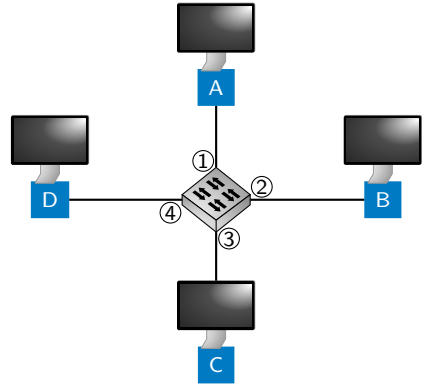
Switch

- Link-layer devices: smarter than hubs, take active role
 - Store & forward of Ethernet frames or cut-through-switching
 - Examine incoming frame's MAC address, **selectively** forward frames to one or more outgoing links
- Transparent
 - Hosts are unaware of presence of switches
- Plug-and-play, self-learning
 - Switches do not need to be configured

Layer 2 switching

Switch: simultaneous transmission

- Hosts have dedicated, direct connection to switch
- Switches buffer packets
- Ethernet protocol used on each incoming link, but no collisions; full duplex
 - each link is its own collision domain
- **Switching:** A-to-C and B-to-D simultaneously, without collisions
 - not possible with dumb hub

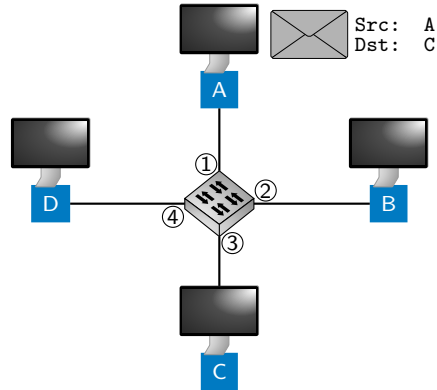


Layer 2 switching

Switch: self-learning

Switches learn which hosts can be reached through which interfaces

- When a frame is received, a switch “learns” location of sender: incoming LAN segment
- Records sender/location pair in switch table
- Expiry time: soft state mechanism



MAC address	interface	time
A	1	60

Table 1: Switch table (after learning location of A)

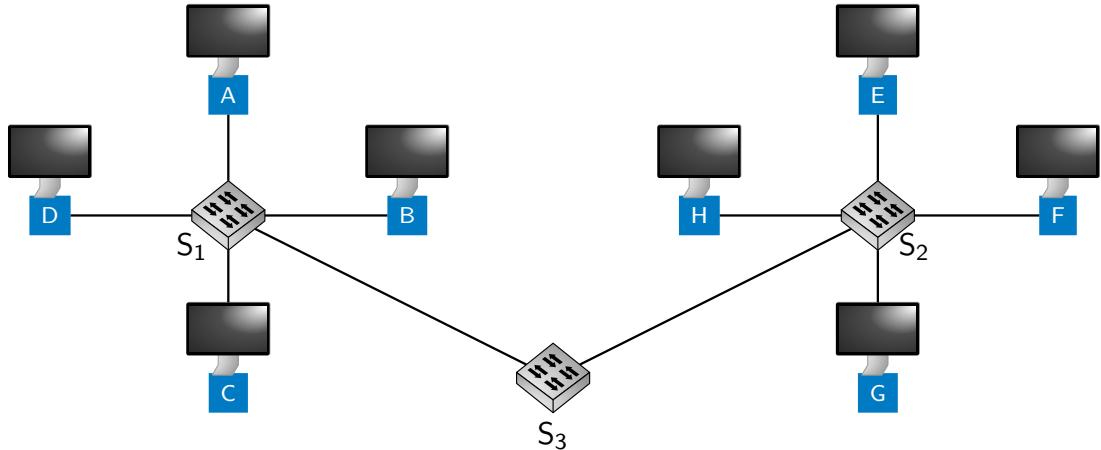
Layer 2 switching

Switch: frame filtering/forwarding

1. record link associated with sending host
 2. index switch table using MAC destination address
 3. if entry found for destination:
 - if destination on segment from which frame arrived:
 - drop the frame
 - else:
 - forward the frame on interface indicated
- else:
flood (*forward on all interfaces except the interface on which frame arrived*)

Layer 2 switching

Interconnecting switches



Q: Sending from A to G - how does S_1 know to forward frame destined to G via S_3 and S_2 ?

A: Self-learning! (works exactly the same as in single-switch case!)

Protocol mechanisms

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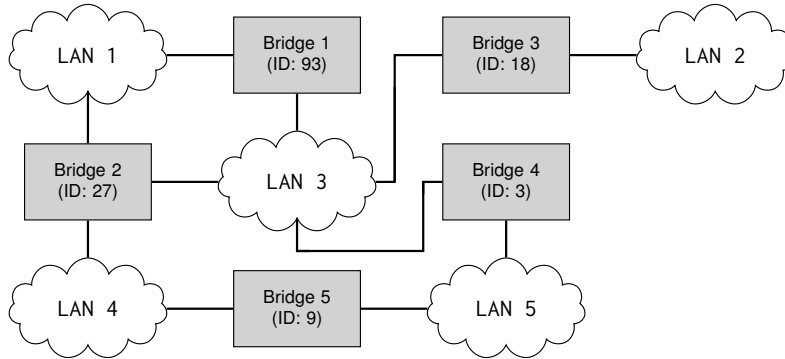
Layer 2 switching

Spanning tree

Bibliography

Spanning tree

Preventing loops



Spanning tree protocol

- Bridges gossip among themselves
- Compute loop-free subset
- Forward data on the spanning tree
- Other links are backups

Spanning tree

Spanning Tree Protocol

- Spanning Tree Protocol (STP): standardized as IEEE 802.1D
- Algorithm by Radia Perlman
- Algorithm:
 - Uses bridge_ID (concatenation of 16 bit bridge_priority and MAC_addr)
 - Step 1: select root bridge, i.e. bridge with lowest bridge_ID
 - Step 2: determine least cost paths to root bridge
 - each bridge determines cost of each possible path to root
 - each bridge picks least-cost path
 - port connecting to that path becomes root port (RP)
 - bridges on network segment determine bridge port with least-cost-path to root, i.e. the designated port (DP)
 - Step 3: disable all other root paths
- Bridge Protocol Data Units (BPDUs) are sent regularly (default: 2 s) to STP multicast address

Spanning tree

Spanning Tree Protocol

Bridge Protocol Data Units (BPDUs)

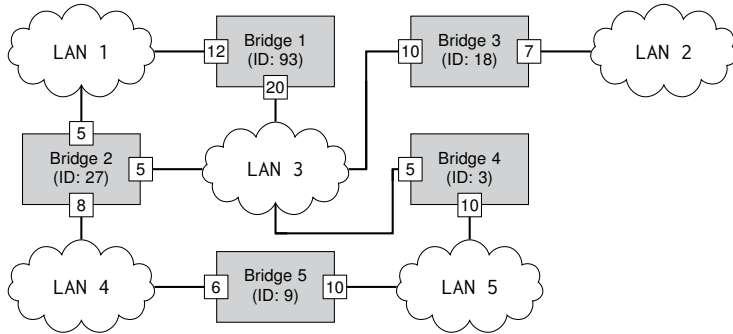
- Configuration BPDUs transmit bridge_IDs and root path costs
- Topology Change Notification (TCN) BPDU announce changes in network topology
- Topology Change Notification Acknowledgment (TCA)

STP switch port states

- Blocking
- Listening
- Learning
- Forwarding
- Disabled

Spanning tree

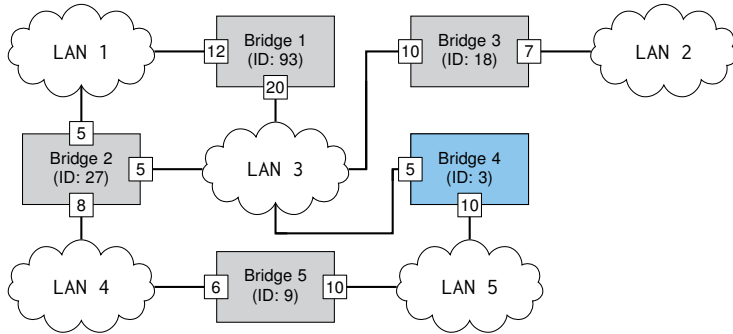
Spanning Tree Protocol



- Select root bridge

Spanning tree

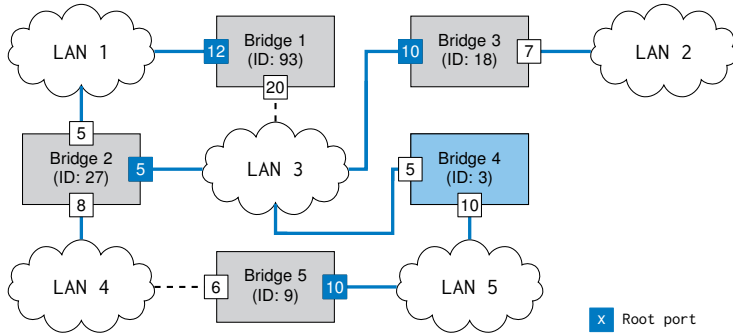
Spanning Tree Protocol



- Find shortest paths to root bridge

Spanning tree

Spanning Tree Protocol

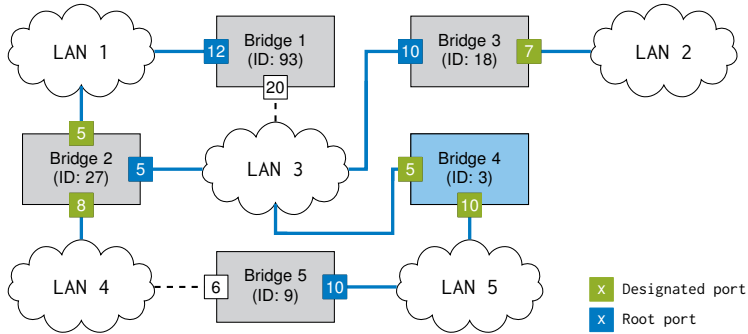


X Root port

Bridge	Costs of paths to root bridge
B3	10 (via LAN 3)
B1	17 = 12 + 5 (via LAN 1 & LAN 3)
	20 (via LAN 3)
	30 = 12 + 8 + 10 (via LAN 1 & LAN 4 & LAN 5)
B2	5 (via LAN 3)
	18 = 8 + 10 (via LAN 4 & LAN 5)
	25 = 5 + 20 (via LAN 1 & LAN 3)
B5	10 (via LAN 5)
	11 = 6 + 5 (via LAN 4 & LAN 3)
	31 = 6 + 5 + 20 (via LAN 4 & LAN 1 & LAN 3)

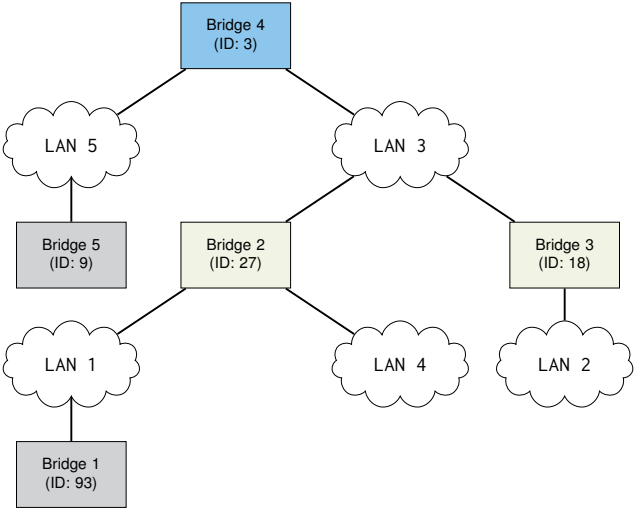
Spanning tree

Spanning Tree Protocol



- Designated port: provides connectivity for LAN
 - e.g., Bridge 2 becomes designated bridge for LAN 1 and LAN 4

Spanning tree
Resulting spanning tree



Spanning tree

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Protocol mechanisms

Link Layer

Ethernet

MAC addresses

Layer 2 switching

Spanning tree

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