OS & Network Summary

Table of Content

Chapter 1

Parts of a Network

Component	Function	Example
Application, or app, user	Uses the network	Skype, iTunes, Amazon
Host , or end-system, edge device, node, source, sink	Supports apps	Laptop, mobile, desktop
Router, or switch, node, hub, intermediate system	Relays messages between links	Access point, cable / DSL moden
Link, or channel	Connects nodes	Wires, wireless

Key interfaces

- Network-application interfaces define how apps use the network (Sockets widely used)
- Network-network interfaces define how nodes work together (ex : Traceroute)

Network service API hides details (Apps don't know what is inside the network)

Protocols and layers

To divide up network functionality

- Each instance of a protocol talks virtually to its peer using the protocol
- Each instance of a protocol uses only the services of the lower layer

Protocol stack example :
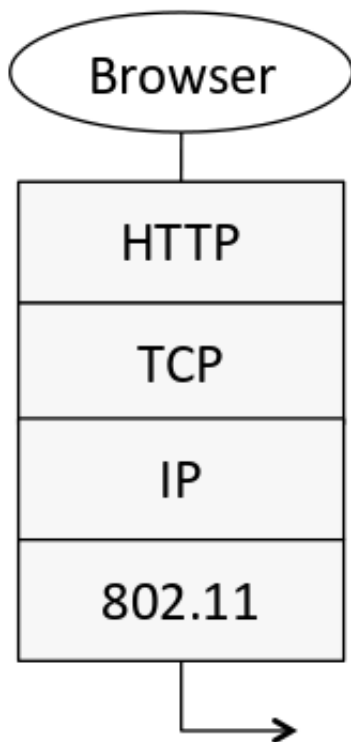
Encapsulation : Lower layer wraps higher layer content and add its own information

Advantage of layering : Information hiding and reusability

Disadvantages of layering : Overhead and hides information

OSI "7 layer" Reference Model

	Layer	Description
7	Application	Provides functions needed by users
6	Presentation	Converts different data representations
5	Session	Manages task dialogs
4	Transport	Provides end-to-end delivery
3	Network	Sends packets over multiple links
2	Data link	Sends frames of information
1	Physical	Sends bits as signals

Four layer model

Based on experience

	Layer	Description

7	Application	Programs that use network service
4	Transport	Provides end-to-end data delivery
3	Internet	Send packets over multiple networks
2 (/1)	Link (/Physical)	Send frames over a link (/Sends bits using signals)

Internet Reference Model
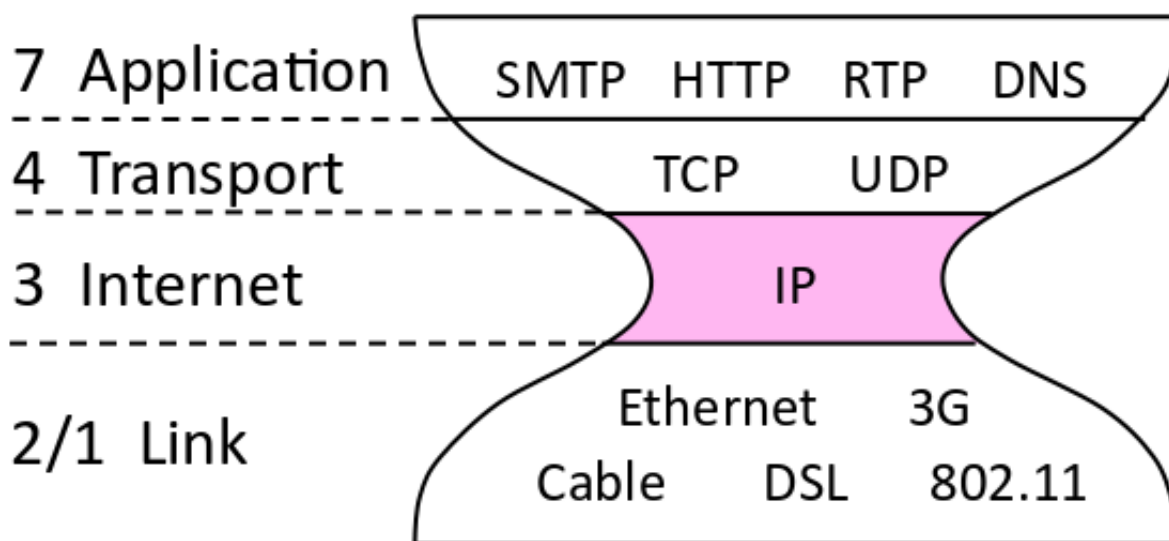
Layer-based names

Layer	Unit of Data
Application	Message
Transport	Segment
Network	Packet
Link	Frame
physical	Bit

Devices in the network :

- Repeater (Hub) : Physical/Physical
- Switch (bridge) : Link/Link
- Router : Network+Link / Network+Link
- Proxy (middlebox, gateway) : App+Transport+Network+Link

Chapter 2 : Physical Layer

Socket API

Primitive	Meaning
SOCKET	Create a new communication endpoint
BIND	Associate a local address with a socket
LISTEN	Announce willingness to accept connections; give queue size
ACCEPT	Passively wait for an incoming connection
CONNECT	Actively attempt to establish a connection
SEND	Send some data over the connection
RECEIVE	Receive some data from the connection
CLOSE	Release the connection

Simple link model

Properties : Rate, Delay/Latency, wether the channel is broadcast, its error rate

Rate

Or bandwith, capacity, speed
in bits/second

Delay / latency

- Transmission delay T: Time to put M-bit message on the wire

$$T = \frac{M[bits]}{Rate\left[\frac{bits}{s}\right]} = \frac{M}{R}\,[s]$$

- Propagation delay D : time for bits to propagate across the wire

$$D = \frac{Length}{Speed\,of\,signals} = \frac{L}{\frac{2}{3}\,C}$$

- Latency L : delay to send a message over a link

$$L = T + D = \frac{M}{R} + \frac{L}{\frac{2}{3}\,C}$$

Bandwidth-delay product

The amount of data "in flight"

$$BD = R \cdot D$$

Types of Media

Media propagate signals that carry bits information.
Common types :

- Wires
- Fiber
- Wireless

Wireless

- Travel at speed of light
- Spread out and attenuate faster than $\frac{1}{d^2}$
- Interference between signals on the same frequency (=> spatial reuse of same freq)
- Multipath : signal interferes with itself after reflexion

Modulation

How the signals represent bits

- NRZ : A high voltage +V represents a 1 and a low voltage -V represents a 0

Clock recovery

Receiver needs frequent signal transitions to decode bits (synchronisation)

4b/5b

- Map every data bits into 5 code bits without long runs of zeros

4b	5b
0000	11110
0001	01001
1110	11100
...	...

| 1111 | 11101 |

- Invert signal level on every 1 (NRZI)

Example :
message : 1111 0000 0001

$$1 \quad 1 \quad 1 \quad 0 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 1$$
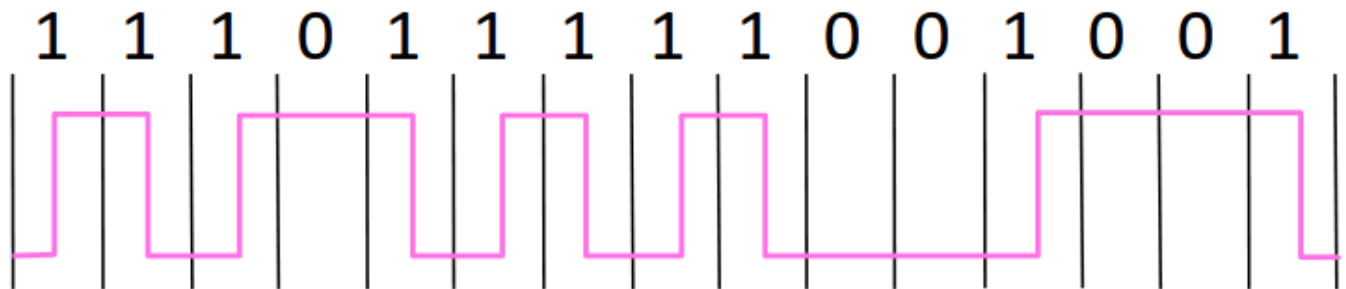
Baseband vs Passband modulation

Baseband : Signal is sent directly on a wire (wires)

Passband : Modulation carries a signal by modulating a carrier (fiber / wireless)

Passband

Carrier is a signal oscillating at desired frequency. We modulate it by changing amplitude, frequency or phase
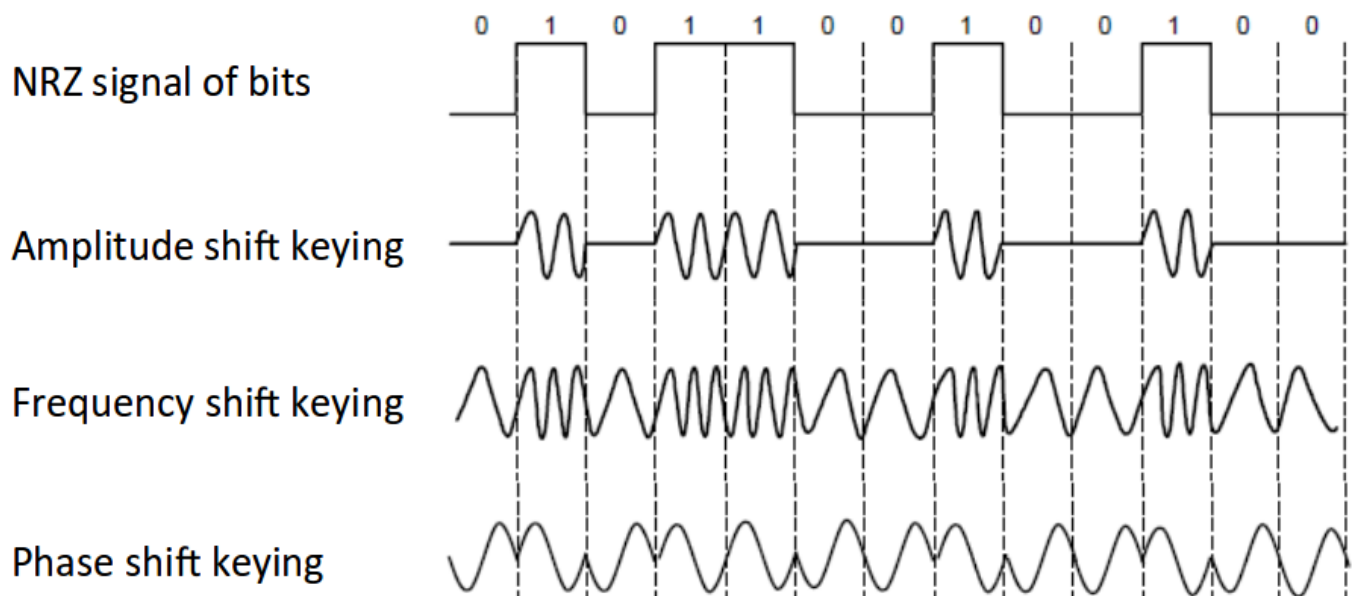
Fundamental limits

Key channel properties

- Bandwidth B
- Signal strength S

- Noise strength N

Nyquist limit/frequency

If we have a channel with a bandwidth B, the maximum symbol rate is $2B$.
If we have V signal levels ($log_2 V$ different bits), the maximum bit rate is

$$R = 2B \cdot log_2 V \left[\frac{bits}{s} \right]$$

Shannon capacity

The number of levels we can distinguish on a channel depends on the SNR (~ S/N)

The Shannon capacity C is the maximum information carrying rate of the channel

$$C = B \cdot log_2 \left(1 + \frac{S}{N} \right) \left[\frac{bits}{s} \right]$$

Wires / Fiber :
Engineer SNR for data rate

Wireless :
Adapt data rate to SNR (can't design for worst case)

Chapter 3 : Link Layer

Concerns how to transfer messages (frames, of limited size) over one or more connected links

Framing

Transform stream of bits from physical layer to sequence of frames

Byte count

- Start each frame with a length field
- Difficult tu resynchronize after framing error

Byte stuffing

- Use a flag byte value for start/end of frame
- Escape the flag (and the escape code) inside the message replacing (stuffing) it with an escape code

Bit stuffing

- Flag with six consecutive 1
- In the message, insert a 0 after five 1 when sending and remove every 0 after five 1 when receiving
- Slightly less overhead than byte stuffing but more complicated -> byte stuffing used in practice

Error coding

Using error codes

Codeword consists of data bits D plus check bits R
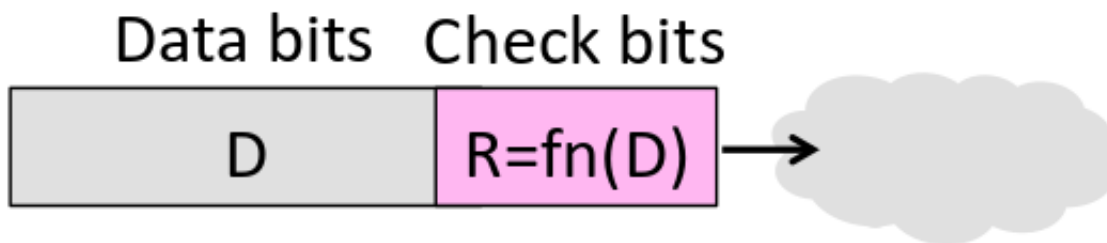
Hamming distance

- The distance is the number of bit flips needed to change $D + R_1$ to $D + R_2$
- The Hamming distance of a code is the minimum distance between a pair of codewords
- For a code of Hamming distance d+1, up to d errors will always be detected
- For a code of Hamming distance 2d + 1, up to d errors can always be corrected by mapping to the closest codeword

Error Detection

- Parity bit : The parity bit is the sum of the bits of D (distance : 2 -> detect 1 error); Little used
- Checksum : Sum up data in N-bit word (Stronger than parity)
- Internet Checksum
- CRC

In practice :

- CRCs used on links (Ethernet, 802.11, ADSL, Cable)
- Checksum used in Internet (IP, TCP, UDP)

Internet Checksum

Sending :

1. Arrange data in 16-bit words
2. Add

3. Add any carryover back to get 16 bits
4. Negate (complement) to get the checksum

Receiving :

1. Arrange data in 16-bit words (including checksum)
2. Add
3. Add any carryover back to get 16 bits
4. Negate the result and check if 0

Example :

```
1.       0001
         f203
         f4f5
2.     + f6f7
       ------
         2ddf0
```

```
         ddf0
3.     +    2
       ------
         ddf2

4. -> 220d
```

Transmit to physical layer : 0001 f203 f4f5 f6f7 220d

```
1.       0001
         f203
         f4f5
         f6f7
2.     + 220d
       ------
         2rffd
```

```
         fff0
3.     +    2
       ------
         ffff
```

```
4. -> 0000
```

- Distance of the code : 2
- Will always detect up to 1 error
- Will detect all burst errors up to 16
- For random errors, probability of miss is $\frac{1}{2^{16}}$ (2^{16} different checksums)

Cyclic redundancy check

For data D of length n, generate check bits R of length k such that the n+k bits are evenly divisible by a generator C.

- Protection depend on generator (standard has 32bits C)
- Humming distance of 4
- Detects odd numbers of errors
- Detects bursts of up to k bits in error
- Not vulnerable to systematic errors

Example :
D = 302, C = 3, k (length of R) = 1
=> R = 1 because $\frac{3021}{3} = 0$

Send procedure :

1. Extend D with k zeros
2. Divide by the generator C
3. Ignore quotient
4. Set check bits R as the remainder

Receive procedure :

1. Divide by C and check for zero remainder

Example :
D = 10111
C = 100
k = length(C) - 1 = 2

```
101 | 1011100
      101
      ---
       001
       000
       ---
        011
```

```
      000

      ---

      110
      101

      ---

        10 = R
```

Transmitted frame : 1011110

Error correction

It is difficult because errors can be in the check bits

Hamming code

Gives a method for constructing a code with a distance of 3.

To encode :

- With k check bits, we can check data of length $n = 2^k - k - 1$; ex: $k = 3, n = 4$
- The check bits are in positions p_i that are powers of 2, starting with position 1 (1, 2, 4, 8...)
- Fill the free positions with the data bits (positions 3, 5, 6, 7...)
- Check bit in position p_i is the parity of the bits at positions p_j for which the ith bit in j is 1 (ex: p_2 is the sum of all the bits at positions p_j where the second bit in j is 1 => 10 (2), 11 (3), 110 (6), 111 (7), 1010 (10), ...)

To decode :

- Recompute check bits p_i (with parity sum including the check bit)
- Arrange as a binary number $(\ldots p_8 p_4 p_2 p_1)$
- If the value (syndrome) is zero, it means there is no error
- Otherwise the syndrome is the position of the error, flip the bit at this position

Detection vs Correction

Correction

- When error are expected and in small number
- When no time for retransmission
- Used in physical layer (LDPC)
- Sometimes used in the application layer

Detection

- When errors are not expected
- When errors are generally large

- Used in the link layer and above

Retransmissions (ARQ)

- Receiver automatically acknowledges correct frames with an ACK
- Sender automatically resends after a timeout if no ACK is received
- Frames and ACKs must carry sequence numbers to avoid duplicates

Stop and wait

Use one bit to distinguish the current frame from the next one. Send one frame at a time

Sliding Window

Generalization of stop-and-wait
Allows W frames to be outstanding

Multiplexing

Network word for the sharing of a resource

- Time Division Multiplexing : Users take turns on a fixed schedule (ex : Round-Robin)
- Frequency Division Multiplexing : Put different users on different frequency bands

Multiple Access Control or Medium Access Control (MAC)

Random Multiple Access

Basis for classic Ethernet

ALOHA protocol

- Node sends when it has traffic
- If there was a collision (no ACK received), wait a random amount of time and resend
- Works well only under low load

Carrier Sense Multiple Access(CSMA)

- Improve ALOHA by listening for activity before sending
- Collision can still occur because of delays

Carrier Sense Multiple Access with Collision Detection(CSMA/CD)

- Reduce the cost of collision by detecting them and aborting (jam) the rest of the frame

For a wire of max length (time) D, we impose a minimum frame size that lasts for 2D seconds. This way everyone who collides knows that it happened. A node can't finish before a collision

CSMA persistence

To avoid collision between nodes who queued up waiting for the current sender to finish
For N queued senders, each one sends with next with probability $\frac{1}{N}$

Binary Exponential Backoff (BEB)

Estimates the probability for CSMA persistence

- Double interval for each successive collision
- Quickly gets large enough to work and very efficient in practice

1st collision : wait 0-1 time frames
2nd collision : wait 0-3 time frames
3rd collision : wait 0-7 time frames

…

Ethernet

- Multiple access with 1-persistent CSMA/CD with BEB (Modern ethernet based on switches)
- Has two addresses for destination and source, CRC-32 for error detection (no ARQ)
- Physical layer preamble to identify start of frame

	Preamble	Destination address	Source address	Type	Data	Pad	Check-sum
Bytes	8	6	6	2	0-1500	0-46	4
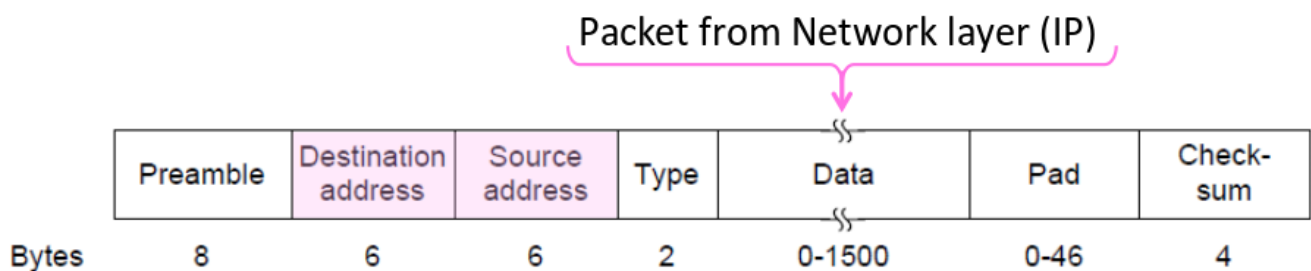
WIreless Multiple Access

- Nodes share a single link
- Nodes can't carrier sense (different areas of coverage)
- Nodes can't hear while sending (can't collision detect)

=> WiFi can't use CSMA/CD

Different Coverage Areas
Signal is bradcast and received nearby where SNR is sufficient
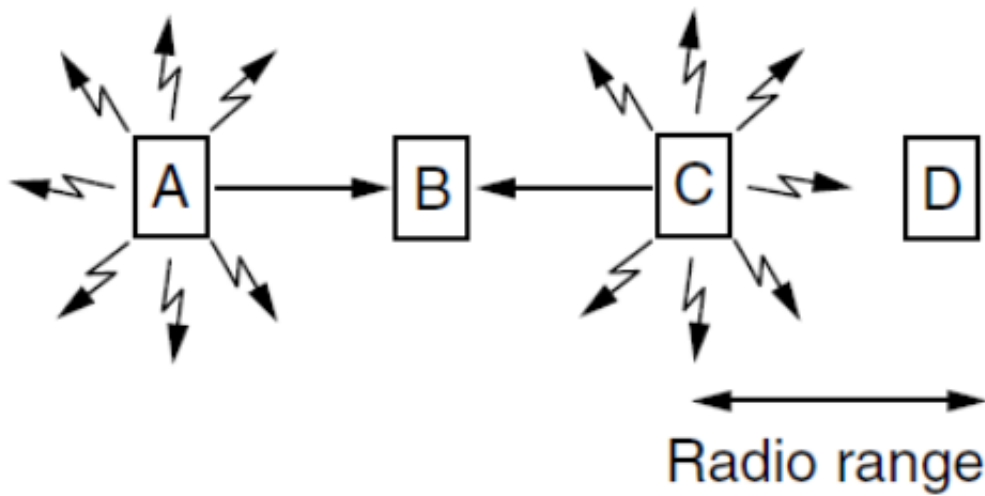
Hidden terminals

A and C are hidden terminals : Can't hear each other but can collide at B
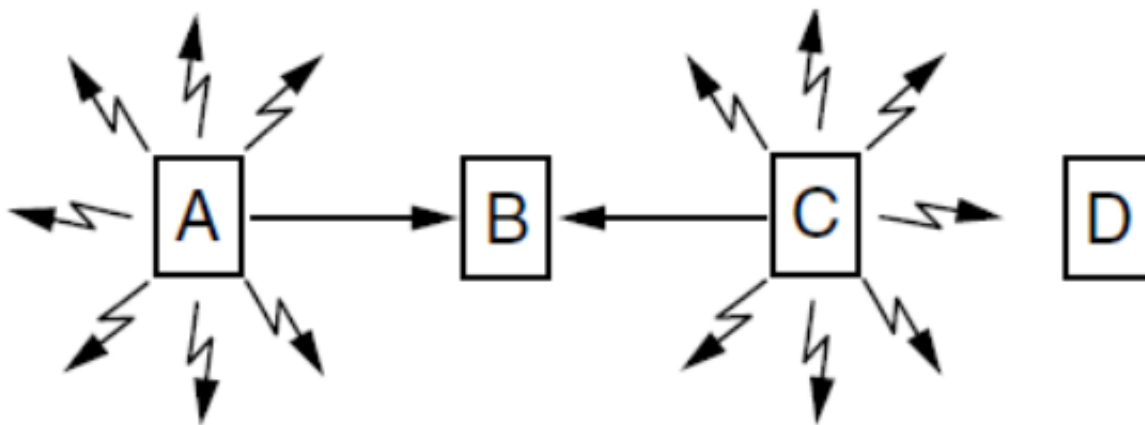
Exposed terminals

B and C can hear each other but don't collide at A and D
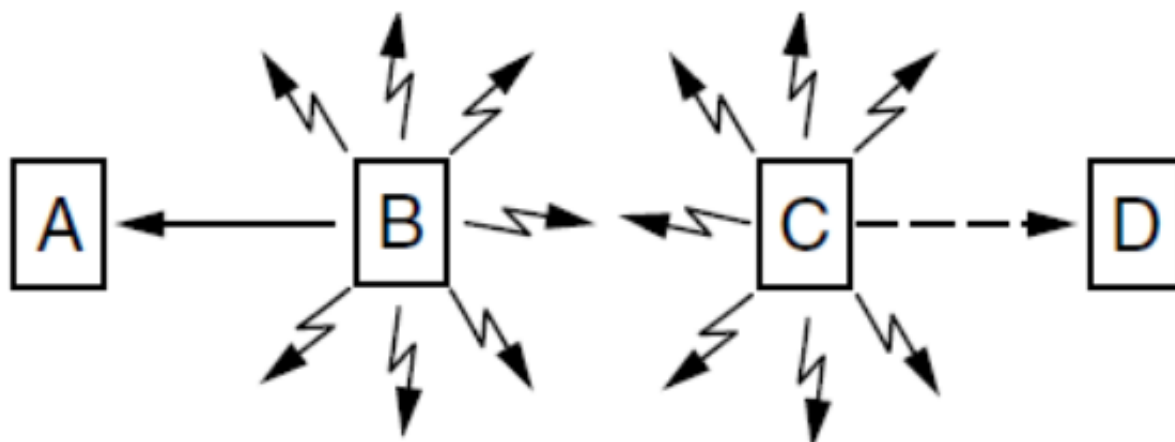
Multiple Access with Collision Avoidance (MACA)

Use short handshake instead of CSMA :

1. Senter node transmits a RTS with frame length

2. Receiver node replies with a CTS with frame length
3. Sender transmits the frame while other nodes hearing the CTS remain silent

Collision are possible but less likely

802.11

- Clients get connectivity from an Access Point (AP)
- OFDM modulation
- Different amplitudes/phases for varying SNRs
- Multiple access uses CSMA/CA; RTS/CTS optional
- ARQ
- Three addresses (due to AP)
- Errors detected with a CRC-32
- Many other features (encryption, power save)
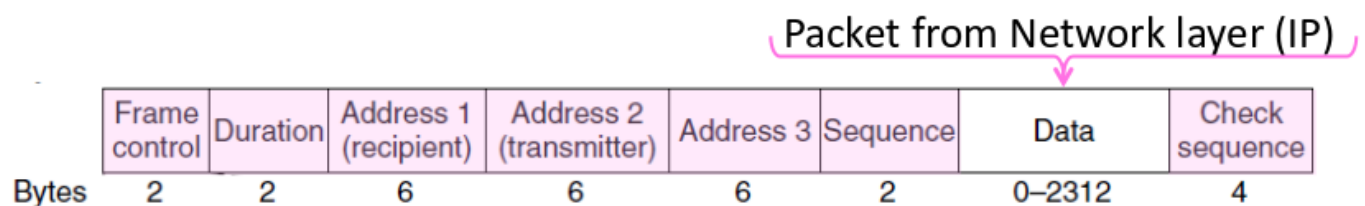
802.11 CSMA/CA :

Sender avoids collision by inserting a small random gap (backoff) before sending
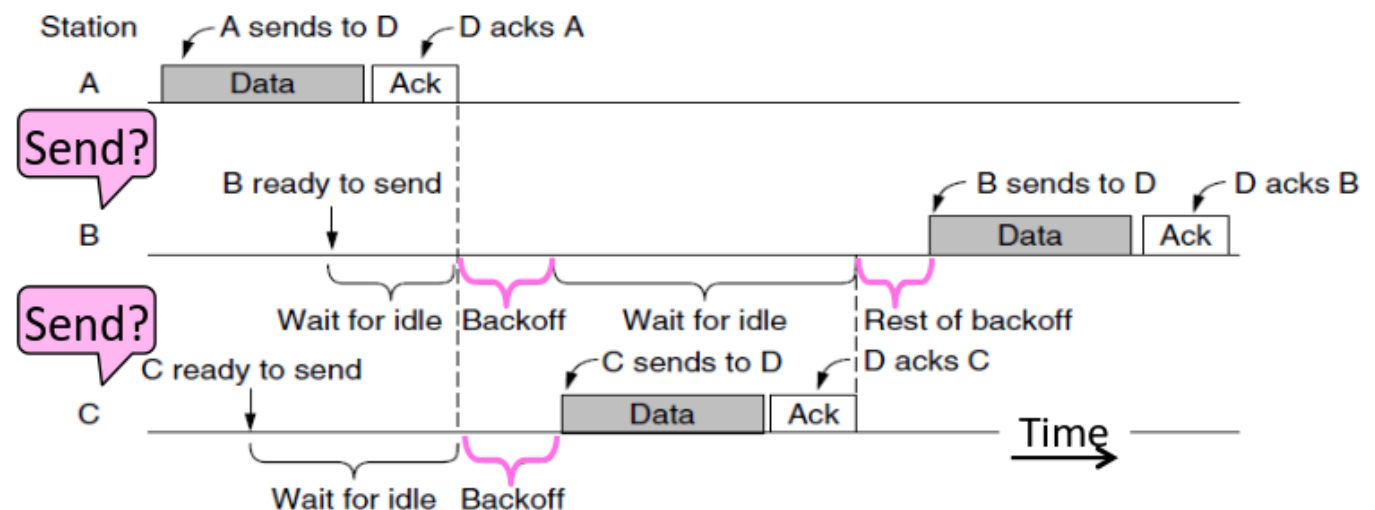
Contention-Free Multiple Access

CSMA is not good enough under high load

Turn-taking Multiple Access Protocols

Define an order in which nodes get a chance to send (or bypass if no traffic)

Can be ordered with a token ring (queue)

- Fixed overhead
- Predictable service
- More complex
- Higher overhead at low load

LAN Switches

Link <=> Link

To replace Multiple Access

Uses addresses to connect input port to the right output port
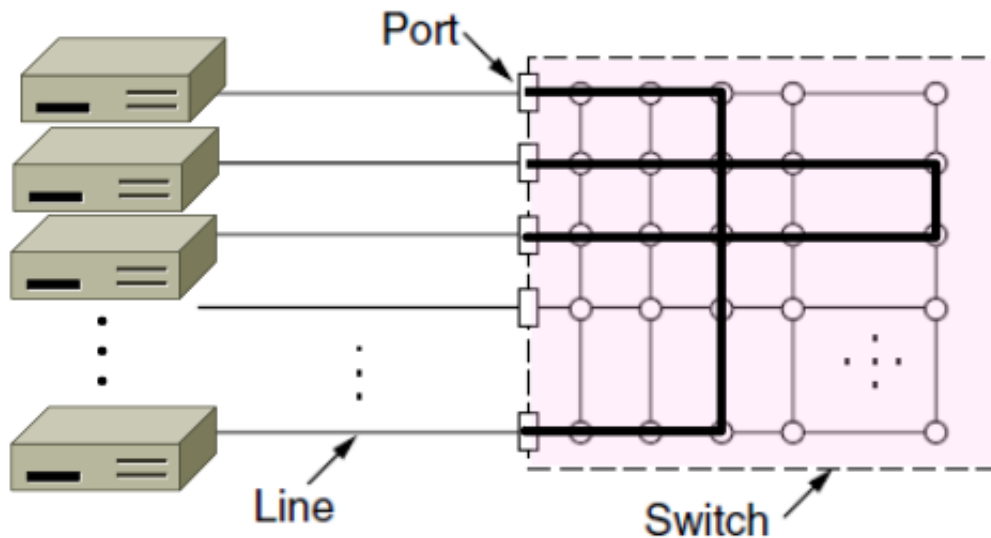
It uses buffers to connect multiple inputs to one outputs (queue)

Switch forwarding

To find the right output port, the switch must know the addresses.
It creates a port address table as follows :

1. To fill the table, it looks at the source address of input frames
2. To forward, it sends to the port, or if not known, it broadcasts to all ports

Forwarding loops :
Switches collectively find a spanning tree to avoid loops. They then forward as normal but only on the spanning tree.

Rules :

- All switches run the same algorithm
- They start with no information
- Operate in parallel and send messages
- Always search for the best solution

Outline :

1. Elect root node of the tree (switch with lowest address)
2. Grow tree as shortest distance from the root (use lowest address to break distance ties)
3. Turn off ports if they are not on the spanning tree

In practice :

1. Each switch initially believes it is the root
2. Each switch sends periodic updates to neighbours with its address, address of root and distance to root

Chapter 4 : Network layer

Builds on the link layer.
Routers send packets over multiple networks

Because switches :

- don't scale to large networks
- don't work across more than one link technology (WiFi, Ethernet,...)
- don't give much traffic control (plan routes / bandwidth)

Network layer :

- Scaling (hierarchy in the form of prefixes)
- Heterogeneity (IP for internetworking)
- Bandwidth control (lowest cost routing, Quality of Service QOS)

Routing and Forwarding

Routing is the process of deciding in which direction to send traffic (network wide / global)
Forwarding is the process of sending a packet on its way (local)

Datagram vs Virtual Circuit

Store and forward

Both models are implemented with store and forward packet switching :

- Router receive a complete packet, stores it temporarily if necessary before forwarding it onwards

Datagram or connectionless service

- Packets contain a destination address
- Each router uses it to forward each packet, possibly on different paths
- Each router has a forwarding table keyed by address. It gives the next hop for each destination address and may change.

Virtual Circuit Model

Three phases :

1. Connection establishment (path chosen, circuit info stored in routers)
2. Data transfer (packets are forwarded along the path)
3. Connection teardown (circuit info removed from routers)

- Packets only contain a short label to identify the circuit.
- Labels don't have a global meaning, they are only unique for a link
- Each router has a forwarding table keyed by circuit (gives output line and next label to place on packet)

Multi-Protocol Label Switching MPLS

A virtual-circuit like technology widely used by ISPs

- ISP sets up circuits inside their backbone ahead of time
- ISP adds MPLS label to IP packet at ingress, undoes at egress
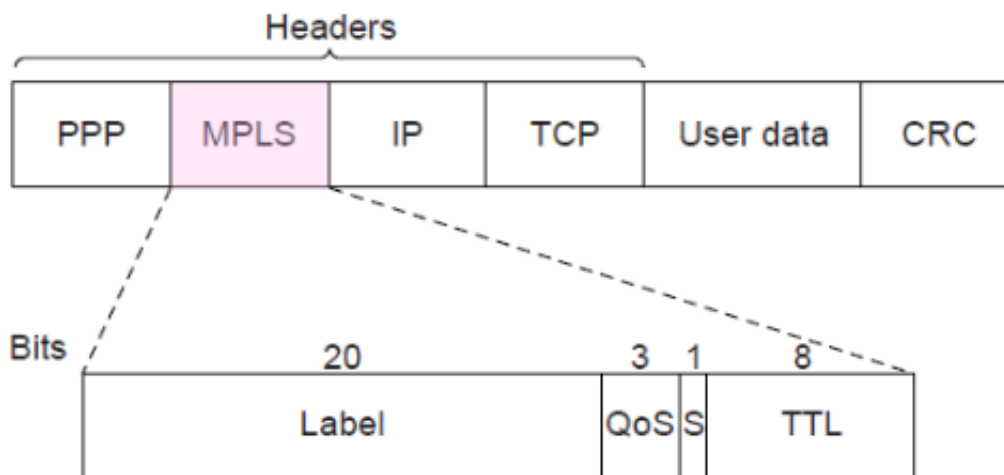
Advantages / Disadvantages

Issue	Datagrams	Virtual Circuits
Setup phase	**Not needed**	Required
Router State	**Per destination**	Per connection
Addresses	Packet carries full address	**Packet carries short label**

Routing	Per packet	**Per circuit**
Failures	**Easier to mask**	Difficult to mask
Quality of Service	Difficult to add	**Easier to add**

Internetworking

How networks may differ :

- Service model (datagrams, VC)
- Addressing
- QOS (priorities / no priorities)
- Packet sizes
- Security

IP (Internet Protocol)

Network layer of the Internet
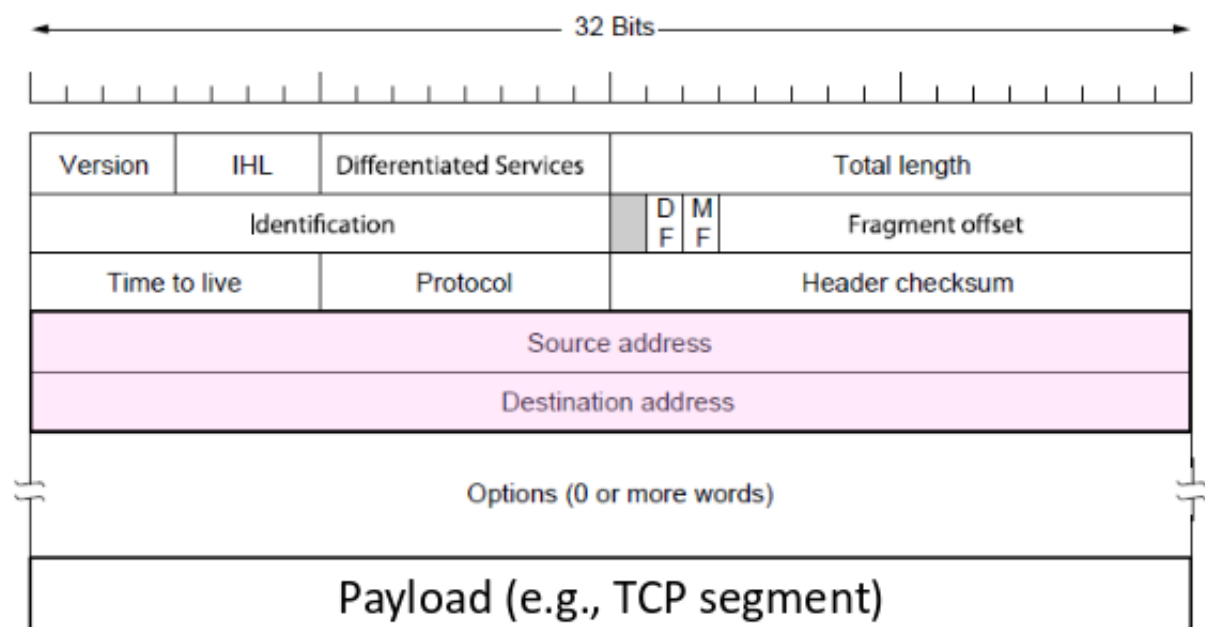
IP Addresses

IPv4 uses 32-bit addresses written in dotted quad notation

aaaaaaaa . bbbbbbbb . cccccccc . dddddddd

IP prefixes

- Address are allocated in blocks called prefixes
- Addresses in an L-bit prefix have the same top L bits
- There are 2^{32-L} addresses with the same L-bit prefix
- Written "IP address/length"
  Ex : 128.13.0.0/16 refers to addresses 128.13.0.0 to 128.13.255.255
- A /24 is 256 addresses, a /32 is one address

IP Forwarding

- IP addresses on one network belong to the same prefix
- Node uses a table that lists the next hop for IP prefixes

Prefix	Next Hop
192.24.0.0/18	D
192.24.12.0/22	B
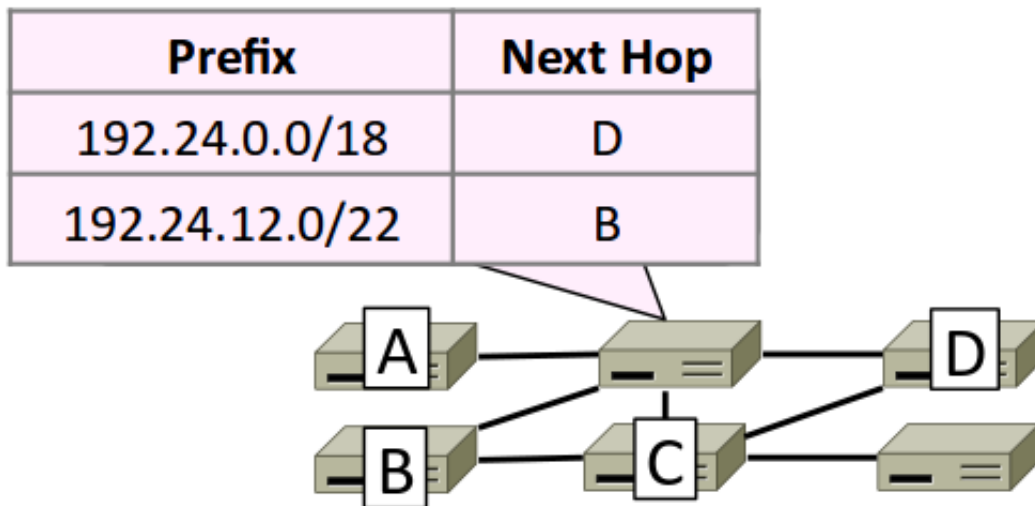
Longest matching prefix forwarding rule :

- Find the longest prefix that contains the destination address (the most specific)
- Forward the packet to the next hop router for that prefix

Host/Router distinction

In the internet :

- Router do the routing, know which way to all destination
- Host send remote traffic (out of prefix to nearest router)

Host forwarding table :

prefix	Next Hop
My network prefix	Send directly to that IP
0.0.0.0/0	Send to my router

Hierarchical routing

- IP prefix (from one host)
- Region (ex: ISP network)
- Route first to the region, then to the IP prefix within the region
- Hide details within a region from outside of the region

Helping IP with ARP, DHCP

- DHCP : getting an IP address
- ARP Mapping IP to link addresses

DHCP

Uses UDP on ports 67 and 68

When a new nodes "wakes up" on a network :

- Node sends broadcast (address all 1s) message that delivered to all nodes on the network.
- DHCP server leases an IP address and sends other infos (network prefix, address of local router, DNS server, time server,...)

To renew an existing lease : REQUEST followed by ACK
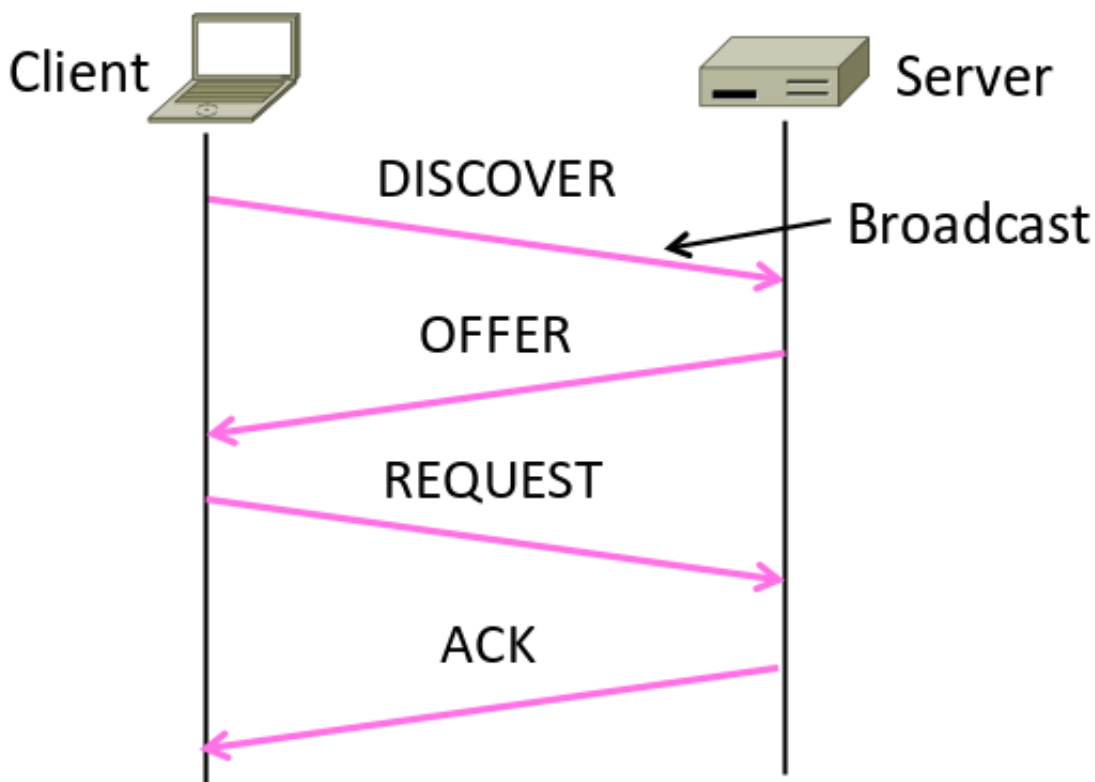
ARP protocol

The node needs the link layer addresse to send a frame over the local link (it only has its IP address)
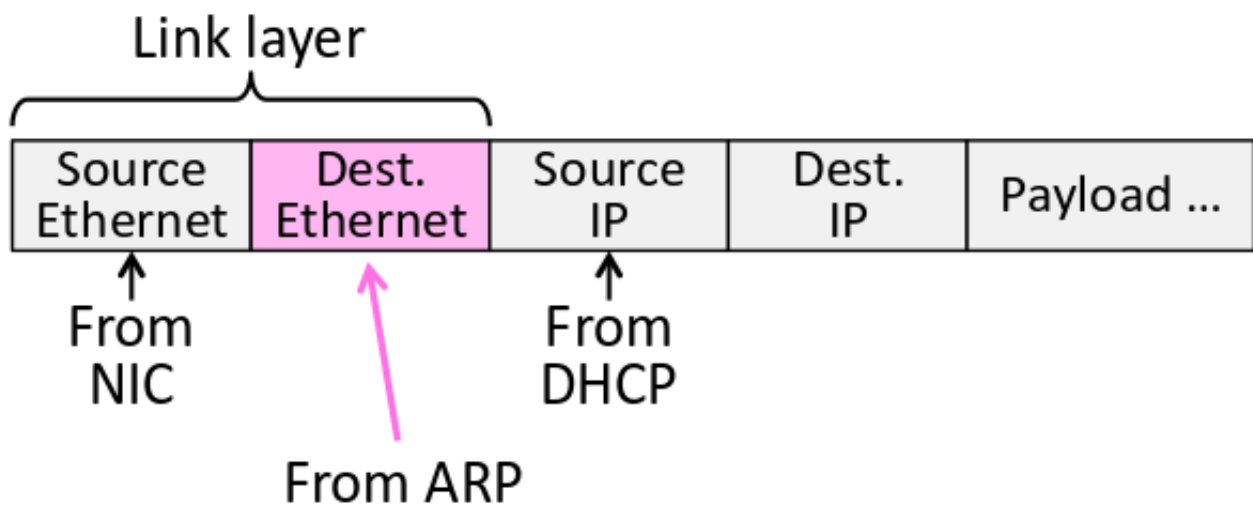
To do this, it just asks (broadcast) the node with target IP to identify itself

Packet size problem

- Different networks have different maximum packet sizes or MTU
- Prefer large packets for efficiency

IPv4 Fragmentation

Routers fragment packets that are too large to forward
Receiving host reassembles to reduce load on routers
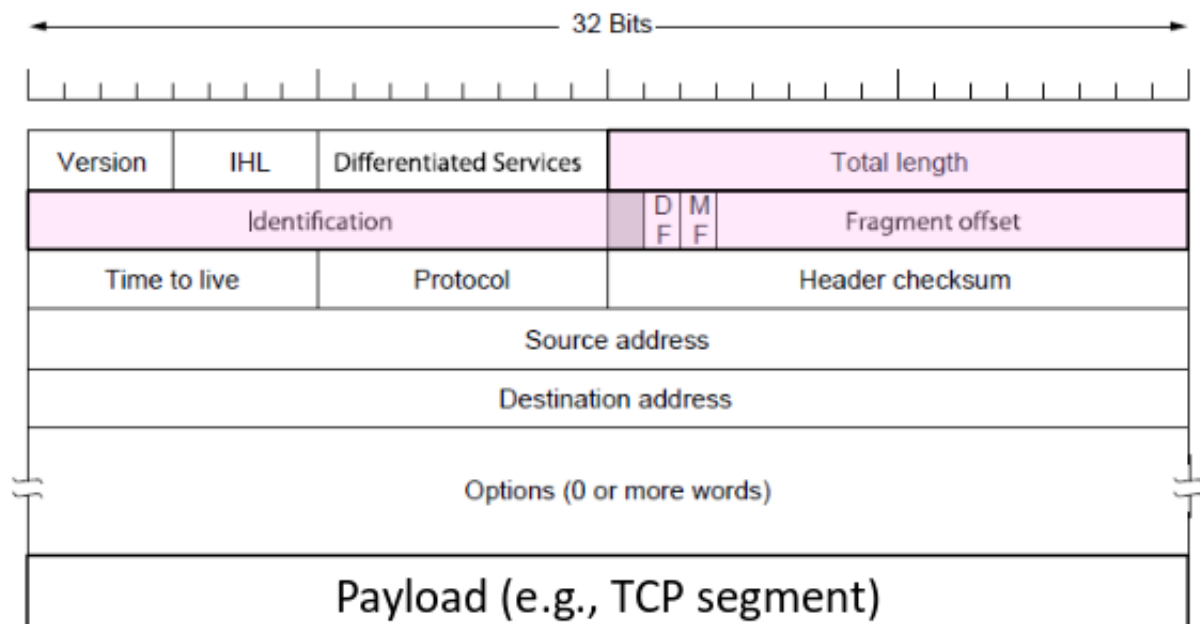
- Gives more work for routers / hosts
- Magnifies packet loss
- Security vulnerabilities

Path MTU Discovery

Discover the max MTU that will fit :

Host test with large packet. If too large, routers tell host what size would have fit

Set DF (Don't Fragment) bit in IP header to get feedback messages from router

Internet Control Message Protocol ICMP

- To find the problem when something goes wrong during forwarding.
- Sits on top of IP
- Provides error report and testing (function that hosts can use)

When router encounters an error while forwarding :

- It sends an ICMP error report to IP source address
- It discards the problematic packet

ICMP message format

Contains a Type, Code and Checksum
Carried in an IP packet
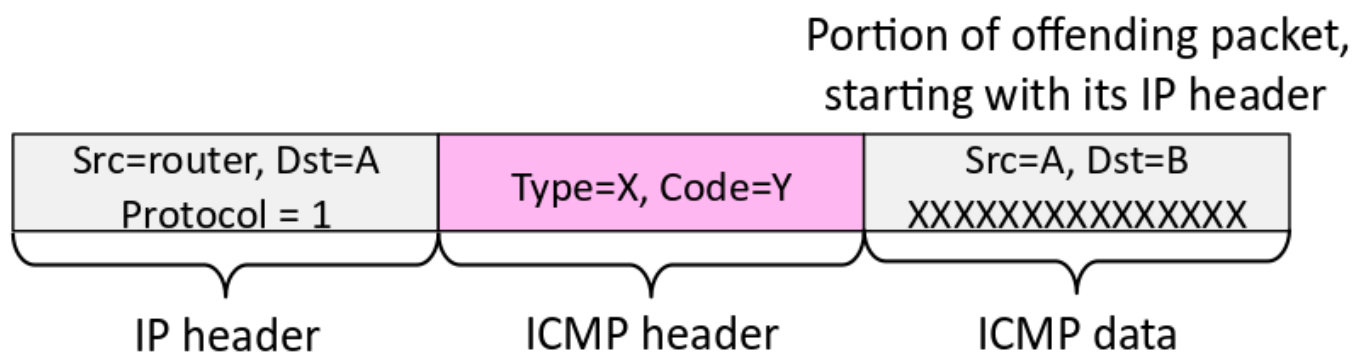
Traceroute

IP header contains TTL (Time To Live) field
It Decrements every router hop with ICMP error when it hits zero (protects against forwarding loops)

IPv6

- Large addresses (128 bits)
- New notation : 8 groups of 4 hex digits (16 bits)
  ex : 2001:0db8:0000:0000:0000:ff00:0042:8329
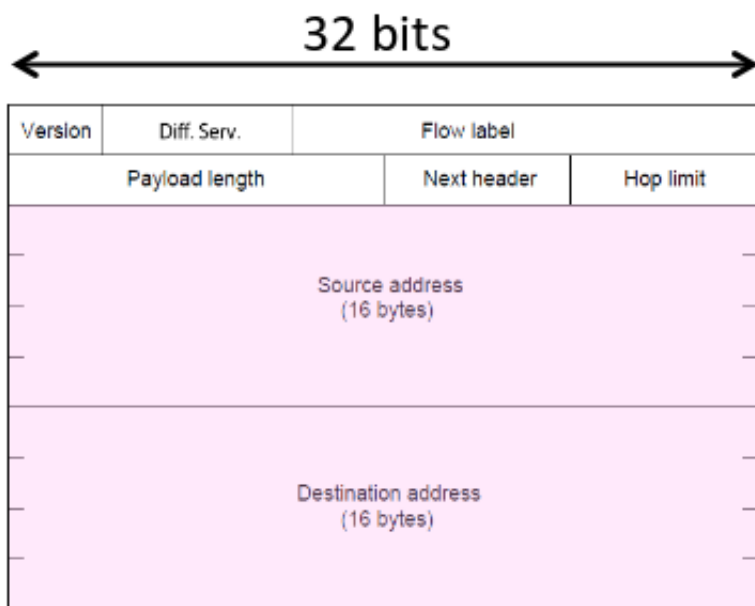
Approaches proposed for transition to IPv6 :

- Dual stack (speak IPv4 and IPv6)
- Translators
- **Tunnels** (carry IPv6 over IPv4)

Network Address Translation NAT

Connects an internal network to an external network

Middlebox that translates addresses (public/private)

- It keeps an internal / external table (IP address + TCP port)
- Needs ports to make mapping (there are fewer external IPs)
- For new translations : it creates an external name when host makes a TCP connection
- Look up and rewrite IP/port

Routing

- Routing has a better method than the spanning tree. It uses all links to find the "best" path
- It allocates network bandwidth adapting to failures

Properties we want :

Property	Meaning
Correctness	Find paths that work
Efficient paths	Uses network bandwidth well
Fair paths	Doesn't starve any node

Fast convergence	Recovers quickly after changes
Scalability	Works well as network grows large

Rules of algorithms :

- All nodes are alike (no controller)
- Nodes only know what they learn by exchanging messages with neighbours
- Nodes operate concurrently
- May be node/link/message failures

Shortest path routing

"Best" path :

- Latency (avoid circuitous paths)
- Bandwidth (avoid small pipes)
- Money (avoid expensive links)
- Hops (reduce switching)

Optimality property : Subpaths of shortest paths are also shortest paths
Sink trees : The sink tree for are destination is the union of all shortest paths towards the destination (similarly source tree)

Forwarding table at a node : Lists next hop for each destination

Dijkstra's algorithm

Set distance from source to 0 for source and ∞ for all other nodes
While tentative node remain :

1. Extract N, a node with lowest distance
2. Add link to N to the shortest path tree
3. Relax the distances of neighbours of N by lowering any better distance estimate

Distance vector routing

- To compute shortest paths in a distributed network
- Used in ARPANET and RIP (Routing Information Protocol)
- Two main approaches :
  - Distributed version of Bellman-Ford (very slow convergence after failures)
  - Link-state algorithms (used in practice)

Settings :

- Nodes know only the cost to their neighbours, not the topology
- Nodes can talk only to their neighbours using messages

- All nodes run the same algorithm concurrently
- Nodes and links may fail, messages may be lost

Algorithm :

Each node maintains a vector of distances (and next hops) to all destinations

1. Initialize vector with 0 cost to self, ∞ to other destinations
2. Periodically send vector to neighbours
3. Update vector for each destination by selecting the shortest distance heard, after adding cost of neighbour link

Use the best neighbour for forwarding

Dynamics :

Adding route : News travels one hop per exchange

Removing routes : When a node fails, no more exchanges, other nodes forget

Partitions (unreachable nodes in divided network) : Problem -> count to infinity scenario (The node don't tell neighbours how near it is and other nodes just tell each other a length which increases every time.)

Flooding

Broadcast a message to all nodes in the network

1. Send an incoming message on to all other neighbours
2. Remember the message so that it is only sent once over each link (duplicate suppression)

Use ARQ to make flooding reliable

RIP (Routing Information Protocol)

- DV protocol with hop count as metric (limits network size with ∞ at 16 hops)
- Includes split horizon, poison reverse (Don't send route back to where you learned it from)
- Runs on top of UDP
- Send vectors every 30 secs (180 sec timeout to detect failures)

Link-State Routing

- Trades more computation than distance vector for better dynamics
- Widely used in practice (Internet, ARPANET)

Settings (same as DV) :

- Nodes know only the cost to their neighbours, not the topology
- Nodes can talk only to their neighbours using messages
- All nodes run the same algorithm concurrently
- Nodes and links may fail, messages may be lost

Algorithm :

1. Each node flood topology in the form of link state packets (LSP) -> Each node learns full topology
2. Each node computes its own forwarding table by running Dijkstra

Complications :

- Seq number reaches max, or is corrupted
- Node crashes and loses seq. number
- Network partitions then heals

Solution : Include age on LSPs and forget old information that is not refreshed

DL vs LS

Goal	Distance Vector	Link State
Correctness	Distributed Bellman-Ford	Replicated Dijkstra
Efficient paths	Approx with shortest paths	Approx. with shortest paths
Fair paths	Approx. with shortest paths	Approx. with shortest paths
Fast convergence	Slow - Many exchanges	**Fast - flood and compute**
Stability	**Excellent - storage/compute**	Moderate - storage/compute

IS-IS and OSPF protocols

Widely used in large enterprises and ISP networks

- IS-IS : Intermediate System to Intermediate System
- OSPF : Open Shortest Path First

Link state protocols with many features added

Equal Cost Multi-Path (ECMP) routing

- For paths with equal costs
- Topology has them for redundancy
- Extend shortest path model by keeping set if there are ties

Routing with multiple parties

Structure of the internet :

- Networks (ISP, CDNs, ...) group hosts as IP prefixes
- Networks are richly interconnected (often using IXPs)

Two problems :

1. Scaling to very large networks (IP prefixes, hierarchy, prefix aggregation)
2. Incorporating policy decision (Parties choose their routes to suit their own needs) => (Hot potato) routing

Routing policies

Transit :

- One party (customer) gets transit service from another party (ISP)

Peer :

- Both parties (for example ISP) get peer service from each other
- They accept traffic from the other ISP only for their customers but do not carry traffic to the rest of the internet for each other
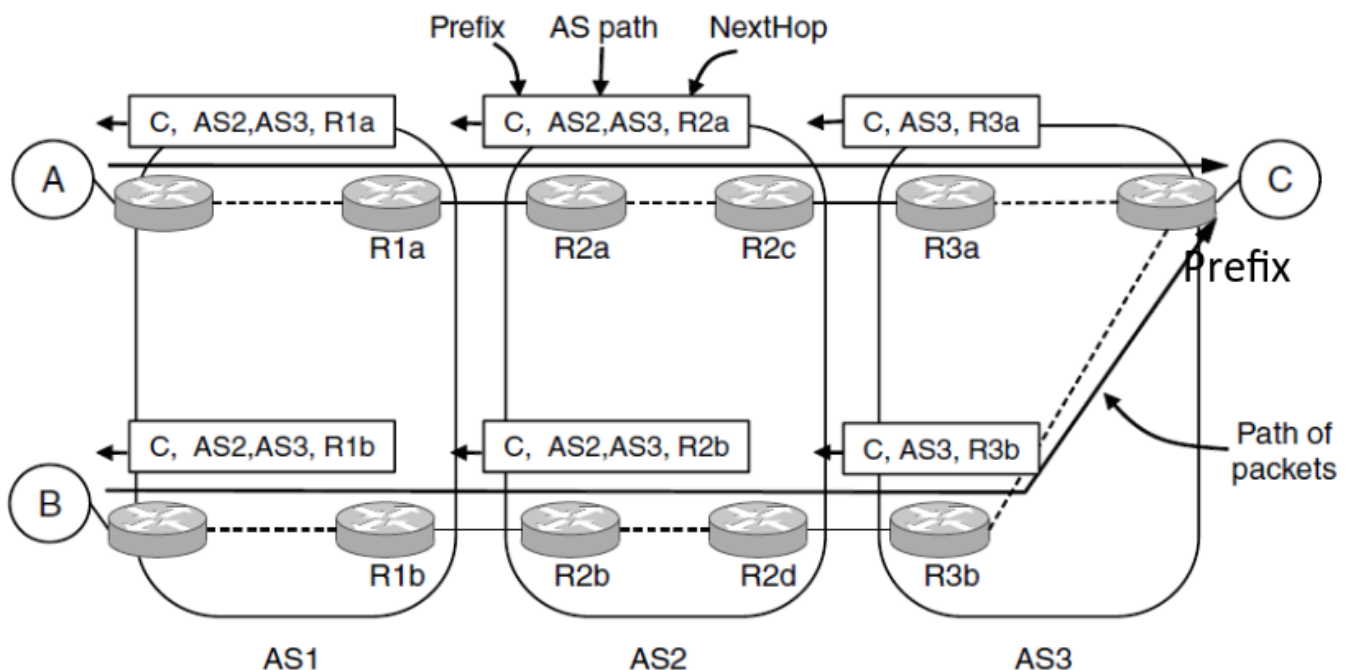
Border Gateway Protocol (BGP)

BGP is the protocol that computes interdomain routes in the Internet
Border routers announce BGP routes to each other

Policy :

1. Border routers of ISP announce paths only to other parties who may use those paths
2. Border routers of ISP select the best path of the ones they hear in any, non-shortest way

Chapter 5 : Transport Layer

Builds on the network layer to deliver data across networks for applications with the desired reliability or quality.

Services :

	Unreliable	Reliable
Message	Datagrams (UDP)	
Bytestream		Streams (TCP)

TCP is full-featured, UDP is a glorified packet

TCP (streams)	UDP (Datagrams)
Connections	Datagrams
Bytes are delivered once, reliably, and in order	Messages may be lost, reordered and duplicated
Arbitrary length content	Limited message size
Flow control matches sender to receiver	Can send regardless of receiver state
Congestion control matches sender to network	Can send regardless of network state

Socket API

- Abstraction to use the network
- Part of all major OSes and languages
- Supports both Internet transport services (streams and datagrams)
- Sockets let apps attach to the local network at different ports

API :

Primitive	Meaning
SOCKET	Create a new communication endpoint
BIND	Associate a local address (port) with a socket
LISTEN	Announce willingness to accept connections
ACCEPT	Passively establish an incoming connection
CONNECT	Actively attempt to establish a connection

SEND(TO)	Send some data over the socket
RECEIVE(FROM)	Receive some data over the socket
CLOSE	Release the socket

Ports

- Application identified by tuple : IP address, Protocol, Port
- Ports are 16-bit integers
- <1024 requires administrative privileges
- Servers often bind to well-known ports, clients often assigned ephemeral ports chosen by OS

Some well-known ports :

Port	Protocol
20,21	FTP
22	SSH
25	SMTP
80	HTTP
110	POP-3
143	IMAP
443	HTTPS
543	RTSP
631	IPP

User Datagram Protocol (UDP)

Used by apps that don't want reliability or bytestreams (es : VOIP, DNS, RPC, DHCP)
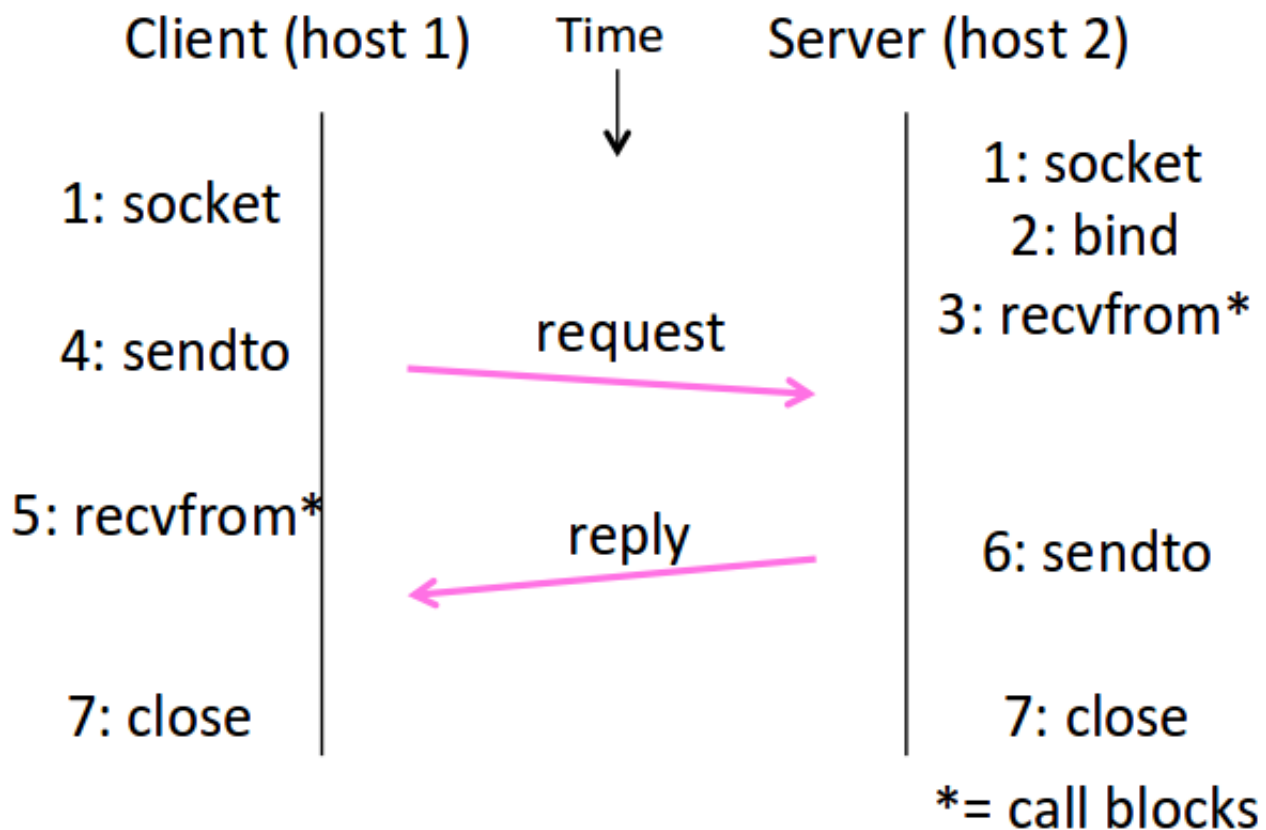
UDP Header

- Uses ports to identify application processes
- Datagram length up to 64K
- Checksum (16 bits for reliability)

Source port	Destination port
UDP length	UDP checksum
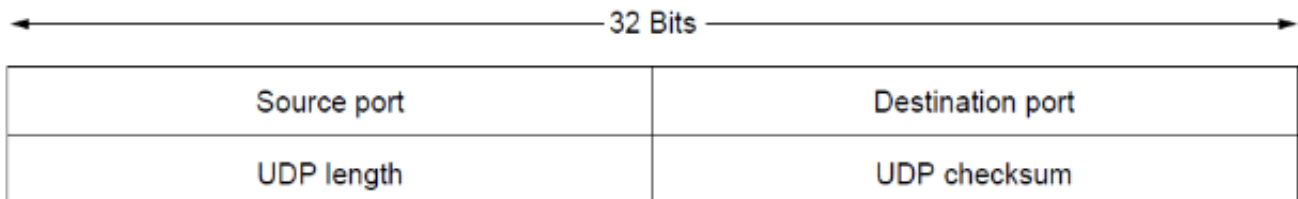
Transmission Control Protocol (TCP)

Connection establishment

Both sender and receiver must be ready before we start the transfer of data. Need to agree on a set of parameters

Three-Way Handshake

Each side probes the other with a fresh Initial Sequence Number (ISN)

Three steps to establish a connection :

1. Client sends SYN(x) (SYNchronize)
2. Server replies with SYN(y)ACK(x+1)
3. Client replies with ACK(y+1)
4. SYNs are retransmitted if lost
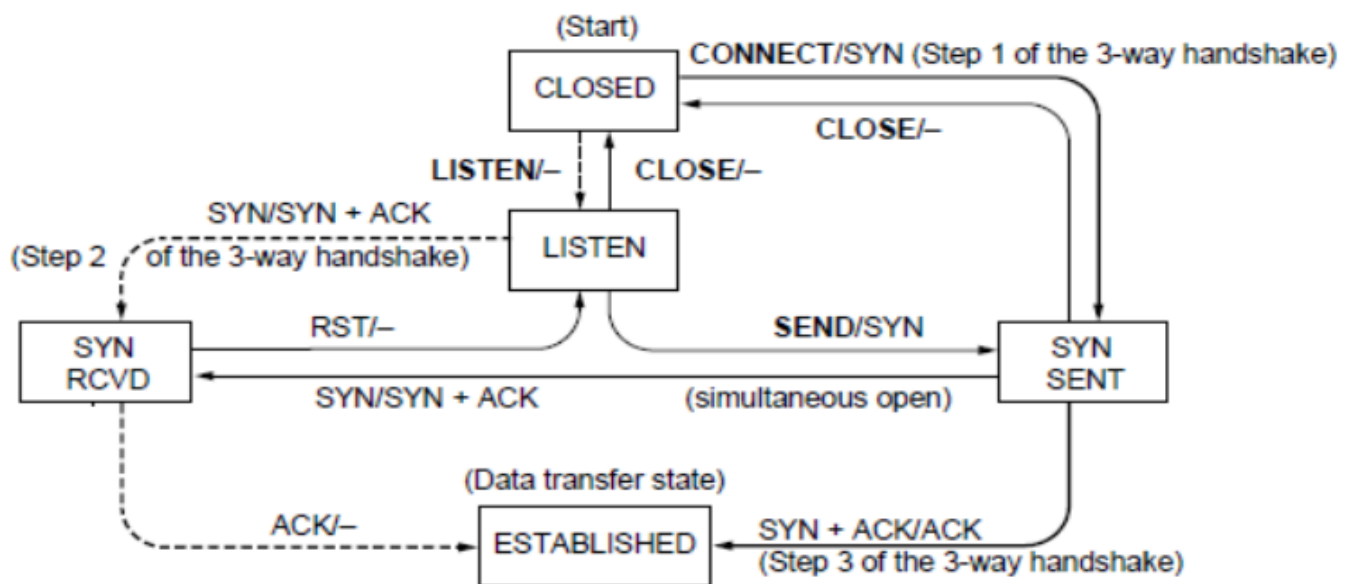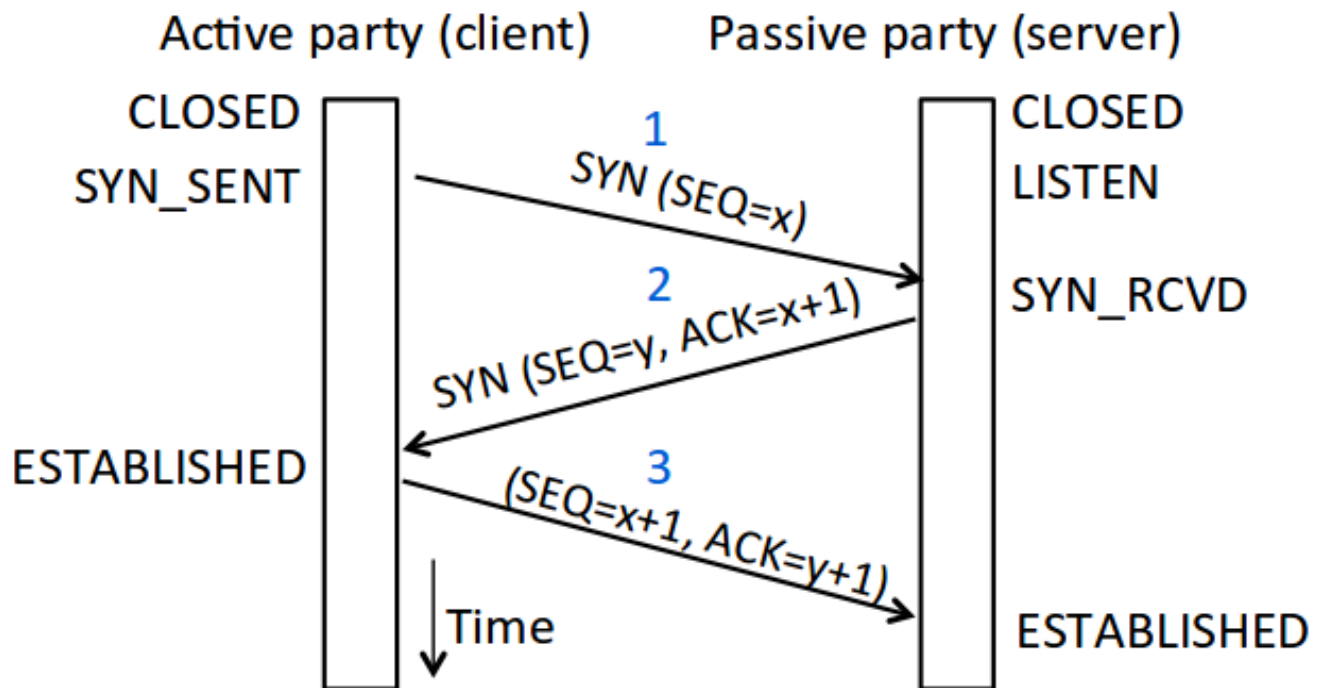
Two steps to close a connection :

1. Active sends FIN(x), passive ACKs
2. Passive sends FIN(y), active ACKs
3. FINs are retransmitted if lost
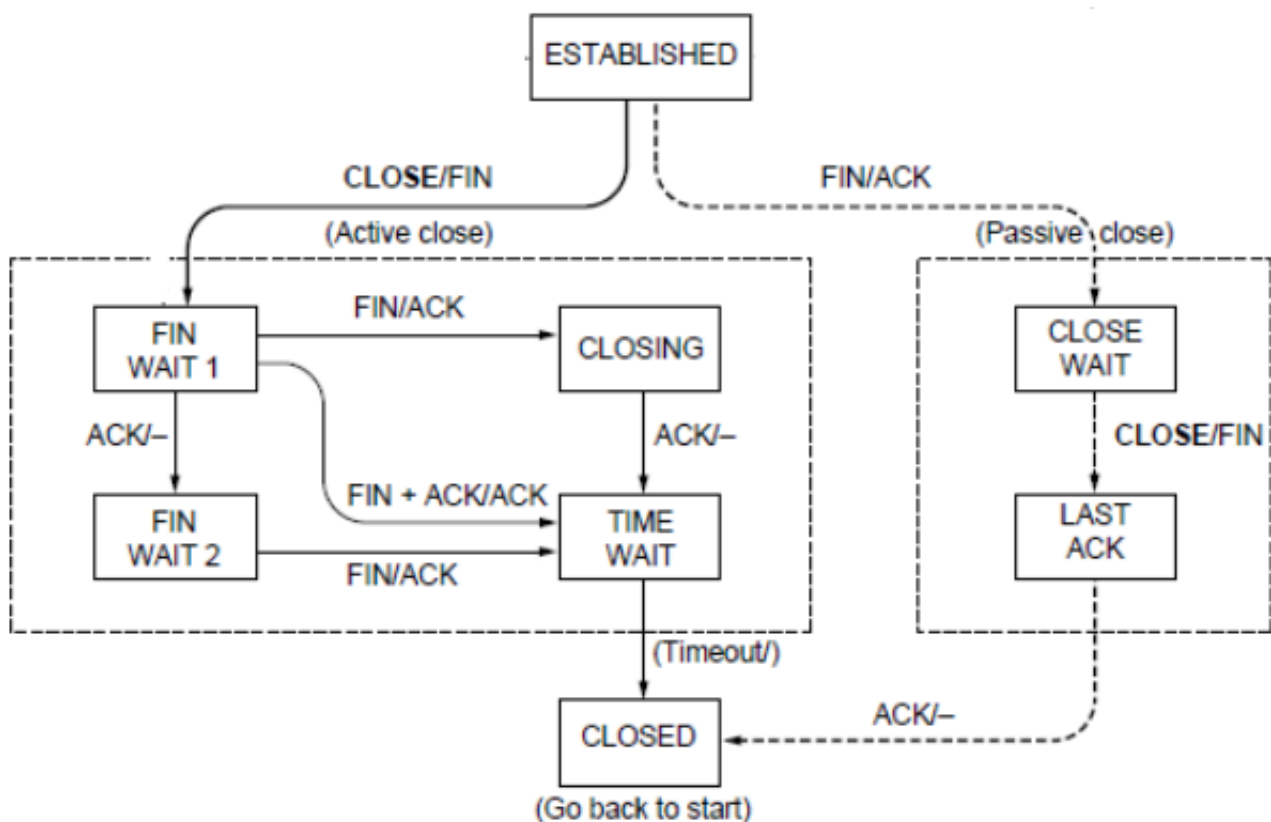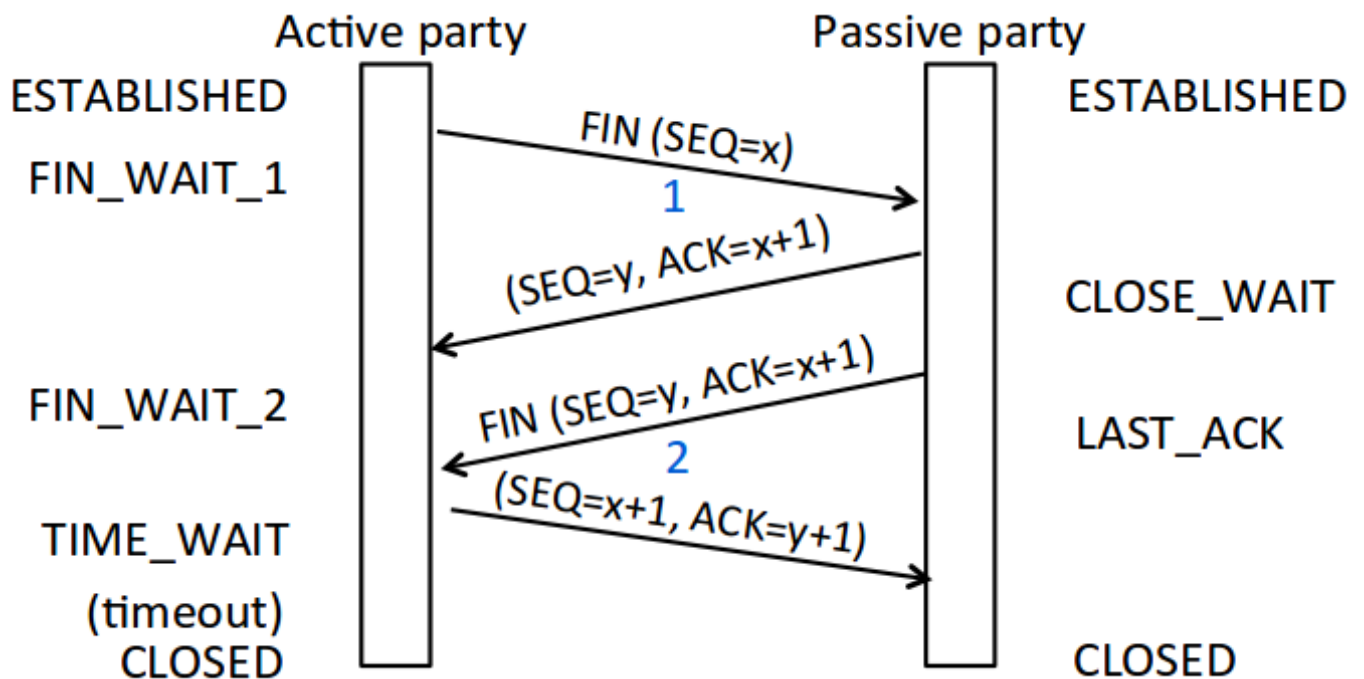
Sliding Windows

- Better than Stop-and-Wait (one message + ARQ)
- Allows W packets to be outstanding
- Needs W=2BD to fill network path

Sender

Sender buffers up to W segments until they are acknowledged

Sends while LFS (Last Frame Sent) - LAR (Last ACK Rec'd) <= W
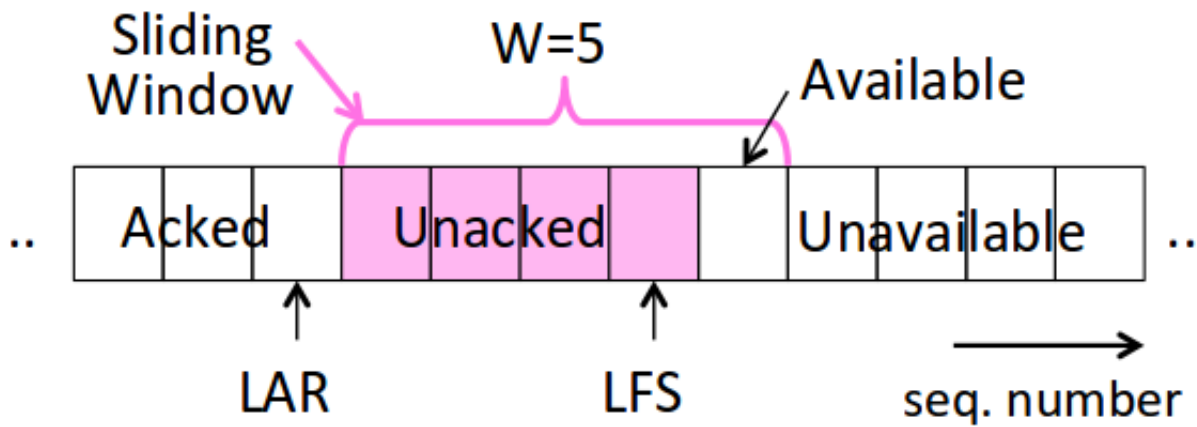
Receiver

Go-Back-N

- Receiver keeps only a single packet buffer for the next segment (state variable LAS = Last Ack Sent)
- Discard if seq. number != LAS+1

Selective Repeat

- Receiver buffers W segments, keeps state variable LAS (Last Ack Sent)
- On receive :
    1. Buffer segments [LAS+1, LAS+W]
    2. Pass up to app in-order segments from LAS+1 and update LAS
    3. Send ACK for LAS

Sequence numbers

Needs 2W seq. numbers for Selective Repeat and W+1 for Go-Back-N

Flow Control

- Receiver tells the sender the available buffer space WIN (Flow Control Window)
- Sender uses the lower of the sliding window and flow control window (WIN) as the effective window size

Timeout problem

- Timeout must be variable on the Internet because RTT (Round Trip Time) varies.
- Adaptive timeout keeps a smoothed estimate of the RTT and its variance :

$$SRTT_{N+1} = 0.9 \cdot SRTT_N + 0.1 \cdot RTT_{N+1}$$

$$Svar_{N+1} = 0.9 \cdot Svar_N + 0.1 \cdot |RTT_{N+1} - SRTT_{N+1}|$$

- Set timeout to an multiple of estimates :
  TCP Timeout = $SRTT_N + 4 \cdot SVAR_N$

Reliable Bytestream

- Messages boundaries are not preserved from send() to recv() but are reliable and ordered.

Four segments, each with 512 bytes of data and carried in an IP packet

2048 bytes of data delivered to app in a single recv() call

- Bidirectional data transfer

TCP Header

Source port										Destination port	
Sequence number											
Acknowledgement number											
TCP header length		C W R	E C E	U R G	A C K	P S H	R S T	S Y N	F I N	Window size		
Checksum										Urgent pointer	
Options (0 or more 32-bit words)											
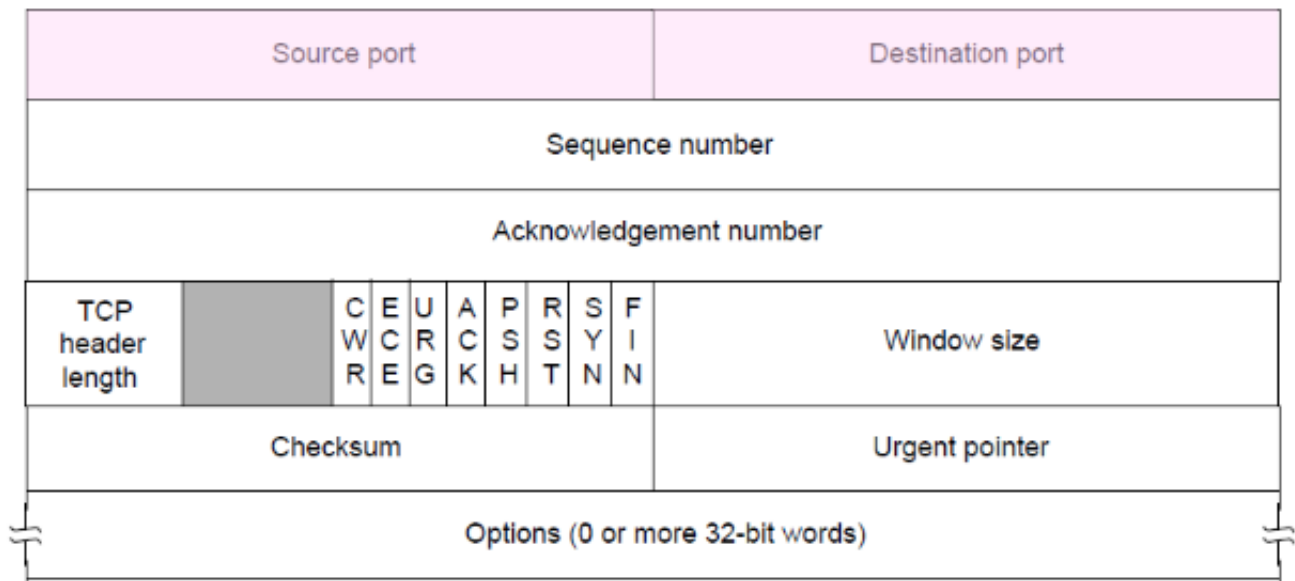
Chapter 6 : Congestion Control

- Congestion is a "traffic jam" in the network
- Happens when the buffering queues from routers/switches overflow (when input > output)
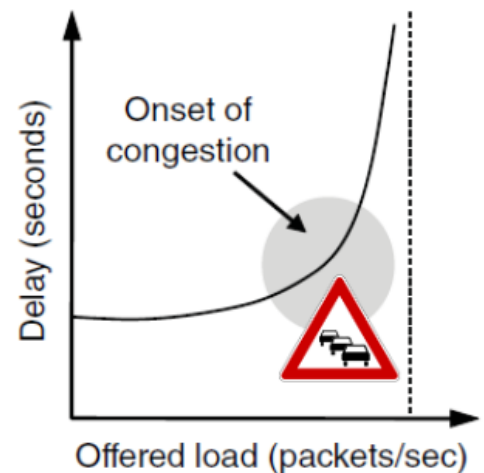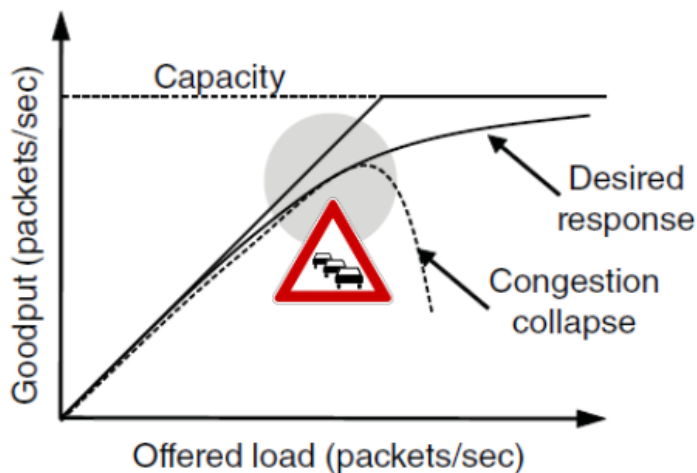
We want to operate the network just before the onset of congestion

Bandwidth allocation

- Efficient : most capacity is used but there is no congestion
- Fair : every sender gets a reasonable share of the network
- We can't have both

- Network layer witnesses congestion : it can provide feedback
- Transport layer causes congestion : it can reduce offered load

Max-Min fairness

Max-min fair allocation is one that :

- Increasing the rate of one flow will decrease the rate of a smaller flow
- When a flow is bottlenecked (at some place in the network), hold it fixed and continue increasing other flows
- This maximizes the minimum flow

Bandwidth allocation models

- Open loop versus closed loop (open : reserve bandwidth before use, closed : use feedback to adjust rates)
- Host versus Network support (Who sets/enforces allocations ?)
- Window versus Rate based (How is allocation expressed ?)

TCP is Closed loop, host-driven, window-based:

- Network layer returns feedback on current allocation to senders
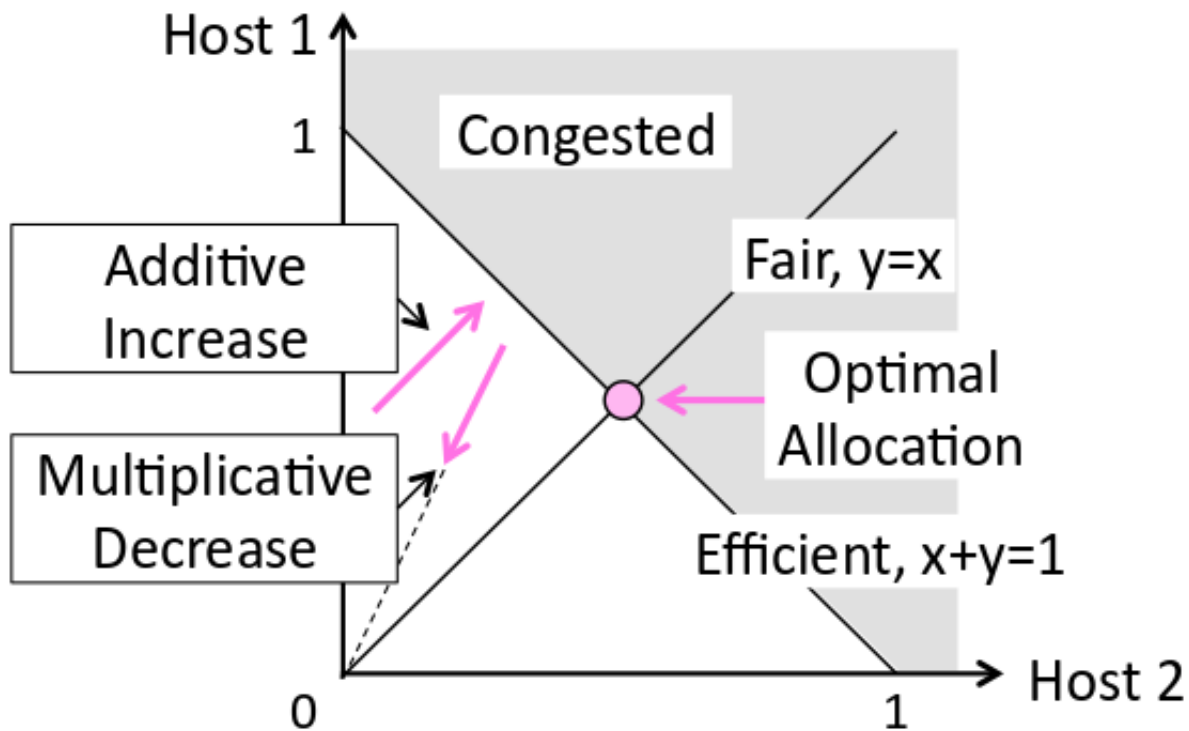- Transport layer adjusts sender's behavior via window in response (control law)

Additive Increase Multiplicative Decrease (AIMD)

AIMD is a control law hosts can use to reach a good allocation.
Used by TCP.

- Hosts additively increase rate while network is not congested
- Hosts multiplicatively decrease rate when congestion occurs

- Produces a "sawtooth" pattern over time for rate of each host
- Converges to an allocation that is efficient and fair (other don't)
- Requires only binary feedback from the network

Feedback signals :

- **Packet loss**
- Packet delay
- Router indication

TCP Tahoe/Reno

Fix timeouts and introduce a congestion window over the sliding window to limit queues/loss

TCP ACK clocking

The self-clocking behavior of sliding windows

- Each in-order ACK advances the sliding window and lets a new segment enter the networks. ACKs clock data segments
- Segments are buffered and spread out on slow link

TCP slow start

- It is a component of the AI in AIMD
- We want to quickly near the right rate but it varies grately
- Start by doubling the the window size every RTT (exponential growth)
- Next time, switch to AI just before congestion rate

Implementation (TCP Tahoe) :

- Initial slow-start phase (double every RTT)
- Later Additive Increase phase (Increment every RTT)
- Switching threshold initially ∞, $\frac{cwnd}{2}$ after loss

Acronyms

Acronym	Meaning	Description
AIMD	Additive Increase Multiplicative Decrease	
AP	Access Point	See 802.11
ARP	Address Resolution Protocol	
ARQ	Automatic Repeat reQuest	
BEB	Binary Exponential Backoff	
BGP	Border Gateway Protocol	Protocol to compute interdomain routes in the Internet
CRC	Cyclic redundancy check	
CSMA	Carrier Sense Multiple Access	
CSMA/CD	Carrier Sense Multiple Access with Collision Detection	
CTS	Clear To Send	
cwnd	Congestion Window	
DHCP	Dynamic Host Configuration Protocol	
DV	Distance Vector (protocol)	
ECMP	Equal-Cost Multi-Path routing	Shortest paths with more than one path
FDM	Frequency Division Multiplexing	
IANA	Internet Assigned Numbers Authority	Allocates public IP addresses (delegates to regional RIRs)

ICMP	Internet Control Message Protocol	
ISN	Initial Sequence Number	
ISP	Internet Service Provider	
IS-IS	Intermediate System to Intermediate System	
IXP	Internet Exchange Point	Permet aux différents ISP d'échanger du trafic Internet entre leurs réseaux
Lan	Local Area Network	ex : WiFi, Ethernet
LDPC	Low Density Parity Check	State of the art today to correct errors in messages
LSP	Link State Packet	
MAC	Multiple Access Control or Medium Access Control	
MACA	Multiple Access with Collision Avoidance	
Man	Metropolitan Area Network	ex : Cable, DSL
MF	More Fragments	Bit in IP header, 1 if more fragments are following
MPLS	Multi-Protocol Label Switching	
MTU	Maximum Transmission Unit	
NAT	Network Address Translation	
NRZ	Non Return to Zero	
OSPF	Open Shortest Path First	
Pan	Personal Area Network	ex : Bluetooth
QOS	Quality Of Service	
RIP	Routing Information Protocol	
RTS	Request To Send	

RTT	Round Trip TIme	
SNR	Signal to Noise Ratio	S/N
TCP	Transmission Control Protocol	
TDM	Time Division Multiplexing	
TTL	Time To Live	
UDP	User Datagram Protocol	
VC	Virtual Circuit	
Wan	Wide Area Network	Large ISP