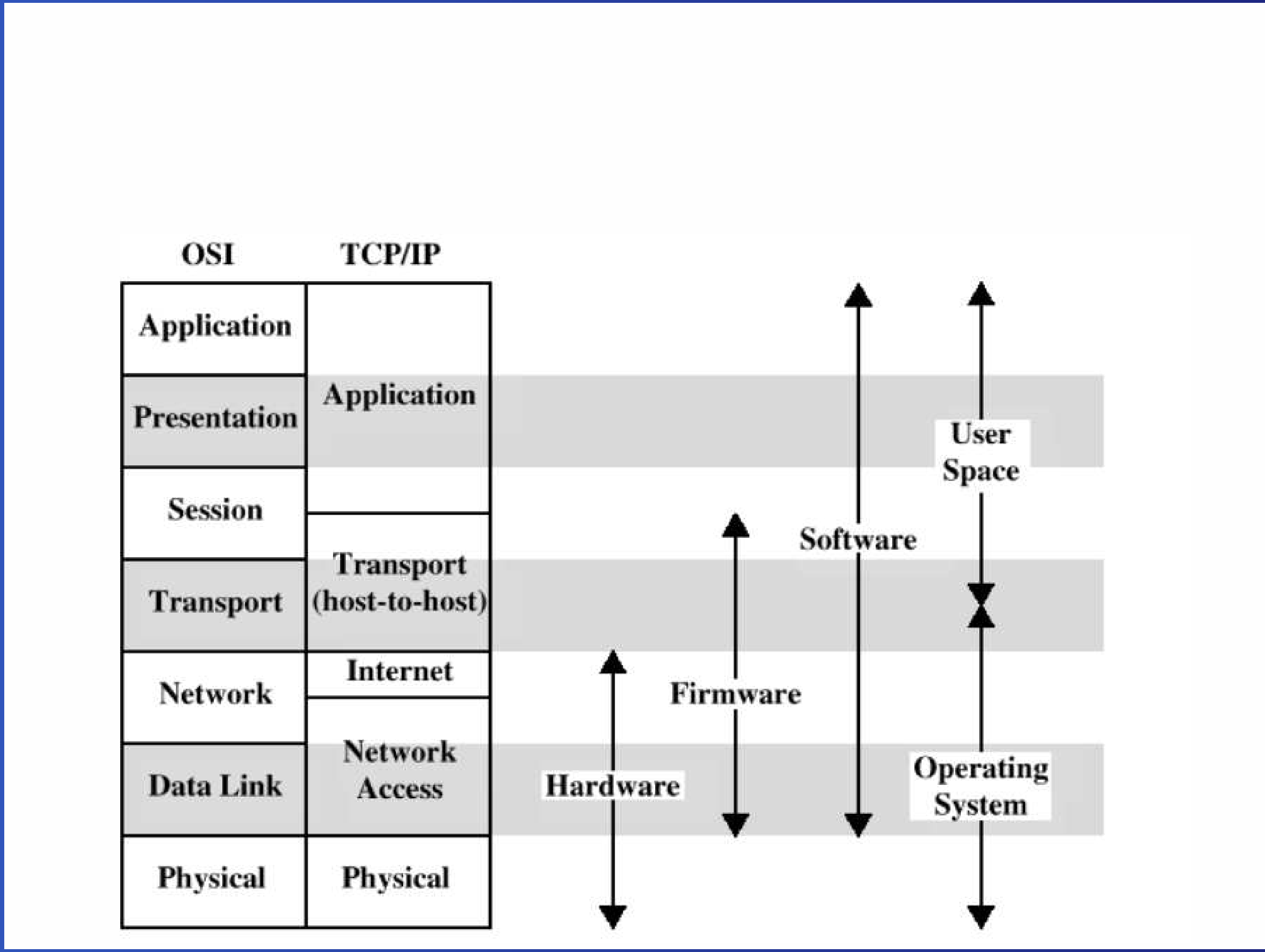
Finally: Data Communication !

- Synchronous, Asynchronous Transmission
- Interfaces: V.24/EIA-232-F (AKA RS-232)
- ISDN: Synchronous, Differential Signals

Where are we now?



Error Detection and Correction

- Parity: add parity bit, number of 1-bits even for even parity, but only detects single-bit errors.
- Hamming Code: More parity bits, detects and corrects errors
  - m: number of data bits, p: number of redundancy bits, p+m bits to be transmitted.
  - $2^p \geq m + p + 1$, i.e. for 7-bit ASCII, 11 Bits are to be transmitted.
  - check bits are positioned at positon $1, 2, 4, \ldots, 2^n$ in the bitstream

Hamming Code Calculation

- The redundancy bit at position i is calculated as the parity of all data bits that contain 2^i in their binary representation of their sequence number.
- for 7-bit ascii, the first redundancy bit contains the parity of data bits 3, 5, 9 and 11. The second redundancy bit contains the parity of the data bits 3, 6, 7 and 11 and so on.

Hamming Code Calculation (2)

- If not, we receive the binary address of the faulty bit and can correct it.
- example: send 1 0 1 1 1 0 0 1 0 0 1, received 1 0 0 1 1 0 0 1 0 0 1
- c1 (positions 1 3 5 7 9 11) =1 c2 (2 3 6 7 10 11)=1 c3(4 5 6 7)=0 c4(8 9 10 11)=0 c4 c3 c2 c1 = (0 0 1 1) =3 -> bit 3 wrong.
- $\rightarrow$ The Hamming code can correct 1-bit-errors.
- Keyword: Forward-Error-Correction (FEC)

Error Detection and Correction

- Arithmetic Checksum: Add all byte values (modulo 255), calculate negative of the sum, add as checksum. On the receiver side, add all including checksum.
- Drawback: does not detect sequence errors
- Cyclic Redundancy Check (CRC)

CRC: The idea

- Cyclic Redundancy Check (CRC)
  - Given k-bit message, the transmitter creates a n-bit sequence (Frame Check Sequence) so that the resulting k + n bit frame is divisible by a predetermined number.
  - The receiver then divides the block by the number. If a residue of 0 is calculated, the test passes and it is assumed that there was no error.

CRC: The Details

- Modulo-2-arithmetic: add and substract without carry
- $T = (k + n)$-bit frame to be transmitted, $n < k$
- $M = k$-bit-message, the first k bits of T.
- $F = n$-bit-FCS, the last n bits of T
- $P =$ pattern of $n + 1$ bits, this is the divisor
- $T = 2^n M + F$

CRC: The Details (2)

$$\frac{2^n M}{P} = Q + \frac{R}{P}$$ use R as FCS

$$T = 2^n M + R$$ is this OK as FCS?

$$\frac{T}{P} = \frac{2^n M + R}{P}$$

$$\frac{T}{P} = Q + \frac{R}{P} + \frac{R}{P}$$

$$\frac{T}{P} = Q + \frac{R + R}{P} = Q$$ due to mod-2 arithmetic

CRC: What P?

- P is one bit longer than the desired FCS and both the high-order and the low-order bit of P should be 1.
- With a good P, the CRC can detect the following:
  - singe-bit errors
  - double-bit errors as long as P has at least 3 ones.
  - Any odd-number of errors as long as P contains 11 as a factor.
  - Any burst error for which the length of the burst is less than the length of P.
  - Most larger burst errors

Error Control

- Possible errors: Lost frame, damaged frame
- Error Detection
- Positive Acknowledgement
- Retransmission after timeout
- Negative acknowledgement and retransmission
- automatic repeat request (ARQ)

ARQs

- Stop-and-Wait ARQ: Each frame is acknowledged
- Go-back-N ARQ: Sliding Window Flow Control. If a damaged frame is received, the frame and all subsequent frames are retransmitted.
- Selective-Reject ARQ: Only retransmit frames with negative acknowledgements

Data Link Control Protocols

- HDLC (High-level data-link control protocol) (ISO 3009, ISO 4335)
- LAP-B (Link Access Procedure, Balanced) Subset of HDLC, used for X.25
- LAP-D (Link Access Procedure, D-Channel) by ITU-T as part of ISDN
- LLC (Link Level Control) Part of the IEEE 802 protocol family
- Frame Relay
- Asynchronous Transfer Mode

Data Link Control Protocols: HDLC

- Widely used, basis for many other data link control protocols (LAP-B, LAP-D)
- HDLC defines:
  - Three station types: Primary, Secondary, Combined
  - Two link configurations: Balanced, Unbalanced
  - Three transfer modes: Normal response mode (NBM), Asynchronous balanced mode (ABM), Asynchronous response mode (ARM)

HDLC Frame Format

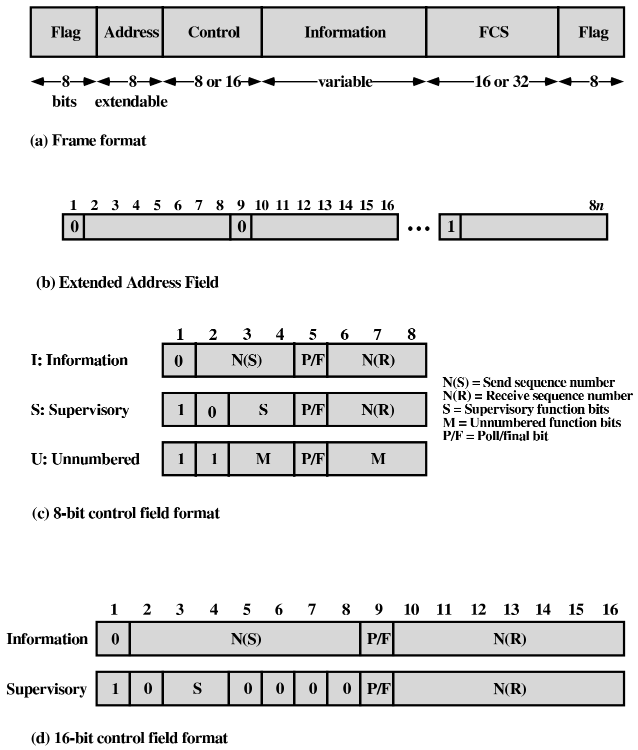
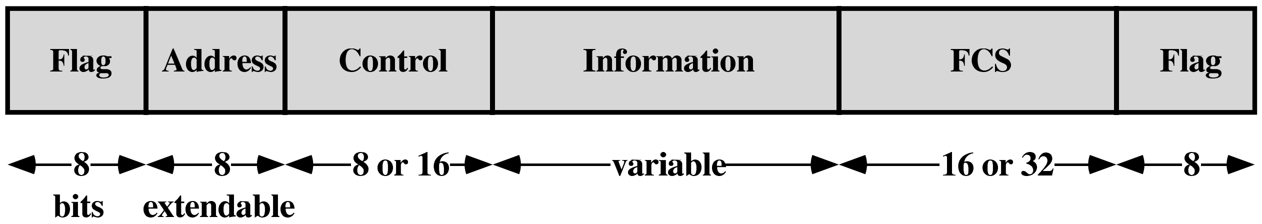


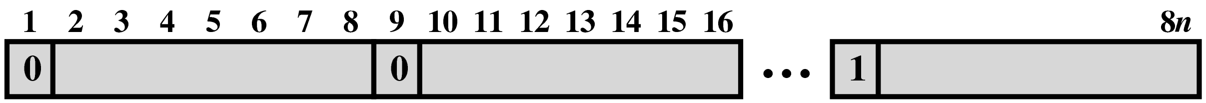
Figure 7.10 HDLC Frame Structure

HDLC Frame Format



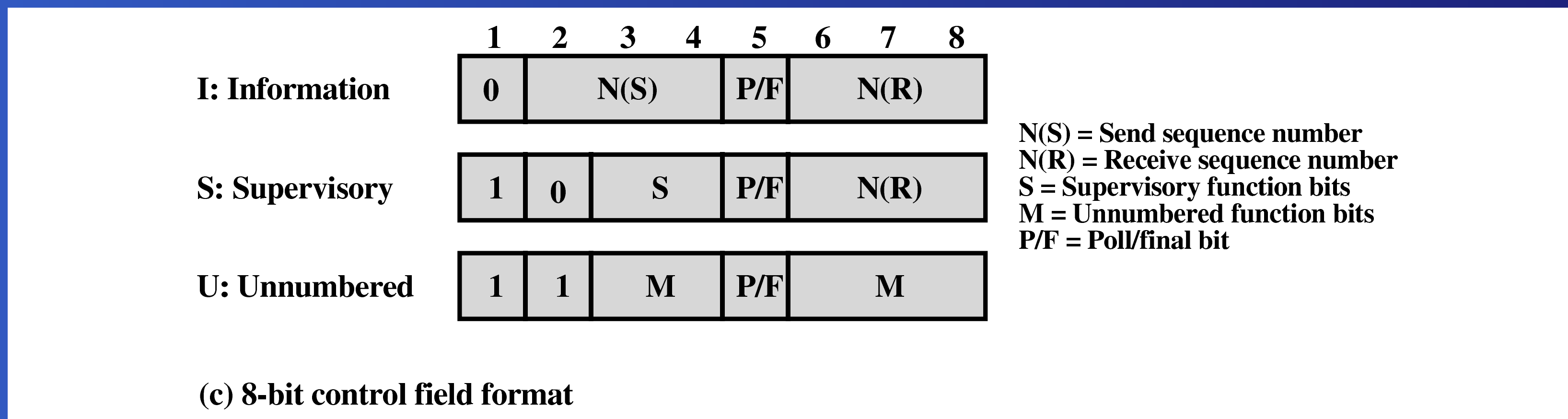
(a) Frame format

HDLC Frame Format



(b) Extended Address Field

HDLC Frame Format



HDLC Frame Format

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Information	0	N(S)							P/F	N(R)						
Supervisory	1	0	S		0	0	0	0	P/F	N(R)						

(d) 16-bit control field format

HDLC Bit Stuffing

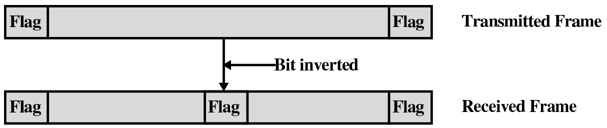
Original Pattern:

111111111111011111101111110

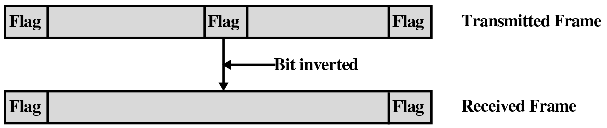
After bit-stuffing

1111101111101101111101011111010

(a) Example



(b) An inverted bit splits a frame in two



(c) An inverted bit merges two frames

Figure 7.11 Bit Stuffing

HDLC Bit Stuffing

Original Pattern:

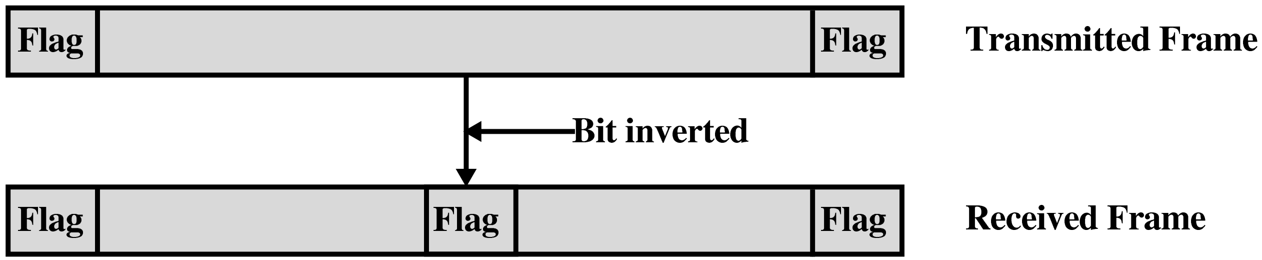
111111111111011111101111110

After bit-stuffing

1111101111101101111101011111010

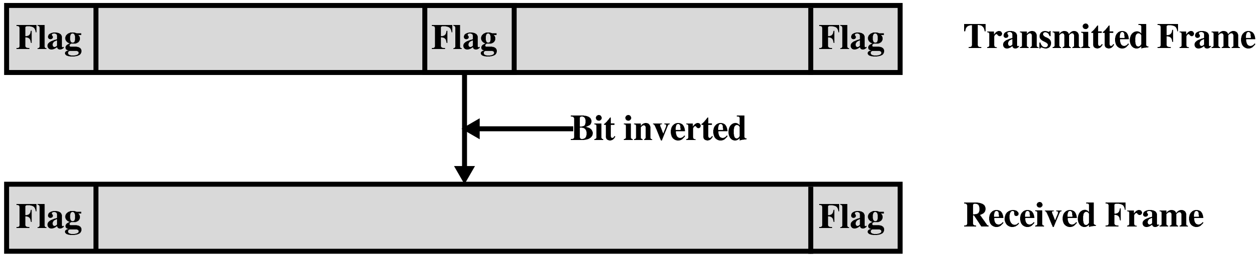
(a) Example

HDLC Bit Stuffing



(b) An inverted bit splits a frame in two

HDLC Bit Stuffing



(c) An inverted bit merges two frames

HDLC Protocol Flow

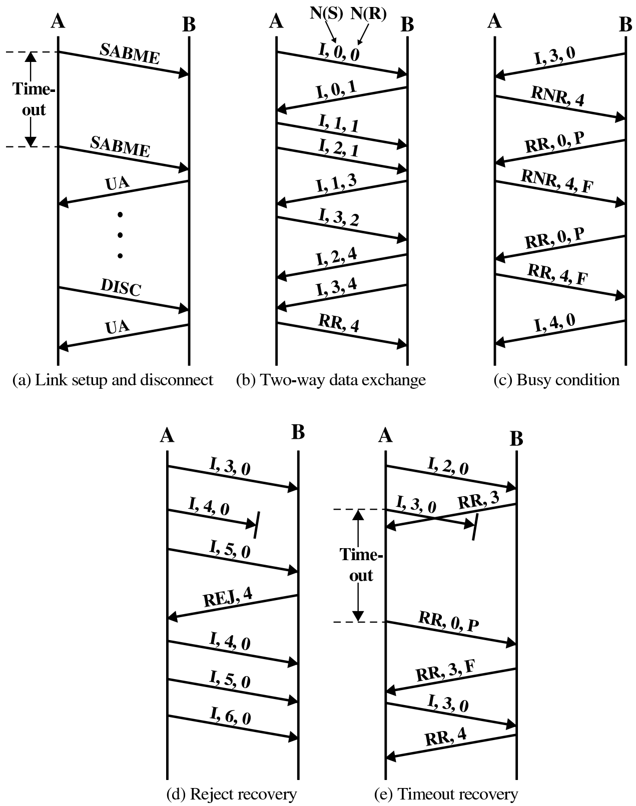
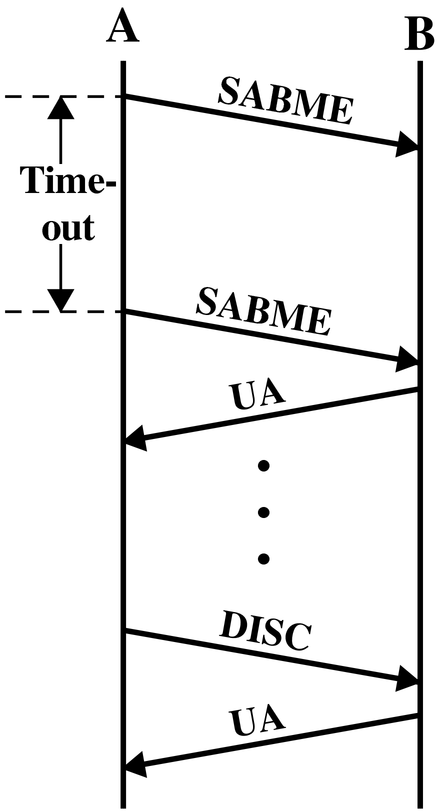


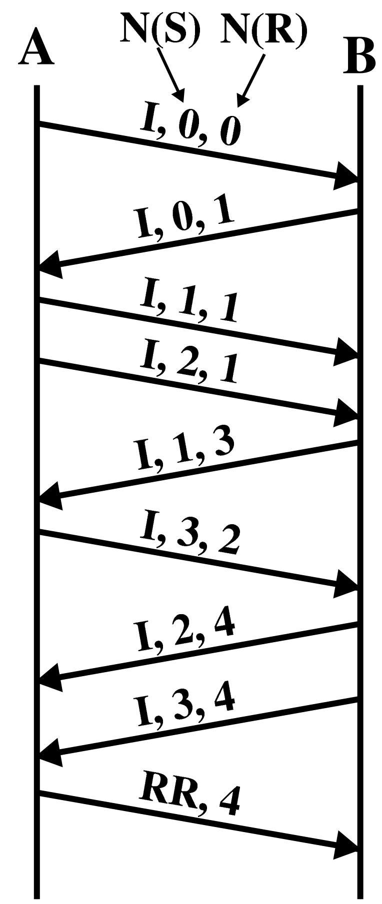
Figure 7.12 Examples of HDLC Operation

HDLC Protocol Flow



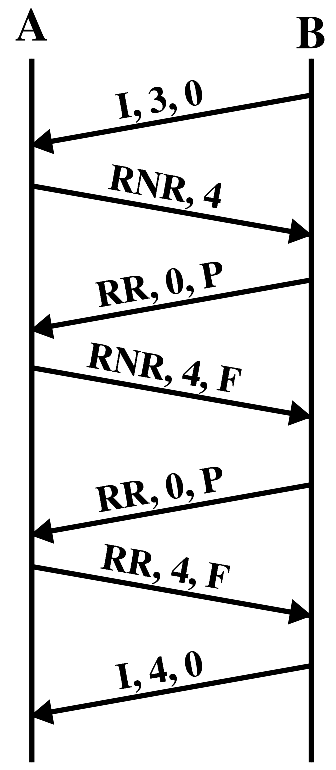
(a) Link setup and disconnect

HDLC Protocol Flow



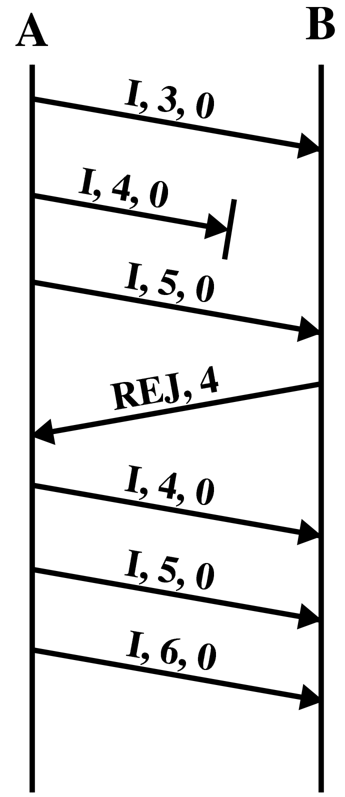
(b) Two-way data exchange

HDLC Protocol Flow



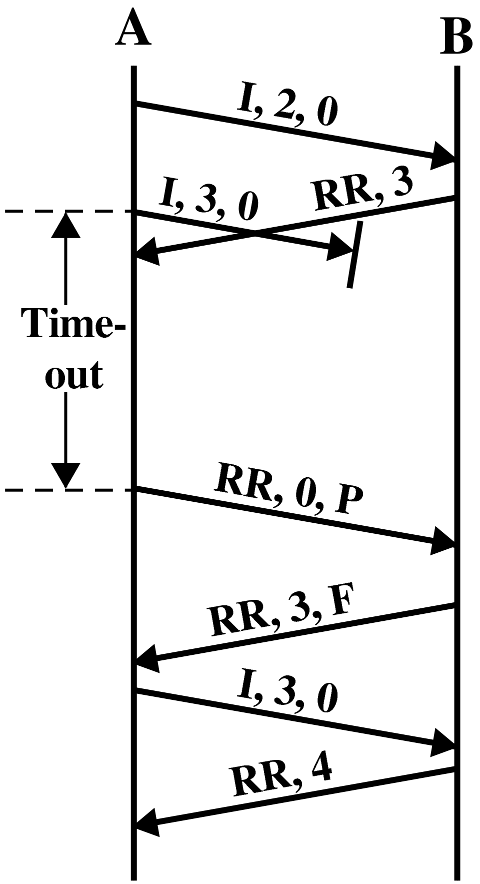
(c) Busy condition

HDLC Protocol Flow



(d) Reject recovery

HDLC Protocol Flow



(e) Timeout recovery

Link Layer: Local Area Networks

- Examples: Token Ring, Ethernet, FC-AL, Wireless LAN
- Applications: PC Lan, Storage Area Networks, High-performance computing
- Protocol Architecture: IEEE 802 Reference Architecture: MAC and LLC

IEEE 802

- Protocol Architecture: IEEE 802 Reference Architecture
  - physical layer (as in OSI)
  - medium access control (MAC) : Assemble frames, control access to communication media, disassemble frames and check for errors.
  - logical link control (LLC) : Perform flow and error control, provide interface to higher layers

Ethernet in the protocol context

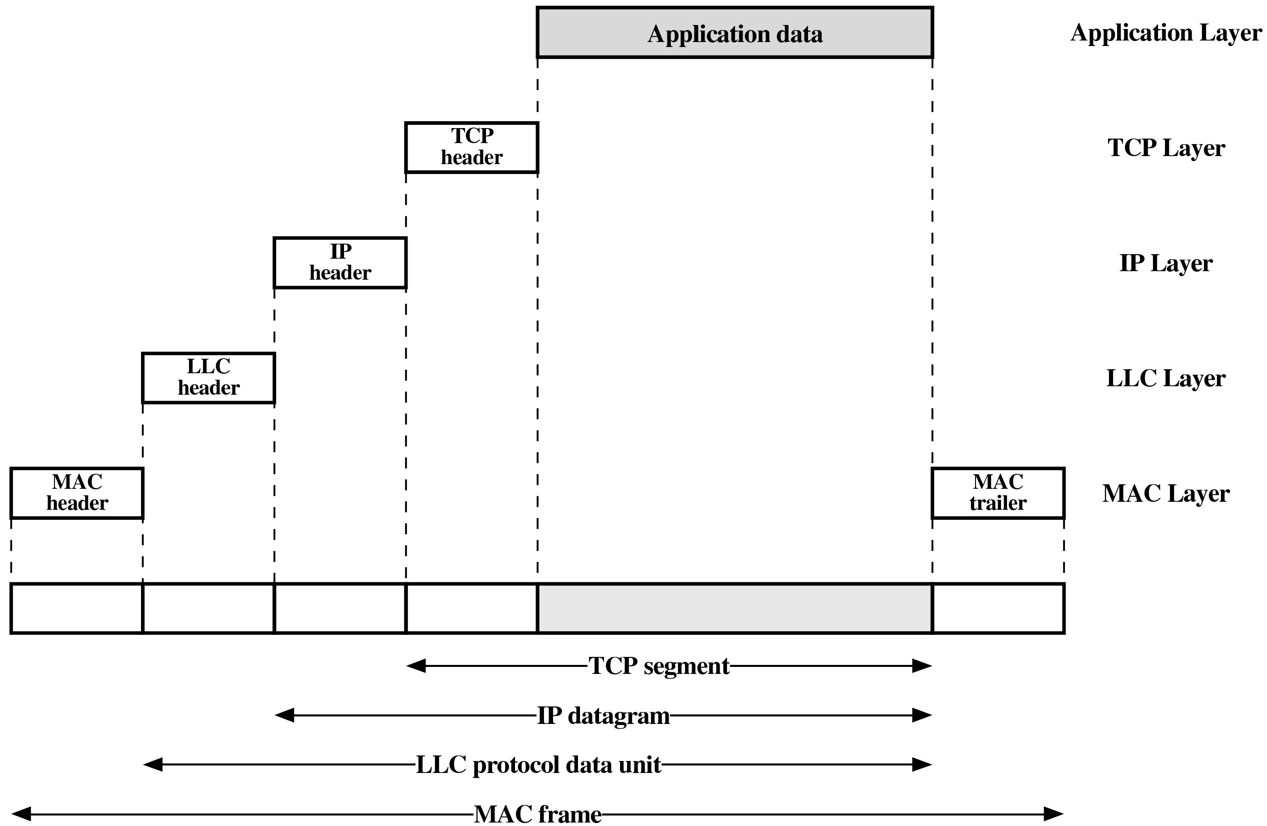


Figure 13.2 LAN Protocols in Context

LAN topologies

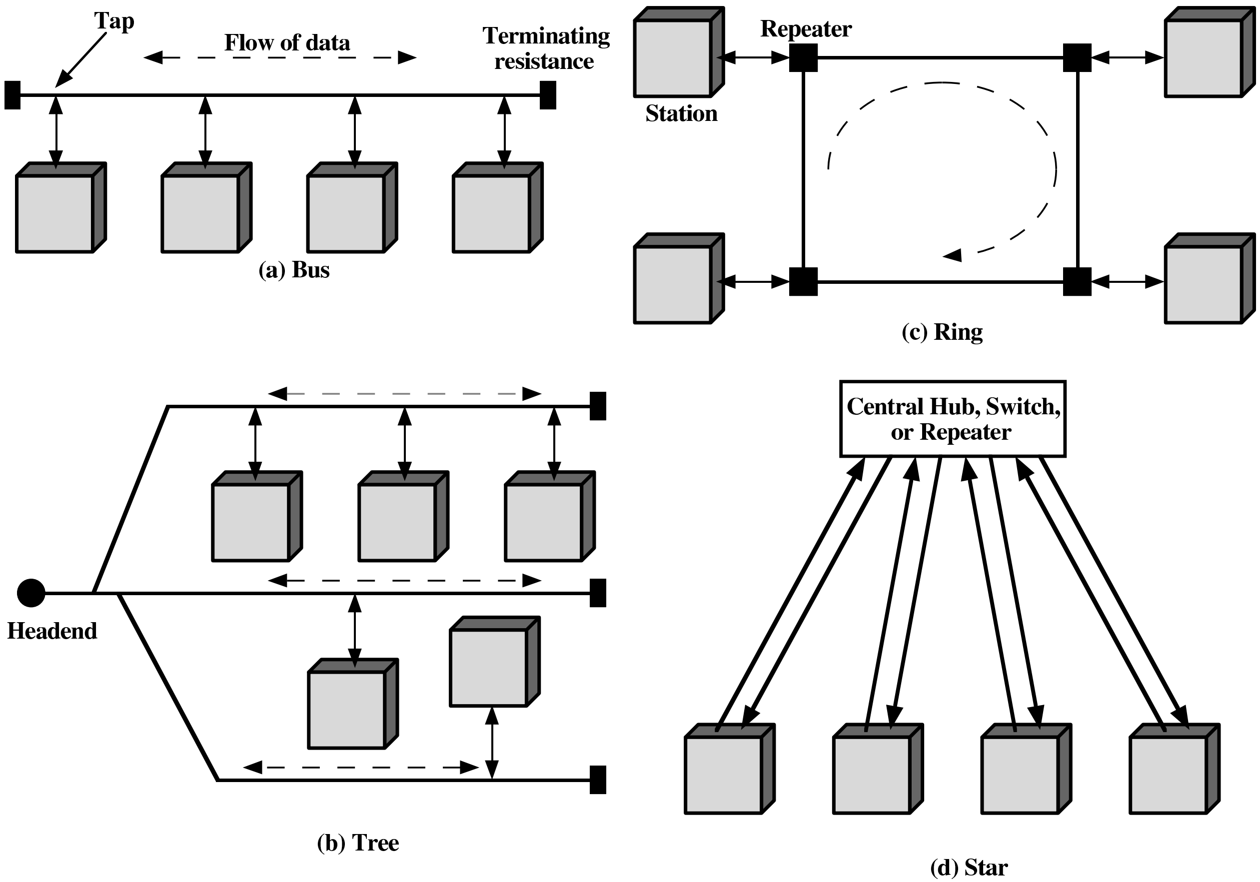
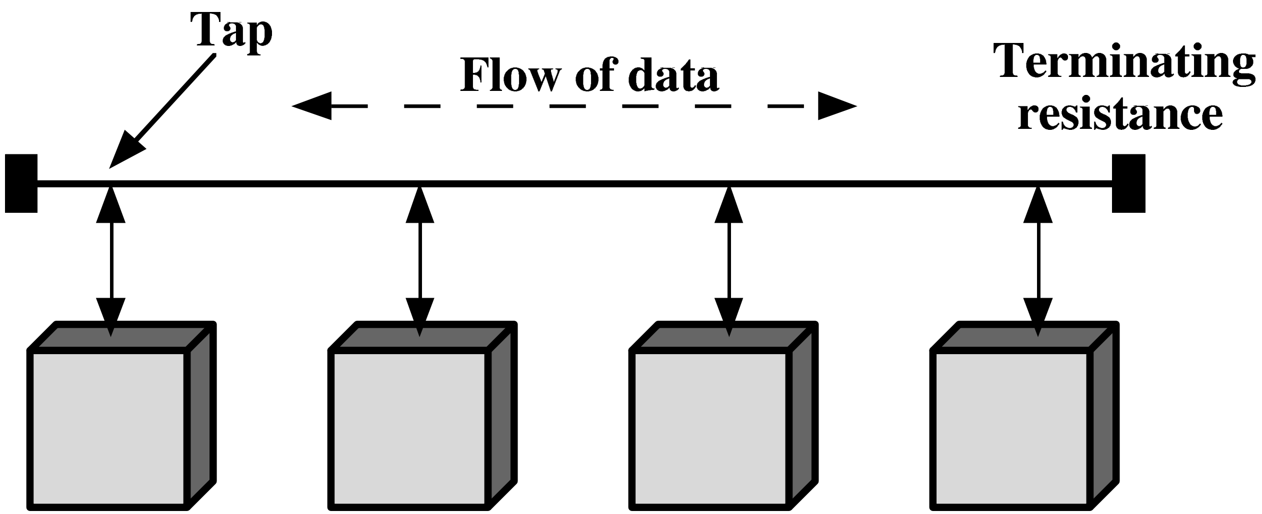


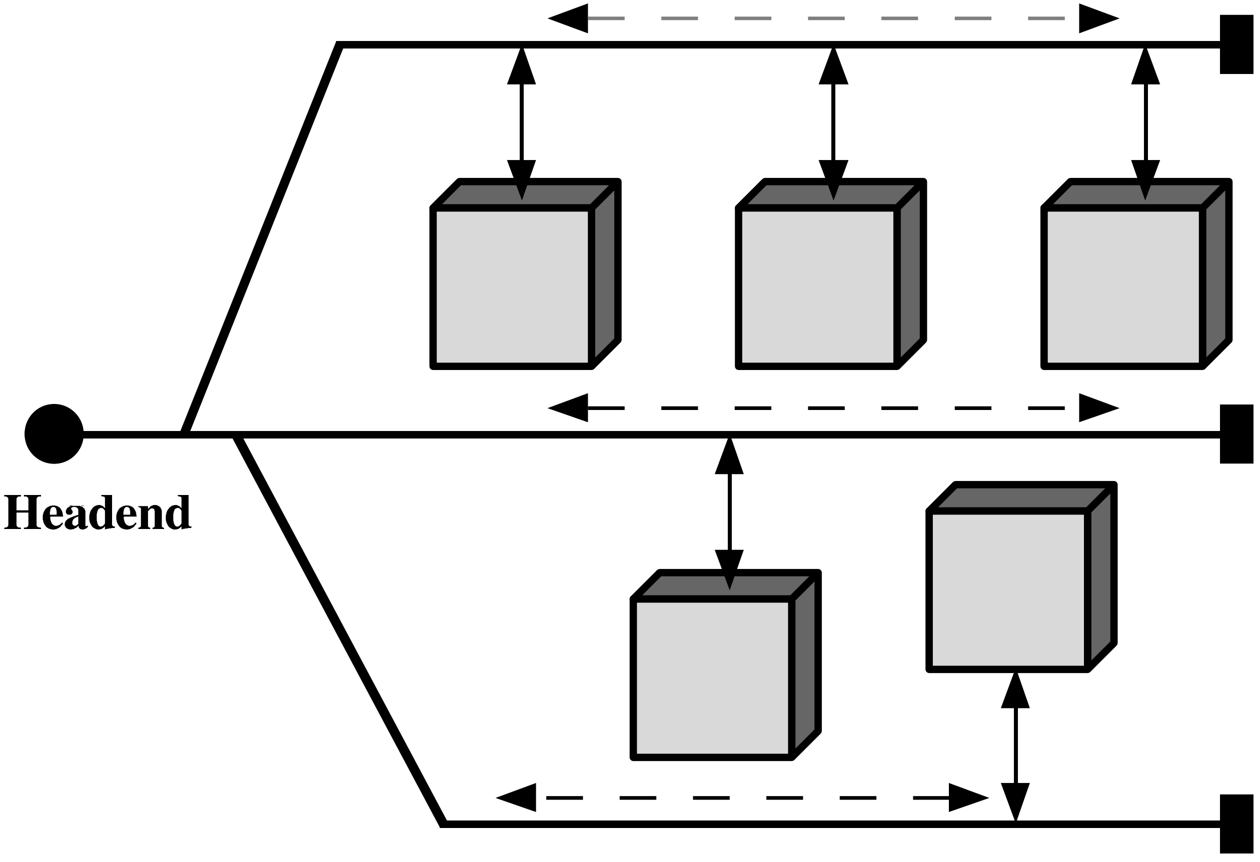
Figure 13.3 Local Area Network Topologies

LAN topologies



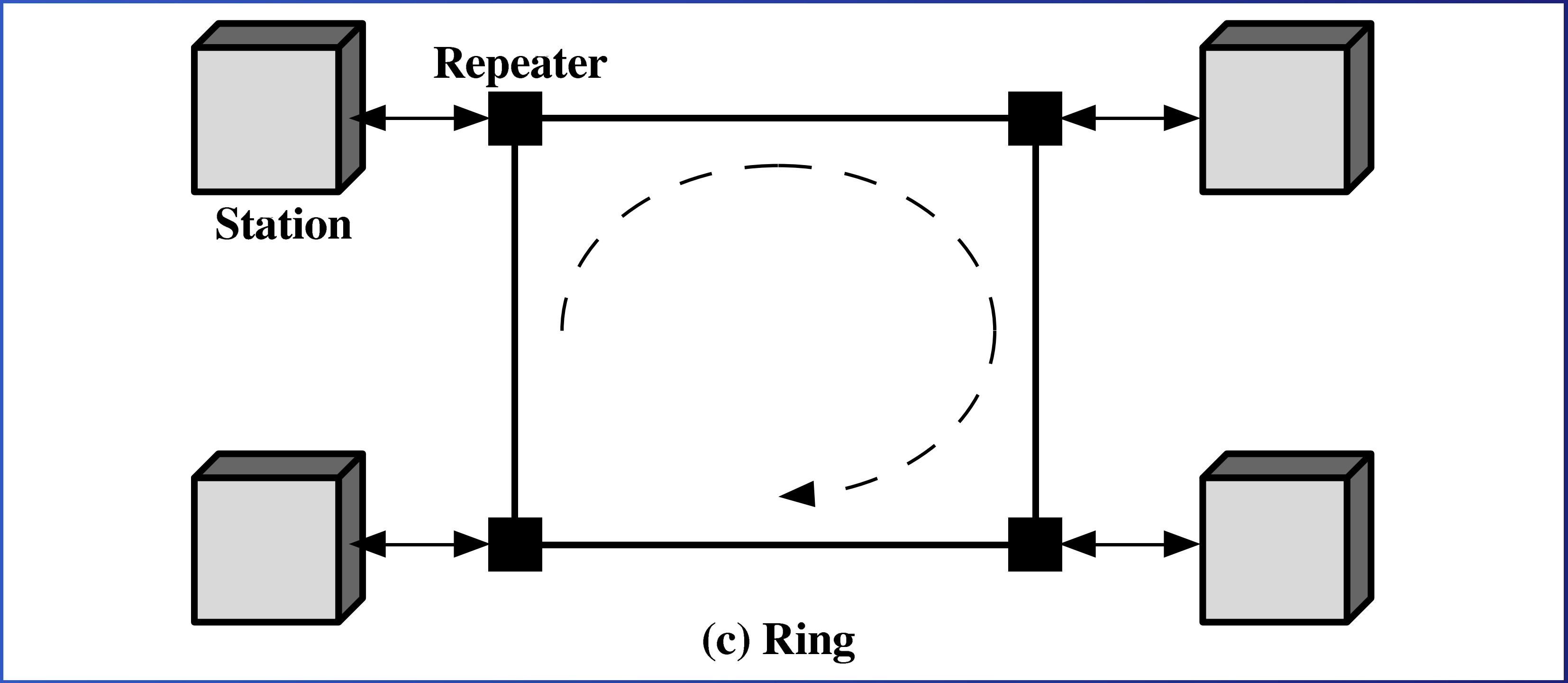
(a) Bus

LAN topologies

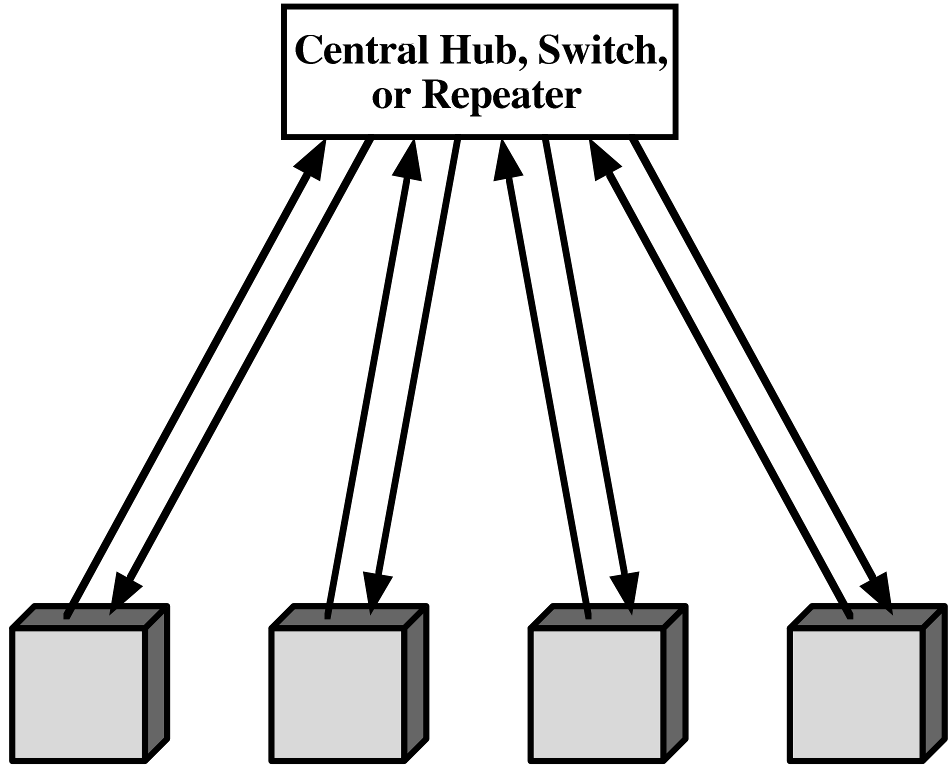


(b) Tree

LAN topologies



LAN topologies



(d) Star

Medium Access Control

- Round Robin: Token Bus (IEEE 802.4), Token Ring (IEEE 802.5). Request/priority (IEEE802.12)
- Reservation: rarely implemented in LANs (IEEE 802.6: DQDB)
- Contention: CSMA/CD (IEEE 802.3), CSMA(/CA) (IEEE 802.11)

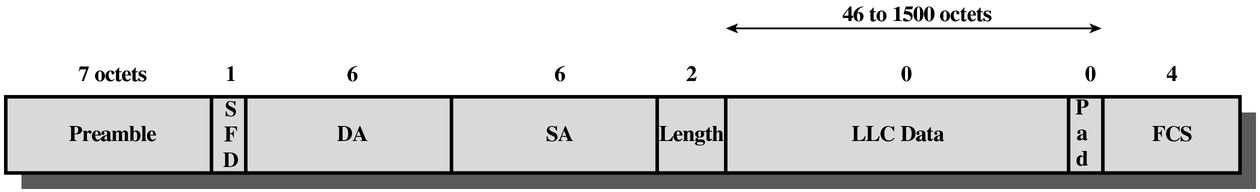
Ethernet

- Standards: IEEE 802
- Ethernet on cables: IEEE 802.3
- different standards/cables/speeds/connectors...
- 10BASE5: Yellow Cable, 10 mbps (old)
- 1000Base-SX: Multimode Glassfiber, 1000 Mbps, 770-860 nm wavelength (IUB Backbone)

Ethernet Frames

- Preamble and SFD
- Destination Address: 48 Bit
- Source Address: 48 Bit
- Length/Type Code: 16 Bit
- LLC Data
- Ethernet Checksum: 32 Bits
- length: 64 to 1518 bytes (excluding SFD and preamble)

Ethernet Frame



SFD = Start of frame delimiter
DA = Destination address
SA = Source address
FCS = Frame check sequence

Figure 14.2 IEEE 802.3 Frame Format

Other things to know about Ethernet

- Special Address: ff:ff:ff:ff:ff:ff (Broadcast address)
- CSMA/CD (Carrier Sensed Multiple Access / Collision Detect)
- Length Limits depending on cable types/ethernet standard
- Number of stations sometimes limited (in bus connections)
- Ethernet Repeaters connect segments
- Ethernet Bridges connect collision domains

CSMA/CD

1. If the medium is idle, transmit
2. If the medium is busy, wait for the medium to become idle, then transmit immediately
3. Listen while transmitting. If a colision is detected, transmit a brief jamming signal (so that everybody notices the collision) and then stop.
4. Wait a random amount of time, then try again from step 1

CSMA/CD Operation

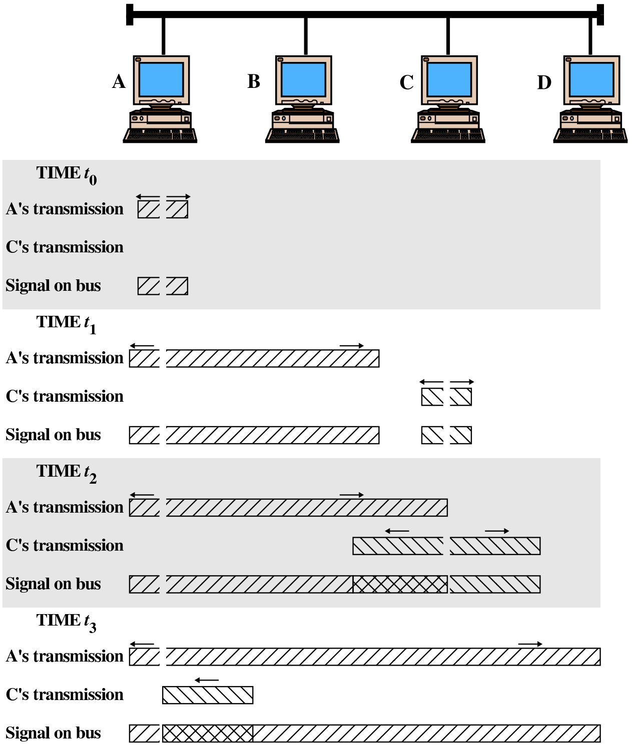


Figure 14.1 CSMA/CD Operation

Token Ring (IEEE 802.5)

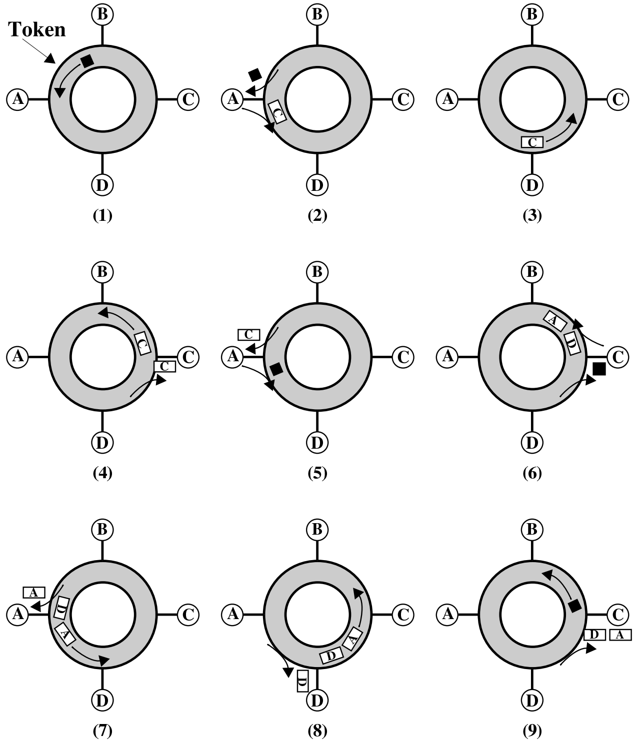
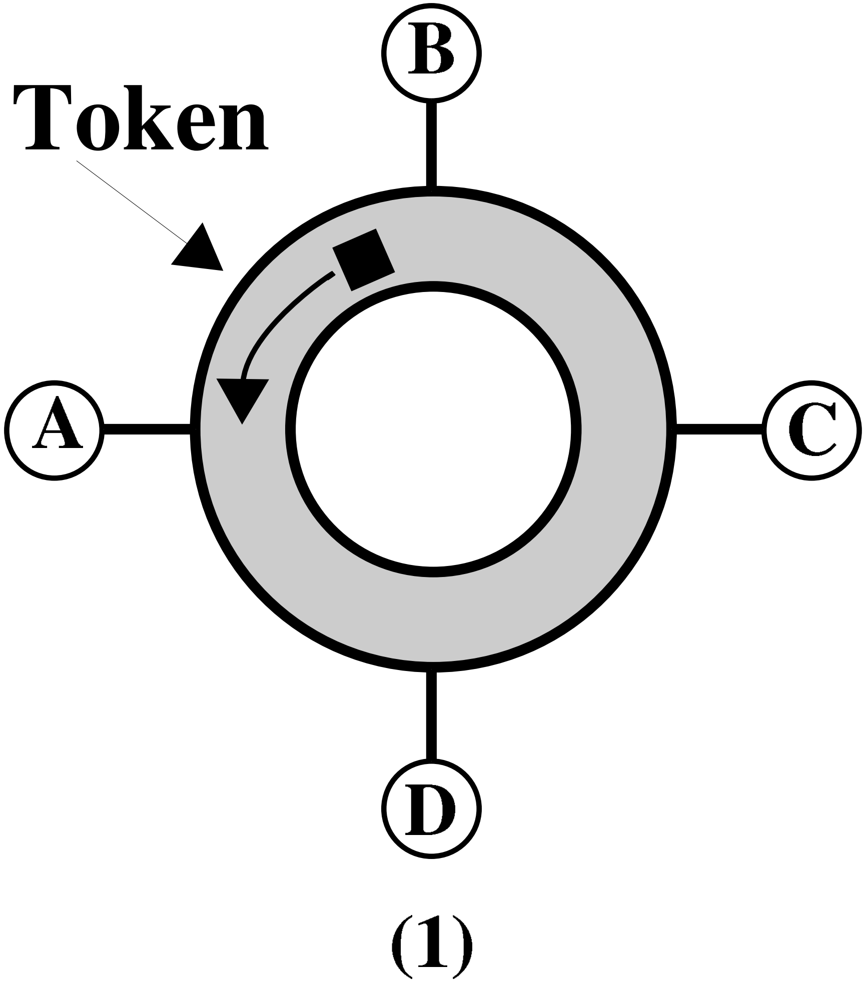
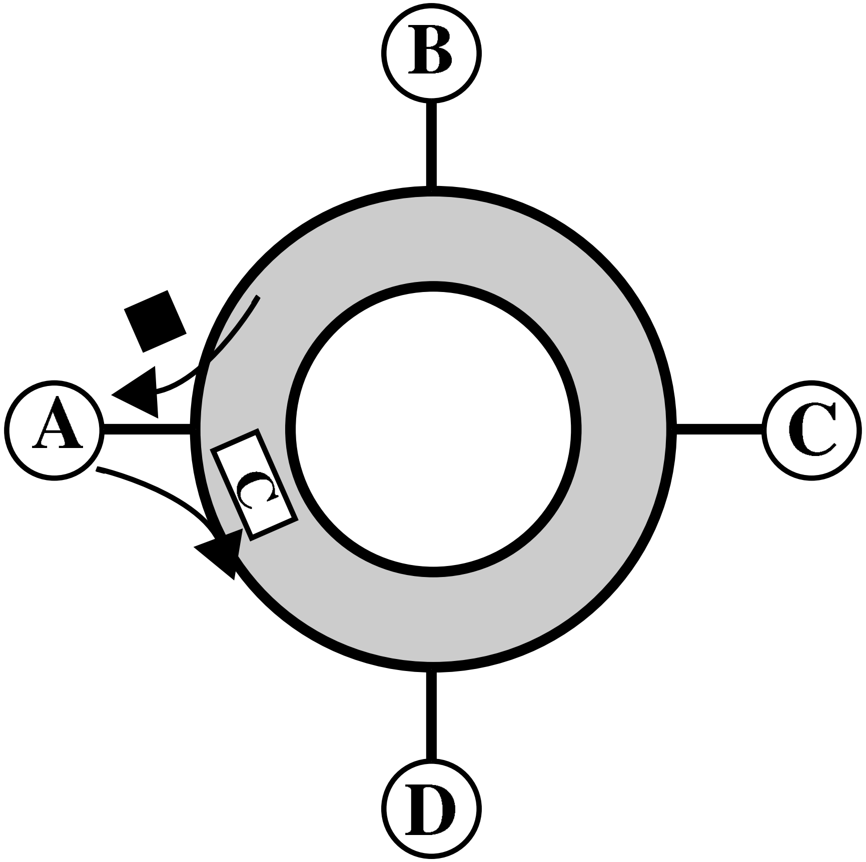


Figure 14.5 Token Ring Operation

Token Ring (IEEE 802.5)

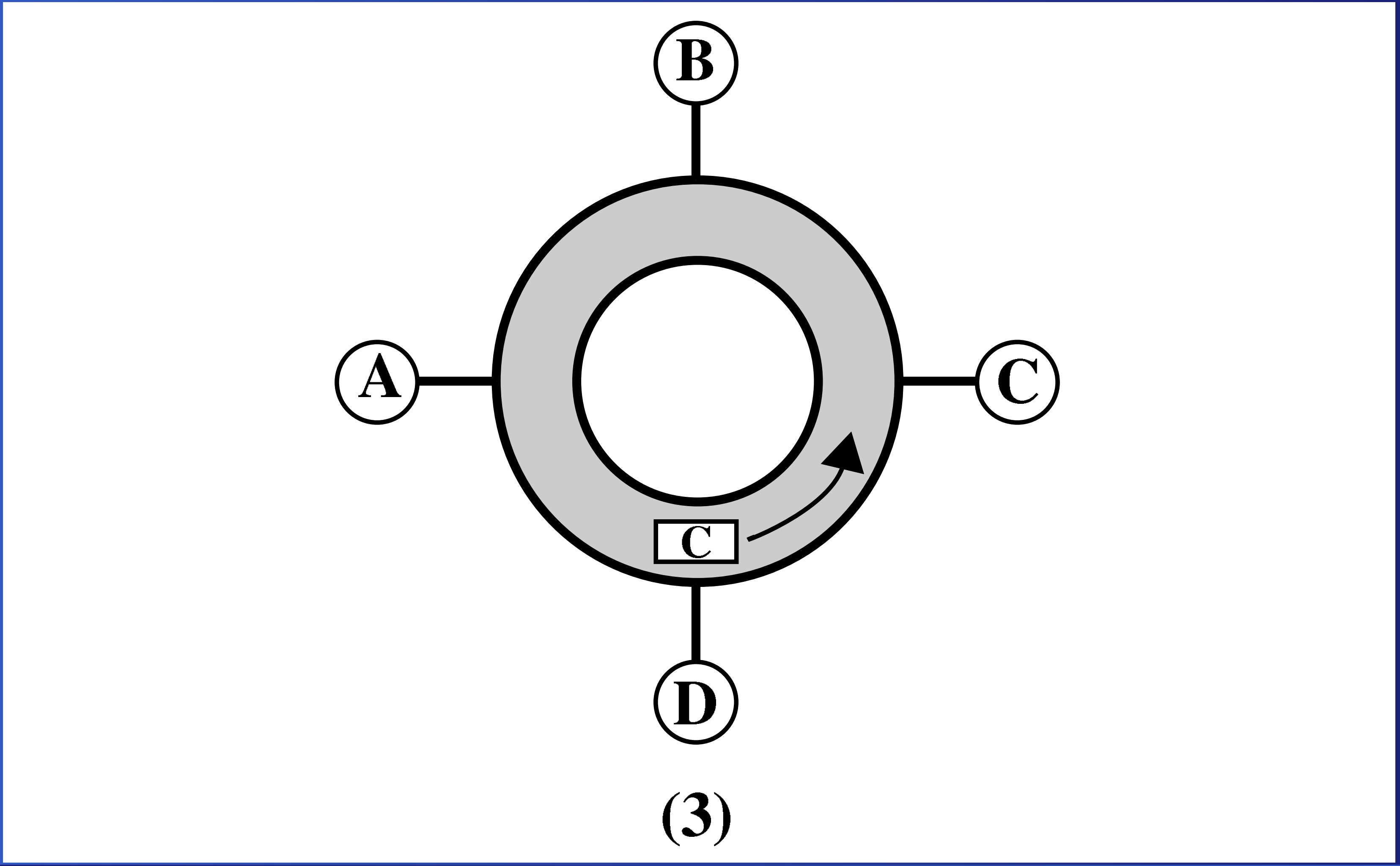


Token Ring (IEEE 802.5)

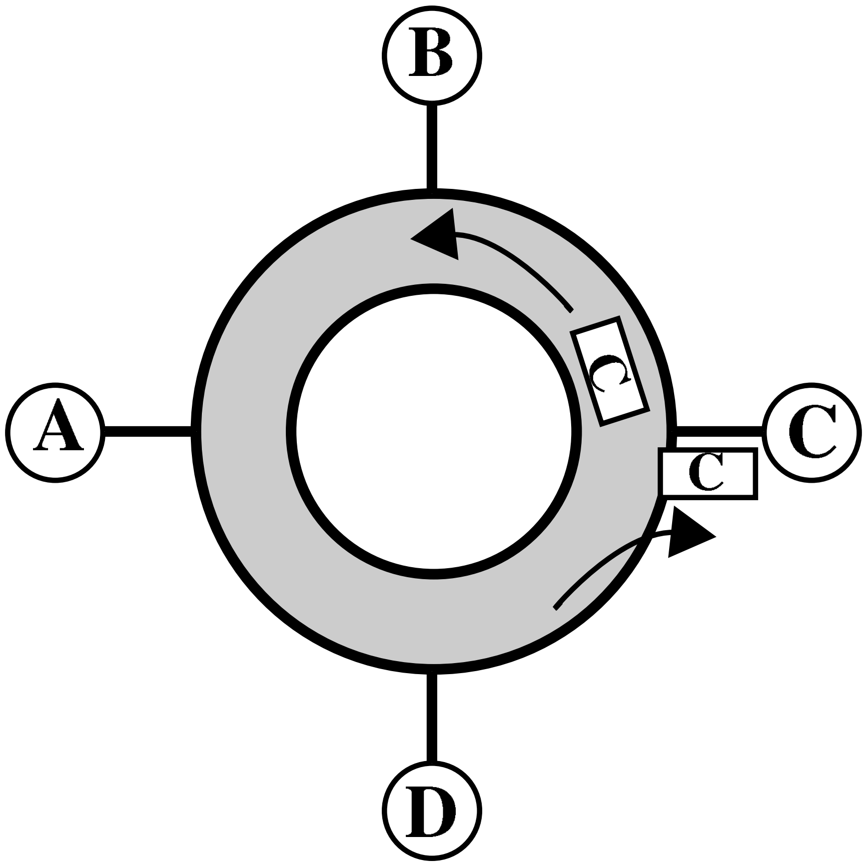


(2)

Token Ring (IEEE 802.5)

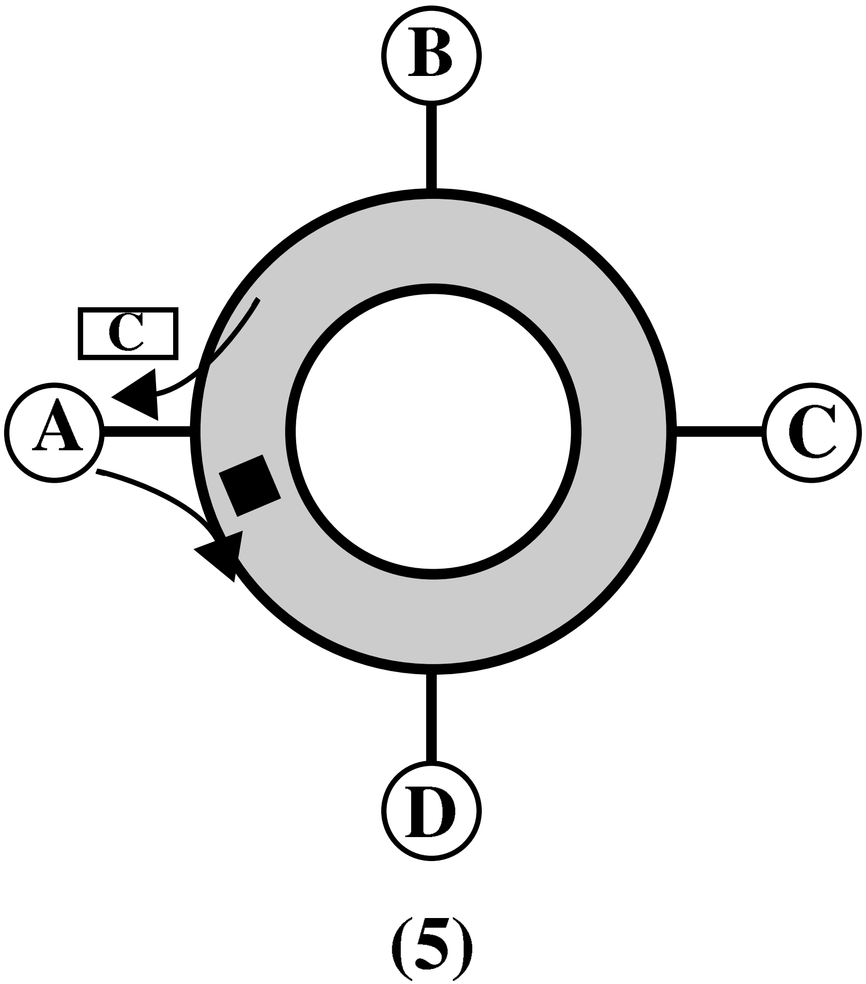


Token Ring (IEEE 802.5)

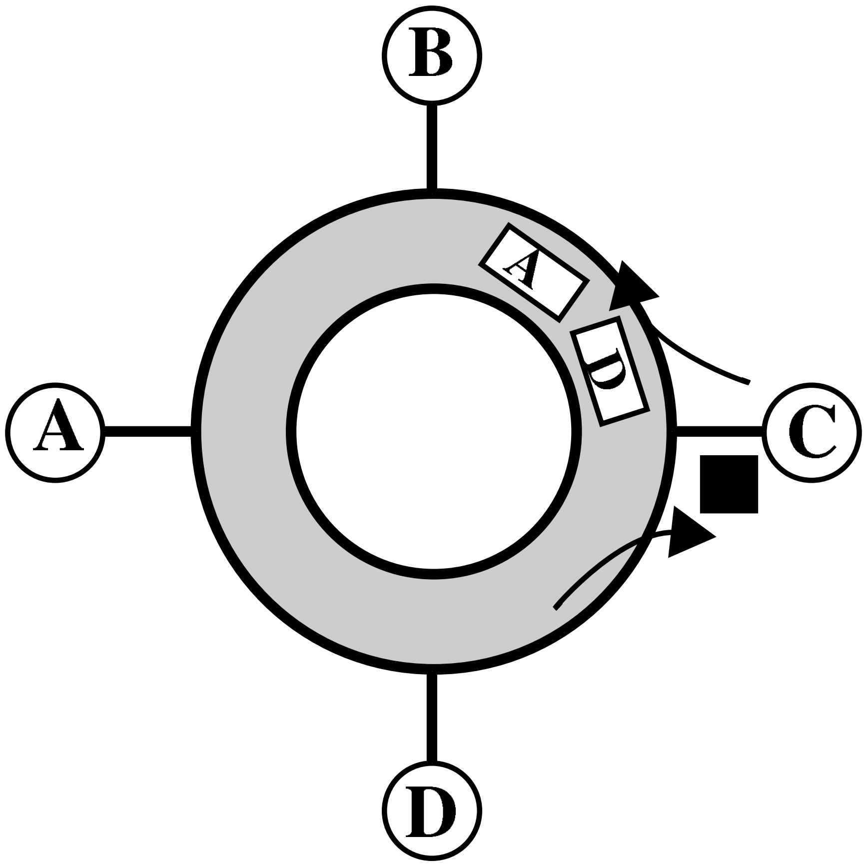


(4)

Token Ring (IEEE 802.5)

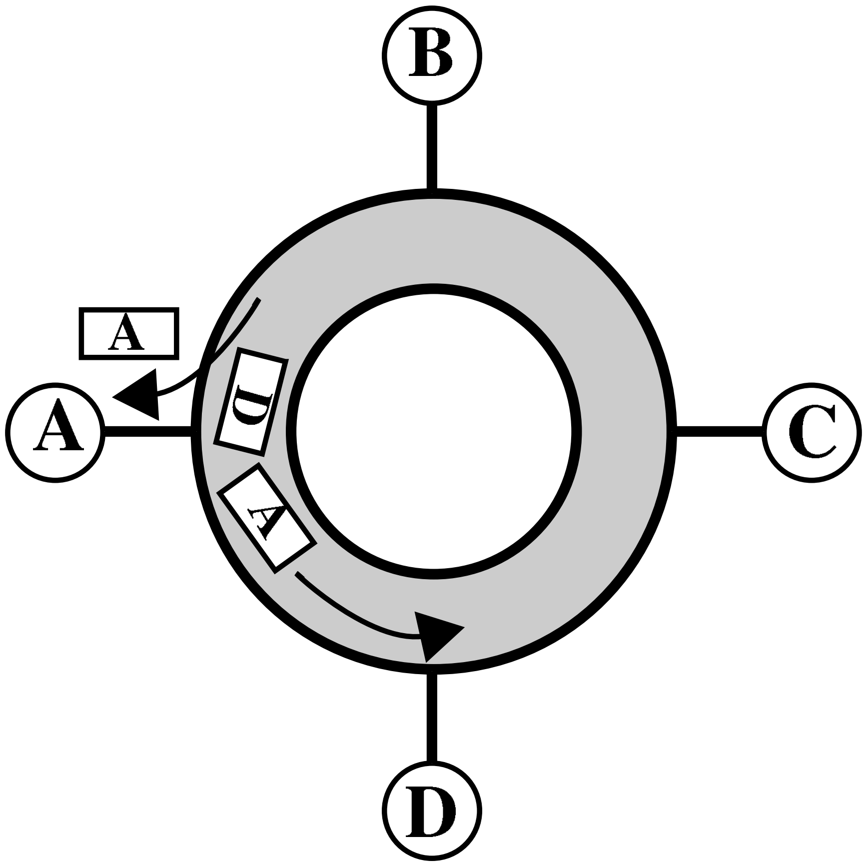


Token Ring (IEEE 802.5)



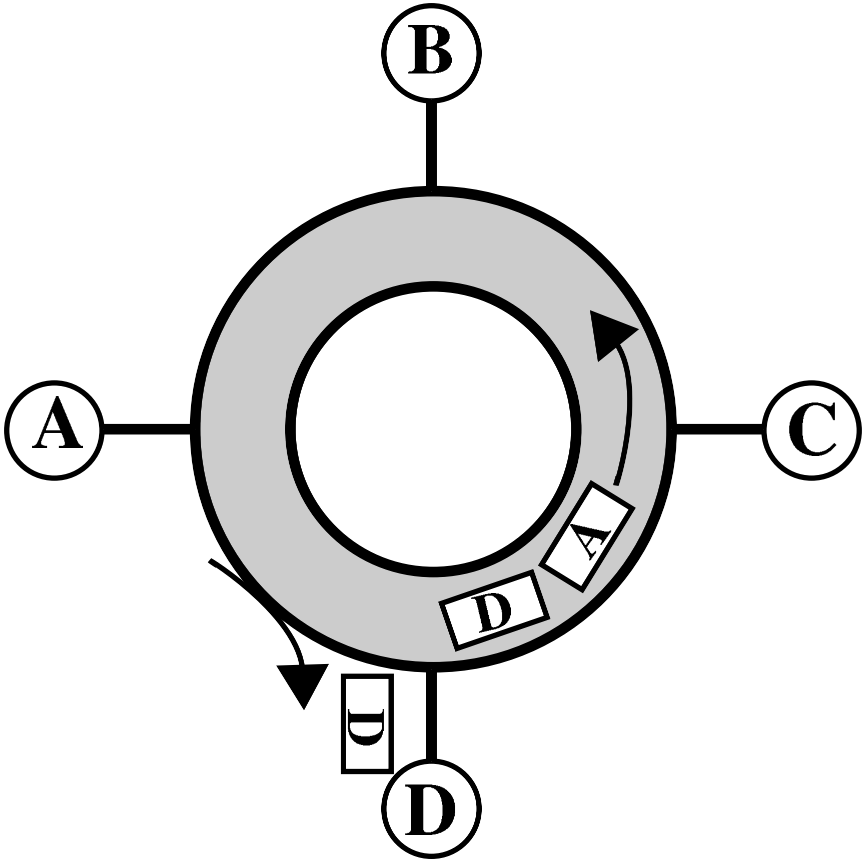
(6)

Token Ring (IEEE 802.5)



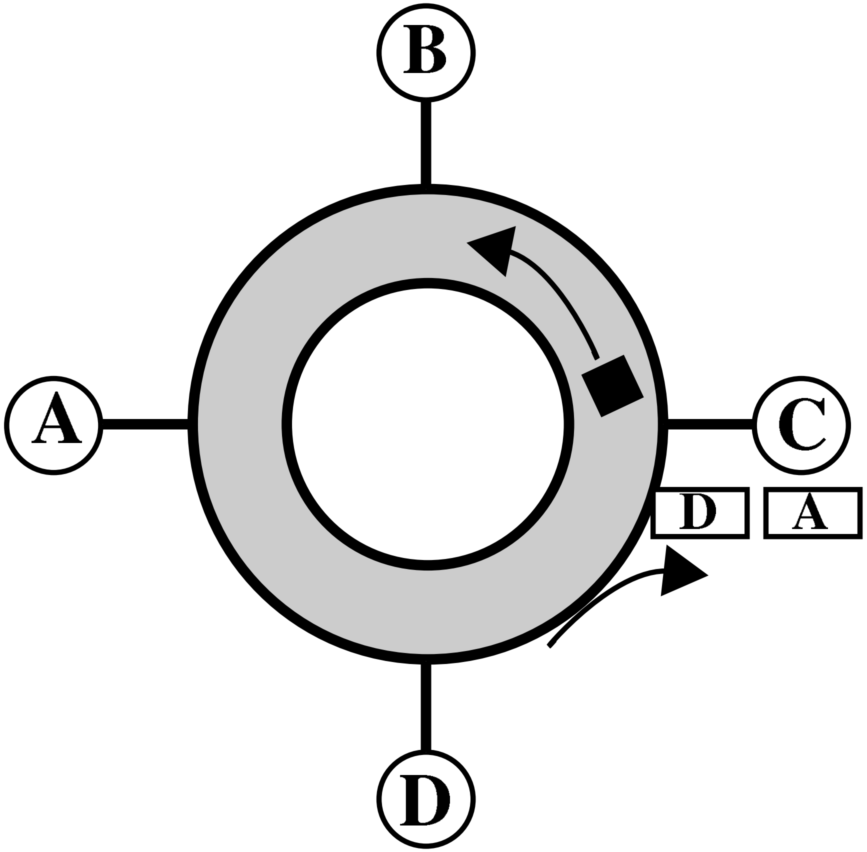
(7)

Token Ring (IEEE 802.5)



(8)

Token Ring (IEEE 802.5)



(9)

Token Ring Frame Format

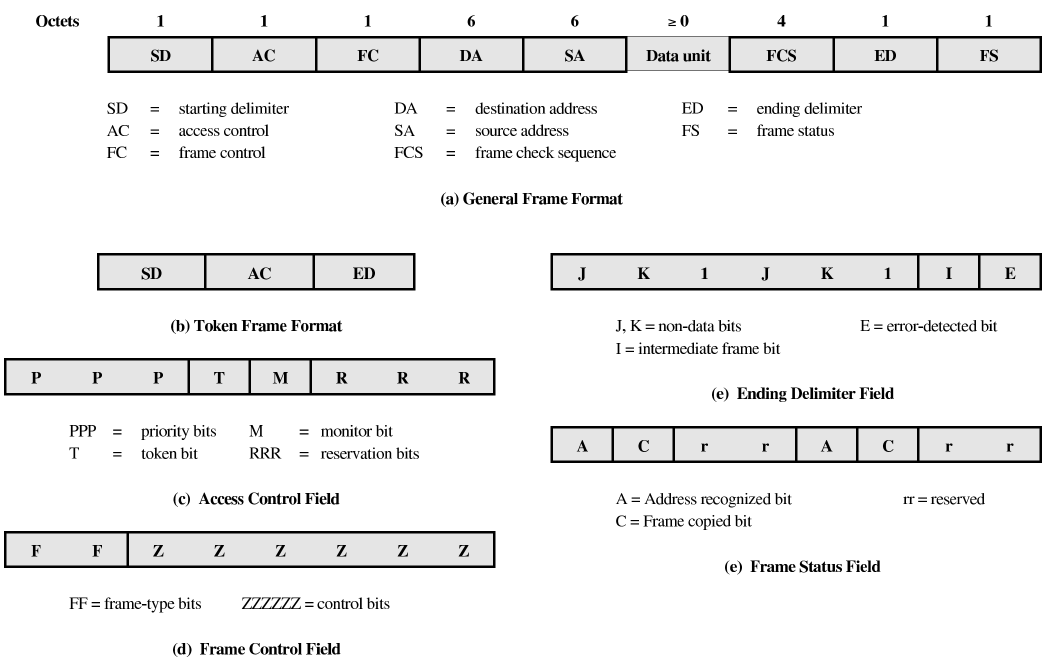


Figure 14.6 IEEE 802.5 Frame Format

Bridges

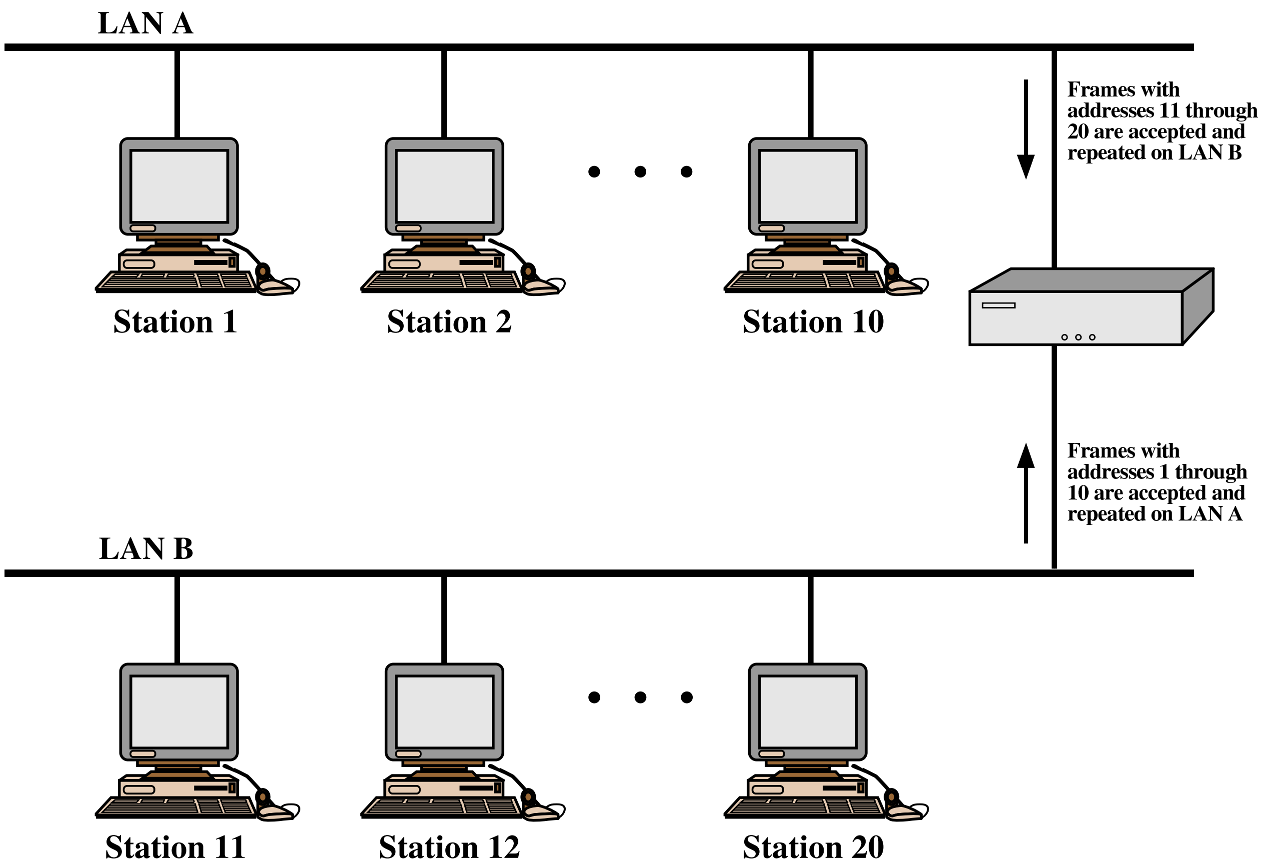


Figure 13.14 Bridge Operation

Bridges: Internal

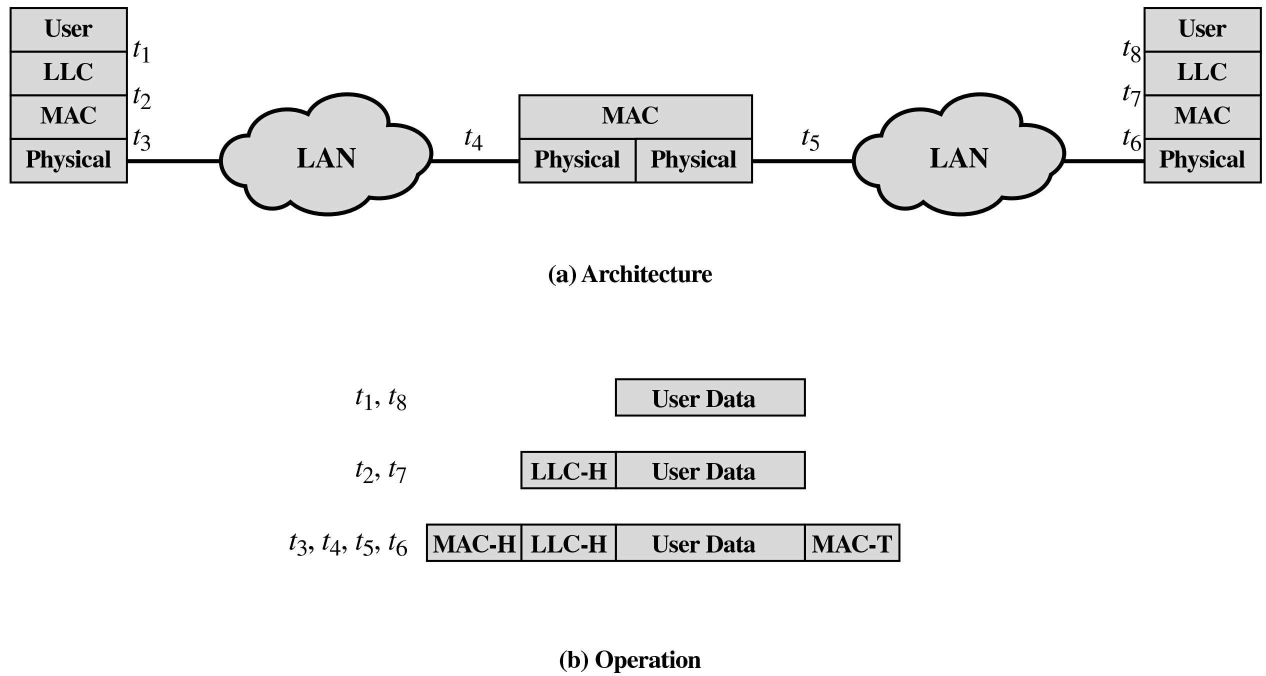


Figure 13.15 Connection of Two LANs by a Bridge

System of Bridges

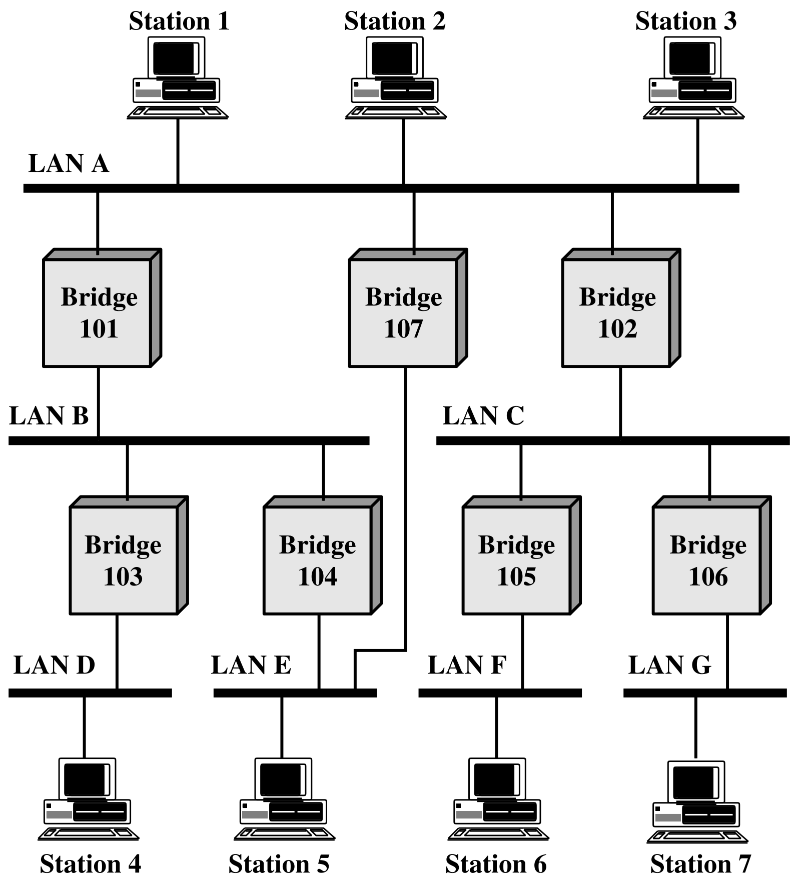


Figure 13.16 Configuration of Bridges and LANs, with Alternate Routes

Loop of Bridges

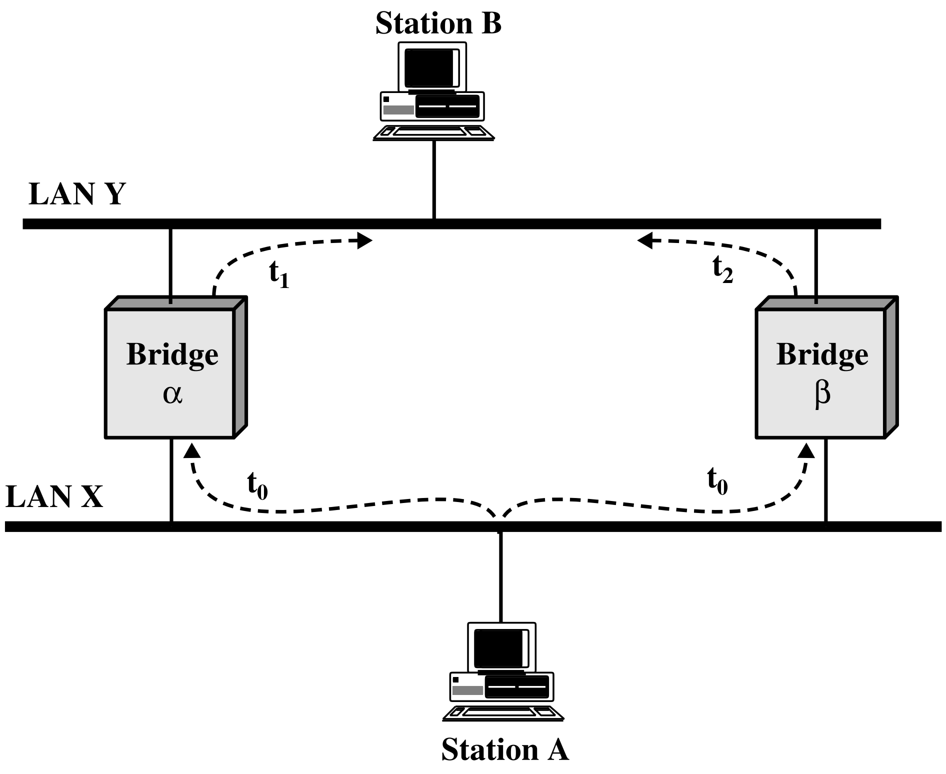


Figure 13.17 Loop of Bridges

TCP/IP

- IP: Internet Protocol
- TCP: Transmission Control Protocol
- Many other protocols: ICMP,IGMP,OSPF,RSVP,FTP,BGP,UDP,ARP,SMTP,MIME, SNMP,HTTP,Sun-RPC,POP-3,IMAP,XNTP,. . .
- Standardization by IETF RFCs
- IP: Two Versions IPv4, IPv6
- IPv4: currently used, IPv6 about to be introduced

TCP/IP Protocol Context

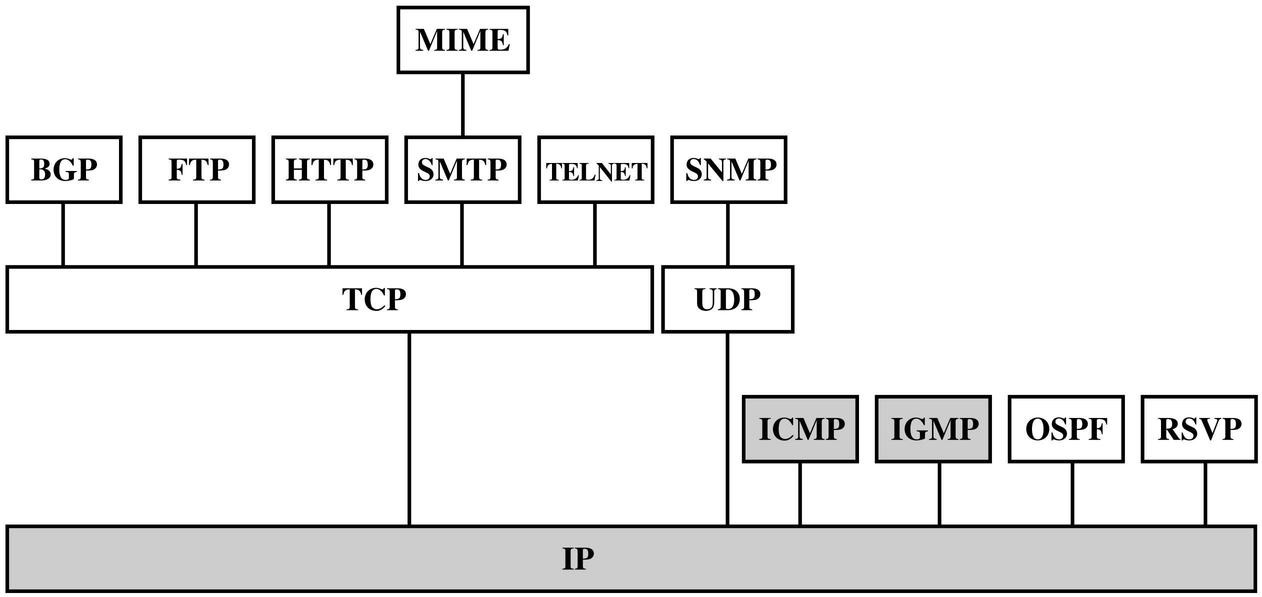
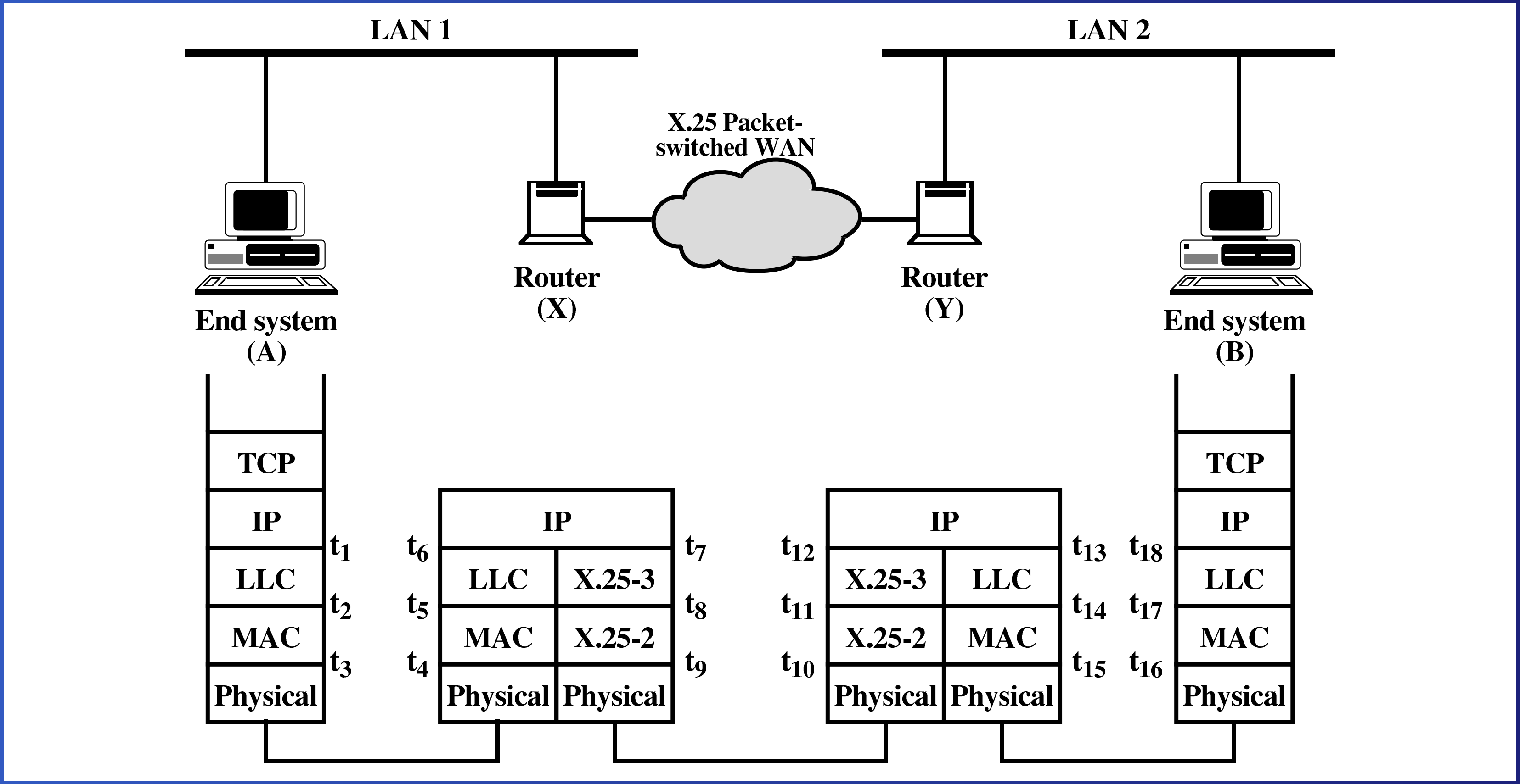


Figure 15.1 Internetworking Protocols in Context

TCP/IP Operation



Internetworking design issues

- Routing
- Datagram Lifetime
- Fragmentation and Reassembly
- Error Control
- Flow Control

IP V4 Header

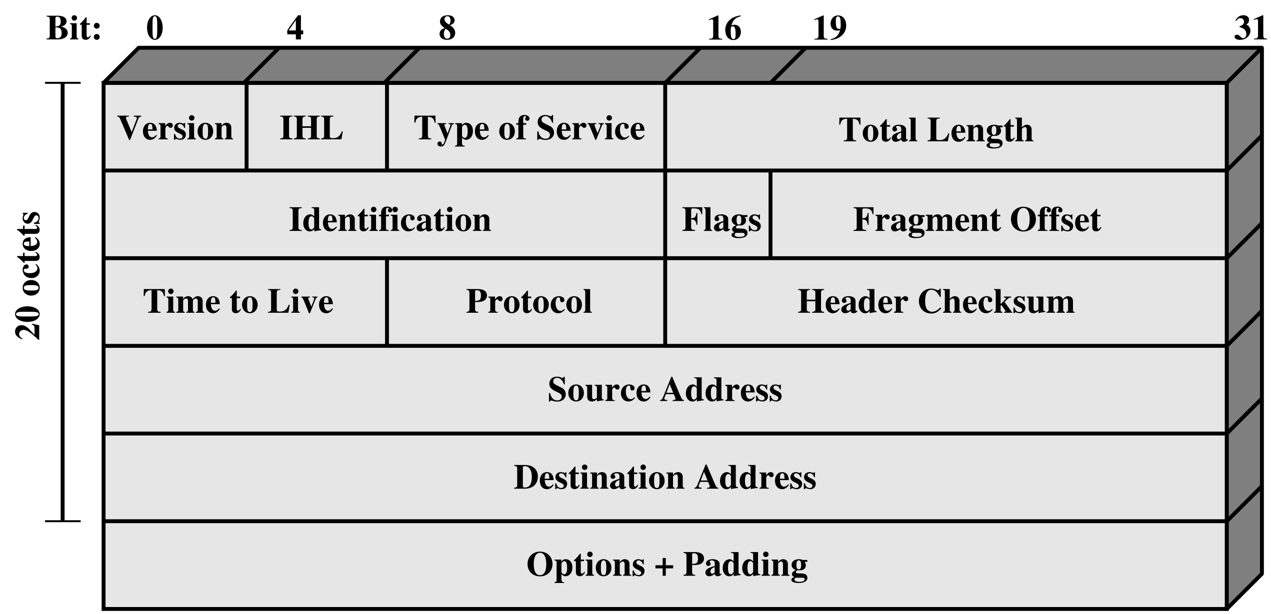


Figure 15.6 IPv4 Header

IP V4 Addressing

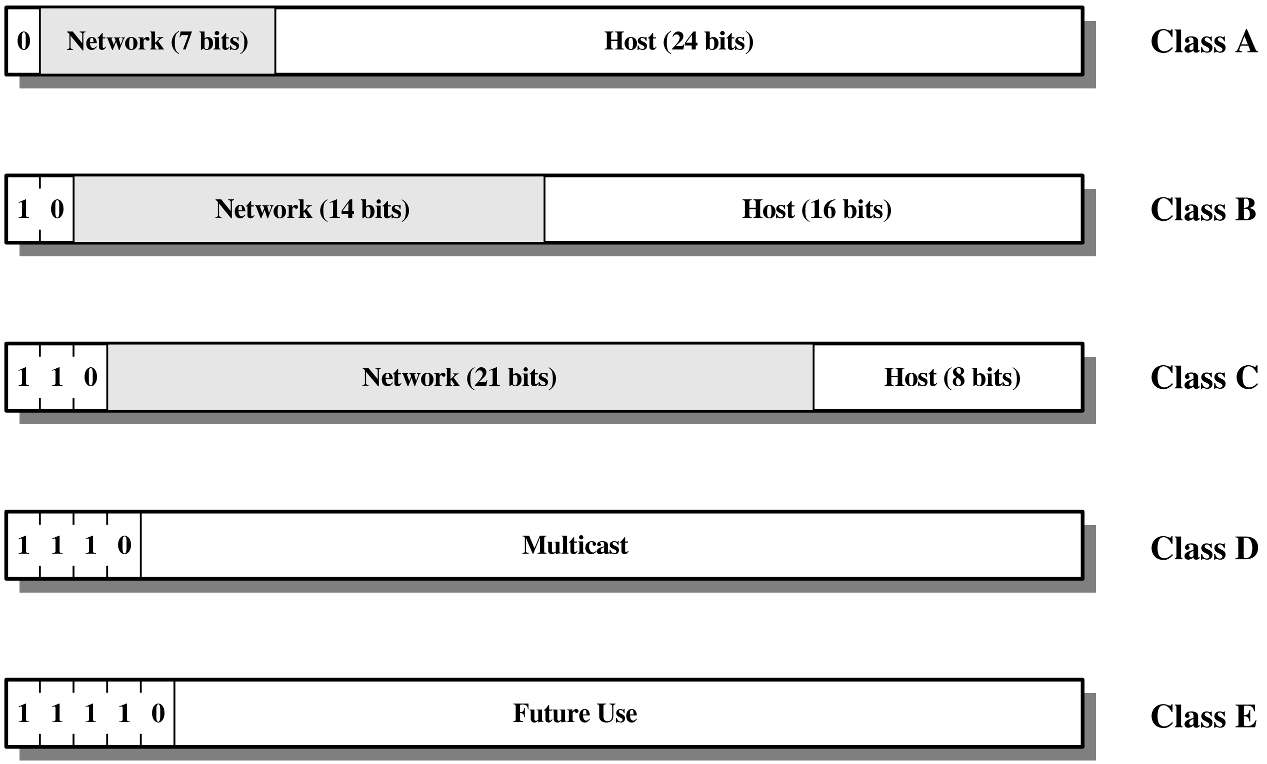


Figure 15.7 IP Address Formats

Subnetting

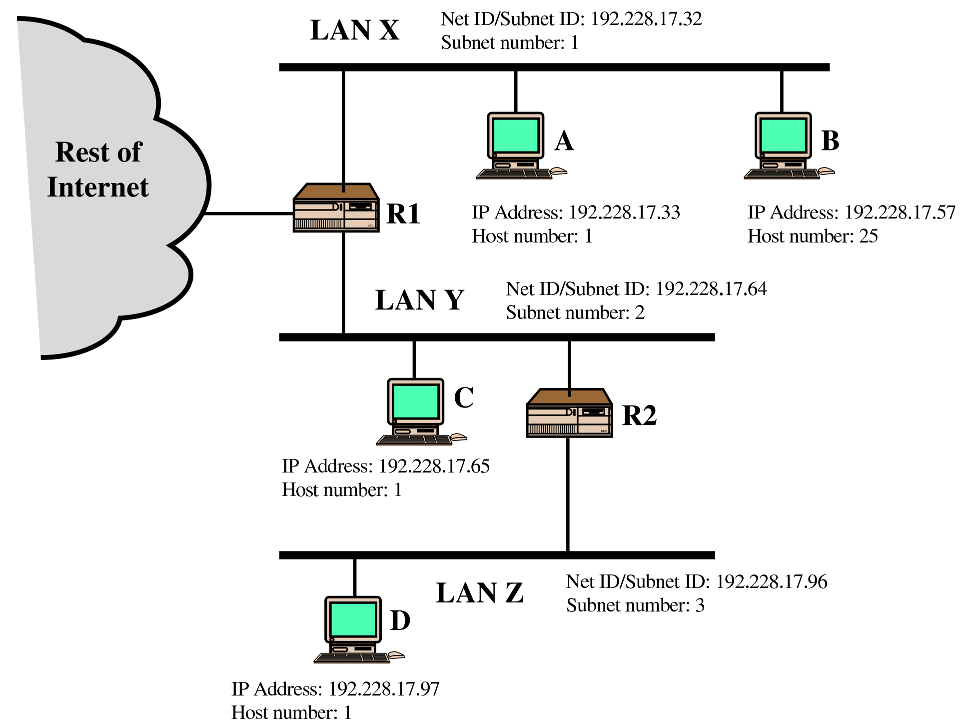


Figure 15.8 Example of Subnetworking

ICMP

0	8	16 – 31
Type	Code	Checksum
Unused		
IP Header + 64 bits of original datagram		

(a) Destination Unreachable; Time Exceeded; Source Quench

0	8	16 – 31
Type	Code	Checksum
Pointer	Unused	
IP Header + 64 bits of original datagram		

(b) Parameter Problem

0	8	16 – 31
Type	Code	Checksum
Gateway Internet Address		
IP Header + 64 bits of original datagram		

(c) Redirect

0	8	16 – 31
Type	Code	Checksum
Identifier		Sequence Number
Optional data		

(d) Echo, Echo Reply

0	8	16 – 31
Type	Code	Checksum
Identifier		Sequence Number
Originate Timestamp		

(e) Timestamp

0	8	16 – 31
Type	Code	Checksum
Identifier		Sequence Number
Originate Timestamp		
Receive Timestamp		
Transmit Timestamp		

(f) Timestamp Reply

0	8	16 – 31
Type	Code	Checksum
Identifier		Sequence Number

(g) Address Mask Request

0	8	16 – 31
Type	Code	Checksum
Identifier		Sequence Number
Address Mask		

(h) Address Mask Reply

Figure 15.9 ICMP Message Formats

IPv6

- 128 Bit addresses ($= 6 \cdot 10^{23}$ unique addresses per m^2 of the earth's surface !)
- Improved Option Mechanism: optional headers
- Address autoconfiguration
- Increased address flexibility
- Ressource Allocation

IPv6 Header Structure

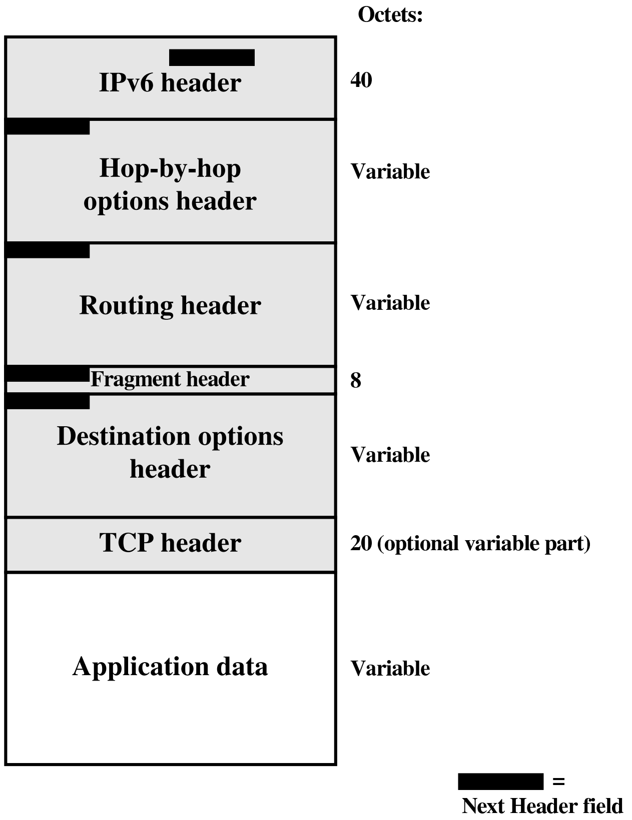


Figure 15.10 IPv6 Packet with Extension Headers (containing a TCP Segment)

IPv6 header

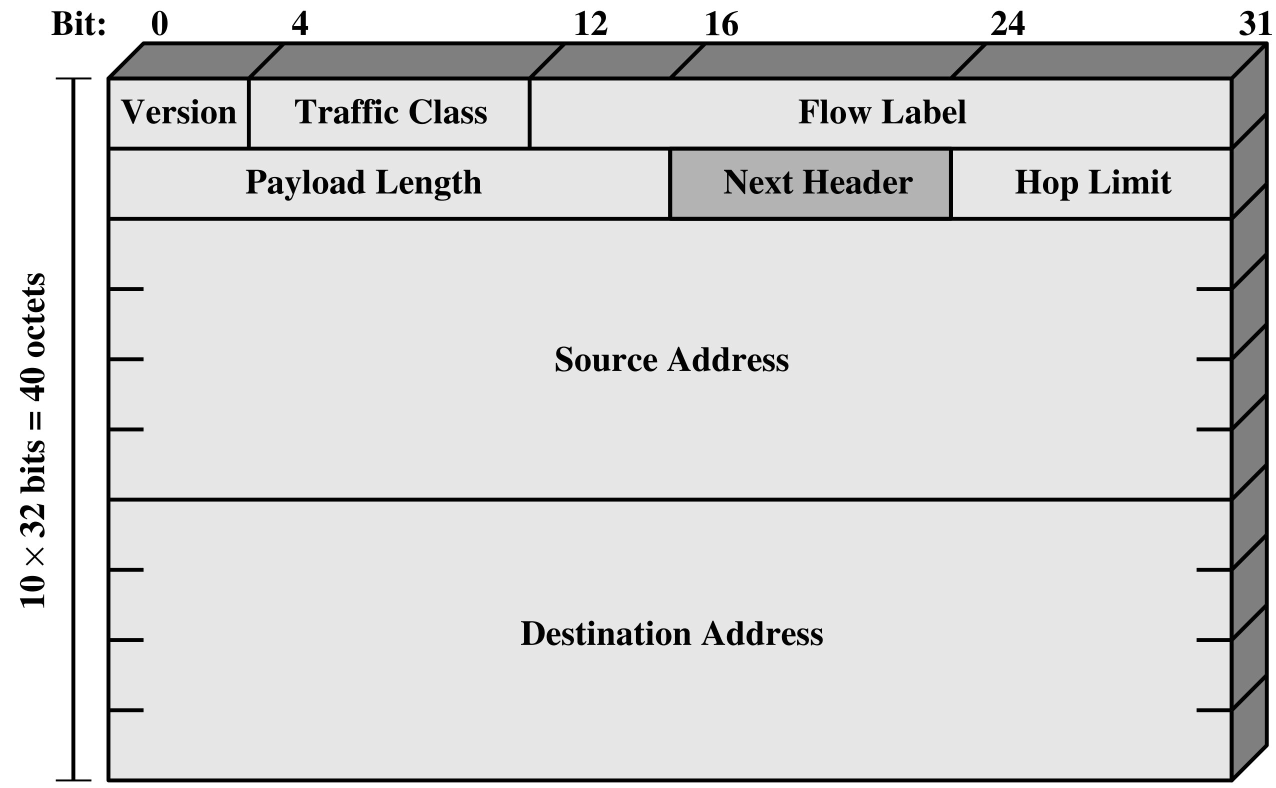


Figure 15.11 IPv6 Header

IPv6 optional headers

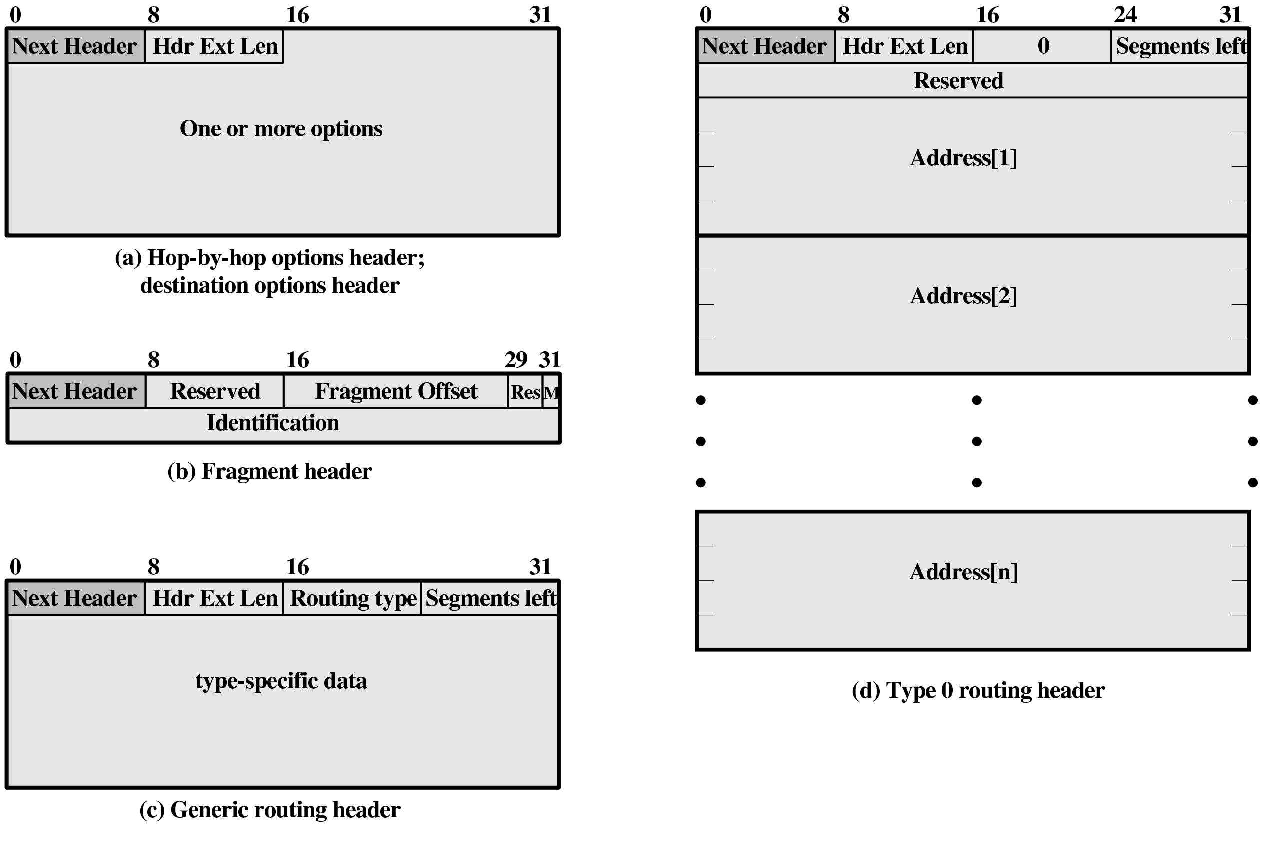


Figure 15.12 IPv6 Extension Headers

Multicasting

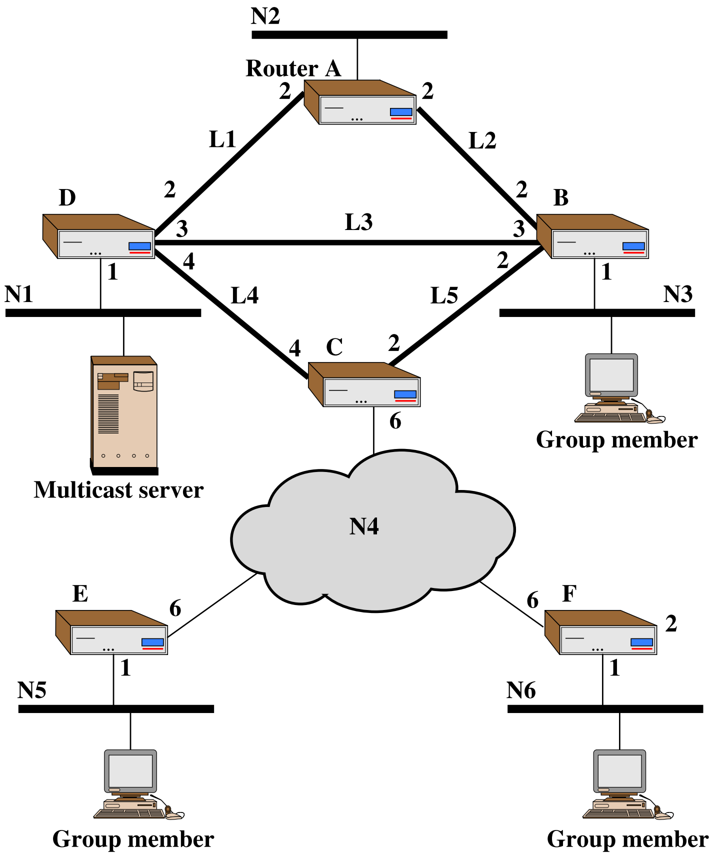
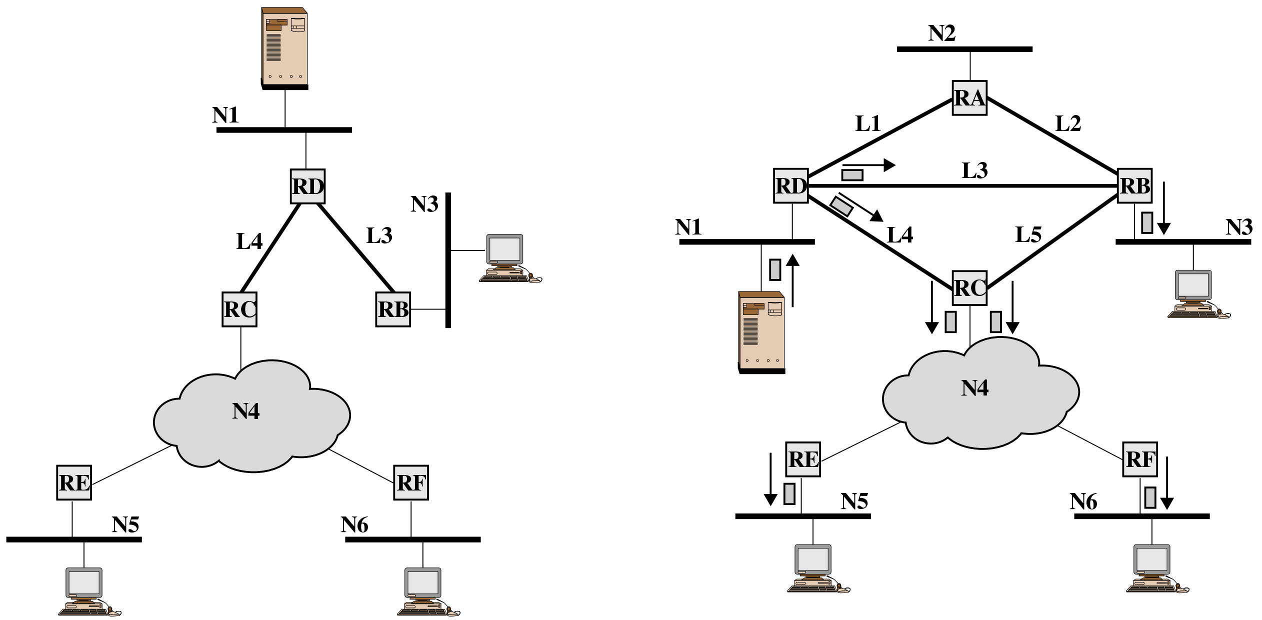


Figure 15.13 Example Configuration

Multicasting



(a) Spanning tree from source to multicast group

(b) Packets generated for multicast transmission

Figure 15.14 Multicast Transmission Example

Multicasting

0	4	8	16 31
Version	Type	Unused	Checksum
Group Address (Class D IPv4 address)			

Figure 15.16 IGMP Message Format

Routing:Characteristics

- Correctness
- Simplicity
- Robustness: against failures of links, overloads
- Stability: predictable behaviour
- Fairness: every packet (or station) is equal
- Optimality: e.g. maximise throughput
- Efficiency

Routing:Strategies

- Fixed Routing
- Flodding
- Random Routing
- Adaptive Routing

Routing:ARPANET

- First Generation (1969): Distributed adaptive routing
  - uses estimated delay (outgoing queue length) as performance criterion
  - distributed Bellman-Ford: Every node maintains one matrix row.
- Second Generation (1979): measured delay
  - uses measured delay (and link data rate) as performance criterion
  - Djikstra's Algorithm: Every node maintains full matrix row.
- Third Generation (1987): new link costs function

Routing: Protocols

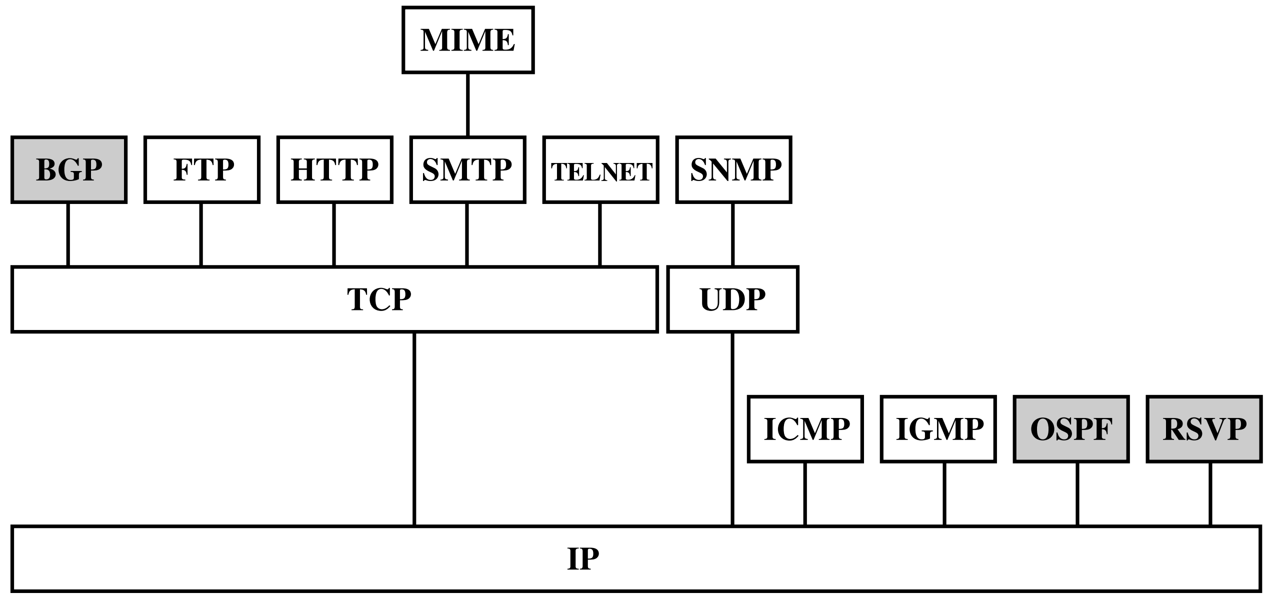


Figure 16.1 Internetworking Protocols in Context

Routing: Autonomous Systems(AS)

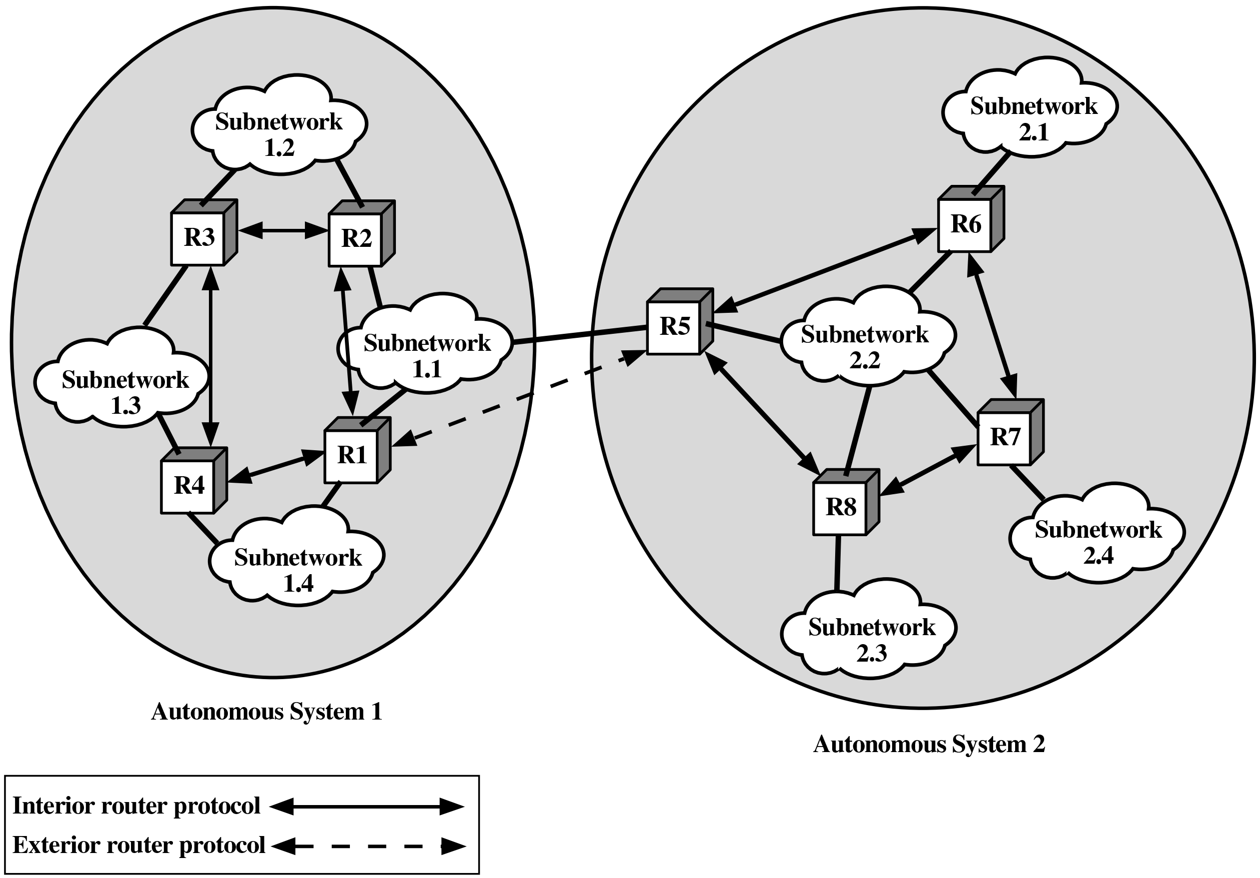


Figure 16.2 Application of Exterior and Interior Routing Protocols

Routing: Protocols

- Border Gateway Protocol (BGP): RFC1771 (BGP-4) exterior router protocol for AS
- Open Shortest Path First (OSPF): RFC2328 interior router protocol for AS, successor of Routing Information Protocol (RIP)
- Integrated Service Architecture (ISA): RFC1633
- Resource Reservation (RSVP): RFC2205 for multicast applications

Routing: BGP

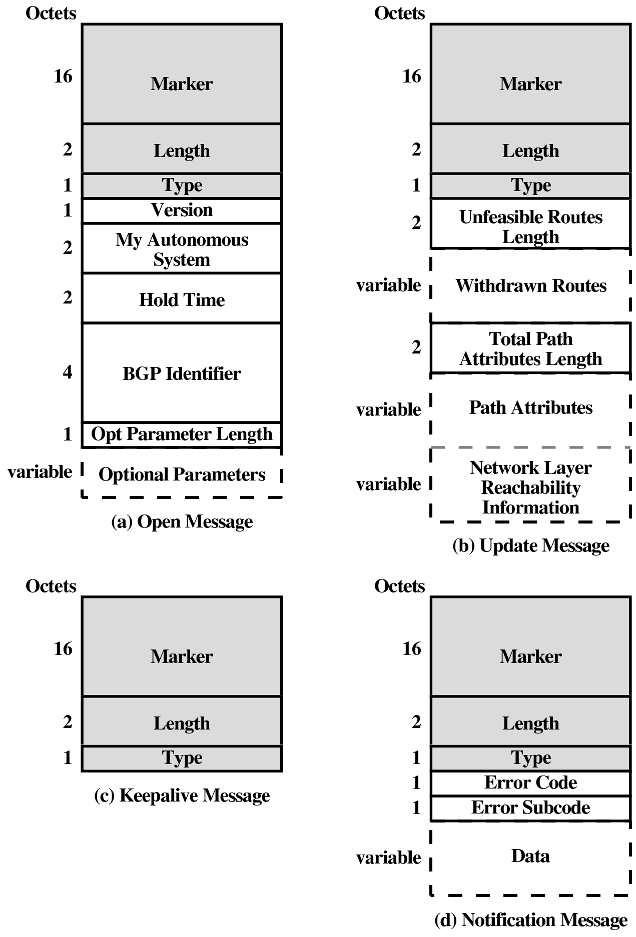


Figure 16.3 BGP Message Formats

Routing: OSPF example AS

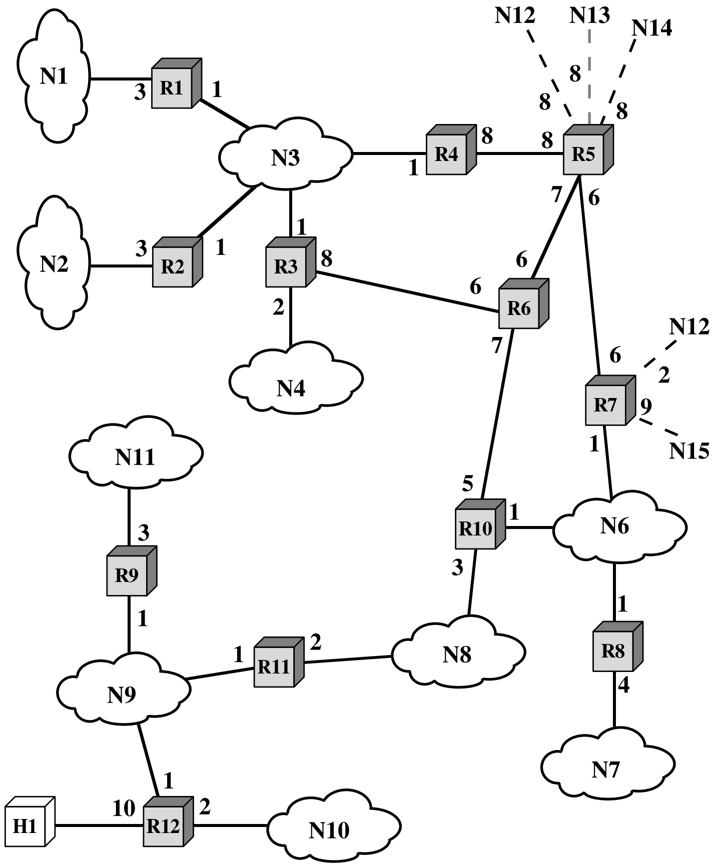


Figure 16.4 A Sample Autonomous System

Routing: OSPF graph for AS

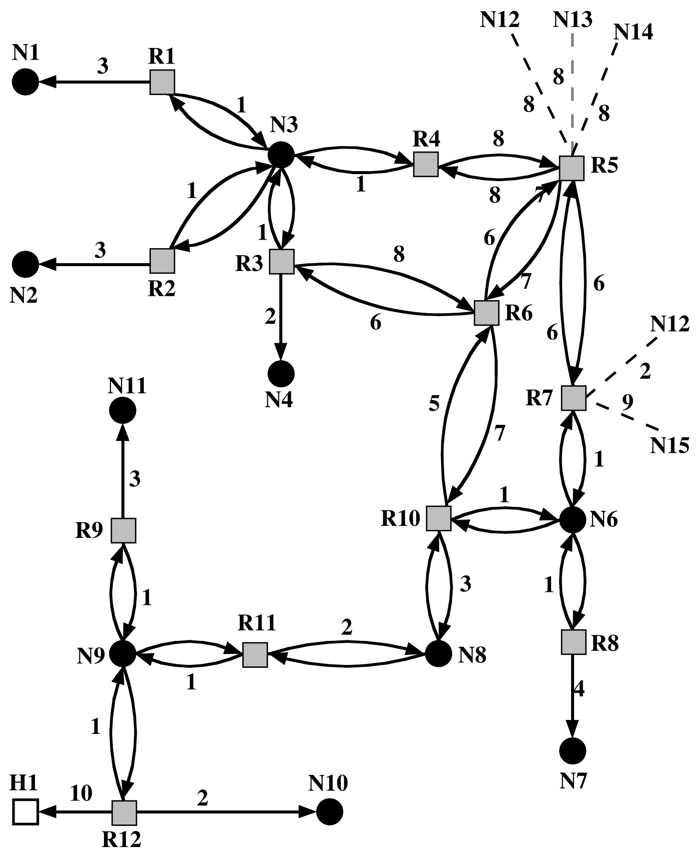


Figure 16.5 Directed Graph of Autonomous System of Figure 16.4

Routing: SPF tree

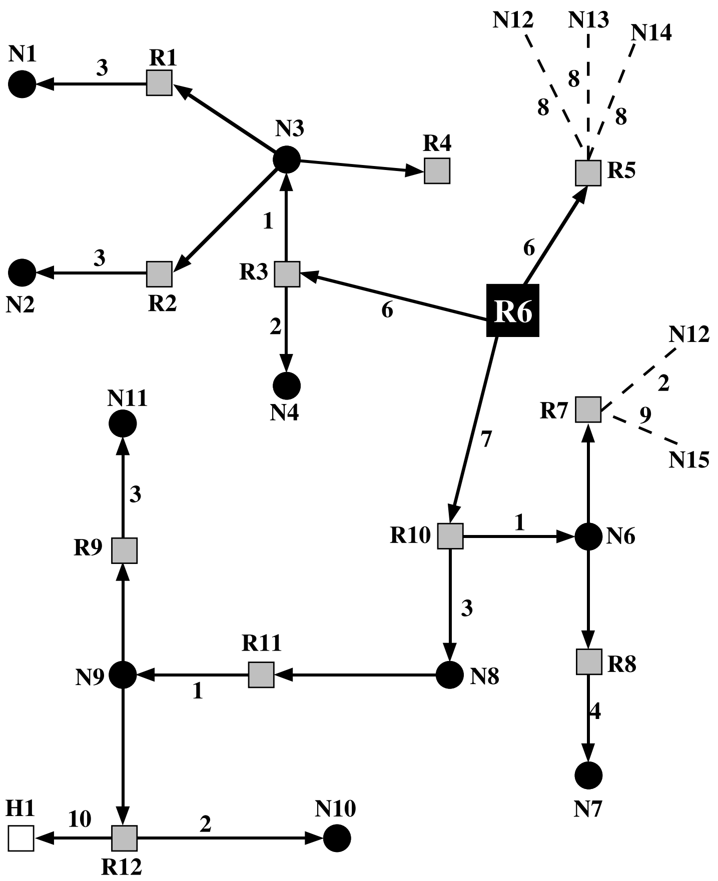


Figure 16.6 The SPF Tree for Router R6

IP over Ethernet: SNAP

- SNAP: Sub Net Access Protocol is used to transmit IP over a network that already knows addresses, i.e. a sub network.
- ARP (Address Resolution Protocol) is the protocol that identifies a subnet station address for a given IP address.
- RARP (Reverse ARP) is a protocol that identifies an IP address for a given ethernet address and was one of the predecessors of DHCP (Dynamic Host Contfiguration Protocol).

IP over Ethernet: SNAP

- ARP uses broadcast packets to find the ethernet address for a given IP address by “asking around”.
- In order to avoid too many ARP broadcasts, all stations use an ARP cache.

Security risks of ARP

- Proxy-ARP: One station can handle traffic for another station
- ARP-Cache-Poisoning: As ARP is implemented stateless and is answered by directed packets, answers can be given before the question was even asked.

TCP and UDP

- TCP and UDP use IP to transmit data
- UDP is the simpler protocol: Unreliable Datagramm Protocol
  - The UDP header just contains four fields: Source Port, Destination Port, Length and Checksum. Every field is 16 bit wide.
  - UDP adds a SAP facility to IP: Every SAP is identified with a port number.
  - UDP does not provide flow control, ARQ, in-order reception, duplicate detection or any guarantees.

TCP

- TCP (Transmission Control Protocol) offers reliable connection-oriented service.
- Like UDP, it adds a SAP facility using 16 bit Port numbers.
- Unlike UDP, TCP offers:
  - Connection Establishment and Termination
  - Flow Control
  - ARQ
  - Ordered Delivery
  - Duplicate Detection

TCP Header

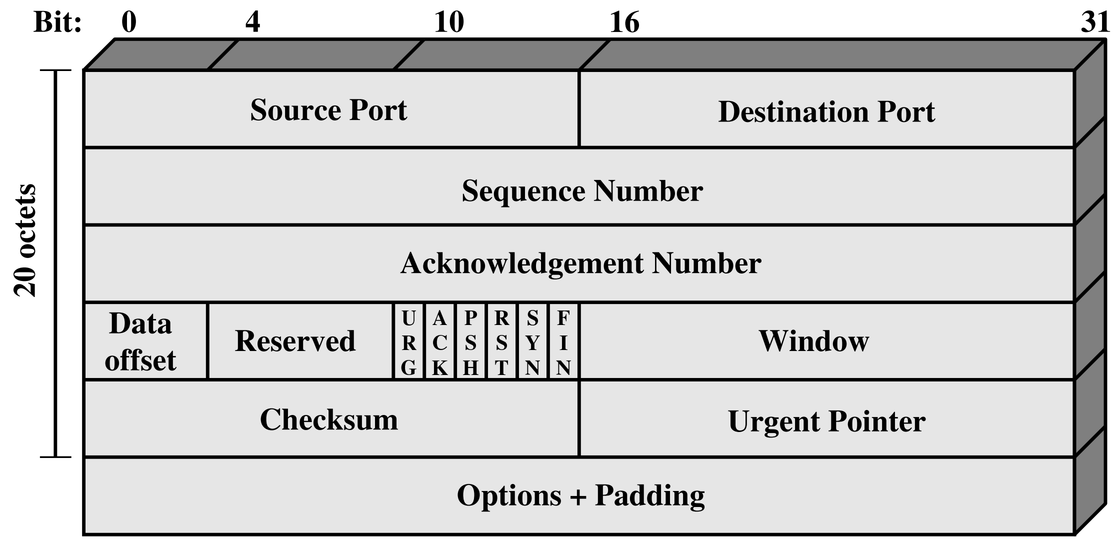


Figure 17.11 TCP Header

Transport Flow Control

- Problem: On the transport layer, flow control is harder to implement than on the link layer as not only the destination may overflow but every link segment inbetween. Possible strategies (for the receiving transport entity) are:
  - Do nothing. Packets will be lost, ARQ will do resends, traffic will slow down.
  - Refuse to accept packets. This is the propagated back to the link layer which will use its means of flow control.

Transport Flow Control

- Use a fixed sliding-window protocol and provide buffers for all possible sequence numbers. Only send acknowledgement if a slot is empty.
- Use a credit scheme, i.e. decouple the acknowledgement from the send credit.

Credit Scheme

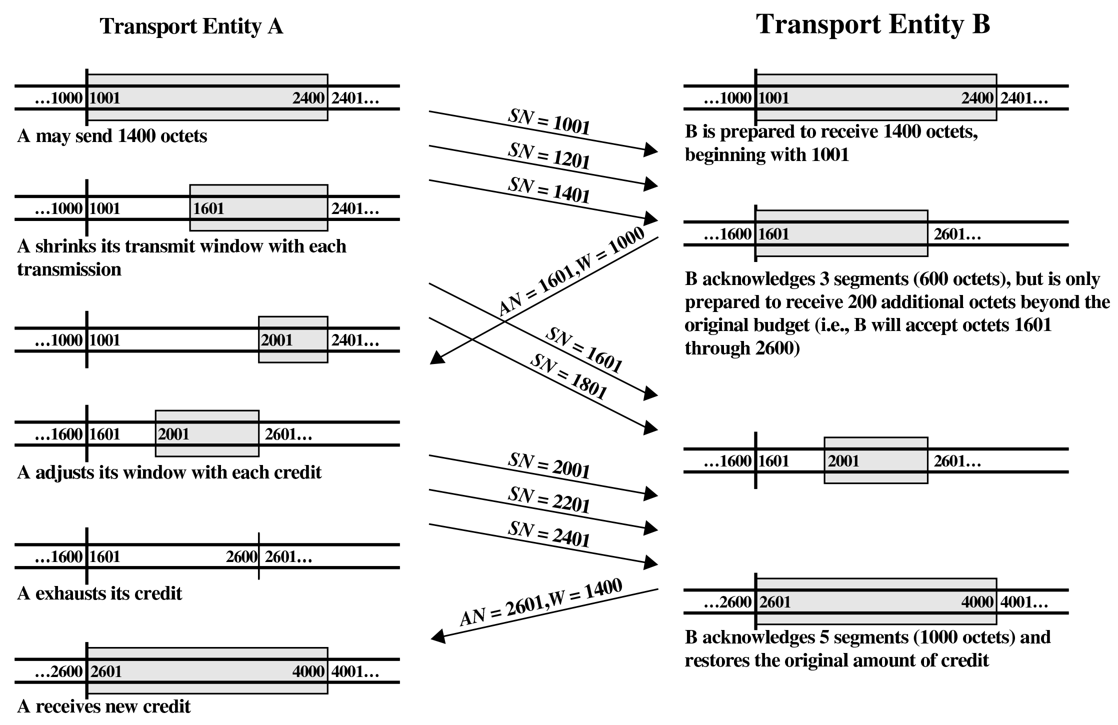


Figure 17.2 Example of TCP Credit Allocation Mechanism

Credit Scheme

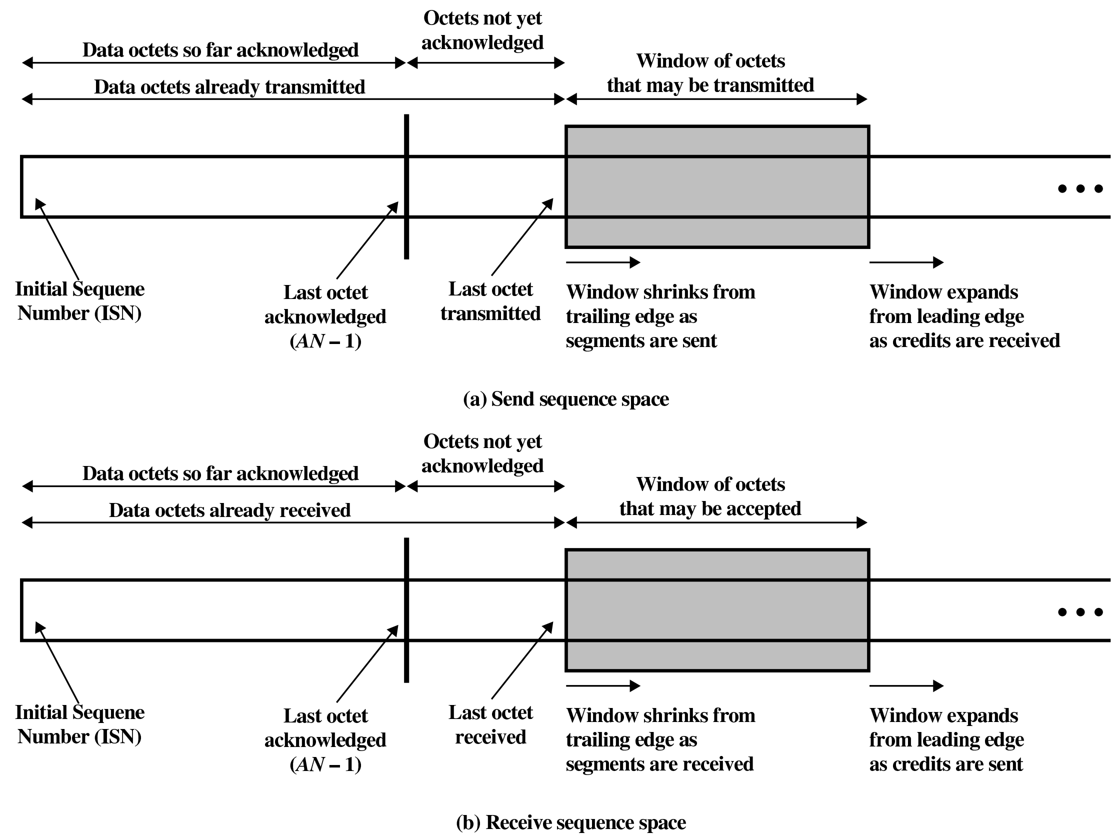


Figure 17.3 Sending and Receiving Flow Control Perspectives

Connection Establishment

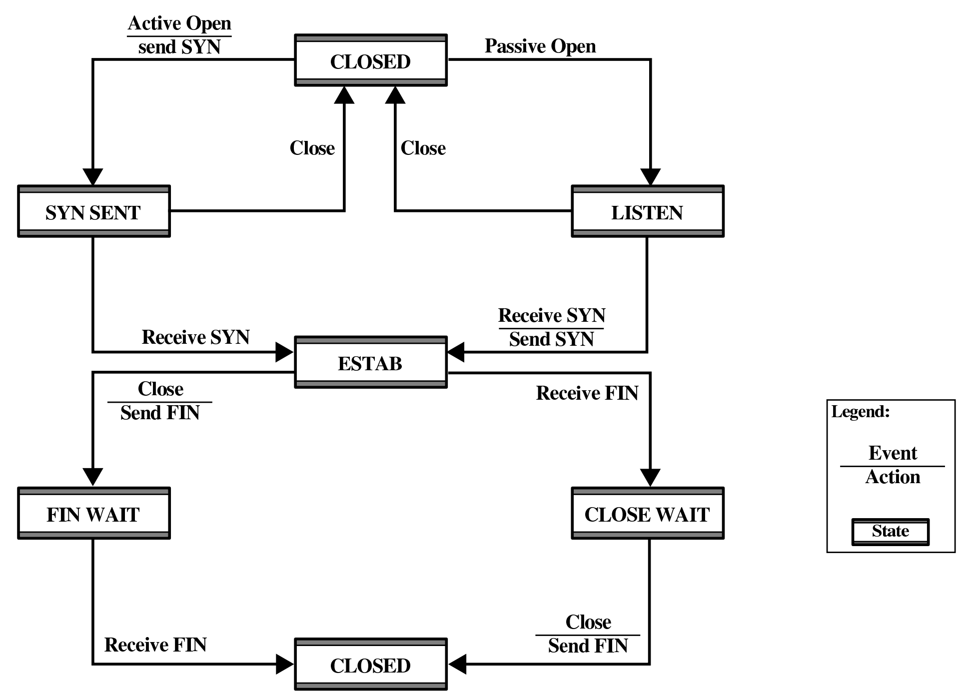


Figure 17.4 Simple Connection State Diagram

Possible Confusion?

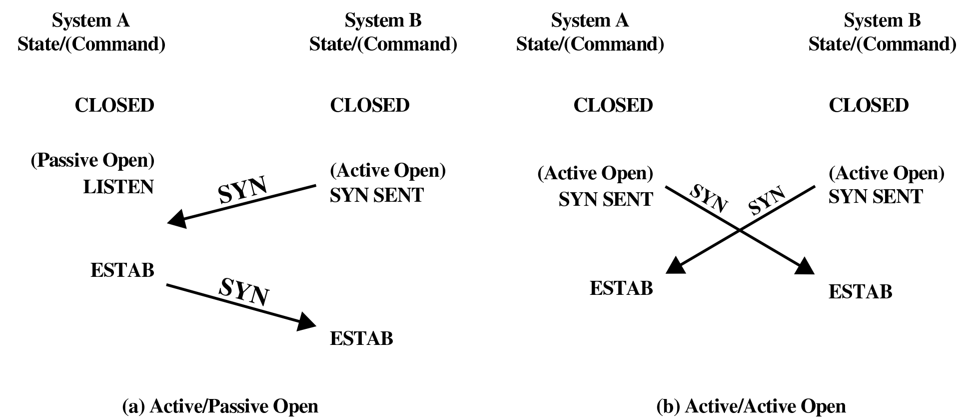


Figure 17.5 Connection Establishment Scenarios

TCP state diagram

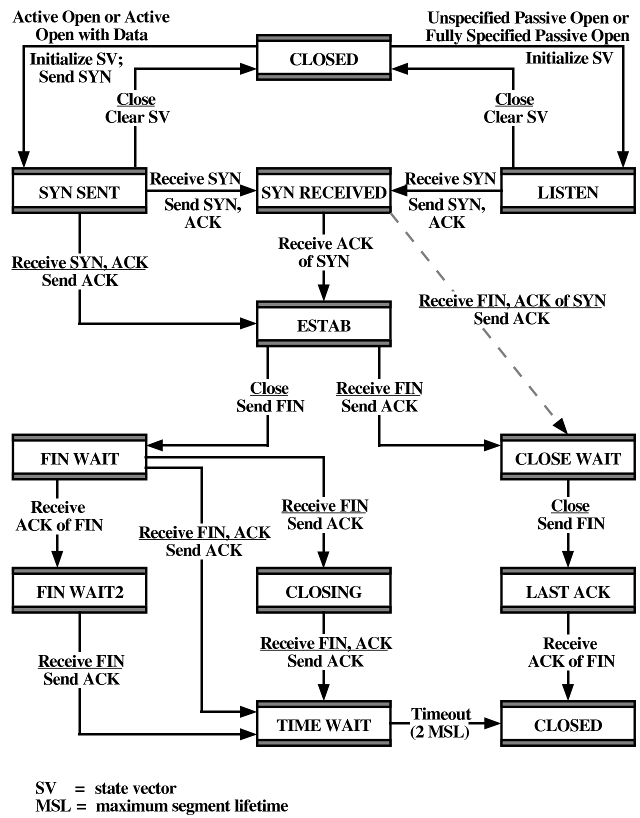


Figure 17.9 TCP Entity State Diagram

TCP Protocol step by step

- Connection Establishment
- ARQ
- Flow Control
- Push
- urgent data
- Disconnection

Protocols using TCP

- daytime
- test protocols: chargen, echo, discard
- SMTP
- POP3
- HTTP
- FTP, Telnet
- SSH