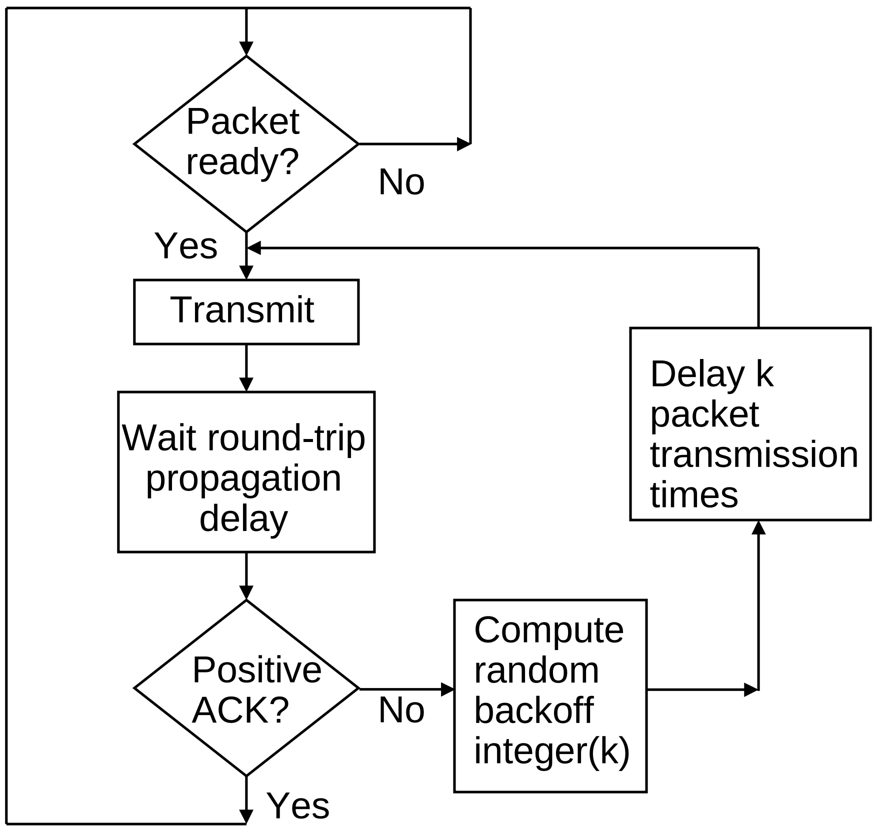
0. PRECURSORS

- Earlier schemes from which CSMA/CD evolved

- ALOHANET
  - First packet radio network developed at U. of Hawaii to connect scattered terminals on several islands to communicate with the university computer.
  - Two independent channels used:
    - inbound terminals → central node; channel at 407.35 MHz
    - outbound central node → terminals; at 413.48 MHz
    - Data rate of 9600 bps
  - Repeaters used to increase range
  - Fixed routing is used with repeaters
  - Inbound channel use ALOAH contention mechanism for channel access
    - Any terminal/repeater with a packet immediately transmits it.
    - Source of packet waits for timeout period for ACK for the packet from central node (0.2 sec).
    - If no ACK is received, packet assumed to have "collided" with some other; retransmitted after random interval (uniform distribution: 0.2 ~ 1.5 sec.)
  - Outbound channel is not contended since only central node originates transmission.

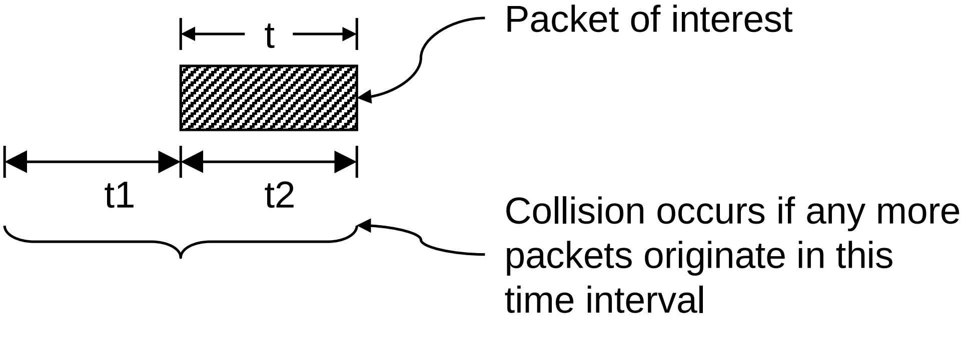
- ALOHA
  - Random access (or contention) techniques used for shared-channel access
  - Was developed for use with packet radio networks, but forms basis for most contention-based shared-medium access techniques.
  - Any node with a newly generated packet:
    - 1. Immediately transmits the packet
    - 2. Waits for a round-trip interval for ACK for packet
    - 3. If ACK is not received, waits for a random timeout interval and retries (step 1.)
  - Also called pure-ALOHA: "Talk when you please"



- Analysis
    - S: throughput of network (rate of successfully received packets; normalized to the network capacity) (carried load)
    - G: offered load (rate of data presented to the network for transmission; in case of collision, count both)
    - I: Input load (rate at which new data is being generated by all stations combined)
    - D: average packet delay (time from generation to successful receipt at destination)
  - Assumptions
    - All packets have constant length (normalized w.r.t. packet-transmission time: "t" =1)
    - Channel is noise-free
    - Throughput = input load (S=I): packets do not pile up at stations
    - G is Poisson distributed:

$$\Pr[\text{k packets in time "t"}] = \frac{G^k e^{-G}}{k!}$$

  - For successful transmission:



$\Rightarrow$ Vulnerable period = 2t

- Pr[successful transmission of a packet]
  = Pr[0 other packets are generated in t1 or t2]
  = Pr[No packets in t1] • Pr[No packets in t2]
  $$= \frac{G^0 e^{-G}}{0!} \bullet \frac{G^0 e^{-G}}{0!} = e^{-G} e^{-G} = e^{-2G}$$
- Pr[successful transmission]
  $$= \frac{\text{Rate of successful packet transmissions}}{\text{Rate of attempted packet transmissions}} = \frac{S}{G}$$
- So $S/G = e^{-2G} \Rightarrow \boxed{S = G\, e^{-2G}}$

  Since $dS/dG = e^{-2G}[1 - 2G] = 0 \rightarrow G = 1/2$

  Maximum throughput = $\frac{1}{2e} = 18\%$

– Average Delay
  = (Expected # of retransmissions) • (Delay per retransmission) + Delay for last (successful) transmission
- Expected # of transmissions per packet
  $$= \frac{\text{Rate of attempted transmissions}}{\text{Rate of successful transmissions}} = \frac{G}{S}$$
- Expected # of retransmissions per packet = $\frac{G}{S} - 1$
- Retransmission algorithm: wait for random time between 1 and k packet transmission times (uniformly distributed)
- Delay per retransmission = 1 + 2a + w + (k+1)/2
  - 1 + 2a : transmission time + 2 propagation times
  - w : time at receiver to generate ACK
  - (k+1)/2 : average timeout delay

- $\therefore D = \underbrace{(e^{2G} - 1)}_{\text{Expected \# of retrans.}} \underbrace{(1+2a+w+(k+1)/2)}_{\text{Expected delay per retrans.}} + \underbrace{a+1}_{\text{Time for final successful trans.}}$

- If packet propagation time is not negligible, modification needed; Now vulnerable period = 2(1+a)t
- Pr[k packets in time (1+a)t]

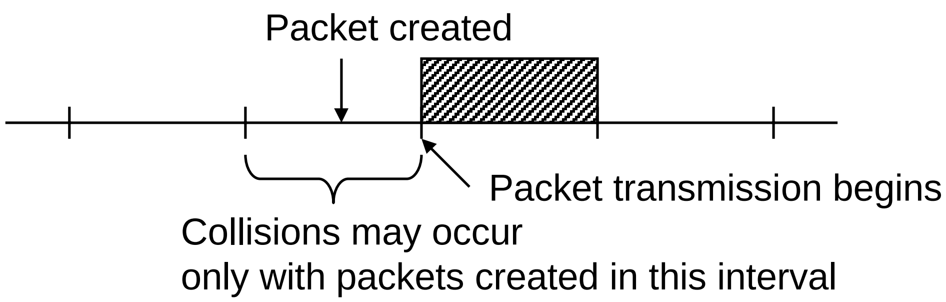
$$= \frac{[(1+a)G]^k e^{-(1+a)G}}{k!}; \text{ for } k = 0 \rightarrow e^{-(1+a)G}$$

$$\text{So } \frac{S}{G} = e^{-(1+a)G} e^{-(1+a)G} = e^{-2(1+a)G}$$

$$\therefore S = G\, e^{-2(1+a)G}$$

$$D = (e^{2(1+a)G} - 1)(1 + 2a + w + \frac{k+1}{2}) + a + 1$$

- Slotted ALOHA
  - Improvements in throughput possible by dividing time into fixed slots
  - Transmission is only allowed at the beginning of slot; if packet is generated in between, node waits till next slot



  - $\therefore$ Vulnerable period = 1 • t = (or (1+a)t if a is not negligible)

- Pr[successful transmission]

$$= \frac{S}{G} = \frac{e^{-G} G^0}{0!} = e^{-G}$$

$$\therefore S = G\, e^{-G}$$

$$D = \underbrace{(e^G - 1)}_{\text{Expected \# of retrans.}} \underbrace{(1 + 2a + w + \frac{k+1}{2})}_{\text{Expected delay per retrans.}} + \underbrace{1.5a + 1.5}_{\text{Extra 1/2 slot avg. waiting time}}$$

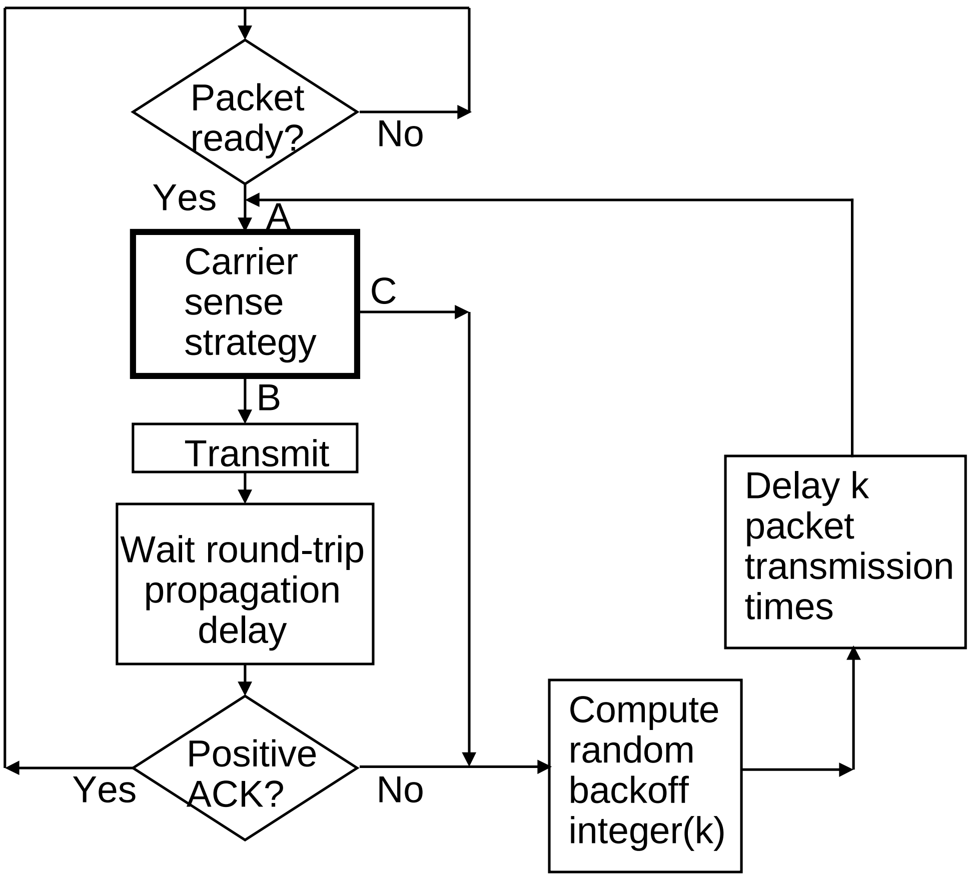
- CSMA (Carrier Sense Multiple Access)
  - When a << 1 (Propagation time << Transmission time), improvements possible by "Listen Before Talk" discipline
  - Now collisions can only occur if two nodes decide to transmit within "a" seconds of each other, rather than 2(1+a) with pure-ALOHA (1+a with S-ALOHA).
  - Three CSMA schemes
    - 1. Nonpersistent CSMA
    - 2. p-persistent CSMA
    - 3. 1-persistent CSMA

- Nonpersistent CSMA
  - 1. If the medium is idle, transmit.
  - 2. If the medium is busy, wait an amount of time drawn from a probability distribution and repeat step 1.

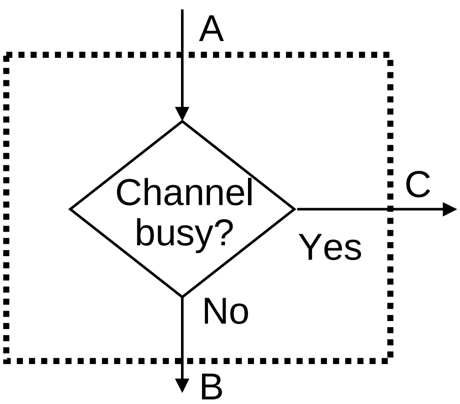
- 1-persistent CSMA
  - 1. If the medium is idle, transmit.
  - 2. If the medium is busy, continue to listen until the channel is sensed idle, then transmit immediately.
  - 3. If there is a collision (determined by a lack of ACK), wait a random amount of time and repeat step 1.

- p-persistent CSMA
  - 1. If the medium is idle, transmit with probability p, and delay with probability (1-p). (The time unit is typically equal to the maximum propagation delay.)
  - 2. If the medium is busy, continue to listen until the channel is idle and repeat step 1.
  - 3. If transmission is delayed one time unit, repeat step 1.

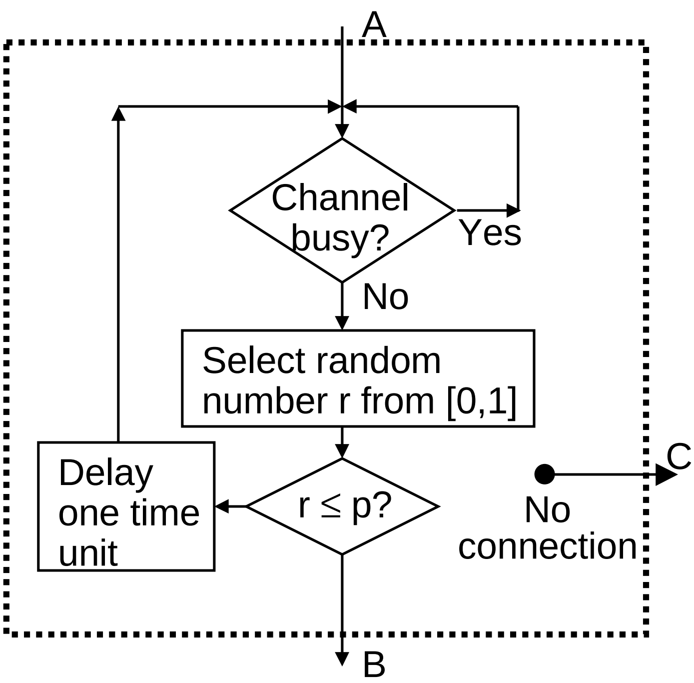
CSMA



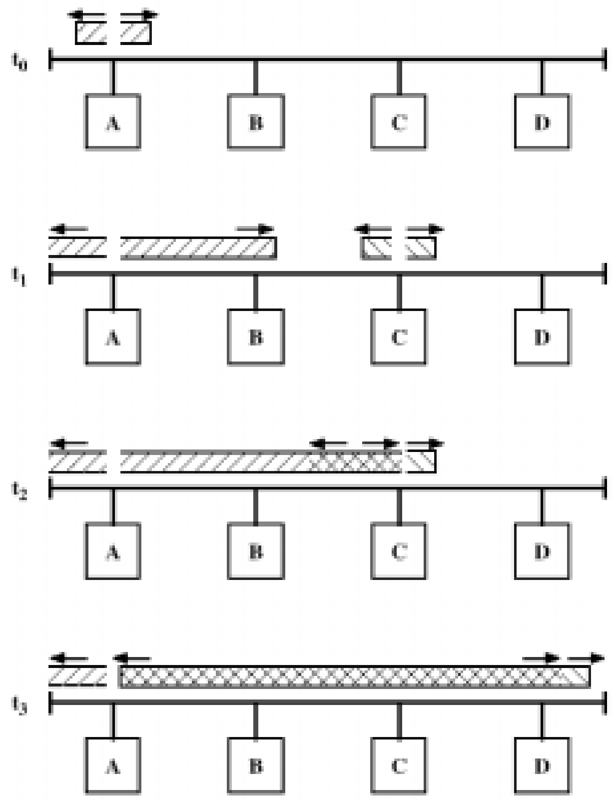
Nonpersistent CSMA



p-persistent CSMA



1. ETHERNET AND FAST EATHERNET (CSMA/CD) IEEE802.3

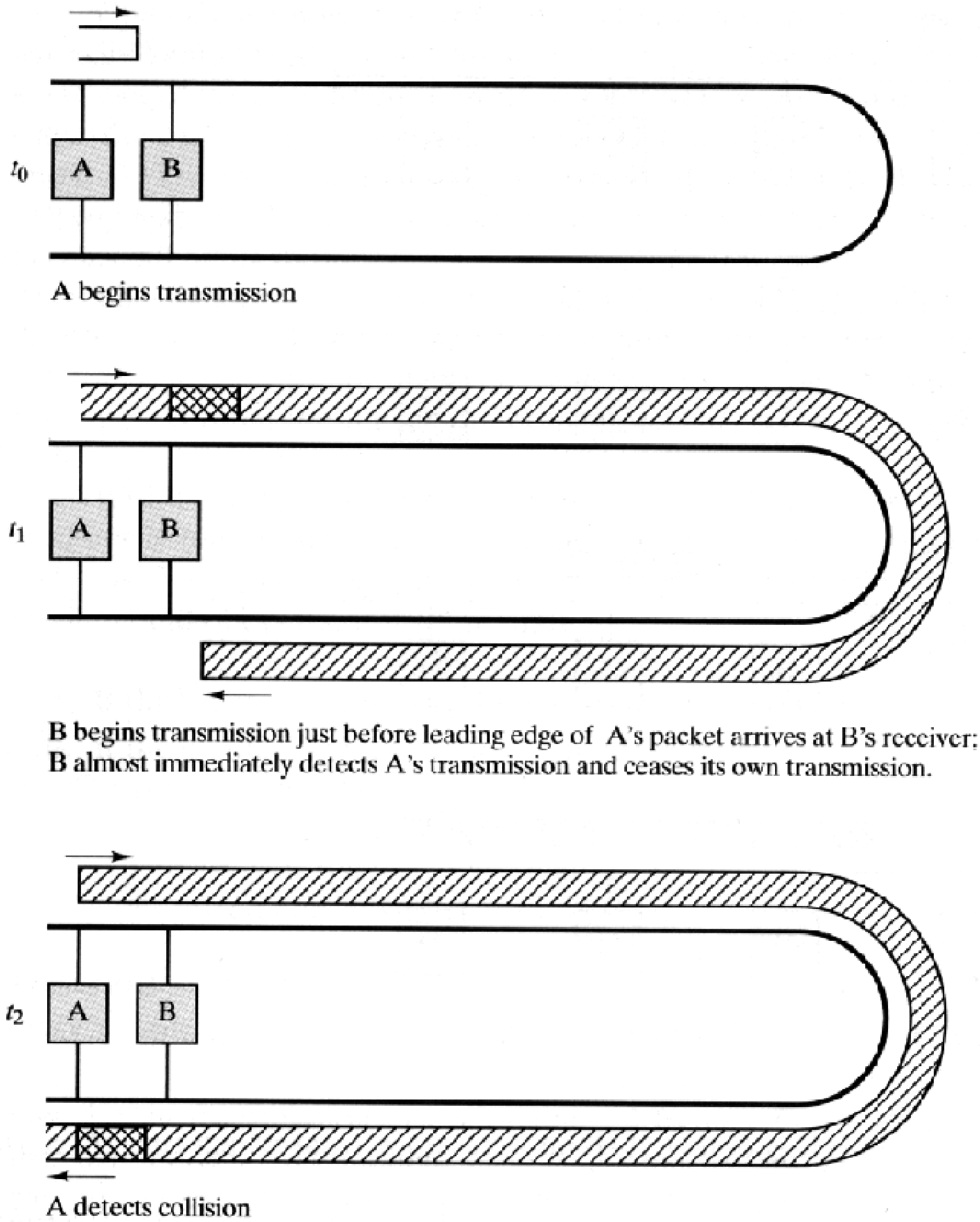


- CSMA/CD: CSMA with Collision Detection
  - "Listen While Talk" scheme:
    - Listen before transmission till channel is free.
    - Additionally continue to monitor channel during transmission.
    - If collision is detected, immediately abort transmission.
  - Reduces "bandwidth waste" when collisions occur.
  - For baseband CSMA/CD, worst-case "wasted-time" due to a collision = $2 \bullet T_{prop}$

    $\Rightarrow$ Minimum packet length $\geq 2 \bullet T_{prop}$

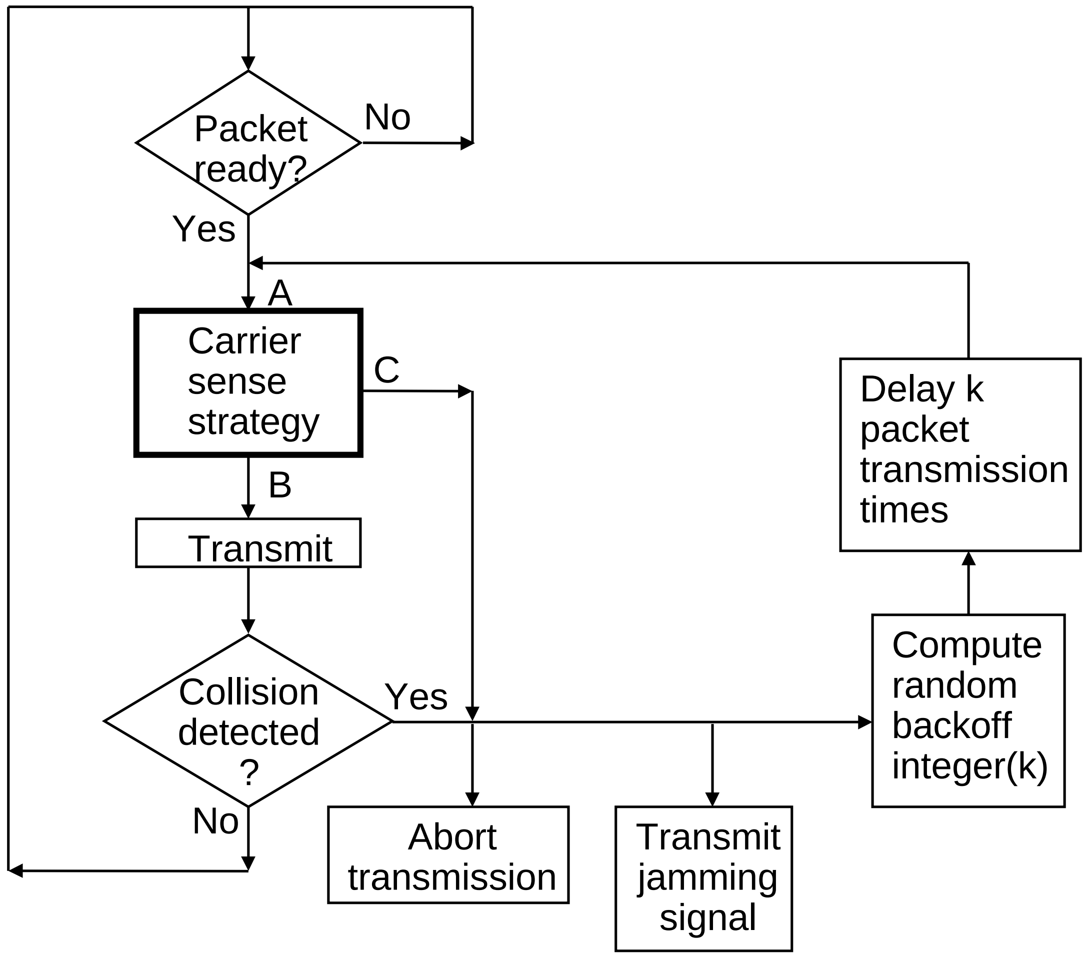
    $\Rightarrow$ Packet length should be at least twice the propagation delay ($a \leq 0.5$)

– For broadband CSMA/CD, the maximum time to detect a collision is four times the propagation delay from an end of the cable to the headend
– 1-persistent CSMA used; low delay at low loads
– To improve utilization at high loads, "binary exponential backoff" is used: doubles mean delay at each collision

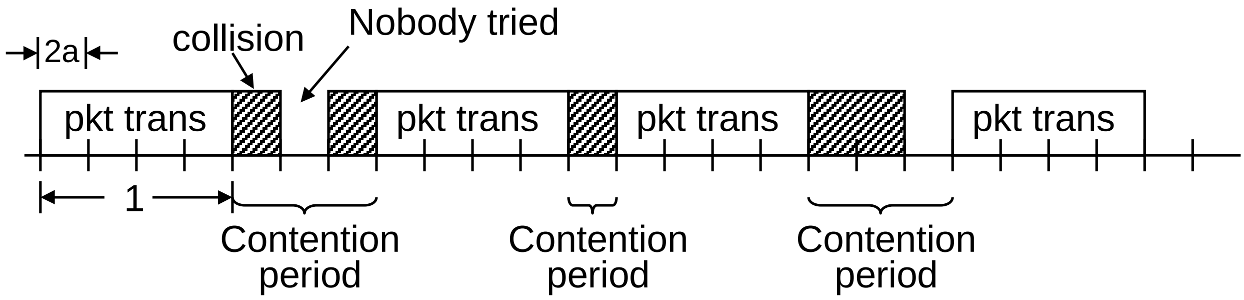


Broadband collision detection timing

CSMA/CD


Packet ready?
No
Yes
A
Carrier sense strategy
C
Delay k packet transmission times
B
Transmit
Compute random backoff integer(k)
Collision detected ?
Yes
No
Abort transmission
Transmit jamming signal

- Performance analysis of CSMA/CD
  - Alternating periods of successful packet transmission and contention. Contention period can have “collisions” and “no-tries”.



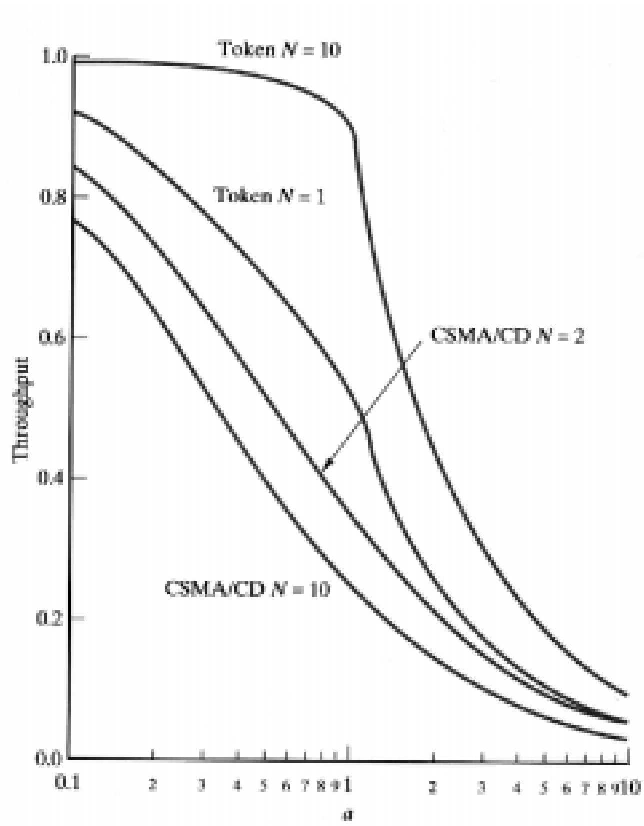
  - S = useful time fraction = $\dfrac{1}{1+\text{Average contention time}}$
  - Average contention time = (Expected value of “# of slots before successful transmission’)*2a
  - Pr[i slots for successful transmission] = Pr[i unsuccessful slots]*Pr[(i+1)th slot is successful)
  - Pr[successful slot] = Pr[exactly one attempt in slots] $= \binom{N}{1} P^1 (1-P)^{N-1} \equiv$
  - Pr[i slots for successful transmission] = $P_i = (1-A)^i \bullet A$
  - Average # of contention slots

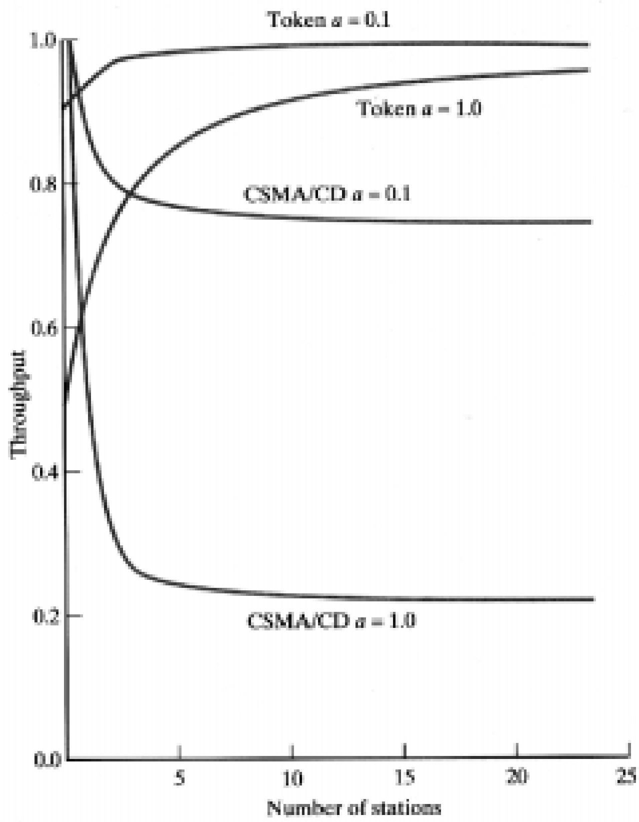
$$= \sum_{i=1}^{\infty} i P_i = \sum_{i=1}^{\infty} i (1-A)^i A = \frac{1-A}{A}$$

  - $\therefore \; S = \dfrac{1}{1+2a(1-A)/A}$

$$S = \frac{1}{1 + 2a(1 - A)/A}$$

– S is max when A is max
  $A = NP(1 - P)^{N-1}$ is max when $P = 1/N$
  $A_{max} = (1 - 1/N)^{N-1}$
  $\left(\lim_{N \to \infty} A_{max} = \frac{1}{e} \Rightarrow \lim_{N \to \infty} S = \frac{1}{1 + 3.44a}\right)$





- IEEE 802.3 MAC Frame Format

Octets	7	1	2 or 6	2 or 6	2	≥ 0	≥ 0	4
	Preamble	SFD	DA	SA	Length	LLC data	Pad	FCS

- **Preamble**: A 7-octet pattern of alternating 0s and 1s used by the receiver to establish bit synchronization (establishes the rate at which bit are sampled.)
- **Start frame delimiter** (SFD): Special pattern 10101011 indicating the start of a frame.
- **Destination address** (DA):
- **Source address** (SA):
- **Length**: Length of the LLC data field
- **LLC data**:
- **Pad**: Octets added to ensure that the frame is long enough for proper CD operation.
- **FCS**: Error checking using 32-bit CRC.

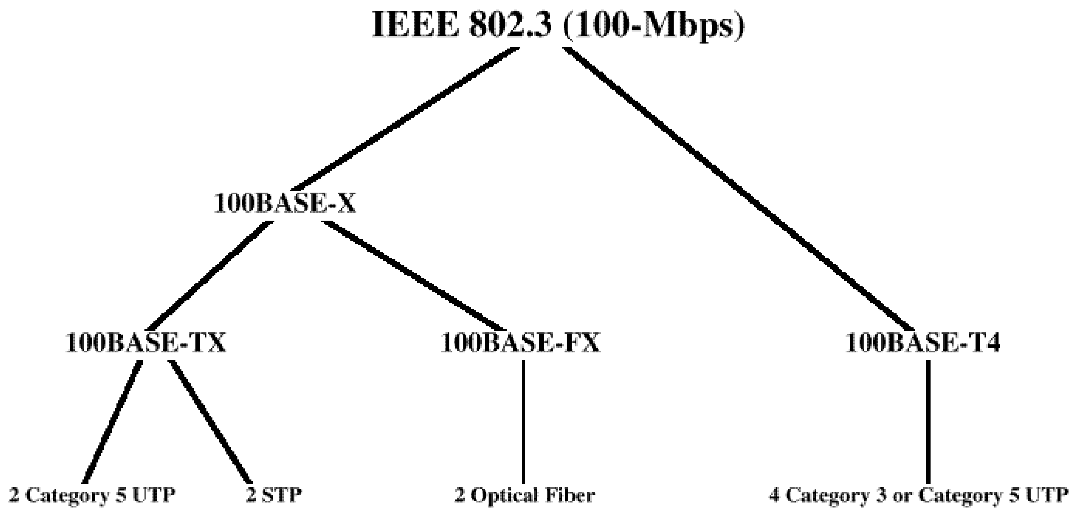
- IEEE 802.3 10-Mbps Specifications (Ethernet)

  – Many alternative physical configurations
    - 10BASE5
    - 10BASE2
    - 10BASE-T (Twisted-pair)
    - 10BROAD36
    - 10BASE-F (optical Fiber)

IEEE 802.3 10-Mbps physical layer medium alternatives

	10BASE5	10BASE2	10BASE-T	10BROAD36	10BASE-FP
Transmission medium	Coaxial Cable (50 ohm)	Coaxial Cable (50 ohm)	Unshielded twisted pair	Coaxial Cable (75 ohm)	850-nm optical fiber pair
Signaling technique	Baseband (Manchester)	Baseband (Manchester)	Baseband (Manchester)	Broadband (DPSK)	Manchester/On-off
Topology	Bus	Bus	Star	Bus/Tree	Star
Maximum segment length (m)	500	185	100	1800	500
Nodes per segment	100	30	—	—	33
Cable diameter (mm)	10	5	0.4 - 0.6	10 - 25	62.5/125 µm

- IEEE 802.3 100-Mbps Specifications (Fast Ethernet)
  - Fast Ethernet: a set of specifications developed by IEEE 802.3 committee to provide a low-cost Ethernet-compatible LAN operating 100 Mbps.



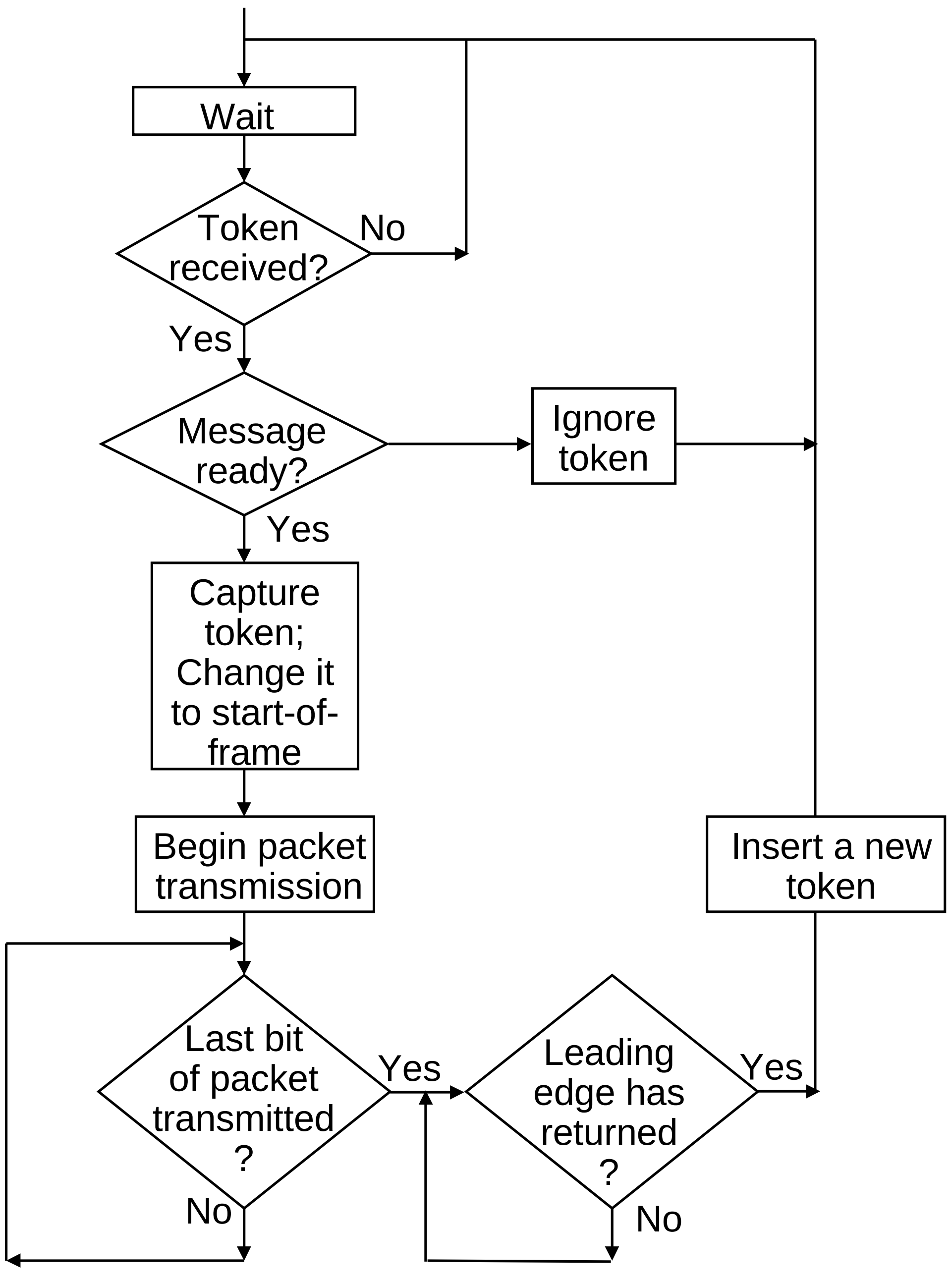
IEEE 802.3 100BASE-T options

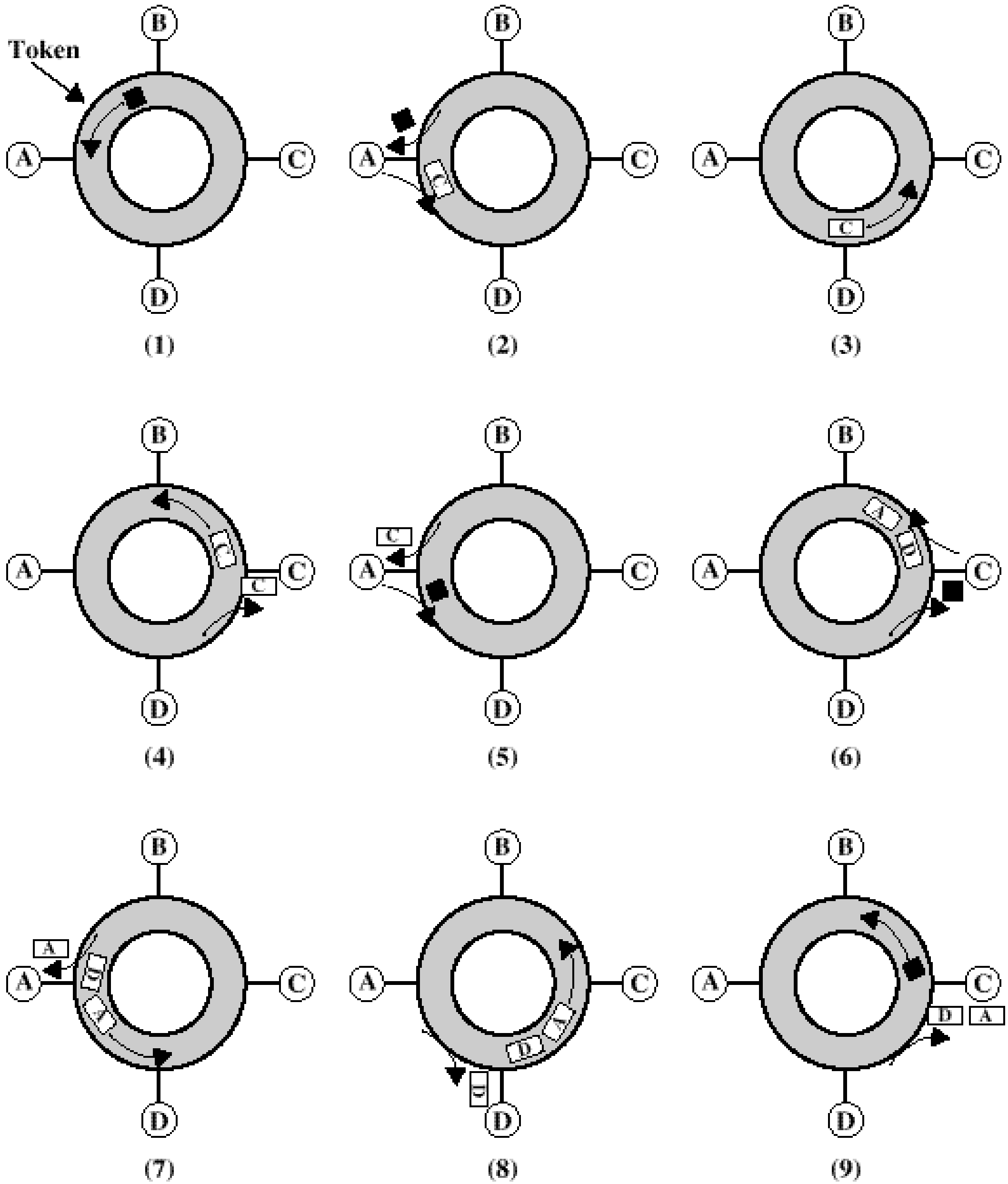
IEEE 802.3 100BASE-T physical layer medium alternatives

	100BASE-TX		100BASE-FX	100BASE-T4
Transmission medium	2 pair, STP	2 pair, Category 5 UTP	2 optical fibers	4 pair, Category 3, 4, or 5 UTP
Signaling technique	4B5B, NRZI	MLT-3	4B5B, NRZI	8B6T, NRZ
Data rate	100 Mbps	100 Mbps	100 Mbps	100 Mbps
Maximum segment length	100 m	100 m	100 m	100 m
Network span	200 m	200 m	400 m	200 m

2. TOKEN RING AND FDDI

- IEEE 802.5 Token Ring Medium Access Control
  - MAC Protocol





Token ring operation

– MAC Frame Format

Octets	1	1	1	2 or 6	2 or 6	≥ 0	4	1	1
	SD	AC	FC	DA	SA	Data	FCS	ED	FS

SD = Starting delimiter
AC = Access control
FC = Frame control
DA =Dest. address
SA =Source address
ED = Ending delimiter
FS = Frame status

(a) General frame format

SD	AC	ED

(b) Token frame format

P	P	P	T	M	R	R	R

PPP = Priority bits
T = Token bit
M = Monitor bit
RRR = Reserv. bits

(c) Access control field

J	K	1	J	K	1	I	E

J,K = Nondata bits
I = Intermediate-frame bits
E = Error-detected bits

(d) Ending delimiter field

A	C	x	x	A	C	x	x

A = Addressed recognized bit
C = Copied bit

(e) Frame status field

- **Starting delimiter (SD):** Indicates start of frame. JK0JK000, J and K are nondata symbols.
- **Access Control (AC):** PPPTMRRR, PPP and RRR are 3-bit priority and reservation variables, T is for indicating whether the frame is a token, M is for the monitor station. If T is 0, then the frame is a token, and the only remaining field is ED.
- **Frame control (FC):** FFZZZZZZ, F: frame type bits and Z: control bits

- **Ending delimiter (ED):** JK1JK1IE, J and K are non data symbols, I is an intermediate frame bit. A communication between two stations may consists of many frames, and bit I is 0 in the last frame and 1 otherwise. E is an error bit, which is set to 1 whenever an error (such as an FCS) is detected.
- **Frame status (FS):** ACXXACXX, A: address recognized bit, C: Frame copied bit, and X: undefined bit.

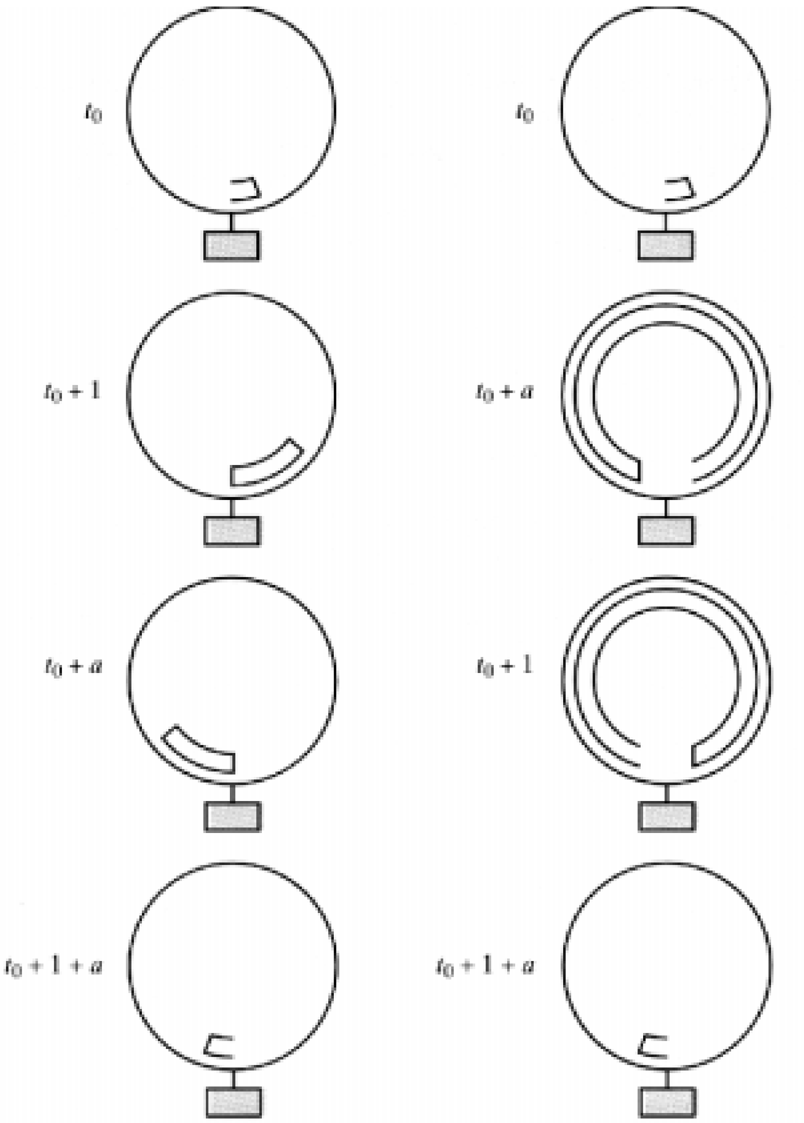
– General Operation:

- If nothing to send, then continue regenerating and forwarding bits across the ring as they are passed through the repeater.
- If something to send, wait for Token to come across. Upon seeing the T bit in AC as 0, change to 1, and send the data.
- Stations between the sender and destination will pass the bits through their repeaters. The destination will detect its own DA and copy the frame in. Also change the A and C bits of the Frame status to 1.
- During or after transmission, the frame will have looped back. The sender can check the A and C bits for a form of ACK.
  - AC: 00 Destination doesn't exist
  - AC: 10 Destination exists, but is too busy to copy
  - AC: 11 Frame copied
- Sender removes frames that it sent off the ring. In general, any bits it receives during transmission must be its own.
- After station is done sending, and after it starts receiving bits from its own transmission, it puts a new token on the ring.
- The P and R bits are used for a priority scheme.

– Performance analysis of simple Token Ring
  - N: # of stations on ring
  - Assumption: Every station is always ready to transmit a packet
  - $S = \dfrac{\text{Average time to transmit a packet (T1)}}{\text{Elapsed time between "starts of transmission" (T2)}}$
  - Case1: a<1

    T1 = 1, T2 = a/N + 1, $\sum S = \dfrac{1}{1+a/N}$

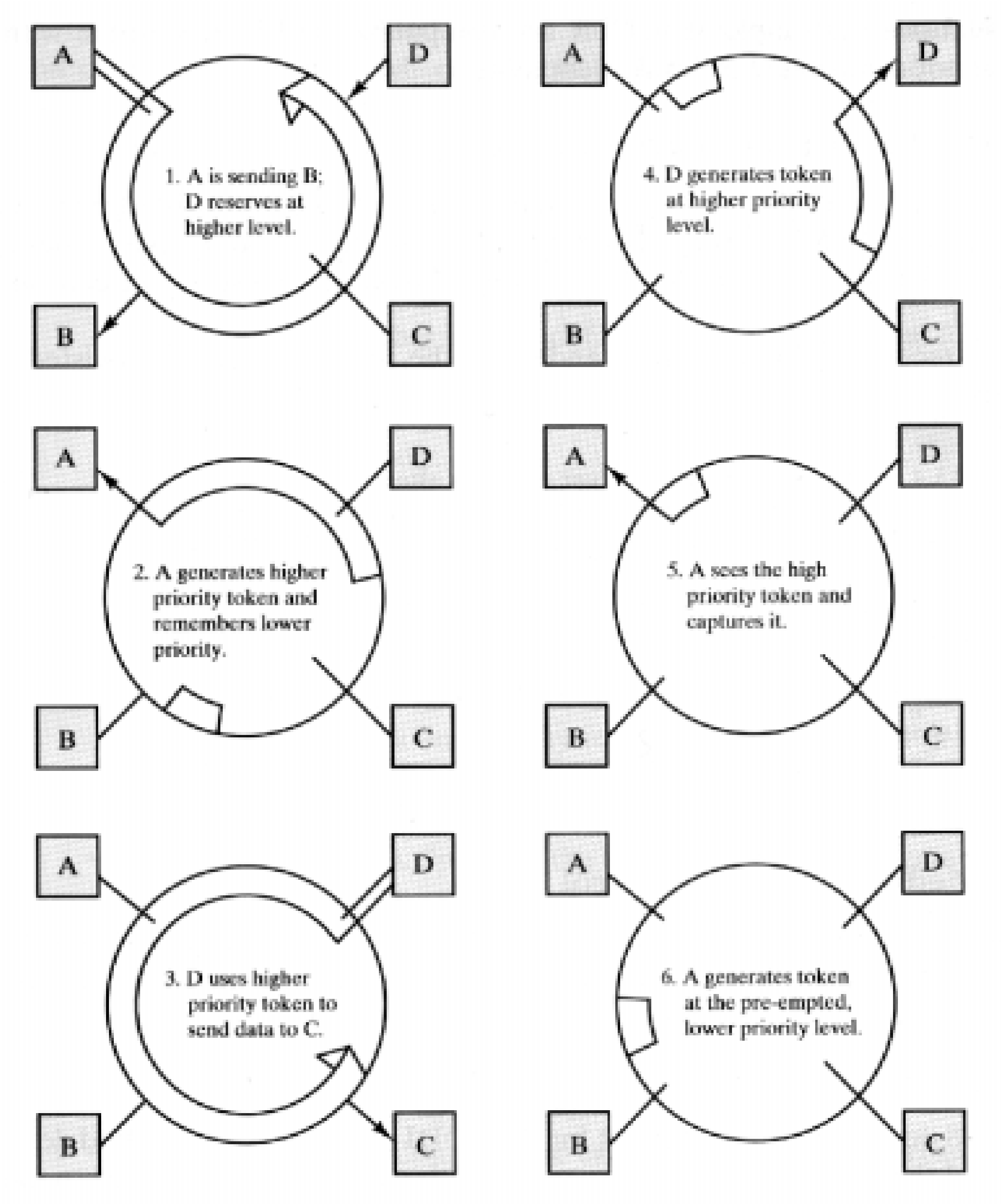
a>1 a<1



  - Case2: a>1

    T1 = 1, T2 = a + a/N

    $\sum S = \dfrac{1}{a(1+1/N)}$



Token ring priority scheme

- IEEE 802.5 Physical Layer Specification

Table 13.4 IEEE 802.5 Physical Layer Medium Alternatives

Transmission Medium	Shielded Twisted Pair	Unshielded Twisted Pair
Data rate (Mbps)	4 or 16	4
Signaling Technique	Differential Manchester	Differential Manchester
Maximum number of repeaters	250	72
Maximum length between repeaters	Not specified	Not specified

FDDI (Fiber Distributed Data Interface) Medium Access Control

– MAC Frame

Bits	64	8	8	16 or 48	16 or 48	≥ 0	32	4	12
	Preamble	SD	FC	DA	SA	Info	FCS	ED	FS

(a) General frame format

Preamble	SD	FC	ED

(a) Token frame format

SD = Start-frame delimiter
FC = Frame control
ED = Ending delimiter
FS = Frame status

- **Preamble:** For synchronization.
- **Starting delimiter (SD):** Indicates start of frame. JK, where J and K are nondata symbols (4 bits).
- **Frame control (FC):** Has the bit format CLFFZZZZ, where C indicates whether this is a synchronous or asynchronous frame; L indicates the use of 16- or 48-bit address; FF indicates whether this is an LLC, MAC control, or reserved frame. For a control frame, the remaining 4 bits indicate the type of control frame. For token frame, FC has the bit format 10000000 or 11000000 to indicate this is a token.
- **Ending delimiter (ED):** Contains a nondata symbol (T), and a pair of nondata symbols (T) for the token frame.
- **Frame status (FS):** Contains the error detected (E), address recognized (A), and frame copied (F) indicators. Each indicator is represented by a symbol, which is R for “reset” or “false” and S for “set” or “true.”

- FDDI MAC Protocol
  - Fundamentally similar to IEEE 802.5
  - Due to the high data rate (100 Mbps) and the longer distance segment than the 802.5, a frame on the FDDI ring may be significantly shorter than the bit-length of the ring.
  - In normal token ring, a station does not give up the token until the following:
    - Finished transmitting all its frame
    - Starts to receive leading edge of last frame transmitted
  - Waiting for the edge of the frame to come back waists potential capacity
  - In FDDI, token is sent immediately after last frame sent: "Fast (Early) token release"
  - In 802.5, station seizes the token by flipping the T bit of a passing token frame from 0 to 1, and then appends its own frame to it.
  - In FDDI, bits move too fast to be modified. Token seizure is done by aborting the rest of frame as soon as it is recognized as a token. Rest of token is read in. Next station will recognize the aborted frame and discard it.

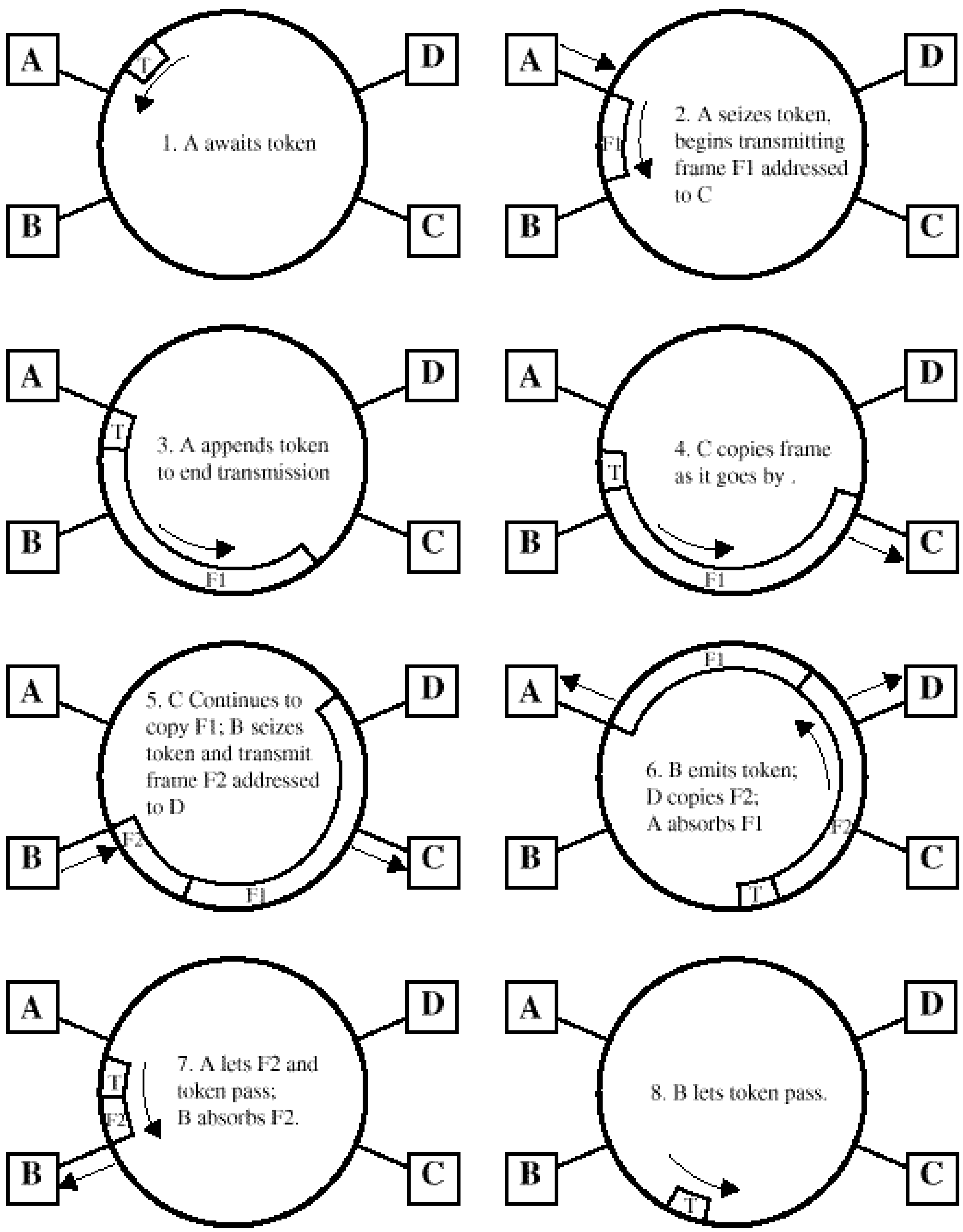


Figure 13.9 Example of FDDI Token Ring Operation

- Capacity Allocation
  - The priority scheme used in 802.5 does not work in FDDI, as a station issues a token before its own transmitted frame returns.
  - FDDI uses a capacity allocation scheme which seeks to accommodate a mixture of stream and bursty traffic.
  - FDDI defines two types of traffic: synchronous and asynchronous.

  - Assume fixed length frame sizes.
  - Rather than defining "capacity" as bps, define it as the number of frames that can be transmitted in a given time period.
  - Define the total amount of frames in a given time period as the "synchronous traffic".
  - Each station is allocated a certain percentage of the synchronous traffic. "Synchronous Allocation" or "SA".
  - Also define the rate at which the token needs to circulate around the ring as TTRT - "Target Token Rotation Time".
  - Thus, each station *i* is allocated a specific SA_i values such that $\sum SA_i \leq TTRT$
  - However, we have to account for the time to actually transmit the token, propagation time, and the time to get at least one frame around the ring:

    Total Synchronous Allocation = $\sum SA_i$ + Time to transmit one token + Propagation time around the ring + Time to transmit a frame

    Total Synchronous Allocation $\leq$ TTRT

- If this summation is less than TTRT, then all time left is considered “asynchronous allocation”.

  Asynchronous allocation = TTRT - Total Synchronous Allocation
- Operation:
  - Each station holds the following variables in a state machine.

    TTRT: Fixed constant, same for all stations

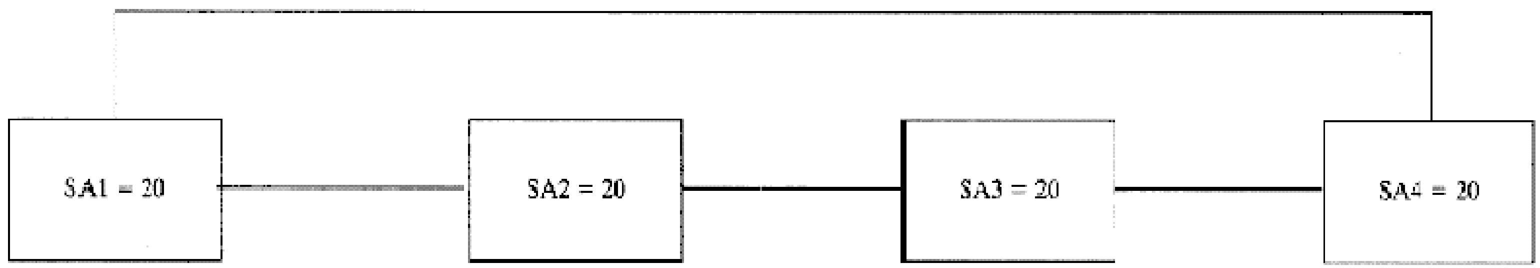
    SA_i : pre-assigned allocation amount

    TRT: Token Rotation Timer - Amount of time before the TTRT time expires

    THT: Token Holding Time - Amount of extra time left

    LC: Late Counter - Either 0,1, or 2, number of TTRT cycles that have elapsed since last token received.
  - TRT is a counter. It continually decrements, unless otherwise stopped, or reset.
  - Initialize: TRT $\leftarrow$ TTRT; LC $\leftarrow$ 0
  - While waiting for a token, the TRT continues to decrement. If it hits 0, then it increments the LC from 0 to 1, resets TRT, then continues waiting for token. If LC gets increment to 2, then the token is considered lost
  - If it receives a token, and the LC is zero, then TRT represents “extra time”. THT $\leftarrow$ TRT, TRT $\leftarrow$ TTRT, enable TRT. Then, the station sends synchronous frames for a time SA_i. After transmitting synchronous frames, or if there were no synchronous frames to transmit, THT is enabled. The station can transmit asynchronous frames as long as THT > 0.
  - If it receives a token and the LC is 1, then LC $\leftarrow$ 0, TRT continues to decrement. The station can only transmit synchronous frames for a time SA_i.
- Example situation:
  - 4 stations. TTRT = 100 frame times. SA_i = 20 frame times for each station. Each station is always prepared to send its full synchronous allocation and as many as asynchronous frames as possible. The total overhead during one complete token circulation is 4 frame times (one frame time per station).

Operation of FDDI capacity allocation scheme



Arrival Time	TRT	Sync	Async	Arrival Time	TRT	Sync	Async	Arrival Time	TRT	Sync	Async	Arrival Time	TRT	Sync	Async
0	100	0	0	1	100	0	0	2	100	0	0	3	100	0	0
4	96	20	96	121	80*	20	0	142	60*	20	0	163	40*	20	0
184	20*	20	0	205	96*	20	0	226	76*	20	0	247	56*	20	0
268	36*	20	0	289	12	20	12	322	80*	20	0	343	60*	20	0
364	40*	20	0	385	4	20	4	410	92*	20	0	431	72*	20	0
452	52*	20	0	473	16	20	16	510	92*	20	0	531	72*	20	0
552	52*	20	0	573	0	20	0	594	8	20	8	623	80*	20	0
644	60*	20	0	665	8	20	8	694	0	20	0	715	88*	20	0
736	68*	20	0	757	8	20	8	786	8	20	8	815	88*	20	0
836	68*	20	0	857	0	20	0	878	8	20	8	907	96*	20	0
928	76*	20	0	949	8	20	8	978	0	20	0	999	4	20	4
1024	80*	20	0	1045	4	20	4	1070	8	20	8	1099	0	20	0

*LC = 1; otherwise LC = 0

– FDDI Physical Layer Specification

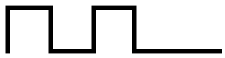
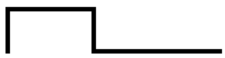
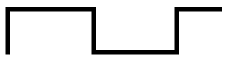
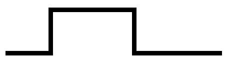
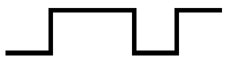
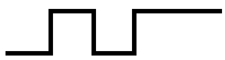
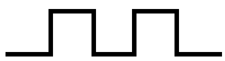
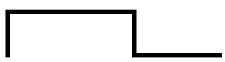
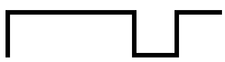
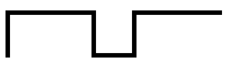
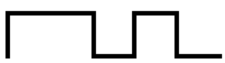
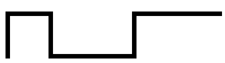
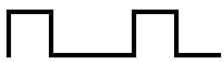
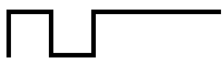
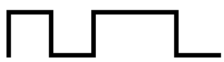
Table 13.5 FDDI Physical Layer Medium Alternatives

Transmission Medium	Optical Fiber	Twisted Pair
Data rate (Mbps)	100	100
Signaling Technique	4B/5B/NRZI	MLT-3
Maximum number of repeaters	100	100
Maximum length between repeaters	2 km	100 m

– FDDI digital signal encoding schemes

- Differential Manchester used in Token ring is not used in FDDI, since 200 million baud rate would be needed for a 100 Mbps data rate.
- To lower the baud rate and to maintain a synchronization ability, FDDI uses a 4B/5B code in conjunction with an NRZI (Nonreturn to zero inverted) technique.
- For every 4 bits of data, a 4B/5B encoder creates a 5-bit code, which is then transmitted using NRZI.
- Using this scheme, a signal will change at most 5 times for each 4 data bits. $\Rightarrow$ 125M baud rate is enough.
- The 4B/5B encoder never codes more than two consecutive binary 0s for data, ensuring that the signal is never constant for long periods.
- This method preserves the self-synchronizing ability using a baud rate just 25% higher than the data rate.

4B/5B code groups

Data Input (4 bits)	Code Group (5 bits)	NRZI pattern	Interpretation
0000	11110		Data 0
0001	01001		Data 1
0010	10100		Data 2
0011	10101		Data 3
0100	01010		Data 4
0101	01011		Data 5
0110	01110		Data 6
0111	01111		Data 7
1000	10010		Data 8
1001	10011		Data 9
1010	10110		Data A
1011	10111		Data B
1100	11010		Data C
1101	11011		Data D
1110	11100		Data E
1111	11101		Data F

Control symbols	Encoded bits
Halt	00100
Idle	11111
non-data-J	11000
non-data-K	10001
Quiet	00000
Reset	00111
Set	11001
Terminate	01101