COMP2001J Computer Networks

Lecture 5 – Data Link Layer
(Medium Access Control)

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About Labs

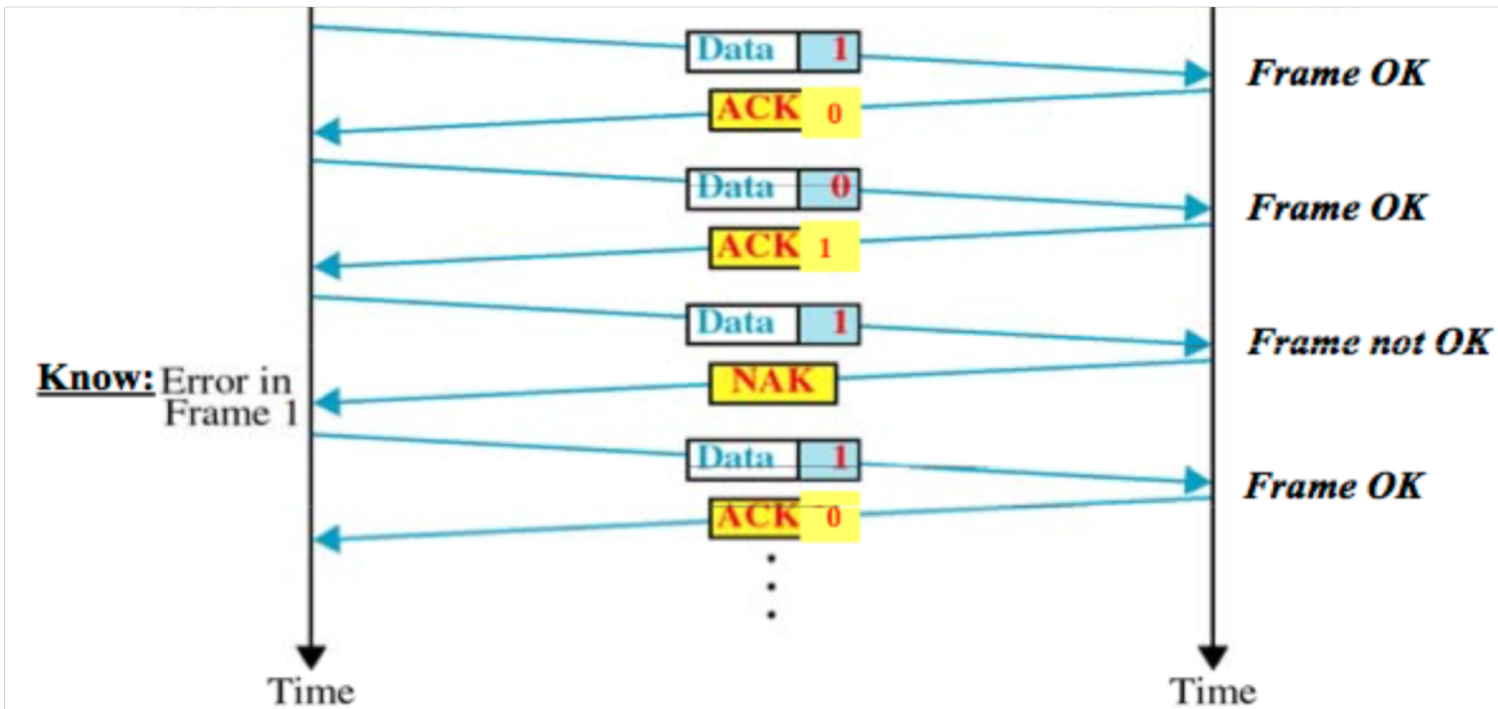
- Q1. Software Version?
  - Better to keep the consistency: I use Packet Tracer **7.1.1** (updated for computers in lab buildings)
  - It does **not** matter to use 32-bit or 64-bit version. They have the same functionalities.
- Q2. Real-time mode? Simulation mode?
  - Real-time mode -> just like running your program
  - Simulation mode -> just like debugging your program
  - Simulation mode actually **stops** your simulation unless you manually control it moving step by step.

About Labs

- Q3. MAC/IP address? IP route.
  - MAC: the identification of your network device
  - IP: the address of your network device
  - IP route: when the target subnet of a received packet is not directly connected to a router, this router needs to know which of its neighboring routers it should forward to.
- Q4. Next quiz?
  - All contents including today's that have not yet covered in Quiz 1.
  - 4 people (3 TAs and me) supervising the Quiz
  - You can only work on yourself!
    - It is OK to read slides, text books, and use calculators.
  - But, don't talk! When caught, 0 mark for your Quiz.

About Lecture 4 – ACK number

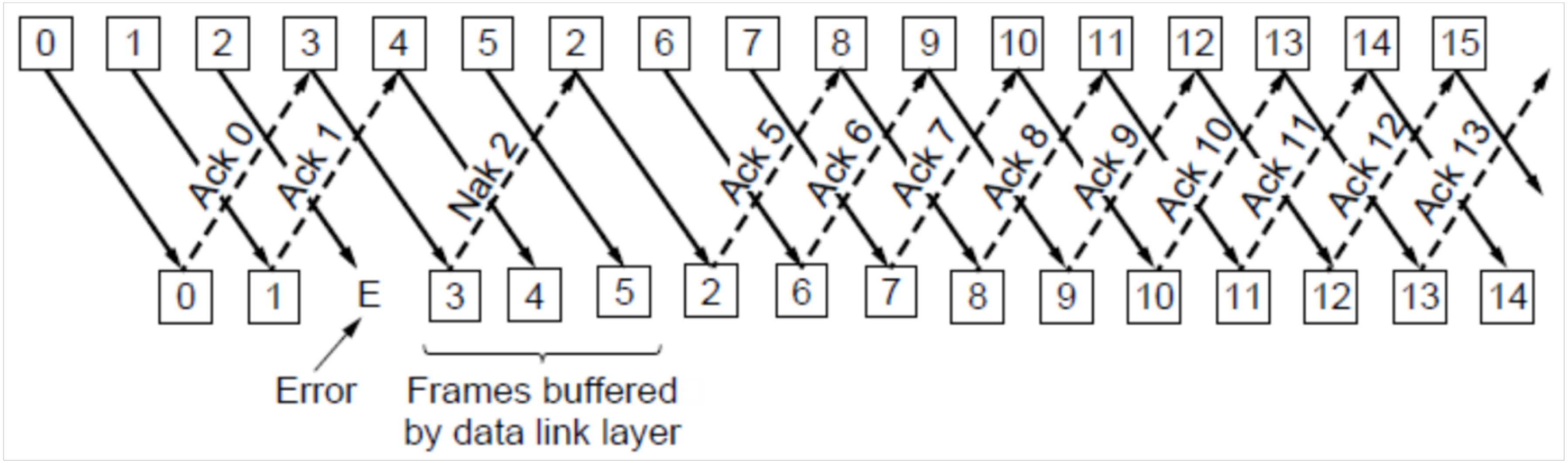
- Stop-and-wait: the sequence number of the frame that **expect to receive the next**
  - To receive frames in order



About Lecture 4 – ACK number

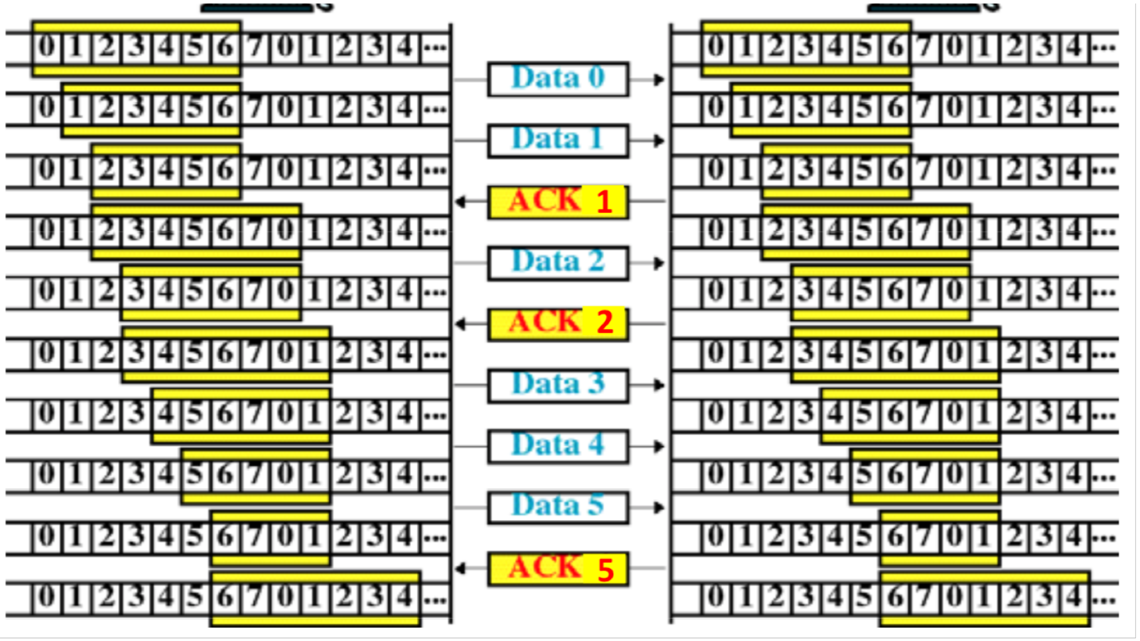
- Go-back-N and Selective Repeat: the sequence number of the frame that has **just received in order**.

This is the Selective Repeat



About Lecture 4 – Cumulative ACK

- When to send accumulative ACK?
  - Timeout at receiver side. Then send the ACK with the highest in-order frame number.
  - When the receiver has data to send back to sender, using piggyback ACK



Every 2 frames?

Each frame?

Every 3 frames?

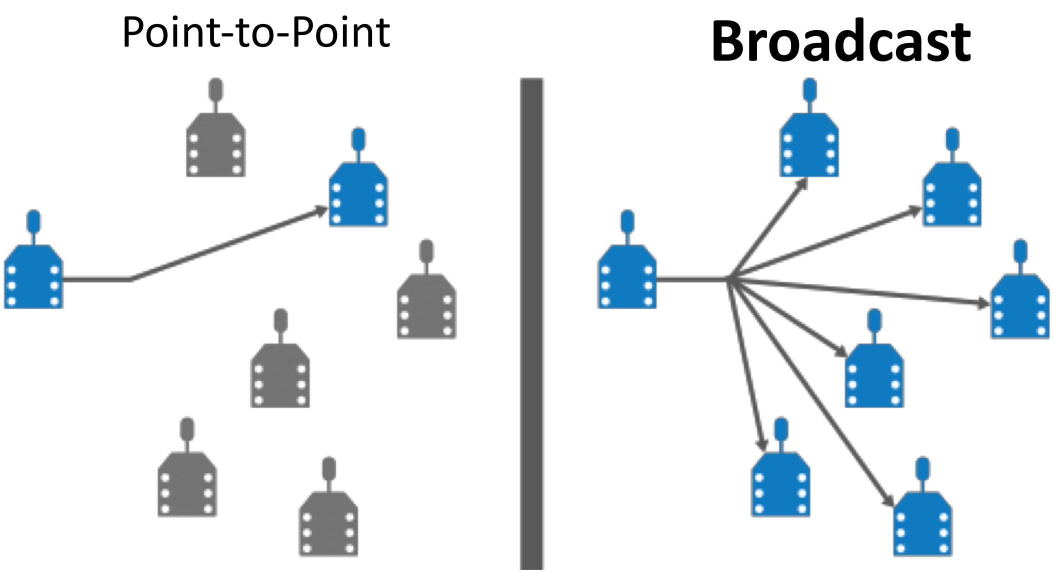
About Lecture 4 - Timers

- Go-Back-N: need only one timer for the frame numbered after the latest ACK number

- Selective Repeat: the number of timers needed is equal to the number of buffers (outstanding frames), not to the size of the sequence space.

Outline

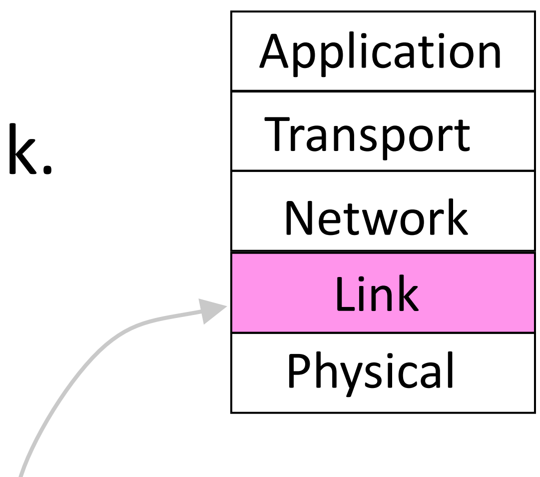
- ALOHA
  - Pure ALOHA
  - Slotted ALOHA
- CSMA
  - 1-persistent
  - Non-persistent
  - P-persistent
  - CSMA/CD
  - CSMA/CA
- Token Ring



MAC sub-layer

- The Medium Access Control (MAC) is a part of the Link layer.

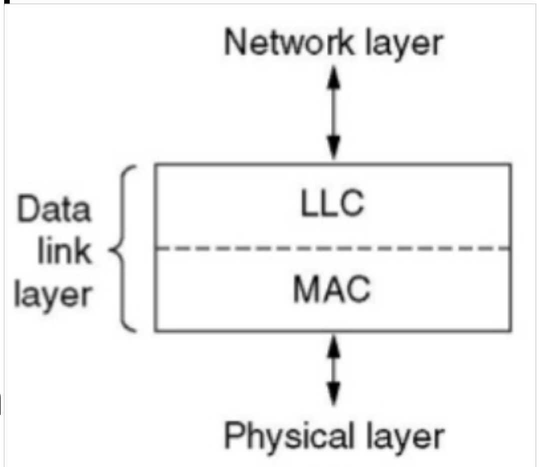
- Responsible for coordinating communications among multiple devices on a single half-duplex link.
  - An important part of the link layer, especially for LANs



MAC is in here!

Data link sub-layers: MAC/LLC

- In IEEE 802 LAN/MAN standards,
  the MAC sublayer and the logical link control (LLC) sublayer together make up the data link layer.
  - the LLC provides flow control and multiplexing for the *logical* link (i.e. EtherType, 802.1Q VLAN tag etc)
  - the MAC provides flow control and multiplexing for the transmission medium

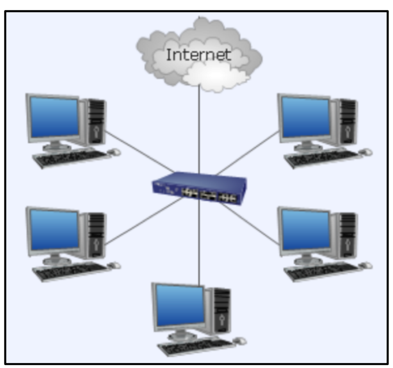


- In other words, MAC converts the physical **broadcast** channel into several logical point-to-point channels.

Broadcast Networks

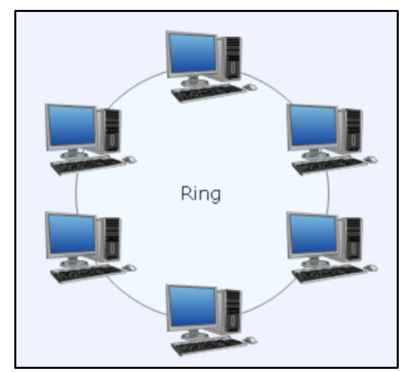
- Broadcast networks are those where all messages are sent to all nodes in the network
  - This includes most local area networks (**LAN**s)

Common Topologies for LANs



Star

Bus



Ring

Broadcast Networks

- A difficult problem to solve is how to determine which node can use the shared channel at any given time.

- When 2 or more nodes want to transmit at the same time, they are said to **contend** for the channel

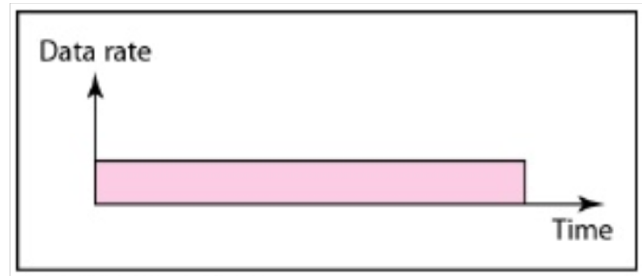
- If 2 or more nodes transmit at the same time, usually the transmission will **collide** and are destroyed
  - No transmission is successful

Channel Allocation Problem

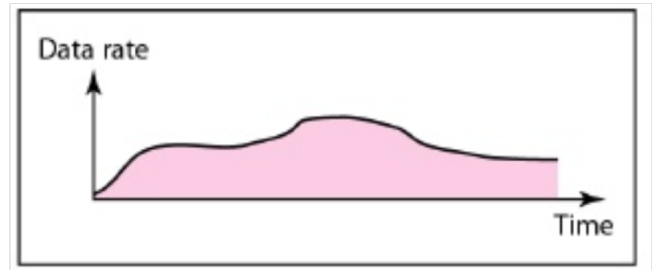
- For fixed channel and traffic from N users
  - Divide up bandwidth using FTM, TDM, CDMA, etc.
  - This is a static allocation (see "**multiplexing**" in physical layer), e.g., FM radio
- This **static** allocation performs poorly for bursty traffic
  - Allocation to a user will sometimes go unused
- **Dynamic** allocation gives the channel to a user when they need it. Potentially N times as efficient for N users.

Bursty Traffic

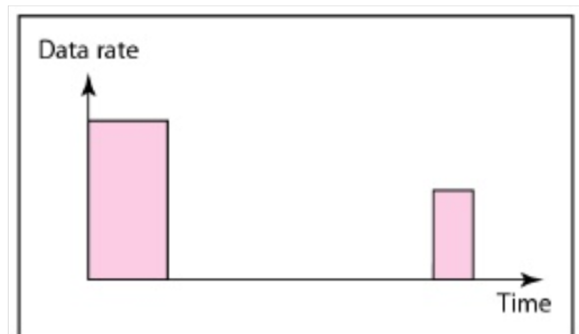
- Constant bit rate (CBR):
  - Data rate does not change over time
- Variable bit rate (VBR):
  - Data rate changes smoothly over time
- **Bursty Traffic**:
  - Data rate changes sharply over time.
  - Major traffic type in computer networks



a. Constant bit rate



b. Variable bit rate



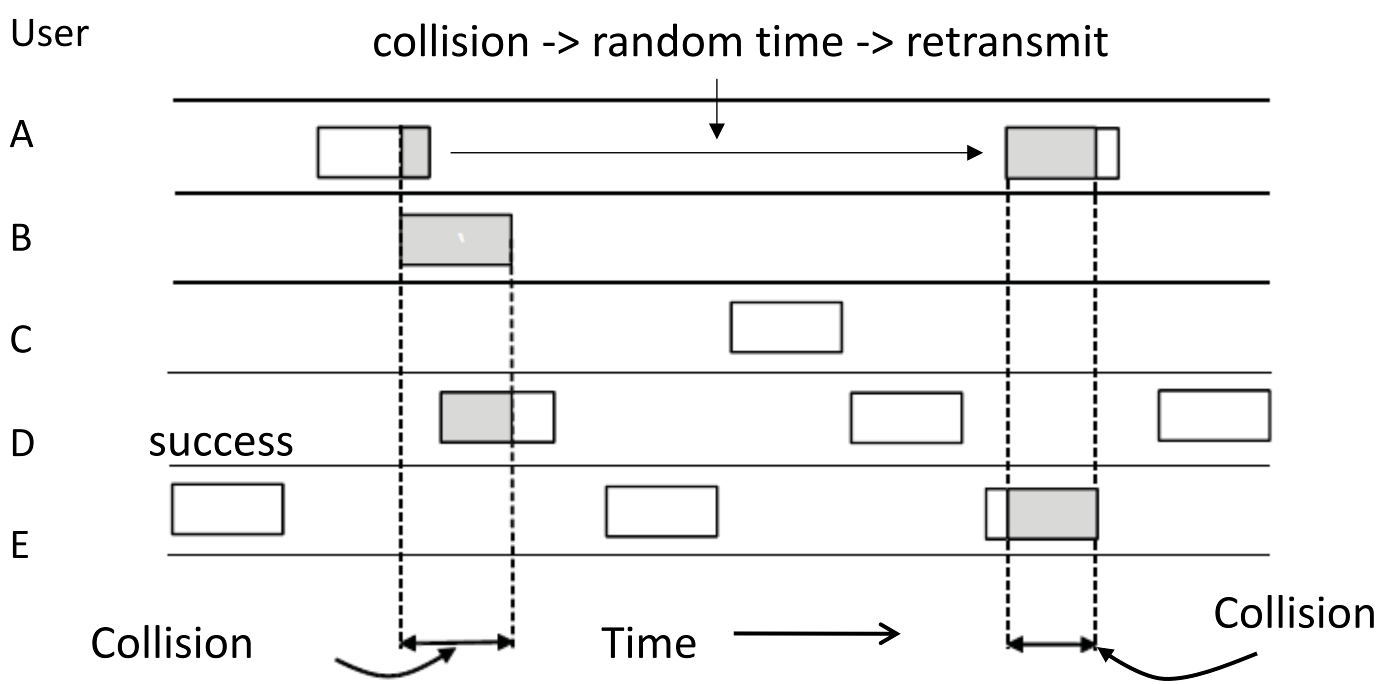
c. Bursty

ALOHA

- Additive Link On-line HAwaii system (ALOHA)
- In pure ALOHA
  - users transmit frames whenever they have data
  - users retry after a random time for collisions
  - efficient and low-delay under low load

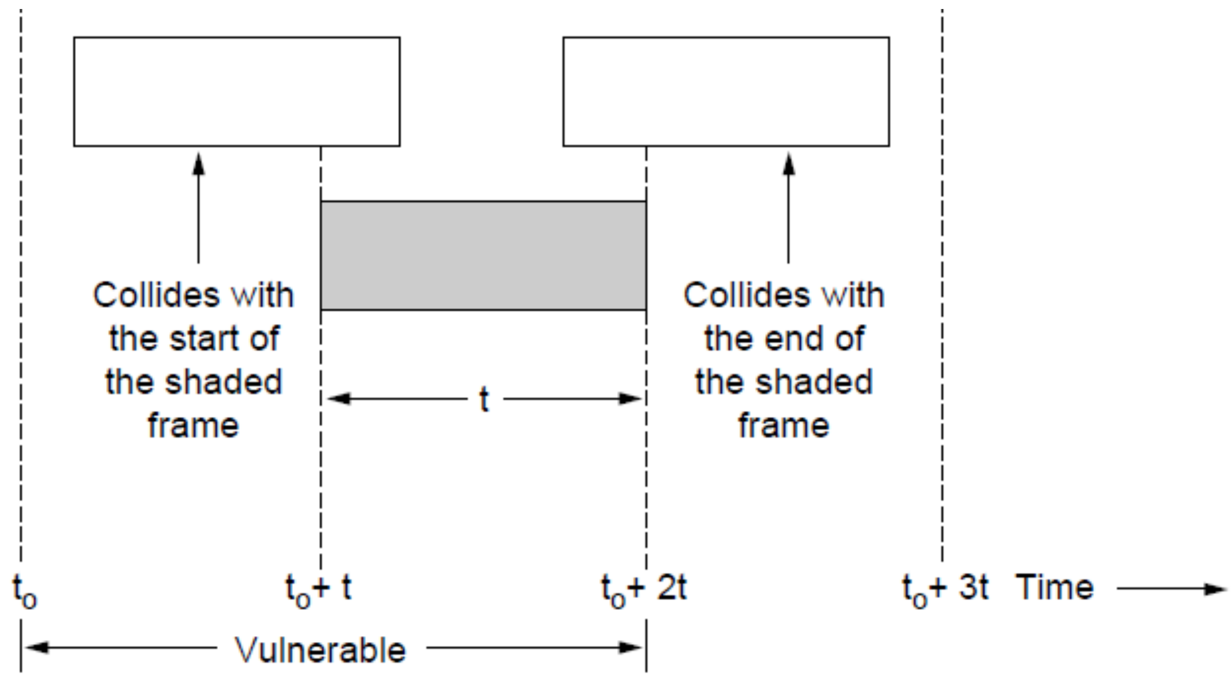
Pure ALOHA

- Each frame length is represented in **time** (not bit).
- Whenever two frames try to occupy the channel at the same time, there will be a collision and both will be garbled



Pure ALOHA

- Collisions happen when other users transmit during a **vulnerable period** that is twice the frame time
  - Synchronizing senders to slots can reduce collisions

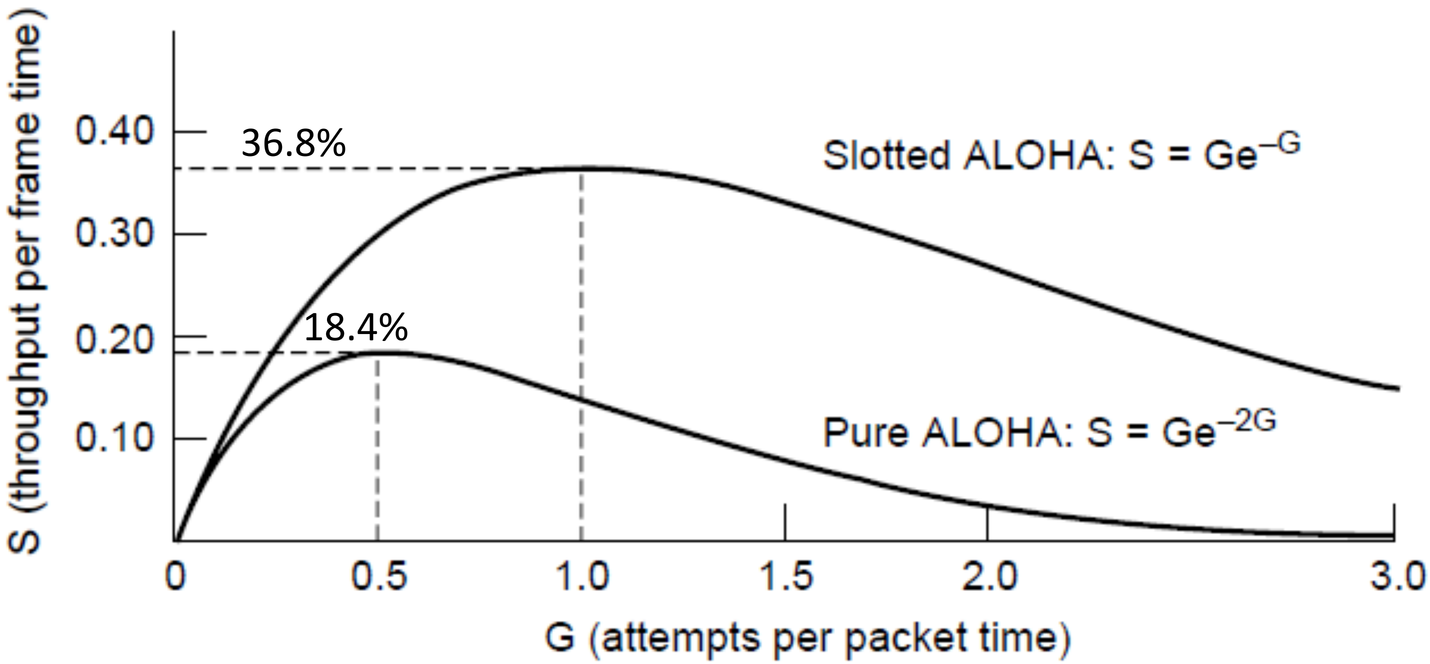


Slotted ALOHA

- Divide time into discrete intervals called **slots**, each interval corresponding to one frame.
  - It requires the users to agree on slot boundaries (synchronisation).
- A station can not send until the next slot begins.
  - It is required to wait for the beginning of the next slot.
- Thus, the continuous time ALOHA is turned into a discrete time one.
  - This halves the vulnerable period.

ALOHA

- Slotted ALOHA is twice as efficient as pure ALOHA
  - *G*: new generated frames and retransmissions
  - *S*: successfully transmitted rate
  - Low load (*G*) wastes slots, high loads (*G*) causes collisions



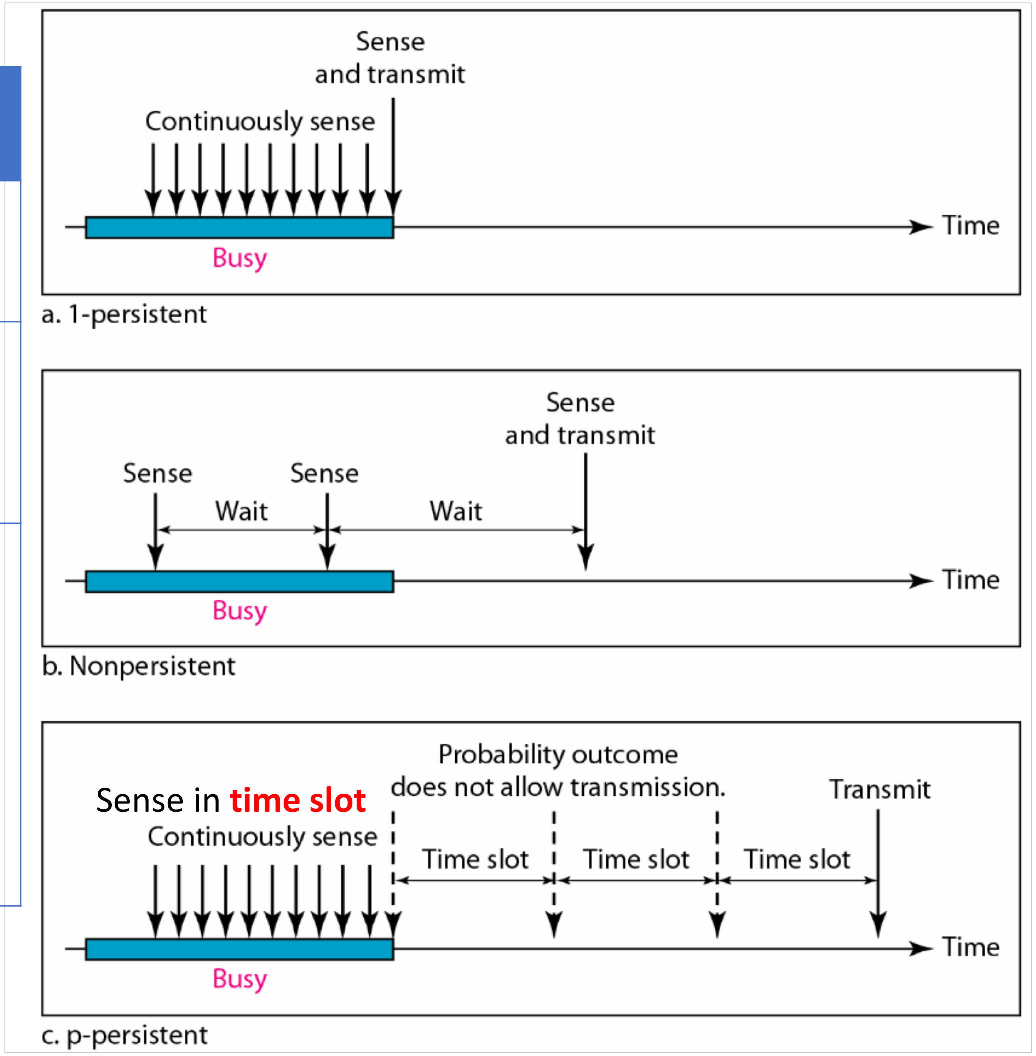
CSMA

- Carrier Sense Multiple Access (CSMA)
- CSMA improves ALOHA:
  - If the channel is busy, some other node is transmitting and our node must wait until it detects that the channel is idle
  - When the channel is determined to be idle, our node can transmit

- Variations on what to do if the channel is idle / busy:
  - 1-persistent CSMA
  - Non-persistent CSMA
  - p-persistent CSMA: slotted channels
    - 802.11 uses a refinement of p-persistent CSMA

CSMA Variants

x-persistent CSMA	Busy	Idle
1	Keep sensing	Send immediately
Non	Sense after a random time	Send immediately
p	Sense at the start of the next slot	Send with a probability *p*, delay to the next slot with a probability (*1-p*)

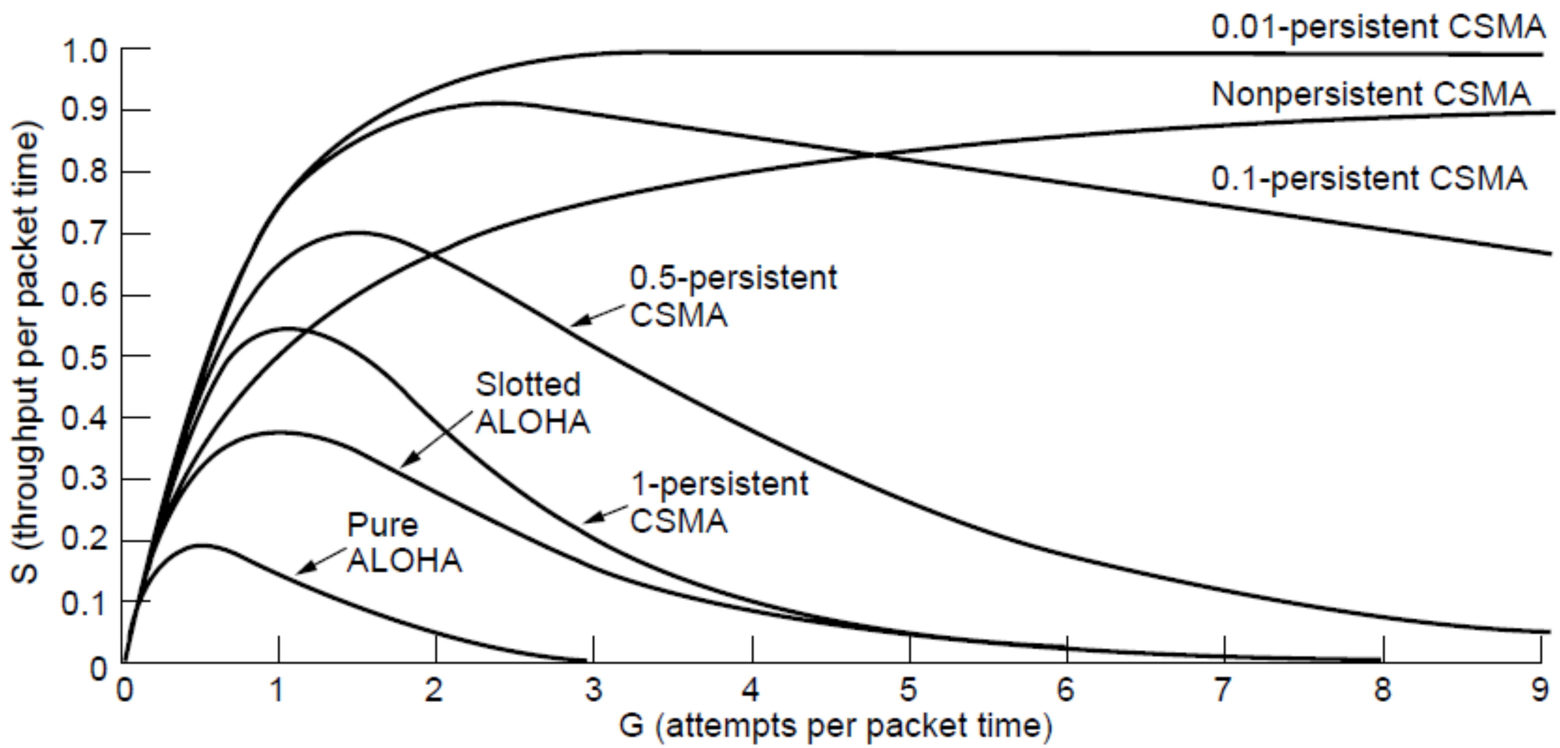


CSMA Variants

- Non-Persistent CSMA
  - High efficiency, high delay
- 1-Persistent CSMA
  - Low delay, low efficiency
- P-persistent CSMA
  - The repetitive (*1-p*) delay stops when the frame successfully transmitted, or when the busy channel is sensed.
  - Performance depends on the value of *p*

CSMA - Persistence

- CSMA outperforms ALOHA, and being less persistent is better under high load



Collision Detection

- CD: <u>during</u> transmission (carrier sensing is done <u>before</u> transmission), our node listens to the channel and if another transmission is detected (e.g. higher voltage level than expected for one transmission), all nodes involved in the collision stop transmitting immediately
  - In full duplex mode no collision detection is required

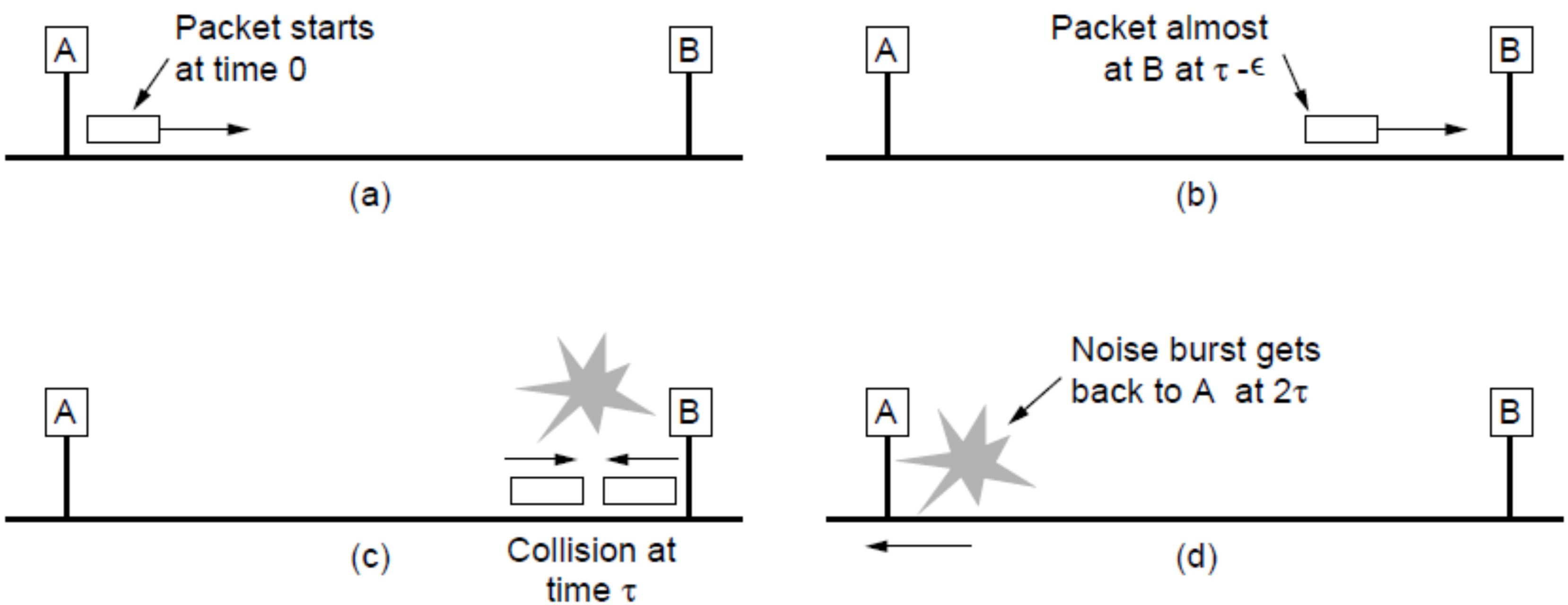
- Each node then computes a **randomly-sized** time interval independently, waits for that amount of time, and begins the transmission attempt again

Collisions in CSMA/CD

- Even with carrier sensing before transmission, collisions can still occur because it takes non-zero time for signal to propagate along the channel
- If the propagation time along the length of the channel is denoted by τ, can show that the ***worst-case collision detection time*** is (approximately) 2τ
- This shows why there is a **minimum frame length** in CSMA/CD systems: all frames must take more than 2τ to transmit
  - minimum frame length: 2 x Bandwidth-Delay-Product
  - "pad" information field, if necessary (smaller)

Contention Time

- Collisions can occur and take as long as 2τ to detect
  - τ is the time it takes to propagate over the transmission link
  - Noise burst generated by B to warn all others about collision



Binary Exponential Backoff (BEB)

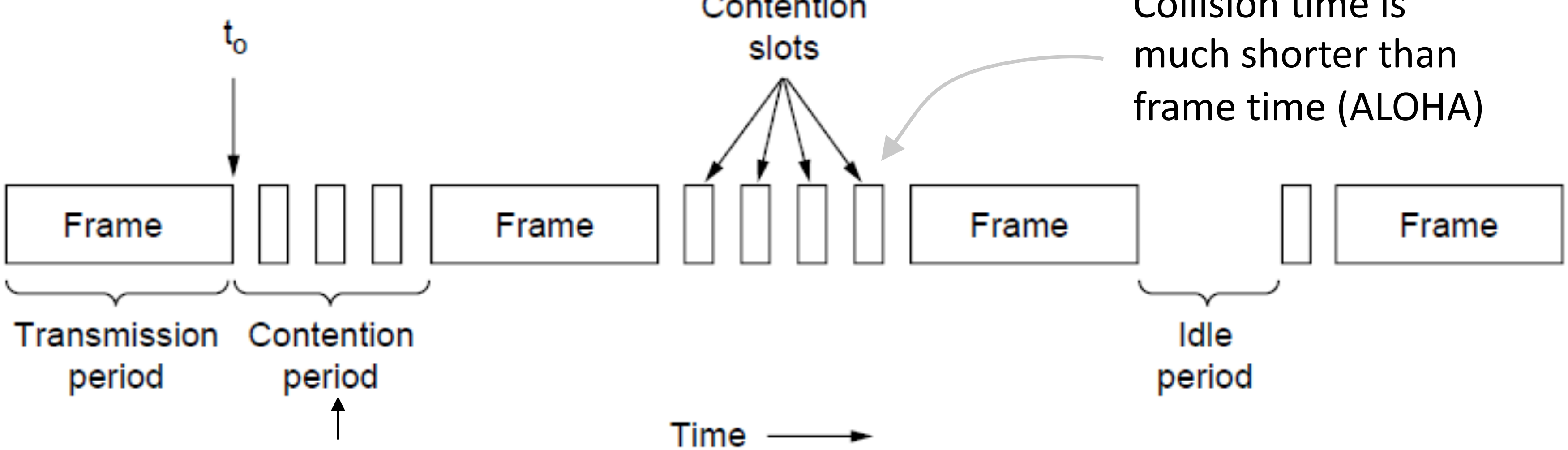
- Backoff time: random waiting time before retry
- Classic Ethernet uses the 1-persistent CSMA/CD with BEB
  - If there is a collision, it aborts the transmission with a short jam signal (noise burst) and retransmit after a random interval (backoff time).
- The basic idea of BEB:
  - the more collisions for a transmission, the longer it have to wait before retry.

Binary Exponential Backoff (BEB)

- After a collision, time is divided into discrete slots (2τ, 51.2 μsec for Ethernet).
- After the 1st collision, each station waits either 0 or 1 slot times at random before trying again.
  - If two stations collide and each one picks the same random number, they will collide again.
- After the 2nd collision, each one picks either 0, 1, 2, or 3 at random and waits that number of slot times.
- After the 3rd collision, the next time the number of slots to wait is chosen at random from the interval 0 to $2^3 - 1$.
  - after *i* collisions, a random number between 0 and $2^i - 1$ is chosen and that number of slots is skipped.
- After 10 collisions, the randomization interval is frozen at a maximum of 1023 slots.
- After 16 collisions, the controller reports failure back to the computer.

CSMA – Collision Detection

- CSMA/CD improvement is to detect/abort collisions
  - Reduced contention times improve performance



Collision time is much shorter than frame time (ALOHA)

But, **how long it could be?** It is the key to the overall performance, roughly (transmission period)/(transmission period + contention period)

Ethernet CSMA/CD

- A problem with CSMA/CD:
  - theoretically, a node wishing to transmit may ***never*** be able to (Maximum Medium Access Time, MMAT = ∞):

- Even with random waiting times, the node's transmission attempts may collide every time!

- Let's do a performance analysis on Ethernet CSMA/CD

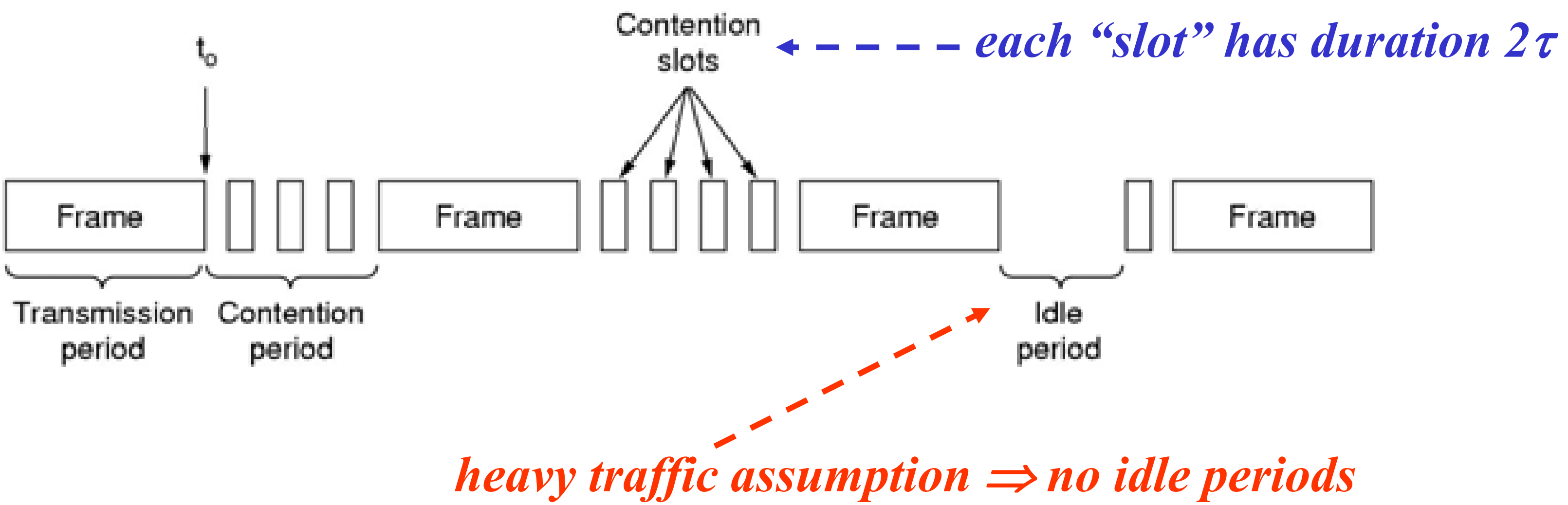
Ethernet Performance

- k: number of stations ready to transmit
- p: probability of a station transmitting in a contention slot
- A: probability that some station acquires the channel in that slot
$$A = kp(1-p)^{k-1}$$
- A is maximized (busy channel, no idle period) when $p = 1/k$, with $A \to 1/e$ as $k \to \infty$
- The probability that the contention interval has exactly j slots in it is $A(1-A)^{j-1}$, so the mean number of slots per contention is given by
$$\sum_{j=0}^{\infty} jA(1-A)^{j-1} = \frac{1}{A}$$
- w: the mean contention interval, when optimal p (busy channel, no idle period)
$$w = 2\tau \times \frac{1}{A} = 2e\tau$$

Some conclusions

- We show that in heavy traffic conditions, BEB results in an ***average contention interval*** (period, not slot):

$$w = 2e\tau \approx 5.4\tau$$



Ethernet Performance

- B: the network bandwidth
- F: the frame length
- L: the cable length
- c: signal propagation speed
- P: number of seconds spent to send the mean frame; $P = F/B$

$$\text{Channel efficiency} = \frac{P}{P+2\tau/A} = \frac{\mathbf{1}}{\mathbf{1+2}\boldsymbol{BLe/cF}}$$

- Channel throughput = channel efficiency * B:

$$\frac{\mathbf{1}}{\mathbf{1}/\boldsymbol{B} + \mathbf{2}\boldsymbol{Le/cF}}$$

Some conclusions

- What if ***length of the channel is increased***?
  - When L increases, ***both efficiency and throughput decrease***
- What if ***channel bandwidth is increased***?
  - When B increases, ***efficiency decreases,*** but ***throughput increases***
- efficiency only measures the fraction of time spent doing "useful work",
  - in this case transmitting frames – if it takes shorter (high bandwidth) to transmit frames and the propagation delay is held constant (meaning the collision detection time is held constant), then a smaller fraction of the time is spent actually transmitting frames!

CSMA/CD Advantages & Disadvantages

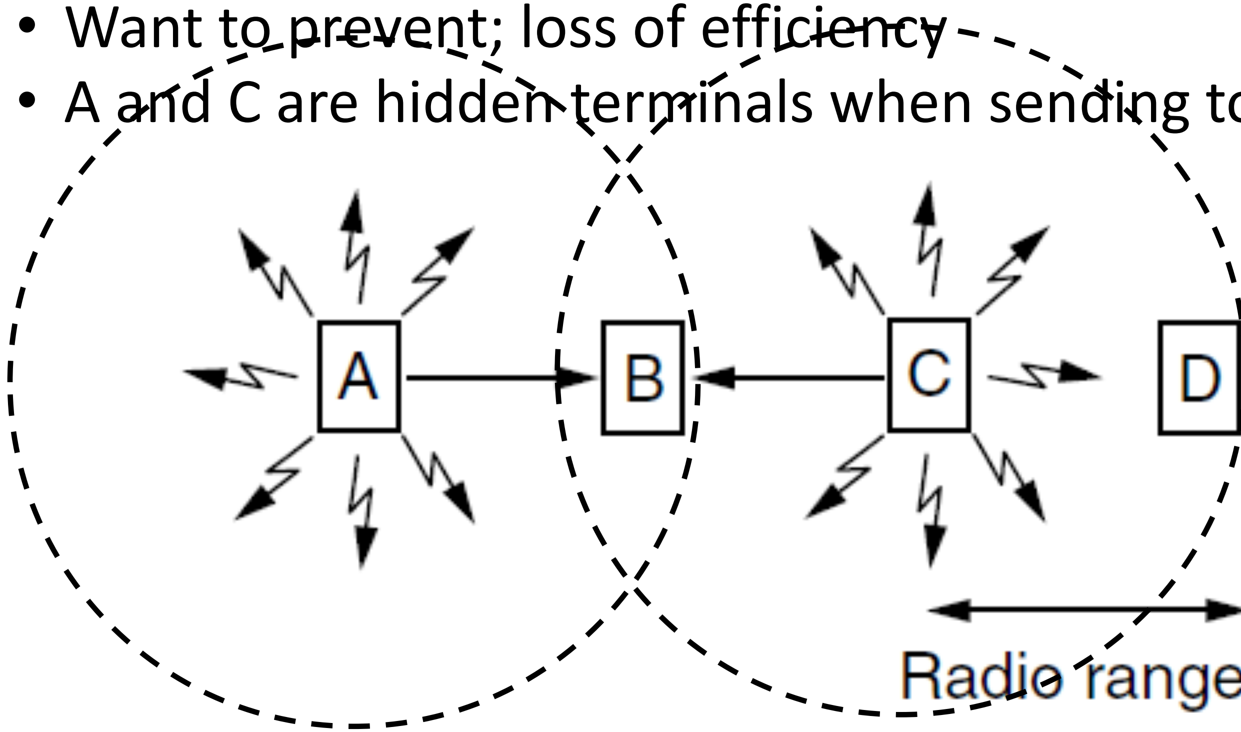
- Advantages
  - Low ***average*** access time under light loading conditions
  - Easy to move/upgrade/change nodes, due to distributed channel access protocol
  - Graceful performance degradation as number of nodes increases
  - The most popular LAN technology, with a huge installed base
- Disadvantages
  - Substantial analogue component: collision detection circuitry
  - Minimum valid frame length is inefficient if data is short
  - Priorities not supported: difficult to support real-time traffic
  - Channel access time unpredictable
    - As load increases: access time increases, and is theoretically unbounded

CSMA for Wireless LAN

- Wireless has complications compared to wired.
- Nodes may have different coverage regions
  - Leads to hidden and exposed terminals
- Nodes can’t detect collisions, i.e., sense while sending
  - Makes collisions expensive and to be avoided
  - Instead of using Collision Detection, **Collision Avoidance** is applied for Wireless LAN (**CSMA/CA**)

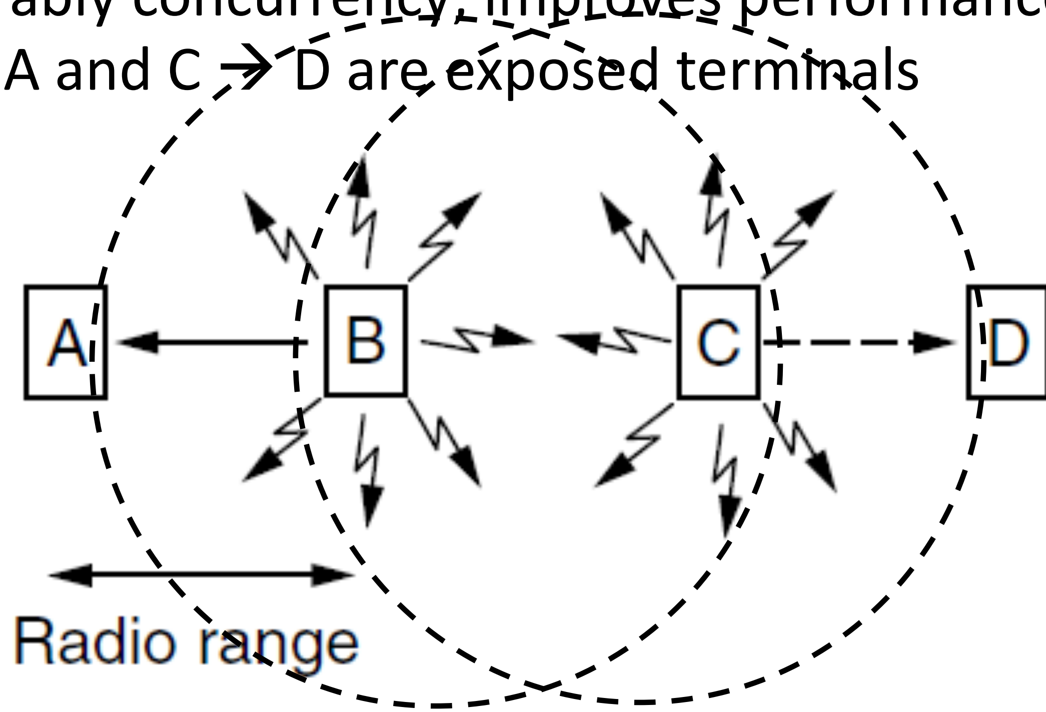
Wireless LANs – Hidden terminals

- Hidden terminals are senders that cannot sense each other but nonetheless collide at intended receiver
  - Want to prevent; loss of efficiency
  - A and C are hidden terminals when sending to B



Wireless LANs – Exposed terminals

- Exposed terminals are senders who can sense each other but still transmit safely (to different receivers)
  - Desirably concurrency; improves performance
  - B → A and C → D are exposed terminals

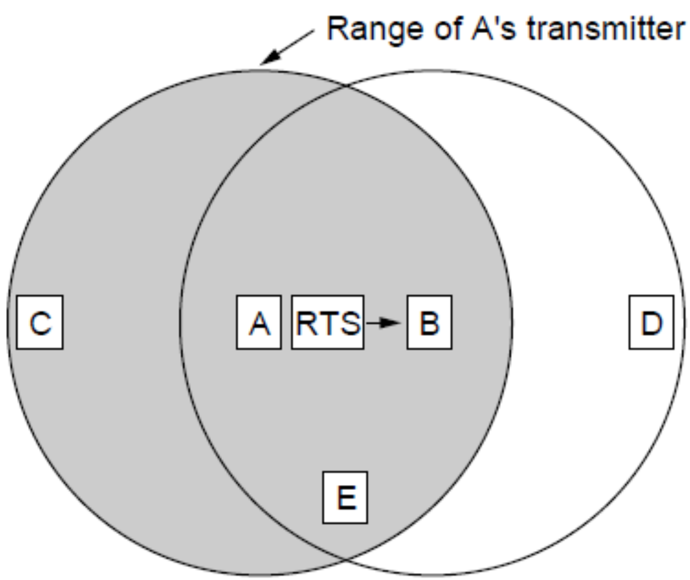


Wireless LANs – CSMA/CA

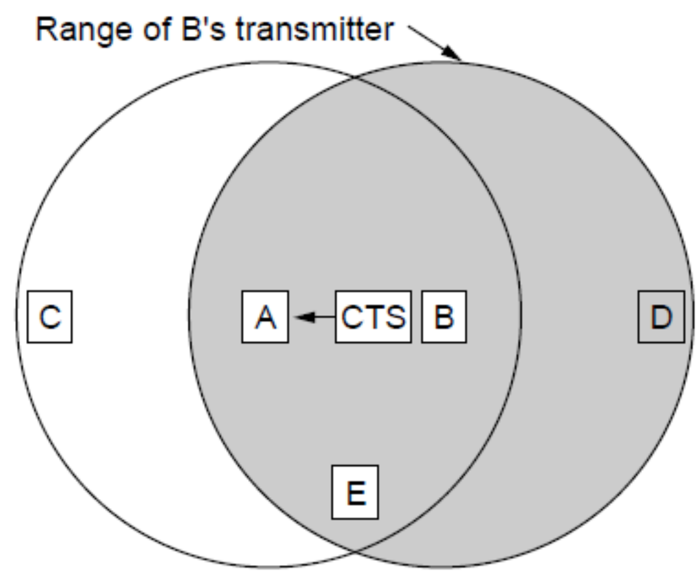
- It grants access for A to send to B:
  - A sends RTS to B [left]; B replies with CTS [right]
  - A can send with exposed but no hidden terminals
- This protocol solves the issue of expensive collisions too, since the RTS/CTS are short packets – if there is a collision it will be brief, not as long as a data frame.
- Request To Send (RTS); Clear to Send (CTS)

Wireless LANs – CSMA/CA

- It grants access for A to send to B:

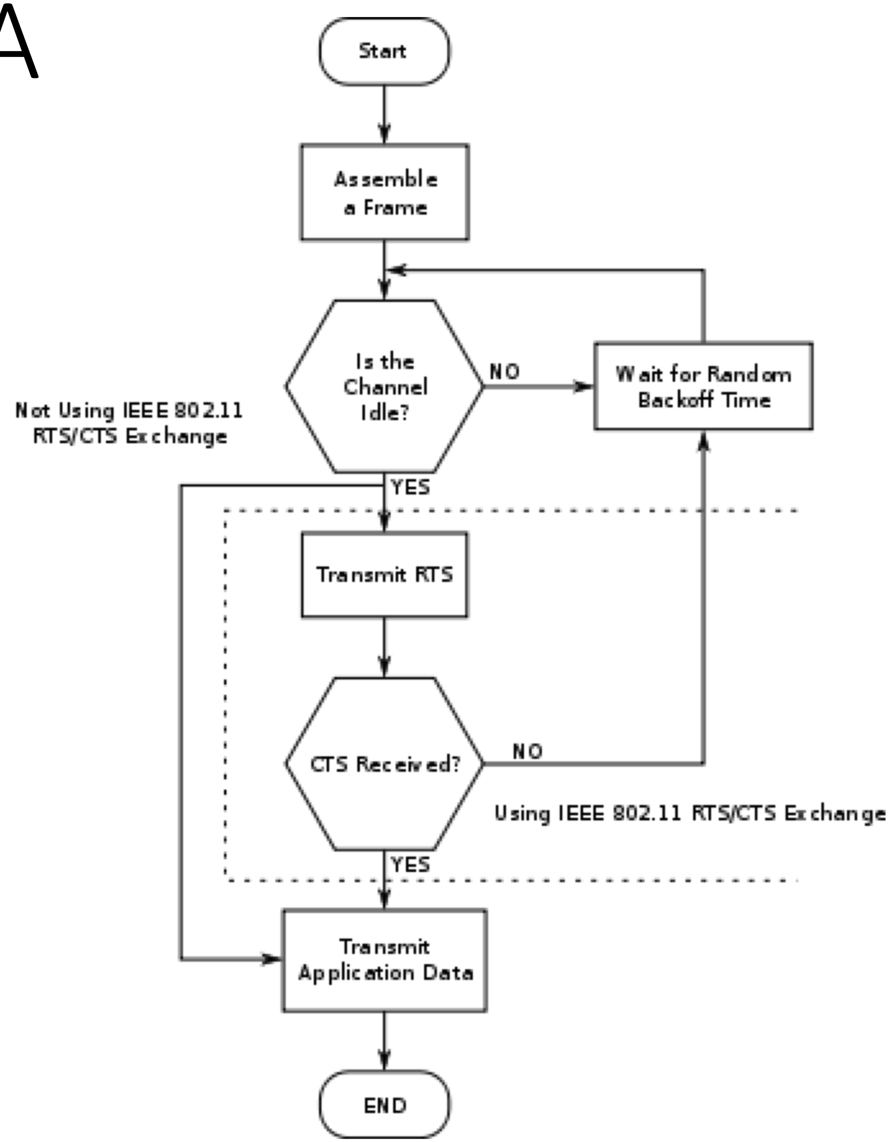


A sends RTS to B; C and E hear and defer for CTS



B replies with CTS; D and E hear and defer for data

CSMA/CA



Start
Assemble a Frame
Is the Channel Idle?
NO
Wait for Random Backoff Time
Not Using IEEE 802.11 RTS/CTS Exchange
YES
Transmit RTS
CTS Received?
NO
Using IEEE 802.11 RTS/CTS Exchange
YES
Transmit Application Data
END

CSMA/CD Alternatives

- The potential problems with Ethernet led to the development of some alternative technologies in the early 80s
  - IBM chose a ***ring topology*** for office automation applications – led to the Token Ring (802.5) standard
  - General Motors, and others interested in factory automation, chose a ***bus topology*** as a good match to layout of assembly lines – led to the Token Bus (802.4) standard

- Key point in both of these cases: the Maximum Medium Access Time (MMAT) is **bounded**, assuming the network is working correctly

Token Ring

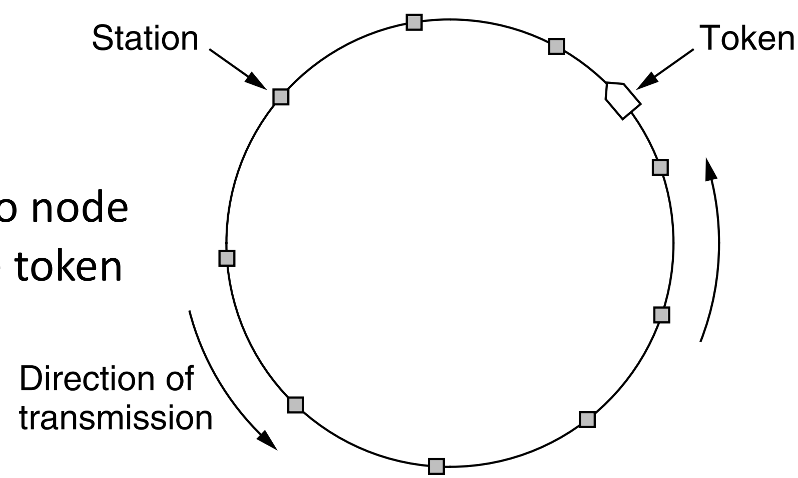
- Token sent round ring defines the sending order
  - Station with token may send a frame before passing
  - Idea can be used without a physical ring too, e.g., token bus (should be a ring, logically)

A **ring** is actually a set of point-to-point links that form a circle.

A ring is (logically) unidirectional.

A **token** is a special frame passed from node to node

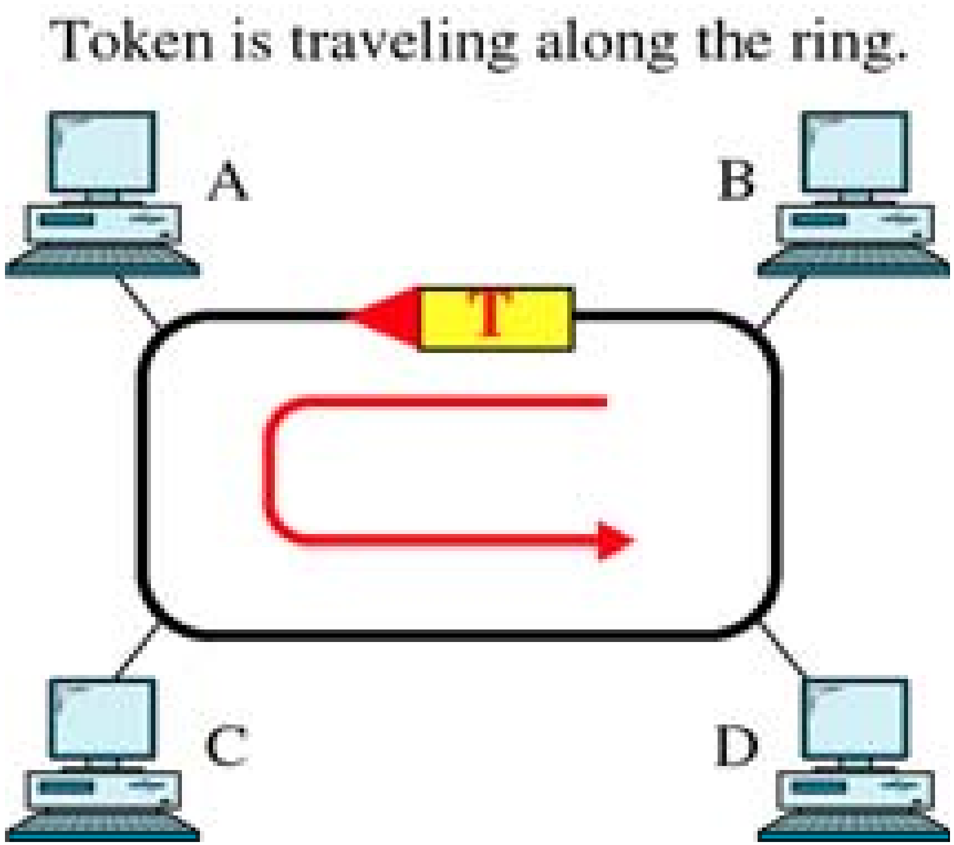
A node can only transmit when it has the token



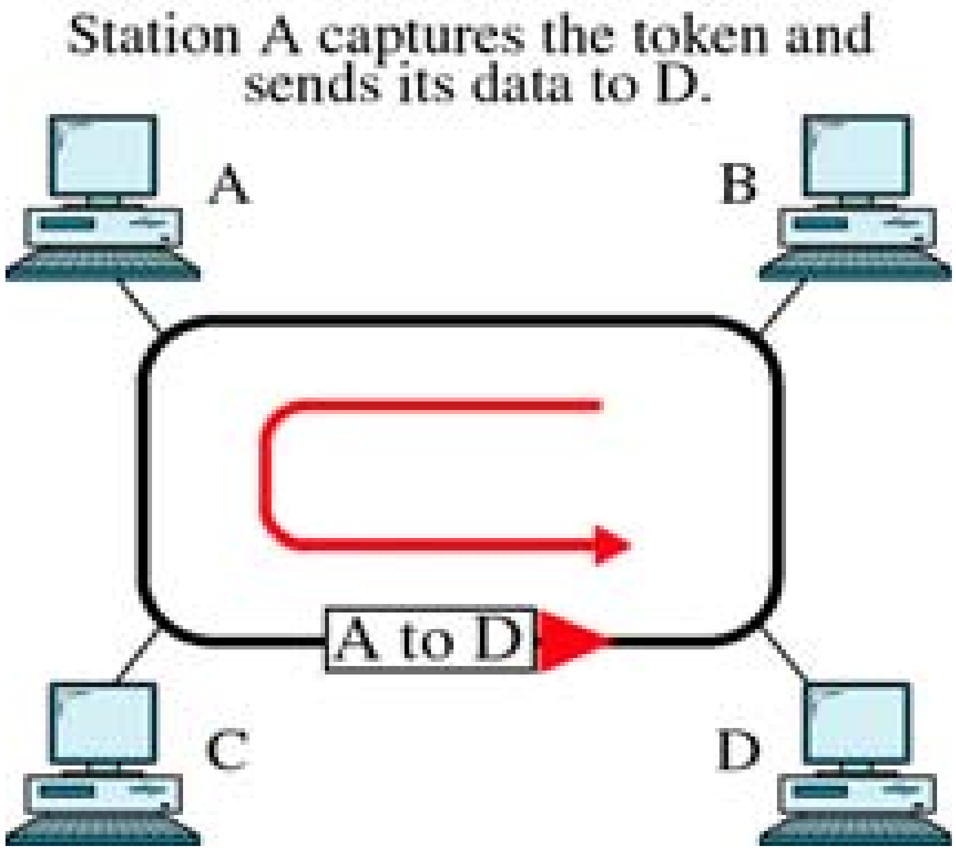
Token Ring Networks

- When a node receives the token, it can choose to transmit a frame (sender)
- This frame is then forwarded around the ring in the same direction as the token
- Each node checks if it is the receiver of that frame. If it is the case, it copies the frame, changes its relevant bit indicating that the frame is now received. Then, the receiver forwards it to the next node.
- When the sender receives the frame that it just sent, it checks its relevant bits for more information about this transmission.
- If it is received successfully, the frame is removed by the sender, the token is put back on the ring

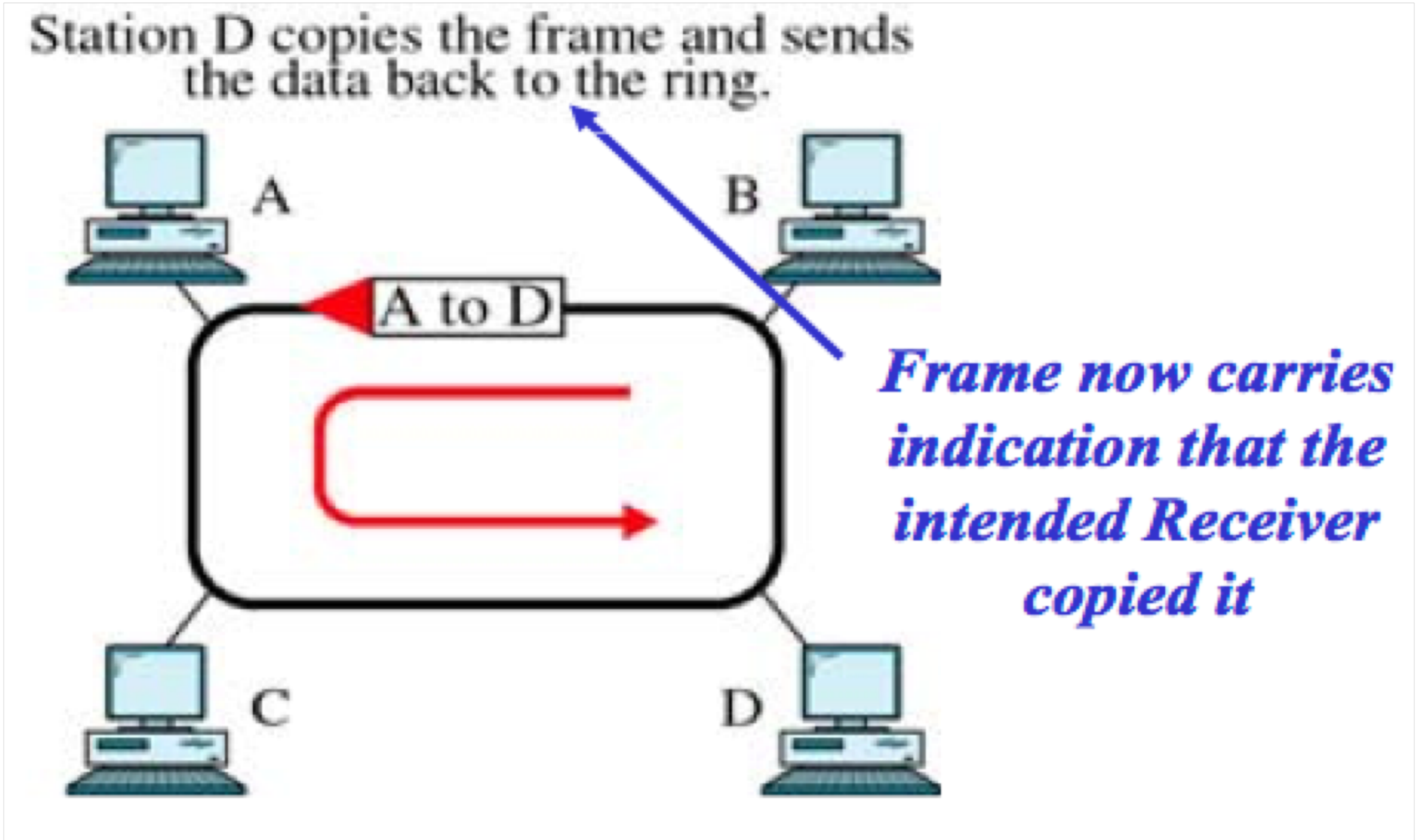
Token Ring Networks



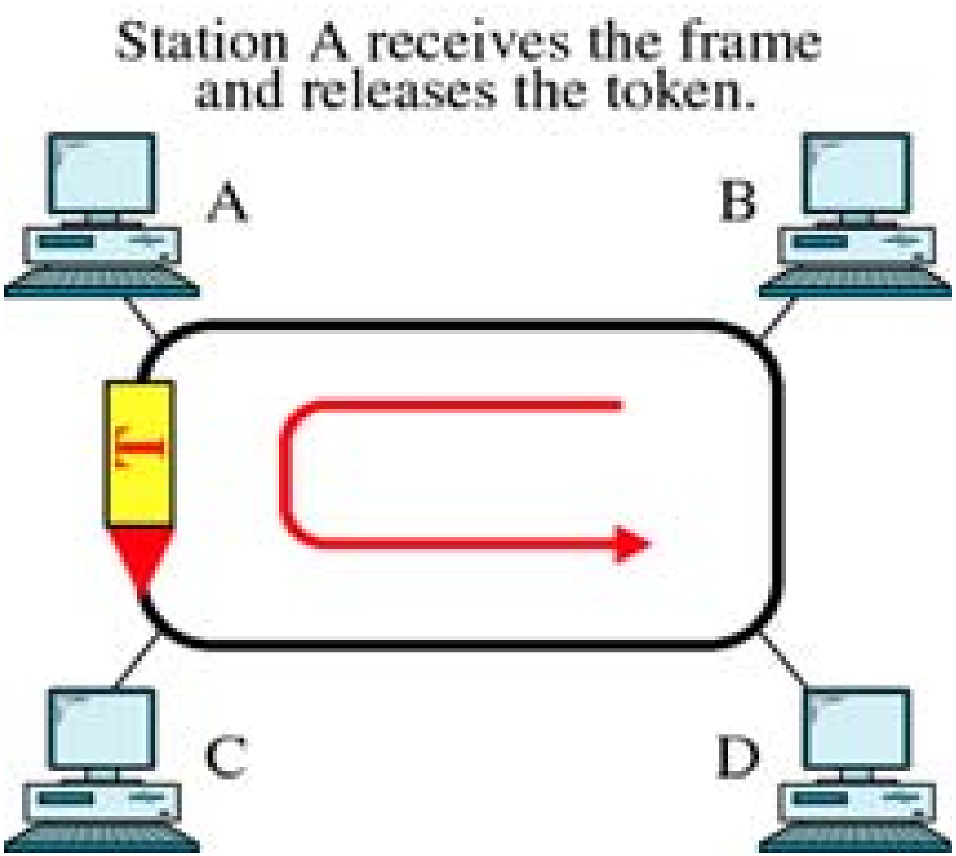
Token Ring Networks



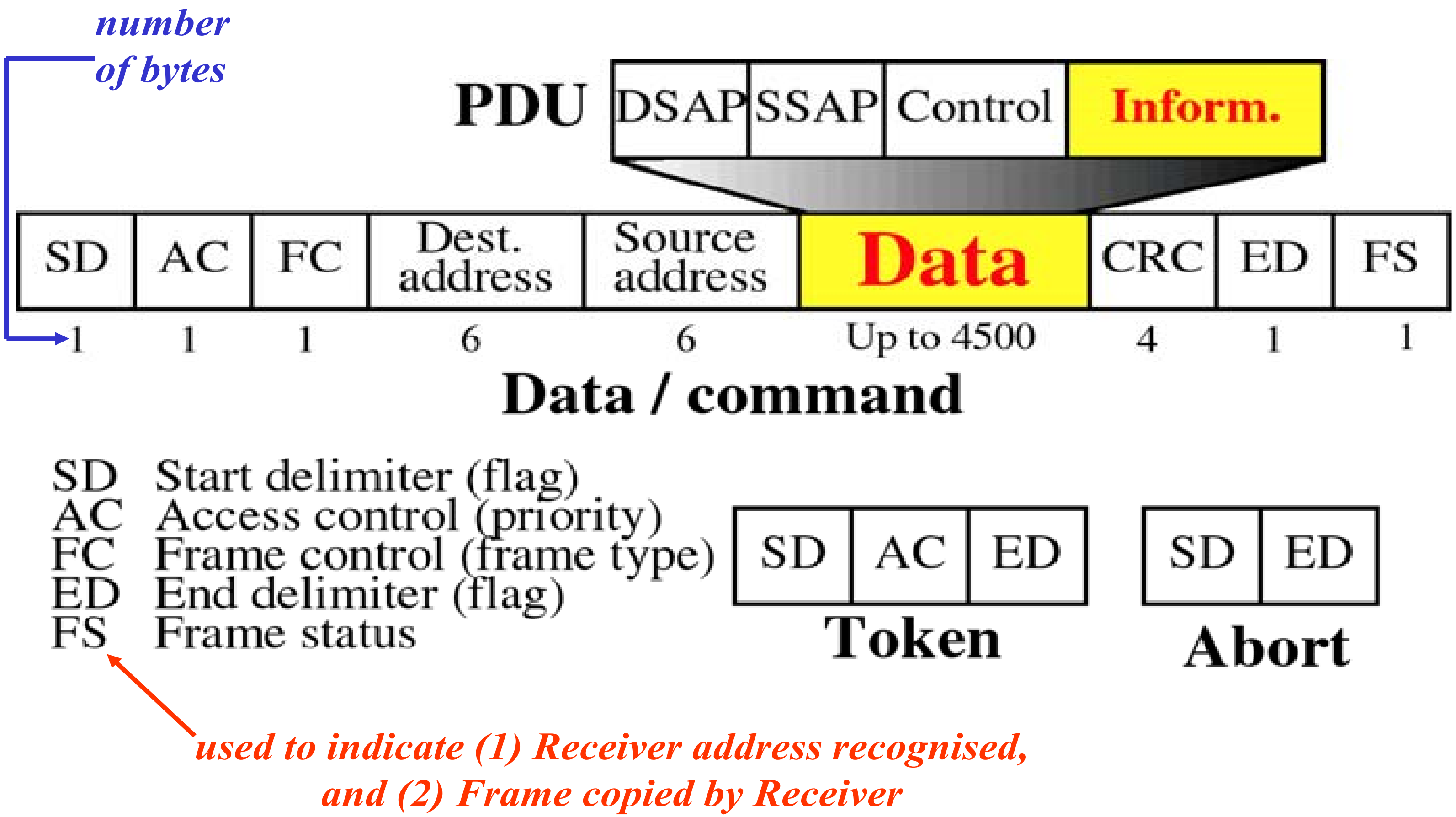
Token Ring Networks



Token Ring Networks



Token Ring Frame Formats



Token Ring Performance

- If we assume all nodes have a frame to transmit then a single cycle where each node transmits one frame is
  - N x (TRANSF + TRANST + PROP) + PROP
    - N = number of nodes
    - TRANSF = frame transmission time
    - TRANST = token transmission time
    - PROP = propagation delay around the whole ring
- The useful time within this cycle is N x TRANSF
  - I.e. the time taken to actually transmit the frames
- This gives us an efficiency of (useful time)/(cycle time)

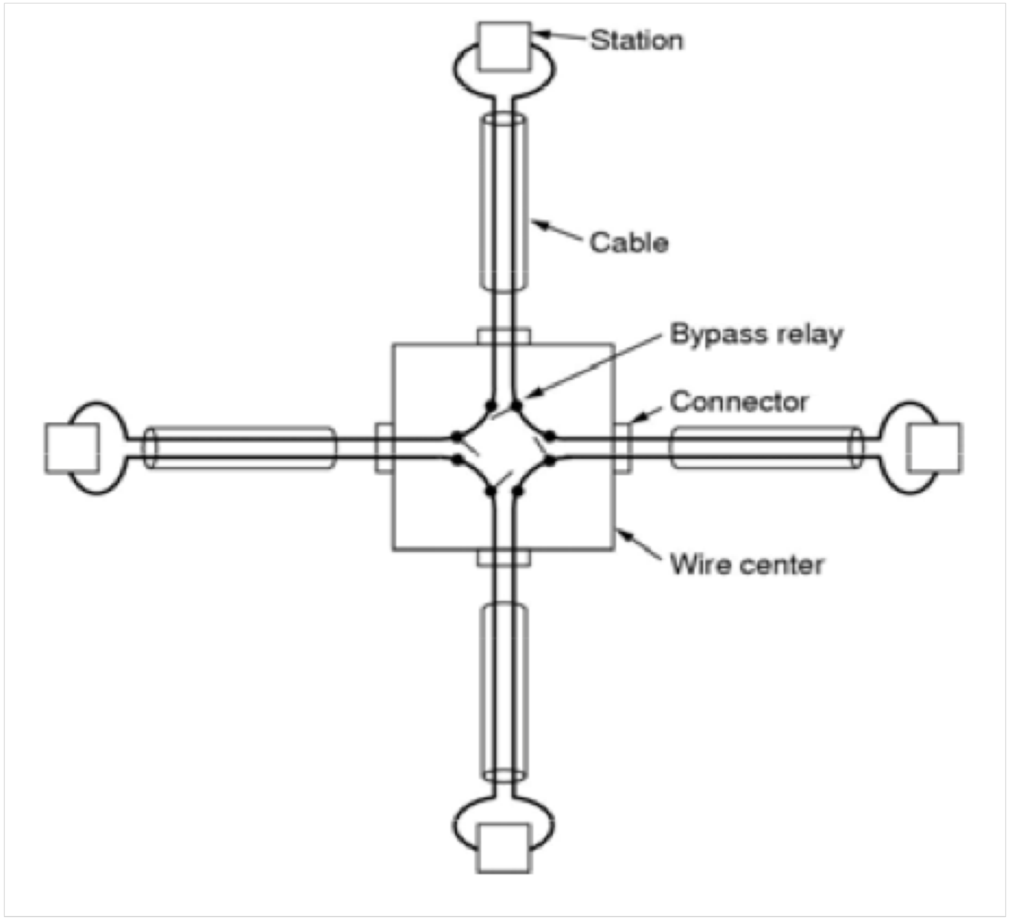
Token Ring Performance

- What is the longest we will have to wait to send a frame (ignoring queuing delay)?
    - This happens just after a node has started transmitting it's last frame and will have to wait for the token to circulate the ring
- This is the same as the time for a single cycle
- More importantly this time is guaranteed unlike the CSMA/CD system used in Ethernet
- Token Ring Network is suitable for a broadcast channel where the probability that everyone to transmit at the same time is very high.

Token Ring Implementation

- The main problem with the network design is that if a single cable breaks or node crashes the network becomes unusable
- This can be solved by having all the cables connected at a central location, then a node that no longer functions can be bypassed

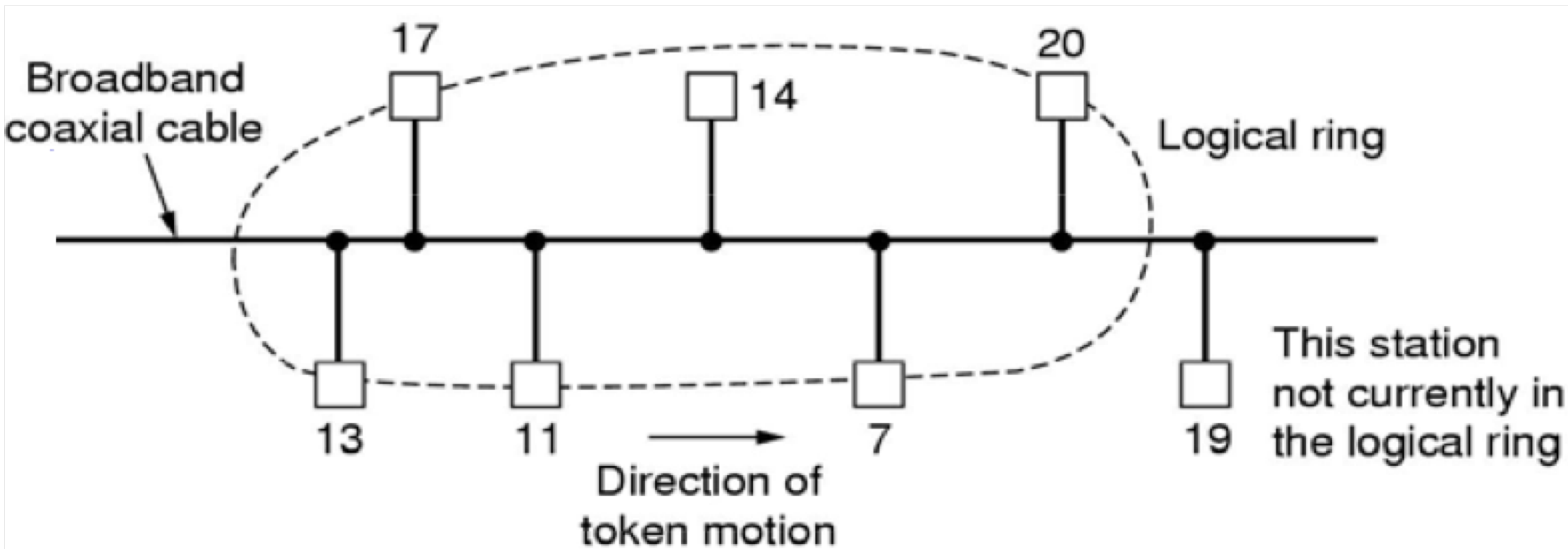
Token Ring Implementation



Token Bus Networks

- Physically this network is similar to a classic Ethernet network
- Logically each node only communicates with the node that is logically next in the ring
- Each node connected receives each frame but ignores those not addressed to it

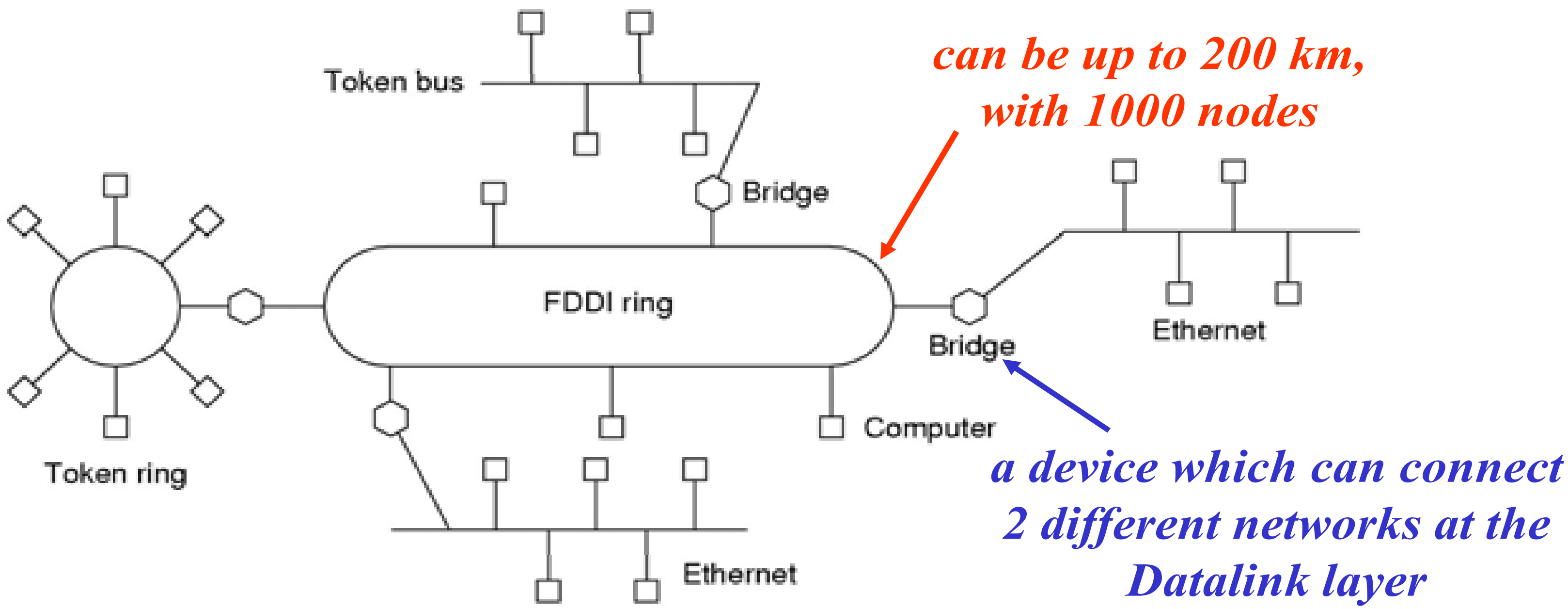
Token Bus Network



Fiber Distributed Data Interface (FDDI)

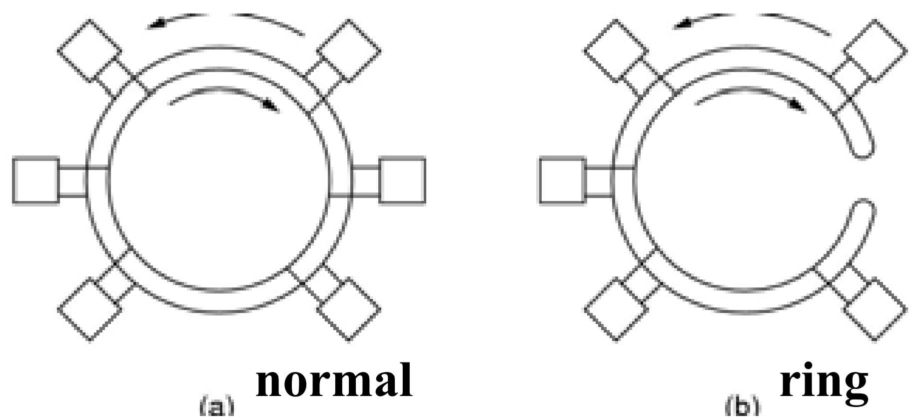
- Originally a high-speed alternative to Ethernet and Token Ring networks
- Uses time limited token passing
- Supports the difference between real-time traffic and normal traffic (means priority is supported)
    - Real-time traffic gets transmitted first when token is received
- Mostly used as backbone to connect other networks

Fiber Distributed Data Interface (FDDI)



Fiber Distributed Data Interface (FDDI)

- Implemented as a dual ring
- Usually all transmission are on the primary ring, and the secondary ring is only used for backup when part of the ring fails
- Token is released immediately after frame transmission



normal operation **ring failure**