CHAPTER 4
THE MEDIUM ACCESS CONTROL (MAC) **SUBLAYER** (介质访问子层)

- The channel allocation problem
- Multiple access protocols
- 802.3: Ethernet
- 802.11: Wireless LANs
- Data link layer switching
- 802.15: Bluetooth*
- 802.16: Broadband wireless*
- RFID*

THE CHANNEL ALLOCATION PROBLEM

- Two types of networks:
  - Those using **point-to-point** connection.
  - Those using **broadcast** channels.
- In any broadcast network, the key issue is how to determine who gets to use the channel when there is competition for it.
  - Consider a telephone conference call.
  - Broadcast channels are sometimes referred to as multiaccess channels or random access channels.
- The protocols used to determine who goes next on a multiaccess channel belong to a ***sublayer*** of the data link layer called the MAC (Medium Access Control). The MAC sublayer is the bottom part of the data link layer.

The Channel Allocation Problem: Introduction

- 信道分配问题: How to allocate a single broadcast channel among competing users
  - **Static channel allocation** in LANs and MANs
    - TDM
    - FDM
  - **Dynamic channel allocation** in LANs and MANs
    - ALOHA
    - CSMA
    - Collision free protocols
    - Limited-contention protocols
    - …

The Channel Allocation Problem: **Static** channel allocation in LANs and MANs

The traditional way of allocating a single channel among multiple competing users is Frequency Division Multiplexing (FDM, 频分多路复用).

- When there is only a small and fixed number of users, each of which has a heavy (buffered) load of traffic, FDM is a simple and efficient allocation.
- When the number of senders is large and continuously **varying** or the traffic is **bursty**, FDM has some problems.

The Channel Allocation Problem: **Static** channel allocation in LANs and MANs

- Mathematical analysis
  - Queueing model
  - N queues → N times worse

- Similar for other static channel allocation methods such as TDM (Time Division Multiplexing)

The Channel Allocation Problem: **Dynamic** channel allocation in LANs and MANs

Five key assumptions for the channel allocation problem

1. Independent Traffic (独立传输). The model consists of *N* independent stations, each with a program or user that generates frames for transmission.
2. Single channel (单信道假设). A single channel is available for all communication.
3. Collision assumption (冲突假设).
4. Time assumption (时间假设): (a) Continuous Time.(b) Slotted Time.
5. Carrier assumption (载波假设): (a) Carrier Sense.(b) No Carrier Sense.

MULTIPLE ACCESS PROTOCOLS

- ALOHA
- Carrier Sense Multiple Access (CSMA) protocols
- Collision-free protocols
- Limited contention protocols

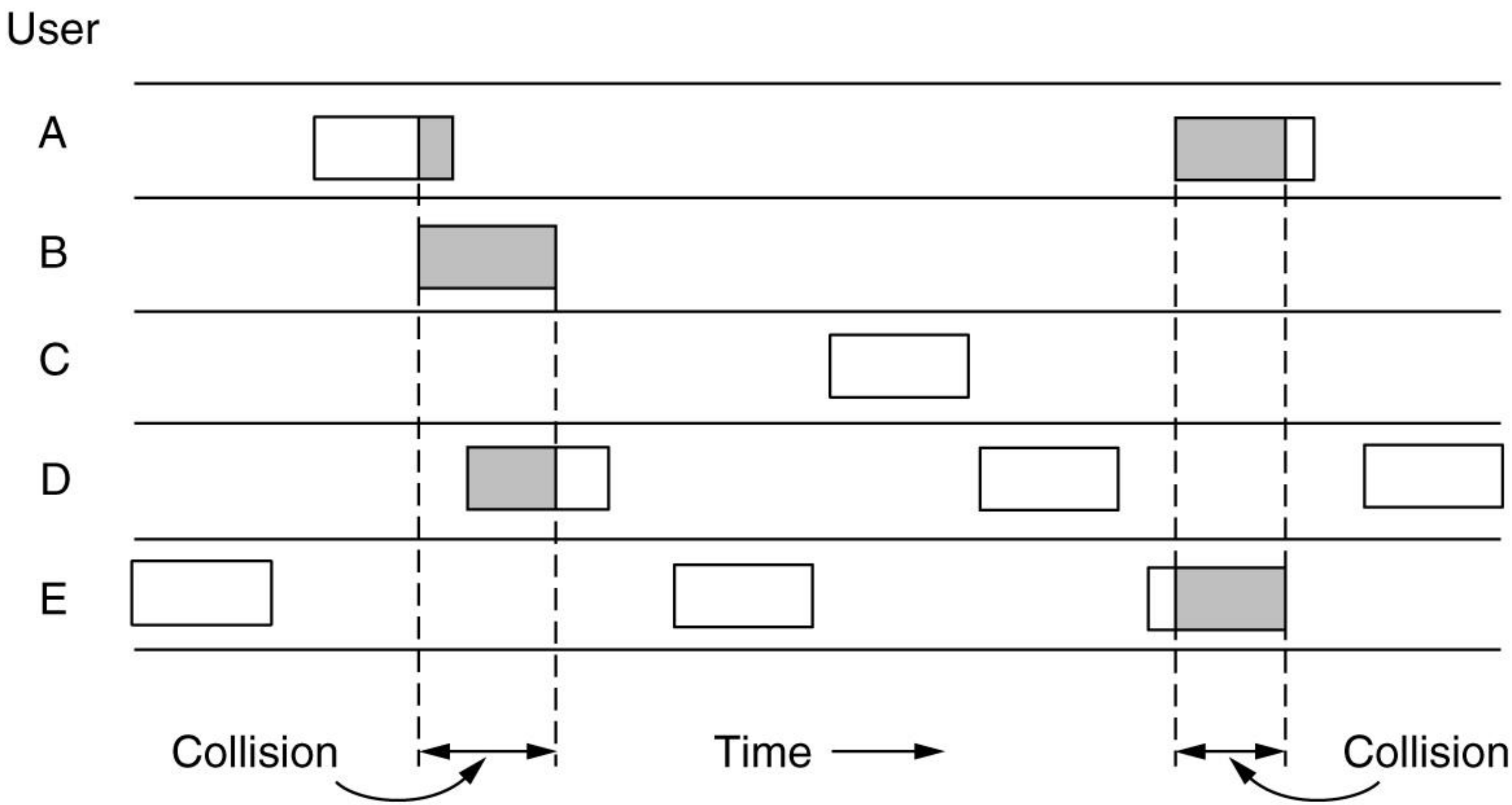
- Wireless LAN Protocols

Multiple Access Protocols: ALOHA

- Let users transmit whenever they have data to be sent.
  - There will be collisions and the colliding frames will be destroyed.
  - The sender just waits a random amount of time and sends it again if a frame is destroyed.

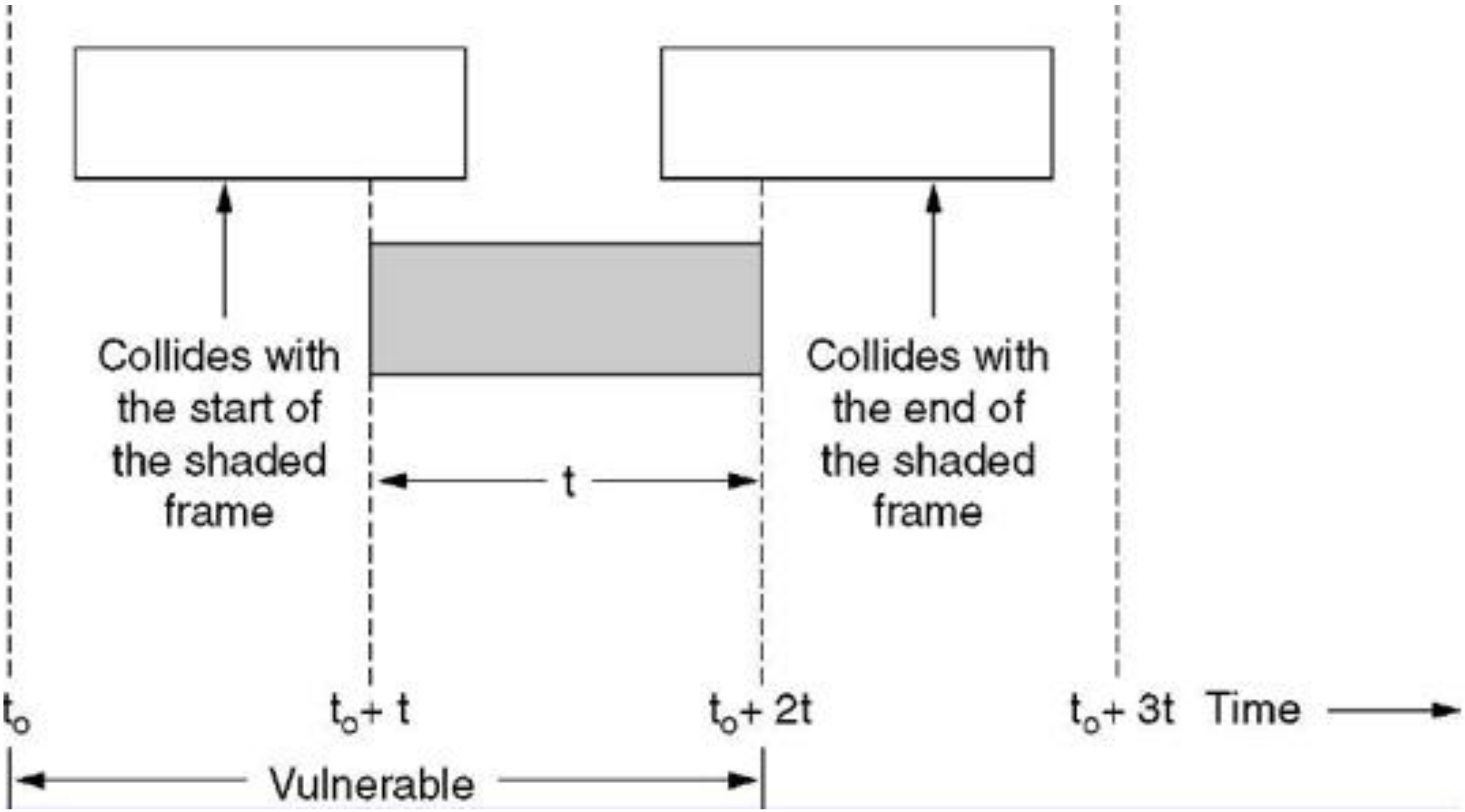
Multiple Access Protocols: ALOHA

In pure ALOHA, frames are transmitted at completely arbitrary times.



Multiple Access Protocols: ALOHA

Vulnerable period for the shaded frame.



Multiple Access Protocols: Efficiency of ALOHA

- Concepts:
  - Frame time: frame length / bit rate
  - Stations generate N (Poisson mean) new frames per frame time
  - Offered load: G (Poisson mean) transmission attempts per frame time. G includes retransmissions.
    - At low loads: $G \approx N$
    - At high loads: $G > N$
  - Throughput $S = GP_0$ where P_0 is the probability that a frame does not suffer a collision.

Multiple Access Protocols: Slotted ALOHA

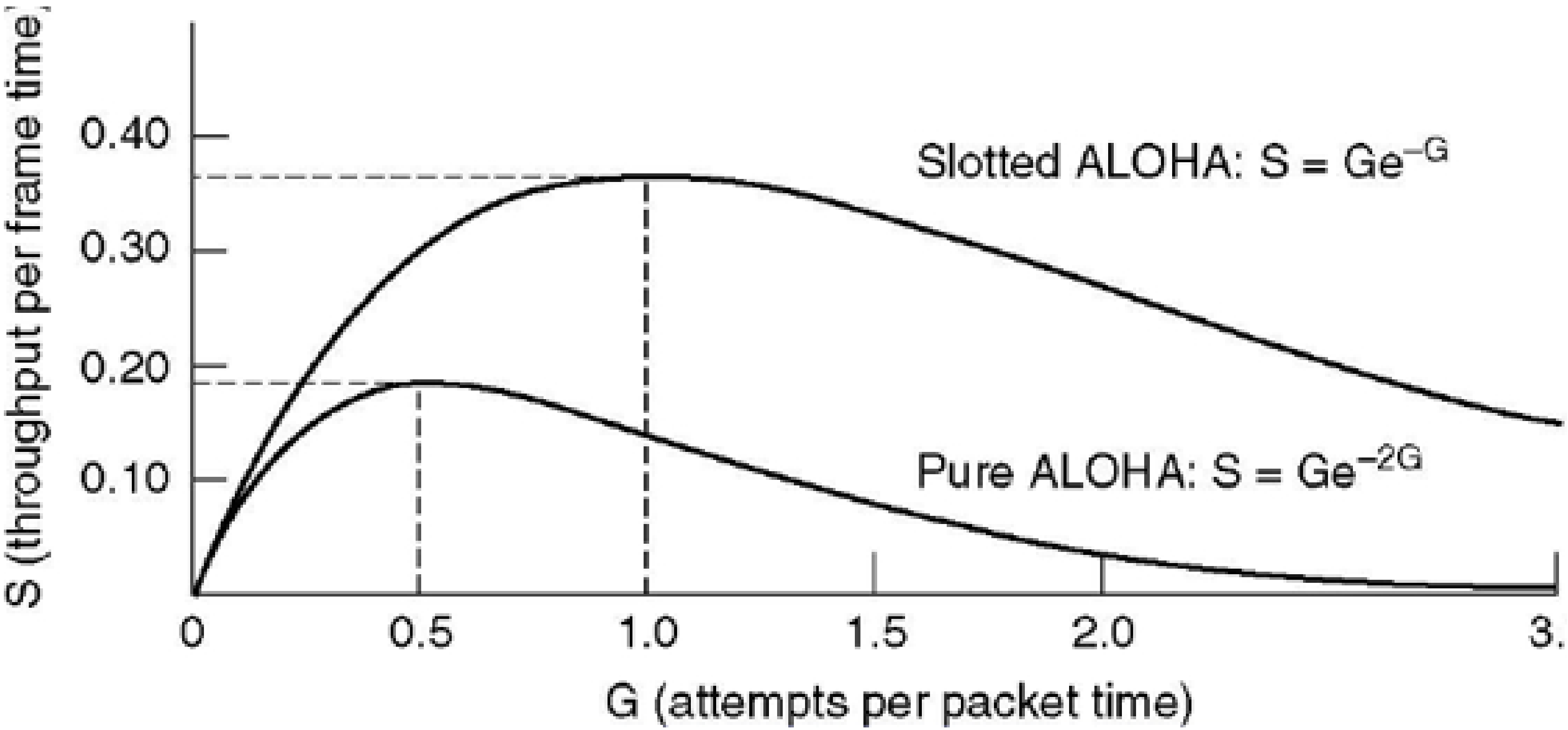
- In 1972, Roberts published a method for doubling the capacity of an ALOHA system.

- **Time is slotted**. A computer is not permitted to send at any time. Instead it is required to wait for the beginning of the next slot.

- **The vulnerable period is halved for Slotted ALOHA**.

Multiple Access Protocols: ALOHA

Throughput versus offered traffic for ALOHA systems.



Multiple Access Protocols: Notes

- **Note**: Protocols that are perfectly valid fall into disuse for political reasons, but years later some clever person realizes that a long-discarded protocol solves his current problem.

→ Study many protocols that are in current use.

→ Study a number of elegant protocols that are not currently in widespread use, but might easily be used in future applications.

Multiple Access Protocols: CSMA

- With stations transmitting at will, without paying attention to what the other stations are doing, there are bound to be many collisions,
  不听就说→ poor channel utilization.
- If stations can detect what other stations are doing and adjust their behavior accordingly,
  先听再说→ better channel utilization.
- Protocols in which stations listen for a carrier and act accordingly are called Carrier Sense Multiple Access Protocols (CSMA Protocols, 载波侦听多路访问协议).

Multiple Access Protocols: CSMA

- CSMA (Carrier Sense Multiple Access) without CD (Collision Detection)
  - Persistent CSMA
  - Non-persistent CSMA
  - p-persistent CSMA

- CSMA with CD

Multiple Access Protocols:

CSMA without CD: Persistent CSMA

Before sending, a station senses the channel.

- If the channel is **idle**, the station **transmits** a frame.
- If the channel is **busy**, the station **waits until** it becomes idle. Then the station transmits a frame.
- If a **collision occurs**, the station **waits a random amount of time** and starts all over again.

The protocol is called *1-persistent* because the station transmits with a probability of 1 whenever it finds the channel idle.

Multiple Access Protocols:
CSMA without CD: Persistent CSMA

Discussion

- This scheme seems to avoid collisions except for the rare case of simultaneous sends, but in fact it does not.
- If two stations become ready in the middle of a third station's transmission,
  - both will wait politely until the transmission ends,
  - both will then begin transmitting exactly simultaneously, resulting in a collision.
- If they were not so impatient, there would be fewer collisions.

Multiple Access Protocols:
CSMA without CD: Persistent CSMA

Discussion (Cont)

- propagation delay has an important effect on collisions
  - There is a chance that just after a station begins sending, another station will become ready to send and sense the channel.
  - If the first station's signal has not yet reached the second one, the latter will sense an idle channel and will also begin sending, resulting in a collision.
  - This chance depends on the number of frames that fit on the channel, or the bandwidth-delay (BD) product of the channel
    - Low BD product → small chance of collision
    - Large BD product → high chance of collision
- Better than ALOHA.

Multiple Access Protocols:

CSMA without CD: Non-persistent CSMA

- Before sending, a station senses the channel.
  - If the channel is **idle**, the station **transmits** a frame.
  - If the channel is **in use**, the station ***does not*** continually sense it. Instead, it **waits a random period of time** and then repeats the algorithm.
  - If a **collision occurs**, the station **waits a random amount of time** and starts all over again.
- Discussion
  - Better channel utilization than 1-persistent CSMA (less greedy)
  - Longer delays than 1-persistent CSMA

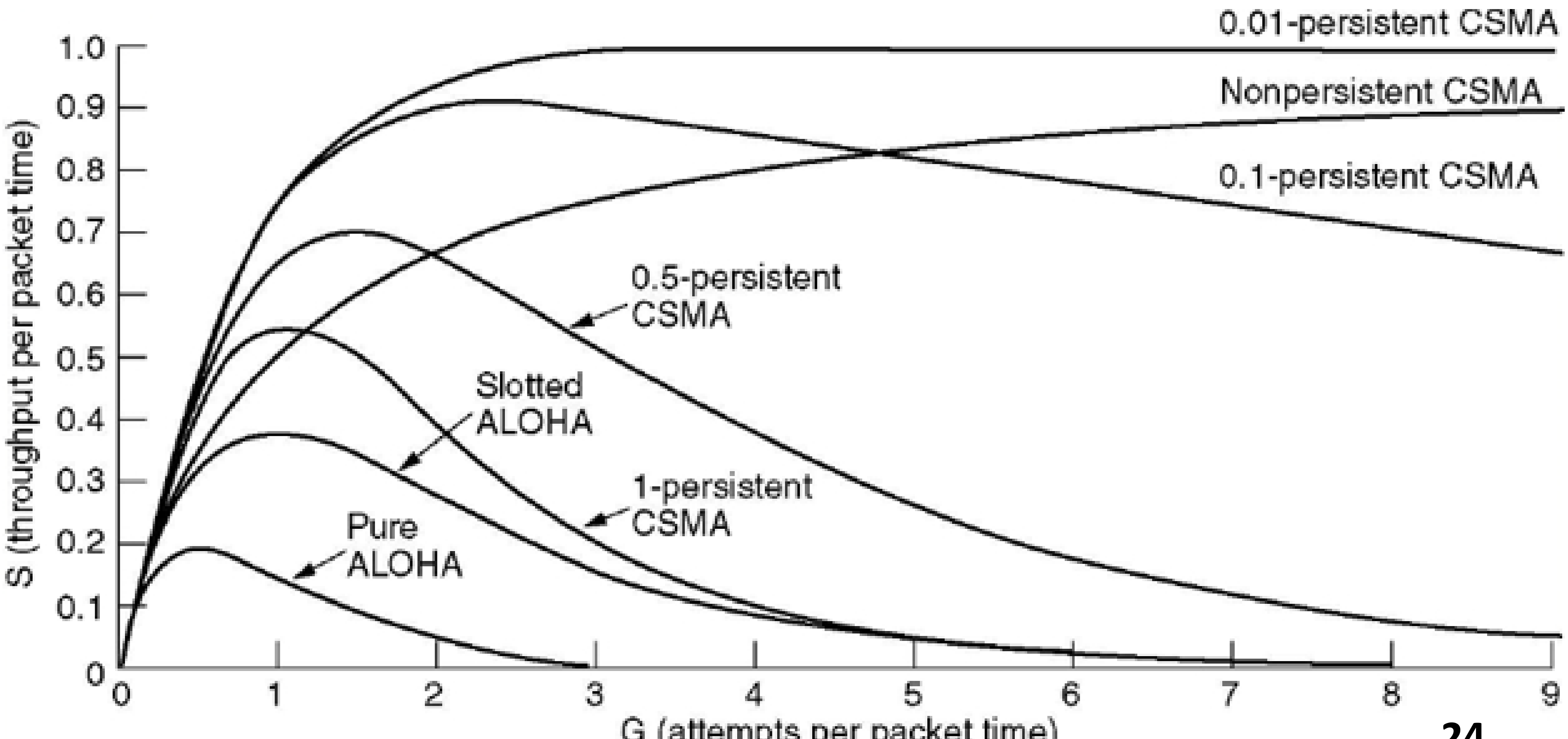
Multiple Access Protocols:
CSMA without CD: p-persistent CSMA

- Applied to **slotted** channels
- Before sending, a station senses the channel:
  - If the channel is **idle**, it **transmits with a probability *p***. With a probability $q=1-p$, it defers until the next slot.
  - If that slot is also idle, it either transmits or defers again, with probabilities p and q.
  - This process is repeated until either the frame has been transmitted or another station has begun transmitting.
  - If the channel is **busy**, it **waits until the next slot** and applies the above algorithm.

IEEE 802.11 uses a refinement of p-persistent CSMA

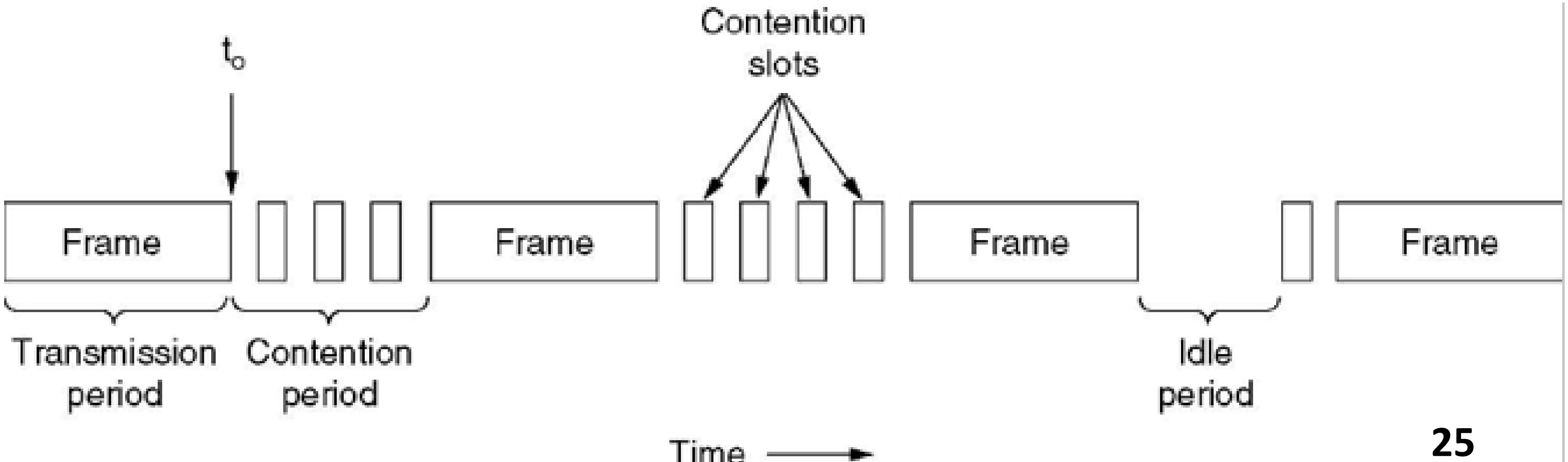
Multiple Access Protocols:
CSMA without CD: Comparison

Comparison of the channel utilization versus load for various random access protocols.



Multiple Access Protocols: CSMA with CD

- CSMA/CD (Carrier Sense Multiple Access with Collision Detection)
  - is an improvement over CSMA without CD.
  - As soon as stations detect a collision, they stop their transmissions.
- CSMA/CD can be in one of three states: **contention**, **transmission**, or **idle**.



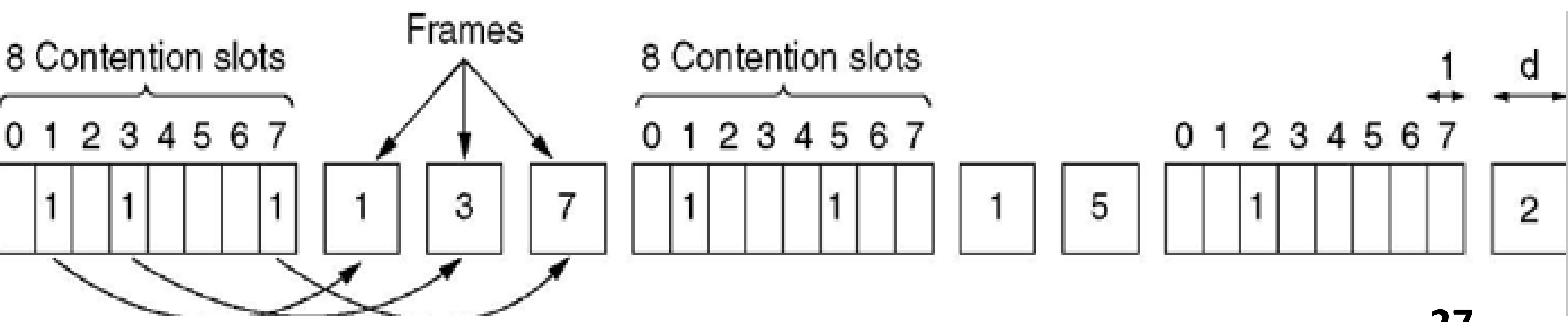
Multiple Access Protocols: CSMA with CD

- How long will it take to detect collisions?
  - The time for transmitting one full frame?
  - The time for transmitting from one end to the other end of the cable?
  - In the worst case, a station cannot be sure that it has seized the channel until it has transmitted for $\boldsymbol{2\tau}$ without hearing a collision. Here τ is the time for a signal to propagate between the two farthest stations.

Multiple Access Protocols:

Collision free protocols: A Bit-Map Protocol

- Each contention period consists of exactly *N* slots.
- In general, station *i* inserts 1 in time slot *i* in order to send data.
- After all *N* slots have passed by, each station has complete knowledge of which stations wish to transmit. Then they begin transmitting in numerical order. **Since everyone agrees on who goes next, there will never be any collisions**.
- After the last ready station has transmitted its frame, another *N* bit contention period is begun.



Multiple Access Protocols:

Collision free protocols: A Bit-Map Protocol

- Notations:
  - The time unit is one contention bit
  - N: contention period
  - d: data frame length
- At low load:
  - Delay for low-numbered stations: $0.5N + 1N = 1.5N$
  - Delay for high-numbered stations: $0.5N$

  → The mean delay for all stations is N.

  → The efficiency: $\mathrm{d}/(N + d)$.
- At high load:
  - the N bit contention period is distributed over N frames, yielding an overhead of only 1 bit per frame,

  → the efficiency: $d/(d + 1)$.

Multiple Access Protocols:
Collision free protocols: Token Passing

- Token passing
  - The token represents permission to send.
  - If a station has a queued frame when it receives the token, it can send that frame before it passes the token to the next station.
  - If a station has no queued frame, it simply passes the token
- Two kinds of token passing
  - Token ring
  - Token bus

Multiple Access Protocols:

Collision free protocols: Token Ring

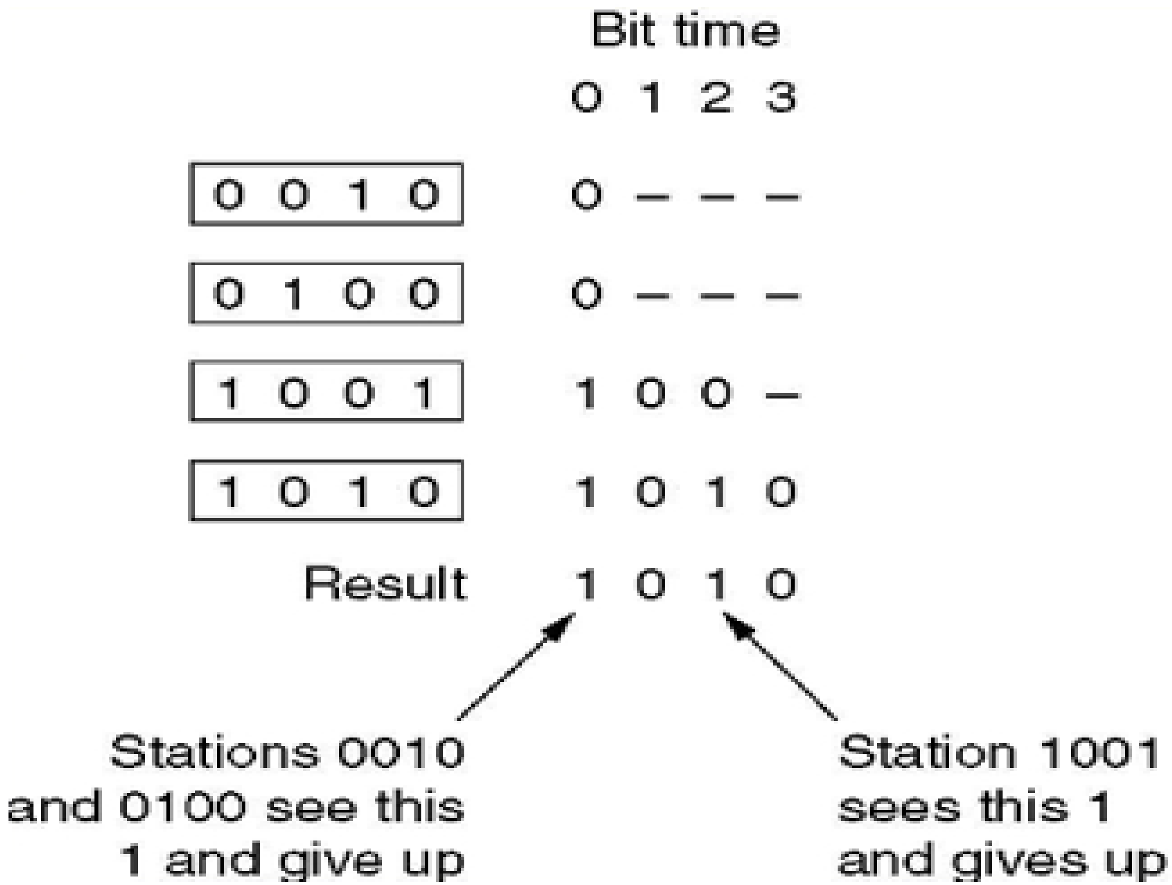
- For a ***token ring*** protocol, the stations are connected one to the next in a single ring.
- Passing the token to the next station then simply consists of receiving the token in from one direction and transmitting it out in the other direction.
- This way they will circulate around the ring and reach whichever station is the destination.
- Since all positions in the cycle are equivalent, there is no bias for low- or high-numbered stations.
- Examples: 802.5 (1980s), FDDI (1990s), RPR (Resilient Packet Ring, 802.17) (2000s), …

Multiple Access Protocols:
Collision free protocols: Binary Countdown

- A station wanting to use the channel now broadcasts its address as a binary bit string, starting with the high-order bit. All addresses are assumed to be the same length.
- The bits in each address position from different stations are BOOLEAN ORed together **by the channel** when they are sent at the same time.
- To avoid conflicts, an arbitration rule must be applied: as soon as a station sees that a high-order bit position that is 0 in its address has been overwritten with a 1, it gives up.

Multiple Access Protocols:
Collision free protocols: Binary Countdown

The binary countdown protocol.
A dash indicates silence.



Multiple Access Protocols:
Limited-Contention protocols

- Methods with contention
  - ***Under low load***, the contention method (i.e., pure or slotted ALOHA, CSMA) is preferable due to its low delay.
  - ***Under high load***, the contention method becomes increasingly less efficient.
- Methods without contention
  - Under low load, the collision-free method has high delay.
  - Under high load, the collision-free method becomes increasingly more efficient.

→ Limited-Contention Protocols

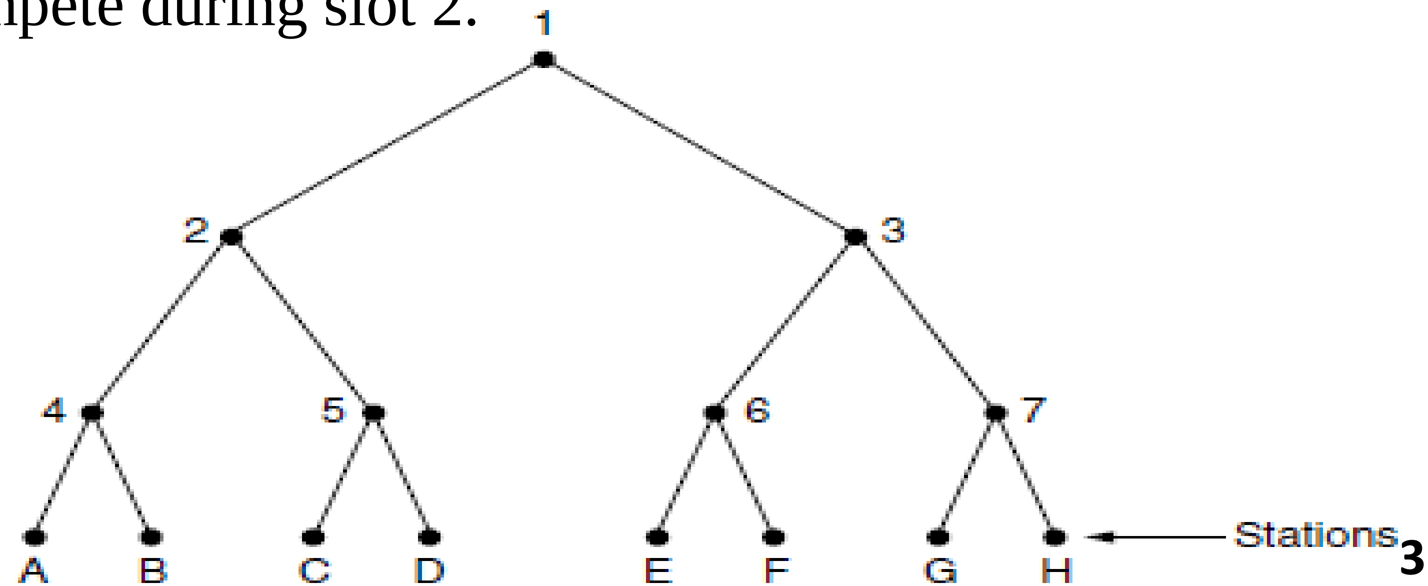
Multiple Access Protocols:
Limited-Contention protocols

- What we need is a way to assign stations to slots dynamically
  - With many stations per slot when the load is low
  - With a few stations per slot when the load is high.

- Adaptive Tree Walk Protocol (自适应树搜索协议)

Multiple Access Protocols: Adaptive Tree Walk

- the stations as the leaves of a binary tree
- In **slot 0**, all stations are permitted to try to acquire the channel.
- If one of them does so, fine.
- If there is a **collision**, then during slot 1 only those **stations falling under node 2** in the tree may **compete**.
- If one of them acquires the channel, the slot following the frame is **reserved for stations under node 3**.
- If there is **collision** under node 2 for slot 1, **stations under node 4** may compete during slot 2.

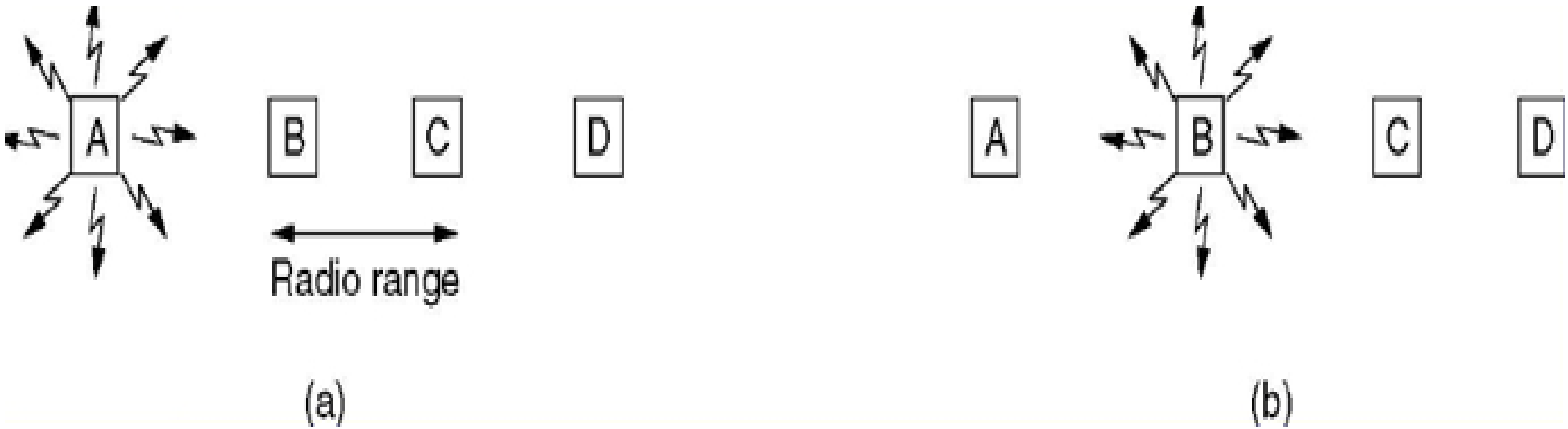


Multiple Access Protocols: Adaptive Tree Walk

- Adaptive Tree Walk Protocol
  - At what level in the tree should the search begin?
  - The heavier the load, the farther down the tree the search should begin.
  - Begin at $i = \log_2 q$ where q is the estimate of the number of ready stations.
  - Numerous improvements to the basic algorithm have been discovered (Bersekas and Gallager, 1992)

Multiple Access Protocols: Wireless LAN Protocols

- Hidden station problem (隐藏终端问题)
- Exposed station problem (暴露终端问题)



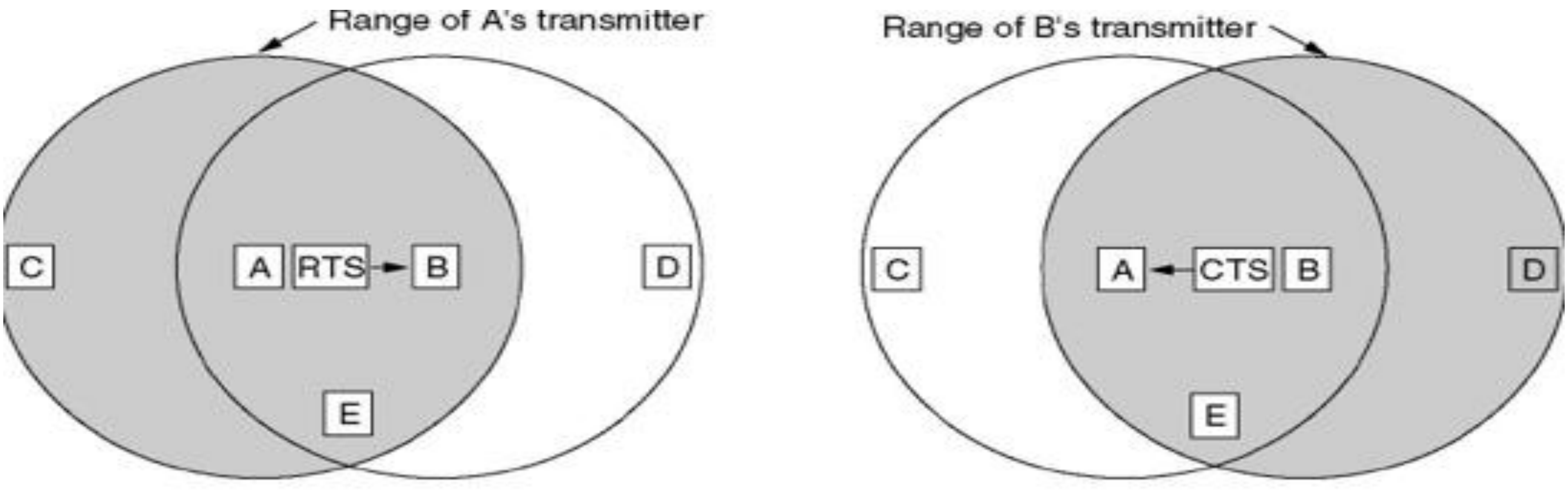
- The problem is that **before starting a transmission, a station really wants to know whether or not there is activity around the receiver not the sender.**

Multiple Access Protocols: Wireless LAN Protocols

The MACA (Multiple Access with Collision Avoidance) protocol. A sending an RTS to B, B responding with a CTS to A.

1. D: A's hidden terminal, hear CTS and stop data
2. E: hear RTS and CTS, stop data
3. C: A's exposed terminal, hear RTS, wait until CTS, can transmit data

Collision can still occur, e.g. RTS



(a) (b)

IEEE 802.3 (Ethernet)

- Classic Ethernet Physical Layer
- Classic Ethernet MAC Sublayer Protocol
- Ethernet Performance

- Switched Ethernet
- Fast Ethernet
- Gigabit Ethernet
- 10-Gigabit Ethernet

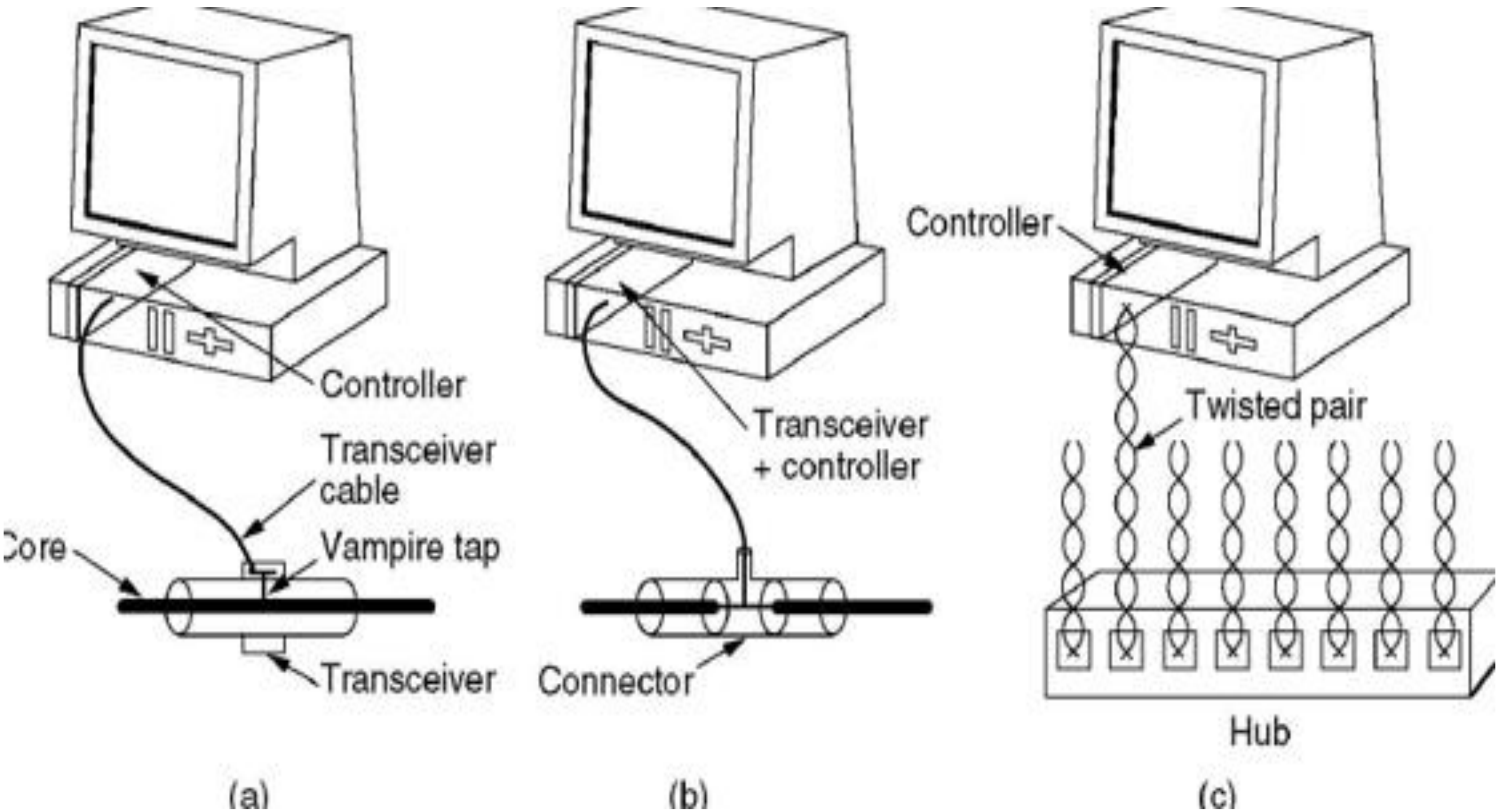
- Retrospective on Ethernet

802.3: Classic Ethernet Physical Layer

- 197x: the real beginning was the ALOHA system constructed to allow radio communication between machines scattered over the Hawaiian Islands.
- Bob Metcalf is interested in Norman Abramson's work → after PhD graduation, Bob spend the summer in Hawaii working with Abramson (before work at Xerox PARC) → first local area network (Ethernet)
- The Ethernet was so successful. **Xerox**, **DEC**, and **Intel** drew up a standard for 10-Mbps Ethernet. (DIX standard)
- 802.3 standard describes a whole family of 1-persistent CSMA/CD system, running at speeds from 1 to 10-Mbps over various media. (802.3 standard)

802.3: Classic Ethernet Physical Layer

Three kinds of Ethernet cabling. (a)10Base5 (thick Ethernet), (b) 10Base2 (thin Ethernet), (c) 10Base-T.



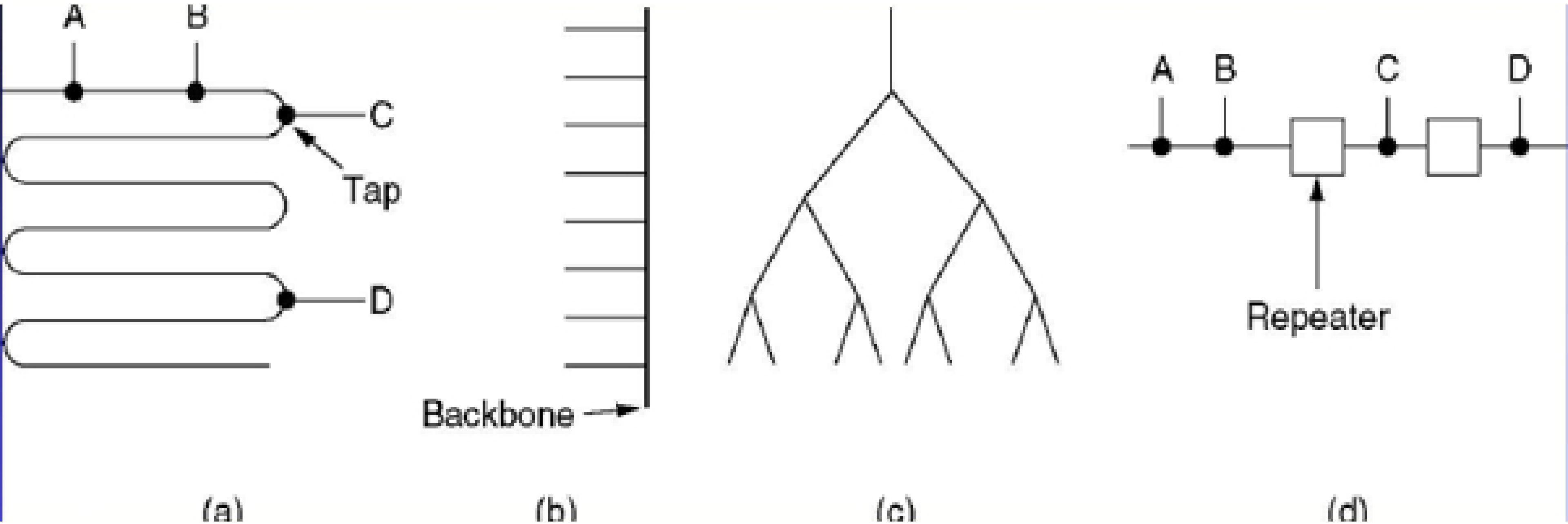
802.3: Classic Ethernet Physical Layer

The most common kinds of
Classic Ethernet cabling.

Name	Cable	Max. seg.	Nodes/seg.	Advantages
10Base5	Thick coax	500 m	100	Original cable; now obsolete
10Base2	Thin coax	185 m	30	No hub needed
10Base-T	Twisted pair	100 m	1024	Cheapest system
10Base-F	Fiber optics	2000 m	1024	Best between buildings

802.3: Classic Ethernet Physical Layer

Cable topologies.
(a) Linear, (b) Spine, (c) Tree, (d) Segmented.



802.3: Classic Ethernet Physical Layer

- With 0 volts for a 0 bit, with 5 volts for a 1 bit.
  - Difficult to tell the difference between an idle sender (0 volts) and a 0 bit (0 volts).

  → If one station sends the bit string 0001000, others might falsely interpret it as 1000000 or 01000000.
- With –1 volts for a 0 bit, with 1 volts for a 1 bit
  - A receiver may sample the signal at a slightly different frequency than the sender used to generate it

  → can be out of synchronization.
- To unambiguously determine the start, end, or middle of each bit without reference to an external clock.
  - **Manchester** encoding
  - **Differential Manchester** encoding

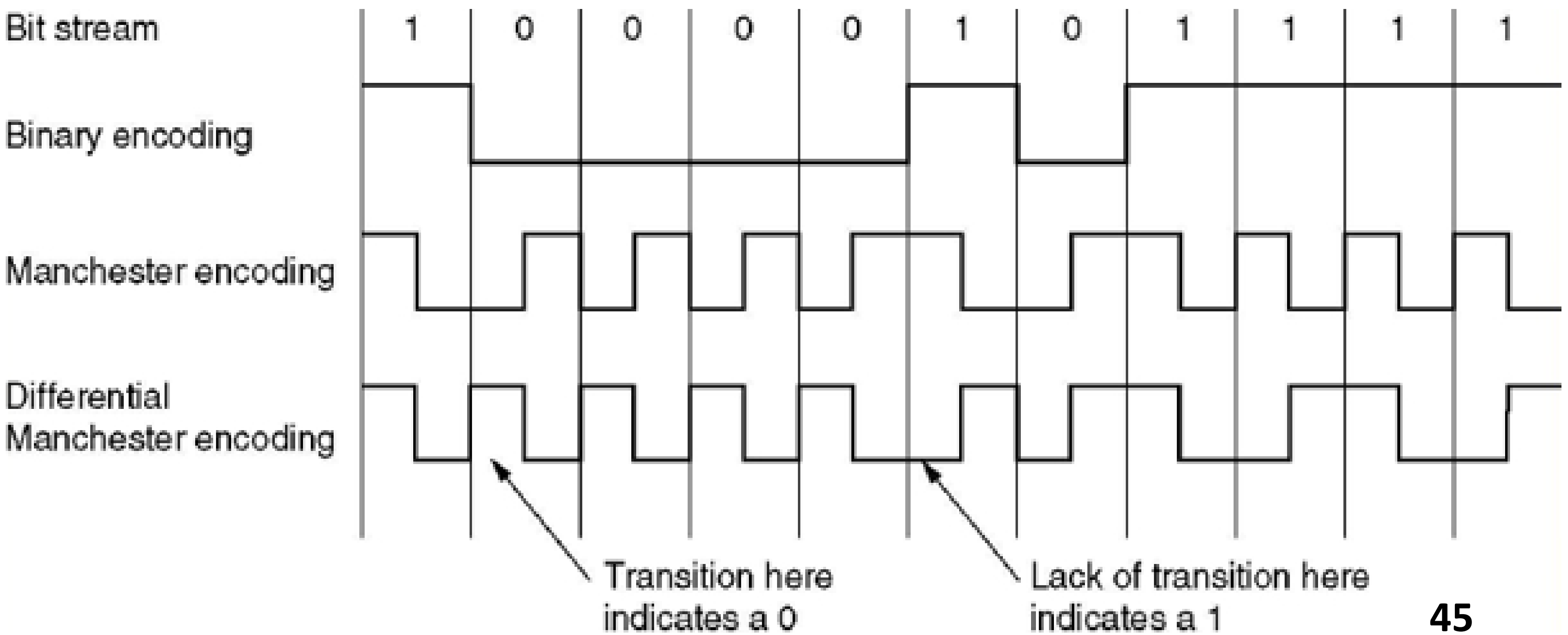
802.3: Classic Ethernet Physical Layer

Manchester encoding (used by Ethernet):

0: low-high; 1: high-low;

Differential Manchester encoding (used by Token Ring):

0: presence of transition; 1: absence of transition



802.3: MAC Sublayer Protocol

Frame formats.

a) DIX Ethernet,

b) IEEE 802.3.

T/L <= 0x600 (1536): length; otherwise, type

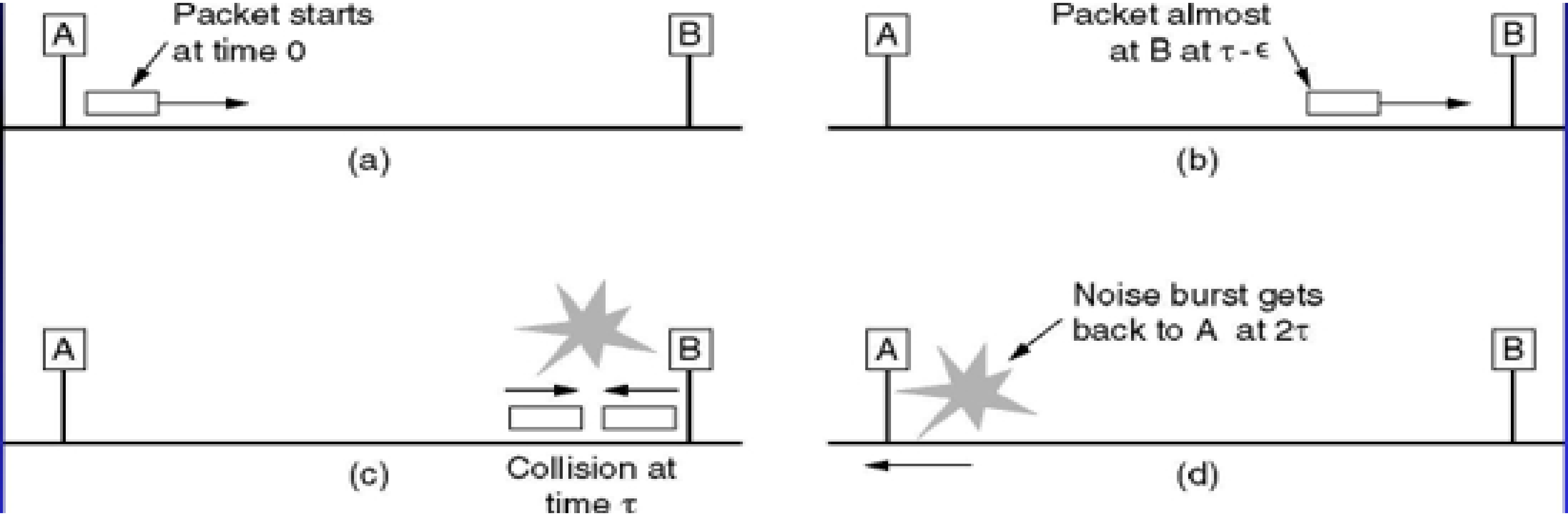
Bytes	8		6	6	2	0-1500	0-46	4
(a)	Preamble		Destination address	Source address	Type	Data	Pad	Check-sum
(b)	Preamble	SOF	Destination address	Source address	Length	Data	Pad	Check-sum

802.3: MAC Sublayer Protocol

- Preamble: 8 bytes, containing the bit pattern 10101010, used for synchronization
- Destination address and source address: 6 bytes each
  - Unicast address
  - Broadcast address
  - Multicast address
- Type field or length field
- Data: 1500 bytes (maximum), 46 bytes (minimum)
- Checksum: 32 bits, CRC

802.3: MAC Sublayer Protocol

How long does it take to find out whether there is a collision or not?



Collision detection can take as long as **2τ**.

802.3: MAC Sublayer Protocol

- All frames must take more than **2τ** to send.
  - Too quick (to miss the collision)
  - Longer than **2τ** to be sure of success.
- For a 10-Mbps LAN with a maximum length of 2500 meters and four repeaters, the maximum RTT is about 50us.

  Min frame length = 50us * 10 Mbps
  $=50*10^{-6}$ s * $10*10^{6}$ bits/s = 500 bits ≈ 64 B

  Min payload length = 64–18 (src:6,dest:6,type:2,crc:4)
  = 46 B (→ Why min payload = 46)

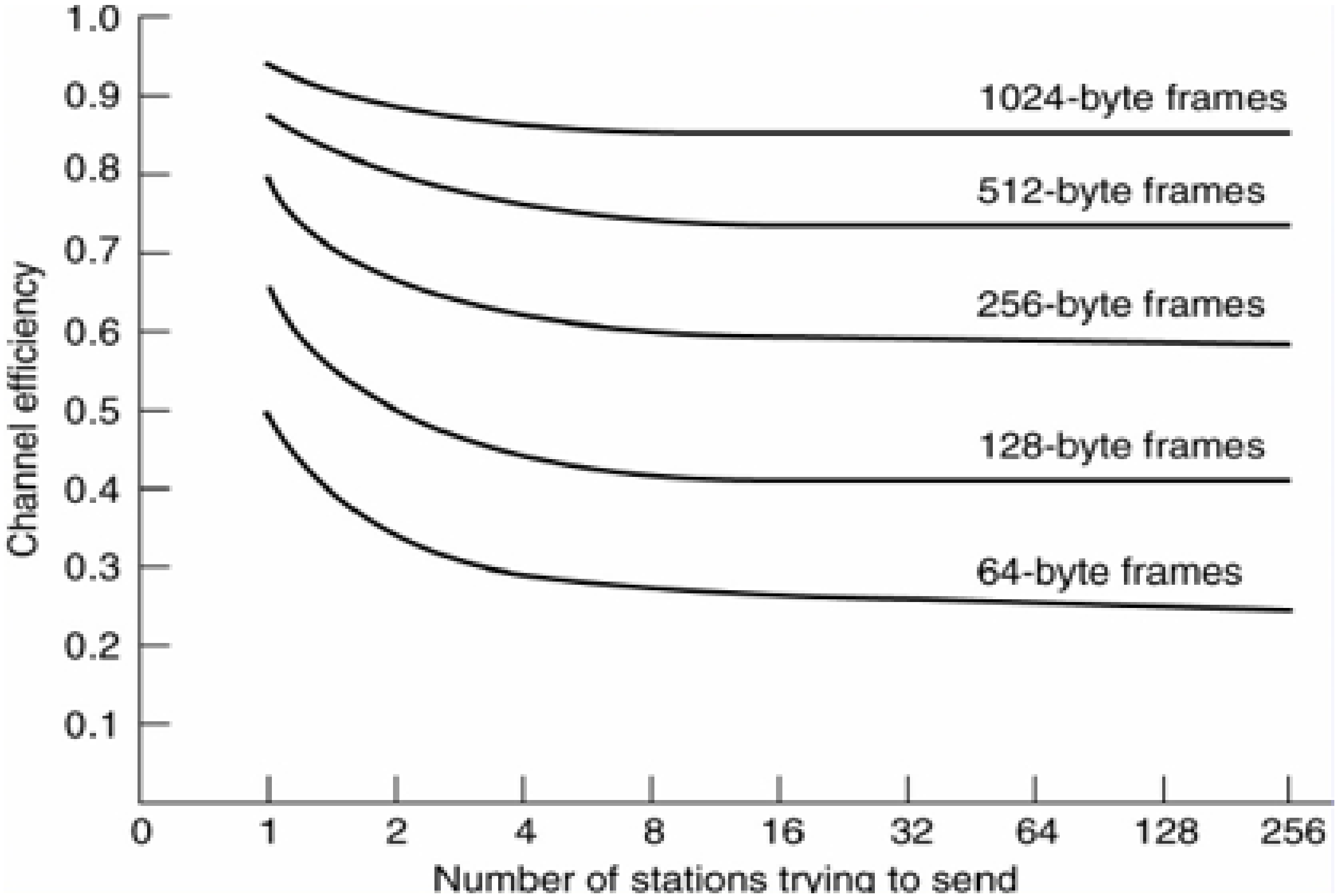
802.3: MAC Sublayer Protocol:

The **Binary Exponential Backoff Algorithm**

- Time is divided into discrete slots (51.2us).
- After the *1st* collision, each station waits either 0 or 1 (k in $0\sim2^1$-1) slot times before trying again.
- After the *2nd* collision, each station picks either 0,1,2,3 (k in $0\sim2^2$-1) at random and waits that number of slot times.
- After *i*-th collisions, each station picks either 0,1,2,…, $2^i - 1$ at random and waits that number of slot times.
- After 10th collisions, the randomization interval is frozen at a maximum of 1023 slots.
- After 16 consecutive collisions, the controller reports failure back to the computer.
  →limited contention.

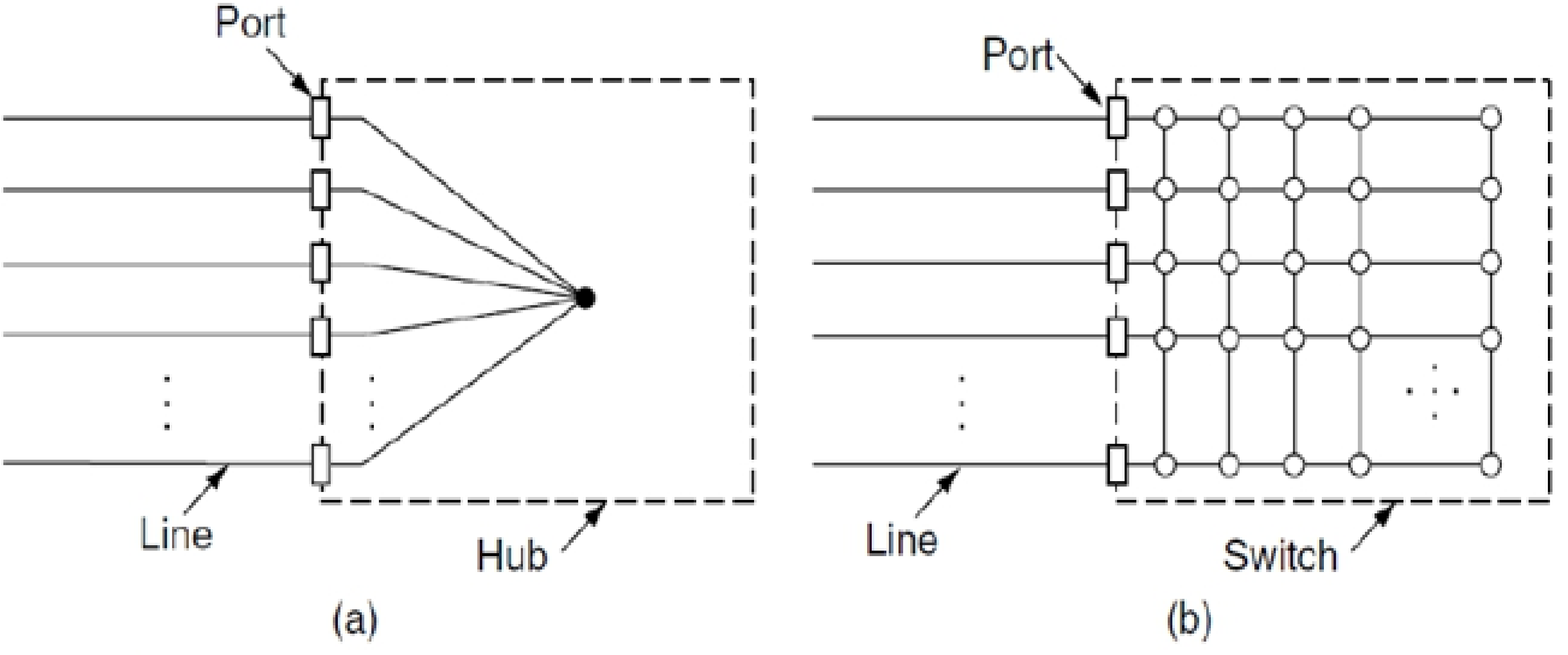
802.3: Performance

Efficiency of Ethernet at 10 Mbps with 512-bit slot times.



802.3: Switched Ethernet

Hub → Switch



802.3: Switched Ethernet

- Switch: The heart of this system is a **switch** containing a **high-speed backplane** that connects all of the ports
- Switch outputs frames to the ports for which those frames are destined. None of the other ports even knows the frame exists.
- What happens if more than one of the ports wants to send a frame at the same time?
  - Can send a frame on the cable at the same time
  - Why? Each port → one **collision domain**, whereas all stations attached to a hub → one collision domain

802.3: Fast Ethernet (100-Mbps)

- FDDI and Fiber Channel
  - Haven't done KISS (Keep It Simple, Stupid)
- IEEE 802
  - → IEEE 802.3u or Fast Ethernet (1992~1995)
  - → IEEE 802.3z or gigabit Ethernet (1995~1998)

The original fast Ethernet cabling.

Name	Cable	Max. segment	Advantages
100Base-T4	Twisted pair	100 m	Uses category 3 UTP
100Base-TX	Twisted pair	100 m	Full duplex at 100 Mbps
100Base-FX	Fiber optics	2000 m	Full duplex at 100 Mbps; long runs

802.3: Gigabit Ethernet (1-Gbps)

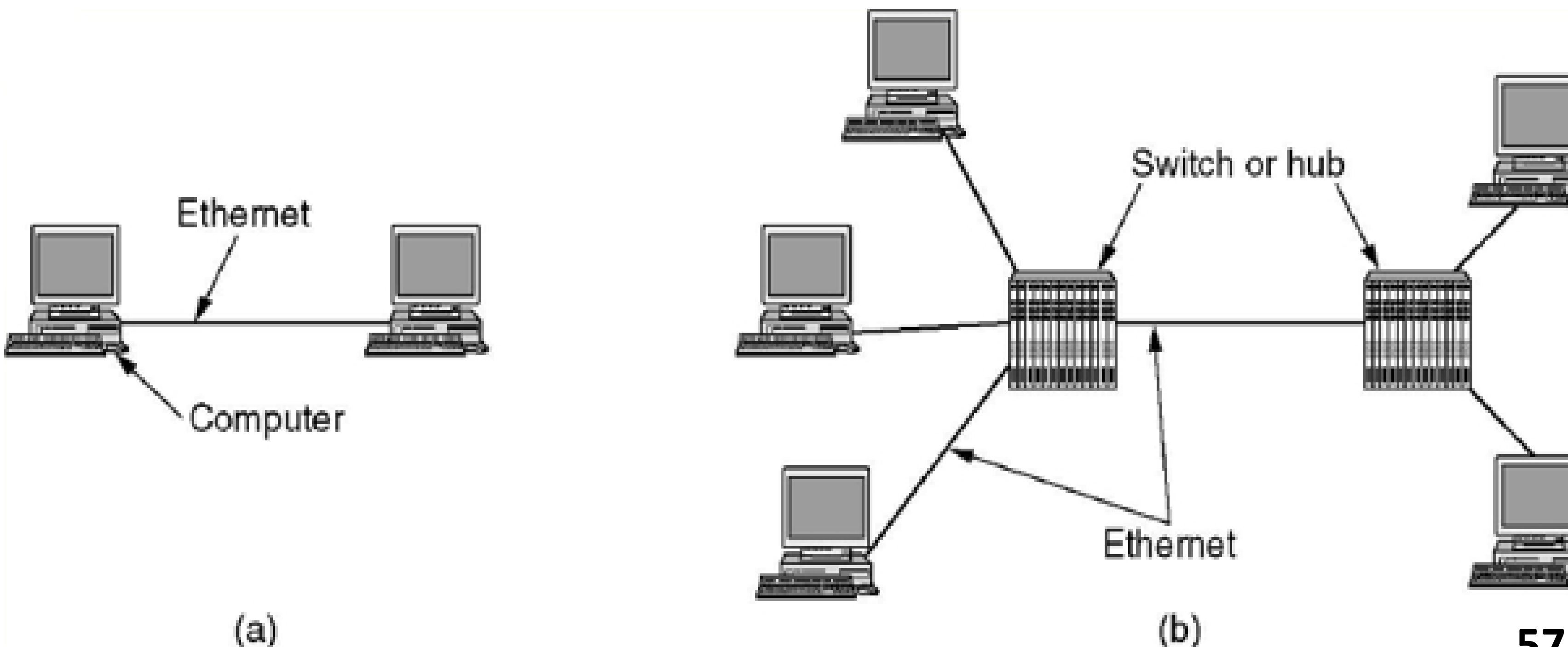
Gigabit Ethernet cabling.

Name	Cable	Max. segment	Advantages
1000Base-SX	Fiber optics	550 m	Multimode fiber (50, 62.5 microns)
1000Base-LX	Fiber optics	5000 m	Single (10 μ) or multimode (50, 62.5 μ)
1000Base-CX	2 Pairs of STP	25 m	Shielded twisted pair
1000Base-T	4 Pairs of UTP	100 m	Standard category 5 UTP

802.3: Gigabit Ethernet (1-Gbps)

Possible connections:

a. A two-station Ethernet.
b. A multistation Ethernet.



802.3: 10-Gigabit Ethernet

10-Gigabit Ethernet cabling.

Name	Cable	Max. segment	Advantages
10GBase-SR	Fiber optics	Up to 300 m	Multimode fiber (0.85μ)
10GBase-LR	Fiber optics	10 km	Single-mode fiber (1.3μ)
10GBase-ER	Fiber optics	40 km	Single-mode fiber (1.5μ)
10GBase-CX4	4 Pairs of twinax	15 m	Twinaxial copper
10GBase-T	4 Pairs of UTP	100 m	Category 6a UTP

802.3: Comments

- Ethernet has been around for over 20 years
- Simple and flexible
  - Cheap
  - Easy to maintain
  - Ethernet works easily with TCP/IP
- There are 3 LAN standards:
  - 802.3 (Ethernet),
  - 802.4 (Token bus),
  - 802.5 (Token ring).
- They use roughly similar technology and get roughly similar performance.

802.3: Comments

802.3 (Ethernet):

- most widely used, simple, easy installation, low delay at low load.
- nondeterministic, no priorities, 64 byte minimum frame, collision problem

802.4 (Token bus(令牌总线))

- more deterministic, short minimum frames, priorities, real-time, multiple channels.
- a lot of analog engineering and including modems and wideband amplifiers, extremely complex protocol, substantial delay at low load, poorly suited for fiber optic implementations and a small installed base of users.

802.5 (Token Ring(令牌环))

- Easy engineering, fully digital, priorities, excellent throughput and efficiency at high load.
- centralized monitor, delay at low load.

→ **the winner is 802.3.**