Computer Networks

L4 – Medium Access Control Sublayer I

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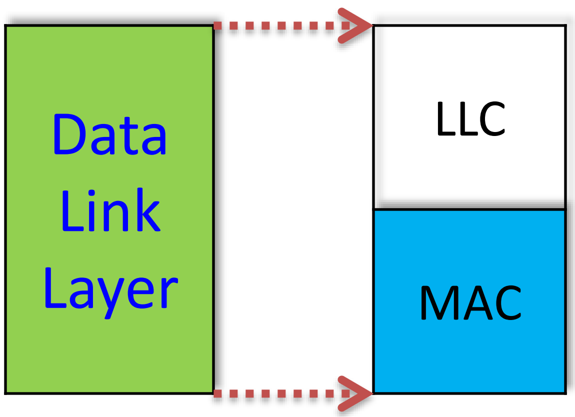
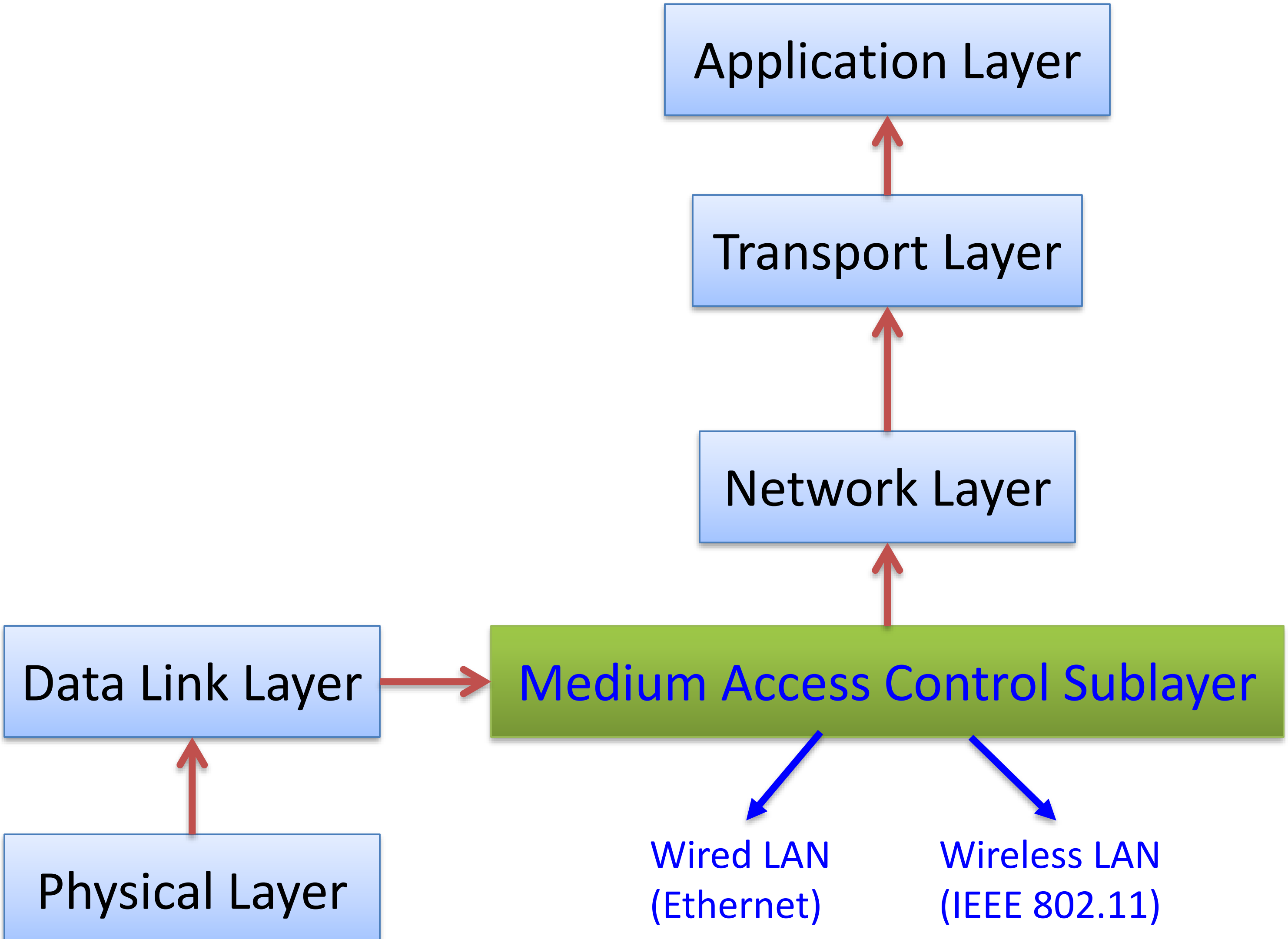
Two Sublayers of Data Link Layer

Data link layer has two sublayers:

- Logical Link Control (LLC)
  - Provides multiplexing mechanisms for network protocols
  - Optionally provide flow control, acknowledgment, and error notification
- Media Access Control (MAC)
  - Control access to the network medium, specially for shared medium

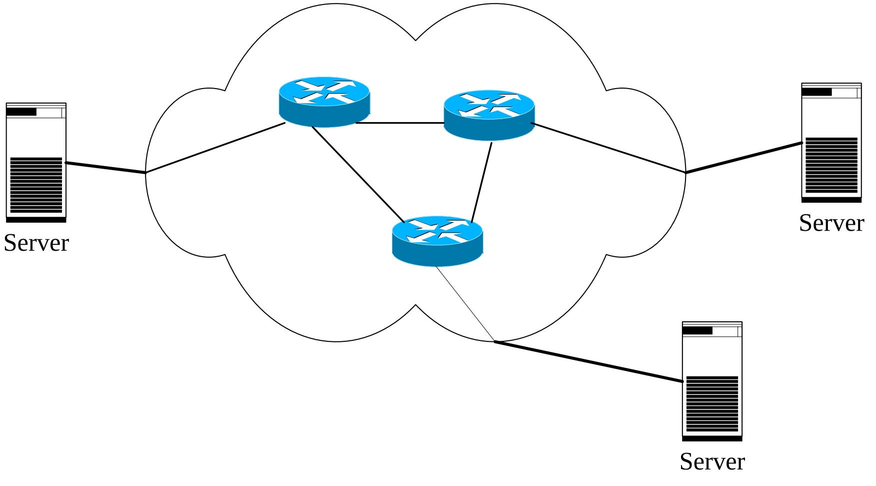


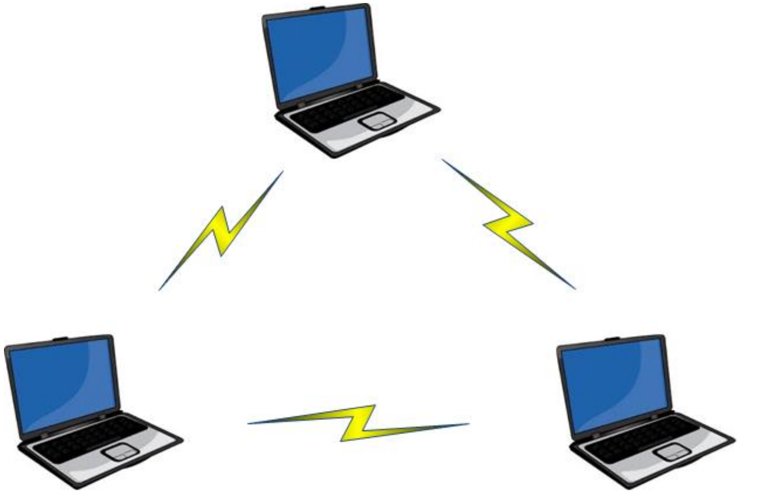
Roadmap of this course



Network Links

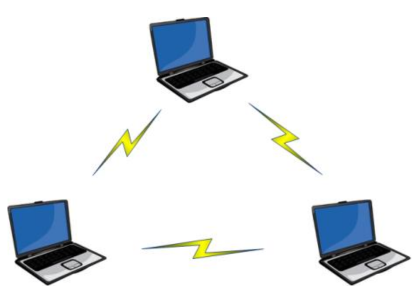
- Point-to-point links
  - Connect individual pairs of machines
- Broadcast links
  - Communication channel shared by all machines

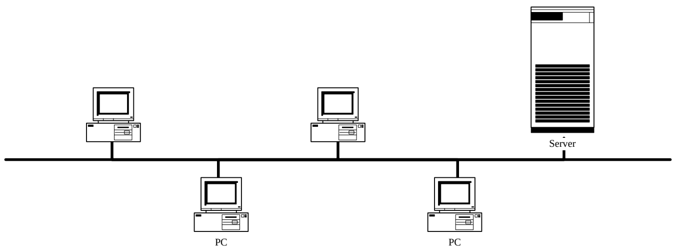


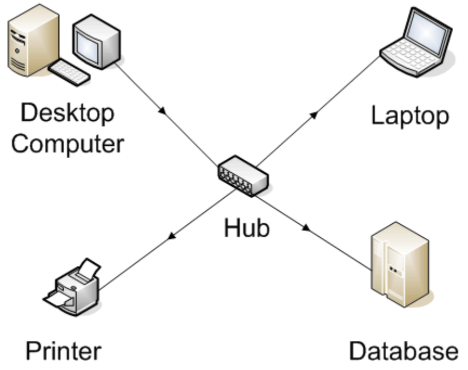


Broadcast Channels

- Broadcast channels (multi-access channels or random access channels):
  - A number of stations that share the same channel
  - If one sends, all the others get to hear it







Multiaccess Channel Chaos

- Problem: two or more stations may decide to send at the same time, leading to collision (冲突)

Who should go next?

The MAC Sublayer

- Responsible for deciding who sends next on a multi-access link
  - MAC is an important part of the link layer, especially for LANs

Application
Transport
Network
Link
Physical

MAC is in here!

Topics for MAC

- Channel Allocation Problem
- Multiple Access Protocols
- Ethernet
- Wireless LANs
- Data Link Layer Switching

Channel Allocation Problem

- How to allocate a single broadcast channel among competing users
  – Static schemes (静态)
  – Dynamic schemes (动态)

Static Channel Allocation

- For fixed channel and traffic from N users
  - Divide up bandwidth using FDM, TDM, etc.
  - This is a static allocation, e.g., FM radio
- Static allocation performs poorly for bursty traffic
  - Allocation to a user may be sometimes unused
  - Quantitative analysis using queue theory (refer to textbook)

Dynamic Channel Allocation

- Dynamic allocation gives the channel to a user when they need it
- All the dynamic channel allocation methods to be discussed are based on five key assumptions

Assumption	Implication
Independent traffic	Often not a good model, but permits analysis
Single channel	No external way to coordinate senders
Observable collisions	Needed for reliability; mechanisms vary
Continuous or slotted time	Slotting may improve performance
Carrier sense	Can improve performance if available

Assumption #2: Single Channel

- A single channel is available for all communication
- All stations can transmit on it and all can receive from it
- As far as the hardware is concerned, all stations are equivalent, although protocol software may assign priorities to them

Assumption #3: Observable Collisions

- If two frames are transmitted simultaneously, they will result in a collision
- All stations can detect collisions
- A collided frame must be transmitted again later
- There are no errors other than those generated by collisions

Assumption #4: Continuous or Slotted Time

- Continuous Time
  - Frame transmission can begin at any instant
  - There is no master clock dividing time into discrete intervals
- Slotted Time
  - Time is divided into discrete intervals (slots)
  - Frame transmissions always begin at the start of a slot
  - A slot may contain 0, 1 or more frames

Assumption #5: Carrier Sense

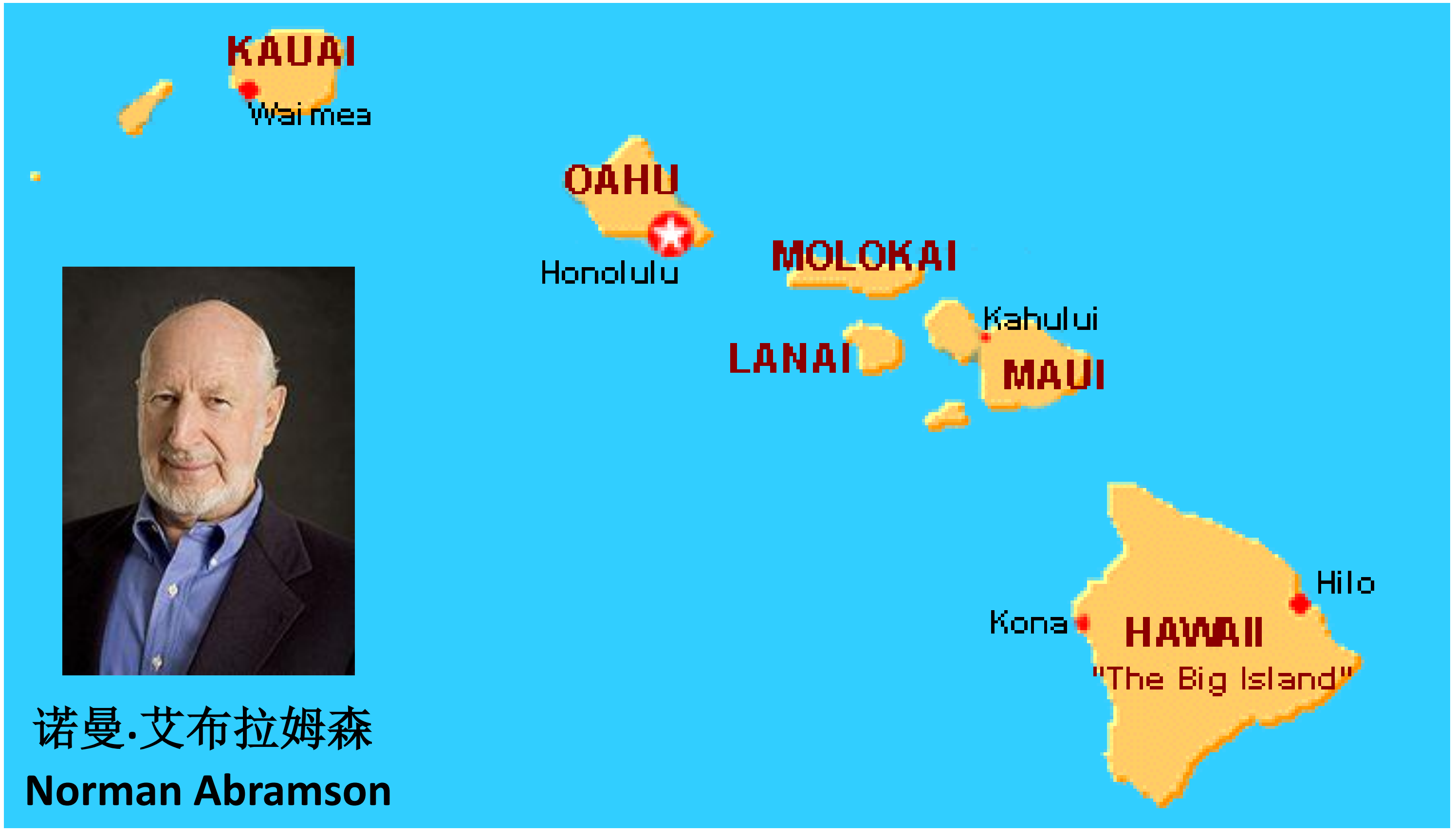
- Carrier Sense (CS, 载波侦听)
  - Stations can tell if the channel is in use before trying to use it
  - If the channel is sensed as busy, no station will attempt to use it until it goes idle
- No Carrier Sense
  - Stations cannot sense the channel before trying to use it
  - They just simply transmit and then determine whether the transmission was successful

Multiple Access Protocols

- ALOHA
- CSMA (Carrier Sense Multiple Access)

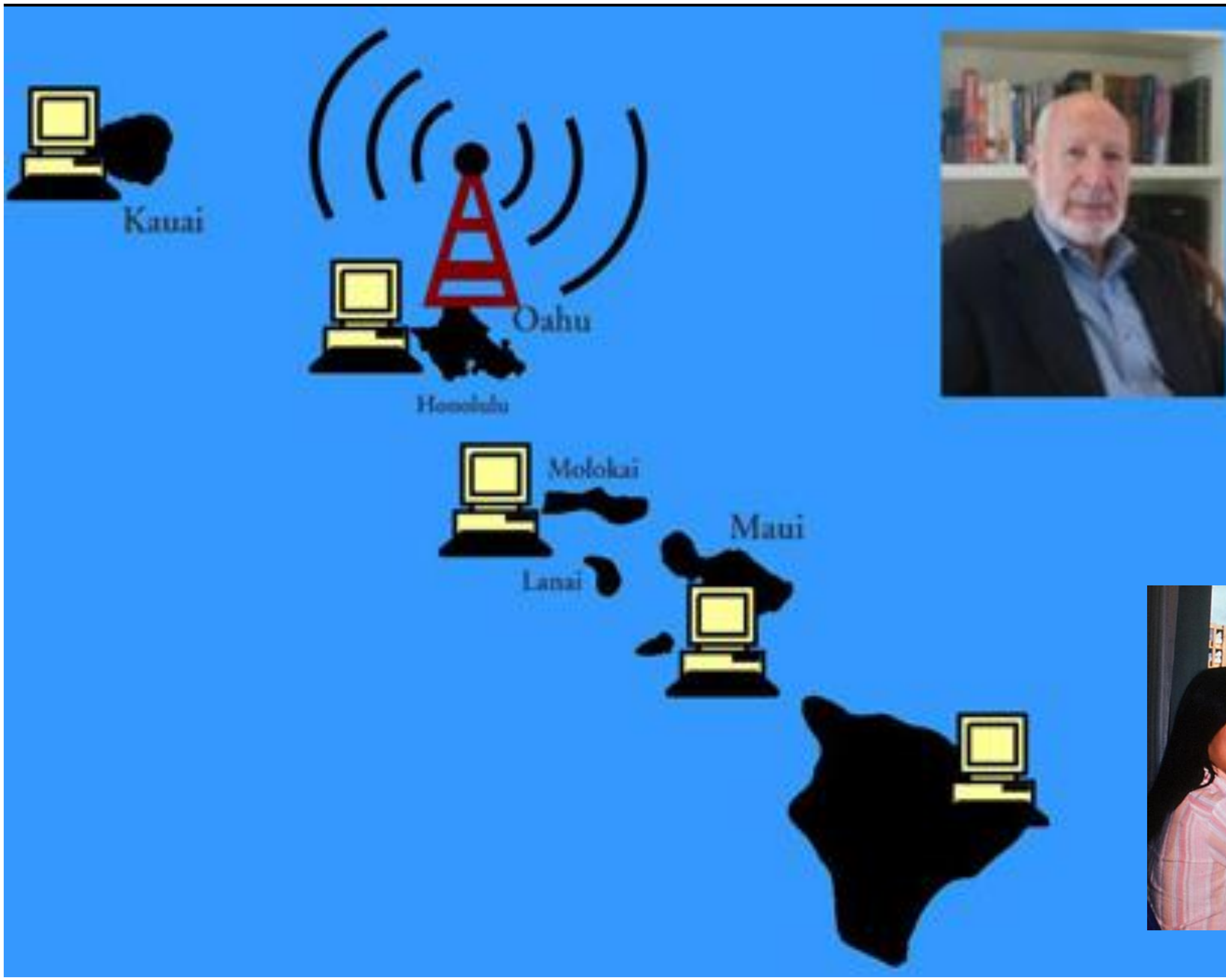
ALOHA: Background

- The earliest wireless communication network (1970s)

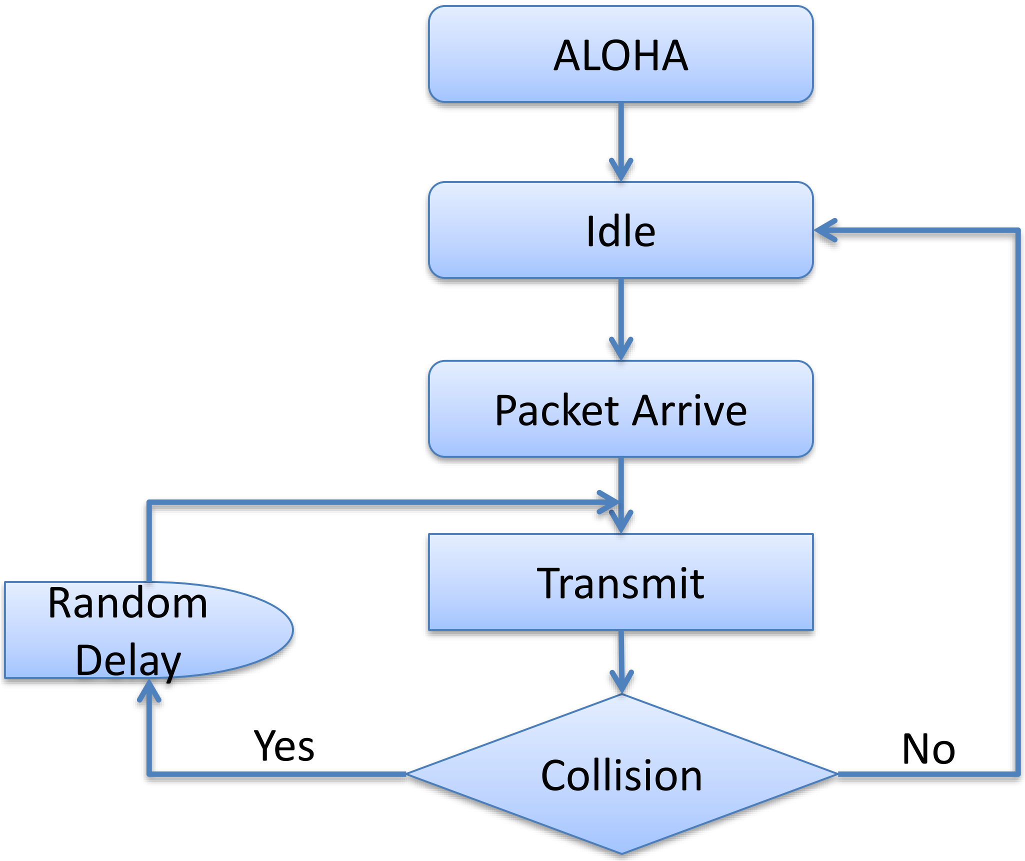


诺曼·艾布拉姆森
Norman Abramson

ALOHA Network



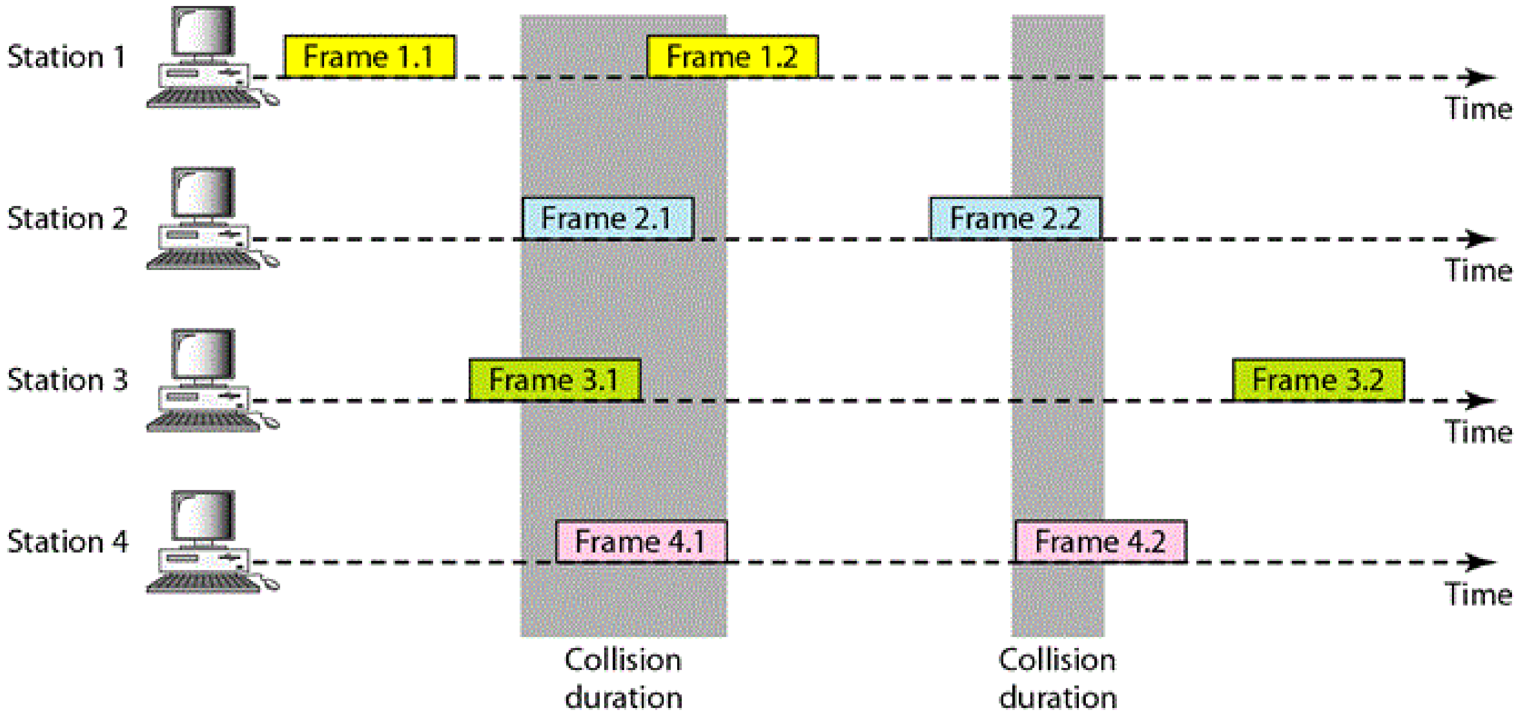
ALOHA Idea



ALOHA
Idle
Packet Arrive
Transmit
Random Delay
Yes
Collision
No

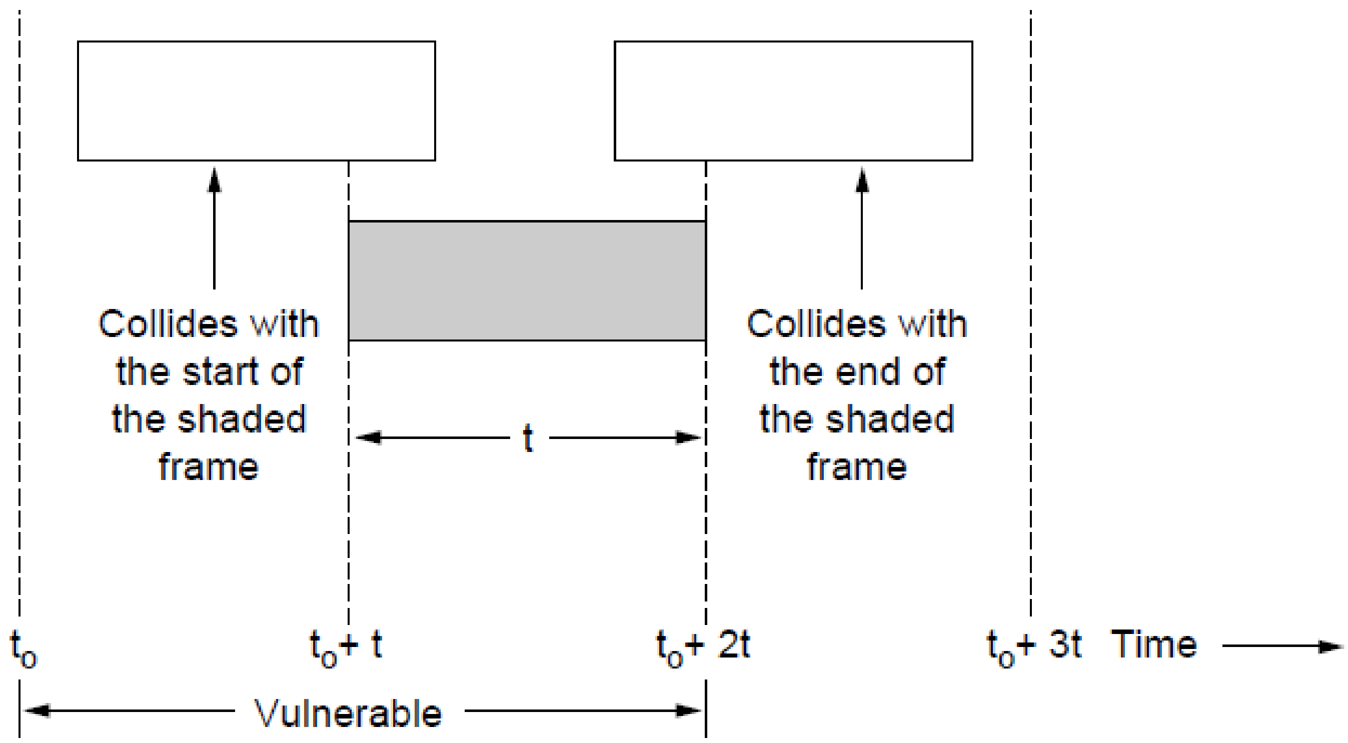
Pure ALOHA

- In pure ALOHA, users transmit frames whenever they have data; retry after a random time for collisions
  - Efficient and low-delay under low load
  - No Carrier Sense



Pure ALOHA

- Collisions happen when other users transmit during a vulnerable period that is twice the frame time



Pure ALOHA

- Efficiency analysis
  - Frame time: time to transmit the standard, fixed-length frame
  - Assume that the new frames generated follow Poisson distribution with a mean of N frames per frame time ($0 < N < 1$)
  - Assume mean of G (old and new) frames per frame time, $G \geq N$
  - The throughput $S = GP_0$, where P_0 is the probability that a frame does not suffer a collision

Pure ALOHA

- Efficiency analysis (cont'd)
  - The probability that *k* frames are generated during a given frame time, in which *G* frames are expected, is given by the Poisson distribution

$$P_r[k] = \frac{G^k e^{-G}}{k!}$$

  - The probability of zero frames is just e^{-G}
  - The probability of no frames being initiated during the entire vulnerable period (two frame times) is $P_0 = e^{-\boxed{2}G}$
  - $S = Ge^{-2G}$, Let *S*'=0, then G=0.5, with

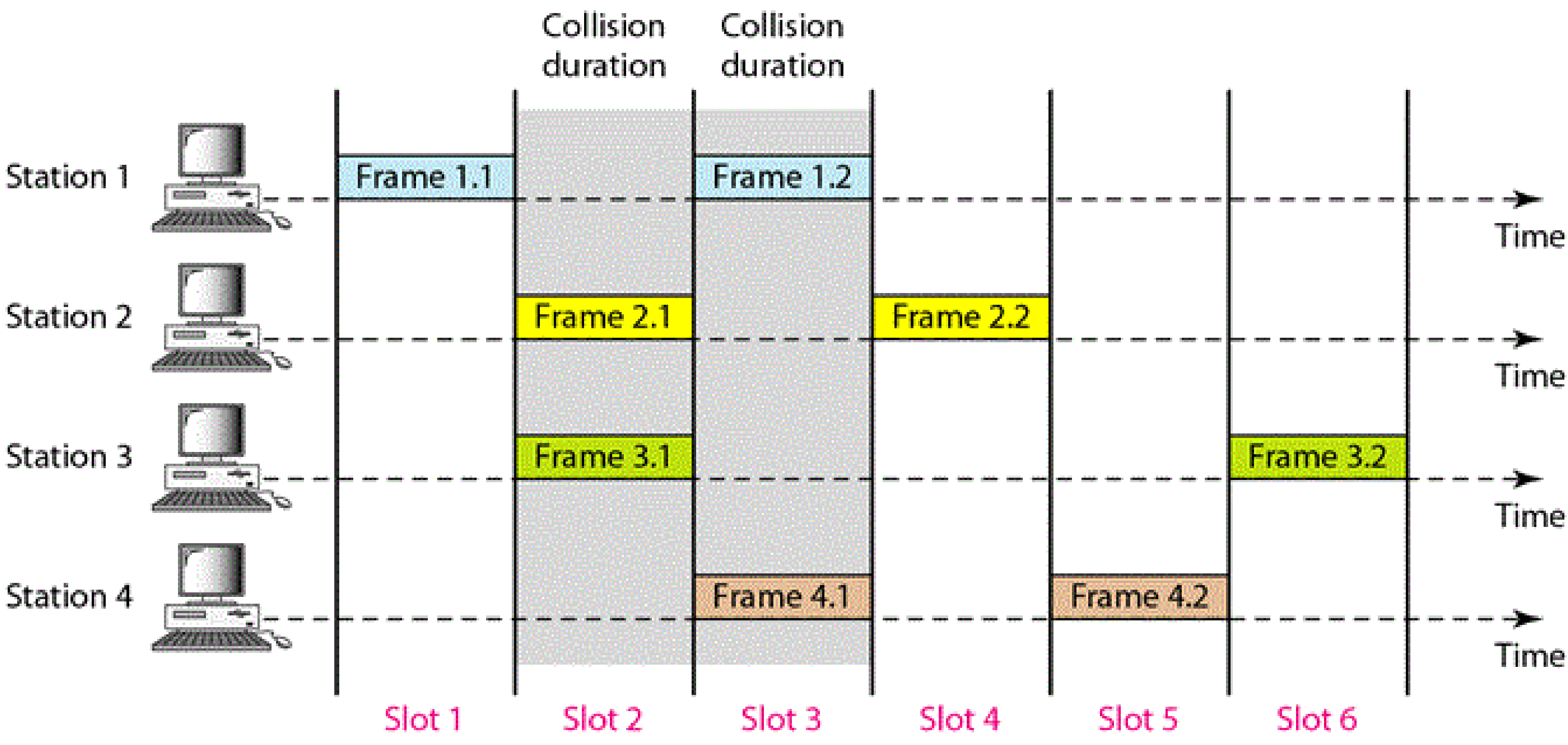
Ï = G*frame * SG*frame Ñ ²•ö„ïý'

$$S = \frac{1}{2e} \approx 18.4\%$$

WolframAlpha

Slotted ALOHA

- Using slotted time and no carrier sense

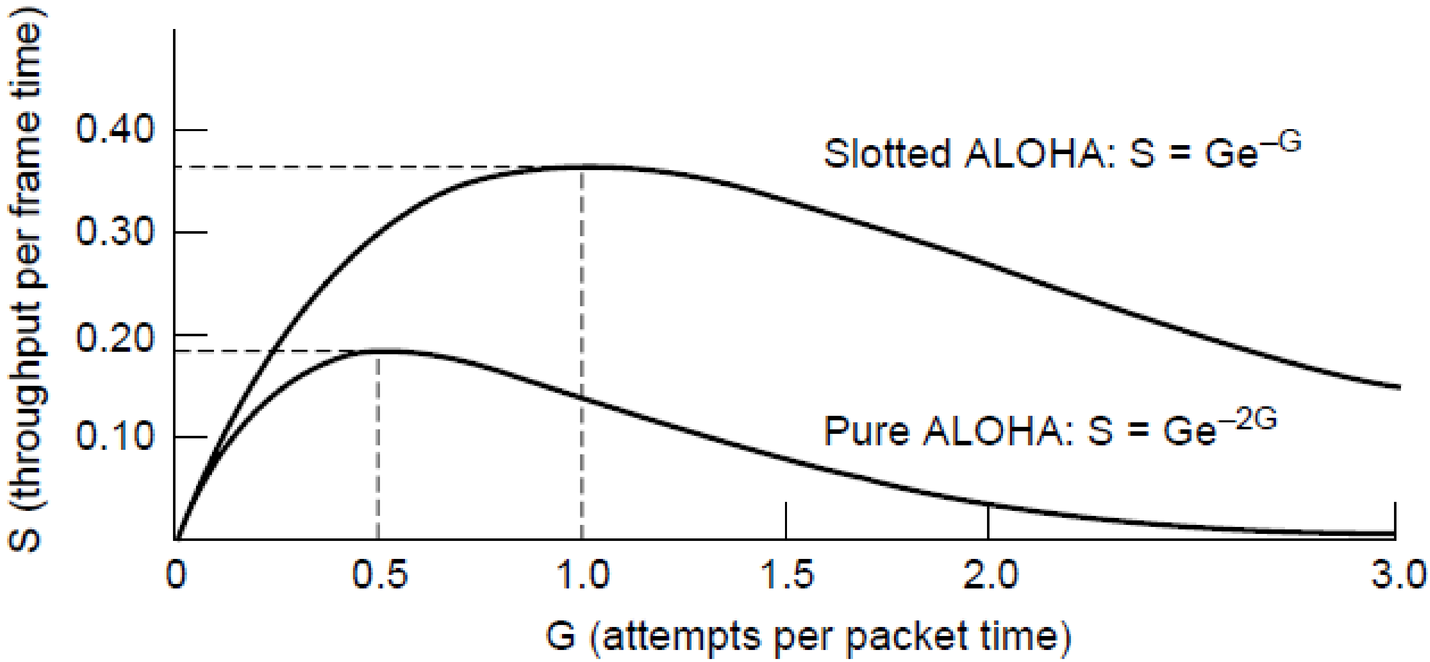


Slotted ALOHA

- Efficiency analysis
  - This halves the vulnerable period
  - The probability of no other traffic during the same slot as our test frame is then e^{-G}
  - $S = Ge^{-G}$, Let S'=0, then G=1, with $S = \frac{1}{e} \approx 36.8\%$

ALOHA Protocol

- Compare slotted ALOHA with pure ALOHA
- Multiple RFID tags talk to the same RFID reader



WolframAlpha

CSMA Protocol

- CSMA: Carrier Sense Multiple Access Protocol
- CSMA improves on ALOHA by sensing the channel
  – User doesn't send if it senses someone else is using the channel
- Variations on what to do if the channel is busy
  – 1-persistent (greedy) sends as soon as idle
  – Nonpersistent waits a random time then tries again
  – *p*-persistent sends with probability p when idle

1-persistant CSMA protocol

- Algorithm
  - A station first senses the channel when it is ready to send
  - If the channel is idle, the station sends its data.
  - Otherwise, the channel is busy, the station just waits until it become idle
    - Then the station sends its frame
  - If a collision occurs, the station waits a random amount of time and then tries again
- Example: Classic Ethernet (传统以太网)

Nonpersistent CSMA protocol

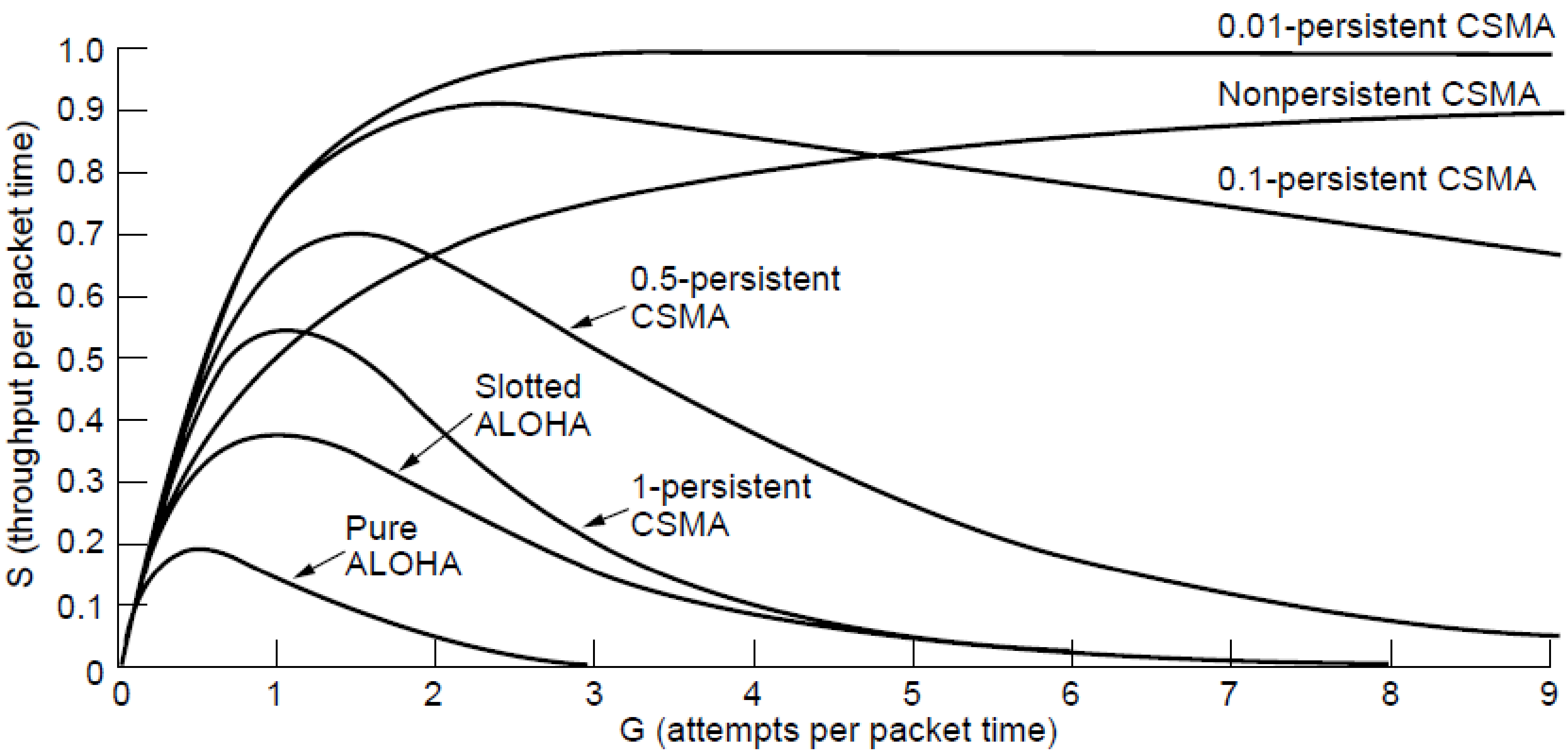
- Algorithm
  - A station first senses the channel when it is ready to send
  - If the channel is idle, the station sends its data
  - If the channel is busy, the station waits a random period of time and then repeats the algorithm
  - If a collision occurs, the station waits a random amount of time and then tries again

p-persistent CSMA protocol

- Apply to slotted channels
  - A station first senses the channel when it is ready to send.
  - If the channel is idle, the station transmits with a probability p, else the station defers until the next slot with a probability $q = 1 - p$
    - Next slot, repeat this process
  - If the station initially senses that the channel is busy, it waits until the next slot and tries again
  - If a collision occurs, the station waits a random amount of time and then tries again
- Example: 802.11 (WiFi)

CSMA – Persistence

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



What if two users sense the channel free and begin transmitting simultaneously?

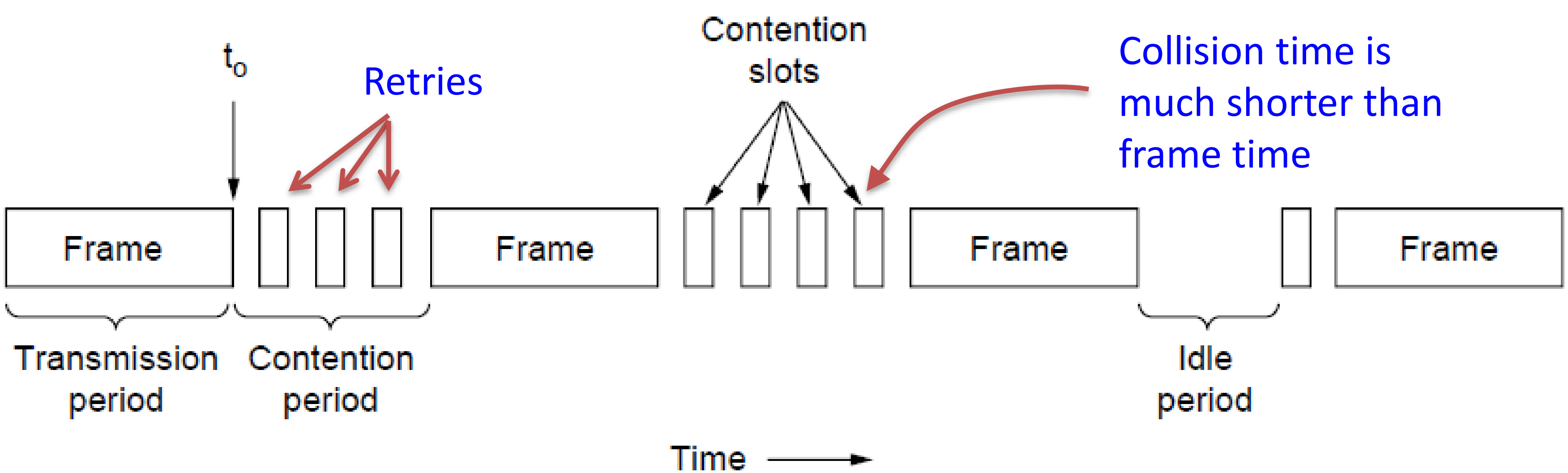
CSMA with Collision Detection

- CSMA/CD improvement is to detect/abort collisions
  - Same as CSMA: sense channel before transmission
  - Listen to the channel while transmitting
  - If collision is detected, wait for a random period and try again

Classic Ethernet LAN (传统以太网)

CSMA with Collision Detection

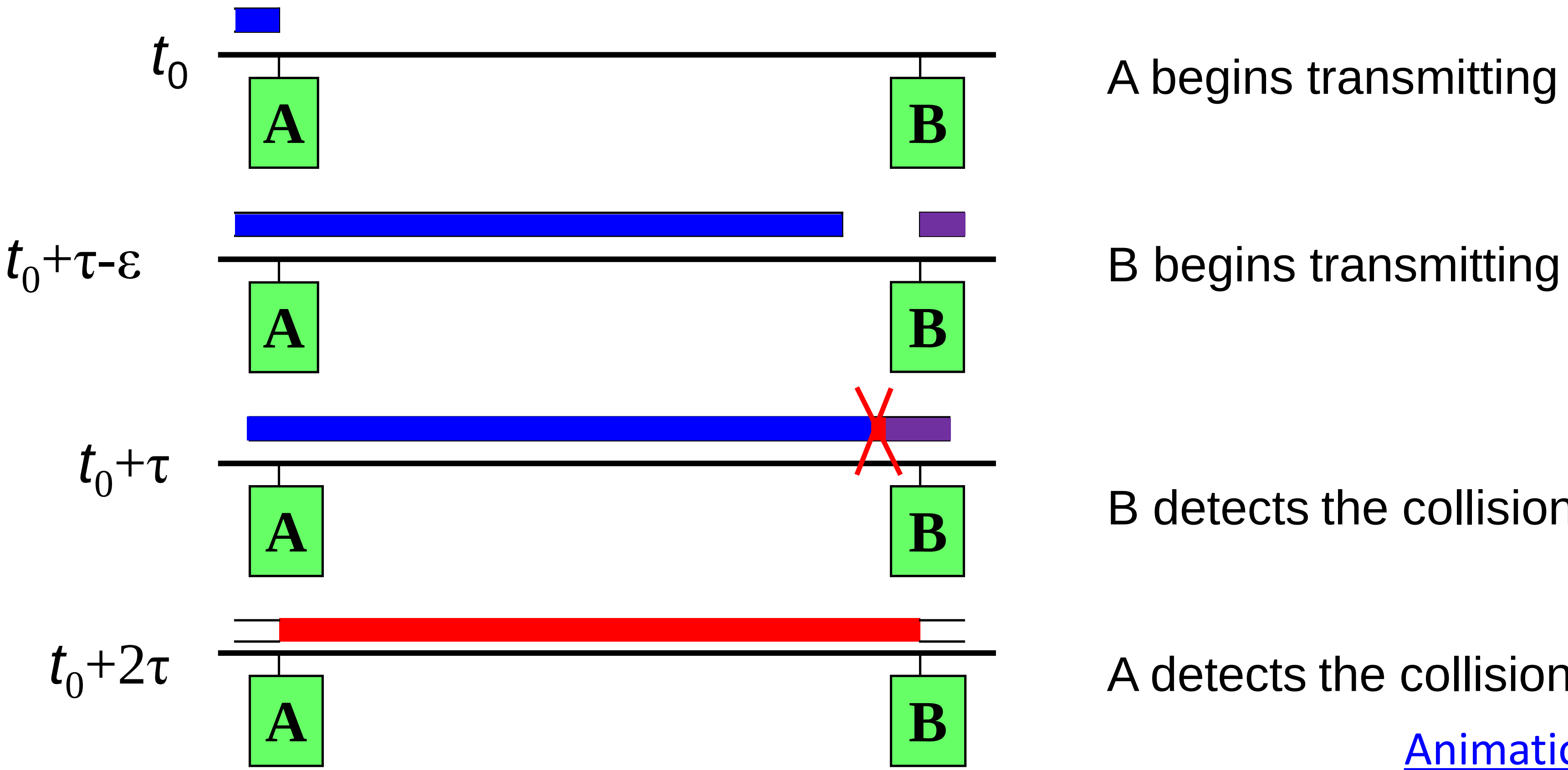
- CSMA/CD improvement is to detect/abort collisions
  - Alternating contention (争用) and transmission period



How long it takes to detect collision?

CSMA/CD

- The worst-case delay in collision detection
  - Let the time for a signal to propagate between the two farthest stations be τ



Animation->

Ethernet

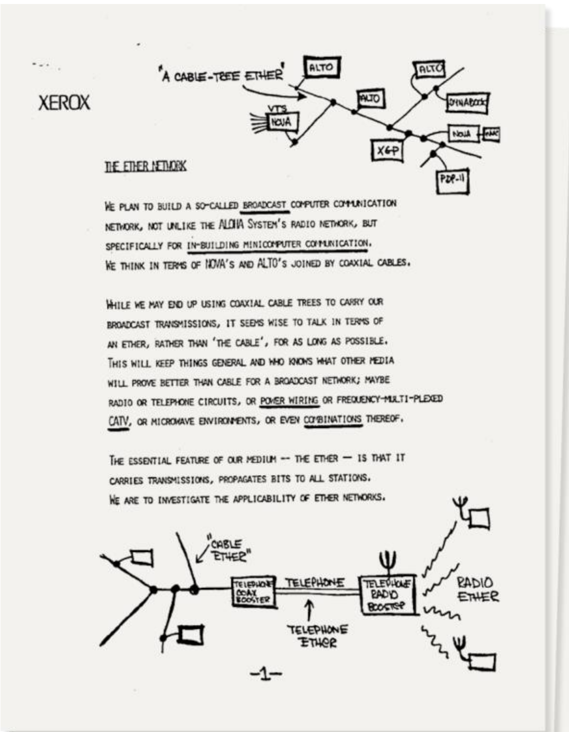
– Classic Ethernet
– Switched/Fast Ethernet
– Gigabit/10 Gigabit Ethernet
– 40/100 Gigabit Ethernet

ACM Turing Award 2022

- 2023.03.28: ACM Turing Award recipient
  - **Bob Metcalfe**
  - For his invention, standardization, and commercialization of **Ethernet**.
- Turing award in Networking:
  - 2004: **Vinton Cerf** and **Robert Kanh**, **contribution: TCP/IP**
  - 2016: **Tim Berners-Lee**, contribution: **WWW**

Bob Metcalfe (left) and
David Boggs (right, 1950-2022)

Metcalfe’s Contribution



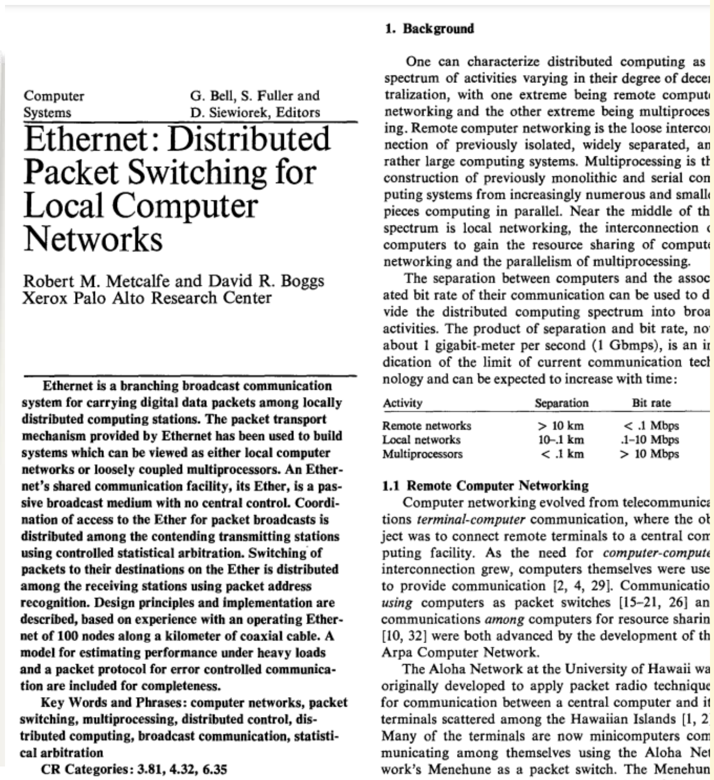
THE ETHER NETWORK

WE PLAN TO BUILD A SO-CALLED BROADCAST COMPUTER COMMUNICATION NETWORK, NOT UNLIKE THE ALOHA SYSTEM'S RADIO NETWORK, BUT SPECIFICALLY FOR IN-BUILDING MINICOMPUTER COMMUNICATION. WE THINK IN TERMS OF NOVA'S AND ALTO'S JOINED BY COAXIAL CABLES.

WHILE WE MAY END UP USING COAXIAL CABLE TREES TO CARRY OUR BROADCAST TRANSMISSIONS, IT SEEMS WISE TO TALK IN TERMS OF AN ETHER, RATHER THAN 'THE CABLE', FOR AS LONG AS POSSIBLE. THIS WILL KEEP THINGS GENERAL AND WHO KNOWS WHAT OTHER MEDIA WILL PROVE BETTER THAN CABLE FOR A BROADCAST NETWORK; MAYBE RADIO OR TELEPHONE CIRCUITS, OR POWER WIRING OR FREQUENCY-MULTI-PLEXED CATV, OR MICROWAVE ENVIRONMENTS, OR EVEN COMBINATIONS THEREOF.

THE ESSENTIAL FEATURE OF OUR MEDIUM -- THE ETHER — IS THAT IT CARRIES TRANSMISSIONS, PROPAGATES BITS TO ALL STATIONS. WE ARE TO INVESTIGATE THE APPLICABILITY OF ETHER NETWORKS.

A page of Memo from1973.05 describes Metcalfe’s idea on Ethernet



Computer Systems — G. Bell, S. Fuller and D. Siewiorek, Editors

Ethernet: Distributed Packet Switching for Local Computer Networks

Robert M. Metcalfe and David R. Boggs
Xerox Palo Alto Research Center

Ethernet is a branching broadcast communication system for carrying digital data packets among locally distributed computing stations. The packet transport mechanism provided by Ethernet has been used to build systems which can be viewed as either local computer networks or loosely coupled multiprocessors. An Ether-net's shared communication facility, its Ether, is a passive broadcast medium with no central control. Coordination of access to the Ether for packet broadcasts is distributed among the contending transmitting stations using controlled statistical arbitration. Switching of packets to their destinations on the Ether is distributed among the receiving stations using packet address recognition. Design principles and implementation are described, based on experience with an operating Ethernet of 100 nodes along a kilometer of coaxial cable. A model for estimating performance under heavy loads and a packet protocol for error controlled communication are included for completeness.

Key Words and Phrases: computer networks, packet switching, multiprocessing, distributed control, distributed computing, broadcast communication, statistical arbitration

CR Categories: 3.81, 4.32, 6.35

1. Background

One can characterize distributed computing as spectrum of activities varying in their degree of decen tralization, with one extreme being remote comput networking and the other extreme being multiproces ing. Remote computer networking is the loose interco nection of previously isolated, widely separated, an rather large computing systems. Multiprocessing is th construction of previously monolithic and serial com puting systems from increasingly numerous and small pieces computing in parallel. Near the middle of th spectrum is local networking, the interconnection computers to gain the resource sharing of comput networking and the parallelism of multiprocessing.

The separation between computers and the assoc ated bit rate of their communication can be used to d vide the distributed computing spectrum into broa activities. The product of separation and bit rate, no about 1 gigabit-meter per second (1 Gbmps), is an in dication of the limit of current communication tech nology and can be expected to increase with time:

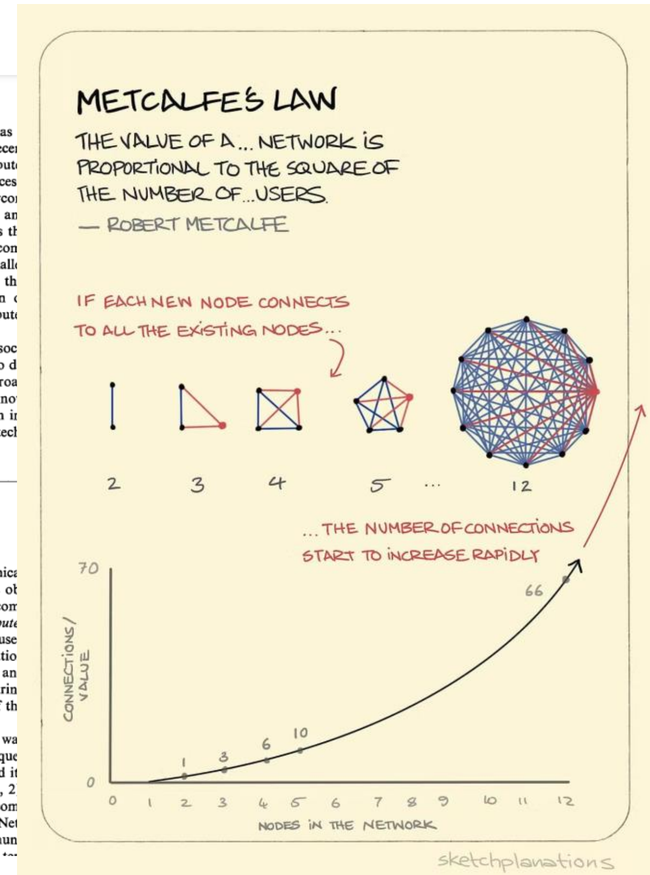
Activity	Separation	Bit rate
Remote networks	> 10 km	< .1 Mbps
Local networks	10–.1 km	.1–10 Mbps
Multiprocessors	< .1 km	> 10 Mbps

1.1 Remote Computer Networking

Computer networking evolved from telecommunica tions *terminal-computer* communication, where the ob ject was to connect remote terminals to a central com puting facility. As the need for *computer-compute* interconnection grew, computers themselves were use to provide communication [2, 4, 29]. Communicatio *using* computers as packet switches [15–21, 26] an communications *among* computers for resource sharin [10, 32] were both advanced by the development of th Arpa Computer Network.

The Aloha Network at the University of Hawaii wa originally developed to apply packet radio technique for communication between a central computer and it terminals scattered among the Hawaiian Islands [1, 2 Many of the terminals are now minicomputers com municating among themselves using the Aloha Net work's Menehune as a packet switch. The Menehun

Communications of the ACM，1976



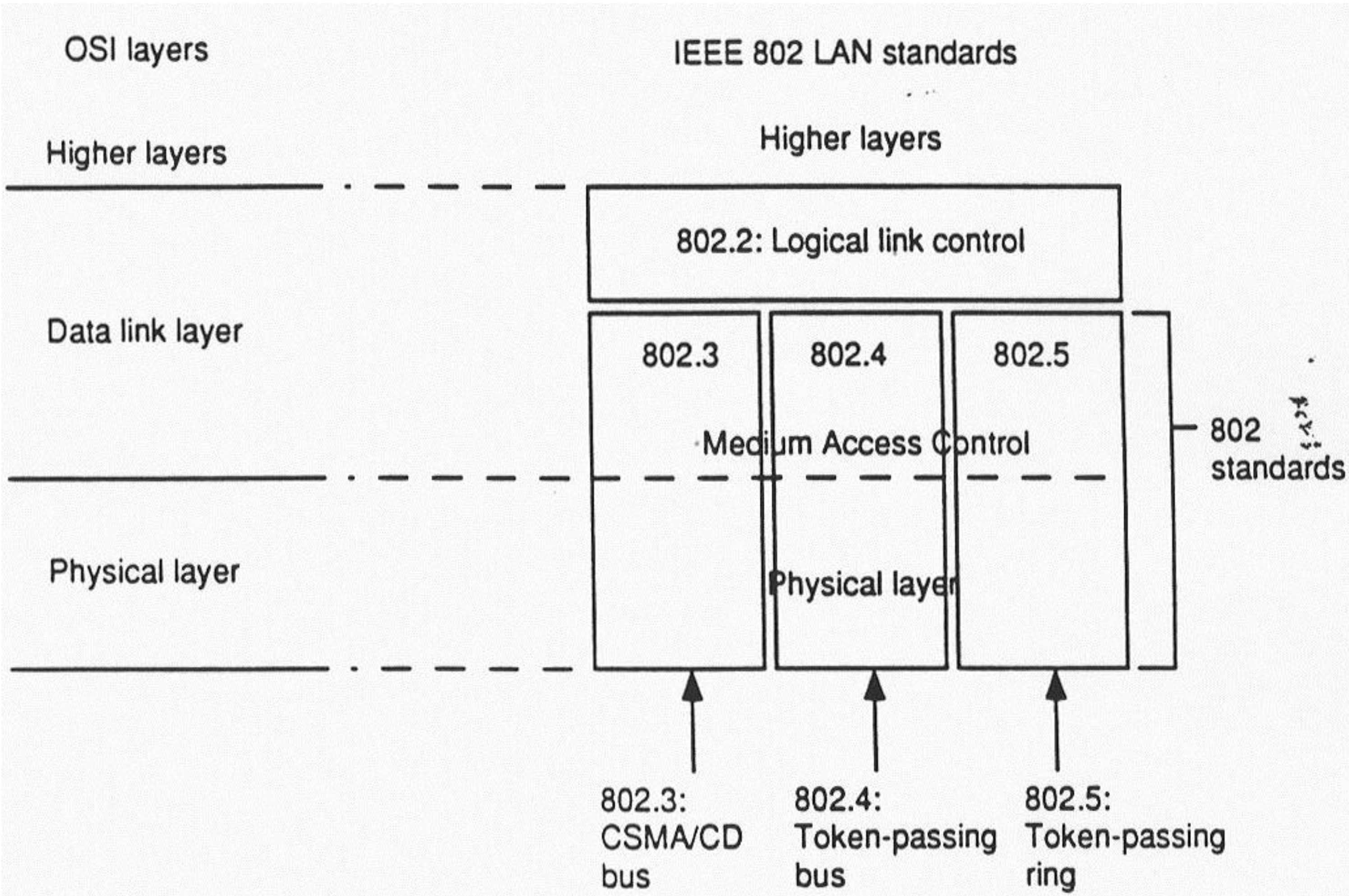
Metcalfe’s Law

IEEE 802 Standards for LAN

Number	Topic
802.1	Overview and architecture of LANs
802.2 ↓	Logical link control
802.3 *	Ethernet
802.4 ↓	Token bus (was briefly used in manufacturing plants)
802.5	Token ring (IBM's entry into the LAN world)
802.6 ↓	Dual queue dual bus (early metropolitan area network)
802.7 ↓	Technical advisory group on broadband technologies
802.8 †	Technical advisory group on fiber optic technologies
802.9 ↓	Isochronous LANs (for real-time applications)
802.10 ↓	Virtual LANs and security
802.11 *	Wireless LANs
802.12 ↓	Demand priority (Hewlett-Packard's AnyLAN)
802.13	Unlucky number. Nobody wanted it
802.14 ↓	Cable modems (defunct: an industry consortium got there first)
802.15 *	Personal area networks (Bluetooth)
802.16 *	Broadband wireless
802.17	Resilient packet ring

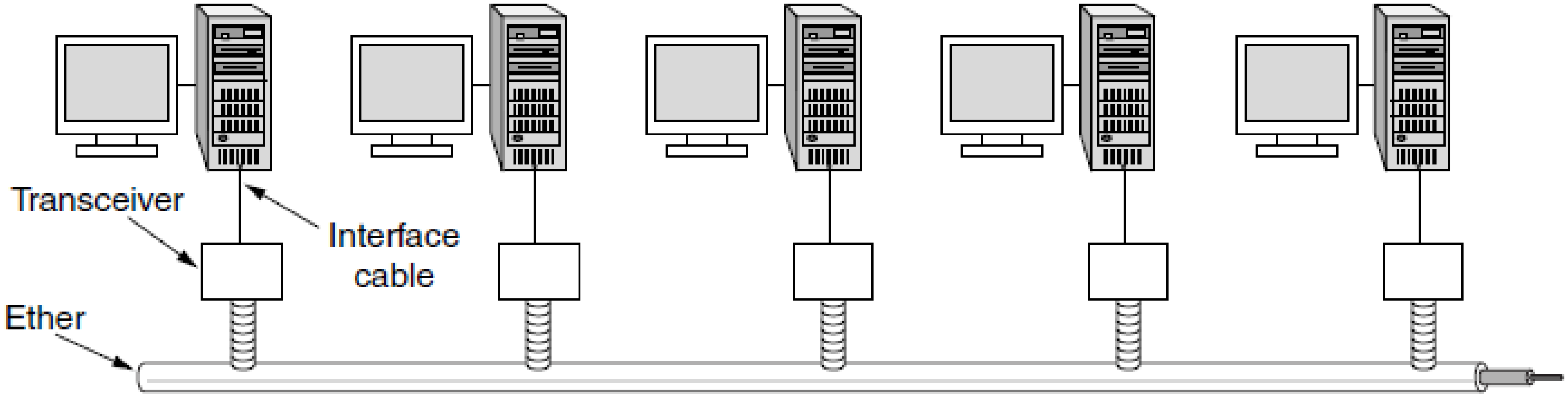
The IEEE 802 working groups. The important ones are marked with *. The ones marked with ↓ are hibernating. The one marked with † gave up and disbanded itself.

IEEE 802 LAN Standards



Classic Ethernet (传统以太网)

- One shared coaxial cable (同轴电缆) to which all hosts attached
  - Up to 10 Mbps, with Manchester encoding
  - Repeaters(中继器) are used to increase cable length
  - Hosts ran the classic Ethernet protocol for access



Classic Ethernet Standard

- DIX Standard
  - DEC, Intel, and Xerox drew up a standard in 1978 for a 10-Mbps Ethernet
  - RFC 894
- IEEE 802.3
  - With a minor change, the DIX standard became the IEEE 802.3 standard in 1983
  - RFC 1042

Ref. to the Course Website

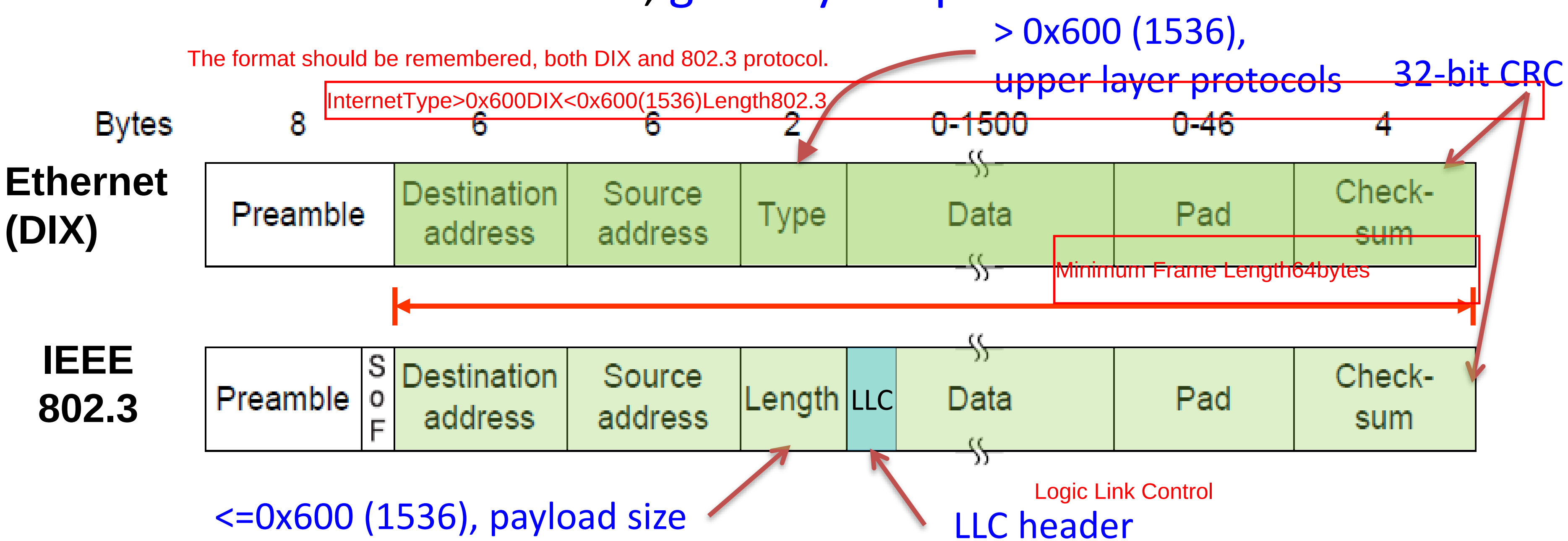
Classic Ethernet MAC Protocol

- Frame format is still used with modern Ethernet
  - Minimum Frame length: 64 ~ 1518 bytes (up to 1500 bytes payload)

This number should be remembered.

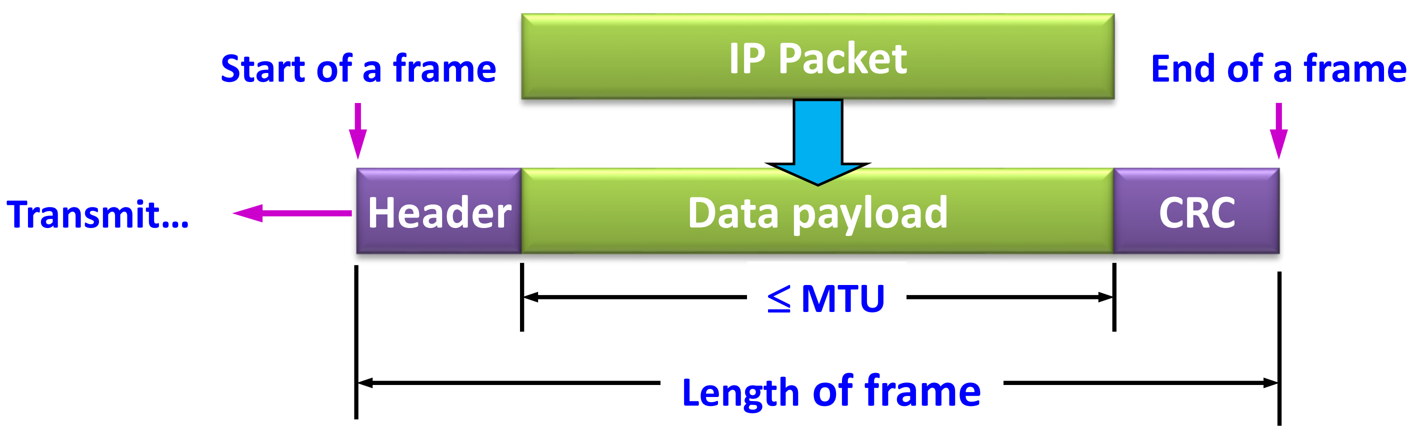
  - *Destination address*: the first bit to be 0 is unicasting address, 1 is multicasting, and all 1 is broadcasting
  - *Source address*: 48 bits, globally unique

The format should be remembered, both DIX and 802.3 protocol.



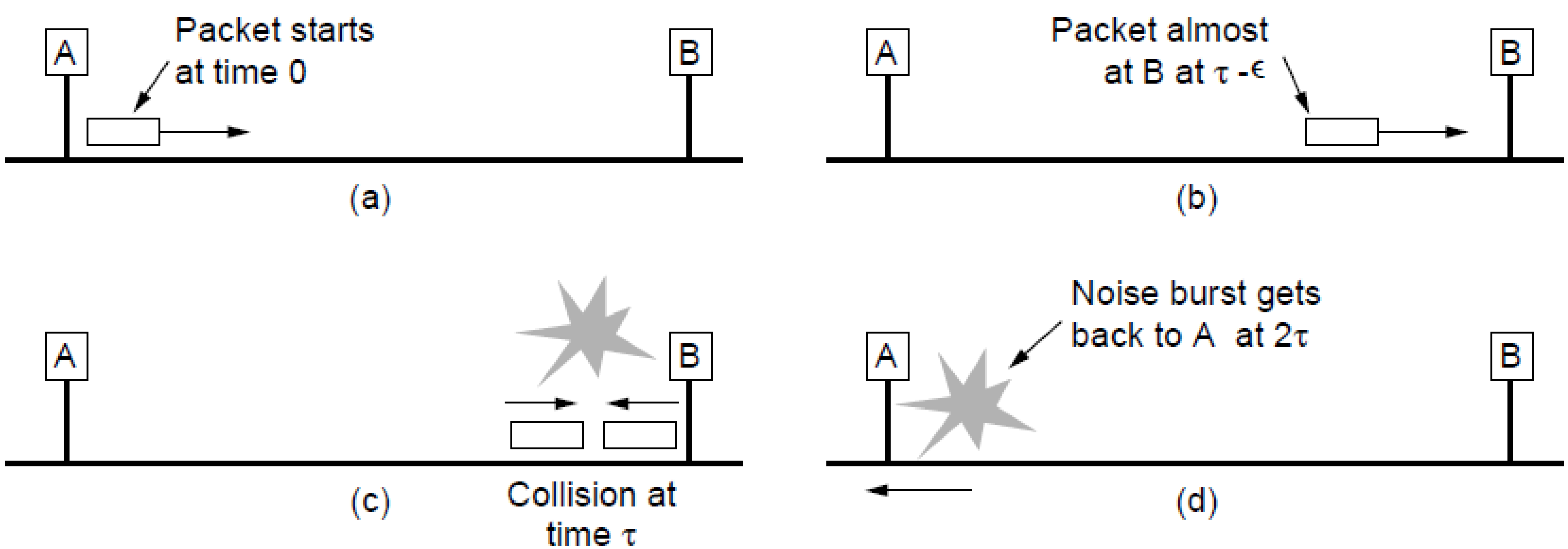
Ethernet Frame Encapsulation

- MTU: Maximum Transmission Unit
  - MTU is the size of the largest protocol data unit (PDU) that can be communicated in a single network layer transaction
  - It relates to the payload size of Ethernet frame, e.g., MTU=1500 bytes in typical Ethernet



Classic Ethernet MAC Protocol

- Collisions can occur and take as long as 2τ to detect
  - τ is the time it takes to propagate over the Ethernet
  - Leads to minimum frame size for reliable detection
  - 2500m max. cable length, 50*us* round-trip time (including up to 4 repeaters), 100nsec per bit (10Mbps) ≈ 512bits or 64 bytes



Classic Ethernet MAC Protocol

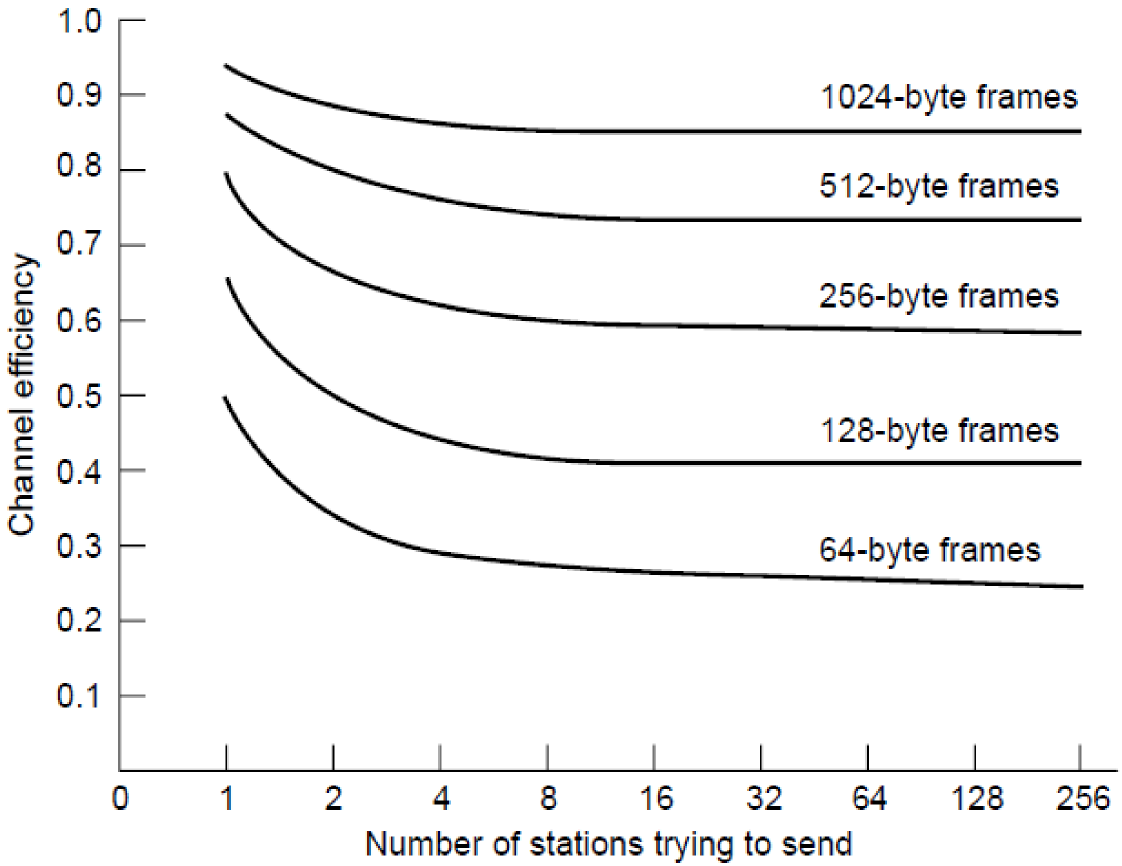
- MAC protocol is 1-persistent CSMA/CD
  - Sense the channel to be idle
  - Send the frame and detect collision at the same time
  - Once collision occurs,
    - Abort the transmission
    - Transmit a 48-bytes jam signal

CSMA/CD with BEB

- Random delay (backoff) after collision is computed with Binary Exponential Backoff (二进制指数后退)
  - Contention slot = 2τ, 512 bit times for classic Ethernet
  - After *i* collisions, a random number *k* between 0 and $2^i - 1$ is chosen and waits *k* slots
  - After 10 collisions, the randomization interval is 1023 slots
  - After 16 collisions, reports failure back to the computer

Classic Ethernet Performance

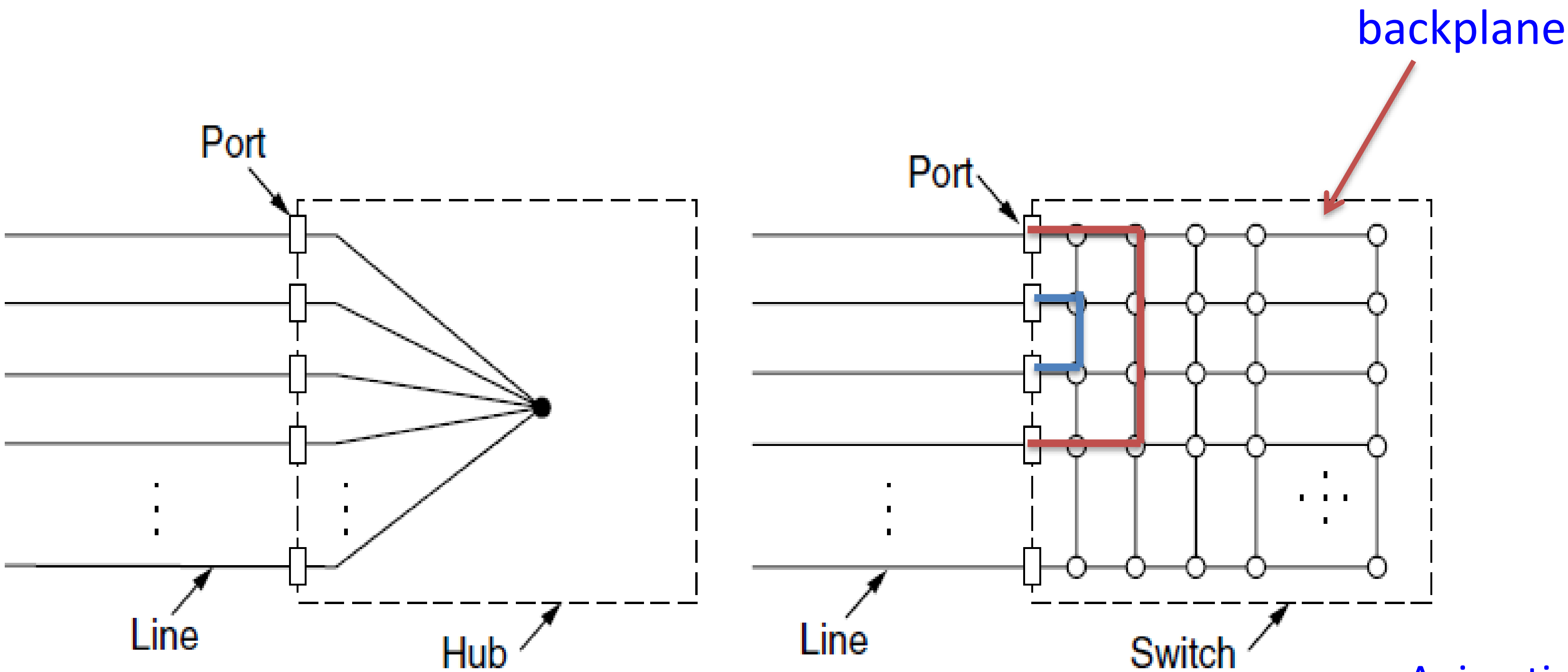
- Efficient for large frames, even with many senders
  - Degrades for small frames (and long LANs)



10 Mbps Ethernet,
64 byte min. frame

Switched Ethernet (交换式以太网)

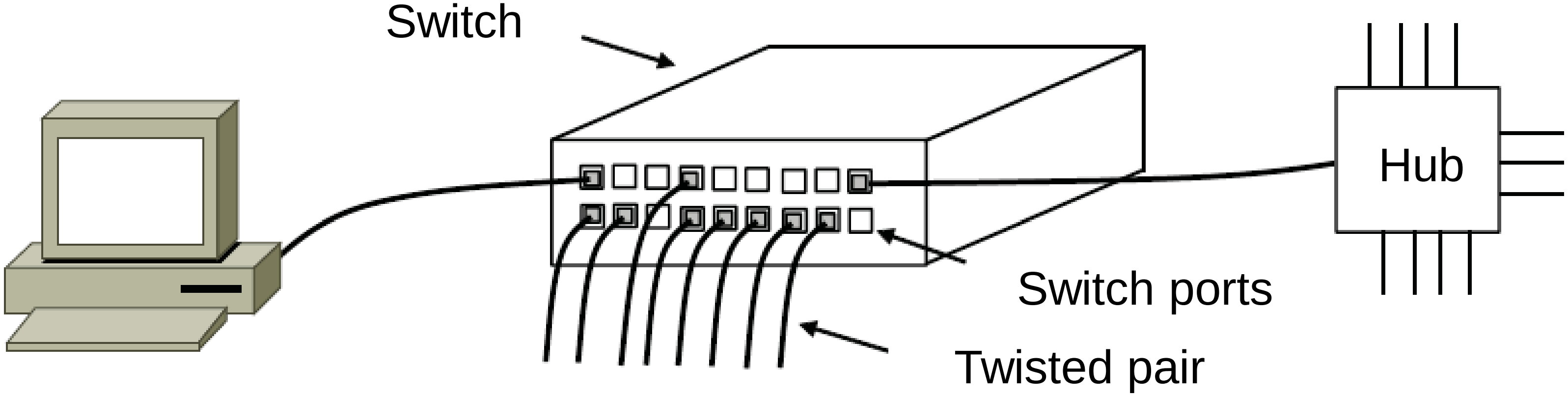
- Hubs (集线器) wire all lines into a single CSMA/CD domain
- Switches (交换机) isolate each port to a separate domain
  - Much greater throughput for multiple ports
  - No need for CSMA/CD with full-duplex lines



Animation->

Switched Ethernet (2)

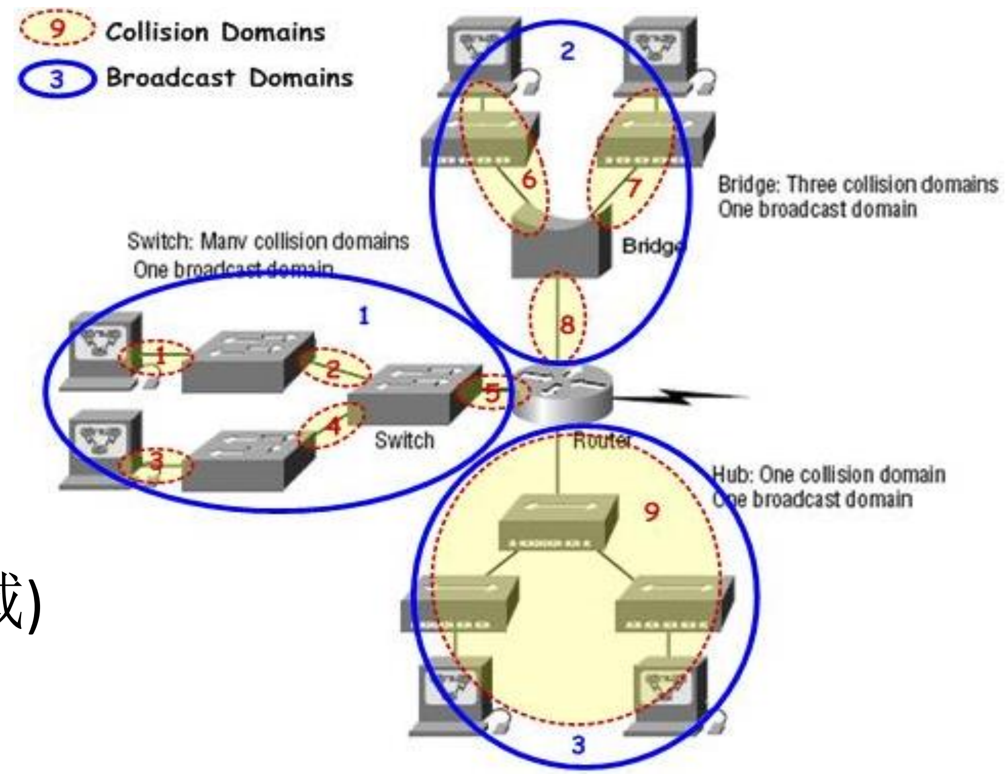
- Switches can be wired to computers, hubs and switches
  - Hubs concentrate traffic from computers/hubs
- One of the most important characters of switched Ethernet is to isolate collision domain



More in Sec. 4.8

Collision domain vs. broadcast domain

- Collision domain (冲突域)
  - An area of the network where frame can collide
  - Can not be broken up by hubs/repeaters
  - Will be broken up by switches/bridges/routers
- Broadcast domain (广播域)
  - All nodes that can be reached by a broadcast frame transmission
  - Will be broken up by routers (路由器)



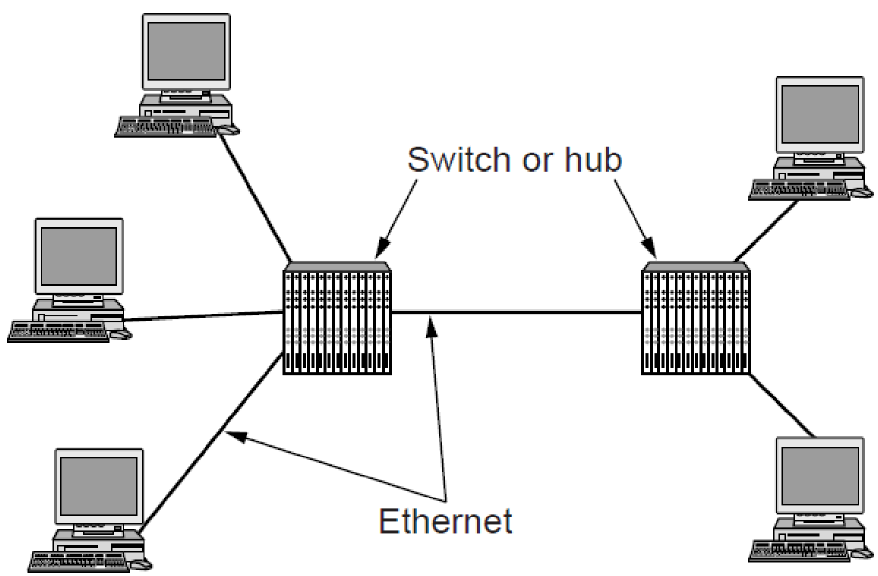
Fast Ethernet (802.3u, 1995)

- Fast Ethernet (快速以太网) extended Ethernet from 10Mbps to 100 Mbps
  - Twisted pair (with Cat 5) dominated the market
- Unchanged Frame format, the restriction of Max./Min. frame length, etc.
- Using 4B/5B encoding scheme
- Autonegotiation (自动协商): Two stations automatically negotiate speed (10 or 100 Mbps) and duplexity (half or full)

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 (Cat 5 UTP)
100Base-FX	Fiber optics	2000 m	Full duplex at 100 Mbps; long runs

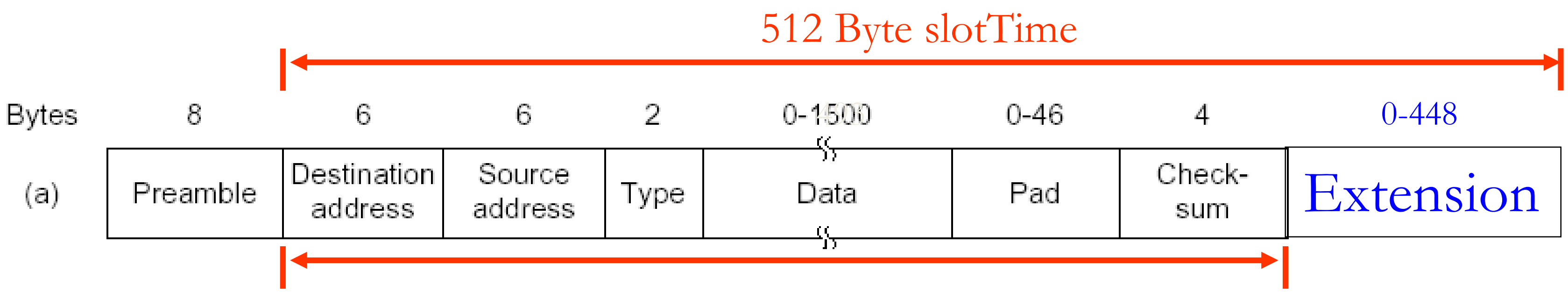
Gigabit Ethernet (802.3ab, 1999)

- Switched Gigabit Ethernet (千兆以太网)
  - Unchanged Frame format, the restriction of Max./Min. frame length, etc.
  - With full-duplex lines between computers/switches
    - NO CSMA/CD
  - With half-duplex lines between computers/Hub
    - CSMA/CD is required



Gigabit Ethernet (2)

- Frame length restriction
  - Carrier extension



  - Frame bursting: concatenate multiple frames in a single transmission
- Jumbo frames
  - Allow frames up to 9KB
  - Not recognized by standard, but supported by many vendors

Gigabit Ethernet (3)

- Gigabit Ethernet is commonly run over twisted pair
- Encoding
  - Using 8B/10B encoding

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

10-Gigabit Ethernet (2002)

- 10 Gigabit Ethernet (万兆以太网) is now widespread in the market
  - Deployed in: Datacenters, high-end routers, servers, and long-distance & high bandwidth trunks
  - Only provide full-duplex link, i.e., no CSMA/CD
  - Using 64B/66B encoding

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

40/100 Gigabit Ethernet (2010)

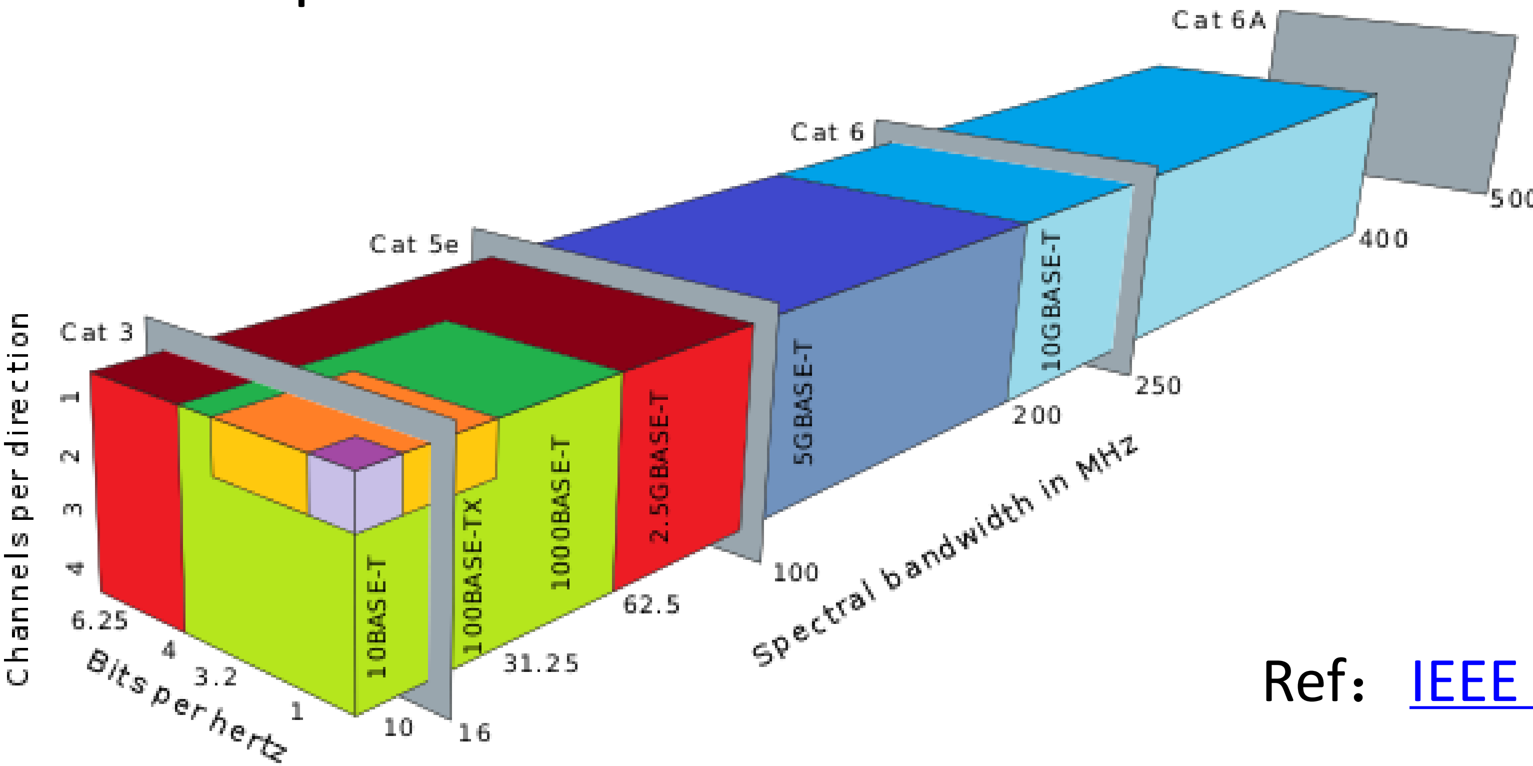
- 40/100 Gigabit Ethernet is already deployed
  - Deployed in: datacenters, Internet backbone, etc.
  - Backward compatibility with 802.3 standards to 1 Gbps
  - Allowing the minimum and maximum frame sizes to stay the same

- 400 Gbps and more are coming…

How NIC works(Animation)→

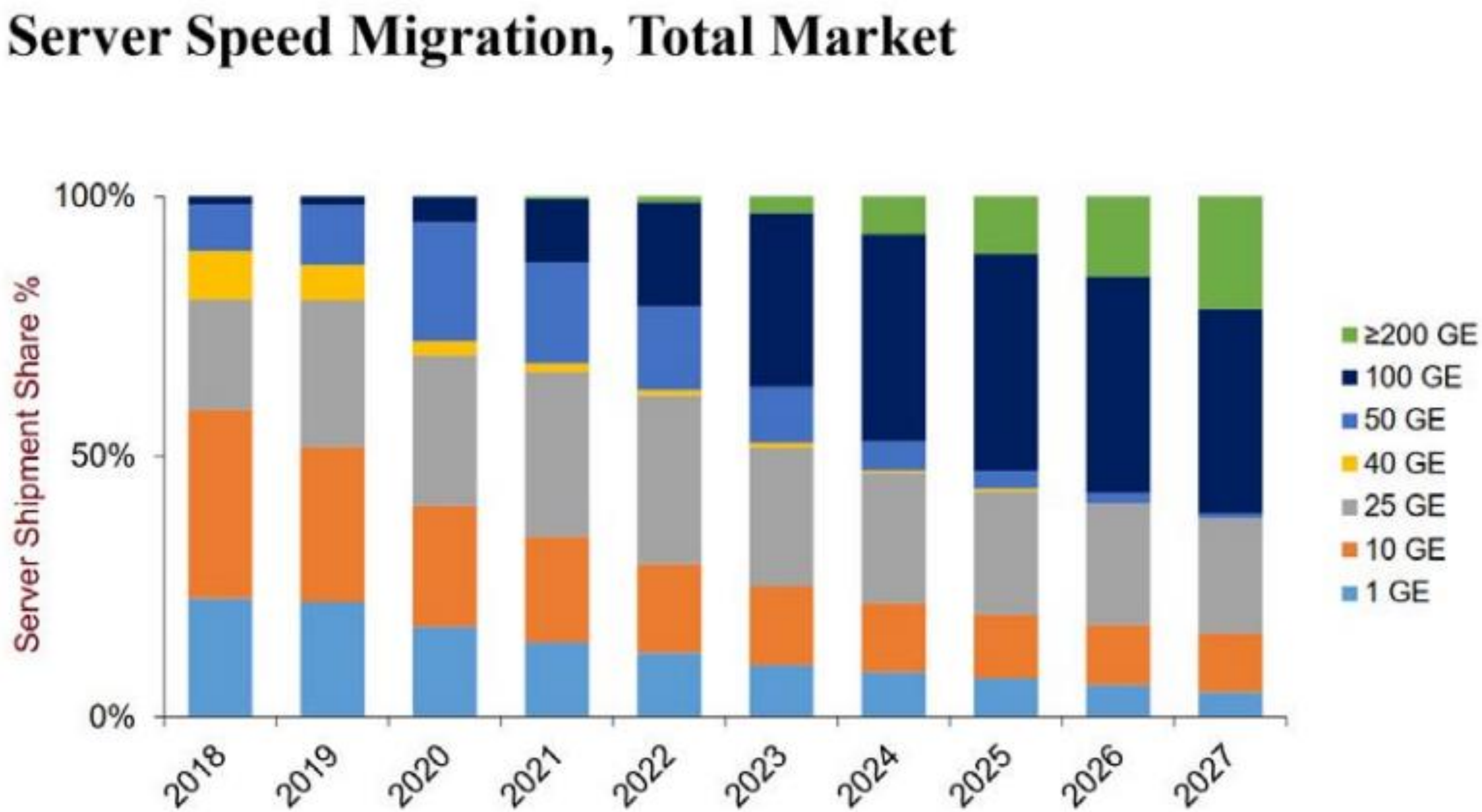
IEEE 802.3bz: New Ethernet standard

- Approved by IEEE on September 23, 2016
  - 2.5Gbps over 100 metres of Cat 5e
  - 5Gbps over 100 metres of Cat 6



Ref: [IEEE 802.3bz]()

Server-class adapter delivery trend



Review

- Pure ALOHA and Slotted ALOHA
- CSMA protocols
- Ethernet
  - Classic Ethernet
  - Switched Ethernet
  - Fast Ethernet
  - Gigabit Ethernet
  - 10-Gigabit Ethernet