南京大學
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Outline

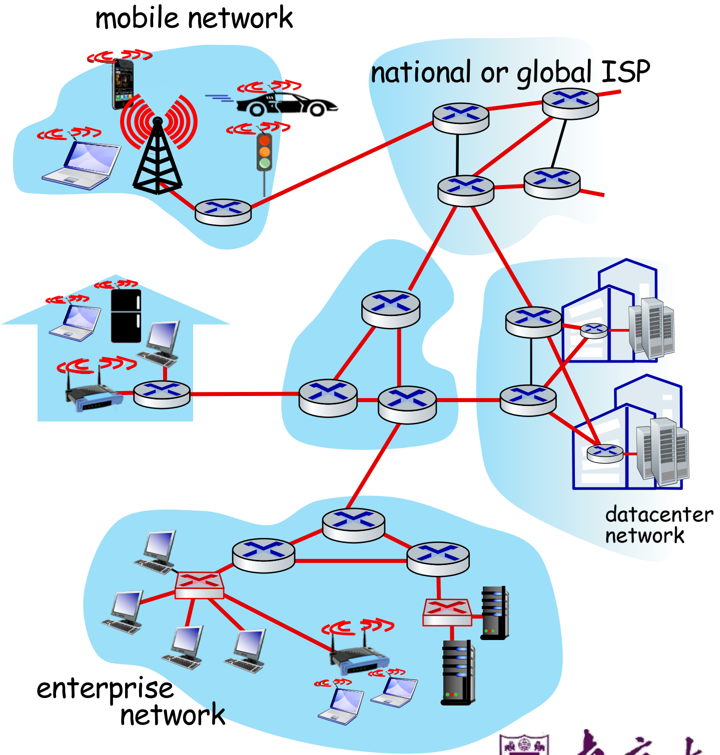
- Introduction
- Error detection, correction
- Multiple access protocols
- LANs
- Link virtualization: MPLS
- Data center networking
- A day in the life of a web request

Link layer: introduction

terminology:

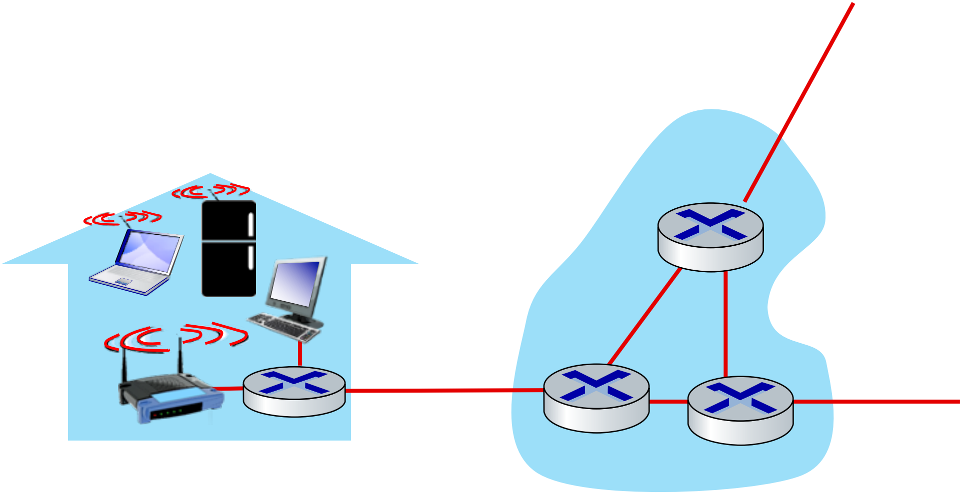
- hosts, routers: nodes
- communication channels that connect adjacent nodes along communication path: links
  - wired , wireless
  - LANs
- layer-2 packet: frame, encapsulates datagram

link layer has responsibility of transferring datagram from one node to physically adjacent node over a link

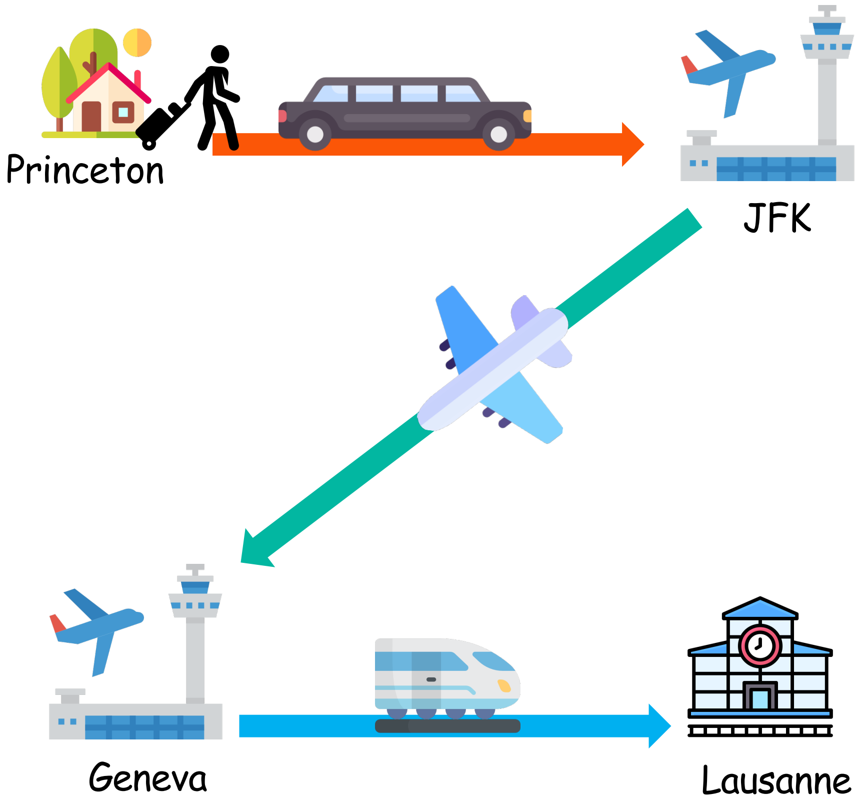


Link layer: context

- datagram transferred by different link protocols over different links:
  - e.g., WiFi on first link, Ethernet on next link
- each link protocol provides different services
  - e.g., may or may not provide reliable data transfer over link



Transportation analogy

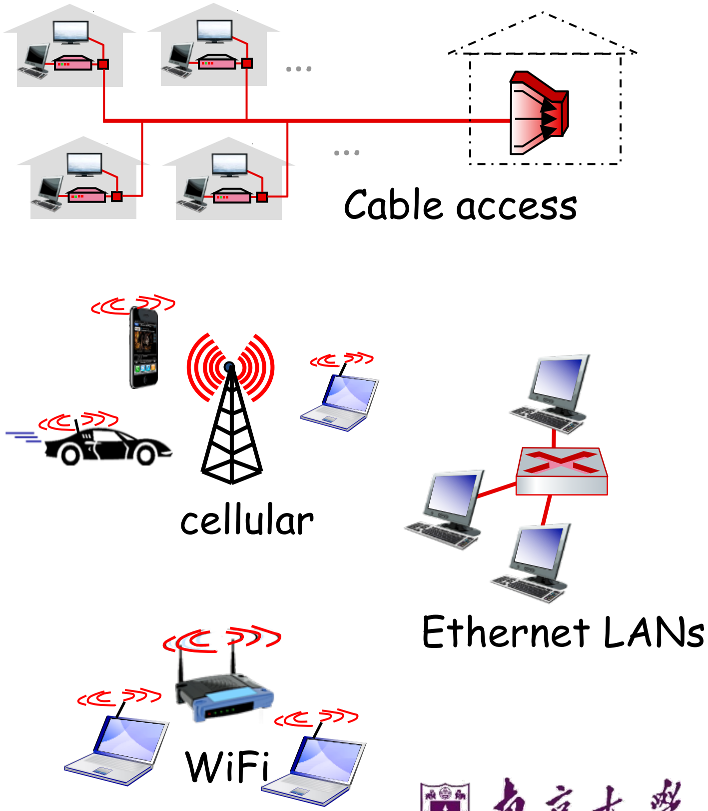


transportation analogy:

- trip from Princeton to Lausanne
  - limo: Princeton to JFK
  - plane: JFK to Geneva
  - train: Geneva to Lausanne
- tourist = datagram
- transport segment = communication link
- transportation mode = link-layer protocol
- travel agent = routing algorithm

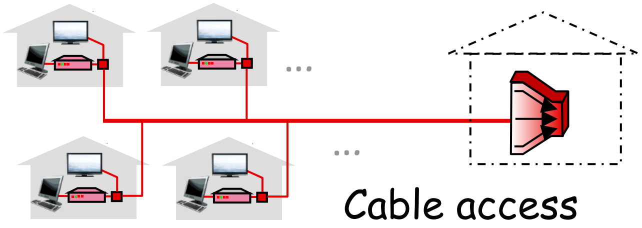
Link layer: services

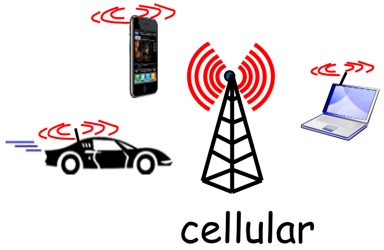
- framing, link access:
  - encapsulate datagram into frame, adding header, trailer
  - channel access if shared medium
  - "MAC" addresses in frame headers identify source, destination (different from IP address!)
- reliable delivery between adjacent nodes
  - we already know how to do this!
  - seldom used on low bit-error links
  - wireless links: high error rates
    - ✓ Q: why both link-level and end-end reliability?

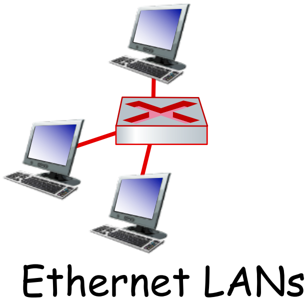


Link layer: services (more)

- flow control:
  - pacing between adjacent sending and receiving nodes
- error detection:
  - errors caused by signal attenuation, noise.
  - receiver detects errors, signals retransmission, or drops frame
- error correction:
  - receiver identifies and corrects bit error(s) without retransmission
- half-duplex and full-duplex:
  - with half duplex, nodes at both ends of link can transmit, but not at same time

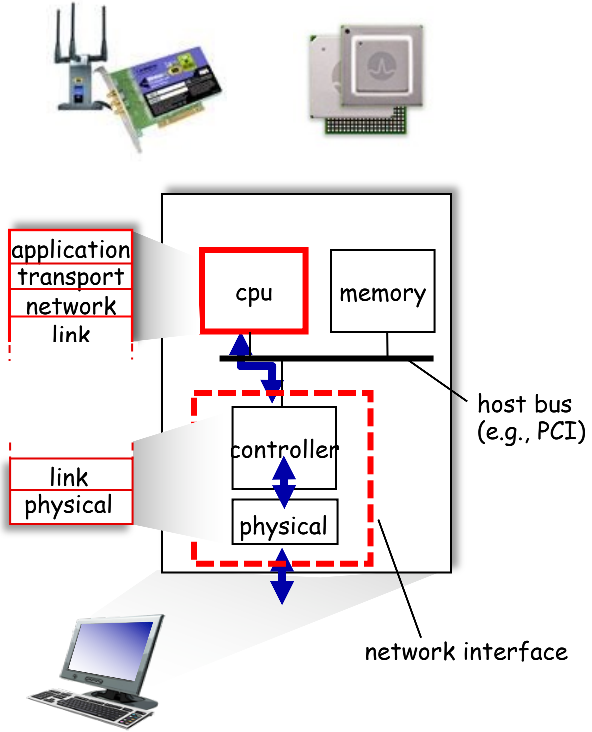




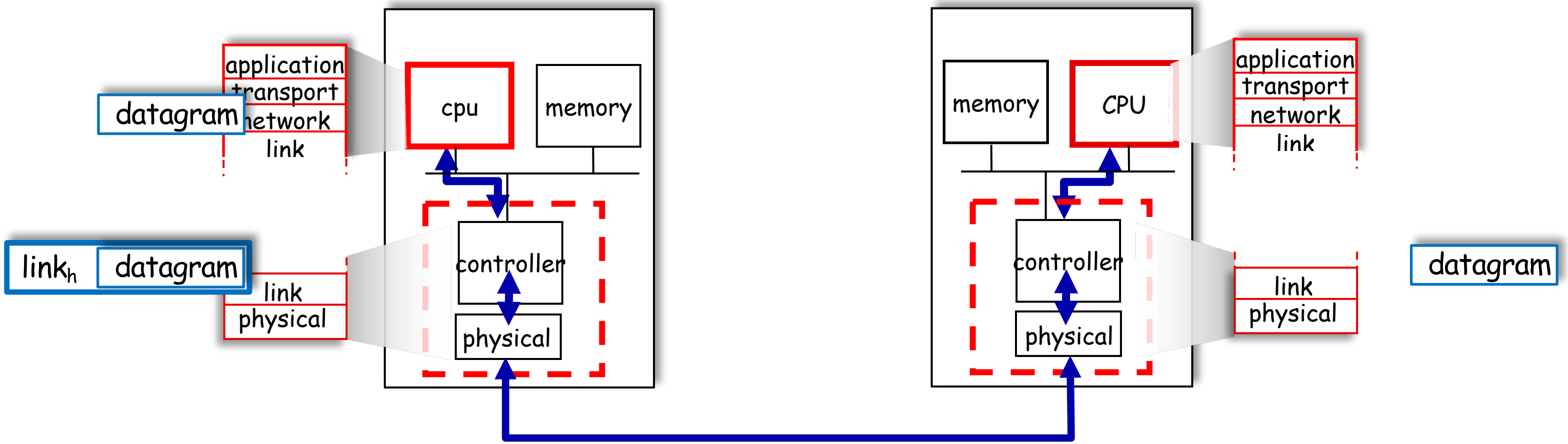


Host link-layer implementation

- in each-and-every host
- link layer implemented on-chip or in network interface card (NIC)
  - implements link, physical layer
- attaches into host's system buses
- combination of hardware, software, firmware



Interfaces communicating



sending side:

- encapsulates datagram in frame
- adds error checking bits, reliable data transfer, flow control, etc.

receiving side:

- looks for errors, reliable data transfer, flow control, etc.
- extracts datagram, passes to upper layer at receiving side

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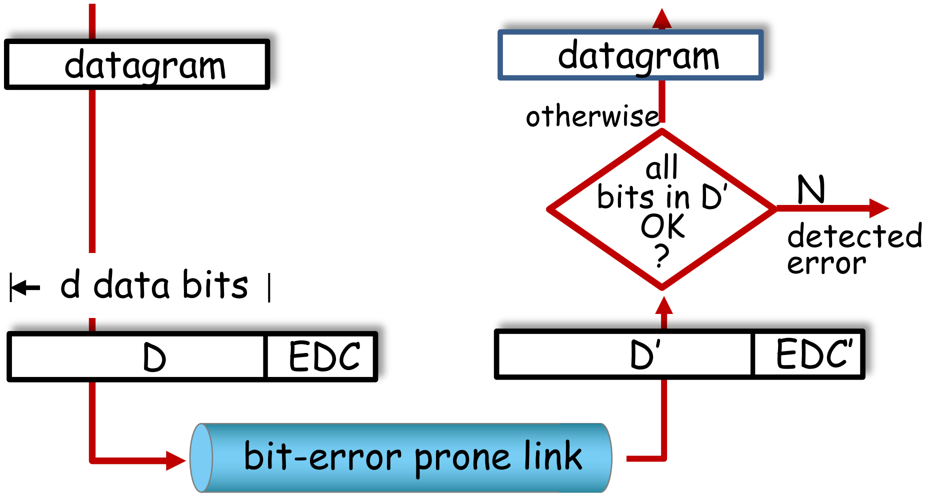
Error detection

EDC: error detection and correction bits (e.g., redundancy)
D: data protected by error checking, may include header fields



Error detection not 100% reliable!

- protocol may miss some errors, but rarely
- larger EDC field yields better detection and correction

Parity checking

single bit parity:

- detect single bit errors

0111000110101011	1

$\leftarrow$ d data bits $\rightarrow$

parity bit

Even/odd parity: set parity bit so there is an even/odd number of 1's

At receiver:

- compute parity of *d* received bits
- compare with received parity bit – if different than error detected

Can detect and correct errors (without retransmission!)

- two-dimensional parity: detect and correct single bit errors

row parity

column parity

$$
\begin{array}{cccc|c}
d_{1,1} & \cdots & d_{1,j} & & d_{1,j+1} \\
d_{2,1} & \cdots & d_{2,j} & & d_{2,j+1} \\
\cdots & \cdots & \cdots & & \cdots \\
d_{i,1} & \cdots & d_{i,j} & & d_{i,j+1} \\
\hline
d_{i+1,1} & \cdots & d_{i+1,j} & & d_{i+1,j+1}
\end{array}
$$

no errors:

$$
\begin{array}{ccccc|c}
1 & 0 & 1 & 0 & 1 & 1 \\
1 & 1 & 1 & 1 & 0 & 0 \\
0 & 1 & 1 & 1 & 0 & 1 \\
\hline
1 & 0 & 1 & 0 & 1 & 0
\end{array}
$$

detected and correctable single-bit error:

$$
\begin{array}{ccccc|c}
1 & 0 & 1 & 0 & 1 & 1 \\
1 & 0 & 1 & 1 & 0 & 0 \\
0 & 1 & 1 & 1 & 0 & 1 \\
\hline
1 & 0 & 1 & 0 & 1 & 0
\end{array}
$$

parity error

parity error

Internet checksum (review, see section 3.3)

Goal: detect errors (i.e., flipped bits) in transmitted segment

sender:

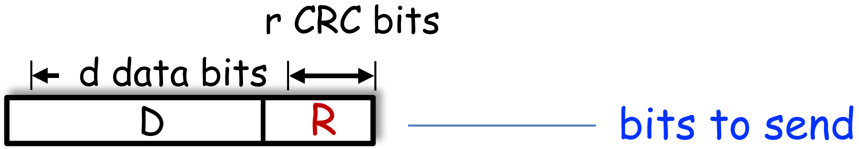
- treat contents of UDP segment (including UDP header fields and IP addresses) as sequence of 16-bit integers
- checksum: addition (one's complement sum) of segment content
- checksum value put into UDP checksum field

receiver:

- compute checksum of received segment
- check if computed checksum equals checksum field value:
  - not equal - error detected
  - equal - no error detected. But maybe errors nonetheless? More later ….

Cyclic Redundancy Check (CRC)

- more powerful error-detection coding
- D: data bits (given, think of these as a binary number)
- G: bit pattern (generator), of $r+1$ bits (given, specified in CRC standard)



$\langle D,R \rangle = D * 2^r$ XOR R — formula for these bits

sender: compute r CRC bits, R, such that <D,R> exactly divisible by G (mod 2)

- receiver knows G, divides <D,R> by G. If non-zero remainder: error detected!
- can detect all burst errors less than r+1 bits
- widely used in practice (Ethernet, 802.11 WiFi)

Cyclic Redundancy Check (CRC): example

Sender wants to compute R

such that:

$D \cdot 2^r \text{ XOR } R = nG$

... or equivalently (XOR R both sides):

$D \cdot 2^r = nG \text{ XOR } R$

... which says:

if we divide $D \cdot 2^r$ by G, we want remainder R to satisfy:

$R = \text{remainder}\left[\frac{D \cdot 2^r}{G}\right]$

algorithm for computing R

```
               1 0 1 0 1 1
 1 0 0 1 ) 1 0 1 1 1 0 0 0 0
           1 0 0 1
             1 0 1
             0 0 0
             1 0 1 0
             1 0 0 1
                 1 1 0
                 0 0 0
                 1 1 0 0
                 1 0 0 1
                   1 0 1 0
                   1 0 0 1
                     0 1 1
```

$\underbrace{1\,0\,0\,1}_{G}$, $\underbrace{1\,0\,1\,1\,1\,0\,0\,0\,0}_{D * 2^r}$ (here, r=3), $\underbrace{0\,1\,1}_{R}$

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Multiple access links, protocols

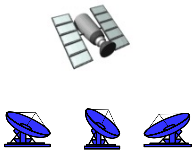
two types of "links":

- point-to-point
  - point-to-point link between Ethernet switch, host
  - PPP for dial-up access
- broadcast (shared wire or medium)
  - old-school Ethernet
  - upstream HFC in cable-based access network
  - 802.11 wireless LAN, 4G/4G. satellite

shared wire (e.g., cabled Ethernet)

shared radio: 4G/5G

shared radio: WiFi



shared radio: satellite

humans at a cocktail party (shared air, acoustical)

Multiple access protocols

- single shared broadcast channel
- two or more simultaneous transmissions by nodes: interference
  - collision if node receives two or more signals at the same time

multiple access protocol

- distributed algorithm that determines how nodes share channel, i.e., determine when node can transmit
- communication about channel sharing must use channel itself!
  - no out-of-band channel for coordination

An ideal multiple access protocol

given: multiple access channel (MAC) of rate R bps

desiderata:

1. when one node wants to transmit, it can send at rate R.
2. when M nodes want to transmit, each can send at average rate R/M
3. fully decentralized:
   - no special node to coordinate transmissions
   - no synchronization of clocks, slots
4. simple

MAC protocols: taxonomy

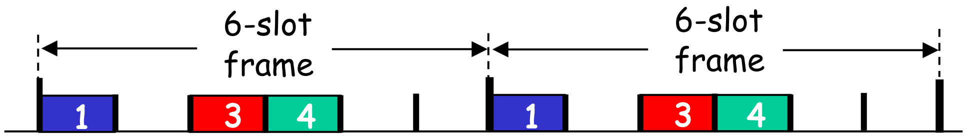
three broad classes:

- channel partitioning
  - divide channel into smaller "pieces" (time slots, frequency, code)
  - allocate piece to node for exclusive use
- random access
  - channel not divided, allow collisions
  - "recover" from collisions
- "taking turns"
  - nodes take turns, but nodes with more to send can take longer turns

Channel partitioning MAC protocols: TDMA

TDMA: time division multiple access

- access to channel in "rounds"
- each station gets fixed length slot (length = packet transmission time) in each round
- unused slots go idle
- example: 6-station LAN, 1,3,4 have packets to send, slots 2,5,6 idle



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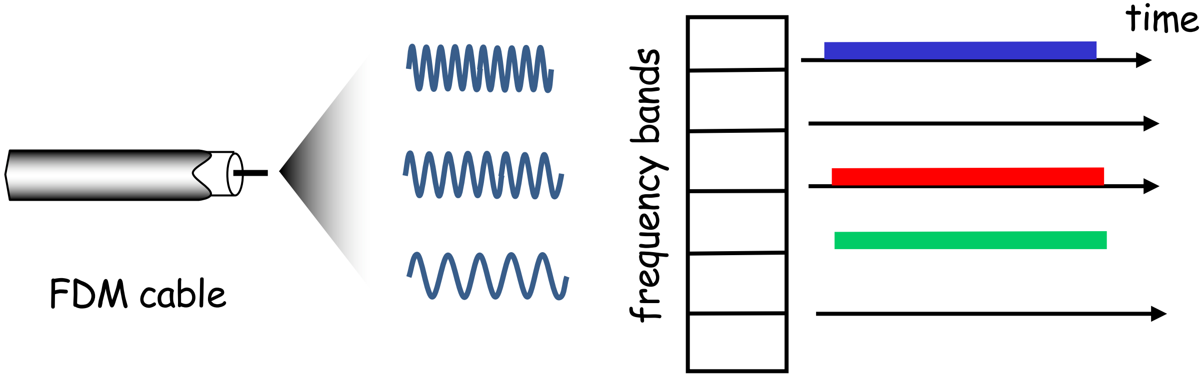
Channel partitioning MAC protocols: FDMA

FDMA: frequency division multiple access

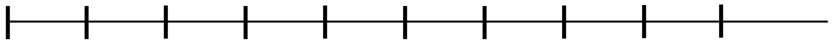
- channel spectrum divided into frequency bands
- each station assigned fixed frequency band
- unused transmission time in frequency bands go idle
- example: 6-station LAN, 1,3,4 have packet to send, frequency bands 2,5,6 idle



Random access protocols

- when node has packet to send
  - transmit at full channel data rate R
  - no a priori coordination among nodes
- two or more transmitting nodes: "collision"
- random access protocol specifies:
  - how to detect collisions
  - how to recover from collisions (e.g., via delayed retransmissions)
- examples of random access MAC protocols:
  - ALOHA, slotted ALOHA
  - CSMA, CSMA/CD, CSMA/CA

Slotted ALOHA



t_0 t_0+1

assumptions:

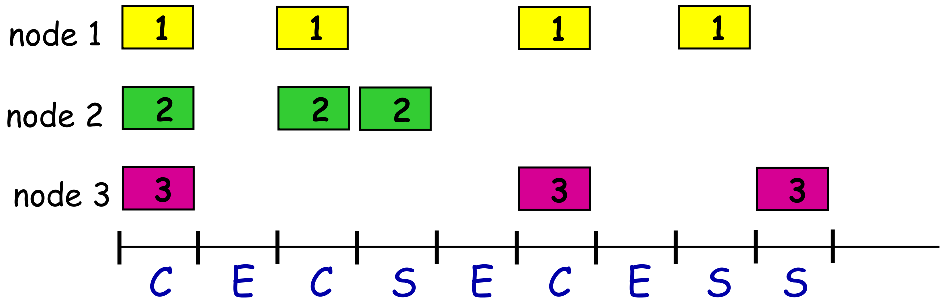
- all frames same size
- time divided into equal size slots (time to transmit 1 frame)
- nodes start to transmit only slot beginning
- nodes are synchronized
- if 2 or more nodes transmit in slot, all nodes detect collision

operation:

- when node obtains fresh frame, transmits in next slot
  - if no collision: node can send new frame in next slot
  - if collision: node retransmits frame in each subsequent slot with probability p until success

randomization – why?

Slotted ALOHA



C: collision
S: success
E: empty

Pros:

- single active node can continuously transmit at full rate of channel
- highly decentralized: only slots in nodes need to be in sync
- simple

Cons:

- collisions, wasting slots
- idle slots
- nodes may be able to detect collision in less than time to transmit packet
- clock synchronization

Slotted ALOHA: efficiency

efficiency: long-run fraction of successful slots (many nodes, all with many frames to send)

- suppose: N nodes with many frames to send, each transmits in slot with probability p
  - prob that given node has success in a slot = $p(1-p)^{N-1}$
  - prob that any node has a success = $Np(1-p)^{N-1}$
  - max efficiency: find p* that maximizes $Np(1-p)^{N-1}$
  - for many nodes, take limit of $Np^*(1-p^*)^{N-1}$ as N goes to infinity, gives:

  max efficiency = 1/e = .37

- at best: channel used for useful transmissions 37% of time!

CSMA (carrier sense multiple access)

simple CSMA: listen before transmit:

- if channel sensed idle: transmit entire frame
- if channel sensed busy: defer transmission

- human analogy: don't interrupt others!

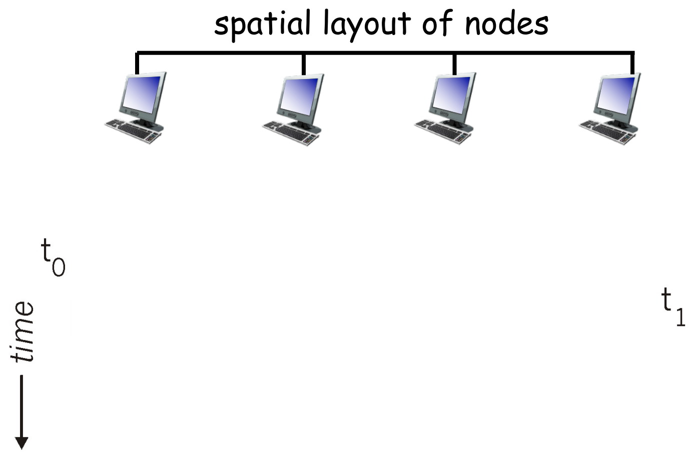
CSMA/CD: CSMA with collision detection

- collisions detected within short time
- colliding transmissions aborted, reducing channel wastage
- collision detection easy in wired, difficult with wireless

- human analogy: the polite conversationalist

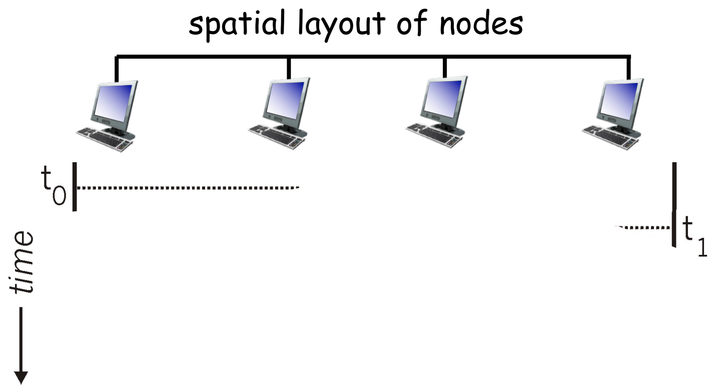
CSMA: collisions

- collisions can still occur with carrier sensing:
  - propagation delay means two nodes may not hear each other's just-started transmission
- collision: entire packet transmission time wasted
  - distance & propagation delay play role in in determining collision probability



CSMA/CD:

- CSMA/CD reduces the amount of time wasted in collisions
  - transmission aborted on collision detection



Ethernet CSMA/CD algorithm

1. Ethernet receives datagram from network layer, creates frame
2. If Ethernet senses channel:
   - if idle: start frame transmission.
   - if busy: wait until channel idle, then transmit
3. If entire frame transmitted without collision - done!
4. If another transmission detected while sending: abort, send jam signal
5. After aborting, enter binary (exponential) backoff:
   - after mth collision, chooses K at random from $\{0,1,2, \ldots, 2^m-1\}$. Ethernet waits K·512 bit times, returns to Step 2
   - more collisions: longer backoff interval

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"Taking turns" MAC protocols

channel partitioning MAC protocols:
- share channel efficiently and fairly at high load
- inefficient at low load: delay in channel access, 1/N bandwidth allocated even if only 1 active node!

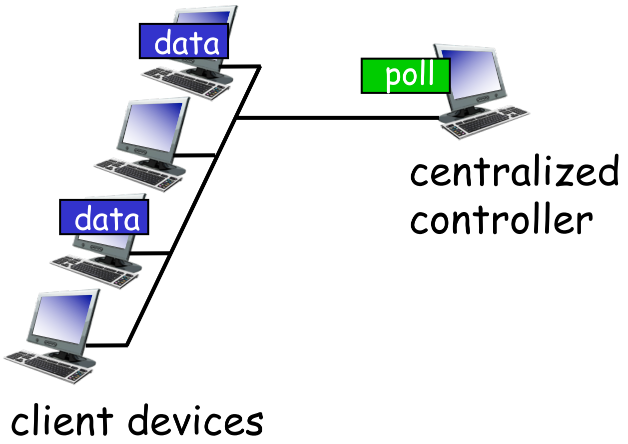
random access MAC protocols
- efficient at low load: single node can fully utilize channel
- high load: collision overhead

"taking turns" protocols
- look for best of both worlds!

“Taking turns” MAC protocols

polling:

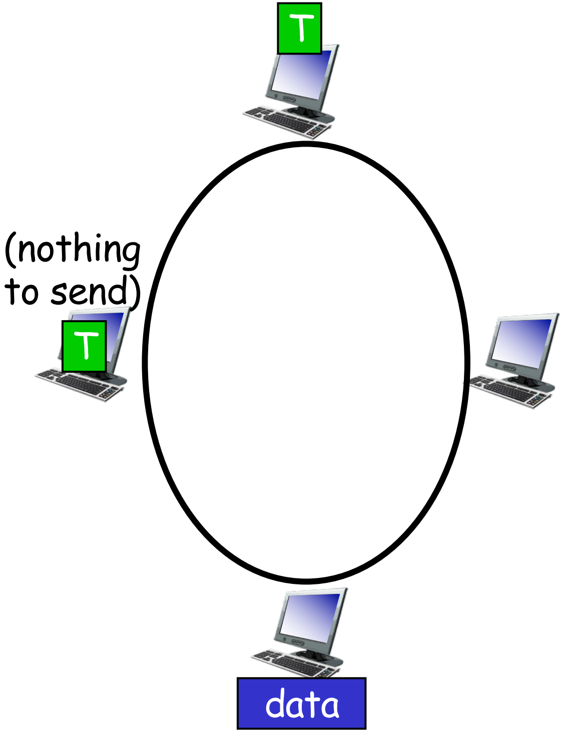
- centralized controller “invites” other nodes to transmit in turn
- typically used with “dumb” devices
- concerns:
  - polling overhead
  - latency
  - single point of failure (master)
- Bluetooth uses polling



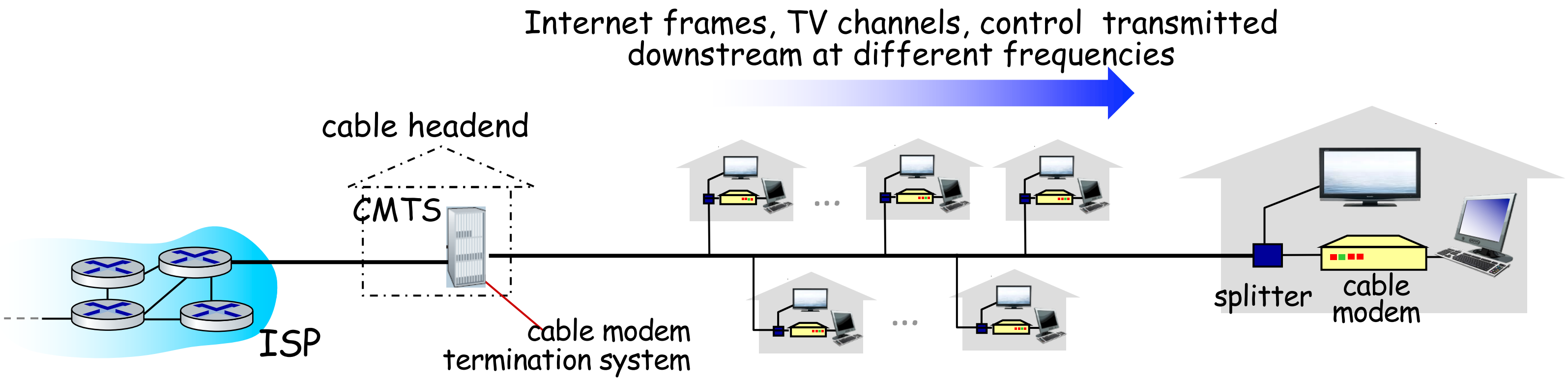
"Taking turns" MAC protocols

token passing:

- control token message explicitly passed from one node to next, sequentially
  - transmit while holding token
- concerns:
  - token overhead
  - latency
  - single point of failure (token)

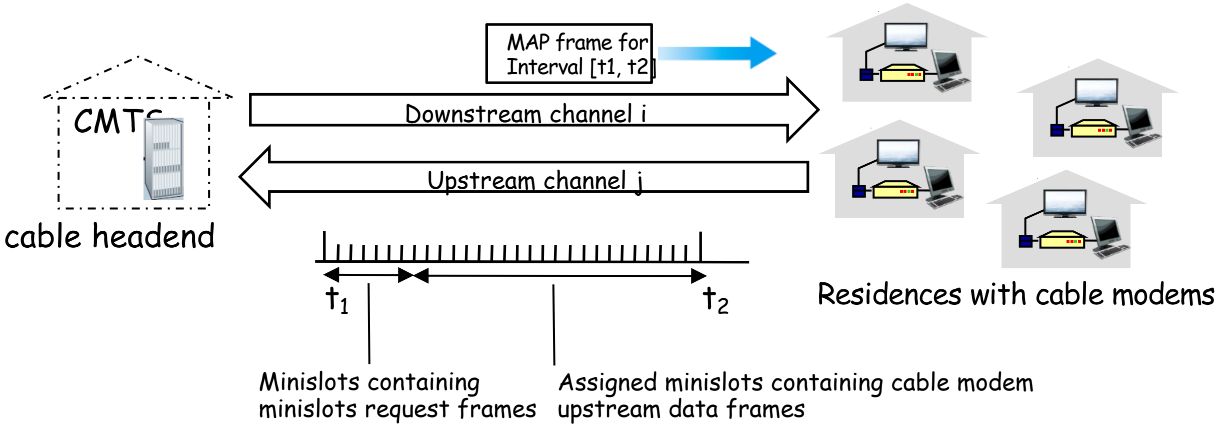


Cable access network: FDM, TDM and random access!



- multiple downstream (broadcast) FDM channels: up to 1.6 Gbps/channel
  - single CMTS transmits into channels
- multiple upstream channels (up to 1 Gbps/channel)
  - multiple access: all users contend (random access) for certain upstream channel time slots; others assigned TDM

Cable access network



DOCSIS: data over cable service interface specification

- FDM over upstream, downstream frequency channels
- TDM upstream: some slots assigned, some have contention
  - downstream MAP frame: assigns upstream slots
  - request for upstream slots (and data) transmitted random access (binary backoff) in selected slots

Summary of MAC protocols

- channel partitioning, by time, frequency or code
  - Time Division, Frequency Division
- random access (dynamic),
  - ALOHA, S-ALOHA, CSMA, CSMA/CD
  - carrier sensing: easy in some technologies (wire), hard in others (wireless)
  - CSMA/CD used in Ethernet
  - CSMA/CA used in 802.11
- taking turns
  - polling from central site, token passing
  - Bluetooth, FDDI, token ring

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MAC addresses

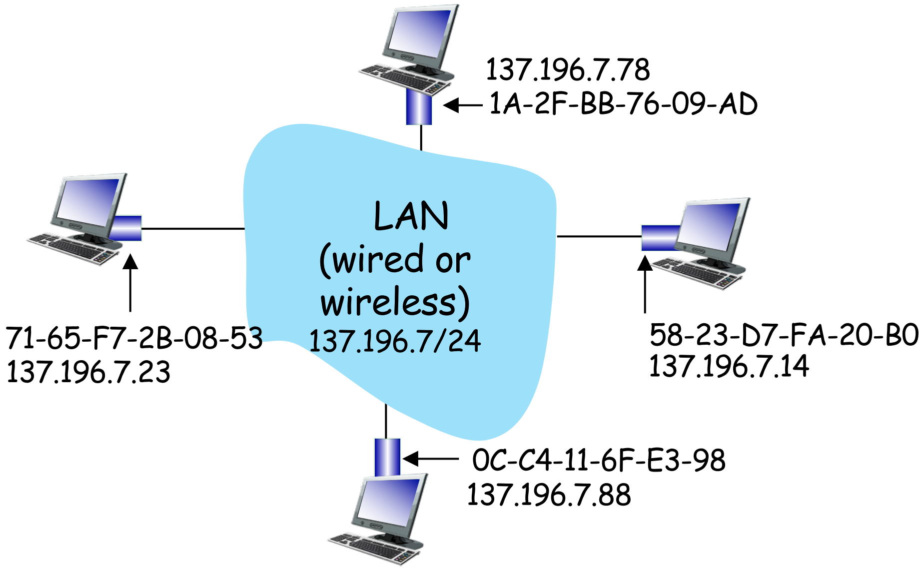
- 32-bit IP address:
  - network-layer address for interface
  - used for layer 3 (network layer) forwarding
  - e.g.: 128.119.40.136

- MAC (or LAN or physical or Ethernet) address:
  - function: used "locally" to get frame from one interface to another physically-connected interface (same subnet, in IP-addressing sense)
  - 48-bit MAC address (for most LANs) burned in NIC ROM, also sometimes software settable
  - e.g.: 1A-2F-BB-76-09-AD

hexadecimal (base 16) notation
(each "numeral" represents 4 bits)

MAC addresses

each interface on LAN
- has unique 48-bit MAC address
- has a locally unique 32-bit IP address (as we've seen)

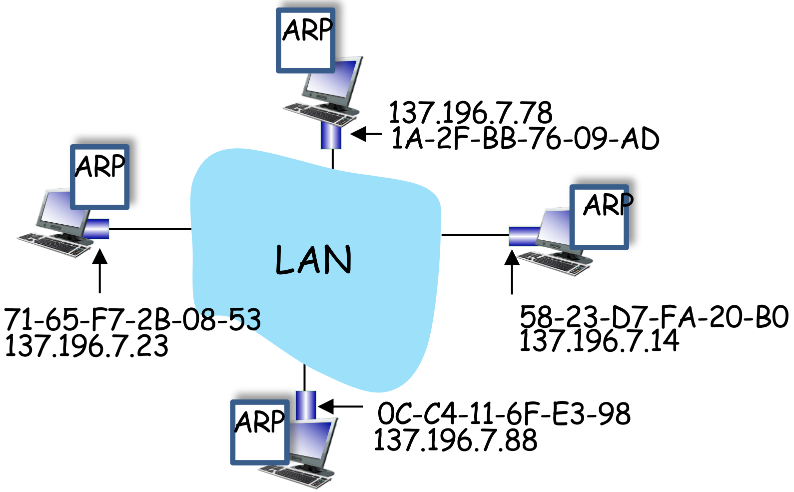


MAC addresses

- MAC address allocation administered by IEEE
- manufacturer buys portion of MAC address space (to assure uniqueness)
- analogy:
  - MAC address: like Social Security Number
  - IP address: like postal address
- MAC flat address: portability
  - can move interface from one LAN to another
  - recall IP address *not* portable: depends on IP subnet to which node is attached

ARP: address resolution protocol

Question: how to determine interface's MAC address, knowing its IP address?



ARP table: each IP node (host, router) on LAN has table

- IP/MAC address mappings for some LAN nodes:

  < IP address; MAC address; TTL>

- TTL (Time To Live): time after which address mapping will be forgotten (typically 20 min)

ARP protocol in action

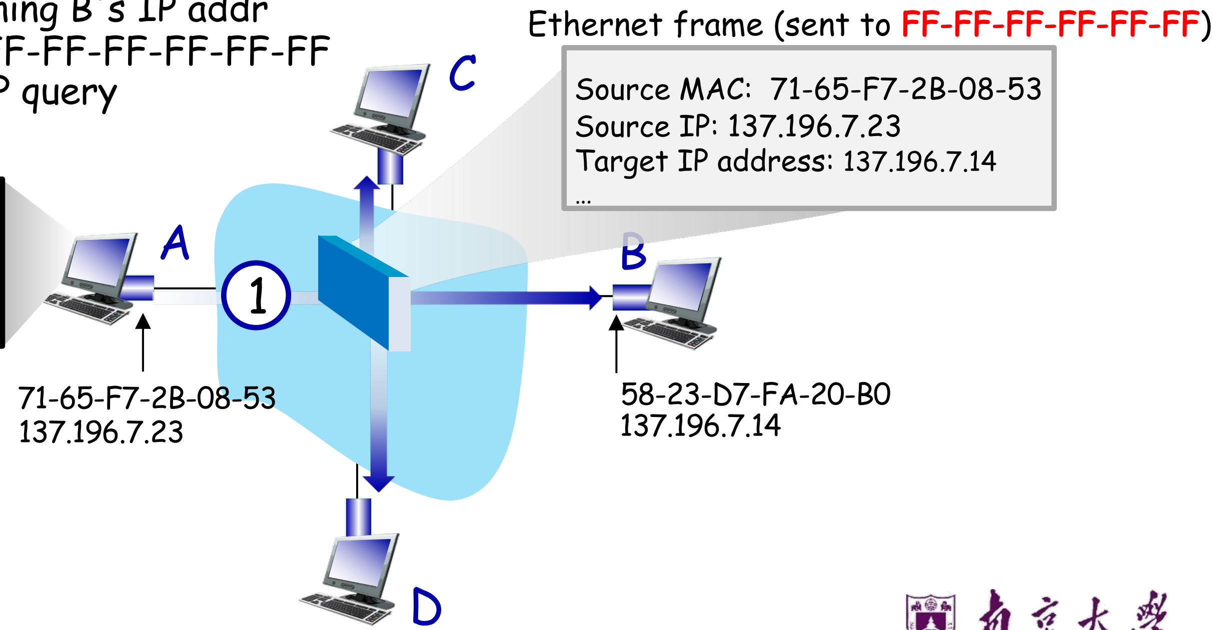
example: A wants to send datagram to B

- B's MAC address not in A's ARP table, so A uses ARP to find B's MAC address

1 A broadcasts ARP query, containing B's IP addr
- destination MAC address = FF-FF-FF-FF-FF-FF
- all nodes on LAN receive ARP query

ARP table in A

IP addr	MAC addr	TTL



ARP protocol in action

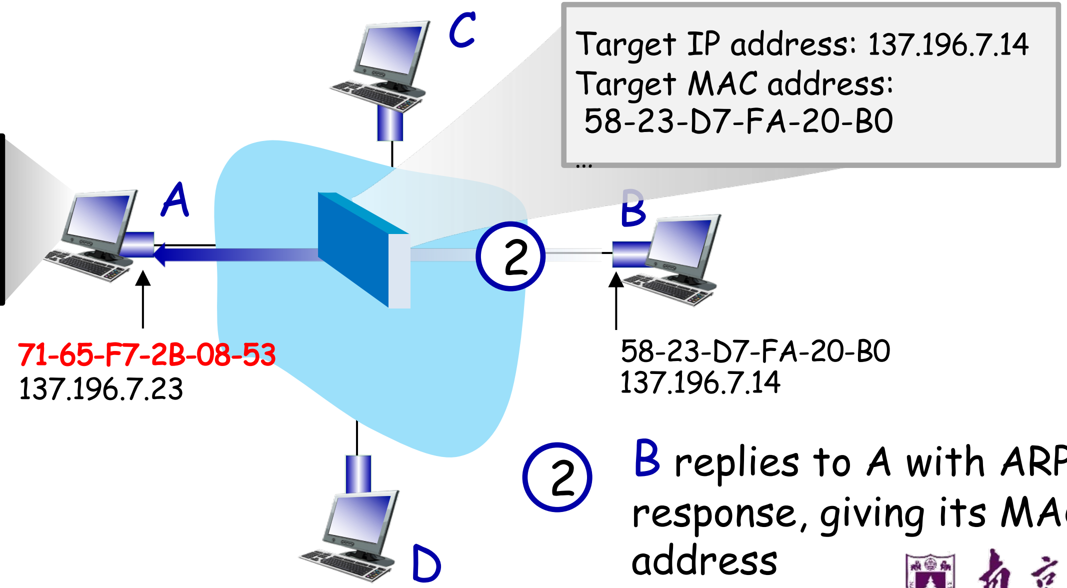
example: A wants to send datagram to B

- B's MAC address not in A's ARP table, so A uses ARP to find B's MAC address

ARP message into Ethernet frame
(sent to 71-65-F7-2B-08-53)

ARP table in A

IP addr	MAC addr	TTL



2 B replies to A with ARP response, giving its MAC address

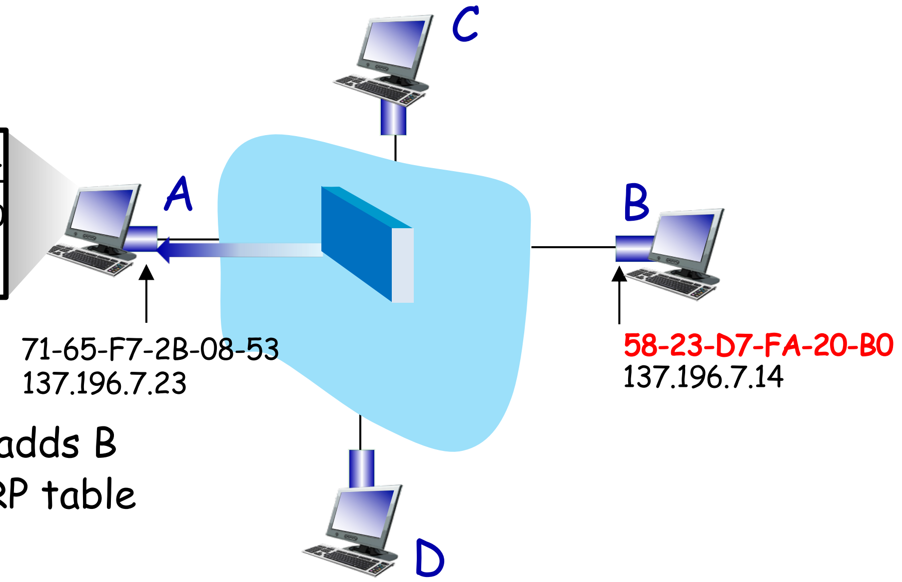
ARP protocol in action

example: A wants to send datagram to B

- B's MAC address not in A's ARP table, so A uses ARP to find B's MAC address

ARP table in A

IP addr	MAC addr	TTL
137.196.7.14	58-23-D7-FA-20-B0	500

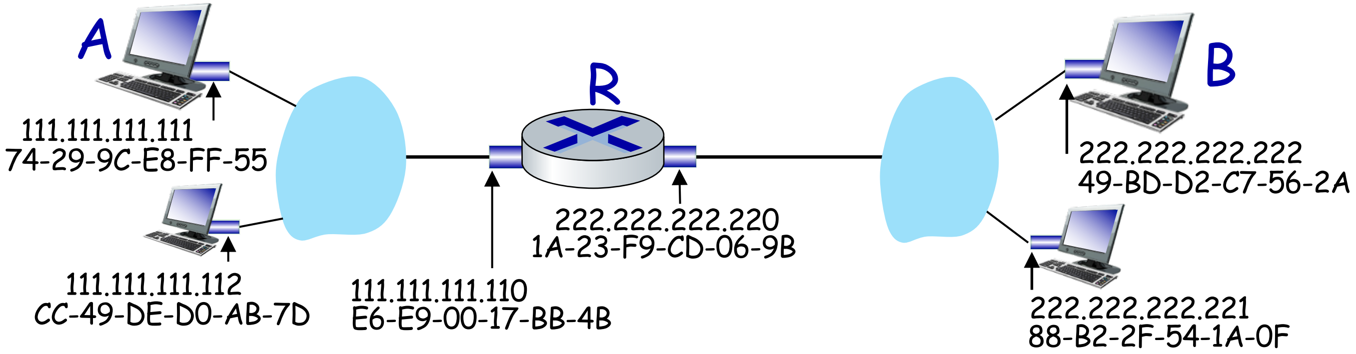


3 A receives B's reply, adds B entry into its local ARP table

Routing to another subnet: addressing

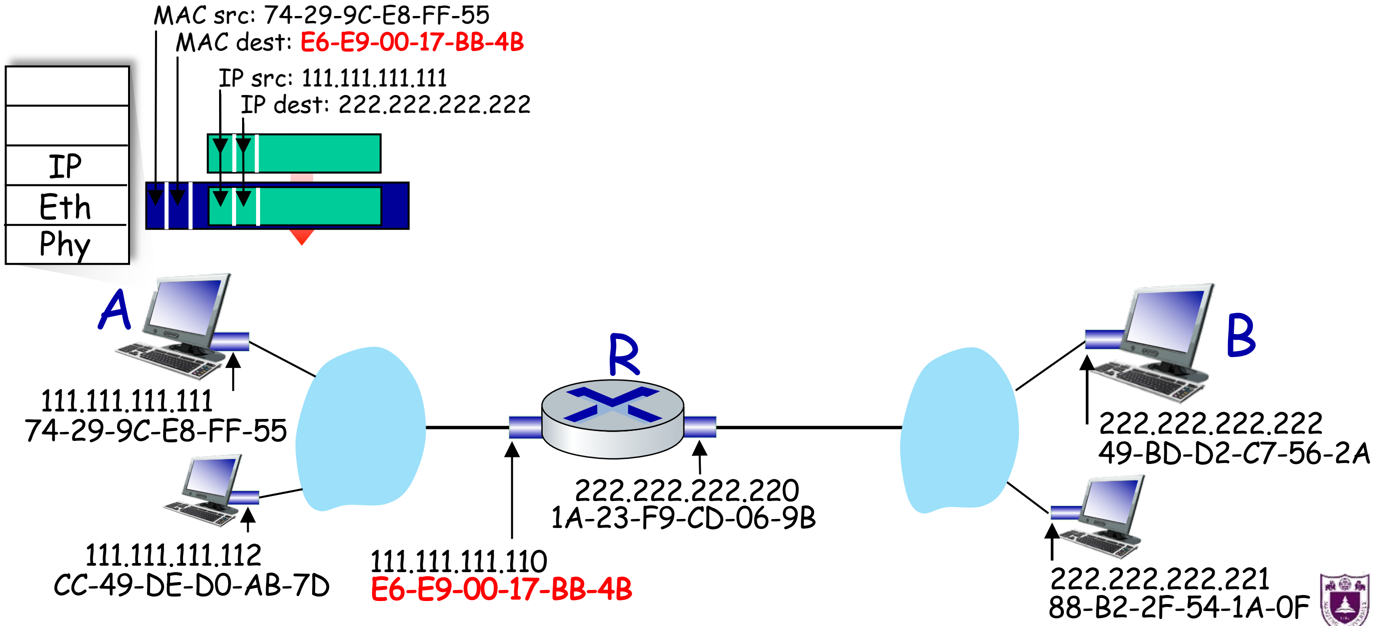
walkthrough: sending a datagram from A to B via R

- focus on addressing – at IP (datagram) and MAC layer (frame) levels
- assume that:
  - A knows B's IP address
  - A knows IP address of first hop router, R (how?)
  - A knows R's MAC address (how?)



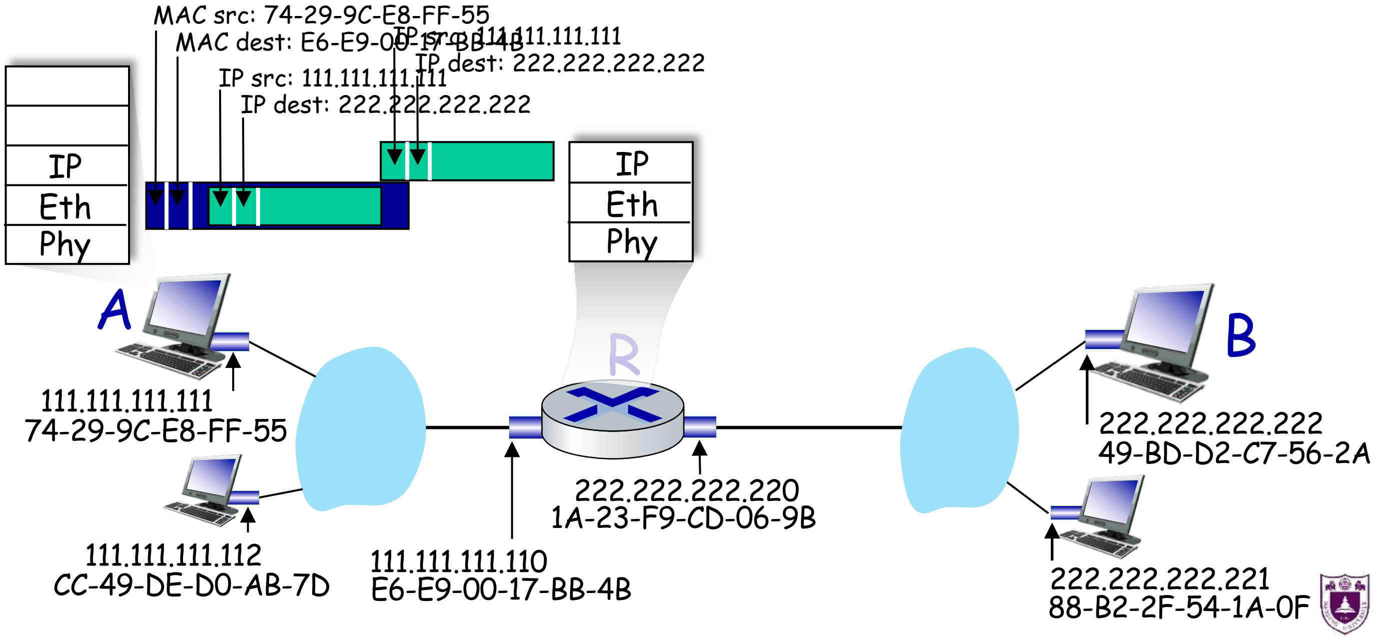
Routing to another subnet: addressing

- A creates IP datagram with IP source A, destination B
- A creates link-layer frame containing A-to-B IP datagram
  - R's MAC address is frame's destination



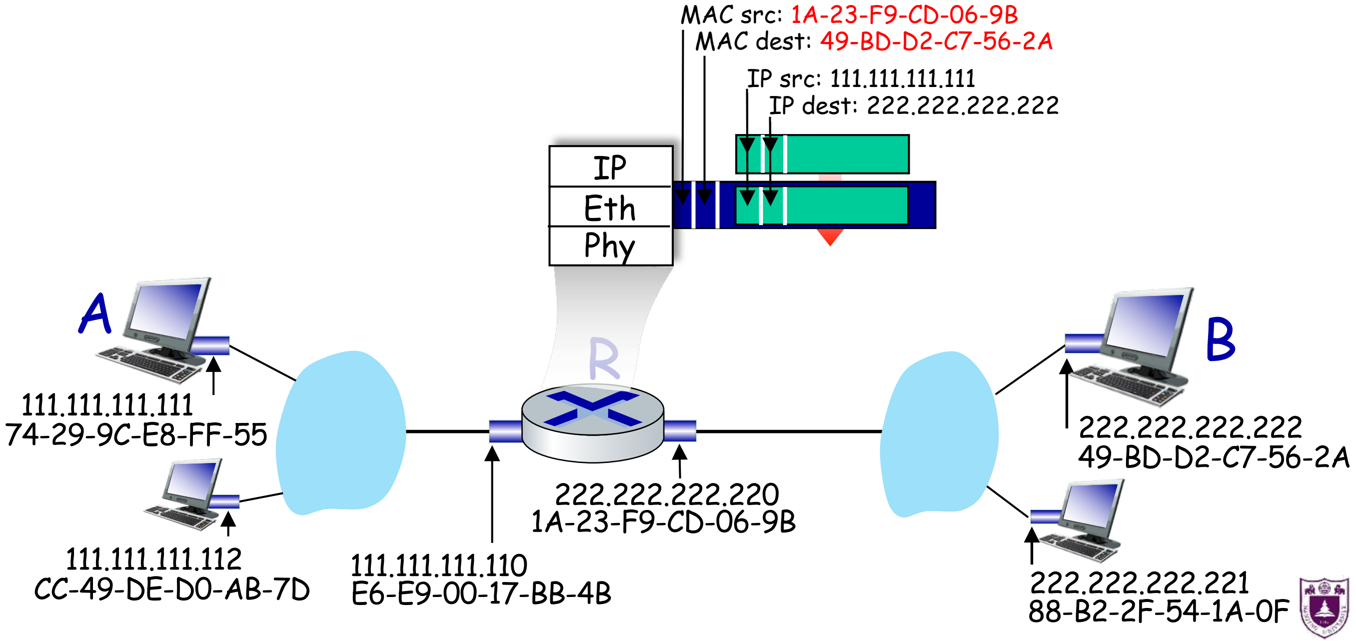
Routing to another subnet: addressing

- frame sent from A to R
- frame received at R, datagram removed, passed up to IP



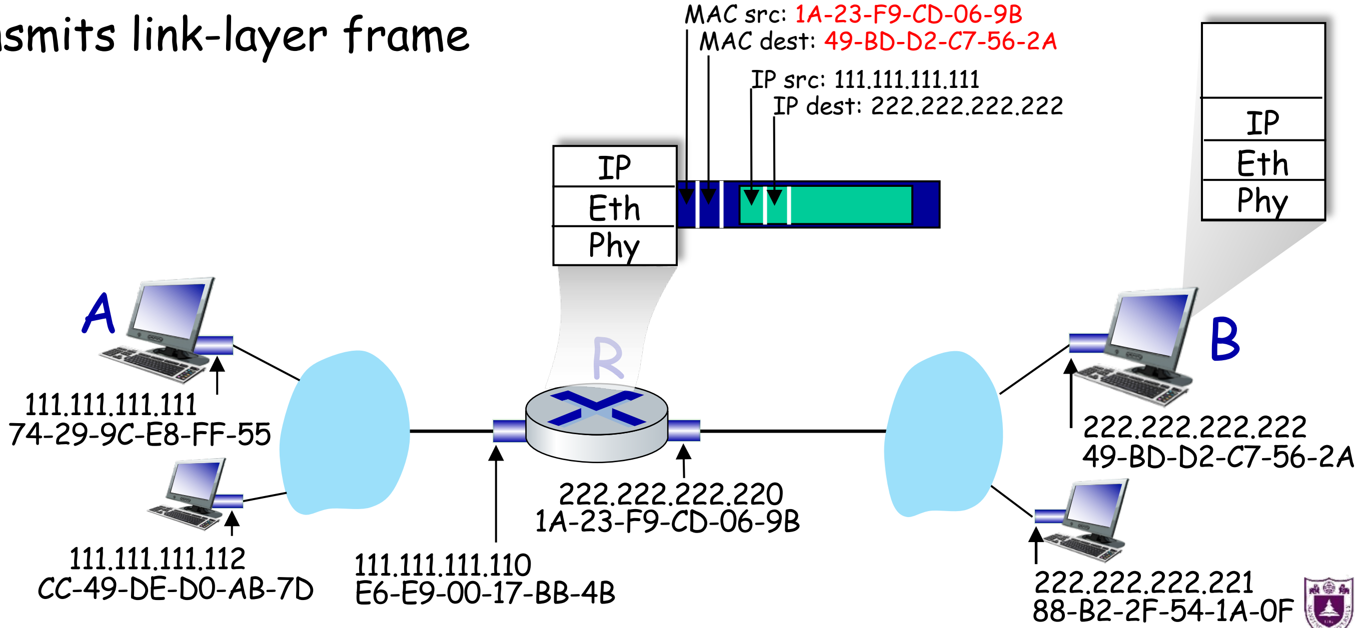
Routing to another subnet: addressing

- R determines outgoing interface, passes datagram with IP source A, destination B to link layer
- R creates link-layer frame containing A-to-B IP datagram. Frame destination address: B's MAC address



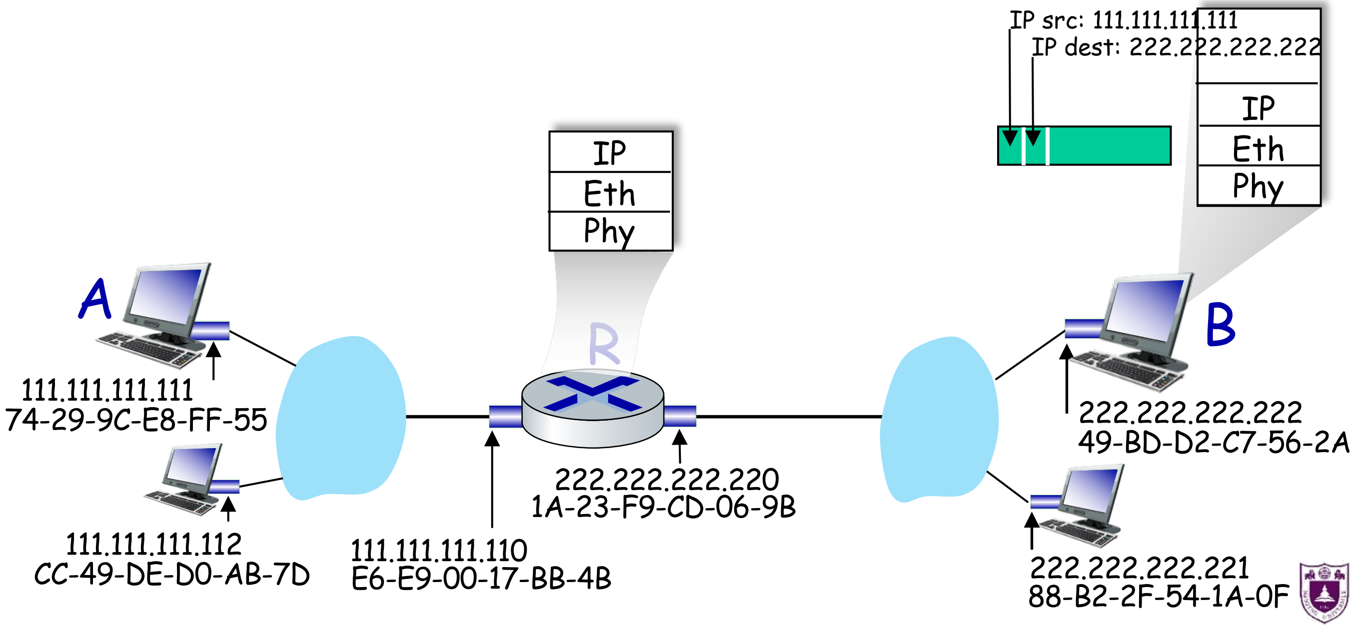
Routing to another subnet: addressing

- R determines outgoing interface, passes datagram with IP source A, destination B to link layer
- R creates link-layer frame containing A-to-B IP datagram. Frame destination address: B's MAC address
- transmits link-layer frame



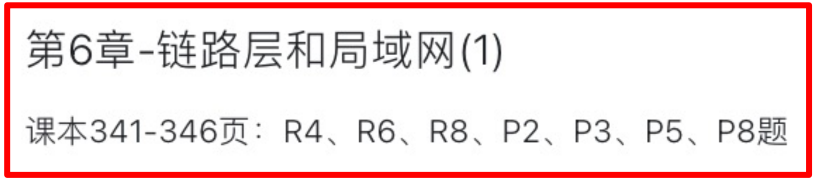
Routing to another subnet: addressing

- B receives frame, extracts IP datagram destination B
- B passes datagram up protocol stack to IP



课程习题（作业）——截止日期：5月13日晚23:59

- **课本341-346页**：R4、R6、R8、P2、P3、P5、P8题
- 提交方式：https://selearning.nju.edu.cn/（教学支持系统）



- 命名：学号+姓名+第*章。
- 若提交遇到问题请及时发邮件或在下一次上课时反馈。

课程习题（作业）——截止日期：5月13日晚23:59

R4. 假设两个节点同时经一个速率为 R 的广播信道开始传输一个长度为 L 的分组。用 d_{prop} 表示这两个节点之间的传播时延。如果 $d_{prop} < L/R$，会出现碰撞吗？为什么？

R6. 在 CSMA/CD 中，在第 5 次碰撞后，节点选择 $K=4$ 的概率有多大？结果 $K=4$ 在 10Mbps 以太网上对应于多少秒的时延？

R8. 如果局域网有很大的周长时，为什么令牌环协议将是低效的？

P2. 说明（举一个不同于图 6-5 的例子）二维奇偶校验能够纠正和检测单比特差错。说明（举一个例子）某些双比特差错能够被检测但不能纠正。

课程习题（作业）——截止日期：5月13日晚23:59

P3. 假设某分组的信息部分（图6-3中的D）包含10字节，它由字符串“Internet”的8比特无符号二进制ASCII表示组成。对该数据计算因特网检验和。

P5. 考虑5比特生成多项式，$G=10011$，并且假设D的值为1010101010。R的值是什么？

P8. 在6.3节中，我们提供了时隙ALOHA效率推导的概要。在本习题中，我们将完成这个推导。

a. 前面讲过，当有N个活跃节点时，时隙ALOHA的效率是$Np(1-p)^{N-1}$。求出使这个表达式最大化的p值。

b. 使用在（a）中求出的p值，令N接近于无穷，求出时隙ALOHA的效率。（提示：当N接近于无穷时，$(1-1/N)^N$接近于$1/e$。）

提问

Q & A

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