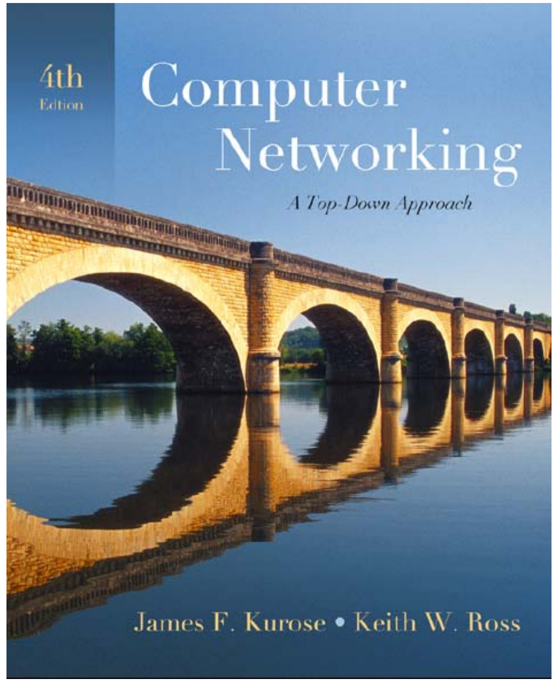
Chapter 5
Link Layer and LANs
連結層與區域網路



Computer Networking: A Top Down Approach
4th edition.
Jim Kurose, Keith Ross
Addison-Wesley, July 2007.

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Chapter 5: The Data Link Layer

Our goals:

- understand principles behind data link layer services: 了解連結層的服務
  - error detection, correction錯誤偵測與錯誤更正
  - sharing a broadcast channel: multiple access 多重存取
  - link layer addressing 連結層定址
  - reliable data transfer, flow control: *done!*
- instantiation and implementation of various link layer technologies

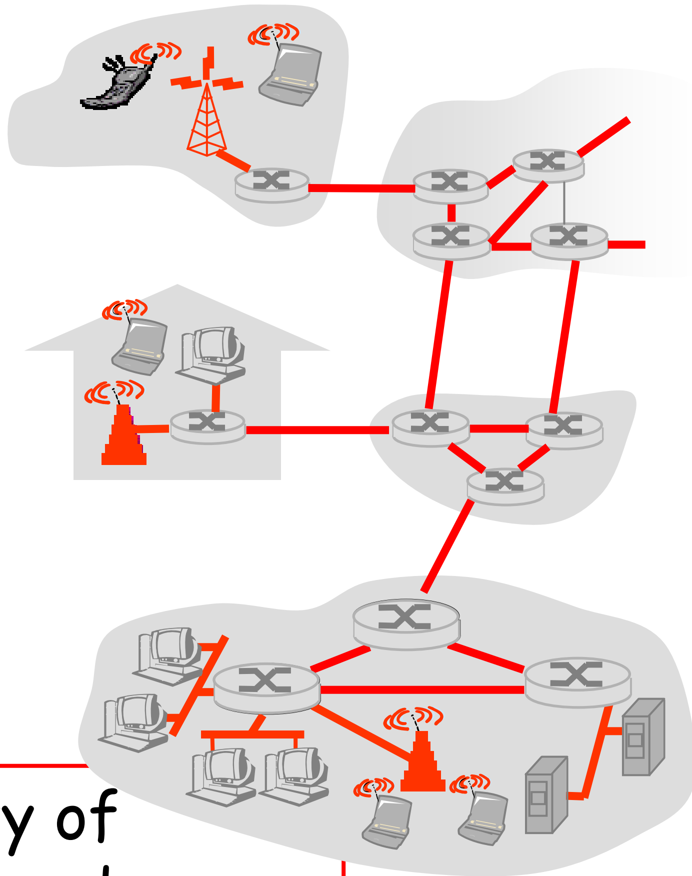
Link Layer

- 5.1 Introduction and services
  連結層服務
- 5.2 Error detection and correction
- 5.3Multiple access protocols
- 5.4 Link-layer Addressing
- 5.5 Ethernet
- 5.6 Link-layer switches
- 5.7 PPP
- 5.8 Link virtualization: ATM, MPLS

Link Layer: Introduction

Some terminology:

- hosts and routers are **nodes**
  節點
- communication channels that connect adjacent nodes along communication path are **links**
  鏈結
  - wired links
  - wireless links
  - LANs
- layer-2 packet is a **frame** **訊框**, encapsulates datagram



data-link layer has responsibility of transferring datagram from one node to adjacent node over a link 兩點之間的傳輸

Link layer: context

- datagram transferred by different link protocols over different links:
  不同連結型態用不同的連結層協定
  - e.g., Ethernet on first link, frame relay on intermediate links, 802.11 on last link
- each link protocol provides different services 提供不同的服務
  - e.g., may or may not provide rdt over link

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

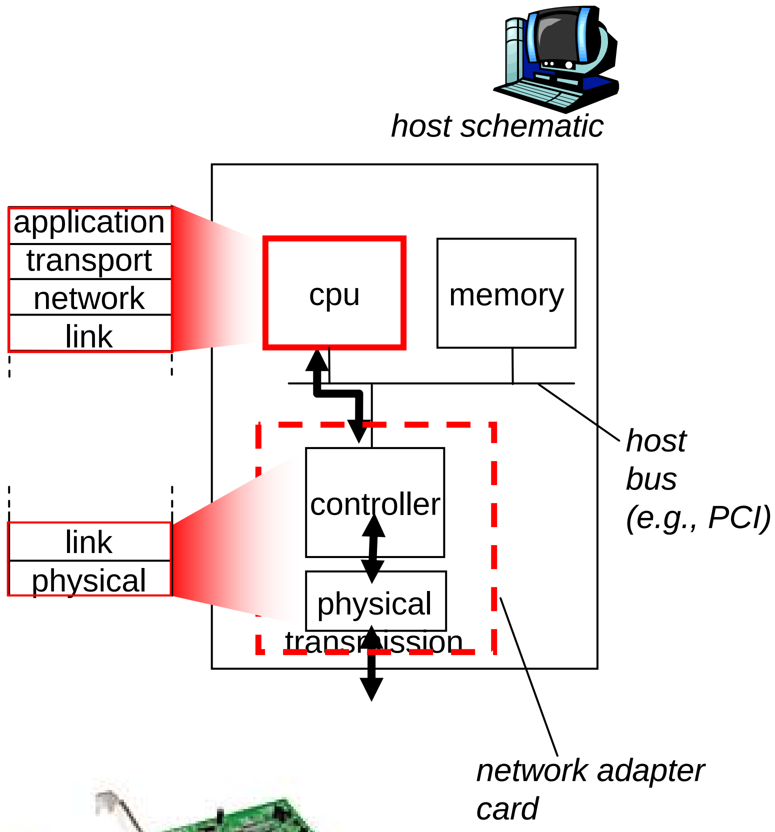
- *framing, link access:* 切割訊框、使用連結
  - encapsulate datagram into frame, adding header, trailer
  - channel access if shared medium
  - "MAC" addresses used in frame headers to identify source, dest 使用 MAC Address
    - different from IP address!
- *reliable delivery between adjacent nodes* 可靠性傳輸
  - we learned how to do this already (chapter 3)!
  - seldom used on low bit-error link (fiber, some twisted pair)
  - wireless links: high error rates
    - Q: why both link-level and end-end reliability?

Link Layer Services (more)

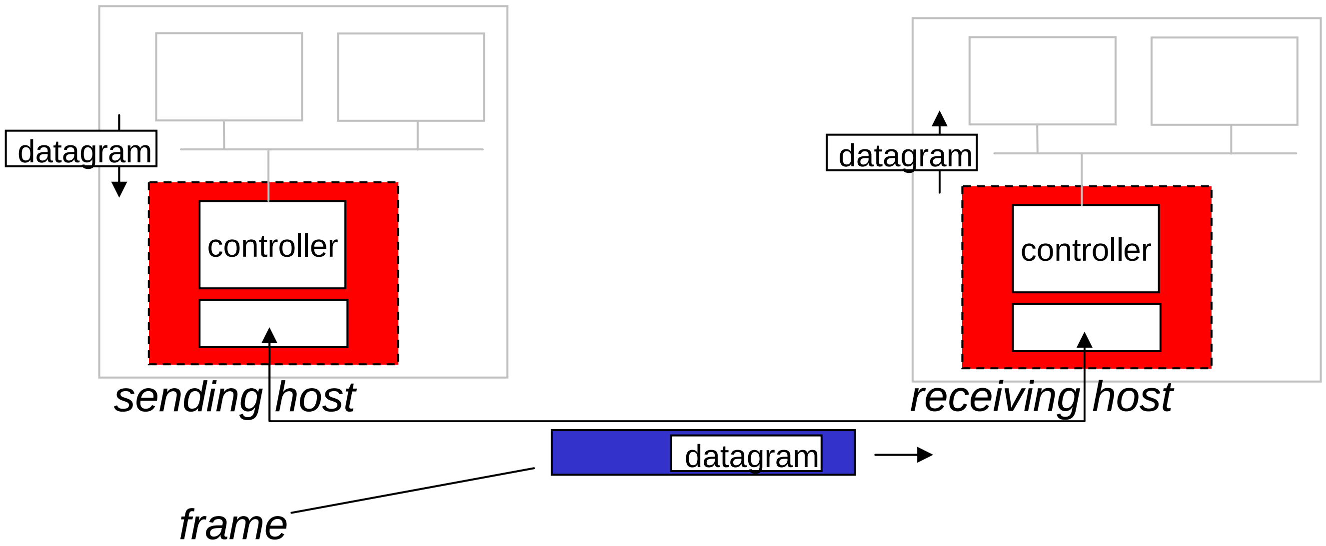
- *flow control:* 流量控制
  - pacing between adjacent sending and receiving nodes
- *error detection*: 錯誤偵測
  - errors caused by signal attenuation, noise.
  - receiver detects presence of errors:
    - signals sender for retransmission or drops frame
- error correction: 錯誤更正
  - receiver identifies *and corrects* bit error(s) without resorting to retransmission
- *half-duplex and full-duplex* 半雙工及全雙工
  - with half duplex, nodes at both ends of link can transmit, but not at same time

Where is the link layer implemented?

- in each and every host
- link layer implemented in "adaptor" (aka *network interface card* NIC網卡)
  - Ethernet card, PCMCI card, 802.11 card
  - implements link, physical layer
- attaches into host's system buses
- combination of hardware, software, firmware



Adaptors Communicating 網卡溝通



- sending side:
  - encapsulates datagram in frame
  - adds error checking bits, rdt, flow control, etc.
- receiving side
  - looks for errors, rdt, flow control, etc
  - extracts datagram, passes to upper layer at receiving side

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  錯誤偵測與更正
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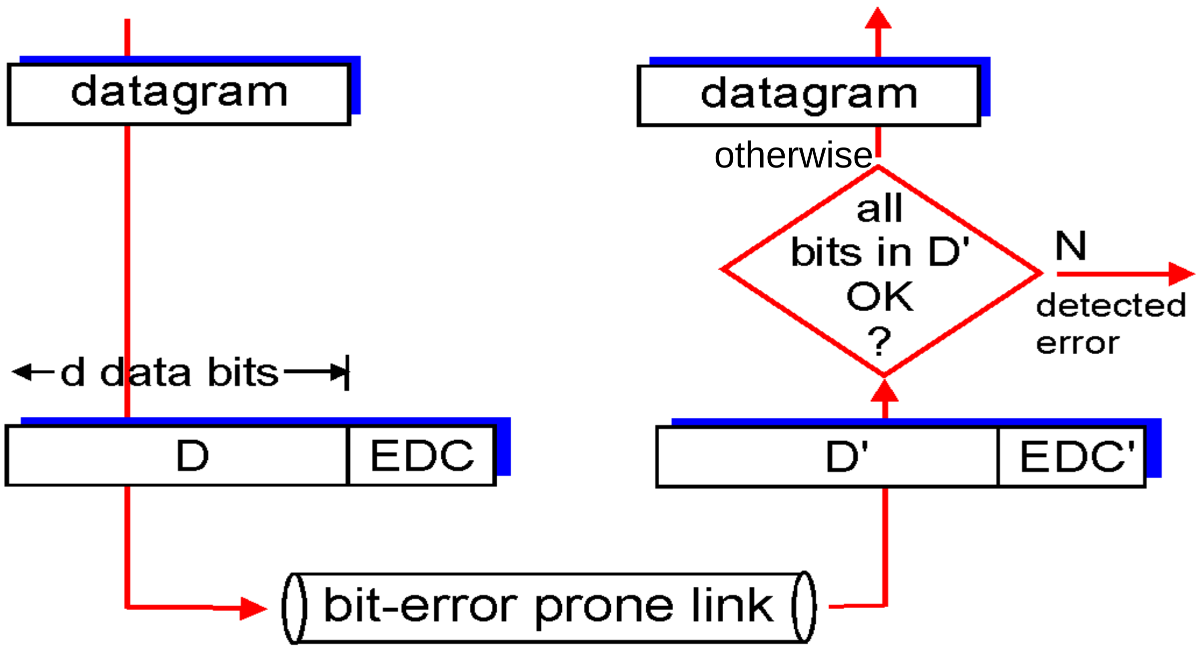
Error Detection 錯誤偵測

EDC= Error Detection and Correction bits (redundancy)
錯誤偵測及更正碼
D = Data protected by error checking, may include header fields

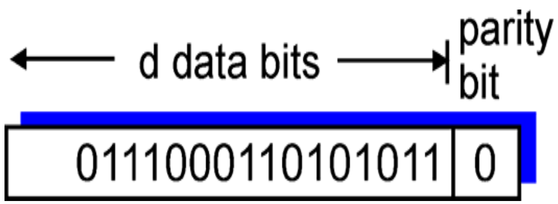
- Error detection not 100% reliable!
  - protocol may miss some errors, but rarely
  - larger EDC field yields better detection and correction



Parity Checking 同位檢查

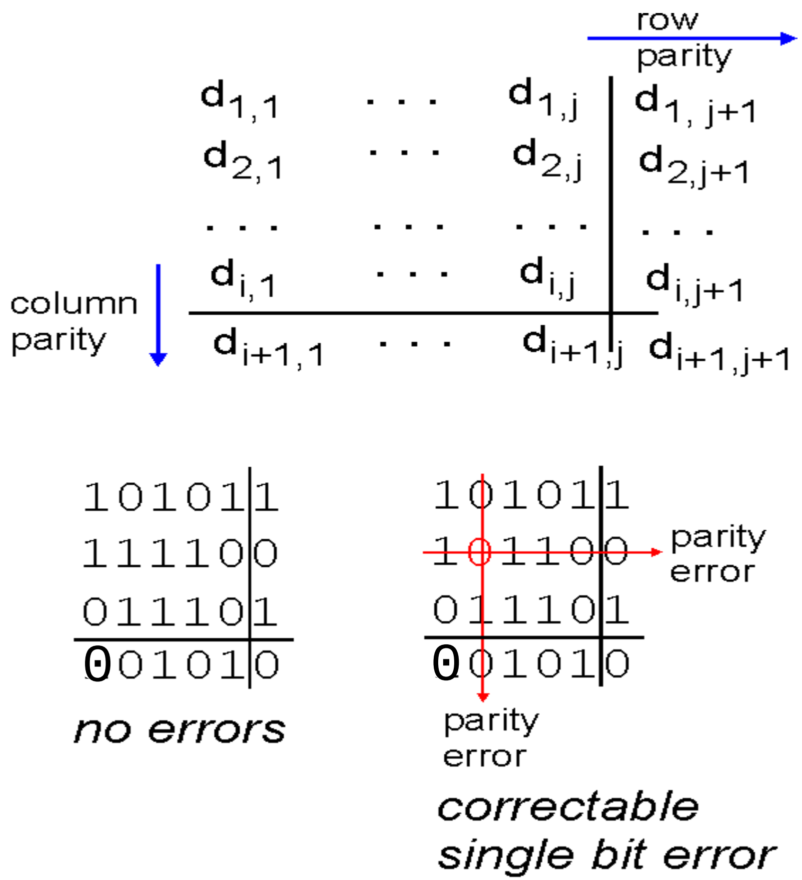
Single Bit Parity:

Detect single bit errors



Two Dimensional Bit Parity:

Detect *and correct* single bit errors



Internet checksum (review) 檢查和

Goal: detect "errors" (e.g., flipped bits) in transmitted packet (note: used at transport layer *only*)

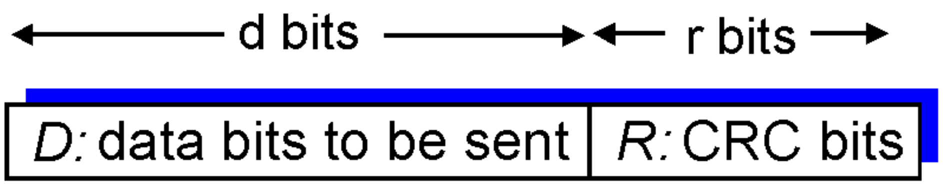
Sender:
- treat segment contents as sequence of 16-bit integers
- checksum: addition (1's complement sum) of segment contents
- sender puts checksum value into UDP checksum field (1's complement)

Receiver:
- compute checksum of received segment
- check if computed checksum equals checksum field value:
  - NO - error detected
  - YES - no error detected. *But maybe errors nonetheless?*

Checksumming: Cyclic Redundancy Check

循環冗餘檢查 CRC

- view data bits, D, as a binary number
- choose r+1 bit pattern (generator), G
- goal: choose r CRC bits, R, such that
  - <D,R> exactly divisible by G (modulo 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 (802.11 WiFi, ATM)



bit pattern

$D * 2^r$ XOR R

mathematical formula

CRC Example 例子

Want:

$D \cdot 2^r$ XOR R = nG

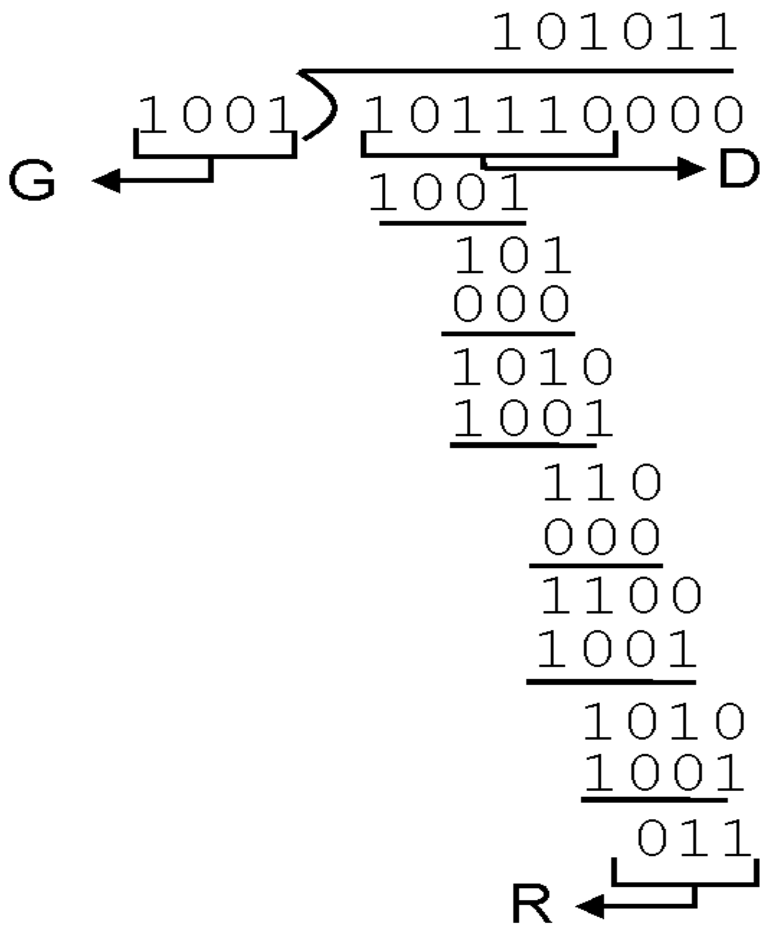
equivalently:

$D \cdot 2^r$ = nG XOR R

equivalently:

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

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



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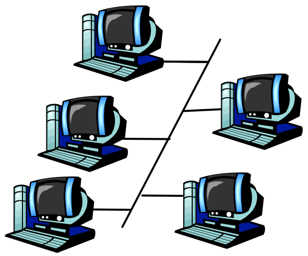
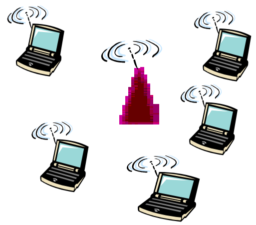
Multiple Access Links and Protocols

Two types of "links":

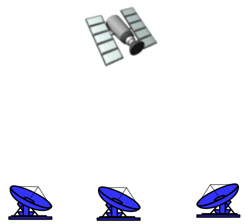
- point-to-point 點對點連結
  - PPP for dial-up access
  - point-to-point link between Ethernet switch and host
- broadcast (shared wire or medium) 廣播連結
  - old-fashioned Ethernet
  - upstream HFC
  - 802.11 wireless LAN



shared wire (e.g., cabled Ethernet)



shared RF (e.g., 802.11 WiFi)



shared RF (satellite)

humans at a cocktail party (shared air, acoustical)

Multiple Access protocols
多重存取協定

- 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

Ideal Multiple Access Protocol
理想化的多重存取協定

Broadcast channel of rate R bps

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 平均使用
3. fully decentralized: 完全分散式
   - no special node to coordinate transmissions
   - no synchronization of clocks, slots
4. simple

MAC Protocols: a taxonomy 分類

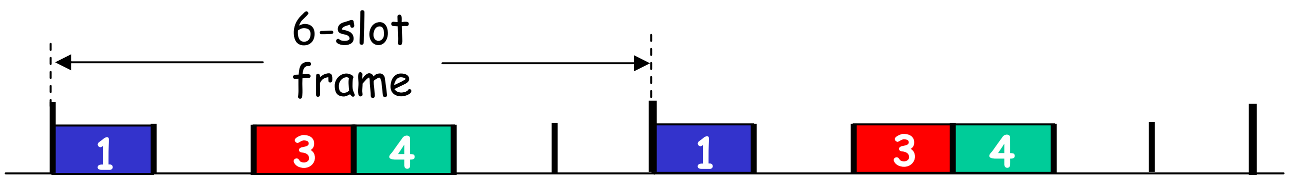
Three broad classes:

- Channel Partitioning 通道分割協定
  - divide channel into smaller "pieces" (time slots, frequency, code)
  - allocate piece to node for exclusive use
- Random Access 隨機存取
  - channel not divided, allow collisions
  - "recover" from collisions
- "Taking turns" 輪流存取
  - nodes take turns, but nodes with more to send can take longer turns

Channel Partitioning MAC protocols: TDMA

TDMA: time division multiple access 分時多工

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

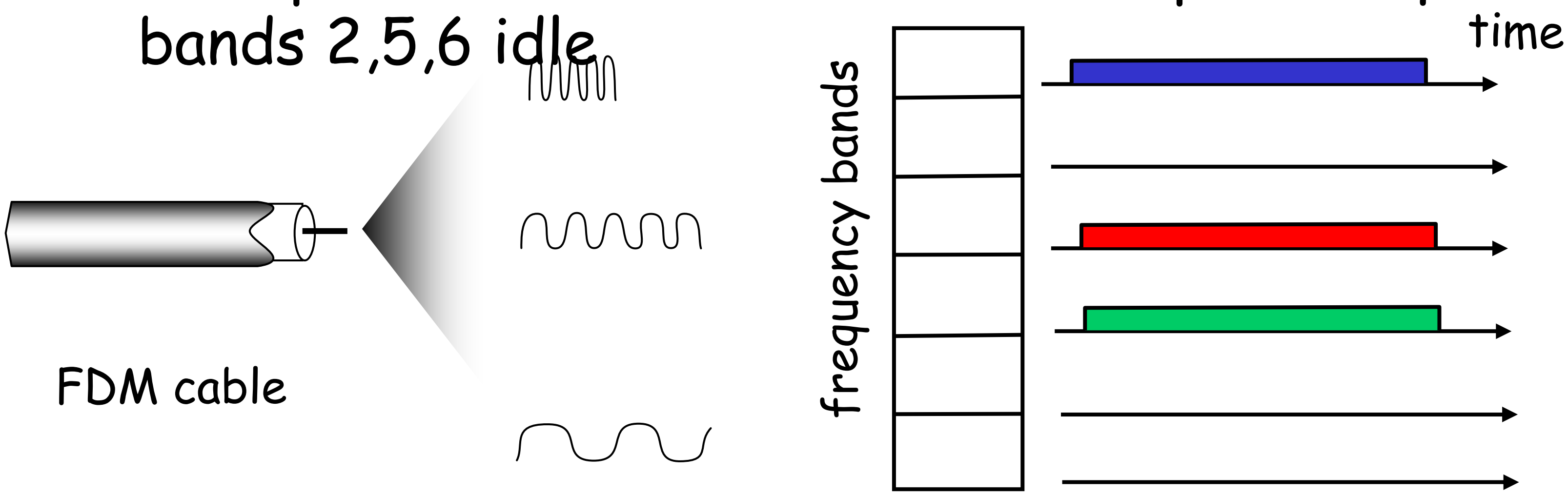


Channel Partitioning MAC protocols: FDMA

FDMA: frequency division multiple access

分頻多工

- 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 pkt, frequency bands 2,5,6 idle



Random Access Protocols 隨機存取

- 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" 碰撞,
- random access MAC protocol specifies:
  - how to detect collisions 如何發現碰撞
  - how to recover from collisions (e.g., via delayed retransmissions) 如何回復狀態
- Examples of random access MAC protocols:
  - slotted ALOHA
  - ALOHA
  - CSMA, CSMA/CD, CSMA/CA

Slotted ALOHA

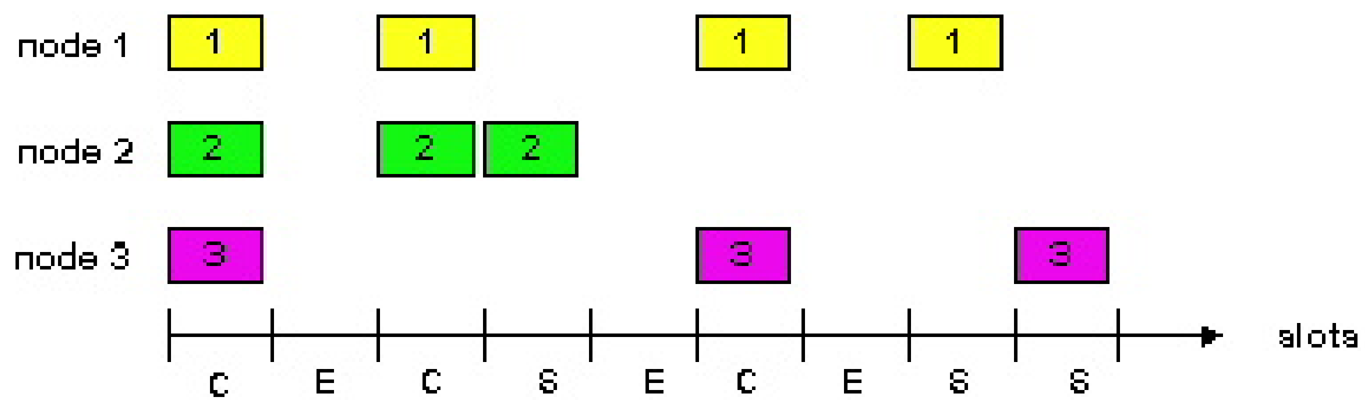
Assumptions:

- all frames same size
  相同大小訊框
- time divided into equal size slots (time to transmit 1 frame)
- nodes start to transmit only slot beginning
  等到slot開始才傳送
- nodes are synchronized
  所有節點同步
- 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 (1-persistent)
  - *if collision:* node retransmits frame in each subsequent slot with prob. p until success(p-persistent)
  - (0-persistent)

Slotted ALOHA



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 效率

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:

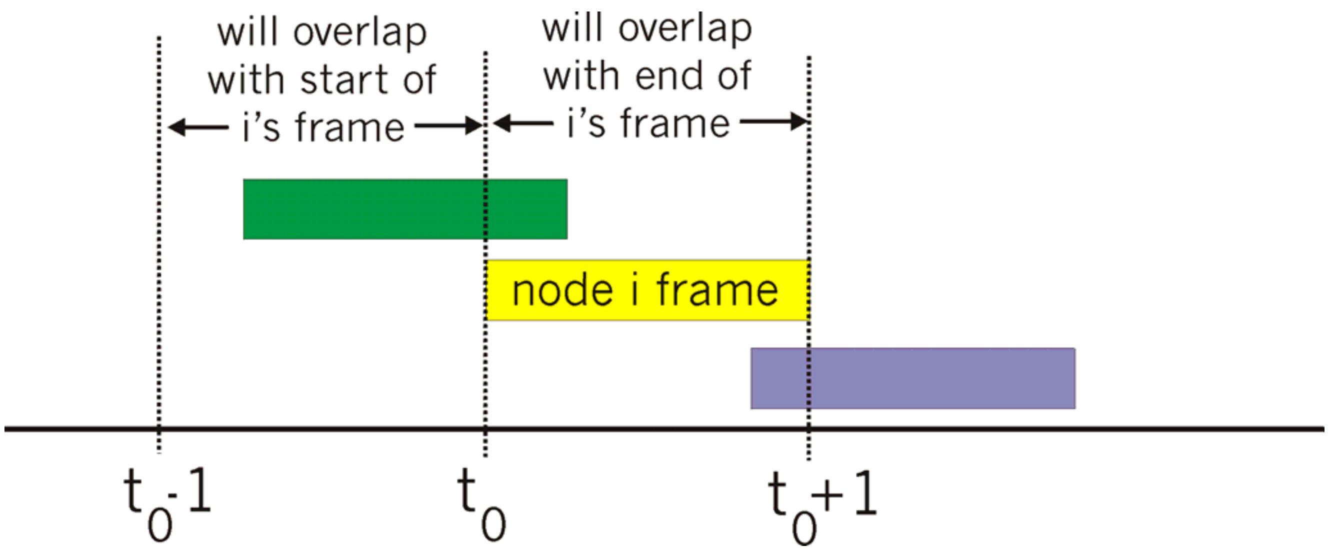
Max efficiency = 1/e = .37

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

!

Pure (unslotted) ALOHA

- unslotted Aloha: simpler, no synchronization 不分時槽
- when frame first arrives
  - transmit immediately 立刻傳送
- collision probability increases:
  - frame sent at t_0 collides with other frames sent in $[t_0-1, t_0+1]$



Pure Aloha efficiency

P(success by given node) = P(node transmits) $\cdot$

P(no other node transmits in $[p_0-1,p_0]$ $\cdot$

P(no other node transmits in $[p_0-1,p_0]$

$= p \cdot (1-p)^{N-1} \cdot (1-p)^{N-1}$

$= p \cdot (1-p)^{2(N-1)}$

… choosing optimum p and then letting n -> infty ...

= 1/(2e) = .18

even *worse* than slotted Aloha!

CSMA (Carrier Sense Multiple Access)

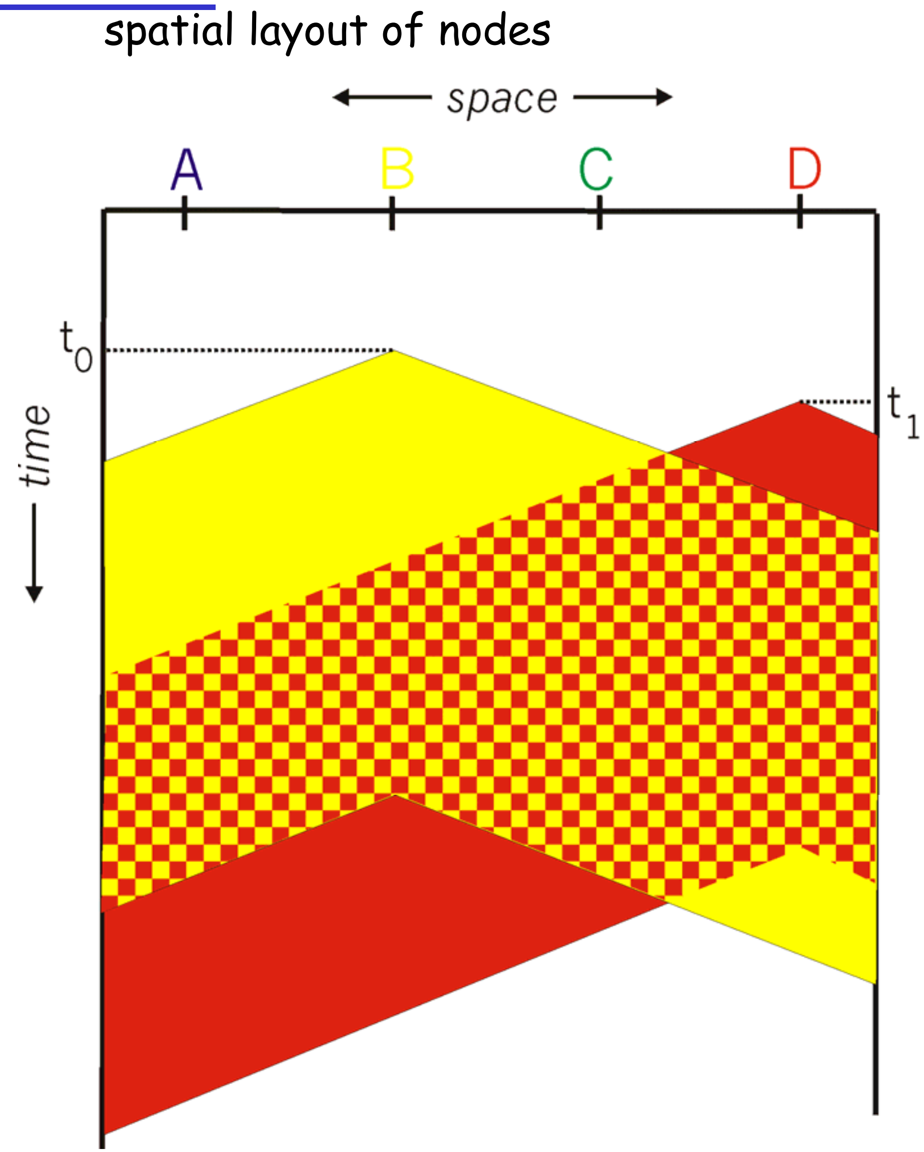
CSMA: listen before transmit: 在傳送前先聽連結狀況

If channel sensed idle: transmit entire frame

- If channel sensed busy, defer transmission

- human analogy: don't interrupt others!

CSMA collisions 碰撞



collisions *can* still occur:

propagation delay means two nodes may not hear each other's transmission

collision:

entire packet transmission time wasted

note:

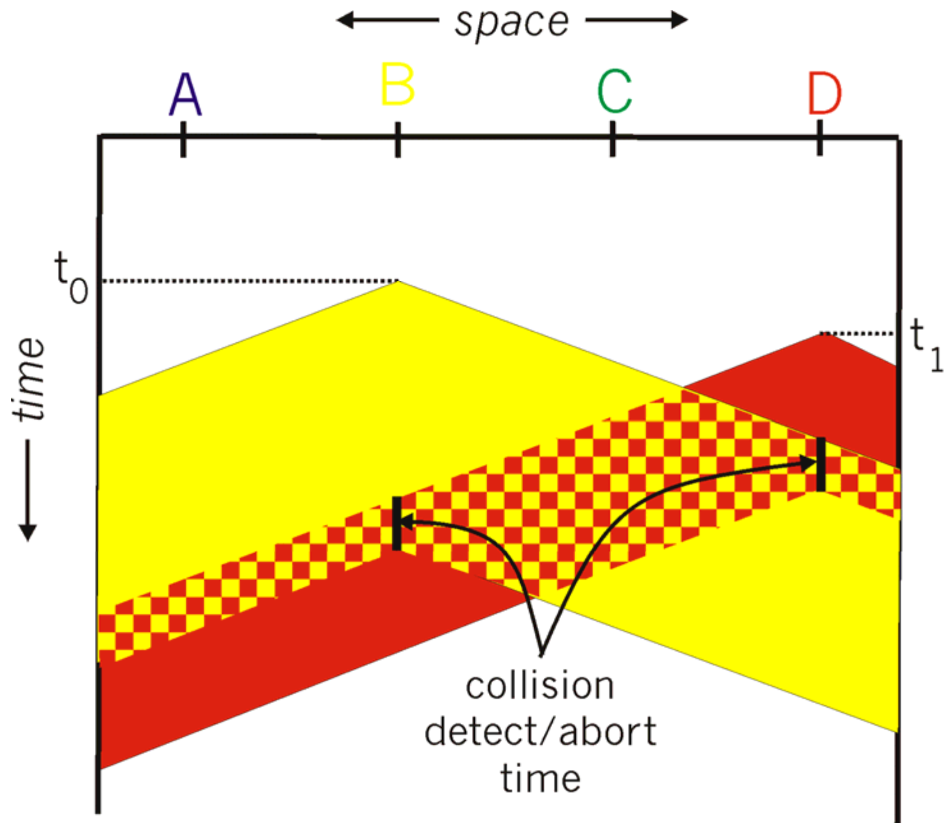
role of distance & propagation delay in determining collision probability

CSMA/CD (Collision Detection)

CSMA/CD: carrier sensing, deferral as in CSMA
- collisions *detected* within short time
- colliding transmissions aborted, reducing channel wastage

- collision detection:
  - easy in wired LANs: measure signal strengths, compare transmitted, received signals
  - difficult in wireless LANs: received signal strength overwhelmed by local transmission strength
- human analogy: the polite conversationalist

CSMA/CD collision detection



"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

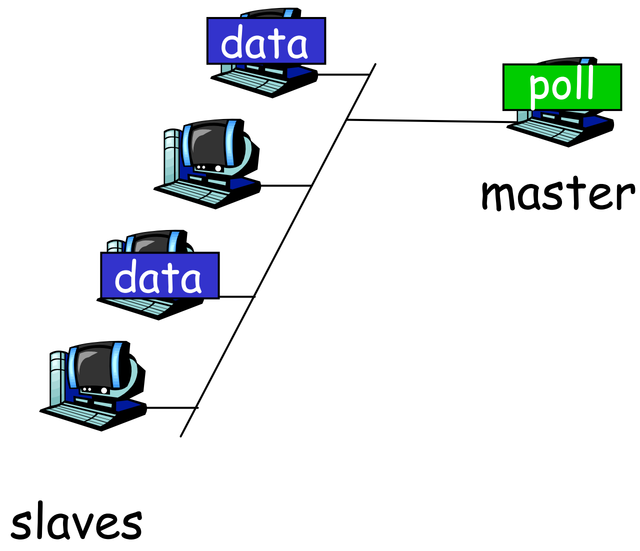
"taking turns" protocols

look for best of both worlds!

"Taking Turns" MAC protocols

Polling: 詢問法

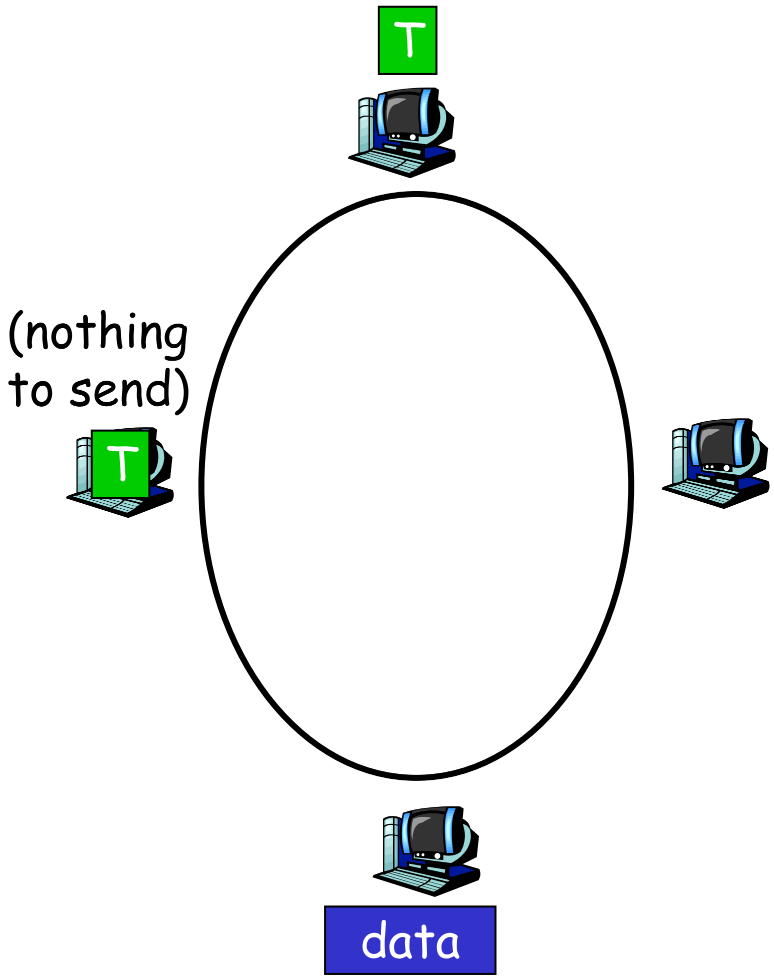
- master node "invites" slave nodes to transmit in turn
- typically used with "dumb" slave devices
- concerns:
  - polling overhead
  - latency
  - single point of failure (master)



"Taking Turns" MAC protocols

Token passing: 記號環

- control **token** passed from one node to next sequentially.
- token message
- concerns:
  - token overhead
  - latency
  - single point of failure (token)



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, IBM Token Ring