The MAC Layer

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What is it all about?

- Consider an audioconference where
  - if one person speaks, all can hear
  - if more than one person speaks at the same time, both voices are garbled
- How should participants coordinate actions so that
  - the number of messages exchanged per second is *maximized*
  - time spent waiting for a chance to speak is *minimized*
- This is the *multiple access problem*

Some simple solutions

- A (simple) centralized solution: use a moderator
  - a speaker must wait for moderator to "poll" him or her, even if no one else wants to speak
  - what if the moderator's connection breaks?
- Distributed solution
  - speak if no one else is speaking
  - but if two speakers are waiting for a third to finish, guaranteed collision
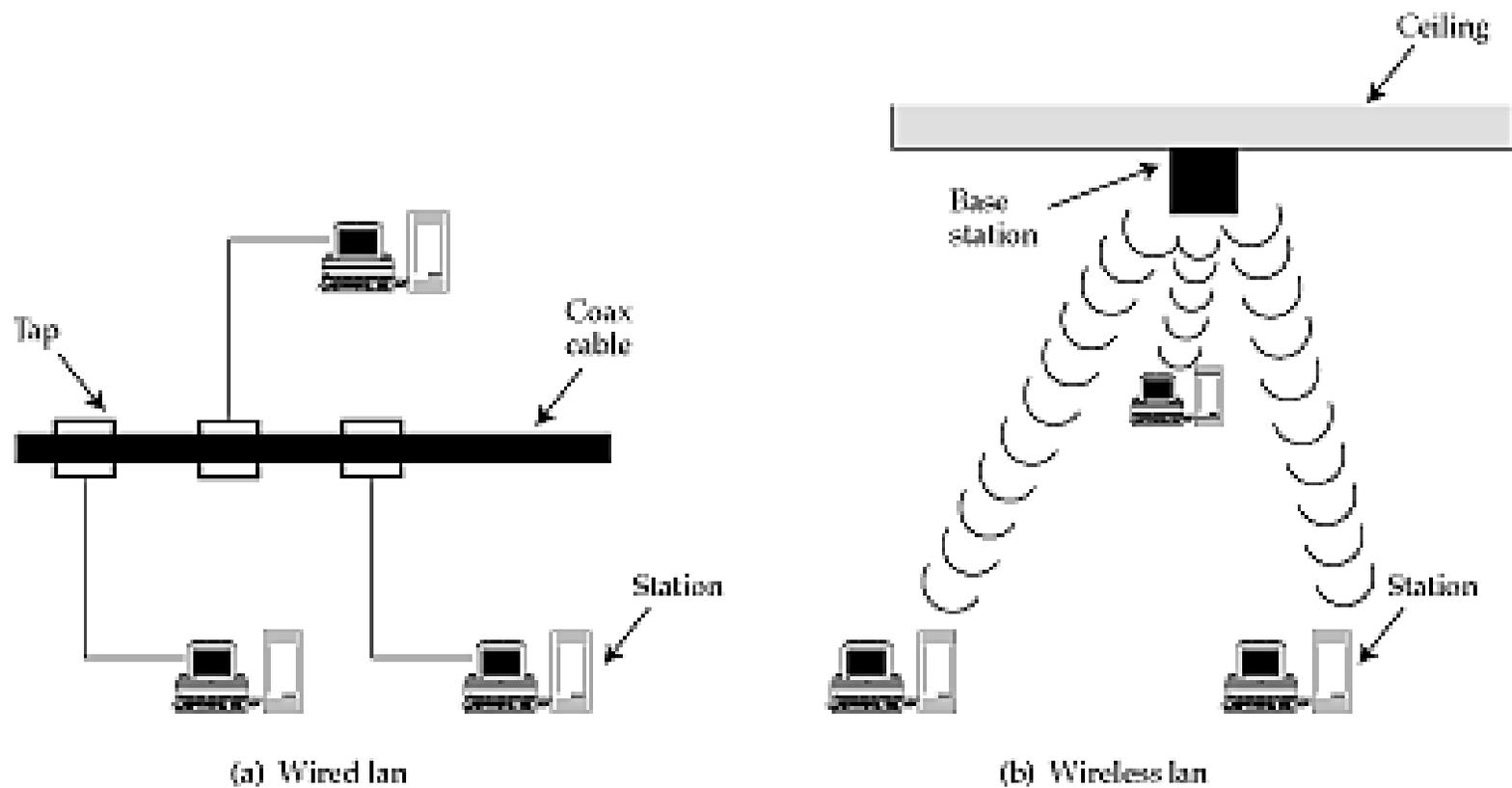- Designing good schemes is surprisingly hard!

Outline

- **Contexts for the problem**

- Choices and constraints

- Performance metrics

- Base technologies
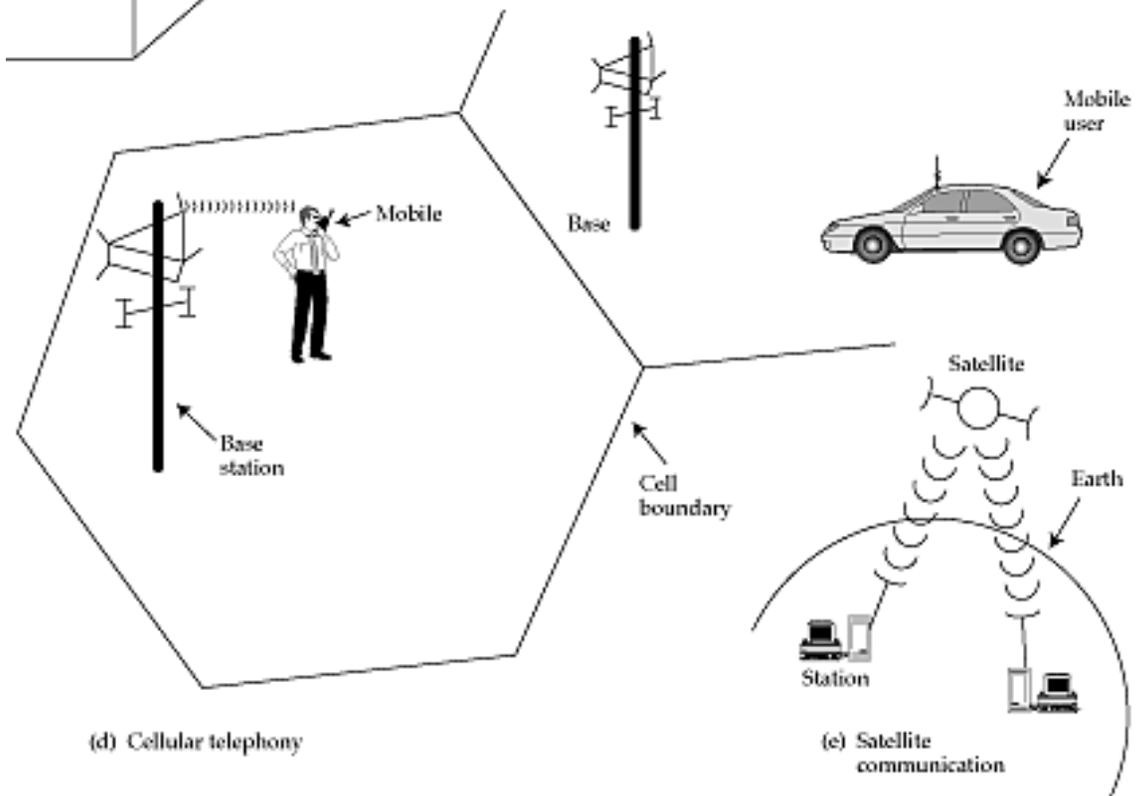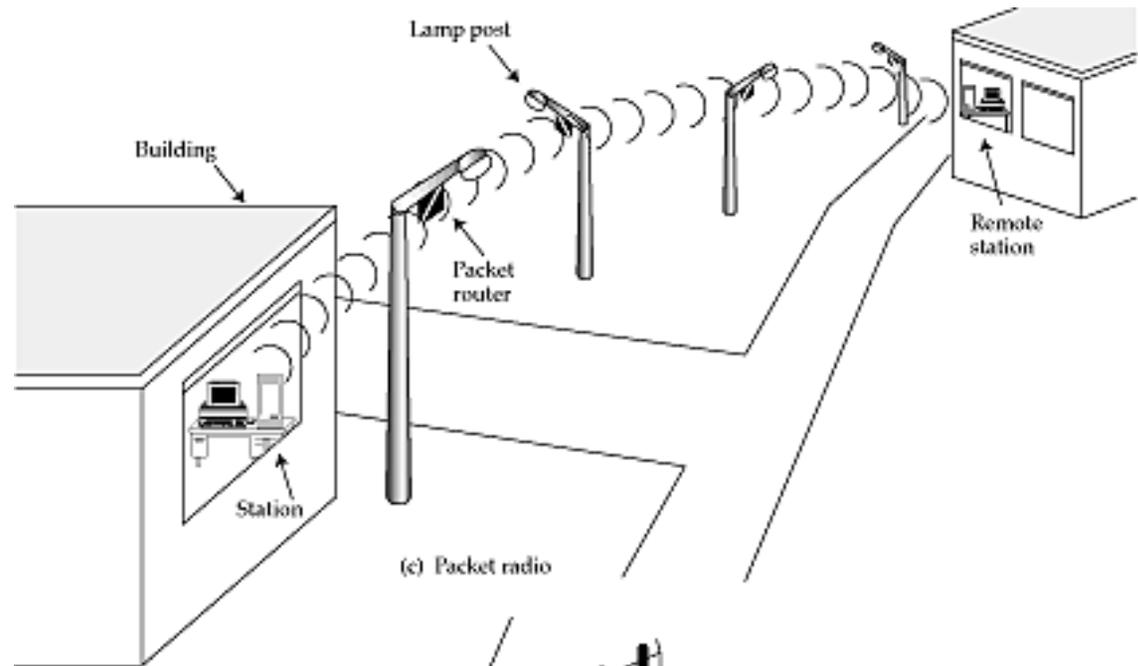
- Centralized schemes

- Distributed schemes

Contexts for the multiple access problem

- *Broadcast* transmission medium

  - message from any "station" is received by all receivers in its listening area

- Colliding messages are garbled

- Goal

  - maximize message throughput

  - minimize mean waiting time

- Shows up in five main contexts

Contexts

(a) Wired lan   (b) Wireless lan

Contents

Labels in the figure:

- Building
- Lamp post
- Remote station
- Packet router
- Station
- (c) Packet radio
- Mobile user
- Mobile
- Base
- Base station
- Cell boundary
- (d) Cellular telephony
- Satellite
- Earth
- Station
- (e) Satellite communication

Solving the problem

- First, choose a *base technology*
  - to isolate traffic from different stations
  - can be in time domain or frequency domain
- But: not enough time slots or frequencies to exclusively dedicate to each user
- Then, choose how to allocate a limited number of transmission resources to a larger set of contending users

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Choices

- **Centralized vs. distributed design**
  - is there a moderator or not?
  - in a centralized solution one of the stations is a *master* (e.g. base station in cellular telephony) and the others are *slaves*
    - master->slave = downlink
    - slave->master = uplink
  - in a distributed solution, all stations are peers
- **Circuit-mode vs. packet-mode**
  - do stations send steady streams or bursts of packets?
  - with streams, doesn't make sense to contend for every packet
  - allocate resources to streams - analogy to long "speeches"
  - with packets, makes sense to contend for every packet to avoid wasting bandwidth - analogy to brainstorming session

Constraints

- **Spectrum scarcity**
  - radio spectrum is hard to come by
  - only a few frequencies available for long-distance (few miles) data communication
  - multiple access schemes must be careful not to waste bandwidth
- **Radio link properties**
  - radio links are error prone
    - fading (signal degradation because of hills, foliage, trucks, etc.)
    - multipath interference
  - hidden terminals
    - transmitter heard only by a subset of receivers
  - capture
    - station with higher power overpowers the other -> no "collision" is detected
    - lower powered station may never get a chance to be heard

The parameter 'a'

- The number of packets sent by a source before the farthest station receives the first bit

- D: max propagation delay between any two stations

- T: time taken to transmit an average size packet

- $a = D/T$ (around 10^{-2} for LANs, 1 for HSLANs, 10^2 for satellite links)

A   B

Transmission
time

Propagation
delay

Small "a"

A   B

Transmission
time

Propagation
delay

Large "a"

● Collision
   Indication

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Performance metrics

- **Normalized throughput**
    - fraction of link capacity used to carry non-retransmitted packets
    - example
        - Ideally (with no collisions) a 1 Mbps link can carry 1000 "125 byte" packets/sec
        - with a particular scheme and workload, we might have 250 packets/sec
        - => goodput = 0.25
- **Mean delay**
    - amount of time a station has to wait before it successfully transmits a packet
        - depends on the MAC protocol, the load and the characteristics of the medium

Performance metrics

- **Stability**
  - with heavy load, is all the time spent on resolving contentions?
  - => unstable
  - with a stable algorithm, throughput does not decrease with offered load
  - if huge number of "uncontrolled" stations share a link, then instability is guaranteed
  - but if sources reduce load when overload is detected, can achieve stability
- **Fairness**
  - no single definition
  - 'no-starvation': source eventually gets a chance to send
  - stricter metric: each station gets an equal share of the transmission bandwidth

Limitation of analytical modeling

- Assumptions on source traffic
    - work of queuing theory is only indicative and not an absolute metric
- Other factors may have greater impact than what models predict
    - battery strength
    - weather conditions
    - presence or absence of foliage or plants
    - workload different from assumptions
- Will only focus on *qualitative* description

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Base technologies

- Isolates data from different sources

- Three basic choices
  - Frequency division multiple access (FDMA)
  - Time division multiple access (TDMA)
 - Code division multiple access (CDMA)

FDMA

- Simplest, best suited for analog links

- Each station has its own frequency band, separated by guard bands

- Receivers tune to the right frequency

- Common for TV and radio broadcast (at most few hundred transmitters in a listening area) - Not in wireless telephony

- Number of frequencies is limited

  - reduce transmitter power; reuse frequencies in non-adjacent cells requiring "complex" handoff
  - trade off complexity for increased number of users

- simplistic example: voice channel = 30 KHz

  - 833 channels in 25 MHz band
  - with 7-cell pattern, partition into 119 channels each
  - but with N cells in a city, can get 119N calls => win if pattern repeated
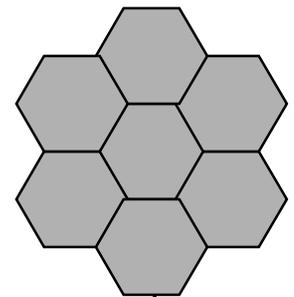
GSM frequency reuse

- Pattern: smallest cell set containing only once all radio channels (repeated on all zones to cover)

- Regular pattern size: 3,4,7,9, 12 & 21

- D_{ru} is re-use distance

- R is cell radius

- K is pattern size (7 in this example)

- $D_{ru}/R = \text{sqrt}(3.K)$
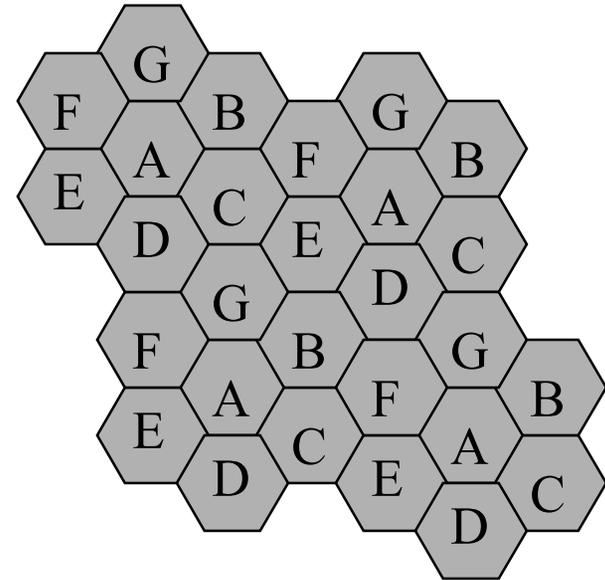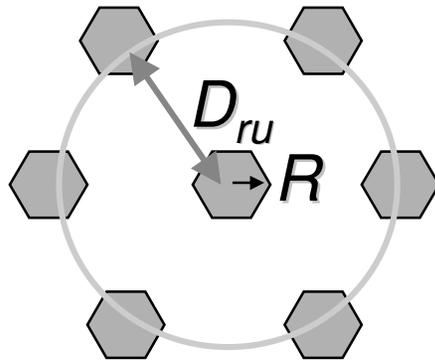
TDMA

- All stations transmit data on same frequency, but at different times

- Needs time synchronization

- supposes that stations resolve contention for access to a time *slot* and limit their transmission to a single slot

- roughly same number of users than FDMA

- Pros

  - users can be given different amounts of bandwidth (time slots)
  - mobiles can use idle times to determine best base station (and handoff to nearer base station to save battery)
  - can switch off power when not transmitting

- Cons

  - synchronization overhead (one of the stations emit sync signal)
  - Still needs handoff (to nearest station in order to save power)
  - greater problems with multipath interference on wireless links (because of wider frequency band than FDMA -> smaller transmission duration -> need for adaptive equalization circuit in each receiver)

CDMA

- Users separated both by time and frequency

  - Aka spread spectrum techniques

- Colliding "frames" are not necessarily totally garbled

- Send at a different frequency at each time slot (*frequency hopping*)

- Or, convert a single bit to a code (*direct sequence*)

  - receiver can decipher bit by inverse process even in presence of narrowband noise
  - assumes that multiple signals add linearly

CDMA/DS example

- Each station has its « chip-sequence » or codeword (bipolar repsentation)

  - EA: (-1-1-1+1+1-1+1+1) (binary 00011011)
  - EB: (-1-1+1-1+1+1+1-1) (binary 00101110)
  - EC: (-1+1-1+1+1+1-1-1) (binary 01011100)
  - ED: (-1+1-1-1-1-1+1-1)   (binary 01000010)

- Send codeword E for a 1 *bit* and its negation -E for a 0 *bit*

A	B	C	D
-	-	1	-
-	1	1	-
1	0	-	-
1	0	1	-
1	1	1	1
1	1	0	1

E1= (EC)	(-1 +1 -1 +1 +1 +1 -1 -1)
E2 = (EB+EC)	(-2 0 0 0 +2 +2 0 -2)
E3 = (EA-EB)	(0 0 -2 +2 0 -2 0 +2)
E4 = (EA-EB+EC)	(-1 +1 -3 +3 -1 -1 -1 -1 +1)
E5 = (EA+EB+EC+ED)	(-4 0 -2 0 +2 0 +2 -2)
E6 = (EA+EB-EC+ED)	(-2 -2 0 -2 0 -2 +4 0)

E1.EC	(1+1+1+1+1+1+1+1)/8 = 1
E2.EC	(2+0+0+0+2+2+0+2)/8 = 1
E3.EC	(0+0+2+2+0-2+0-2)/8 = 0
E4.EC	(1+1+3+3+1-1+1-1)/8 = 1
E5.EC	(4+0+2+0+2+0-2+2)/8 = 1
E6.EC	(2-2+0-2+0-2-4-0)/8 = -1

CDMA

- **Pros**
  - hard to spy
  - immune from narrow band noise
  - Unlike TDMA, no need for all stations to synchronize (only sender and receiver)
  - no hard limit on capacity of a cell, but noise increases and effective bit-rate per station decreases with the number of stations
  - all cells can use all frequencies, no need for frequency planning
- **Cons**
  - implementation complexity (receiver perfectly synchronized with senders)
  - need for complicated power control to avoid *capture*
    - hard because of multiple moving receivers
  - need for a large contiguous frequency band (for direct sequence) -> problems installing in the field

FDD and TDD

■ Two ways of converting a wireless medium to a duplex channel

■ In Frequency Division Duplex, uplink and downlink use different frequencies

■ In Time Division Duplex, uplink and downlink use different time slots

■ Can combine with FDMA/TDMA

■ Examples

  ◆ TDD/FDMA in second-generation cordless phones
  ◆ FDD/TDMA/FDMA in digital cellular GSM phones

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Centralized access schemes

- One station is master, and the other are slaves
  - slave can transmit only when master allows

- Natural fit in some situations
  - wireless LAN, where base station is the only station that can see everyone
  - cellular telephony, where base station is the only one
    - with a wired connection to the network and
    - capable of high transmit power

Centralized access schemes

- **Pros**
  - ◆ simple
  - ◆ master provides single point of coordination
- **Cons**
  - ◆ master is a single point of failure
    - ✦ need a re-election protocol => complicates the system!
    - ✦ master is involved in every single transfer => added delay
- **Circuit mode schemes: cellular telephony**
- **Packet mode schemes: polling/probing and reservation**

Circuit mode: the cellular telephony example

- When station wants to transmit, it sends a message to master using simple (ALOHA) packet mode multiple access protocol

- Master allocates transmission resources to slave

- Slave uses the resources until it is done

- No contention during data transfer

- Used primarily in cellular phone systems
    - EAMPS: analog FDD/FDMA
    - GSM : FDD/TDMA/FDMA
    - IS-95: CDMA

Polling and probing

- Packet-mode: station must contend for medium access for each packet

- Centralized controller mediates this contention

- Polling
  - master asks each station in turn if it wants to send (roll-call polling)
  - inefficient if (a) time to query a station is long, (b) overhead for polling messages is high, or (c) system has many terminals

- Probing
  - stations are numbered with consecutive logical addresses
  - assume station can listen both to its own address and to a set of multicast or "group" addresses
  - master does a binary search to locate next active station
    - skip chunks of address space with no active station
    - But repeated polls in sections with more than one active station
  - Efficient if few stations are active, doubles polls if all active

Reservation-based schemes

- When 'a' is large, collisions are expensive
  - polling overhead is too high
  - better use reservation than polling
  - mainly for satellite links
- Master coordinates access to link using reservations
- Some time slots devoted to reservation messages
  - can be smaller than data slots => *minislots*
- Stations contend for a minislot (PDAMA) (or own one FPODA)
- Master decides winners and grants them access to link
- Packet collisions are only for minislots, so overhead on contention is reduced

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Distributed schemes

■ Compared to a centralized scheme

- more reliable
- have lower message delays
- often allow higher network utilization
- but are more complicated
  - e.g. to synchronize stations to the same time base

■ Almost all distributed schemes are packet mode

- difficult to establish and maintain circuits without a central controller (the one-time coordination is amortized over many packets for circuit-mode in centralized schemes)

Decentralized polling

- Just like centralized polling, except there is no master

- But, all stations must share a time base

- Each station is assigned a slot that it uses

  - if nothing to send, slot is wasted
  - this is just TDMA :-)

Decentralized probing

- Also called *tree based multiple access*

- All stations in left subtree of root allowed to place packet on medium in first slot

- If a collision, root <- root ->left_son, and try again in next slot

- On success, everyone in root->right_son contend for access etc.

- Works well if 'a' is small

  - otherwise: either introduce idle time to wait for possible collision (inefficient) or roll back state if collision detected later (complex)

Carrier Sense Multiple Access (CSMA)

- Polling/probing may waste time if number of stations is large but number of simultaneously active stations is small

- A fundamental advance: check whether the medium is active before sending a packet (i.e *carrier sensing*)

- Unlike polling/probing a node with something to send doesn't have to wait for a master, or for its turn in a schedule

- If medium idle, then can send

  - just like a participant in a meeting

- If collision happens, detect and resolve

- Works when 'a' is small (0.1 or smaller)

- In slotted version, time *slot* is chosen to be the maximum *propagation* delay (considered small comparing to T)

Simplest CSMA scheme

- Send a packet as soon as medium becomes idle

- If, on sensing busy, wait for idle -> *persistent*

- If, on sensing busy, set a timer and try later -> *non-persistent*

- Problem with persistent: two stations waiting to speak will collide

How to solve the collision problem

- Two solutions

- *p-persistent*: when media becomes idle, transmit with probability *p:*
  - hard to choose *p* (< 1/Number of stations waiting)
    - balance message delay with higher utilization under heavy loads
  - if *p* small, then wasted time (if media idle)
  - if *p* large, more collisions

- *exponential backoff*

  - need to detect collisions: explicit ACK or *collision detect circuit* => CSMA/CD
  - on collision detection, choose retransmission timeout randomly from doubled range; on success reset timeout value
  - backoff range adapts to number of contending stations
  - no need to choose *p* (even 1-persistent CSMA with backoff is stable)

Summary of CSMA schemes
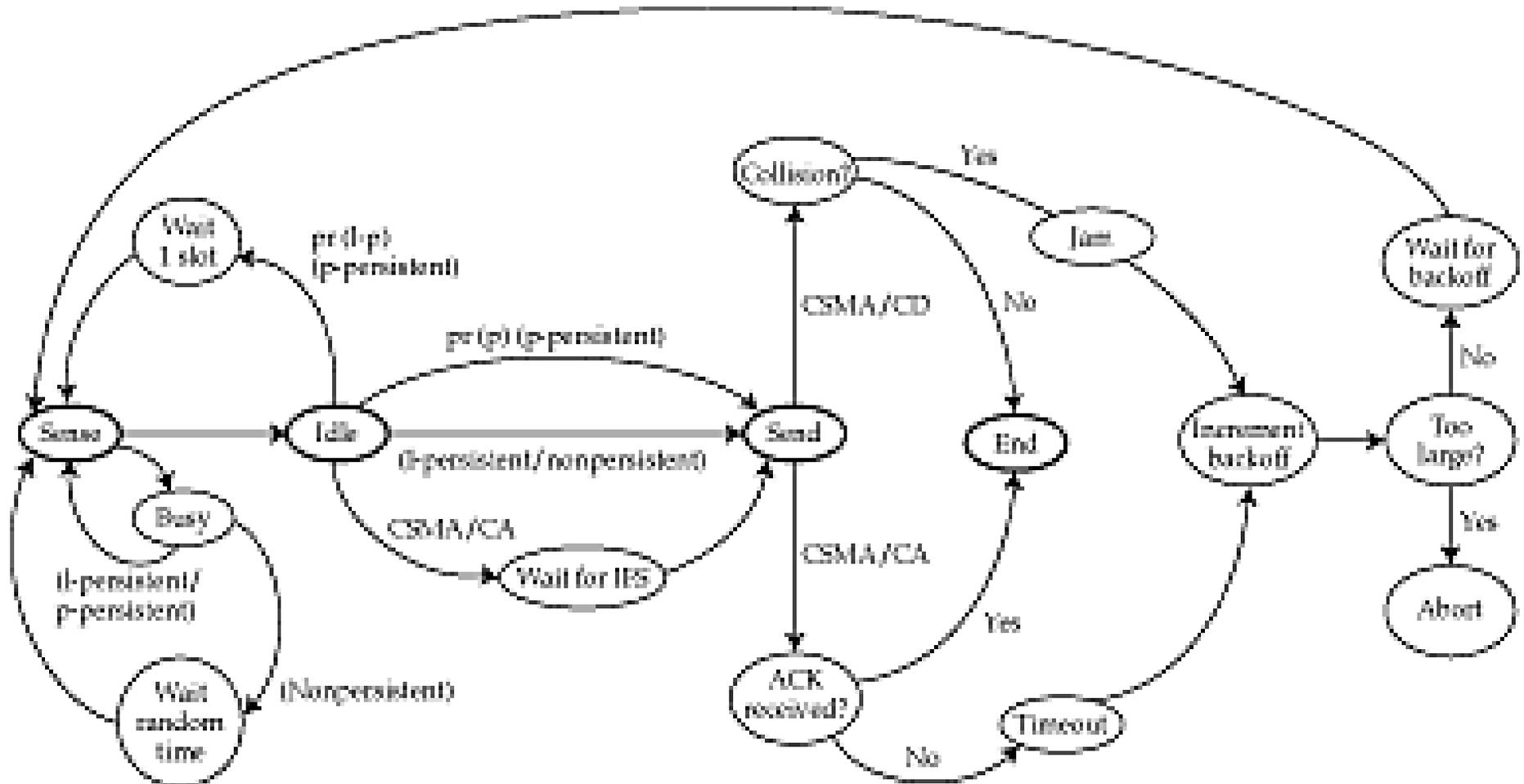
Ethernet

- The most widely used LAN

- Standard is called IEEE 802.3

- Uses 1-persistent CSMA/CD with exponential backoff

- Also, on collision, place a *jam* signal on wire, so that all stations are aware of collision and can increment backoff timeout range

- 'a' small =>time wasted in collision is around 50 microseconds

- Ethernet requires packet to be long enough that a collision is detected before packet transmission completes (a <= 1)
  - packet should be at least 64 bytes long for longest allowed segment
- Max packet size is 1500 bytes
  - prevents hogging by a single station

More on Ethernet

- First version ran at 3 Mbps

- Early versions ran at 10 Mbps, and uses 'thick' or 'thin' coax, or twisted pair

- Ethernet types are coded as <Speed><Baseband or broadband><physical medium>

  - Speed = 3, 10, 100 Mbps
  - Baseband = within building, broadband = on cable TV infrastructure
  - Physical medium:
    - "5" is thick coax, up to 500 meters
    - "2" is cheap 50 Ohm cable, up to 200 meters
    - "T" is unshielded twisted pair (also used for telephone wiring)

Enhancing Ethernet

- ■ Ease of maintenance
  - ◆ use a hub as in 10BaseT
    - ✦ add/remove
- ■ Increase performance
  - ◆ divide in multiple « contention domains »
    - ✦ use bridges
    - ✦ or (even) switches : Switched Ethernet
  - ◆ increase speed
    - ✦ 100BaseT

Some definitions

- **Contention or collision domain:** sum total of devices that compete with each other for access to the transmission media

- **Hub:** a centrally-located device in a star topology that propagates the signal transmitted by each node to ALL other ports. Nodes still constitute a single contention domain. Collision is detected by simultaneous activity on the Data Out (DO) and Receive Data (RD) circuits

- **Bridge:** device connecting « segments » with level 2 filtering capability. Splits LAN to N contention domains (N=number of ports). Packets are usually stored then forwarded.

- **Switch:** a « bridge » with N=number of nodes. If switch is full duplex capable, no collision will occur. Each pair gets 20Mbps

Recent developments

- **Switched Ethernet**
  - each station is connected to switch by a separate UTP wire
    - as in 10BaseT
  - however, line card of switch has a buffer to hold incoming packets
  - fast backplane switches packet from one line card to others
  - simultaneously arriving packets do not collide (until buffers overflow)
  - higher intrinsic capacity than 10BaseT (and more expensive)

Comparison

	Topology	Cable	Max distance	Nodes	Advantages	HalfDpX/FDX
10Base5	bus	Thick coax	500 x5seg	100/seg	backbones	HDX
10Base2	bus	Thin coax	185x5seg	30/seg	cheap	HDX
10BaseT	logical bus	2 UTPs	100 (Hub to Node)	few100s/CD	maintenance	HDX
Bridged	scalable	"bus" / port	No	per segment	multiple CDs	HDX in each CD
Switched	crossbar	UTPs	100 (btw swt.)	__	No contention	FDX

Fast Ethernet variants

- **Fast Ethernet (IEEE 802.3u)**
  - same as 10BaseT, except that line speed is 100 Mbps
  - spans only 205 m
  - big winner
  - most current cards support both 10 and 100 Mbps cards (10/100 cards) for about $80
- 100VG Anylan (IEEE 802.12)
  - station makes explicit service requests to master
  - master schedules requests, eliminating collisions
  - not a success in the market

- **Gigabit Ethernet**
  - aims to continue the trend
  - works over 4-pair UTP

- **10Gigabit Ethernet**
  - No CSMA, only over optical fiber

Evaluating Ethernet

- **Pros**
  - ◆ easy to setup
  - ◆ requires no configuration
  - ◆ robust to noise

- **Problems**
  - ◆ at heavy loads, users see large delays because of backoff
  - ◆ non-deterministic service
  - ◆ doesn't support priorities
  - ◆ big overhead on small packets

- **But, very successful because**
  - ◆ problems only at high load
    - ✦ loads rarely exceed 30%
  - ◆ can segment LANs to reduce load
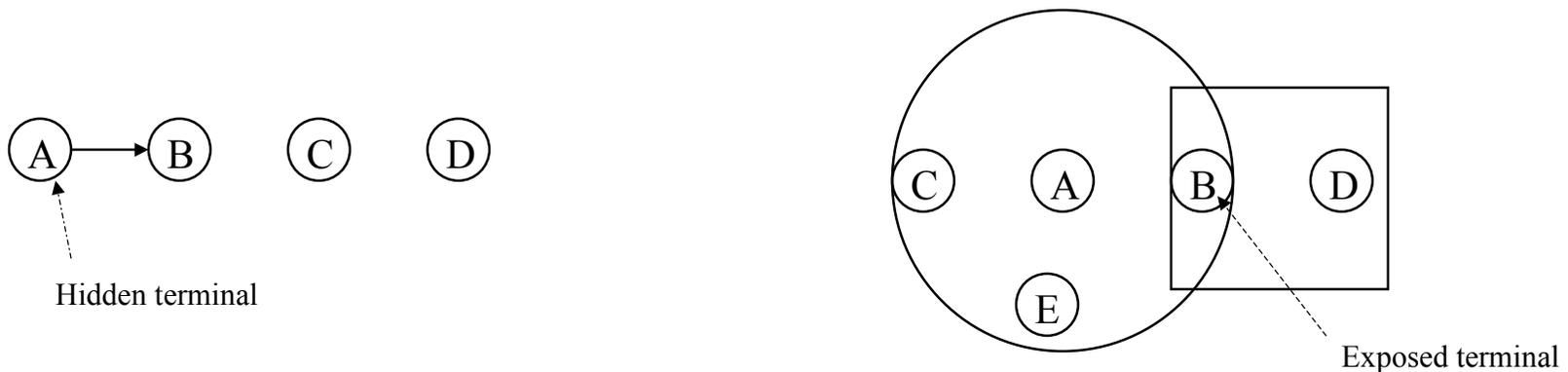
CSMA/CA

- Used in wireless LANs

- Can't detect collision because transmitter overwhelms colocated receiver

- So, need explicit acks

- But this makes collisions more expensive

  - => try to reduce number of collisions
- Standardized as IEEE 802.11

CSMA/CA algorithm

- First check if medium is busy

- If so, wait for medium to become idle

- if idle: wait for inter-frame spacing before contending for a slot (low IFS means higher priority)

- then, set a *contention timer* to an interval randomly chosen in the range [0, CW] (CW predefined contention window)

- On timeout, send packet and wait for ack

- If no ack, assume packet is lost
  - try again, after doubling CW

- If another station transmits while counting down, freeze CW and unfreeze when packet completes transmission

- station will get higher priority in next round of contention

Dealing with hidden terminals

- **CSMA/CA works when every station can receive transmissions from every other station**

- **Not always true**

- **Hidden terminal**
  - some stations in an area cannot hear transmissions from others, though base can hear both (C cannot sense A is sending to B)

- **Exposed terminal**
  - some (but not all) stations can hear transmissions from stations not in the local area (B should be able to send to D, while A sending to C)

A ──▶ B   C   D

Hidden terminal

C   A   B   D

E

Exposed terminal

Dealing with hidden and exposed terminals

- **In both cases, CSMA/CA doesn't work**
  - ◆ with hidden terminal, collision because carrier not detected
  - ◆ with exposed terminal, idle station because carrier incorrectly detected
  - ◆ what matters is collision "at the receiver"
- **Two solutions**
- **Busy Tone Multiple Access (BTMA)**
  - ◆ assumes symmetric wireless links
  - ◆ uses a separate "busy-tone" channel
  - ◆ when station is receiving a message, it places a tone on this channel
  - ◆ everyone who might want to talk to a station knows that it is busy
    - ✦ even if they cannot hear transmission that this station hears
  - ◆ this avoids both problems of hidden and exposed terminals
    - ✦ transmitters ignore their carrier-sense circuit and sends only if busy-tone channel is idle

Multiple Access Collision Avoidance

- BTMA requires us to split frequency band
  - more complex receivers (need two tuners)
- Separate bands may have different propagation characteristics
  - scheme fails!
- Instead, use a single frequency band, but use explicit messages to tell others that receiver is busy
- In MACA, before sending data, send a Request to Sent (RTS) to intended receiver
- Station, if idle, sends Clear to Send (CTS)
- Sender then sends data
- If station overhears RTS, it waits for other transmission to end
- Solves both problems

Token passing

- In distributed polling, every station has to wait for its turn

- Time wasted because idle stations are still given a slot

- What if we can quickly skip past idle stations?

- This is the key idea of token ring

- Special packet called 'token' gives station the right to transmit data

  - analogy with "right to speak or microphone"

- When done, it passes token to 'next' station

  - => stations form a logical ring

- No station will starve

- In addition, stations no longer need precise time synchronization
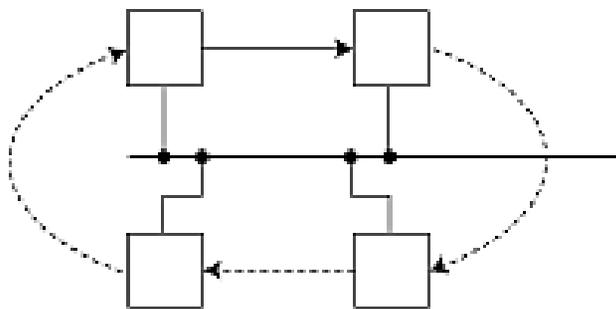
Logical rings

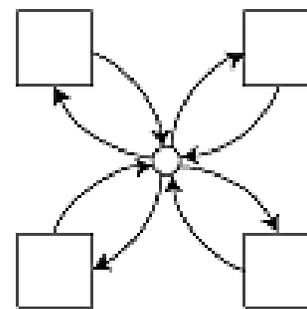■ Can be on a non-ring physical topology
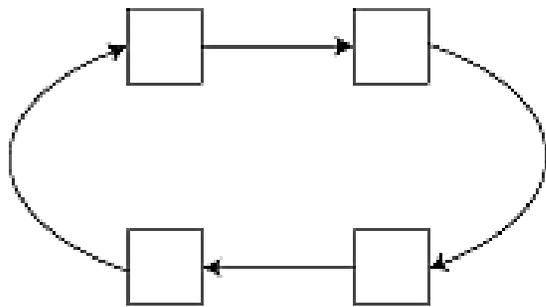
(a) Single ring
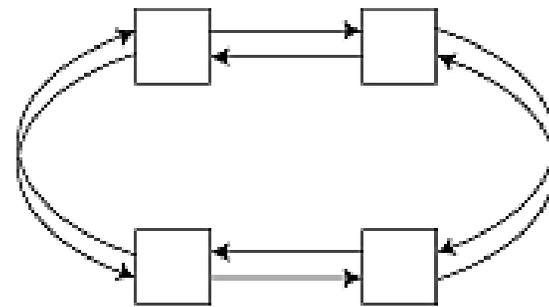
(b) Dual ring

(c) Token bus

(d) Hub or star-ring

Ring operation

- During normal operation, copy packets from input buffer to output

- If packet is a token, check if packets ready to send

- If not, forward token

- If so, delete token, and send packets

- Receiver copies packet and sets 'ack' flag

- Sender removes packet from the ring

- When done, reinserts token

- If ring idle and no token for a long time, regenerate token

Single and double rings

- With a single ring, a single failure of a link or station breaks the network => fragile

- With a double ring, on a failure, go into *wrap mode*

- Used in FDDI

Hub or star-ring

- **Simplifies wiring**

- **Active hub is predecessor and successor to every station**
  - ◆ can monitor ring for station and link failures

- **Passive hub only serves as wiring concentrator**
  - ◆ but provides a single test point

- **Because of these benefits, hubs are practically the only form of wiring used in real networks**
  - ◆ even for Ethernet

Evaluating token ring

- **Pros**
  - medium access protocol is simple and explicit
  - no need for carrier sensing, time synchronization or complex protocols to resolve contention
  - guarantees zero collisions
  - can give some stations priority over others
- **Cons**
  - token is a single point of failure
    - lost or corrupted token trashes network
    - need to carefully protect and, if necessary, regenerate token
  - all stations must cooperate
    - network must detect and cut off unresponsive stations
  - stations must actively monitor network
    - to detect token loss and duplication
    - usually elect one station as *monitor*

Fiber Distributed Data Interface

- FDDI is the most popular token-ring base LAN

- Dual counter-rotating rings, each at 100 Mbps

- Uses both copper (CDDI) and fiber links

- Supports both non-realtime and realtime traffic
  - token is guaranteed to rotate once every Target Token Rotation Time (TTRT)
  - station is guaranteed a *synchronous allocation* within every TTRT
- Supports both *single attached* and *dual attached* stations
  - single attached (cheaper) stations are connected to only one of the rings

ALOHA and its variants

- ALOHA is one of the earliest multiple access schemes

- Just send it!

- Wait for an ack

- If no ack, try again after a random waiting time
   - no backoff

Evaluating ALOHA

- **Pros**
  - useful when 'a' is large, so carrier sensing doesn't help
    - satellite links
  - simple
    - no carrier sensing, no token, no timebase synchronization
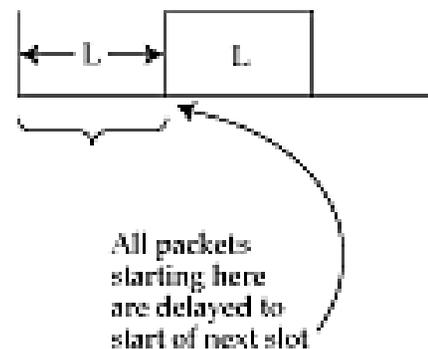 - independent of 'a'
- **Cons**
  - under some mathematical assumptions, goodput is at most .18
    - much higher goodput is achievable (e.g. a single user Trx)
  - at high loads, collisions are very frequent
  - sudden burst of traffic can lead to instability
    - unless backoff is exponential

Slotted ALOHA

■ A simple way to double ALOHA's capacity

■ Make sure transmissions start on a slot boundary

  ◆ synchronize to a broadcast pulse

■ Halves *window of vulnerability*

■ Used in cellular phone uplink (to request a frequency)

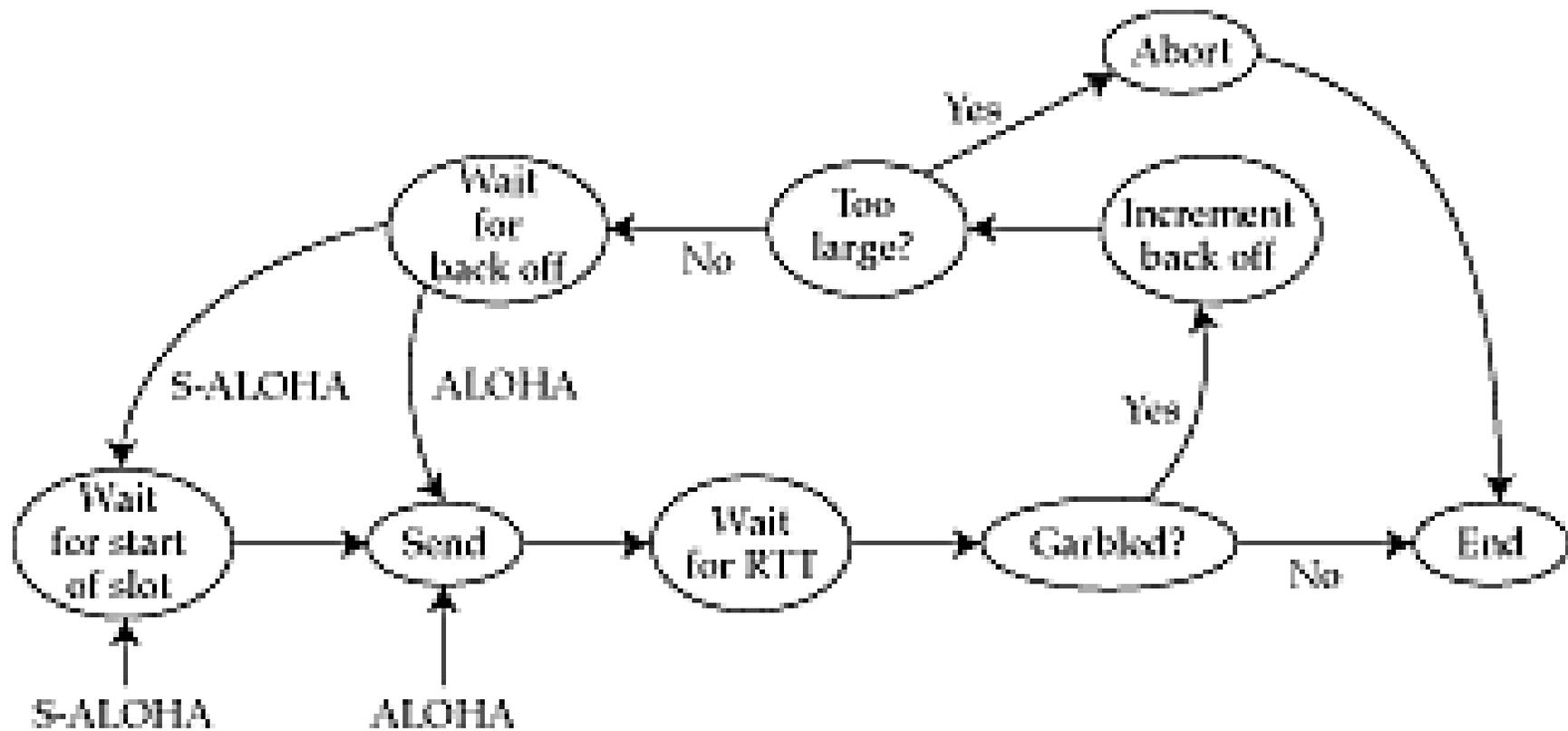 ◆ stations need to synchronize for TDMA anyway -> little additional overhead
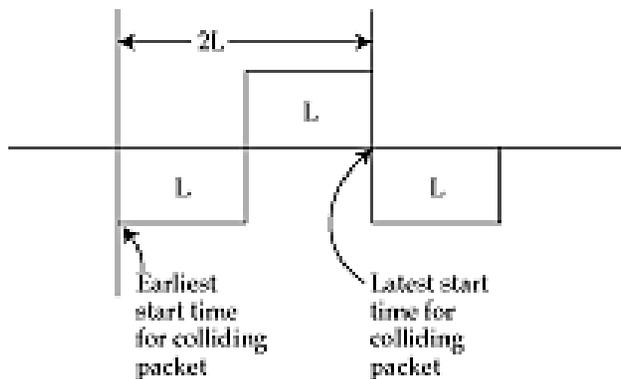
(a) ALOHA

(b) Slotted ALOHA

ALOHA schemes summarized

Reservation ALOHA

- Similar to FPODA but no master, slot time = time to transmit a (constant length) packet

- Contend for implicit reservation using slotted ALOHA

- Stations independently examine reservation requests and come to consistent conclusions

  - all stations have same priority

- Simplest version

  - divide time into frames = fixed length set of slots (spans prop delay)
  - station that successfully transmit in a slot using S-ALOHA (this is known implicitly in satellite Aloha and with explicit ACK with cellular Aloha) makes implicit reservation and can keep slot as long as it wants
  - station that loses keeps track of idle slots and contends for them in next frame

Evaluating R-ALOHA

■ Pros

 ◆ supports both circuit and packet mode transfer

 ◆ works with large 'a'

 ◆ simple

■ Cons

 ◆ arriving packet has to wait for entire frame before it has a chance to send (frame length is at least 'a')

 ◆ cannot preempt hogs

 ◆ variants of R-ALOHA avoid these problems

Classification of multiple access schemes

Base technologies	FDMA			
	TDMA			
	CDMA			
	FDD			
	CDD			
Access schemes	Centralized	Circuit mode	EAMPS	Cellular telephony
			GSM	
			IS-95	
		Packet mode	Polling and probing	Wired LAN
			Reservation based — FPODA	satellite
			Reservation based — PDAMA	
	Distributed	Packet mode	Polling and probing	Wired LAN
			CSMA — CSMA/CD	Wired LAN
			CSMA — CSMA/CA	Wireless LAN
			BTMA — MACA	
			BTMA — MACAW	
			Token ring — FDDI	Wired LAN
			ALOHA — P-ALOHA	satellite
			ALOHA — S-ALOHA	
			ALOHA — R-ALOHA	