

# Multiple Access

An Engineering Approach to Computer Networking

## 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

- Use a moderator
  - ◆ a speaker must wait for moderator to call on 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, guarantee collision
- Designing good schemes is surprisingly hard!

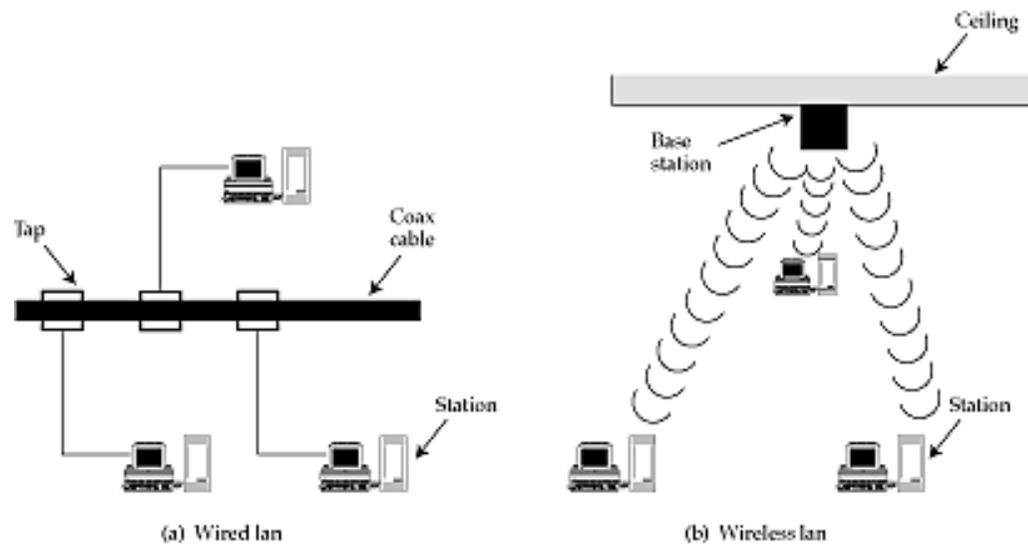
# Outline

- Contexts for the problem
- Choices and constraints
- Performance metrics
- Base technologies
- Centralized schemes
- Distributed schemes

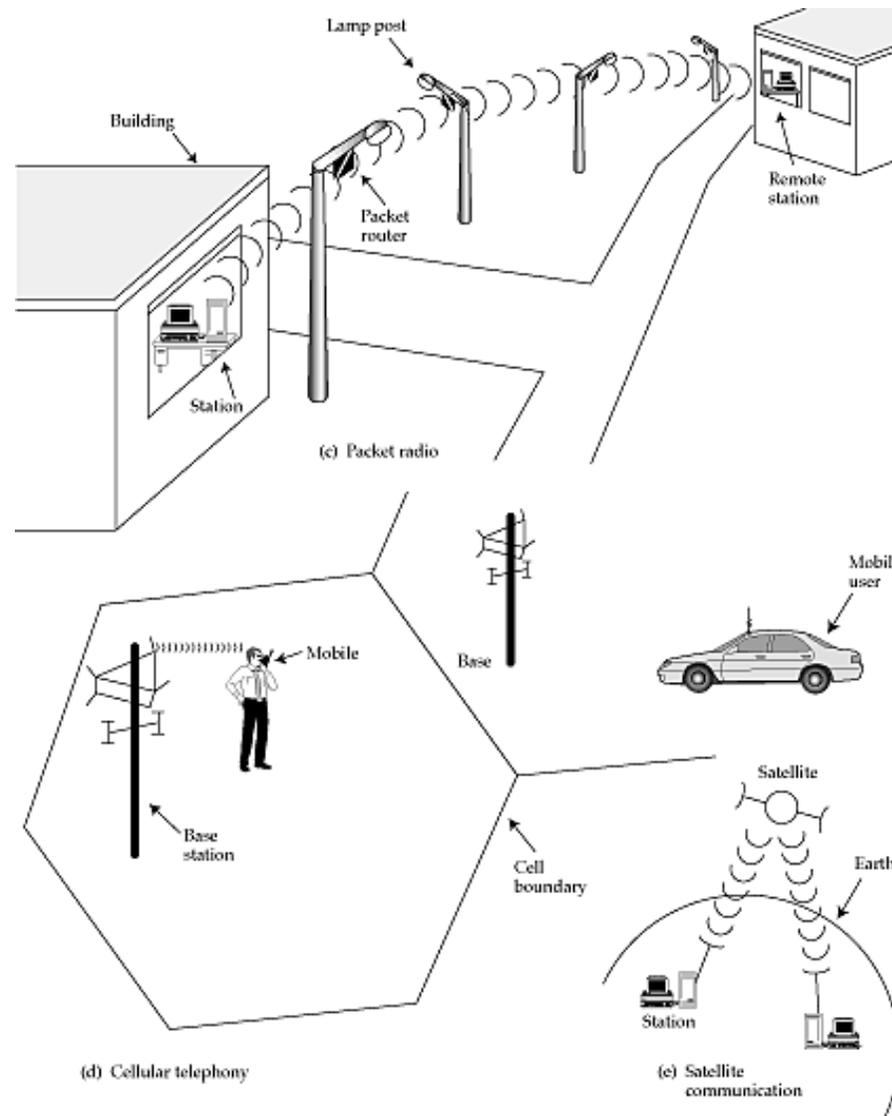
## Contexts for the multiple access problem

- *Broadcast* transmission medium
  - ◆ message from any transmitter is received by all receivers
- Colliding messages are garbled
- Goal
  - ◆ maximize message throughput
  - ◆ minimize mean waiting time
- Shows up in five main contexts

# Contexts



# Contexts



## Solving the problem

- First, choose a *base technology*
  - ◆ to isolate traffic from different stations
  - ◆ can be in time domain or frequency domain
- 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* 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
- ◆ with packets, makes sense to contend for every packet to avoid wasting bandwidth

# Constraints

## ■ Spectrum scarcity

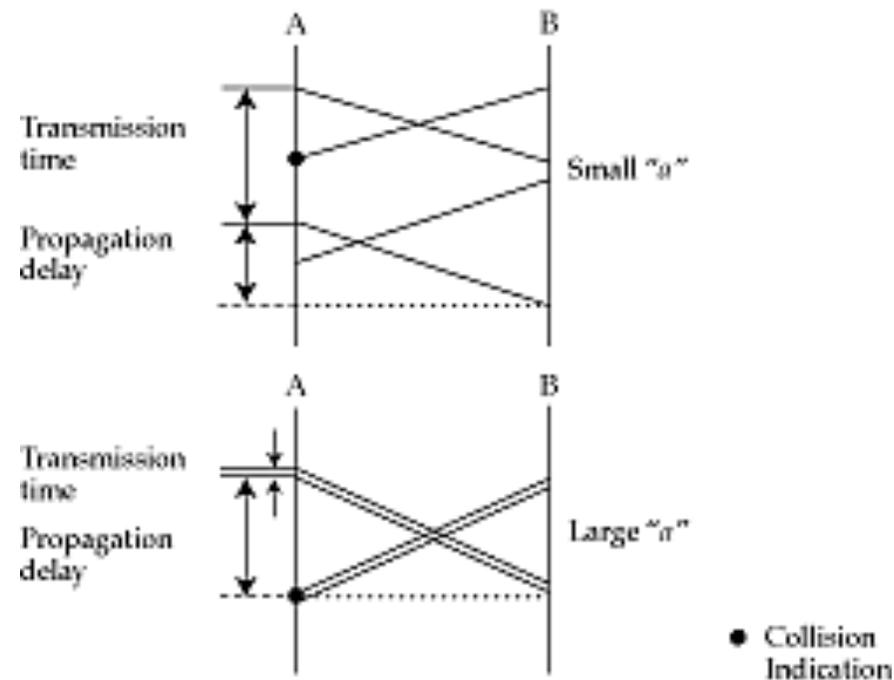
- ◆ radio spectrum is hard to come by
- ◆ only a few frequencies available for long-distance communication
- ◆ multiple access schemes must be careful not to waste bandwidth

## ■ Radio link properties

- ◆ radio links are error prone
  - ✦ fading
  - ✦ multipath interference
- ◆ hidden terminals
  - ✦ transmitter heard only by a subset of receivers
- ◆ capture
  - ✦ on collision, station with higher power overpowers the other
  - ✦ 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



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# Performance metrics

## ■ Normalized throughput

- ◆ fraction of link capacity used to carry non-retransmitted packets
- ◆ example
  - ✦ with no collisions, 1000 packets/sec
  - ✦ with a particular scheme and workload, 250 packets/sec
  - ✦  $\Rightarrow$  goodput = 0.25

## ■ Mean delay

- ◆ amount of time a station has to wait before it successfully transmits a packet
  - ✦ depends on 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 infinite 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
- ◆ max-min fair share: will study later

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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
- Number of frequencies is limited
  - ◆ reduce transmitter power; reuse frequencies in non-adjacent cells
  - ◆ example: voice channel = 30 KHz
  - ◆ 833 channels in 25 MHz band
  - ◆ with hexagonal cells, partition into 118 channels each
  - ◆ but with N cells in a city, can get 118N calls => win if  $N > 7$

# TDMA

- All stations transmit data on same frequency, but at different times
- Needs time synchronization
- Pros
  - ◆ users can be given different amounts of bandwidth
  - ◆ mobiles can use idle times to determine best base station
  - ◆ can switch off power when not transmitting
- Cons
  - ◆ synchronization overhead
  - ◆ greater problems with multipath interference on wireless links

# CDMA

- Users separated both by time and frequency
- 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
- Pros
  - ◆ hard to spy
  - ◆ immune from narrowband noise
  - ◆ no need for all stations to synchronize
  - ◆ no hard limit on capacity of a cell
  - ◆ all cells can use all frequencies

# CDMA

## ■ Cons

- ◆ implementation complexity
- ◆ need for power control
  - ◆ to avoid capture
- ◆ 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 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 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
  - ✦ master is involved in every single transfer => added delay

## Circuit mode

- When station wants to transmit, it sends a message to master using packet mode
- 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: FDMA
  - ◆ GSM/IS-54: TDMA
  - ◆ IS-95: CDMA

# Polling and probing

- Centralized packet-mode multiple access schemes
- Polling
  - ◆ master asks each station in turn if it wants to send (roll-call polling)
  - ◆ inefficient if only a few stations are active, overhead for polling messages is high, or 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 addresses
  - ◆ master does a binary search to locate next active station

## Reservation-based schemes

- When 'a' is large, can't use a distributed scheme for packet mode (too many collisions)
  - ◆ mainly for satellite links
- Instead 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 (or own one)
- 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
- Almost all distributed schemes are packet mode (why?)

## Decentralized polling

- Just like centralized polling, except there is no master
- Each station is assigned a slot that it uses
  - ◆ if nothing to send, slot is wasted
- Also, all stations must share a time base

## Decentralized probing

- Also called *tree based multiple access*
- All stations in left subtree of root place packet on medium
- If a collision, root  $\leftarrow$  root  $\rightarrow$  left\_son, and try again
- On success, everyone in root  $\rightarrow$  right\_son places a packet etc.
- (If two nodes with successive logical addresses have a packet to send, how many collisions will it take for one of them to win access?)
- Works poorly with many active stations, or when all active stations are in the same subtree

## Carrier Sense Multiple Access (CSMA)

- 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
- If collision happens, detect and resolve
- Works when 'a' is small

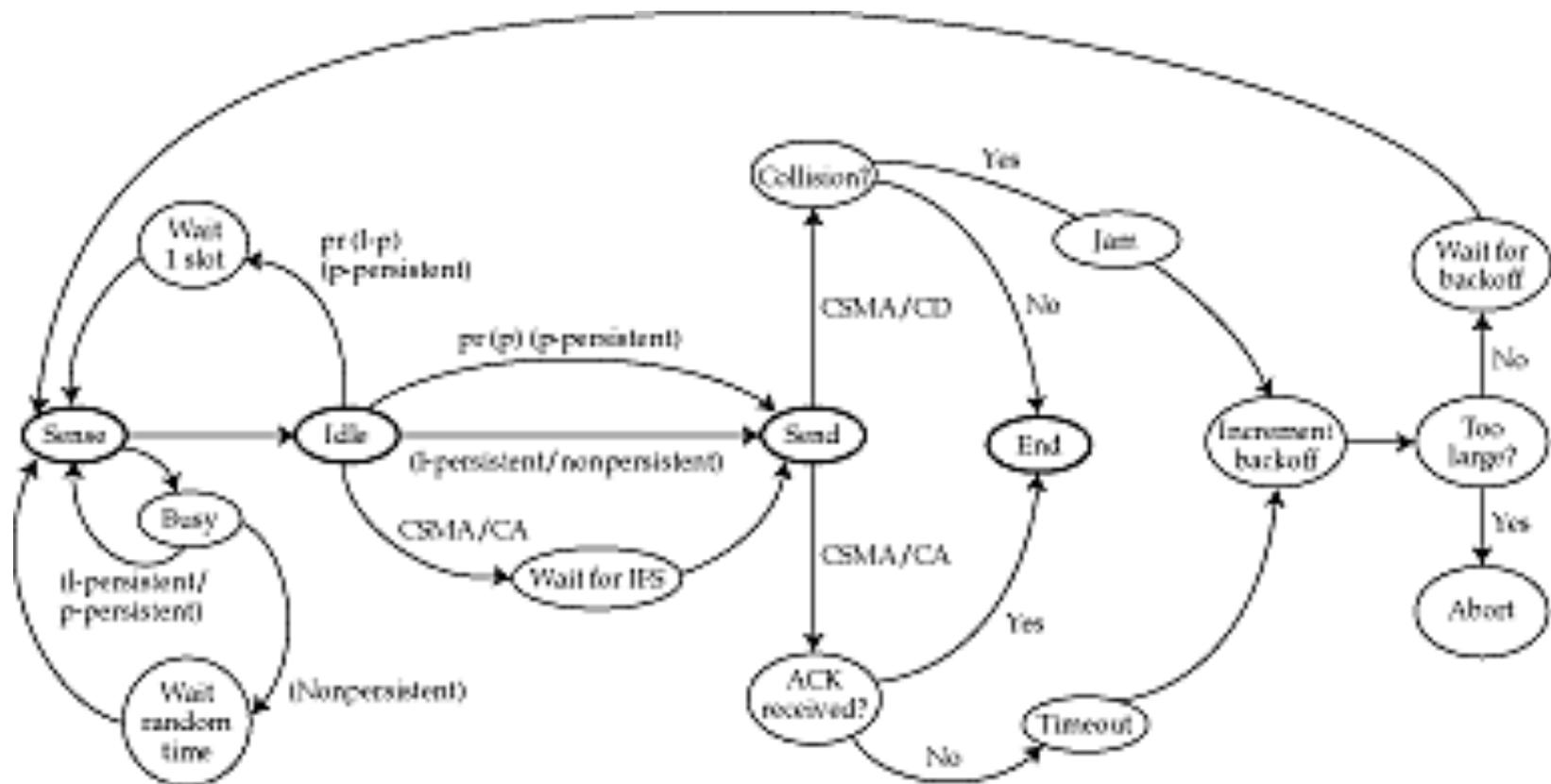
## Simplest CSMA scheme

- 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*: on idle, transmit with probability  $p$ :
  - ◆ hard to choose  $p$
  - ◆ if  $p$  small, then wasted time
  - ◆ if  $p$  large, more collisions
- *exponential backoff*
  - ◆ on collision, choose timeout randomly from doubled range
  - ◆ backoff range adapts to number of contending stations
  - ◆ no need to choose  $p$
  - ◆ need to detect collisions: *collision detect circuit* => CSMA/CD

## Summary of CSMA schemes



# Ethernet

- The most widely used LAN
- Standard is called IEEE 802.3
- Uses 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 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 ( $a \leq 1$ )
  - ◆ 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 and used ‘thick’ coax
- These days, runs at 10 Mbps, and uses ‘thin’ coax, or twisted pair (Category 3 and Category 5)
- Ethernet types are coded as <Speed><Baseband or broadband><physical medium>
  - ◆ Speed = 3, 10, 100, 1000, 10000 Mbps
  - ◆ Baseband = within building, broadband = on cable TV
  - ◆ Physical medium:
    - ✦ “2” is cheap 50 Ohm cable, upto 185 meters
    - ✦ “T” is unshielded twisted pair (also used for telephone wiring)
    - ✦ “36” is 75 Ohm cable TV cable, upto 3600 meters

# developments

## ■ Switched Ethernet

- ◆ each station is connected to switch by a separate UTP wire
- ◆ 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)

# Fast Ethernet variants

- Fast Ethernet (IEEE 802.3u)
  - ◆ same as 10BaseT, except that line speed is 100 Mbps
  - ◆ Common way to present fast bband in home now
  - ◆ spans only 205 m
  - ◆ big winner
  - ◆ most current cards support both 10 and 100 Mbps cards (10/100 cards) for about \$10
- 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 & 10GigE & 100GigE
  - ◆ continues the trend
  - ◆ still undefined, but first implementation will be based on fiber links

# Evaluating Ethernet

## ■ Pros

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

## ■ Problems

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

## ■ But, very successful because

- ◆ problems only at high load
- ◆ can segment LANs to reduce load

## CSMA/CA

- Used in wireless LANs
- Can't detect collision because transmitter overwhelms colocated receiver - might change in future...
- So Collision Avoidance (CA) not Detection (CD)
- So, need explicit acks
- But this makes collisions more expensive
  - ◆ => try to reduce number of collisions

## CSMA/CA algorithm

- First check if medium is busy
- If so, wait for medium to become idle
- Wait for interframe spacing
- Set a *contention timer* to an interval randomly chosen in the range  $[1, CW]$
- 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
- (Why does this scheme reduce collisions compared to CSMA/CD?)

## 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
- Exposed terminal
  - ◆ some (but not all) stations can hear transmissions from stations not in the local area

## 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
- Two solutions
- Busy Tone Multiple Access (BTMA)
  - ◆ 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 that station hears
  - ◆ this avoids both problems (why?)

# Multiple Access Collision Avoidance

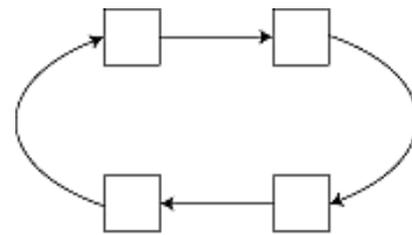
- BTMA requires us to split frequency band
  - ◆ more complex receivers (need two tuners)
- Separate bands may have different propagation characteristics
  - ◆ scheme fails!
- Instead, use a single frequency band, but use explicit messages to tell others that receiver is busy
- In MACA, before sending 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
- (why does this work?)

## Token passing

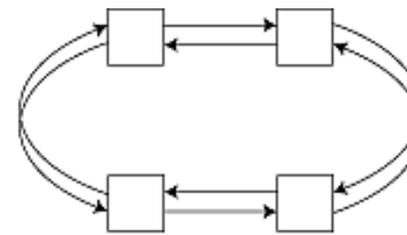
- In distributed polling, every station has to wait for its turn
- Time wasted because idle stations are still given a slot
- What if we can quickly skip past idle stations?
- This is the key idea of token ring
- Special packet called 'token' gives station the right to transmit data
- When done, it passes token to 'next' station
  - ◆ => stations form a logical ring
- No station will starve

# Logical rings

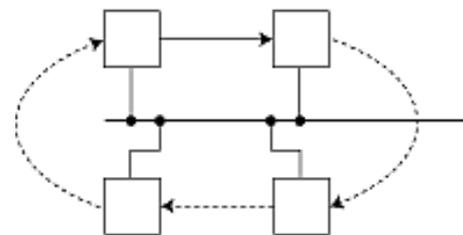
- Can be on a non-ring physical topology



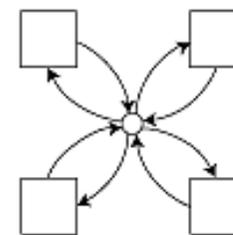
(a) Single ring



(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 and deletes it
- 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
  - ✦ usually elect one station as monitor

# Fiber Distributed Data Interface

- FDDI is the most popular token-ring base LAN
- Dual counterrotating rings, each at 100 Mbps
- Uses both copper 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

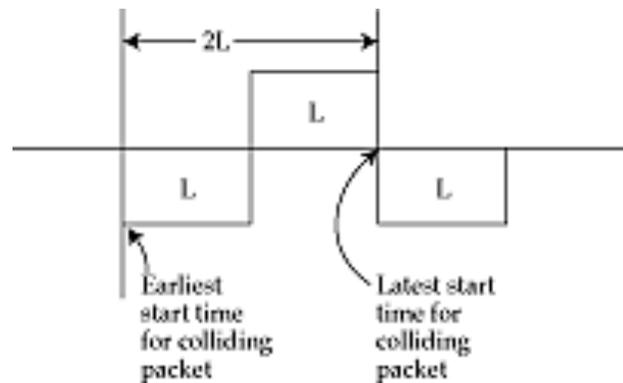
- ◆ useful when 'a' is large, so carrier sensing doesn't help
  - ✦ satellite links
- ◆ simple
  - ✦ no carrier sensing, no token, no timebase synchronization
- ◆ independent of 'a'

## ■ Cons

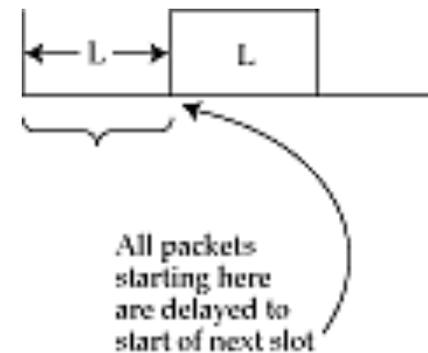
- ◆ under some mathematical assumptions, goodput is at most .18
- ◆ at high loads, collisions are very frequent
- ◆ sudden burst of traffic can lead to instability
  - ✦ unless backoff is exponential

# Slotted ALOHA

- A simple way to double ALOHA's capacity
- Make sure transmissions start on a slot boundary
- Halves *window of vulnerability*
- Used in cellular phone uplink

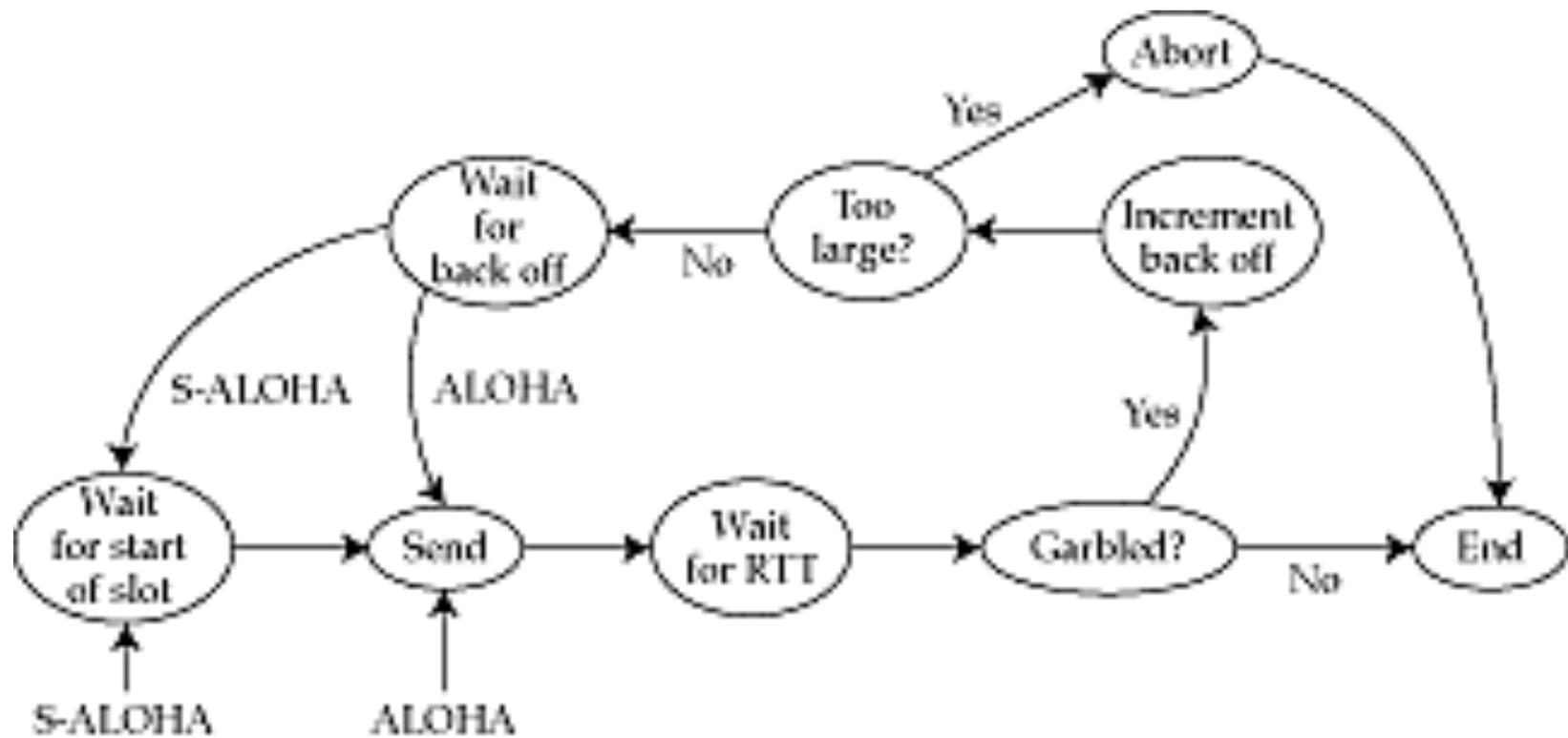


(a) ALOHA



(b) Slotted ALOHA

## ALOHA schemes summarized



## Reservation ALOHA

- Combines slot reservation with slotted ALOHA
- Contend for reservation minislots using slotted ALOHA
- Stations independently examine reservation requests and come to consistent conclusions
- Simplest version
  - ◆ divide time into frames = fixed length set of slots
  - ◆ station that wins access to a reservation minislot using S-ALOHA 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
- ◆ cannot preempt hogs
- ◆ variants of R-ALOHA avoid these problems

## ■ Used for cable-modem uplinks