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!

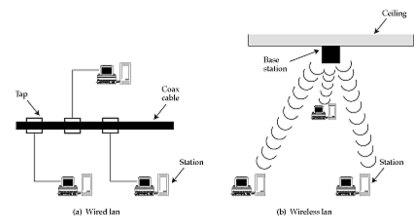
Outline

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

Contexts for the multiple access problem

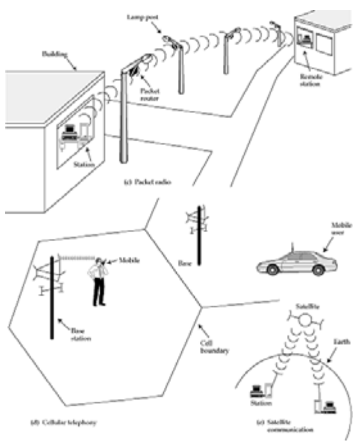
- *Broadcast* transmission medium
  - message from any transmitter is received by all receivers
- Colliding messages are garbled
- Goal
  - maximize message throughput
  - minimize mean waiting time
- Shows up in five main contexts

Contexts



(a) Wired lan (b) Wireless lan

Contexts



(c) Packet radio (d) Cellular telephony (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
- Then, choose how to allocate a limited number of transmission resources to a larger set of contending users

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Choices

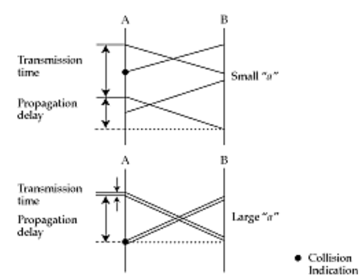
- Centralized vs. distributed design
  - is there a moderator or not?
  - in a centralized solution one of the stations is a *master* and the others are *slaves*
    - master->slave = downlink
    - slave->master = uplink
  - in a distributed solution, all stations are peers
- Circuit-mode vs. packet-mode
  - 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
    - => 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 <- root ->left_son, and try again
- On success, everyone in root->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

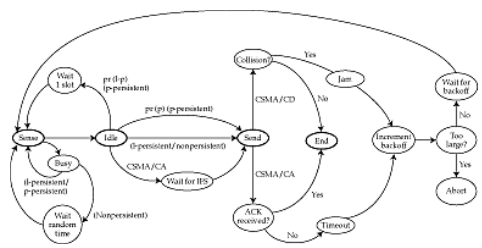
Simplest CSMA scheme

- 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 <= 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 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

Recent 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
  - 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
  - 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
- 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

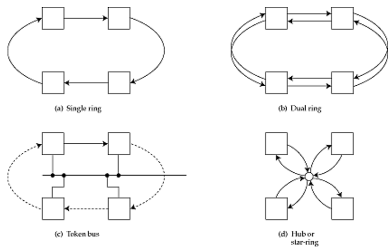
- BTMA requires us to split frequency band
  - more complex receivers (need two tuners)
- Separate bands may have different propagation characteristics
  - scheme fails!
- Instead, use a single frequency band, but use explicit messages to tell others that receiver is busy
- In MACA, before sending data,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



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

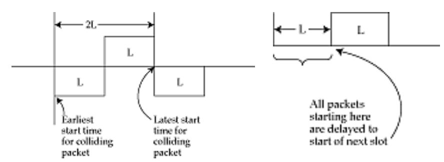
- ALOHA is one of the earliest multiple access schemes
- Just send it!
- Wait for an ack
- If no ack, try again after a random waiting time
  - no backoff

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

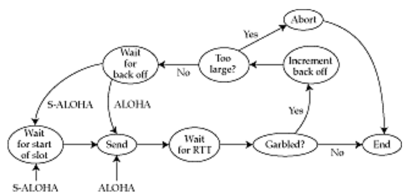
Slotted ALOHA

- 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