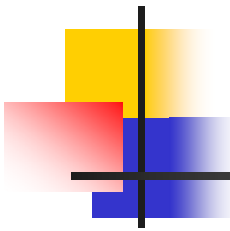


Lecture 2

Media Access Control I

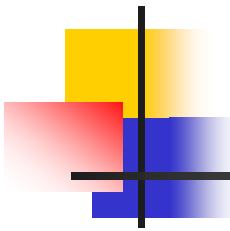
Reading:

- “Multiple Access Techniques,” in *Ad Hoc Wireless Networks: Architectures and Protocols*, Chapter 1.6.
- A. Chandra, V. Gummalla, and J. Limb,
“Wireless Medium Access Control Protocols,”
IEEE Communications Surveys, Second Quarter 2000.
<http://www.comsoc.org/livepubs/surveys/public/2q00issue/gummalla.html>



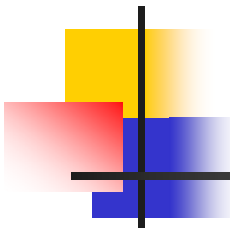
Media Access Control (MAC)

- Protocols that enable multiple users to share a finite amount of frequency and time resources
 - Needed for efficient operation and good performance for wireless systems
 - Goal: minimize overhead while maximizing overall network capacity



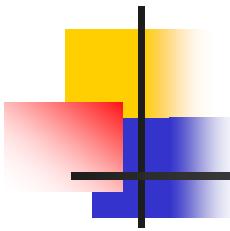
MAC Performance Parameters

- Throughput (S): average number of messages successfully transmitted per unit time
- Delay (D): average delay experienced by a packet
- Fairness: how well a MAC protocol shares the bandwidth among multiple users
- Stability: performance under load fluctuations
- Robustness against channel fades
- Power consumption: power-saving features of the protocol
- Multimedia support: how well the protocol supports different types of traffic (e.g., real-time, high-priority data, etc.)



Main Types of MAC

- Fixed assignment techniques
 - Frequency-division multiple access (FDMA)
 - Time-division multiple access (TDMA)
 - Spread-spectrum multiple access (SSMA)
 - Frequency-hopped spread-spectrum (FHSS)
 - Direct-sequence spread-spectrum (DSSS) / Code-division multiple access (CDMA)
 - Space-division multiple access (SDMA)
- Random access (RA) techniques
 - Packet-radio techniques (PR)
- Controlled random access
 - Combination fixed assignment and RA
 - Use RA to obtain fixed resources

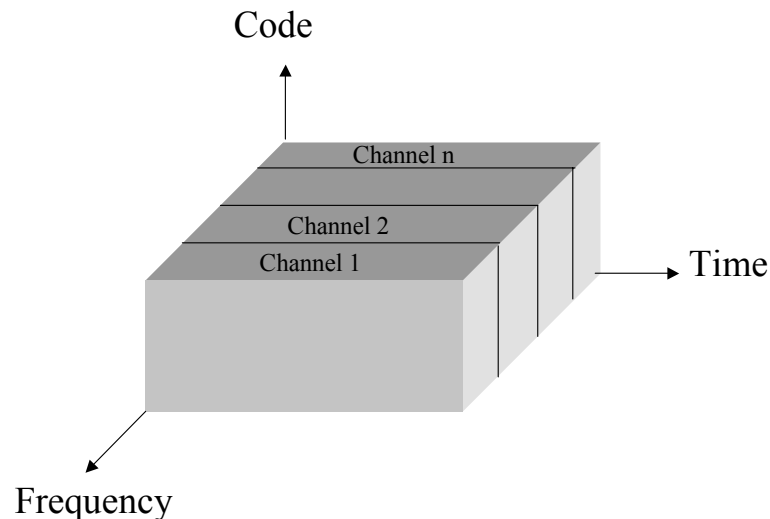


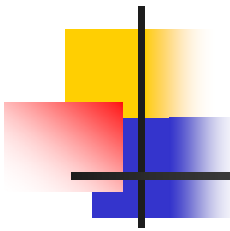
Party Analogy

- Suppose there are people at a party who all want to talk
- If everyone talked at once, no one would be able to hear anyone
- If one person raises his voice to be heard, others will raise their voices and eventually everyone will be shouting and no one will be able to communicate
- How can this situation be resolved?
 - Each person could be given a turn to speak (TDMA)
 - Each group could be given a language in which to speak to each other (CDMA)
 - Each group could be given a corner of the room to hold their conversation (SDMA)
 - Each person talks with a certain probability p when they determine that no one else is currently speaking (PR)

Frequency-Division MA

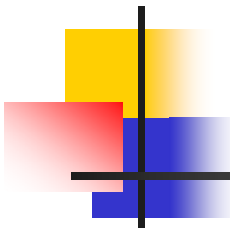
- Radio spectrum broken into frequency bands (channels)
- Each channel allocated to a different user (only 1 user per frequency band)
- Each channel must contain guard bands





FDMA (cont.)

- Channels can be assigned on-demand when a user needs to communicate
- Each user can only be assigned 1 channel → if not enough users for the number of channels, the radio spectrum is unused (i.e., wasted)
- FDMA usually used in narrowband systems (e.g., 30 kHz frequency bands)
- Large symbol time compared to average delay spread → low ISI
- Little synchronization required because transmission is continuous in FDMA → reduces overhead

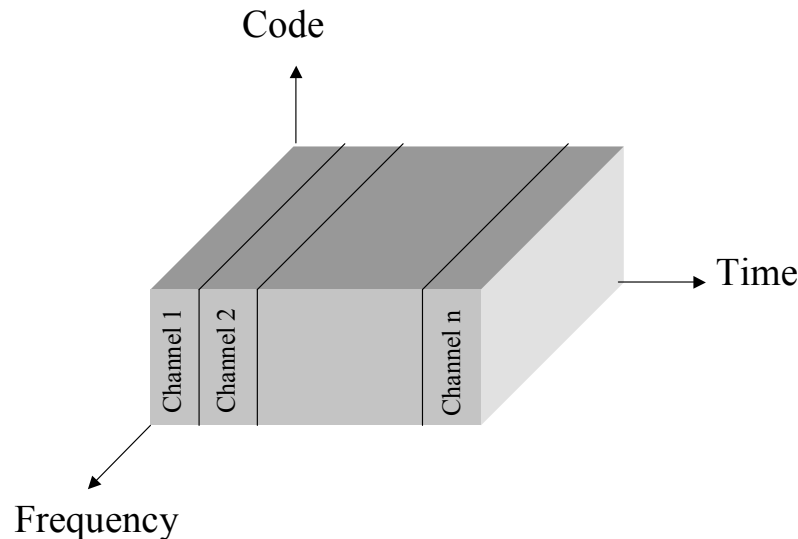


FDMA (cont.)

- Requires expensive filters to reduce adjacent channel interference
- Intermodulation (IM)
 - Nonlinearities in power amplifiers cause signal spreading in freq domain
 - Undesired RF radiation that leaks into other channels in FDMA systems
 - Adjacent-channel interference
 - Generation of undesirable harmonics that cause interference to other users in mobile system or other systems in adjacent spectrum bands

Time Division MA (TDMA)

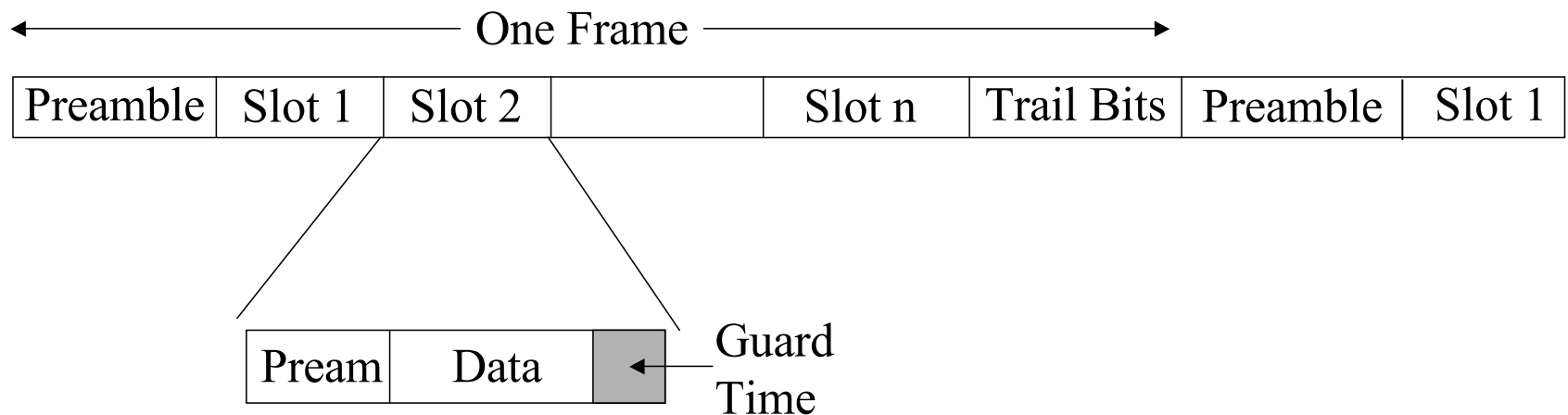
- Users access entire radio spectrum for a given time slot (channels)

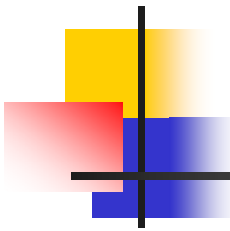


- Only 1 user can transmit or receive data per slot
- Time divided into frames
 - Preamble (with synchronization info)
 - Several slots of data
 - Number of data slots per frame depends on modulation, bandwidth, average data rates and required latencies

TDMA (cont.)

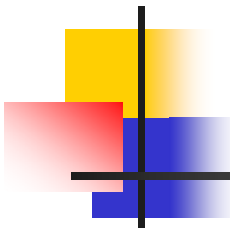
- Slot contains
 - Preamble for addressing and synchronization
 - Data
 - Guard times between the slots to reduce cross-talk between channels





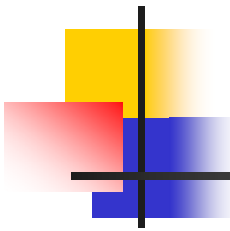
TDMA (cont.)

- Can use multi-slot assignments to support increased user data rate
- Channels can be assigned on-demand when a user needs to communicate



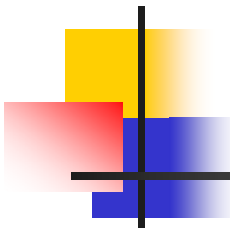
TDMA Advantages

- Narrowband filters not needed → cheaper than FDMA
- Mobile devices can save battery power by turning off transmitter and receiver during slots when not transmitting or receiving data
- Can allocate multiple time slots to a user to provide increased data rate → more BW efficient than FDMA



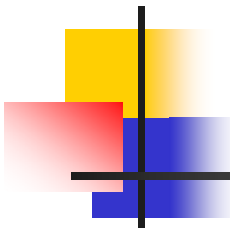
TDMA Disadvantages

- Requires guard time between time slots to separate users and accommodate
 - Time inaccuracies due to clock instability
 - Delay spread of transmitted symbols
 - Transmission time delay
- Requires signal processing techniques and high overhead for synchronization due to burst transmissions



Spread-Spectrum MA (SSMA)

- Transmission bandwidth is several orders of magnitude greater than minimum required bandwidth
- Immunity to frequency-selective fades and multipath interference
- Multiple users share the same RF spectrum at the same time
 - No hard limit on the number of users
 - Bandwidth inefficient when few users sharing the channel
 - Bandwidth efficient when lots of users share the channel
- Direct-sequence (DS): pseudo-noise (PN) sequence converts narrowband signal to wideband signal with noise-like properties
- Frequency-hopped (FH) spread spectrum: pseudorandom hopping sequence used to vary carrier signal

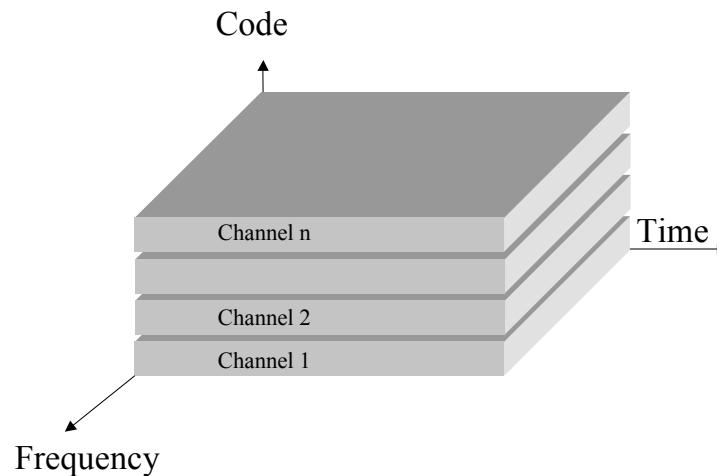


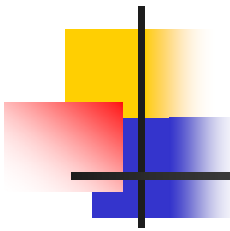
SSMA Advantages

- SS signals can be overlaid onto bands where other systems are already operating with minimal impact to or from the other systems
- SS signals have good immunity to multi-path and frequency-selective fading
- SS systems have greater flexibility and overall system capacity than FDMA or TDMA systems → no hard capacity limit
- Unlicensed SS systems can be used in the ISM bands

Direct-Sequence SS (DSSS)

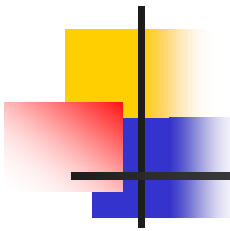
- Each user occupies bandwidth several times larger than the message bandwidth
- Message signal multiplied by a very large BW “spreading signal”, a PN-code sequence with a “chip rate” several orders of magnitude larger than the message data rate
- In CDMA (code-division multiple access), spreading signals (codes) are approximately orthogonal





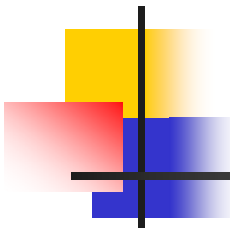
DSSS (cont.)

- Receiver correlates received signal with a particular codeword to detect desired signal
 - Correlating received signal $r(t) = \sum_i m_i(t)c_i(t) + n(t)$ with code $c_i(t)$ will filter out other orthogonal signals since $\int_{-\infty}^{\infty} c_i(t)c_j(t)dt = 0$
 - In theory, only noise corrupts received signal
- SNR determined by the power of the other users relative to the power of the desired user
 - DSSS systems reject interference by spreading it in time-frequency



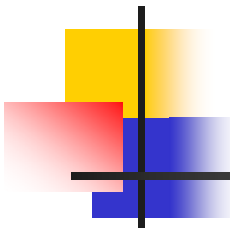
Near-Far Problem

- If all mobiles transmit with the same power, the signals from mobiles closest to the BS will be received with much larger power than signals from mobiles further away. Therefore, the SNR for signals from mobiles far from the BS will be low
 - Signals from mobiles close to the BS will drown out signals from mobiles far away from the BS
- Requires power control to ensure the power of all signals received at the base station is approx. equal
 - BS determines received power from each mobile (using RSSI—received signal strength indicator)
 - Tells the mobile to increase or decrease its transmit power to ensure all signals received with the same power
- Power control conserves battery power and minimizes interference to other users



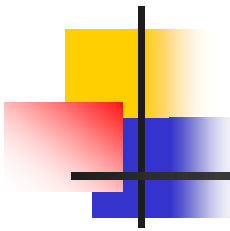
Advantages of DSSS

- Multipath fading and frequency-selective fading effects reduced due to spreading of the signal bandwidth
- Channel data rates high → chip duration is short and usually much less than channel delay spread
 - PN-sequences have low autocorrelation, multipath which is delayed more than a chip will appear as noise
 - RAKE receiver can be used to improve reception by collecting time-delayed versions of the signal
- Soft capacity limit on the number of users—each user sees degradation in performance as # of users increased and improvement in performance as # of users decreased
- Can take advantage of voice activity patterns that cannot be effectively exploited in FDMA or TDMA systems
- Security: need to know spreading code to intercept signal



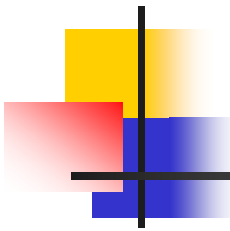
Disadvantages of DSSS

- Implementation complexity: high channel data rates
 - Expensive receivers
- Self-jamming due to non-perfect orthogonality of spreading codes
 - Other users' signals will appear as noise and reduce SNR of desired signal
- Near-far problem causes reduced performance if receiver cannot control the power level of the near mobile



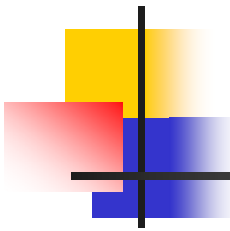
Frequency-Hopped SS (FHSS)

- System bandwidth (B_t) broken into smaller channels (bandwidth = B_c), data stream broken into bursts
- Carrier frequency varied for each data burst in a pseudorandom fashion
 - User “hops” among the different channels
 - T_h = hop period
 - Instantaneous bandwidth of each transmission is small, but spread bandwidth is large
- Multiple users can access the channel at the same time due to pseudorandom hopping sequence
 - Ensures low probability of multiple users accessing same hop frequency at the same time



FHSS (cont.)

- Fast frequency hopping
 - $T_h > T_s$, there is a frequency hop for each transmitted symbol
 - Hopping rate equals or exceeds the information symbol rate
- Slow frequency hopping
 - $T_h \geq T_s$, one or more symbols are transmitted in the time interval between frequency hops
- FHSS systems reject interference by trying to avoid it



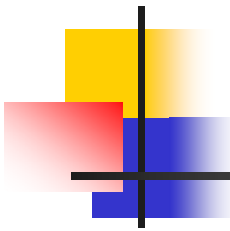
FHSS (cont.)

- Advantages of FHSS

- Immunity to frequency-selective fades using channel coding, interleaving, and disjointed frequency channels
- Security: use of pseudorandom hopping pattern makes it hard for others to intercept full message
- Soft capacity
- Immune to the near-far problem

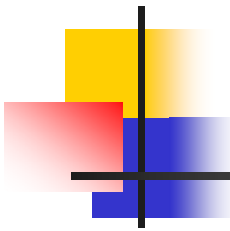
- Disadvantages of FHSS

- Multi-user interference possible if two or more users simultaneously occupy a frequency channel
 - Can use channel coding and interleaving to protect against this



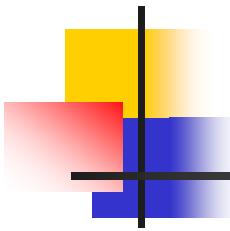
Space-Division MA (SDMA)

- Segments a coverage area in space
- Uses directional antennas that transmit signals only in a certain direction
 - Within each space sector, can use TDMA, FDMA, or SSMA to divide the time-frequency resources among users
 - Adaptive antennas track users and direct energy in direction
- Ideal SDMA
 - Adaptive antennas with infinitesimal beamwidth and infinitely fast tracking ability
 - Provides unique channel for each user with no interference from other users in cell
 - All users could communicate at the same time using the same channel
 - Not realizable!



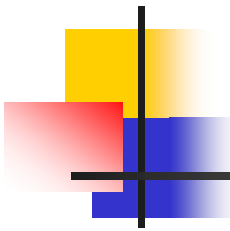
Hybrid MAC

- FDMA/CDMA
 - Spectrum divided into channels
 - Each channel is a narrowband CDMA system with processing gain lower than original CDMA system
- DSSS/FHSS
 - Direct sequence modulate signal and hop center frequency using pseudorandom hopping pattern
 - Avoid near-far effect
- TDMA/CDMA
 - Different spreading codes assigned to different cells
 - One user per cell allotted particular time slot
 - Only 1 CDMA user tx in each cell at any given time
 - Avoids near-far effect



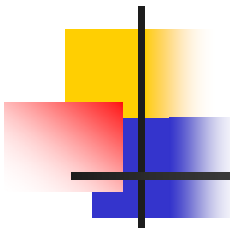
Hybrid MAC (cont.)

- TDMA/FHSS
 - Hop to new frequency at start of new TDMA frame
 - Avoids severe fades on particular channel
 - Used in GSM
 - Hopping sequence predefined, unique per cell
 - Avoid co-channel interference if other BSs transmit on different frequencies at different times



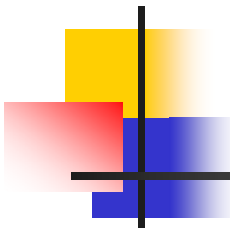
Random Access MAC Protocols

- Users attempt to access the channel in an uncoordinated manner
- Collisions detected at destination
 - Destination sends ACKs
 - Perfect feedback via ACKs but traffic delay may be high
- Vulnerable period = V_p = time interval during which packets are susceptible to collisions with transmissions from other users



Summary of RA Approaches

- ALOHA
 - Pure ALOHA
 - Slotted-ALOHA
- CSMA: carrier sense multiple access
 - 1-persistent CSMA
 - non-persistent CSMA
 - p-persistent CSMA
- CSMA/CA: CSMA with collision avoidance
 - BTMA: Busy-tone MA
 - DSMA: Data-sense MA
- MACAW: MA with CA for wireless networks

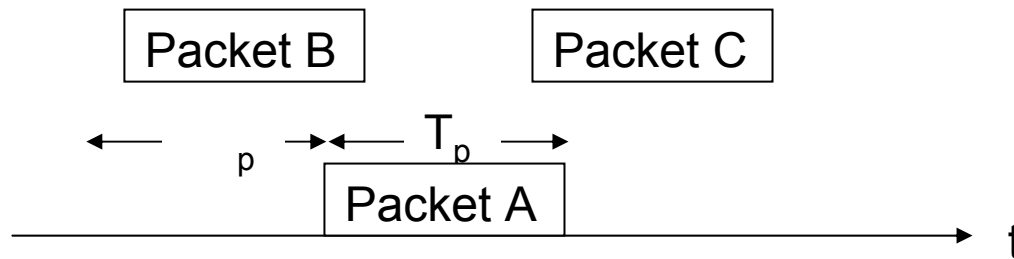


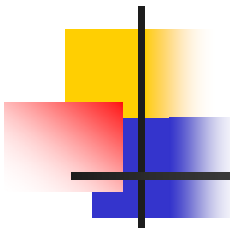
Pure ALOHA

- Data packetized
- Nodes transmit whenever have information to send
- Nodes transmit packets at arbitrary times
- Collisions occur if packet transmissions overlap by any amount of time
 - Collision → both packets must be retransmitted
- Node waits for an ACK from receiver
 - If no ACK received, packet assumed lost in collision and retransmitted after a random delay – why wait?

Pure ALOHA (cont.)

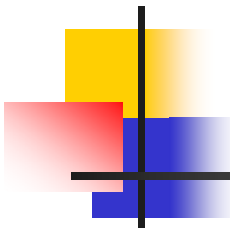
- Assume all packets have same length (L) and require T_p seconds for transmission
- Each packet vulnerable to collisions for time $V_p = ??$
 - Suppose packet A sent at time t_o
 - If pkt B sent any time between $t_o - T_p$ and $t_o \rightarrow$ end of packet B collides with beginning of packet A
 - If pkt C sent any time between t_o and $t_o + T_p \rightarrow$ start of packet C will collide with end of packet A
 - Total vulnerable interval for packet A is $2T_p$





Throughput of Pure ALOHA

- Channel throughput S = average number of successful packet transmissions per time interval T_p
- G = total traffic offered to the channel = number of packet transmissions attempted per packet time T_p , including new packets as well as retransmissions of old packets
- Standard unit of traffic flow is the Erlang
 - If channel segmented into intervals of T_p seconds, a traffic flow of one packet per T_p seconds has a value of 1 Erlang
 - Throughput cannot exceed 1 Erlang without collisions
 - $0 \leq S \leq 1$
- If G small, few collisions, few retransmissions, so $S \sim G$
- If G large, many collisions, many retransmissions, so $S \ll G$ and $S \rightarrow 0$

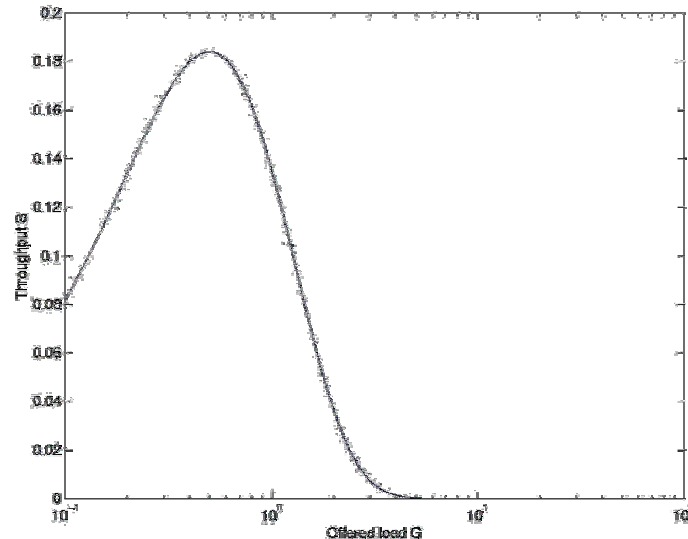


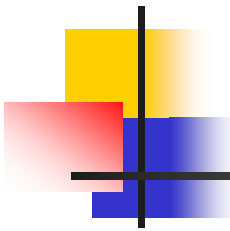
Traffic Model

- Probability that k packets generated during given packet time
 - Obeys Poisson distribution with a
 - Mean of I packets per second
 - Mean of G packets per packet period T_p
 - $G = IT_p$
- $P(k) = \Pr(k \text{ packets generated in time } T_p)$
 $= G^k e^{-G} / k!$
- Poisson arrival model provides good approximation for network serving large numbers of nodes

Throughput Analysis

- Throughput $S = G * \Pr(\text{no collisions})$
- $V_p = 2T_p$
 - $P'(k) = (2G)^k e^{-(2G)} / k! = \Pr(k \text{ pkts gen. in time } 2T_p)$
- $\Pr(\text{no collisions}) = \Pr(\text{no other packet generated during the vulnerable interval} = 2 \text{ packet slots}) = P'(0) = e^{-2G}$
- $S = Ge^{-2G}$





Maximum Throughput

- Max Throughput

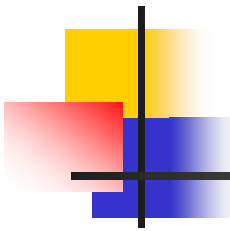
- $dS/dG = e^{-2G} - 2Ge^{-2G} = 0$
- $G_{\max} = 1/2 \rightarrow S_{\max} = 1/(2e) \sim 0.184$
- ALOHA can achieve maximum throughput of 18.4%

- Ex.

- System supports 10 Mbps
- Using pure ALOHA, nodes can get at most 1.84 Mbps of info through network
- At that peak, total traffic from terminals is

$$0.5 * 10 \text{ Mbps} = 5 \text{ Mbps}$$

- 1.84 Mbps is successfully delivered pkts (old and new)
- 3.16 Mbps is packets that suffer collisions

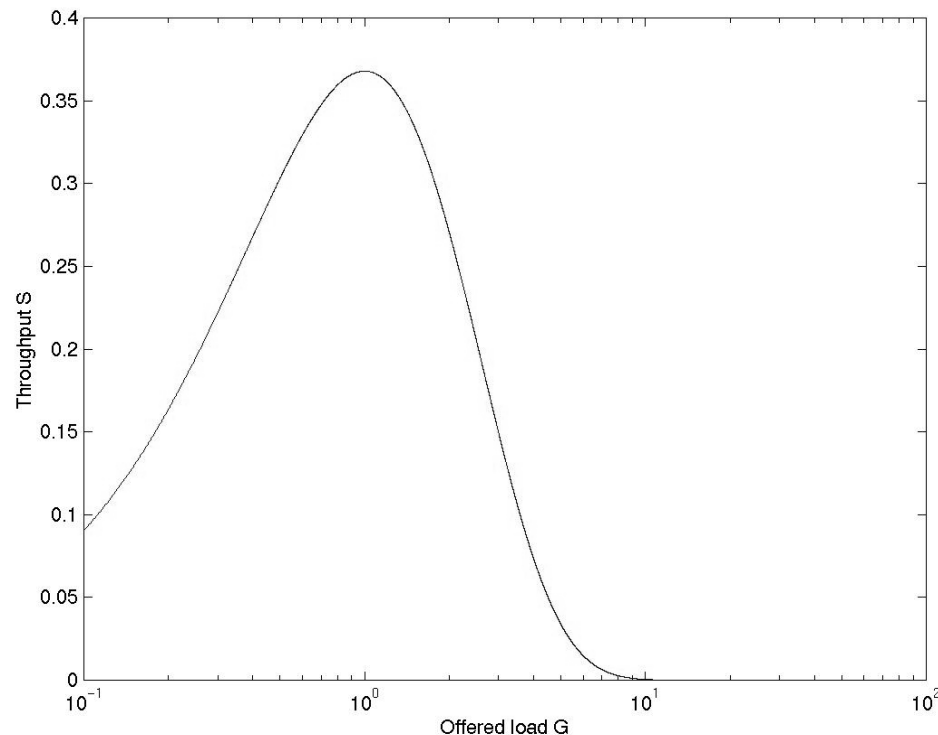


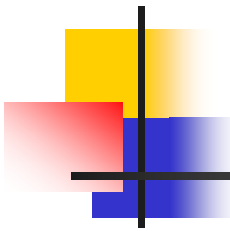
Slotted ALOHA

- Can increase efficiency of ALOHA using slotted system
- Transmission time divided into time slots, each slot equal to packet Tx time
- All users synchronized to these time slots
 - Packets held until next time slot for transmission if generated in-between transmission slots
 - Synchronization achieved by transmitting periodic synch pulses from one designated station in the network
- Vulnerable period reduced to T_p

Throughput of Slotted ALOHA

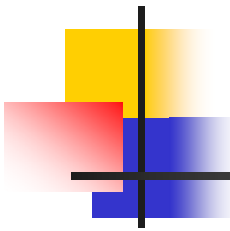
- $\Pr(\text{no collisions}) = \Pr(\text{no other pkts generated during } T_p) = P(0) = e^{-G}$
- $S = Ge^{-G}$





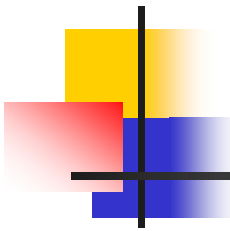
Maximum Throughput

- $dS/dG = e^{-G} - Ge^{-G} = 0$
- $G_{\max} = 1.0 \rightarrow S_{\max} = 1/e \sim 0.368$
 - $2 \times S_{\max}$ for pure ALOHA
 - 37% of slots have successful data transmissions
- $G = 1 \rightarrow \Pr(0 \text{ packets offered}) = e^{-G} = 1/e \sim 0.368$
 - 37% of slots are empty
 - 26% of slots are in collision
- At higher traffic loads, number of successful slots and empty slots decreases and number of collision slots increases
- Slotted ALOHA also not efficient



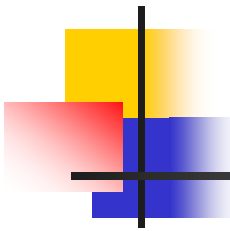
Carrier Sense Multiple Access

- ALOHA is an unstable protocol
 - If G increases to greater than 1 due to fluctuation in offered load, S will decrease
 - Reduction in throughput means fewer successful packet transmissions and more collisions
 - Number of retransmissions increases, backlogging messages to be transmitted and traffic load G
 - This in turn decreases S
 - Results in operating point moving to right and $S \rightarrow 0$
- Random access protocols can be made stable using backoff parameters



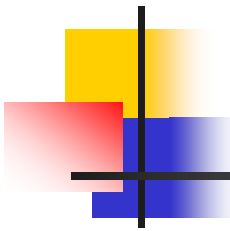
CSMA (cont.)

- Inefficiency of ALOHA
 - Users do not take note of transmissions of other users
 - Leads to high collision probability
 - Collisions can be reduced by reducing offered load
 - Leaves channel underutilized
- More efficient approach: users listen to the channel before attempting to transmit a packet
 - Basis for CSMA or “listen-before-talk” protocols



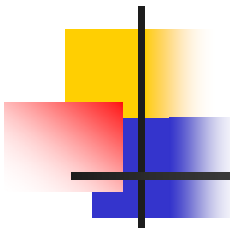
CSMA (cont.)

- Detection and propagation delay important parameters
 - Detection delay = time required for node to sense whether or not channel is idle
 - Propagation delay = time required for packet to travel from one node to the furthest node on the network
 - Want both small detection time and small propagation delay to minimize collisions
- Several flavors of CSMA
 - 1-persistent CSMA
 - non-persistent CSMA
 - p-persistent CSMA



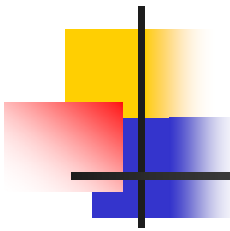
1-persistent CSMA

- Node listens to channel to determine if idle or busy
- If channel is busy, node listens continuously, waiting until the channel becomes free
- Once channel is free, node sends pkt immediately
- Strategy: transmit packet with $P_r = 1$ when channel is free
- Node waits for an ACK
- If no ACK received, node waits a random amount of time and resumes listening to the channel
- When channel again sensed idle, pkt immediately retransmitted



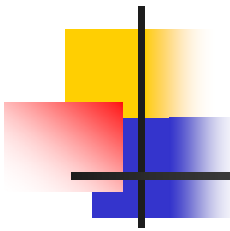
1-persistent CSMA (cont.)

- Collisions can occur
 - Propagation delays: Node A might sense idle channel even though Node B already began transmitting
 - If Node A and Node B are sensing a busy channel at the same time, as soon as the channel is free, both A and B will begin transmitting their data
- Throughput performance much better than ALOHA
- Slotted 1-persistent CSMA where nodes begin transmission at given time slots



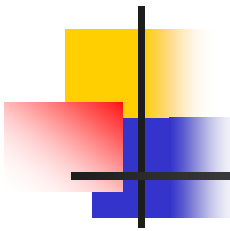
Nonpersistent CSMA

- Node listens to channel
- If channel idle, node transmits data
- If channel busy, node waits a randomly selected interval of time before sensing again
 - If channel idle, node transmits data immediately
 - Otherwise, node again waits a randomly selected interval of time before sensing again
- Randomized waiting times between channel sensings eliminate most collisions resulting from multiple users transmitting simultaneously upon sensing the transition from busy to idle



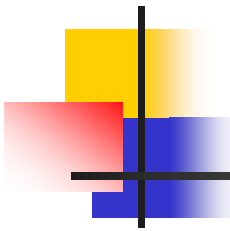
Nonpersistent CSMA (cont.)

- Throughput values much higher than 1-persistent CSMA at high traffic loads
 - Max throughput values of 80% or higher
 - At low traffic loads, throughput poor because waiting strategy does not give benefit when there are few users trying to transmit
- Slotted version of nonpersistent CSMA



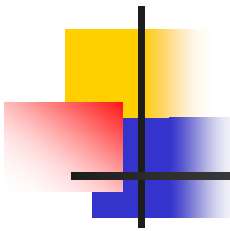
p-persistent CSMA

- Slotted channels where slot length typically chosen to be maximum propagation delay
- Node senses the channel
 - If the channel is idle, node transmits with probability p
 - With probability $1-p$ the node defers action to the next slot, where it senses the channel again
 - If that slot is idle, the station transmits with probability p or defers again with probability $1-p$
 - Procedure repeated until either the packet transmitted or the channel sensed to be busy
 - When channel detected busy, node senses continuously
 - When the channel again becomes free, the node starts the procedure again



p-persistent CSMA (cont.)

- For low/intermediate values of propagation delay and with p optimized, throughput of p-persistent CSMA lies between that of slotted and unslotted nonpersistent CSMA
- For long propagation delays, p-persistent CSMA throughput exceeds that of nonpersistent CSMA

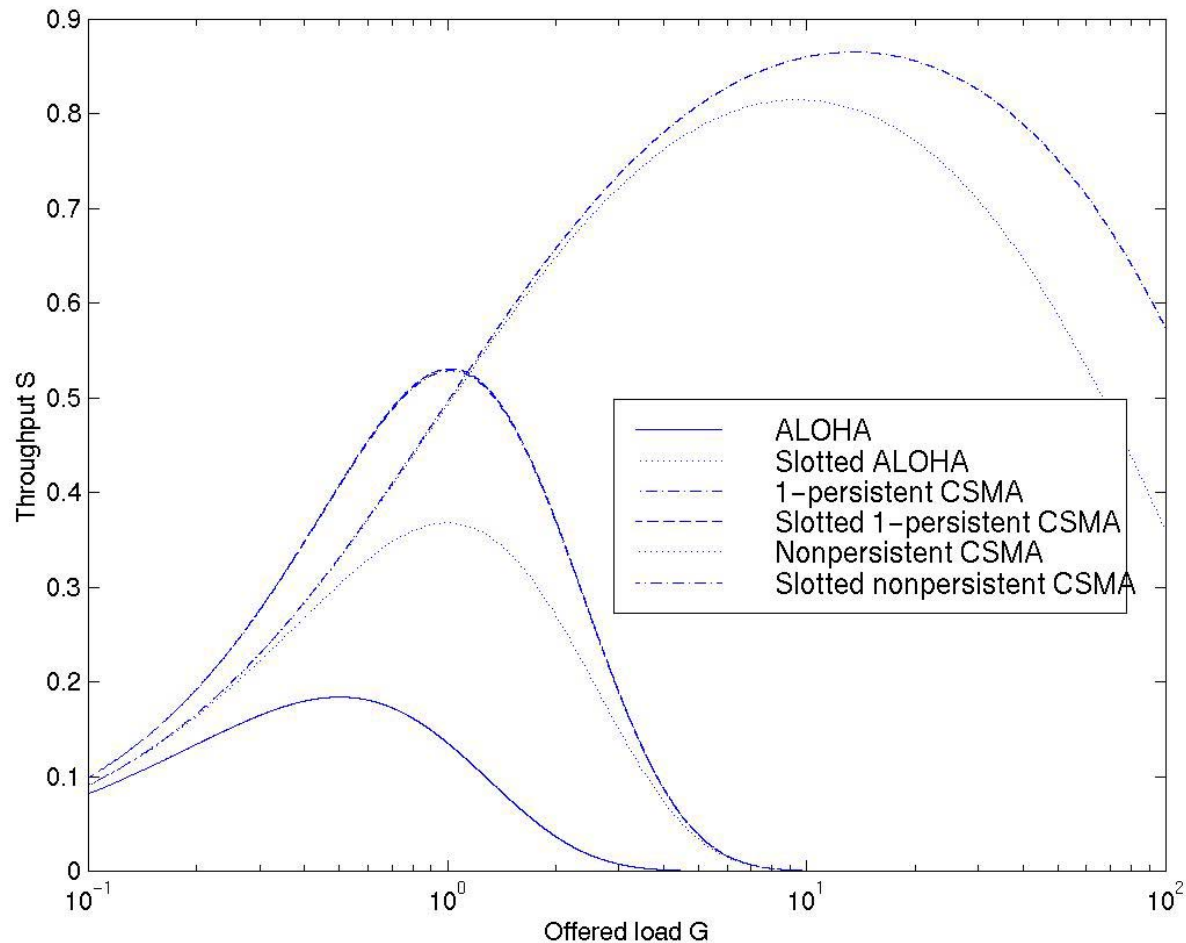


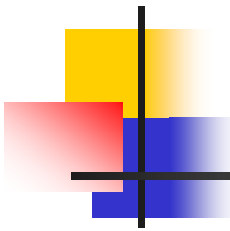
Comparison

- Throughput performance
 - For CSMA protocols, S is a function of $a = tT_p$ where T_p = pkt. transmission time and t = propagation delay
 - a is the time interval, normalized to packet duration time, during which a transmitted packet can suffer a collision
 - $t = d \text{ m} / 3 \times 10^8 \text{ m/s} = 3.33 \text{ ns/km}$ so $a \ll 1$

Comparison (cont.)

- Comparison of throughput vs traffic load ($a=0.01$)



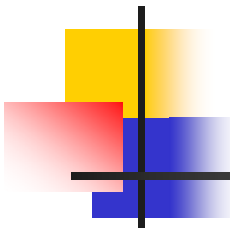


Throughput Comparison (cont.)

- Slotted and unslotted 1-persistent CSMA essentially indistinguishable
- For low levels of traffic, persistent protocols provide best throughput
- For high levels of traffic load, nonpersistent protocols are by far the best
- Slotted nonpersistent CSMA has a peak throughput almost twice that of persistent CSMA
- Capacity = peak value of S over entire range of offered traffic load G

Throughput Comparison (cont.)

- For CSMA protocols, capacity a function of a
 - For large a , ALOHA has better capacity
 - With long propagation delay relative to packet transmission time, channel state information arrives too late to be used effectively in reducing collisions → large time in which sender's packet is vulnerable to collisions
- Typically want $a < 0.01$ for good performance using CSMA protocols
 - If max distance between nodes is 100 m, $t = 0.33$ ms
 - T_p should be greater than 33 ms to keep $a < 0.01$
 - If $R_b = 1$ Mbps → minimum packet length = 33 bits
 - If $R_b = 10$ Mbps → minimum packet length = 333 bits



CSMA/CD: CSMA with Collision Detection (CD)

- Node monitors its own transmission to detect collision
- Node must receive while transmitting—if received data different from transmitted data → collision
- Requires transmitter and receiver capable of “listen-while-talk” operation
 - Easy to perform CD over Ethernet → check voltage levels and if different than what was sent, a collision has occurred
 - Hard to detect collisions in wireless media
 - Transmitter drowns out interfering signal at transmitting node
 - Hidden terminal problem
- Too complex to be implemented in most systems