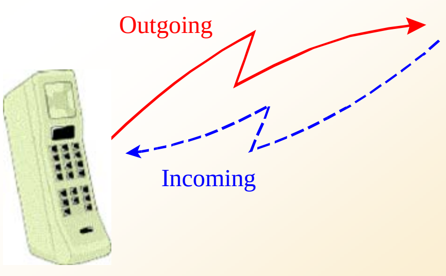
EE 577 - Wireless and Personal Communications

Chapter 8: Multiple Access Techniques

Full-Duplex Systems

- Systems are often designed as dual-simplex and not true full-duplex
- One channel is for outgoing traffic and one is for incoming traffic
- Keeps interference lower



Multiplexing

- **Multiplexing** is the general name for partitioning the channels
- Two general multiplexing schemes:
  - **Frequency-division duplex (FDD):** Input/Output channels are sent at the same time but on different frequencies
  - **Time-division duplex (TDD):** Input/Output channels are sent at different times but on the same frequency

Frequency-Division Duplex (FDD)

- Uplink and downlink channels are sent over two RF channels
- Consists of two simplex channels
- Duplexer is used to allow two-way RF transmission using the same antenna => results in duplexer loss
- Frequency separation between uplink/downlink channels is constant throughout the system
- Frequency separation should be designed to allow reasonable RF circuit design

Time-Division Duplex (TDD)

- Uplink and downlink channels are sent over same RF channel but each occupies different time slots
- Duplexer is not needed => less complexity
- Time separation is small so that users do not sense it as delay
- Sensitive to propagation delays in the channel
  => not suitable for mobile communications
- Used usually in fixed wireless systems

Why Multiple Access?

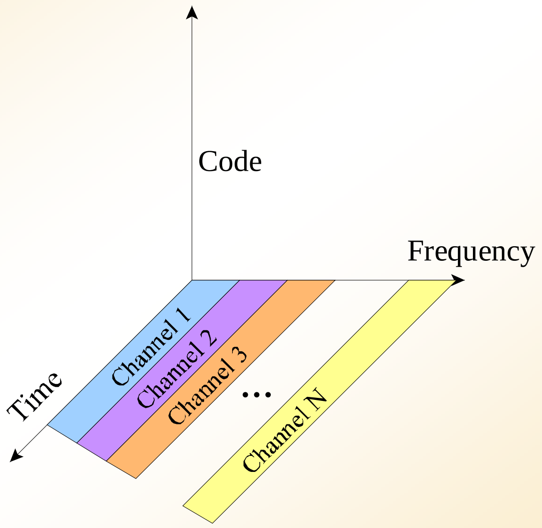
- Normally, a given resource (frequency, time slot, PN code) is not active all the time
- Usually, there are more potential users than resources
- Not all users require a resource at a given time
- Resources will need to avoid self-interference when being used

Multiple Access

- **Multiple Access** is the general term for sharing the resources among many different users
  - Time Division Multiple Access (TDMA)
  - Frequency Division Multiple Access (FDMA)
  - Code Division Multiple Access (CDMA)
  - Space Division Multiple Access (SDMA)

- Normally, there will be a **protocol** description stating how a user can access a shared channel and how to operate on the channel

FDMA



FDMA

- Each user obtains a slice (band) of frequency spectrum for his exclusive use for a given time period (e.g., duration of a phone call)
- Usually, there is one frequency channel for the forward link and one for the return link (FDD)
- Channels are separated by a **guard band** to avoid adjacent channel interference (ACI)
- FDMA channels are a pooled resource that are allocated when users initiate a call
- It only requires a small amount of time for call initiation and management

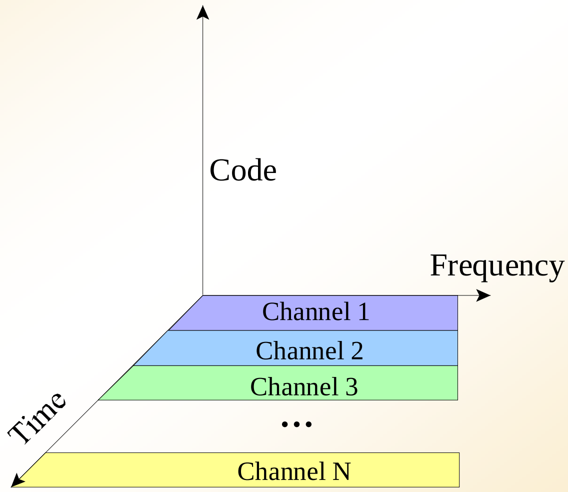
FDMA

- If a channel is not used it is a wasted resource
- Transmission is continuous during the call time
- FDMA channels are narrow
  => flat fading => no need for equalizers
- Few bits are needed for overhead and channel setup
- Costly bandpass filters and duplexers are needed
  => high cost for BS and MS
- Tight RF filtering is needed to reduce ACI

FDMA Interference

- Multiple carriers are transmitted through a common amplifier
- FM transmission and non-linear amplification has the potential to produce **intermodulation distortion** (side-lobes regeneration)
- A harmonic from one user may end up on another user's channel

TDMA



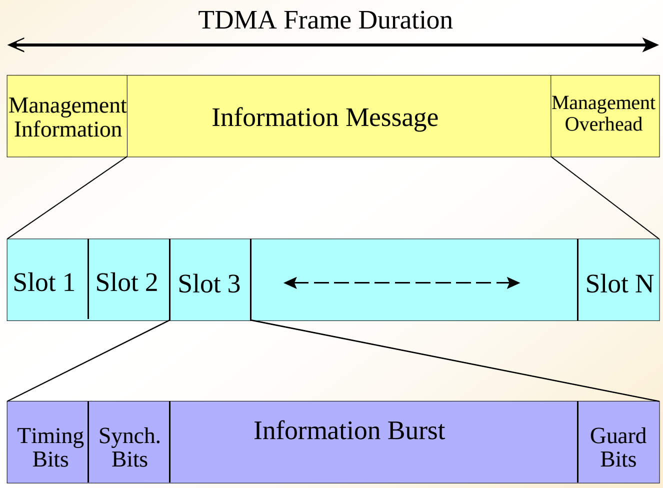
TDMA

- Users share the same BW and transmit over the same carrier, but each user is assigned a time burst (slot) for his transmission
- Users synthesize a continuous transmission via these short time slices of data
- Usually, there is one time burst for the forward link and one for the return link
- Each time slot is considered as a channel in TDMA
- Channels are separated in time to avoid overlap

TDMA

- Transmission is discontinuous in time
  => simpler handoff techniques (MAHO)
- No duplexers are needed
- TDMA traffic bursts are arranged in **frames** where each user burst is assigned a **slot** in the frame and the frame pattern repeats on a periodic basis
- There is management overhead involved with integrating/removing a user in the frame structure
- **Frame efficiency =** useful bits / overall bits in a frame

TDMA



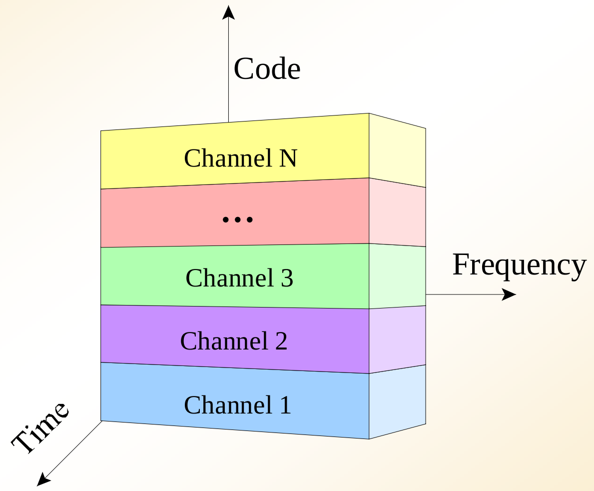
TDMA Channels

- Use some time bursts for forward-traffic and some for return-link traffic
- Each user burst has a relatively large timing overhead penalty
- Use symbol and timing synchronization markers to allow receivers to lock onto the signal
- Use reference bursts to allow all stations to maintain timing synchronization with the network
- TDMA systems have higher synchronization overhead than FDMA systems

TDMA

- **Advantages:**
  - Sharing among N users
  - Variable bit rate can be obtained by assigning more than a time slot to a high-rate users
  - Less stringent power control
- **Disadvantages:**
  - Pulsating power envelope (shorter battery life)
  - Inherent complexity in slot-frequency allocation
  - Equalization is required for high data rates

CDMA



CDMA

- Each user obtains a PN code to mix with his data transmission
- PN codes for users are orthogonal to allow all users to share the channel
- Users need to know/be assigned PN codes to decode the data properly
- PN codes may be assigned temporarily for a finite time or frequency (within a cell or call boundary)

CDMA Channels

- Suffer from near/far problems where a near user to the central tower may swamp other users
  => power control is necessary
- Codes are not always perfectly orthogonal
  => multi-user interference => performance loss
- Interference cancellation should be used
  => high complexity in general
- CDMA can overcome multipath
- Further, it can convert it into diversity using the RAKE receiver

FHMA

- Each user hops between carriers within a wide transmission band
- The hopping sequence for each user is dictated by the PN code assigned to him
- PN codes have to be perfectly orthogonal to avoid collisions
- Otherwise, irreducible error floor results from the non-zero probability of collision

Hybrid CDMA Schemes

- **TD-CDMA –** The same PN code is shared with multiple users but each can use it in a particular time slot within a frame
- **FD-CDMA –** The available frequency band is divided into sub-bands and each narrow-band CDMA operates within a sub-band
- **FH-CDMA –** Same as FD-CDMA but each narrow-band CDMA transmission is hopped between different sub-bands

SDMA

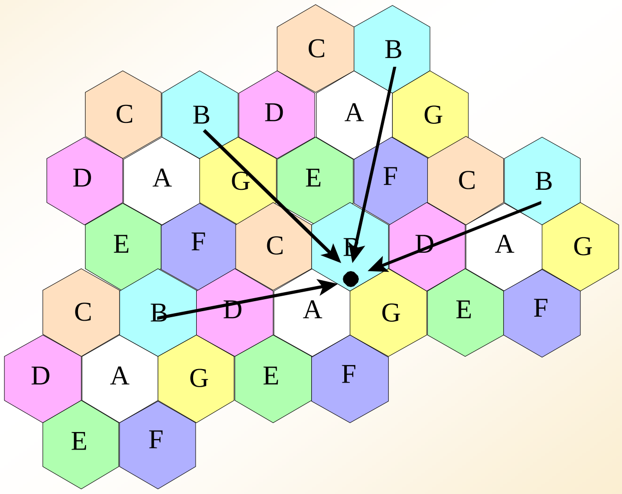
- SDMA partitions a geographic area into regions and controls the energy radiated into various directions
- Sectoring used in cell design is a basic form of this technique
- **Potential Problems:**
  - Power control
  - Requires highly directional antennas
  - May need some form of adaptive techniques

System Capacity - Review

- Carrier-to-Interference Ratio (C/I):
  - Co-channel Interference
  - Adjacent Channel Interference
  - 6 nearest neighbors for $N = 7$
- Co-Channel Re-use Ratio:

$$Q = D/R = (3N)^{1/2}$$

System Capacity - Review



System Capacity - Review

- **C/I relationship:**

$$\frac{C}{I} = \frac{D_0^{-n}}{\sum_{k=1}^{M} D_k^{-n_k}}$$

- **C/I with 6 closest neighbors:**

$$\frac{C}{I} = \frac{D_0^{-n}}{6D^{-n}}$$

System Capacity - Review

- The co-channel reuse ratio, Q, can be expressed in terms of the minimum C/I required for proper operation:

$$Q = \left(6 \left(\frac{C}{I} \right)_{\min} \right)^{1/n}$$

- Often, the C/I is the limiting factor and not the channel noise => **interference-limited** systems

System Capacity - FDMA

- Given a minimum C/I, how many FDMA users can the system accommodate?
- Estimate the number of radio channels per cell, m, in terms of:
  - Number of cells in a frequency re-use pattern, N
  - System and channel bandwidth using:

$$m = \frac{B_{total}}{B_{channel} N}$$

System Capacity - FDMA

- The capacity can be estimated using:

$$m = \frac{B_{total}}{B_{channel}\left(\frac{6}{3^{n/2}}\left(\frac{C}{I}\right)_{\min}\right)^{2/n}}$$

- When $n = 4$:

$$m = \frac{B_{total}}{B_{channel}\sqrt{\frac{2}{3}\left(\frac{C}{I}\right)_{\min}}}$$

System Capacity - FDMA

- This capacity is related to system parameters that may vary from one operator to another
- Therefore, normalize the C/I in terms of a reference bandwidth

$$\left(\frac{C}{I}\right)_{eq} = \left(\frac{C}{I}\right)_{\min}\left(\frac{B_{reference}}{B_{channel}}\right)^2$$

System Capacity - FDMA

- The system with the smallest $(C/I)_{eq}$ is the best system to use based on these criteria
- **Question:** Suppose a reference bandwidth of 6.25 kHz is chosen, which of the following systems is the "best"

System Capacity - FDMA

System	$B_{channel}$	$(C/I)_{min}$	$(C/I)_{eq}$
A	30 kHz	18 dB	4.375 dB
B	25 kHz	14 dB	1.96 dB
C	12.5 kHz	12 dB	6 dB
D	6.25 kHz	9 dB	9 dB

System Capacity - FDMA

- For digital data transmission using FDMA systems, the channel power is given by in terms of the energy per bit and the channel bit rate:

$$C = E_b R_b$$

- Systems are rated based on the relative energy per bit and relative bandwidth as in the analog case

System Capacity - TDMA

- TDMA has the potential to improve capacity by having the users share the channel bandwidth
- However, the transmission rate is usually higher so there is a question as to how efficient it can be overall
- TDMA systems often use speech processors to determine when channels are utilized
- By active speech processing, users can be mixed in time at a very fine resolution and more users can occupy the channel simultaneously (factor of 3 is common)

TDMA vs. FDMA

- **TDMA:**
  - 3 time slots
  - $B' = 30$ kHz
  - $R_b' = 30$ kbps
- **FDMA:**
  - 3 frequency slots
  - $B = 10$ kHz/channel
  - $R_b = 10$ kbps/channel

TDMA vs. FDMA

- **TDMA:**
  - $C' = E_b R_b' = 30000\ E_b$
  - $I' = I_0 B' = 30000\ I_0$
- **FDMA:**
  - $C = E_b R_b = 10000\ E_b$
  - $I = I_0 B = 10000\ I_0$
- The TDMA has a C/I that is 3x the C/I of FDMA
- However, each TDMA user only has the channel 1/3 the time
- Each user has the same performance!

System Capacity - TDMA

- In practice, TDMA systems improve capacity by a factor of 3 to 6 times as compared to analog systems

- This is attributed to the use of:
  - Powerful error control coding that reduce energy required for acceptable performance
    => less interference => higher capacity
  - Speech coding which reduces the required transmission rate

Capacity Comparisons

Parameter	AMPS	GSM	USDC	PDC
Bandwidth (MHz)	25	25	25	25
Voice Channels	833	1000	2500	3000
Frequency Reuse (Cluster sizes)	7	4 or 3	7 or 4	7 or 4
Channels/Site	119	250 or 333	357 or 625	429 or 750
Traffic (Erlangs/sq. km)	11.9	27.7 or 40	41 or 74.8	50 or 90.8
Capacity Gain	1.0	2.3 or 3.4	3.5 or 6.3	4.2 or 7.6

System Capacity - CDMA

- The other users are the limiting factor for capacity NOT the channel noise (interference-limited system)
- Other users are modeled as AWGN when there are large number of multiple users (Central-Limit Theorem)
- At the BS receiver:

$$\frac{E_b}{N_o} = \frac{S/R}{(N-1)(S/W)} = \frac{W/R}{N-1}$$

System Capacity - CDMA

- Adding in the thermal noise, η, as well as the channel bandwidth, *W*, the bit rate, *R*, and signal power, *S*, gives

$$\frac{E_b}{N_o} = \frac{W/R}{(N-1)+(\eta/S)}$$

- The factor *W/R* is the "Processing Gain"

System Capacity - CDMA

- The number of users that can be served in the system for a given SNR is estimated as:

$$N = 1 + \frac{W/R}{E_b/N_o} - \frac{\eta}{S}$$

- We can also account for the voice duty factor, α, to improve the capacity estimate
- We can also improve the access by using sectored antennas

System Capacity - CDMA

- The number of users per sector, N_s, can be estimated as:

$$N_s = 1 + \frac{1}{\alpha}\left[\frac{W/R}{E_b/N_o'}\right]$$

where N_0' is the noise within the sector (less than omnidirectional noise)

System Capacity - CDMA

- **Example:** W = 1.25 MHz, R = 9.6 kbps, E_b/N_0=10 dB; assume interference-limited (I.e., $\eta/S \approx 0$)
- How many users when there is one sector per cell
- If three sectors per cell are used and 3/8 duty factor for voice, how many users can be on the system?

System Capacity - CDMA

- **Case #1:** Omnidirectional antenna:
  - $N = 1 + 1250/9.6/10 = 14$ users/cell
- **Case #2:** 3 Sectors:
  - $N_s = 1 + 8/3\ [1250/9.6/10] = 35.7$ users/sector
  - $N = 3N_s = 107$ users/cell

System Capacity - CDMA

- Consider a cell in a multi-cell CDMA system
- Adjacent cells may use the same frequency band as the cell under study (with different PN codes)
- These cells are under the control of different BS's
- Therefore, they may cause interference to the cell under study due to the lack of power control

System Capacity - CDMA

- The frequency reuse factor can be defined as:

$$f = \frac{N_o}{N_o + \sum_i U_i N_{\alpha i}}$$

- U_i is the number of users in the adjacent cells
- $N_{\alpha i}$ is the average interference power for the users in the adjacent cells

System Capacity - CDMA

- In a perfect system, $f = 1$
- Based on simulations, factoring in different path loss factors and cell parameters, a typical re-use value:

$$0.3 < f < 0.7$$

- This means that the system will not be able to have as many users as theory would predict

System Capacity - SDMA

- With directional antennas, the situation can be improved:
  - Number of users interfering will be smaller
  - Noise will be reduced
  - In principle, the reuse factor will be larger
- Improvement will be a function of the antenna pattern and directivity

System Capacity - SDMA

The system probability of error can be estimated as:

$$P_e = Q\left(\sqrt{\frac{3fDN}{K-1}}\right)$$

D is the directivity,
f is the reuse factor,
N is the processing gain,
K is the number of users

Packet Radio

Packet Radio

- Packet networks are based on shared access and need to have a means of detecting packet collisions and recovery from the collisions
- There is a tradeoff between the degree of synchronization, control, and management and the data throughput available (high control allows for high throughput)
- Systems rated on relative throughput

Packet Radio Assumptions

- All potential users do not need to transmit at the same time (idle)
- The user can tell if the data does arrive correctly (by listening to the transmission or by an explicit feedback signal)
- The data to be transmitted can be segmented into packets of finite size
- Collisions happen if more than one user transmit at the same time

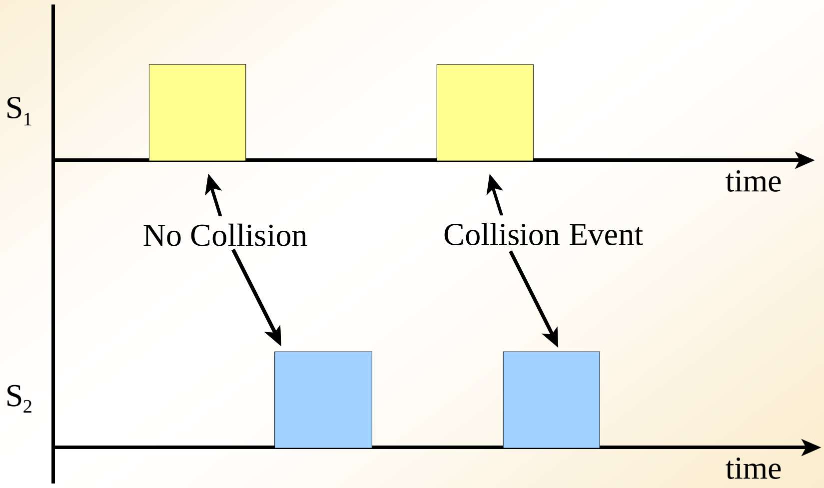
Typical System Parameters

- Packet size (maximum, minimum, or fixed)
- Time between packets (fixed, allow continuous, random)
- End-to-end propagation time (time to detect collisions)
- System data rate
- Offered load per user and in the system

Packet Radio System Measures

- Probability of packet collisions (two or more packets on the link at the same time)
- Average transmission delay
- Percent of channel utilization (throughput)

Packet Radio

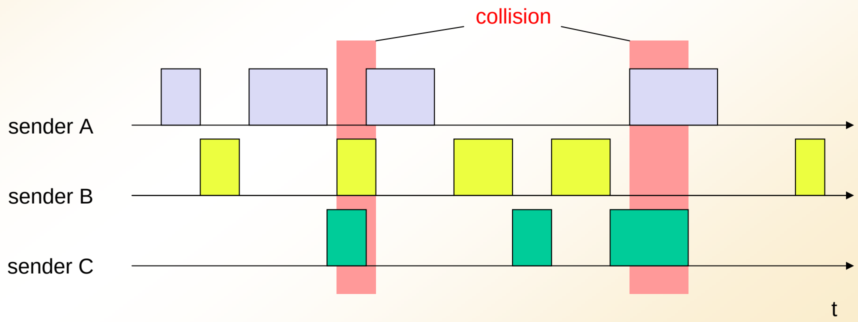


Protocol Families

- Protocols are based on the Aloha protocol developed for packet radio
- Newer protocols add management layers to improve performance and allow networking control
- Basic system works on radios, wireless LANs, space systems, etc.

ALOHA

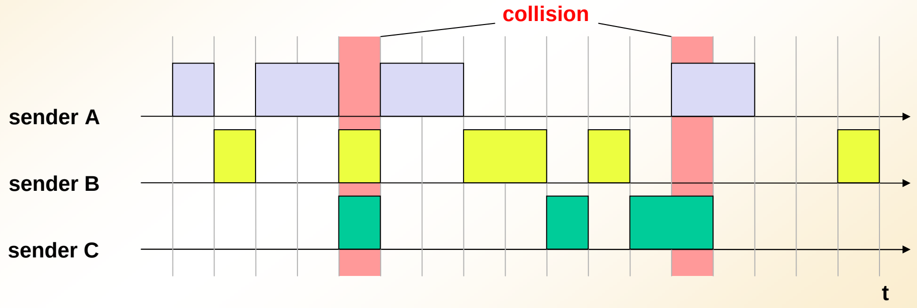
- Each user transmits as needed
- Wait for ACK/NAK after transmission; NAK says re-transmit after a random time period



Slotted ALOHA

- Time is divided into equal-time slots
- User can only send at the start of the time slot
- If two or more terminals transmit their packets in a slot, a collision occurs and no packet is successfully transmitted
- The colliding packets are buffered and retransmitted after random retransmission delay
- Requires synchronized transmitters

Slotted ALOHA



Protocol Performance

- Throughput (*T*) is the average fraction of time slots that contain a successfully transmitted packet
- The performance (probability of a collision, channel throughput) is a function of the protocol
- The more structured the channel, the higher the throughput
- The more structure, the more complicated (hardware and software) the protocol realization
- The most popular measure of performance is the throughput

Protocol Performance Assumptions

- Each user transmits randomly as described by a **Poisson probability distribution** with a mean arrival rate of λ packets/second
- Fixed packet duration of τ seconds
- Each user presents an offered load,

$$R = \lambda\,\tau \text{ (Erlangs)}$$

- Throughput, T, is given by:

$$T = R \Pr[\text{no collision}]$$

Protocol Performance

- The probability of no collision is not only the probability of no collision on the first transmission attempt but also on subsequent attempts if necessary
- This is a function of the probability of packet generation

Protocol Performance

- Using Poisson statistics, the probability of n packets being generated during an interval is given by:

$$\Pr(n) = \frac{R^n e^{-R}}{n!}$$

- This is used to determine the probability of collisions during the collision vulnerability interval

Protocol Performance - ALOHA

- Vulnerability interval is equal to 2τ
- Probability of no collisions

$$\Pr(n = 0) = \frac{(2R)^n e^{-2R}}{n!}$$

- Throughput, $T = Re^{-2R}$

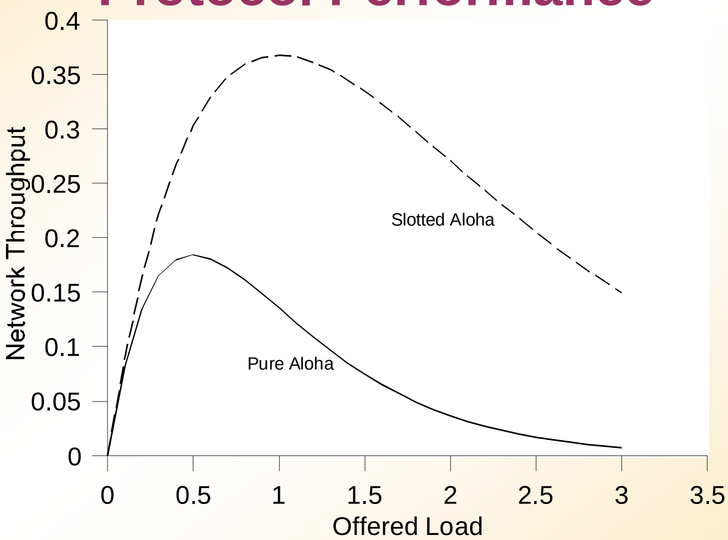
Protocol Performance – Slotted ALOHA

- Vulnerability interval is equal to τ
- Probability of no collisions

$$\Pr(n=0)=\frac{(R)^n e^{-R}}{n!}$$

- Throughput, $T = R\, e^{-R}$

Protocol Performance



Protocol Performance

- Maximum Throughput:
  - **Pure ALOHA:** $T = 0.1839$
  - **Slotted ALOHA:** $T = 0.3679$
- Slotted Aloha permits twice as much traffic as Pure Aloha at the cost of synchronizing the transmitters
- Notice, beyond this point for each, performance becomes worse - why?

Performance in Fading Environments

- Packets may be lost to fading even if no collision occurs
- If collisions occur not all packets involved are lost
- The strongest user may be detected successfully
- This effect is called **capture effect**

Capture Effect

- The "**capture effect**" has been adopted to describe the fact that any practical radio receiver may successfully receive a message, despite the presence of interference from other (weaker) signals.

- A packet is received correctly if and only if its received power exceeds the joint interference power by at least a threshold factor (or capture ratio) z_o.

Capture Effect

- The packet with the highest received power is selected as the test packet. The other n packets are considered as interference.
- The ratio of the test packet power P_s to the interference packets power P_n is computed during the beginning of the time slot.
- This ratio is compared to the capture parameter z_o.
- If this ratio is higher than the capture parameter, the test packet survives the collision.

Performance of Slotted ALOHA

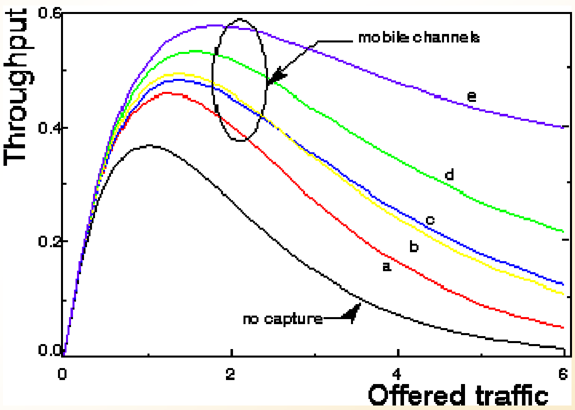
With Capture (receiver threshold is 4)

a: Rayleigh fading only

c: Shadowing and Rayleigh fading

e: Near far effect and Rayleigh fading

b,d: Some other capture models



Parameters Affecting the Performance

- ❑ Receiver capture performance
- ❑ Distance from the central receiver, path loss
- ❑ Channel fading, dispersion and shadowing
- ❑ Contending packet traffic (from same cell)
- ❑ Interference from co-channel cells
- ❑ Channel noise
- ❑ Modulation method and bit rate
- ❑ Type of coding and packet length
- ❑ Signal processing at the receiver
- ❑ Access protocol

Major Problem with ALOHA

- In Aloha systems, collisions occur frequently for high offered traffic loads
- This reduces the throughput and may lead to instability

Carrier Sense Multiple Access (CSMA)

- Transmit as needed but listen for channel to be vacant before transmission
- Chance of users that both believe that channel is vacant and will transmit at the same time

Non-persistent CSMA

- Sense the medium:
  - If it is idle, transmit
  - Otherwise wait a random amount of time and resense the channel
- Used with systems having a longer packet length than end-to-end propagation delay
- LAN-based protocol

1-Persistent CSMA

- Sense the medium
- If it is idle, transmit
- Otherwise, continue listening until channel is idle, then transmit immediately

p-Persistent CSMA

- Sense the medium:
- If it is idle, transmit with a probability of *p*
- If medium is busy, continue listening until channel is idle
- Then transmit with a probability of *p*

CSMA/Collision Detection

- Like Non-persistent CSMA but the transmitter listens to detect collisions
- When collision is detected, transmitter aborts transmission and re-starts after a random delay
- CSMA-CD adopts ``Listen-before-talk" approach
- No new packet transmission is initiated when the channel is busy
- This enhances the throughput
- Problem for wireless: transmitter may not be able to detect (hidden transmitter)

CSMA/CA—Collision Avoidance

- When carrier is quiet, WAIT a random time and try again
- If still quiet, then transmit
- No guarantee that just because the transmitter obtains the medium that the receiver can hear the transmission

Inhibit Sense Multiple Access (ISMA)

- If busy, base station transmits a busy signal to inhibit all other terminals from transmitting
- A disadvantage of ISMA is the necessity of a real-time (continuous) feedback channel
- ISMA is used by the Cellular Digital Packet Data (CDPD) system
- Collisions still occur, because of:
  - Signaling delay
  - Persistent terminals

CSMA Performance

- CSMA performance is a strong function of:
  - Packet size relative to propagation time (usually greater than propagation time)
  - Number of users as well as each user's offered load
  - Typically, systems run at 30% to 50% of available capacity due to collisions

Throughput Expressions

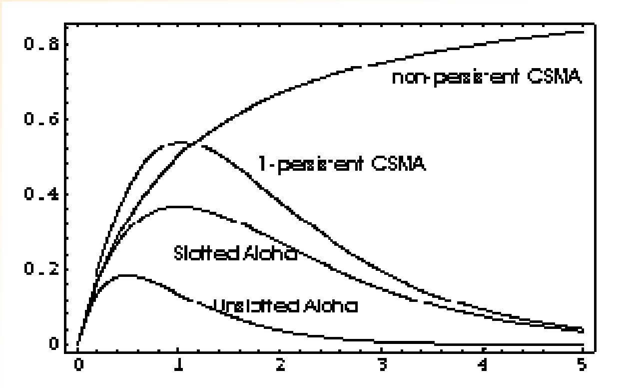
- Non-persistent CSMA and ISMA

$$T = \frac{G}{1+G}$$

- For 1-persistent CSMA and ISMA

$$T = \frac{G+G^2}{1+Ge^G}$$

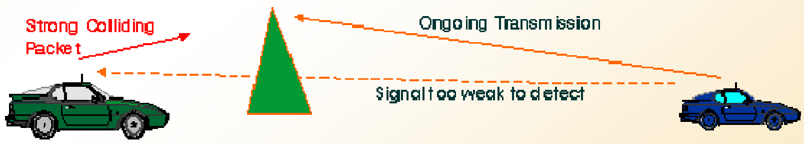
Performance of Access Schemes



- *T* is approximately equal to *G* for small *G*, i.e., if the channel is lightly loaded
- At larger traffic loads (larger *G*), conflicts, called "collisions" occurs, so $T < G$

Hidden Terminal Problem

- In CSMA, all terminals listen to terminal-to-base channel.
- No new packet transmission is initiated when the inbound channel is sensed busy.
- This requires that all mobile terminals can receive each others signals on the inbound frequency.
- However, a mobile terminal might not be able to sense a transmission by another (remote) terminal.
- This is called the **hidden terminal problem**.



Hidden Terminal Problem

- The hidden-terminal problem is avoided in ISMA
- The base station transmits a busy signal on an outbound channel to inhibit all other mobile terminals from transmitting as soon as an inbound packet is being received
- ISMA is sometimes called Busy Tone Multiple Access

Reservation ALOHA

- Allow users to reserve transmission slots
- Reservation can be permanent or as needed
- For high traffic conditions, reservations on request offer better throughput

Packet Reservation Multiple Access (PRMA)

- PRMA is a multiple access scheme with frames of a fixed number of slots
- If a terminal has a series of data packets (or speech segments) to transmit, it competes for access in any free slot
- If it successfully captures the BS, the terminal gains reservation in the corresponding slots of the next frames, until it releases the reservation

How Do We Choose?

Traffic Type	MA Technique
Bursty, short message	Contention
Bursty, long messages, large number of users	Reservation protocols
Bursty, long messages, small number of users	Reservation with TDMA reservation channel
Stream or deterministic (voice)	FDMA, TDMA, CDMA