MSIT 413: Wireless Technologies

Week 7

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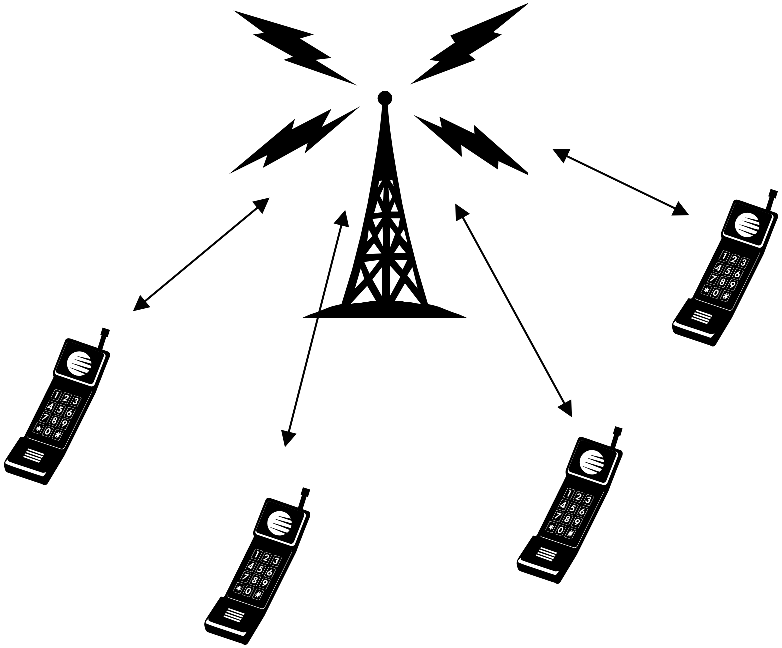
Outline

- Finish discussion of CDMA
- Frequency hopping
- Random access
- Midterm review

The Multiple Access Problem

How can multiple mobiles access (communicate with) the same base station?

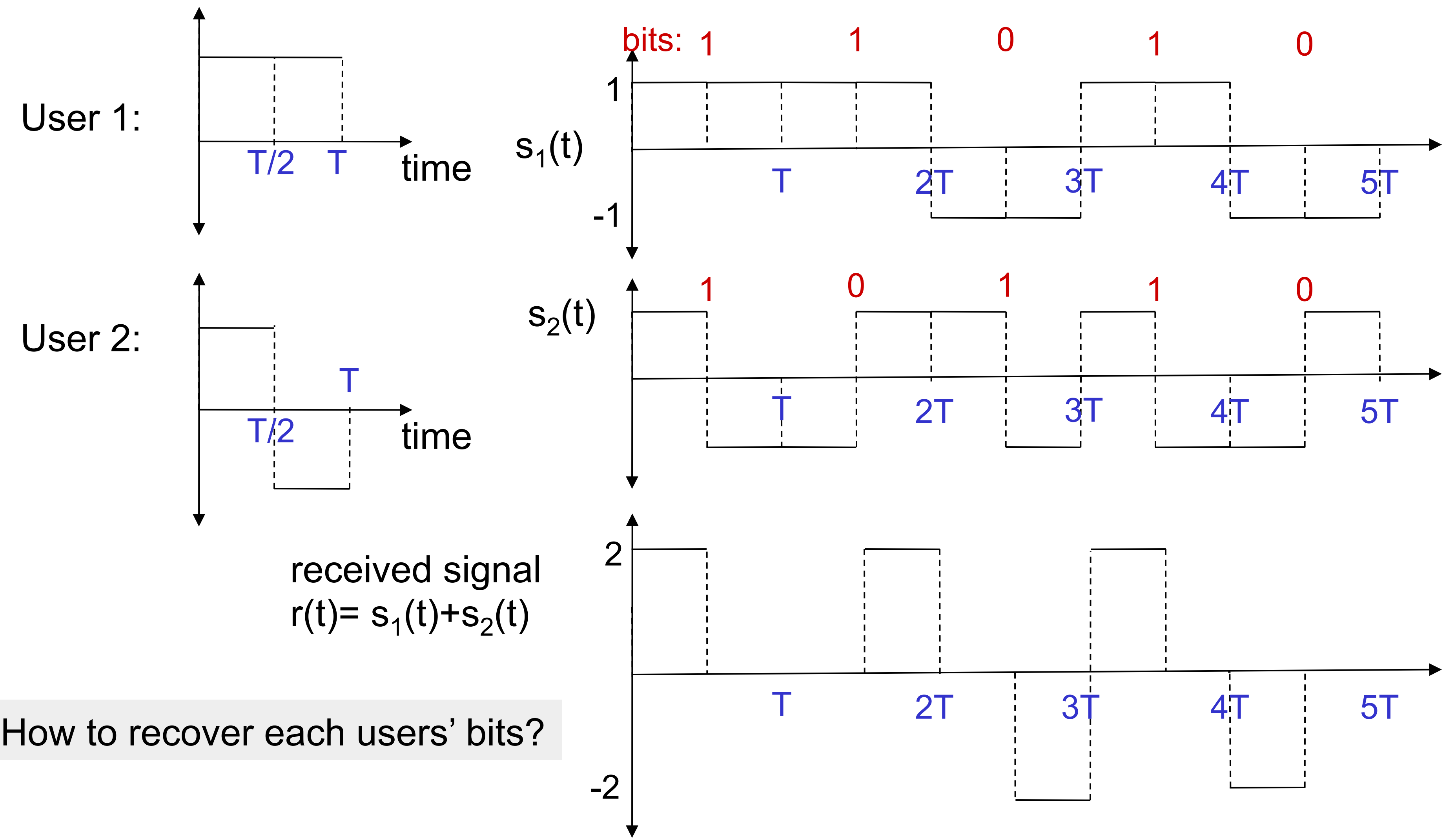


- Use different frequencies (FDMA)
- Use different time slots (TDMA)
- Use different pulse shapes (CDMA)

Code Division Multiple Access

- Users transmit simultaneously over the same frequency band
- Performance limited by interference

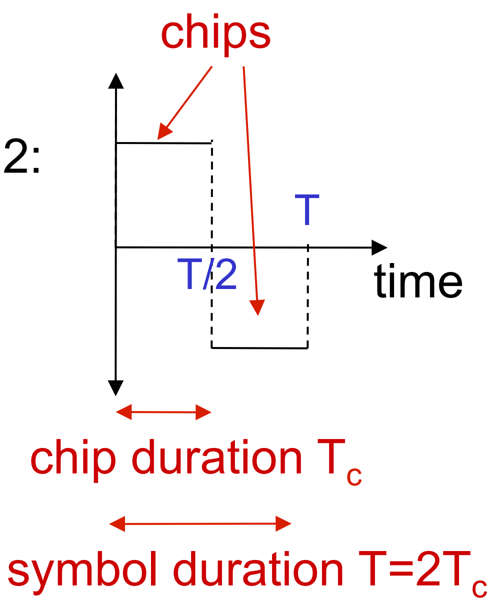
Two-User Example



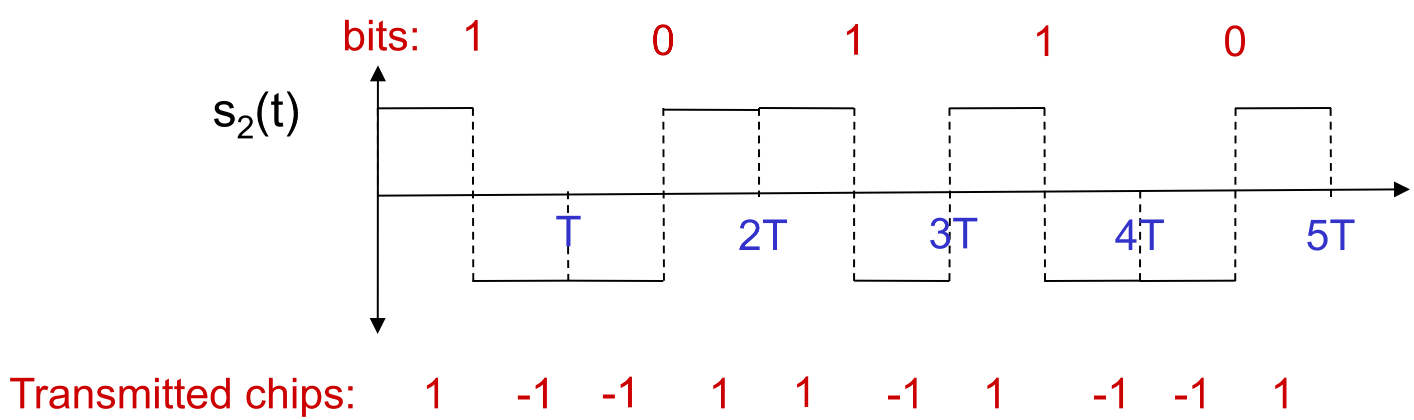
How to recover each users' bits?

Chip Sequence

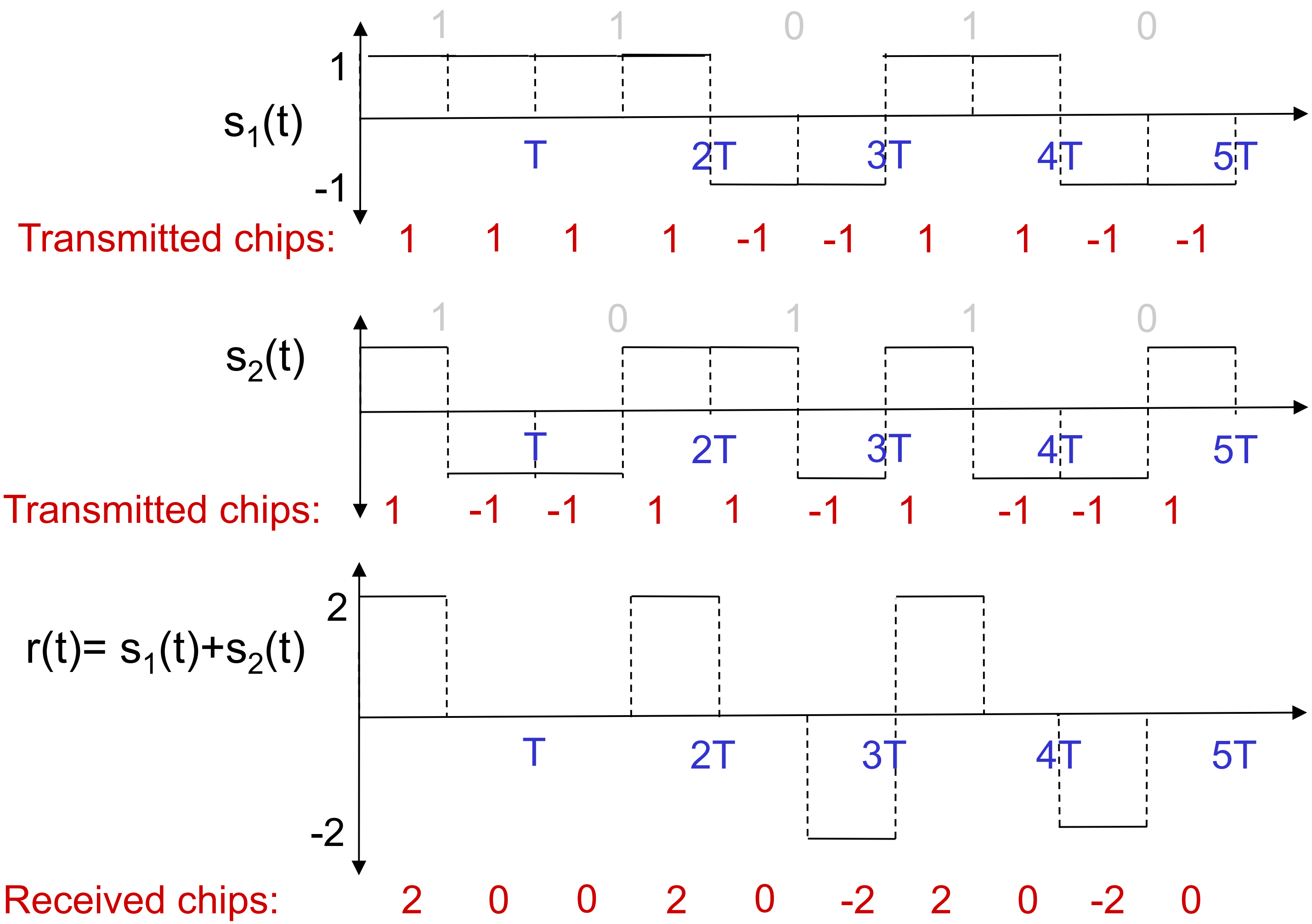
User 2:



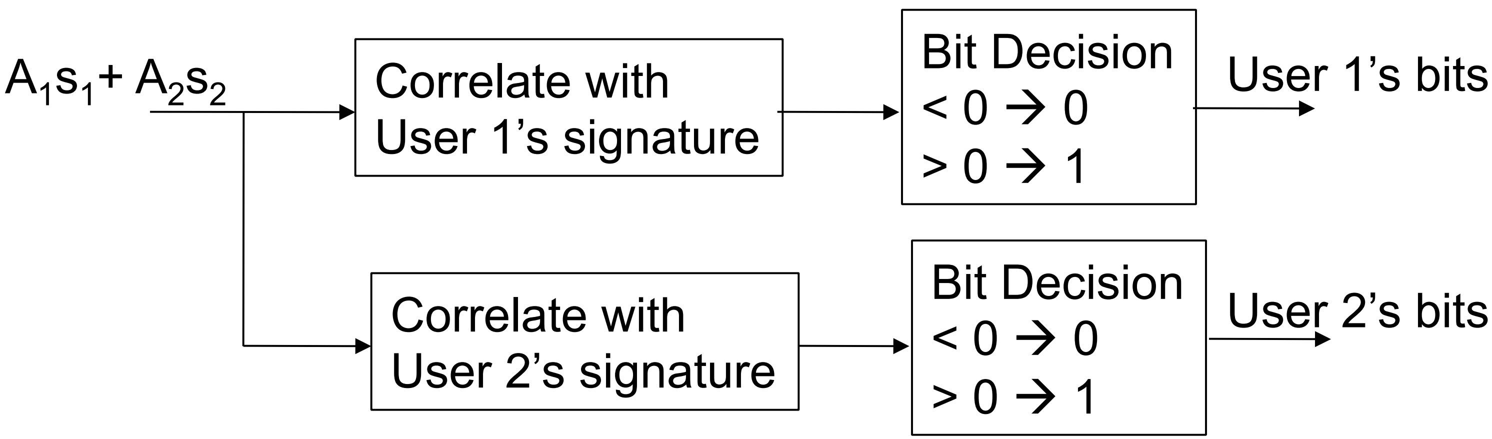
User 2's chip sequence (1, -1) is called a signature.



Two-User Example



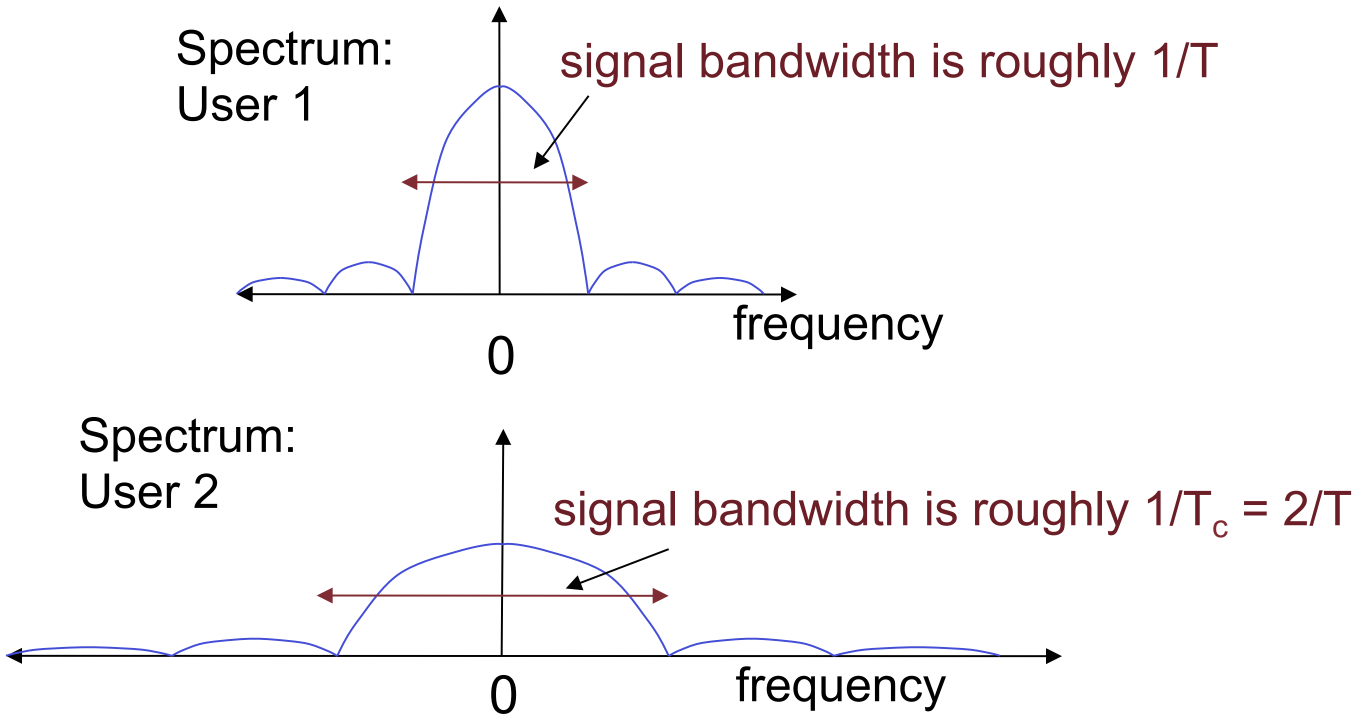
Correlator, or "Matched Filter" Receiver



The correlator is "matched" to user 1's signature s_1, and rejects s_2 (and vice versa).

Observations

- Users transmit simultaneously (not TDMA).
- Users overlap in frequency (not FDMA).

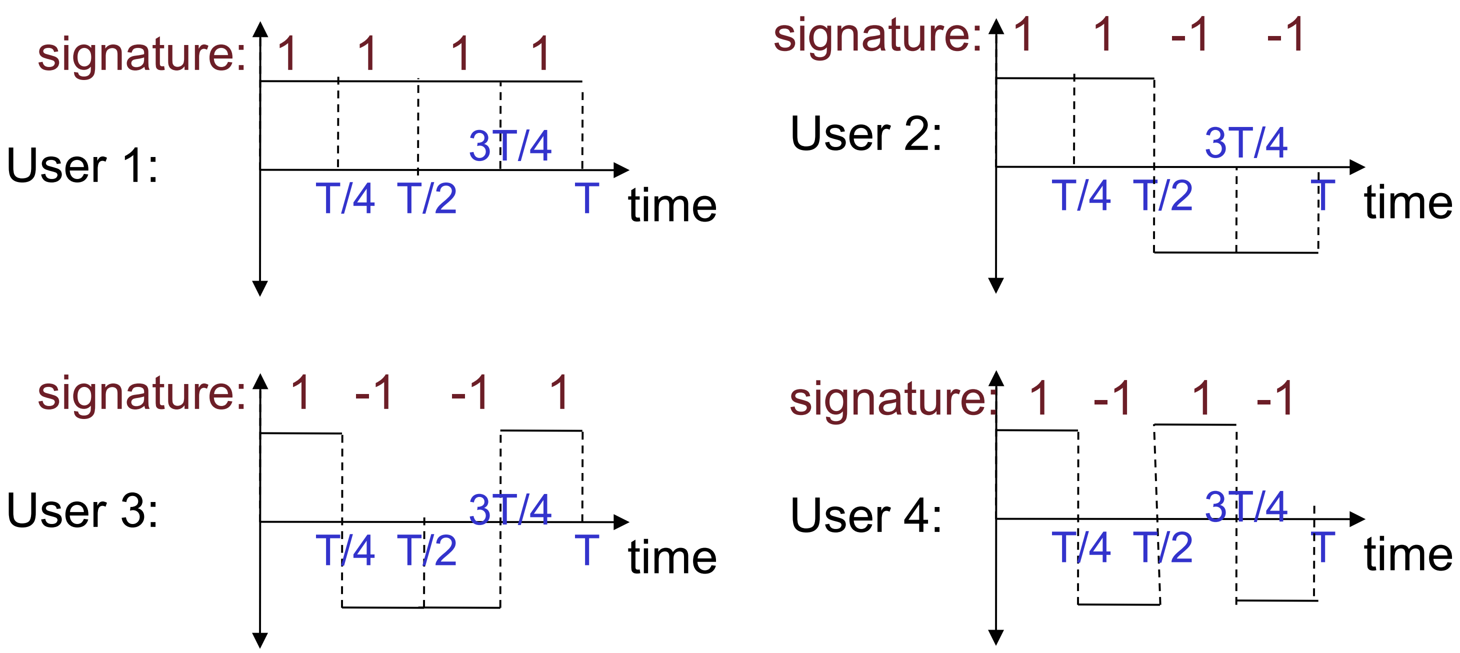


Bandwidth expansion (factor of 2) → "spread spectrum" signaling.

Users and Bandwidth Expansion

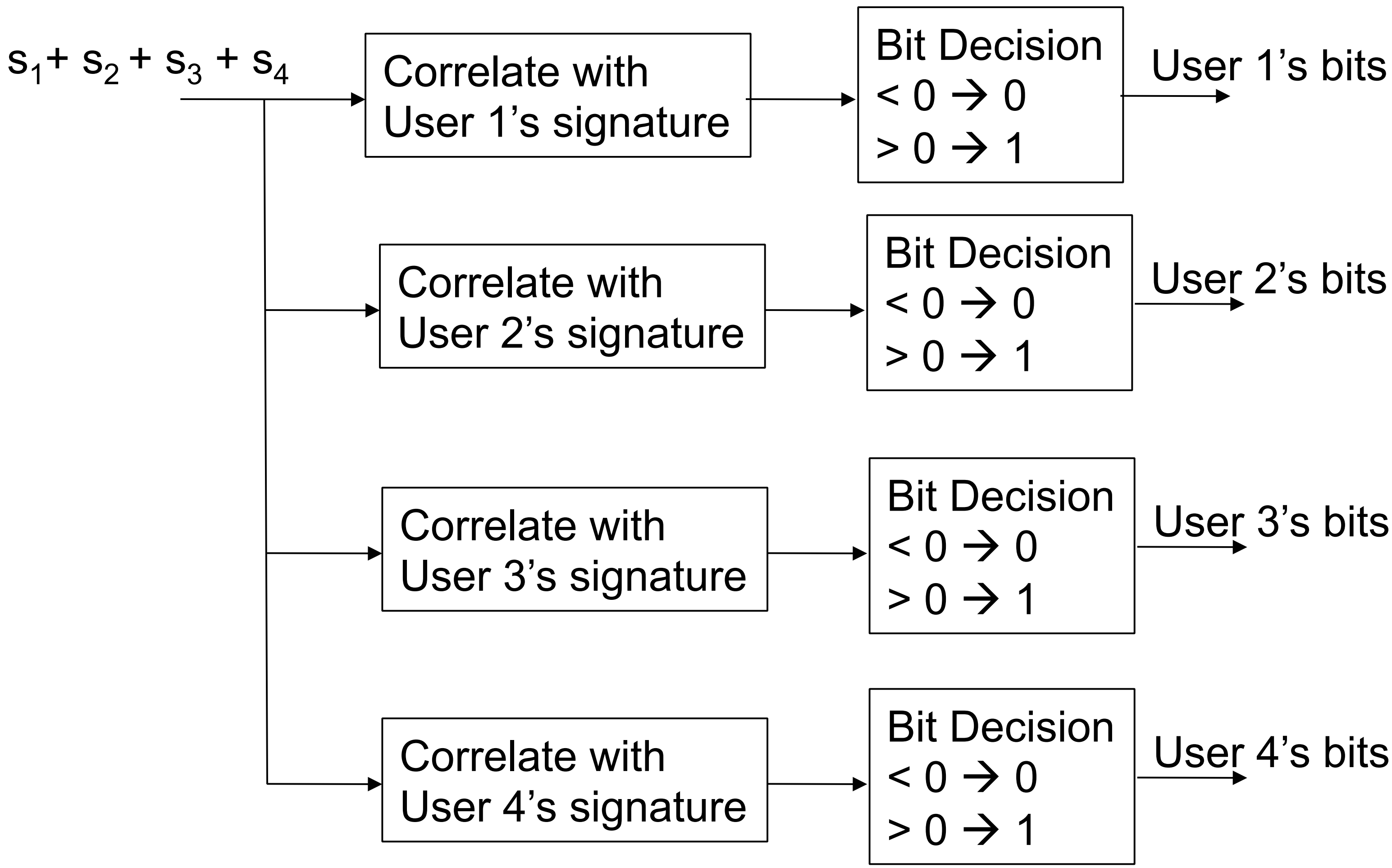
To guarantee orthogonal signatures (no interference), the length of the signatures must be ≥ the number of users.

Example (4 users):

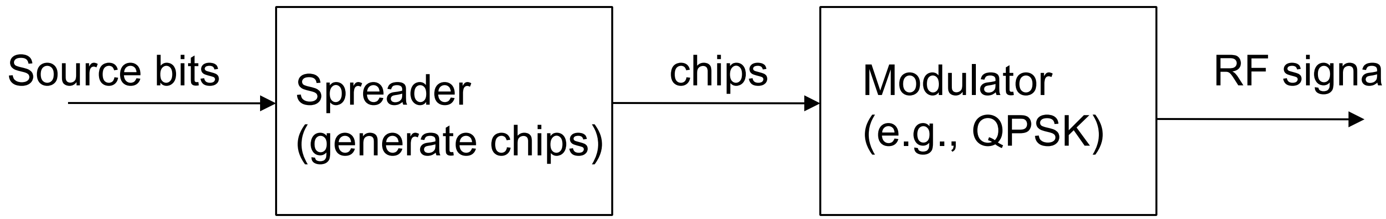


The chip rate is 4 times the symbol rate, hence the bandwidth expansion is a factor of 4.

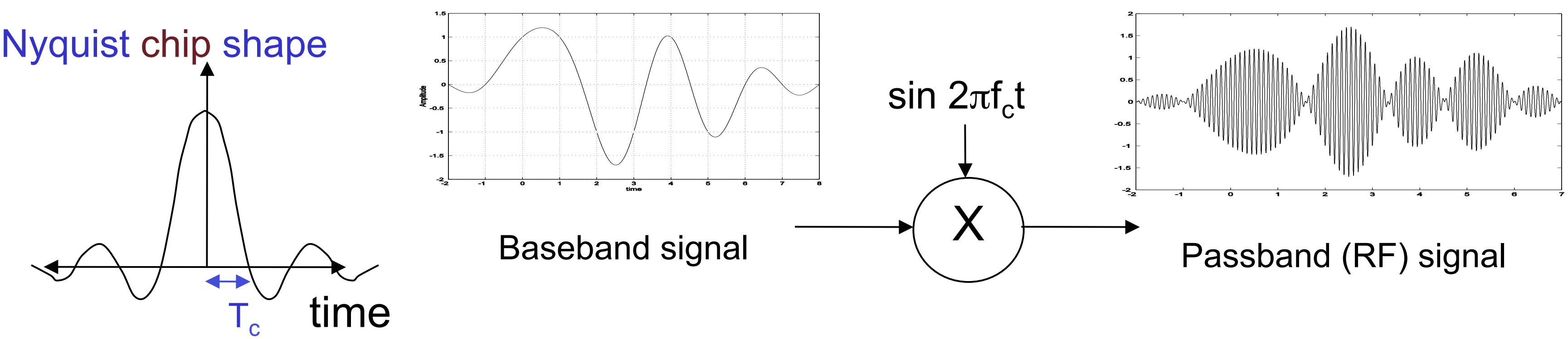
Correlator Receiver (4 users)



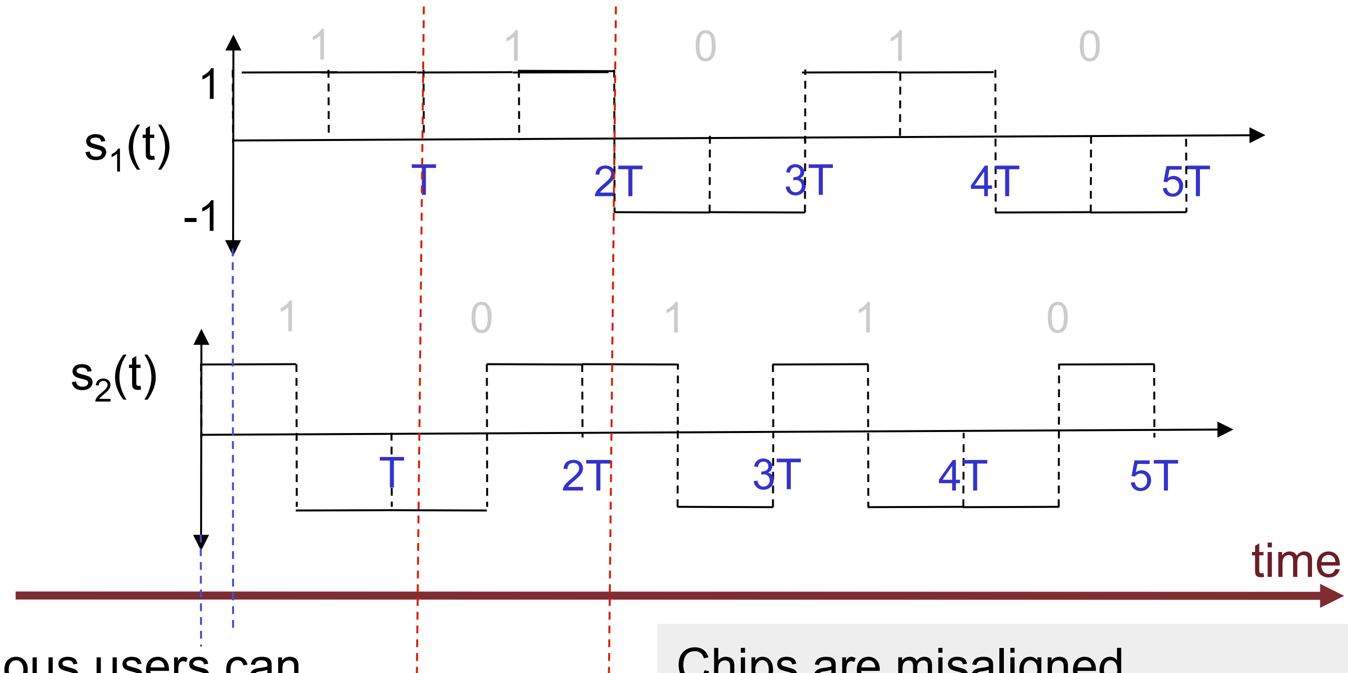
DS-CDMA Transmitter



Ex: 100 source symbols, processing gain = 10 ➔ 1000 chips



Orthogonality and Asynchronous Users

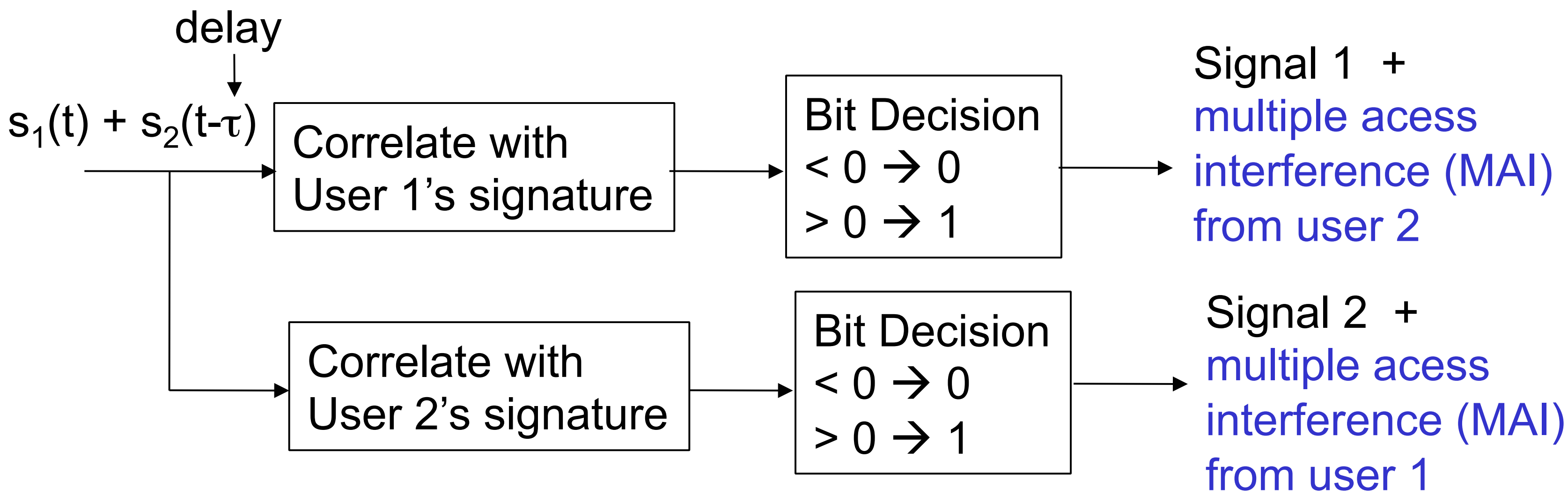


Asynchronous users can start transmissions at different times.

Chips are misaligned
➔ signatures are no longer orthogonal!

- Orthogonality among users requires:
  - Synchronous transmissions
  - No multipath

Correlator, or "Matched Filter" Receiver



The multiple access interference adds to the background noise and can cause errors. For this reason, CDMA is said to be *interference-limited*.

Because CDMA users are typically asynchronous, and because of multipath, it is difficult to maintain orthogonal signatures at the receiver. Consequently, in practice, the signatures at the transmitter are *randomly generated*.

Processing Gain (PG)

The performance of CDMA depends crucially on the Processing Gain:

Bandwidth of spread signal / Symbol rate (minimum bandwidth needed)

or equivalently,

Number of chips per symbol

Correlation and PG

Example: PG=4

s_1: 1 -1 -1 1
s_2: 1 1 1 -1

Correlation = -2

Energy in s_1 (or s_2) is $1^2 + (-1)^2 + (-1)^2 + 1^2 = 4$
Normalized correlation = correlation/energy = -2/4 = -1/2

Example: PG=10

Conclusion: On average, the correlation between signatures decreases as the signature length (PG) increases.

Processing Gain (PG)

The performance of CDMA depends crucially on the Processing Gain:

Bandwidth of spread signal / Symbol rate (minimum bandwidth needed)

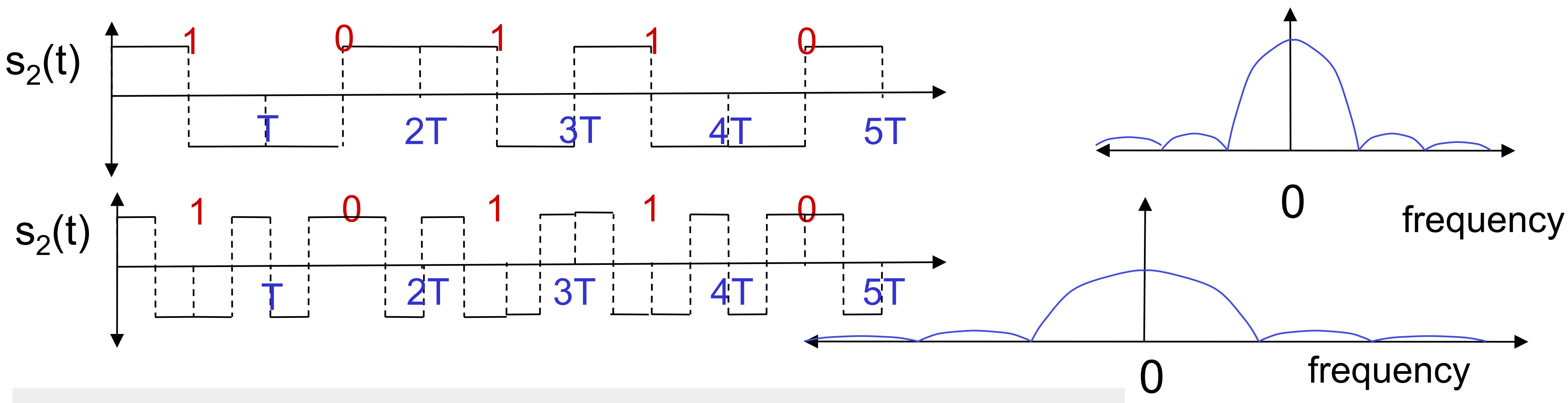
or equivalently,

Number of chips per symbol

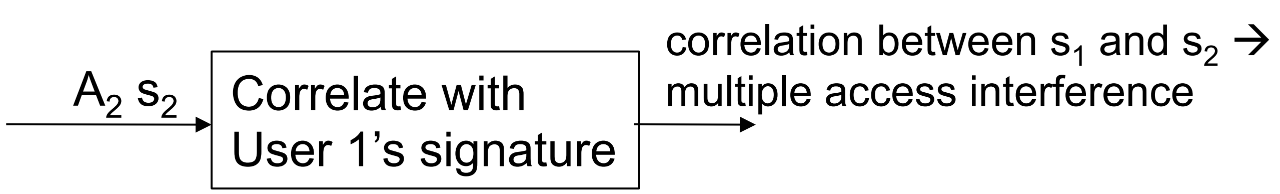
Fundamental tradeoff: increasing the PG

- decreases the correlation between random signatures.
- decreases interference.
- increases the bandwidth of the signal.

Correlation and Bandwidth



Increasing the PG increases bandwidth, but decreases the correlation between user signatures.



Increasing the PG decreases multiple access interference.
Bandwidth expansion therefore provides "immunity" to interference
(all kinds: analog, multiple access, multipath, narrowband, etc).

Example

- IS-95 (2G CDMA)
  - Total bandwidth = 1.25 MHz
  - Data rate = 9.6 kbps
  - PG ≈ 130

- 3G/CDMA2000
  - Total bandwidth = 1.25 MHz
  - Data rate varies between 14.4. kbps (voice) up to 2 Mbps (1X-DO)
  - PG varies from 1 to 130

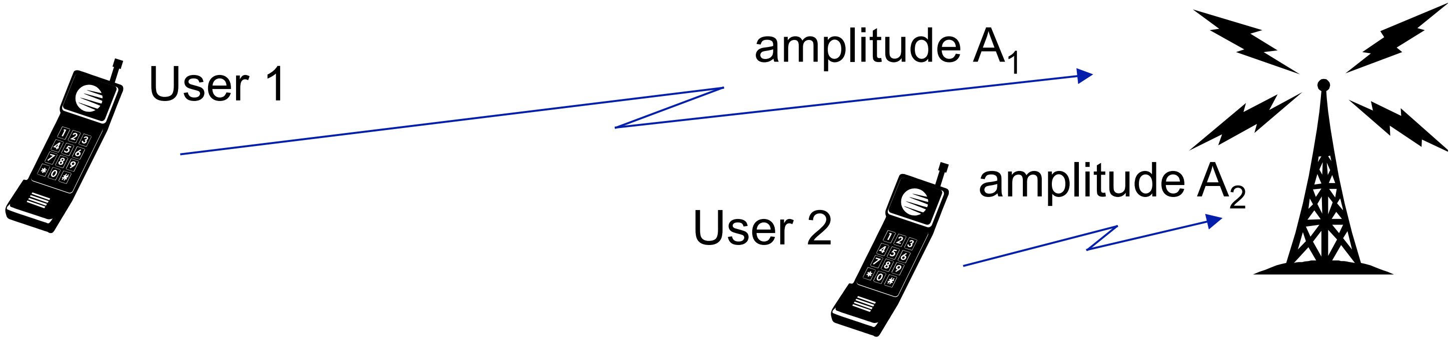
Properties of CDMA

- Robust with respect to interference
- No frequency assignments (eases frequency planning)
- Asynchronous
- High capacity with power control
  - Power control needed to solve near-far problem.
- Wideband: benefits from frequency/path diversity.
- Benefits from voice inactivity and sectorization.
- No loss in trunking efficiency.
- Soft capacity: performance degrades gradually as more users are added.
- Soft handoff

Near-Far Problem

SO… THEN THE THIRD TIME I CALLED CUSTOMER SERVICE, I SAID &%$#%^…

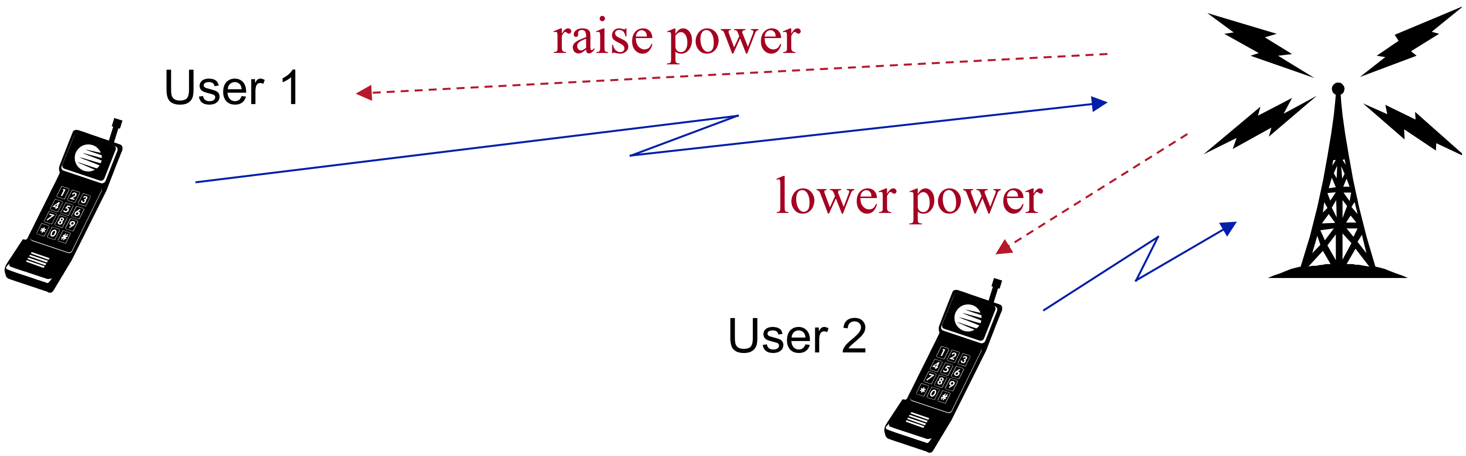
Near-Far Problem



Output of correlator receiver is signal + interference. As the interferer moves closer to the base station, the interference increases.
In practice, power variations can be up to 80 dB!

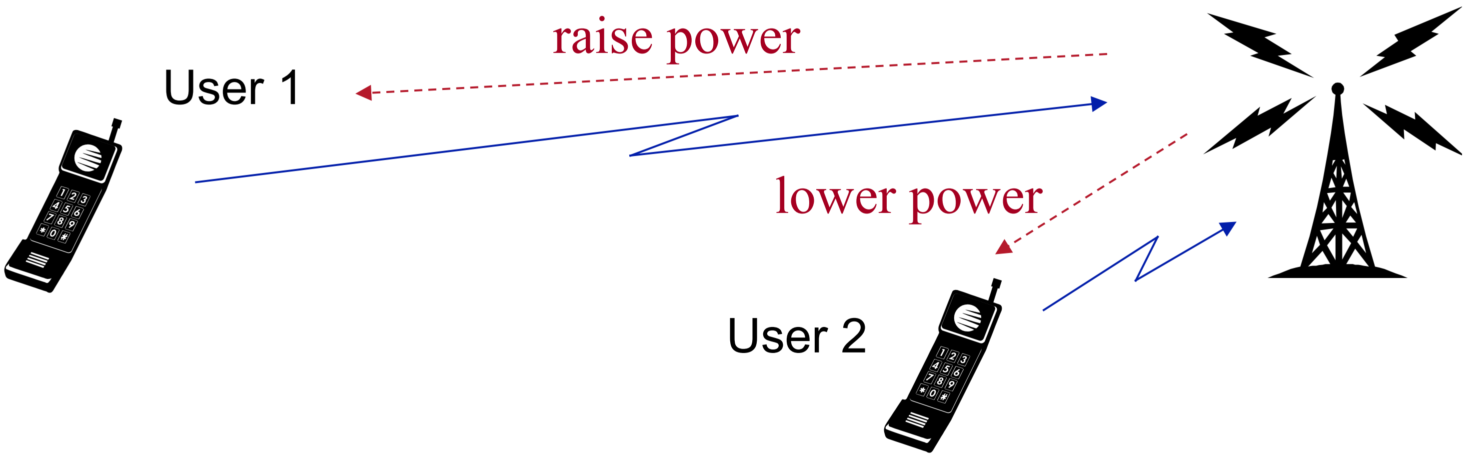
Conclusion: User 1’s signal is overwhelmed by interference from user 2!

Closed-Loop Power Control



- Base station gives explicit instructions to mobiles to raise/lower power.
- Needed to solve near-far problem (equalizes received powers).
- Introduced by Qualcomm in the late 80’s.

Closed-Loop Power Control: Properties



- Crucial part of CDMA cellular systems (IS-95, 3G).
- Minimizes battery drain.
- Complicated (increases cost)
- Requires overhead: control bits in feedback channel to tell transmitter to lower/raise power

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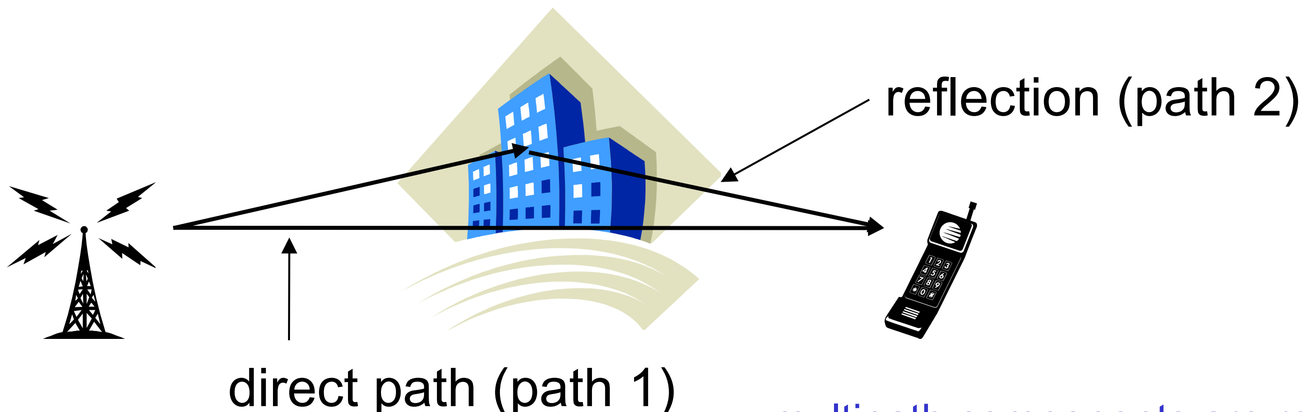
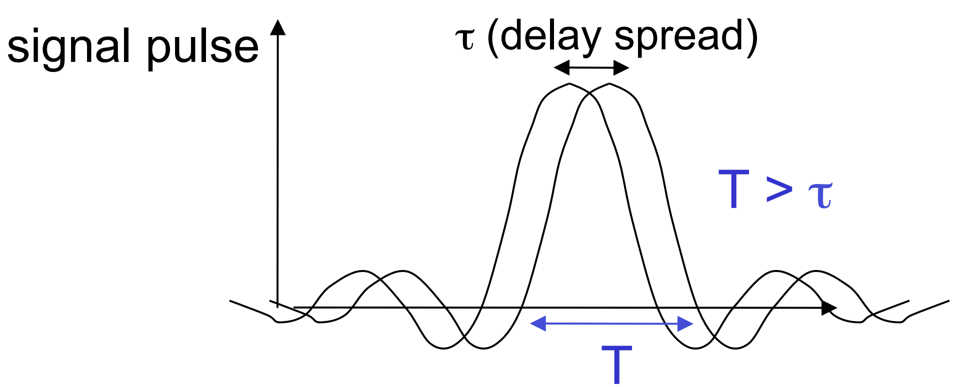
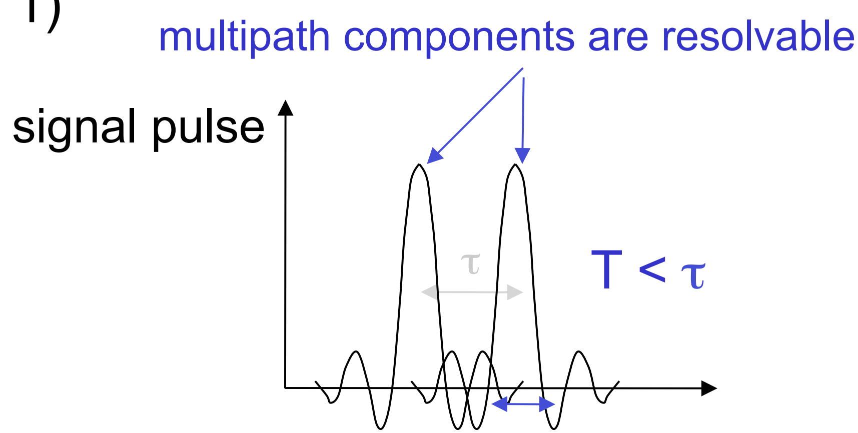
Bandwidth and Multipath Resolution





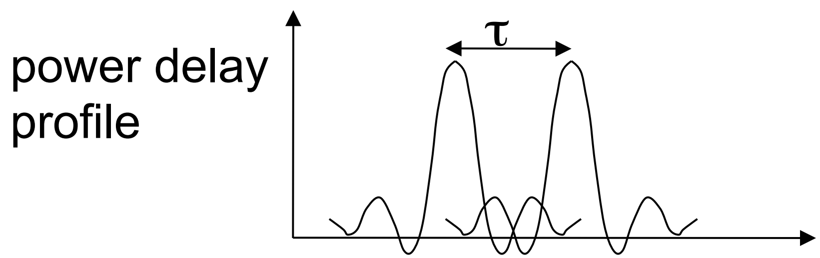


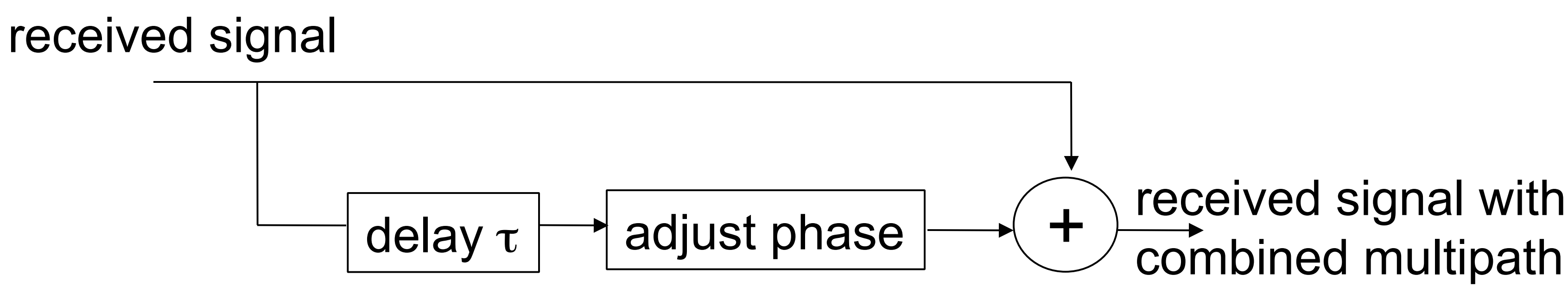
Narrow bandwidth ➔ low resolution
Receiver cannot distinguish the two paths.

Wide bandwidth ➔ high resolution
Receiver can clearly distinguish two paths.

CDMA and Path Diversity

- CDMA uses wideband signals (chips are very narrow pulses), so that multipath is resolvable.
- A “RAKE” receiver collects (“rakes up”) the energy in the paths:





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CDMA Capacity

Performance depends on

$$\frac{E_b}{N_0} \equiv \frac{\text{Energy per bit}}{\text{Interference + Noise power per unit bandwidth}}$$

Let S= Transmitted power (per user), R= information rate (bits/sec),
W= Bandwidth, K= Number of users

E_b= S/R (energy per second / bits per second)
N_0= (Number of interferers x S)/W = ((K-1) x S)/W

Therefore E_b/N_0 = (W/R)/(K-1) = (Processing Gain)/(K-1)

For a target E_b/N_0, the number of users that can be supported is K = (Processing Gain)/(E_b/N_0) + 1

CDMA Capacity: Example

- For IS-95, want $E_b/N_0 \geq 7$ dB
- For 3G, want $E_b/N_0 \geq 3$ to 5 dB

- Suppose W=1.25 MHz (single-duplex), R= 14.4 kbps, target E_b/N_0 = 7 dB:

$$K = 1 + [(1.25 \times 10^6)/(14.4 \times 10^3)]/5.01 \approx 18$$

- Compare with GSM, cluster size N=3:

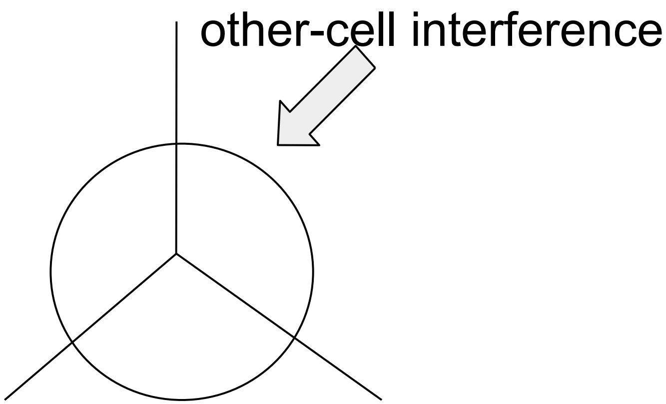
$$K = 8 \text{ (users/channel)} \times (\text{\# of 200 kHz channels})$$

$$= 8 \times 1.25 \times 10^6 / (200 \times 10^3 \times 3) \approx 16$$

Increasing CDMA Capacity

- Must reduce interference

- Antenna sectorization
  - Interference reduced by 1/3
  - Trunking efficiency is not a major issue (no channels/time slots).



- Voice inactivity automatically increases the capacity relative to TDMA with dedicated time slots.

- CDMA has a “soft” capacity: each additional user marginally degrades performance for all users.

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Interference and CDMA Capacity

If interference is reduced by a factor 1/g, then the number of interferers can be increased by g (N_0 is replaced by g x N_0):

$$K = 1 + \frac{W/R}{(1/g)(E_b/N_0)}$$

If W/R is large, then reducing interference by 1/g (approximately) increases the capacity by a factor of g.

Previous example: voice activity of 1/3 combined with 120^o sectors increases capacity by a factor of 9!

Refining the Capacity Estimate

- Capacity for previous example is $9 \times 18 \approx 162$
- Have not accounted for:
  - Other-cell interference
    - Approximately 1/3 to 1/2 of total interference power
      $K \rightarrow 1/(1+1/2) \times K \approx 108$
  - Multipath / fading
    - Some multipath is combined by the Rake receiver, the rest is interference
  - Power control inaccuracy

Precise capacity predictions become difficult, best to rely on field trials…

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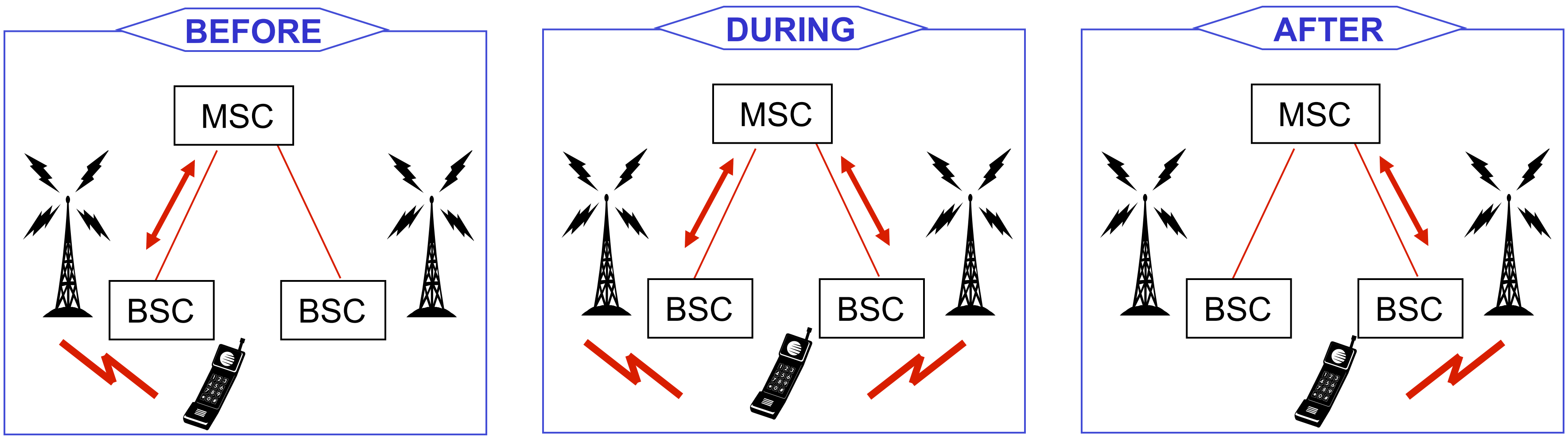
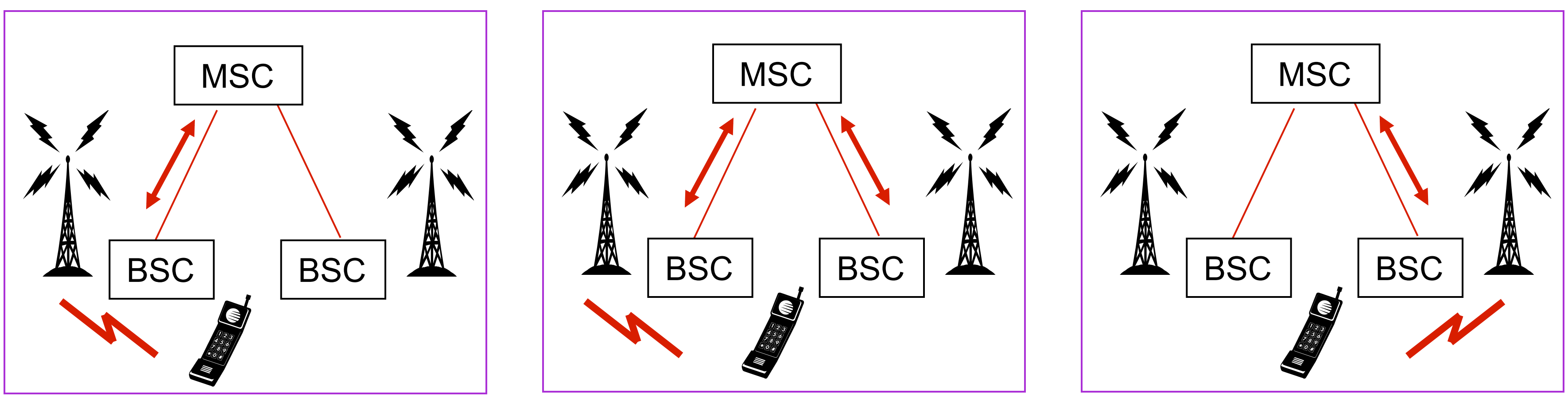
Soft Handoff (CDMA) "Make before break"



Hard Handoff (TDMA)

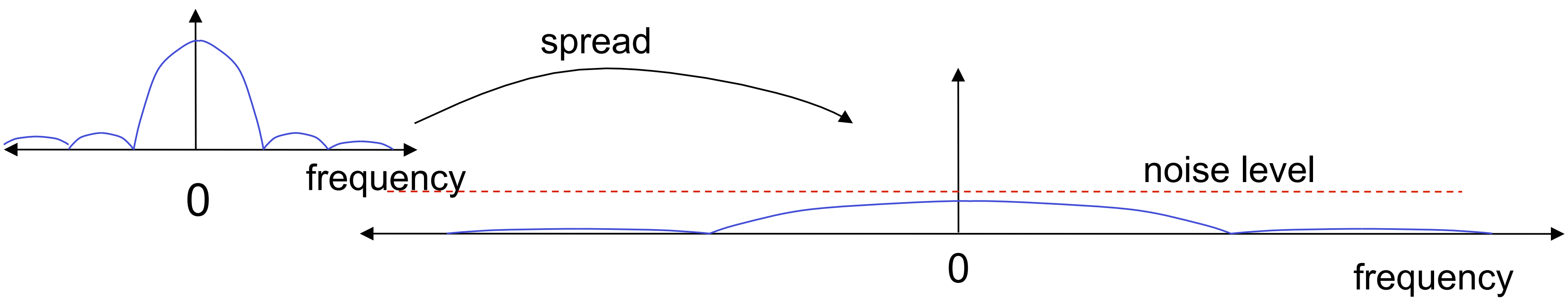


Applications of Spread-Spectrum

- Military (preceded cellular applications)
- Cellular
- Wireless LANs (overlay)

Military Spread Spectrum

- Can "hide" a signal by "spreading it out" in the frequency domain.



- Requires a very large PG (several 100 – 1000).
- Enemy must know spreading code (the "key" containing 100's of bits) to demodulate – too complicated for simple search.
- Spread spectrum signals have the "LPI/LPD" property: low probability of intercept / low probability of detect.

Spread spectrum used for covertness, not multiple access.

Applications of Spread-Spectrum

- Military (preceded cellular applications)
- Cellular
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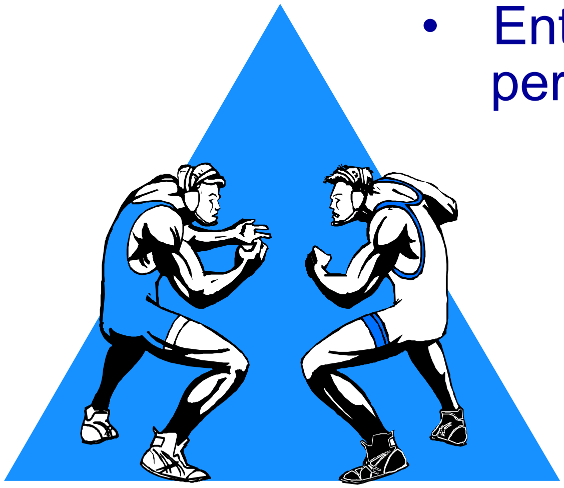
CDMA vs. TDMA (early 1990s)

TDMA

- Proven technology
- Large investment in research, development

CDMA

- Earlier military applications
- Near-far problem
- Enticing (exaggerated?) performance claims



2G CDMA: IS-95 or cdmaOne

- Introduced by Qualcomm (San Diego)
- Direct-Sequence Spread Spectrum signaling
- FDD
- Wideband channels (1.25 MHz)
- Tight, closed-loop power control
- Sophisticated error control coding
- Multipath combining to exploit path diversity
- Noncoherent detection
- Soft handoff
- High capacity
- Air-interface only: uses IS-41

3G Air Interfaces

cdma2000

- Also referred to as “multicarrier” CDMA
- 1X Radio Transmission Technology (RTT): 1.25 MHz bandwidth (1 carrier)
  - *Supports 307 kbps instantaneous data rate in packet mode*
  - *Expected throughput up to 144 kbps*
- 1xEV (Evolutionary): High Data Rate standard introduced by Qualcomm
  - *1xEV-DO: data only, 1xEV-DV: data and voice*
  - *Radio channels assigned to single users (not CDMA!)*
  - *2.4 Mbps possible, expected throughputs are a few hundred kbps*
  - *1xEV-DV has twice as many voice channels as IS-95B*

Wideband (W)-CDMA

- Also referred to as Universal Mobile Telecommunications System (UMTS)
- European proposal to ITU (1998)
- Backwards compatibility with 2G GSM and IS-136 air interfaces
- Network and frame structure of GSM
- ``Always on’’ packet-based data service
- Supports packet data rates up to 2 Mbps
- Requires minimum 5 MHz bandwidth, FDD, coherent demodulation
- 6 times spectral efficiency of GSM

Service Providers and Technologies

Verizon[2]	Cellular & PCS (850 & 1900 MHz)	CDMA 2000; 1 x EV-DO	8-128 Kbps up to 2.5 Mbps
ATT/Cingular	Cellular (850 & 1900 MHz)	GSM/GPRS/EDGE UMTS/HSPA	up to 512 kbps
Sprint; Clearwire[3]	PCS (1900 MHz)	CDMA2000; 1 x EV-DO	8-128 Kbps up to 2.5 Mbps
T-Mobile	PCS (1900 MHz)	GSM/GPRS/EDGE	8-350 Kbps
NexTel[1]	Public service band (800 MHz)	iDEN (TDMA) & WiDEN[4]	25-64 kbps near 100 kpbs
U. S. Cellular	Cellular & PCS (850 & 1900 MHz)	1 x EV-DO	up to 2.5 Mbps

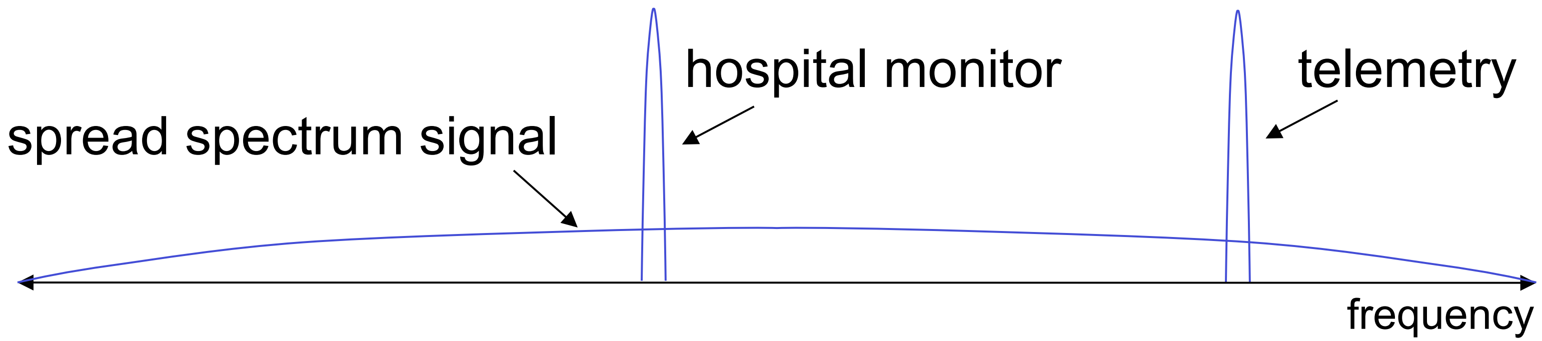
[1]Merged with Sprint.
[2]Plans to deploy LTE.
[3]Rolled out WiMax in Baltimore, Portland.
[4]Wideband version of iDEN.

Applications of Spread-Spectrum

- Military (preceded cellular applications)
- Cellular
- Wireless LANs (overlay)

Spread Spectrum Underlay

- FCC requirements on spectrum sharing in the unlicensed (Industrial, Scientific, Medical (ISM)) bands:
  - "Listen before talk"
  - Transmit power is proportional to the square root of the bandwidth.



- Spread spectrum signaling is robust with respect to a narrowband interferer.
- To a narrowband signal, a spread spectrum signal appears as low-level background noise.

Variable-Rate CDMA

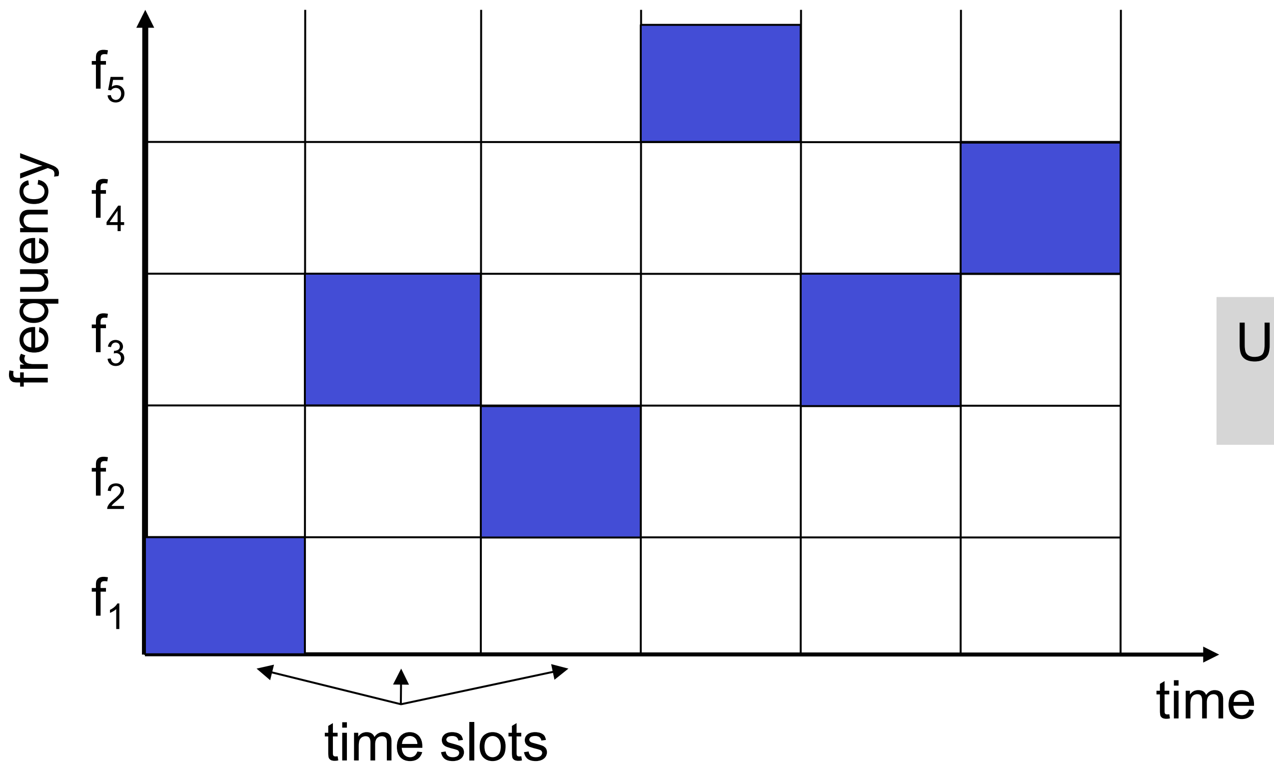
Variable-Rate CDMA

To increase the data rate we can:

- Increase the number of signatures per user
  - More signatures → more power, more interference
- Reduce the number of chips per bit
  - Decreases immunity to interference (must increase power)
- Increase the number of bits per symbol
  - QPSK → 8-PSK → 16 QAM …
    requires more power
- How is voice capacity affected by the presence of high-rate data users?

Frequency-Hopped CDMA

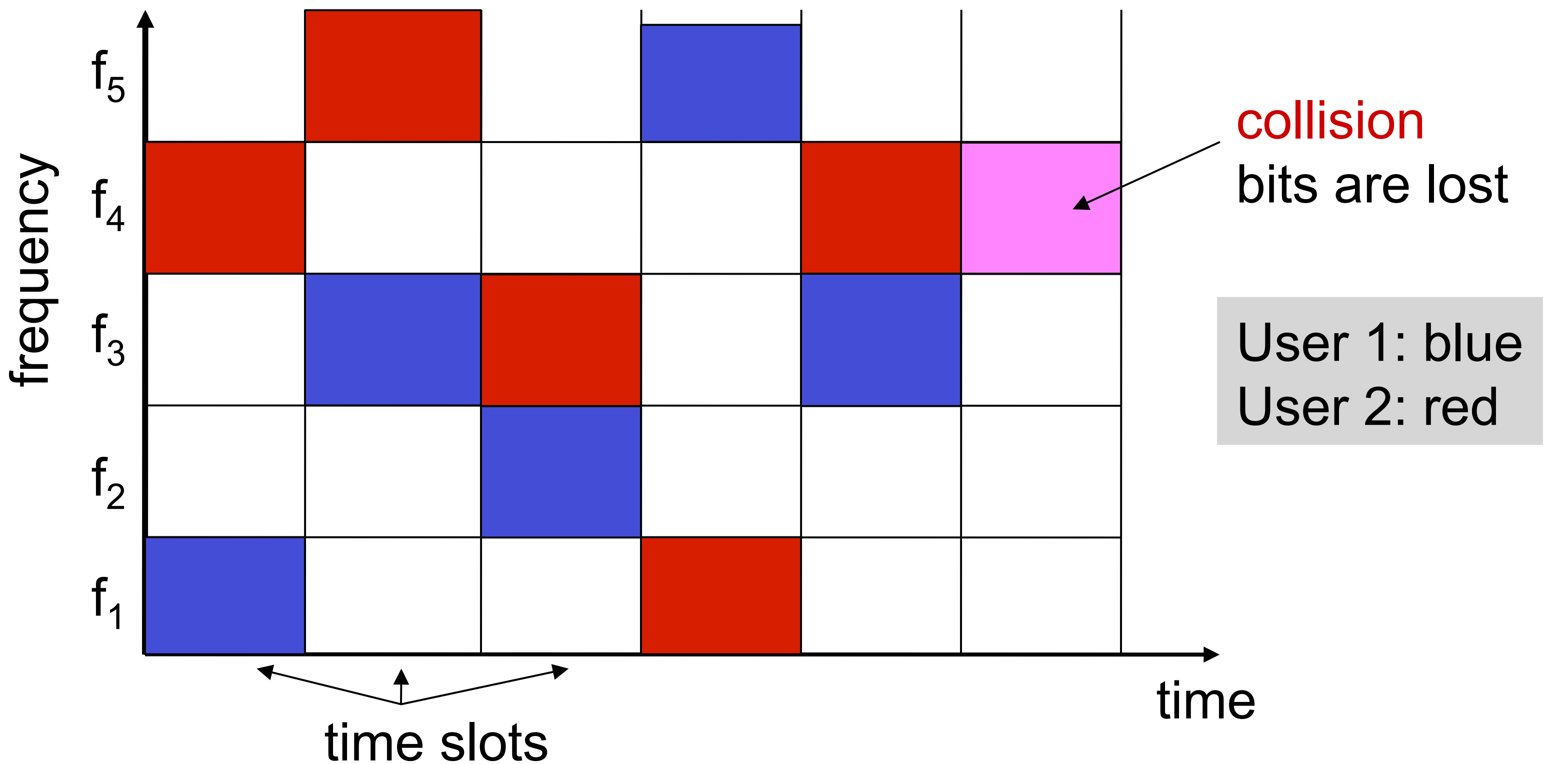
Idea: “Hop” from channel to channel during each transmission.



User 1: blue

Frequency-Hopped CDMA

Idea: "Hop" from channel to channel during each transmission.



Hop Rate

- Can make synchronous users orthogonal by assigning hopping patterns that avoid collisions.
- “Fast” hopping generally means that the hopping period is less than a single symbol period.
- “Slow” hopping means the hopping period spans a few symbols.
- The hopping rate should be faster than the fade rate (why?).

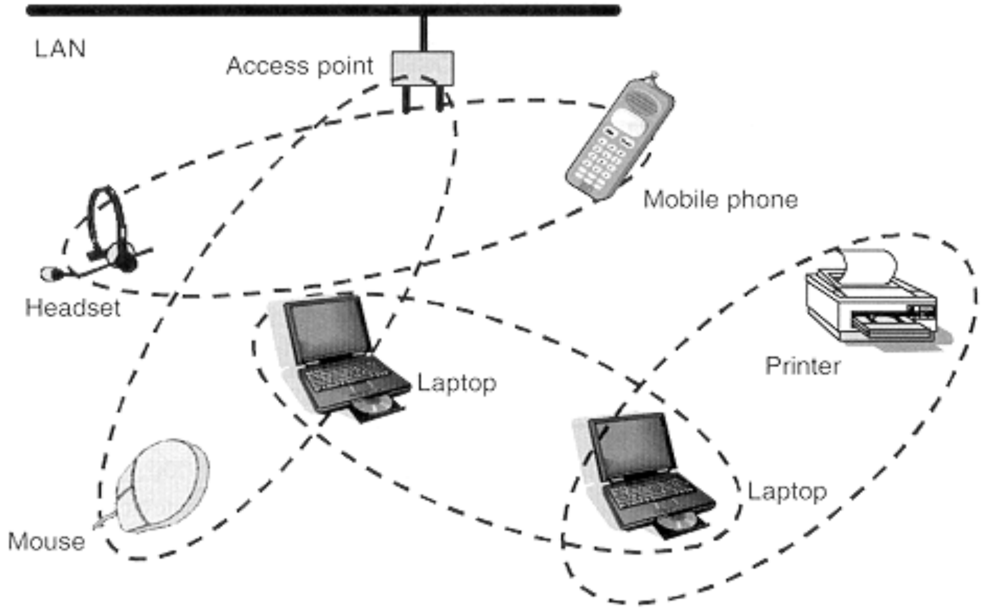
Hop Rate

- Can make synchronous users orthogonal by assigning hopping patterns that avoid collisions.
- “Fast” hopping generally means that the hopping period is less than a single symbol period.
- “Slow” hopping means the hopping period spans a few symbols.
- The hopping rate should be faster than the fade rate so that the channel is stationary within each hop.

Properties of FH-CDMA

- Exploits frequency diversity (can hop in/out of fades)
- Can avoid narrowband interference (hop around)
- No near-far problem (Can operate without power control)
- Low Probability of Detect/Intercept
- Spread spectrum technique – can overlay
- Cost of frequency synthesizer increases with hop rate
- Must use error correction to compensate for erasures due to fading and collisions.
- Applications
  - Military (army)
  - Part of original 802.11 standard
  - Enhancement to GSM
  - Bluetooth

Bluetooth: A Global Specification for Wireless Connectivity



- Wireless Personal Area Network (WPAN).
- Provides wireless voice and data over short-range radio links via low-cost, low-power radios ("wireless" cable).
- Initiated by a consortium of companies (IBM, Ericsson, Nokia, Intel)
- Standard has been developed (IEEE 802.15.1).

Bluetooth Specifications

- Allows small portable devices to communicate together in an ad-hoc "piconet" (up to eight connected devices).
- Frequency-hopped spread-spectrum in the 2.4 GHz UNII band.
- Interferes with 802.11b/g/n
- 1600 hops/sec over 79 channels (1 MHz channels)
- Range set at 10m.
- Gross data rate of 1 Mbps (TDD).
  - *64 kbps voice channels*
- Second generation (Bluetooth 2.0+) supports rates up to 3 Mbps. Competes with Wireless USB.

The Multiple Access Problem

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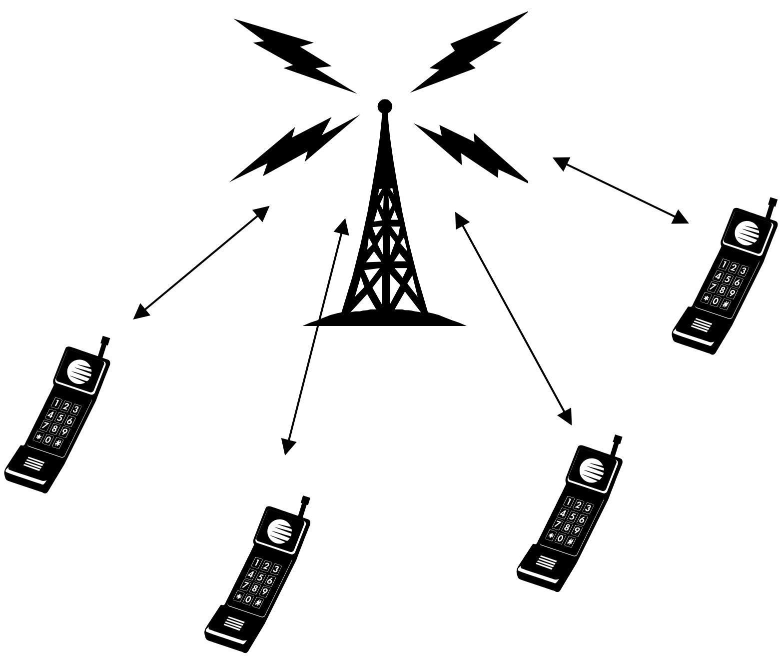
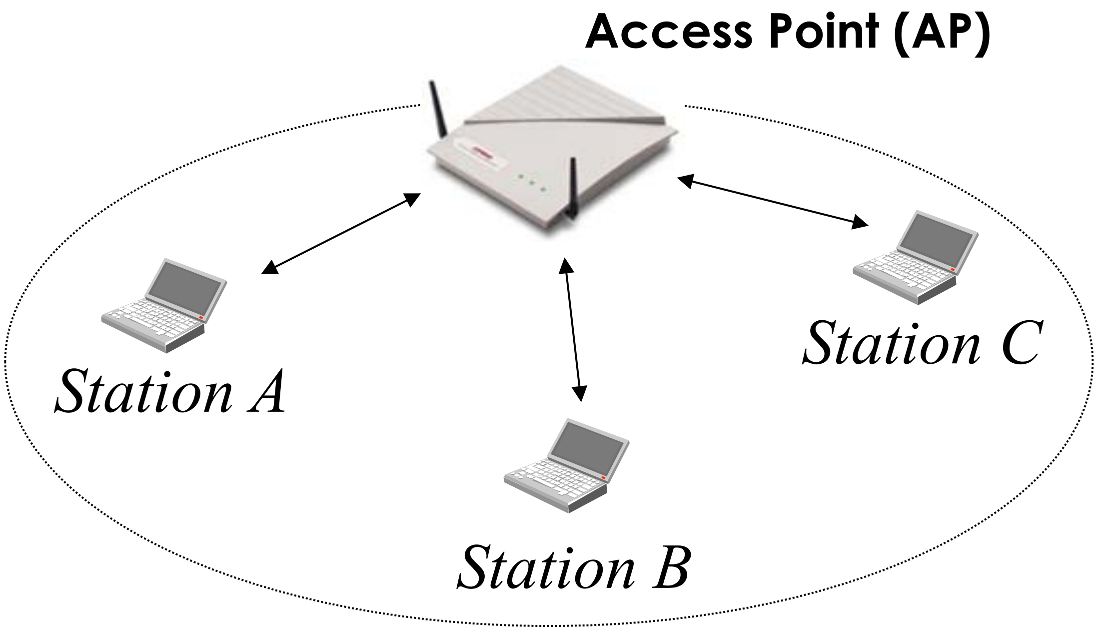


- Frequency-Division (AMPS)
- Time-Division (IS-136, GSM)
- Code-Division (IS-95, 3G)
  Direct Sequence/Frequency-Hopped
- Orthogonal Frequency Division (WiMax, 4G)
- Random Access (802.11, wireless data)

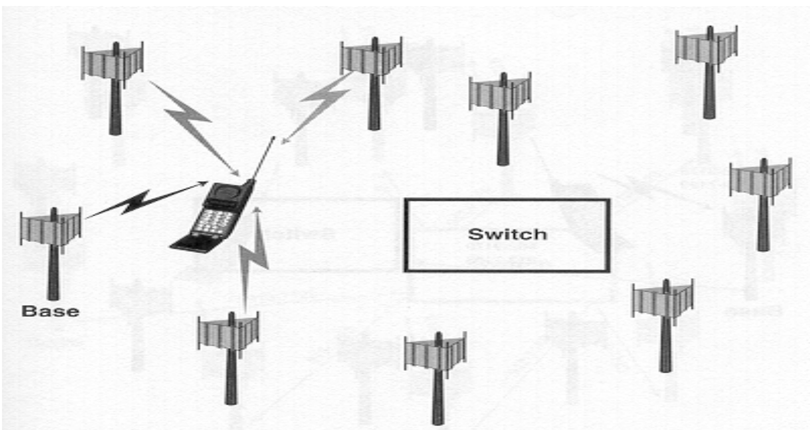
802.11 Random Access



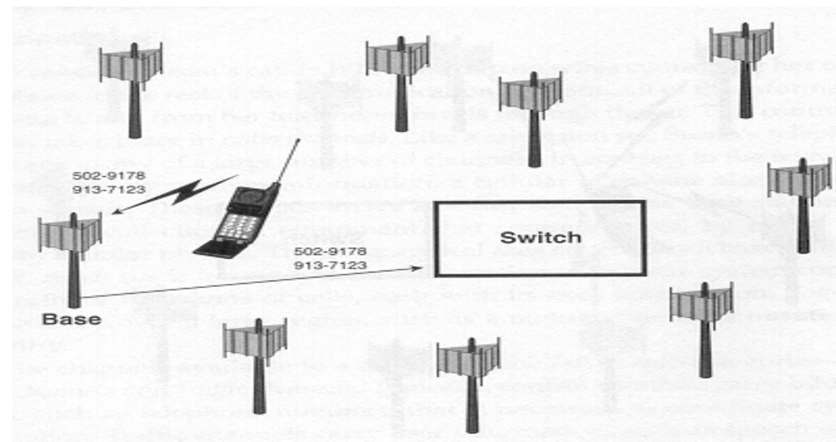
Terminals send/receive messages (packets) to/from the AP at random times (i.e., when they appear).

Cellular Call Setup (Random Access)

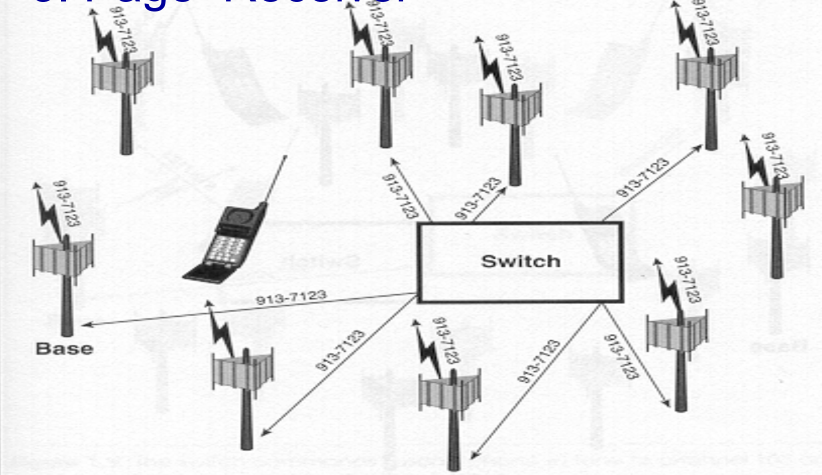
1. Call Request



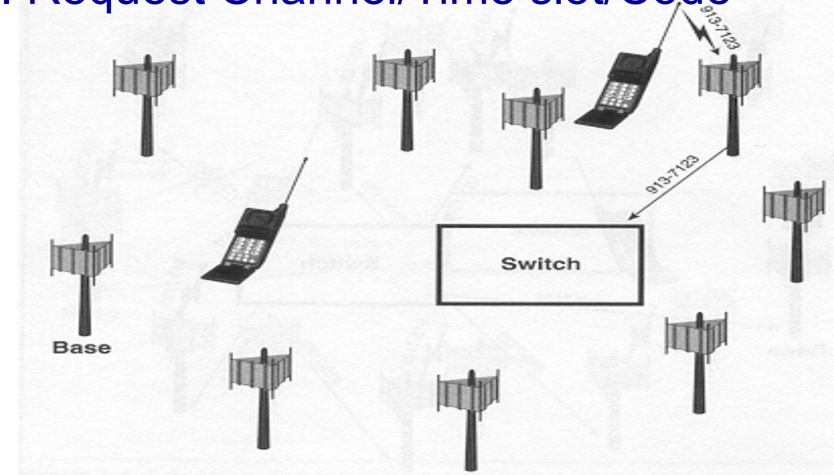
2. Send numbers to switch



3. Page Receiver



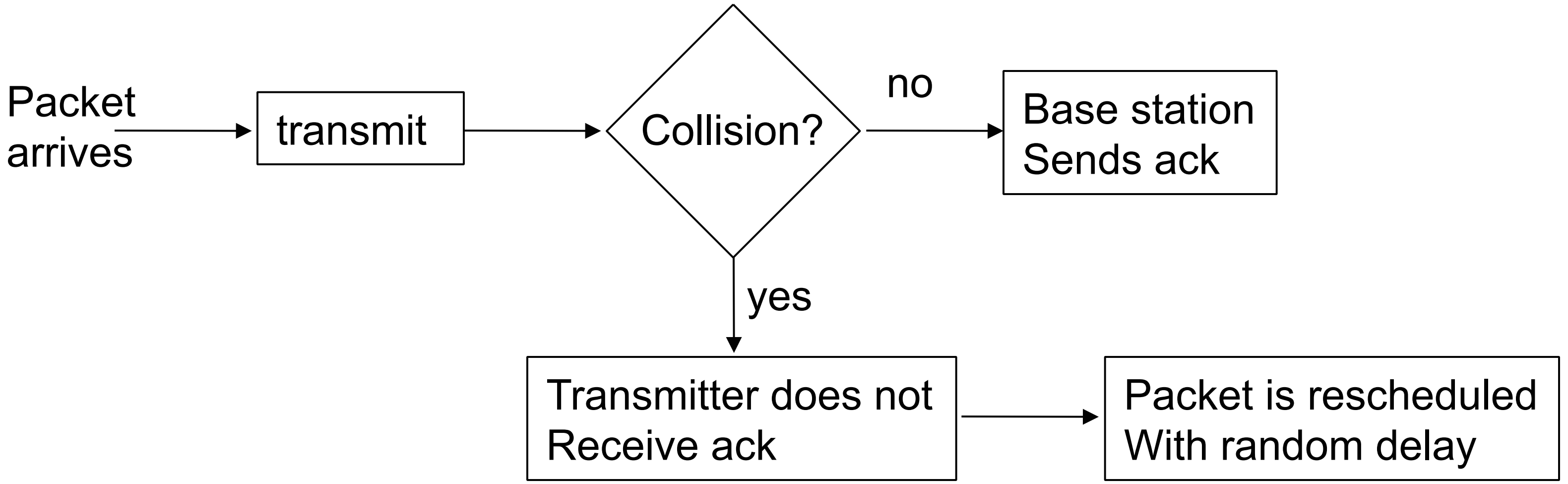
4. Request Channel/Time slot/Code



Medium Access Control (MAC)

- Fixed assignment access
  - Each user is assigned a dedicated channel, time slot, or code
  - Appropriate for circuit-switched traffic, transferring long data files
- Random access: users contend for access to the channel
  - Users may collide, losing packets.
  - Sometimes can negotiate rate (bandwidth, time slots, codes) and power
  - Widely used in wired networks
  - Used in wireless networks for requesting channel/time slot/code, WiFi

ALOHA-Based Random Access



- Simple: asynchronous
- Low throughput under heavy loads
(maximum is 18% of incoming packets)

- Slotted ALOHA
  - Synchronous, maximum throughput increases to 36%
  - Used in GSM to reserve a time slot for voice connection
- Reservation ALOHA
  - Contention period followed by reserved message slots

ALOHA Protocols

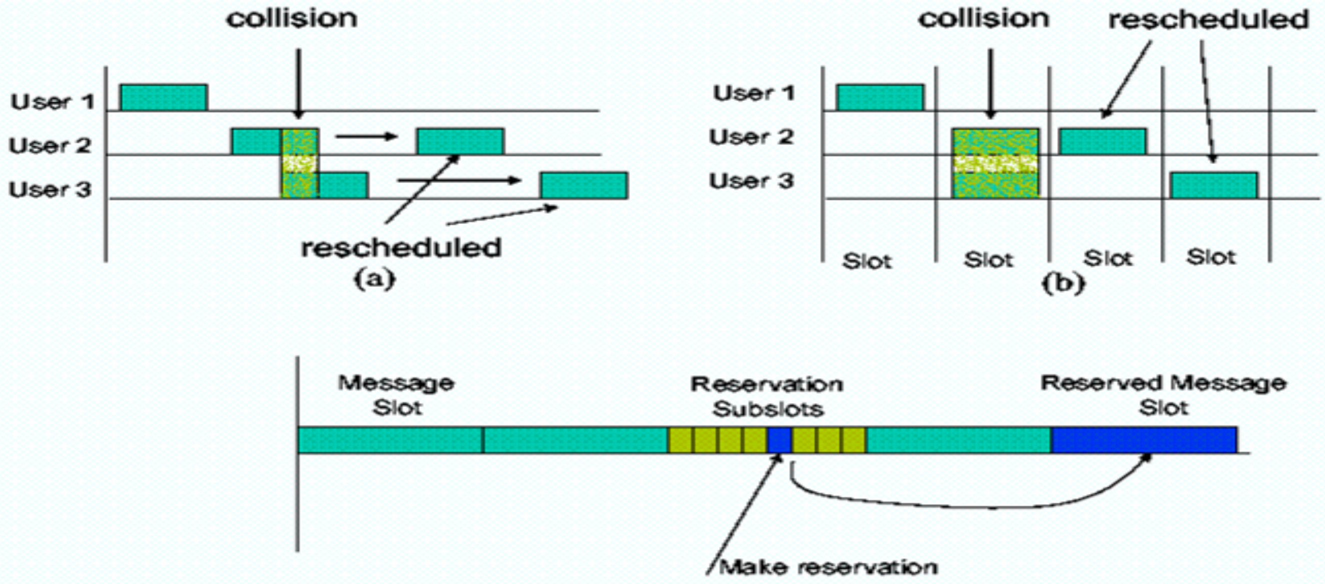
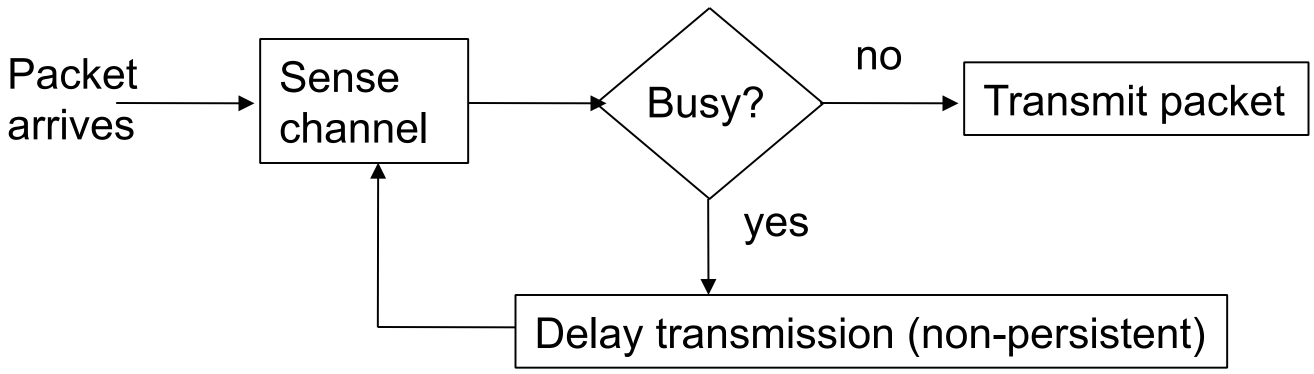


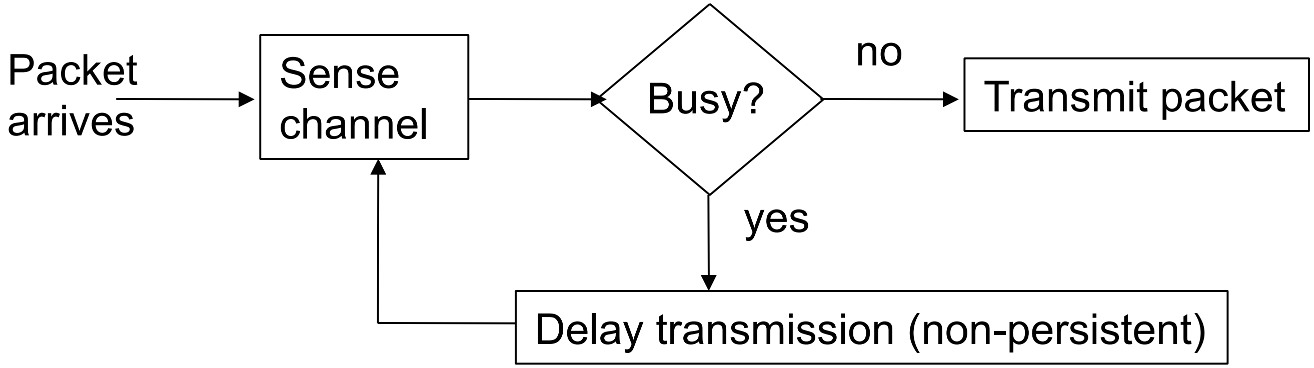
Figure 10: (a) Pure ALOHA protocol (b) Slotted ALOHA protocol (c) Reservation ALOHA

Carrier Sense Multiple Access (CSMA)



- “Listen before talk” (LBT) protocol
- How do collisions occur?

Carrier Sense Multiple Access (CSMA)



- "Listen before talk" (LBT) protocol
- Collisions occur if transmitters cannot sense the other transmission (e.g., due to large propagation delay)
  - Lower probability of collision/higher throughput than ALOHA
- Long propagation times ➔ more collisions
  - ALOHA preferred for wide area applications

CSMA Example

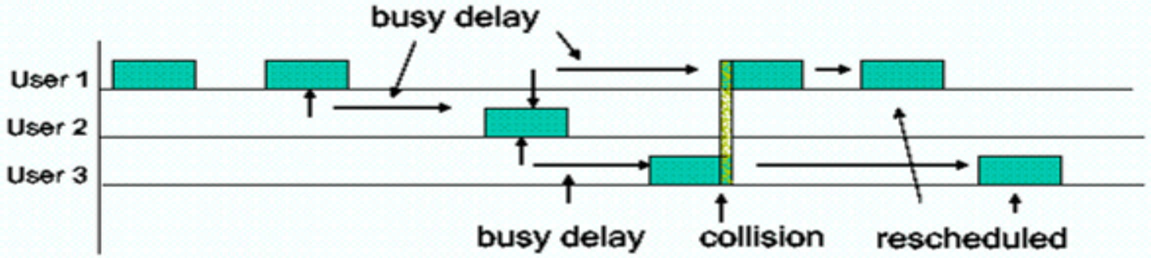
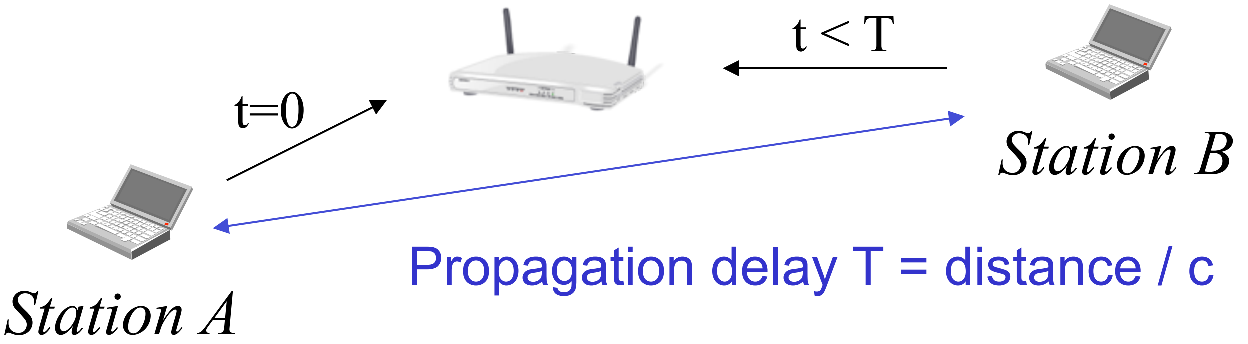


Figure 12: Basic operation of CSMA

Collision Detection: Worst-Case Delay

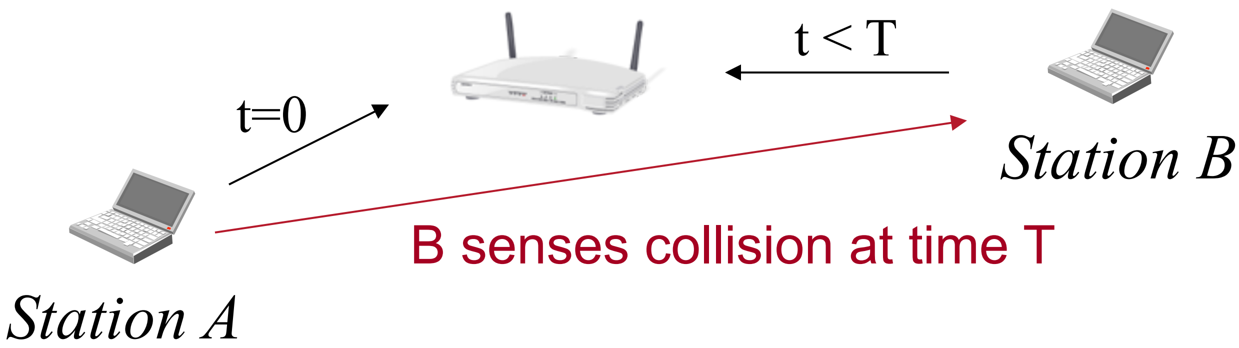
- A starts transmitting at time 0

Collision Detection: Worst-Case Delay



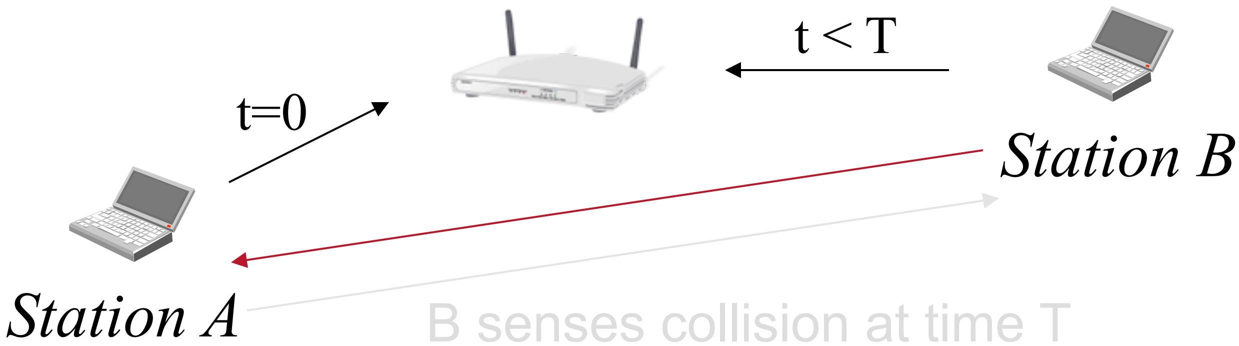
- A starts transmitting at time 0
- B starts transmitting just before time T (channel is clear)

Collision Detection: Worst-Case Delay



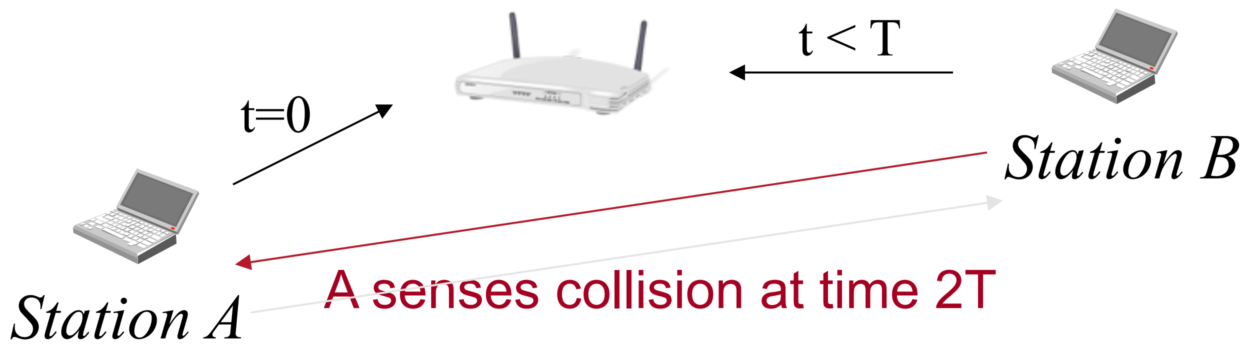
- A starts transmitting at time 0
- B starts transmitting just before time T (channel is clear)
  - B hears A just after it starts to transmit.

Collision Detection: Worst-Case Delay



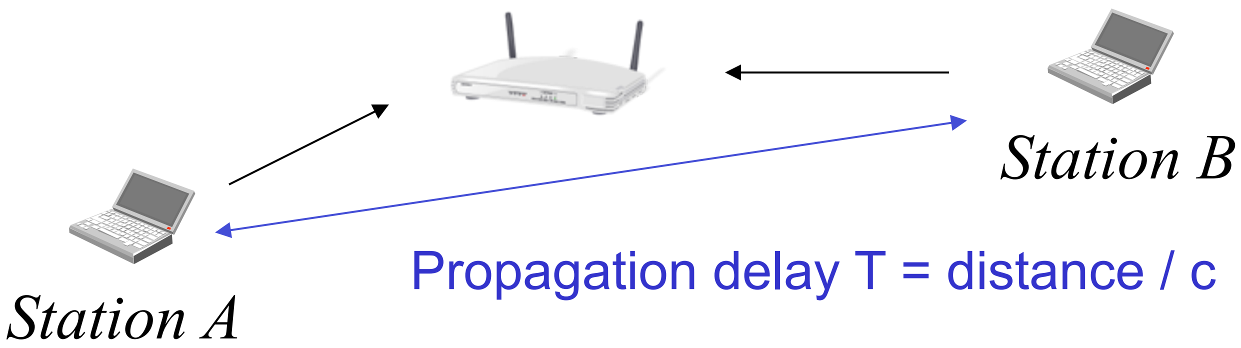
- A starts transmitting at time 0
- B starts transmitting just before time T (channel is clear)
  - B hears A just after it starts to transmit.
- B's initial transmission travels back to A

Collision Detection: Worst-Case Delay



- A starts transmitting at time 0
- B starts transmitting just before time T (channel is clear)
  - B hears A just after it starts to transmit.
- B's initial transmission travels back to A
  - A senses a collision at time 2T

Maximum Separation



- Worst-case delay before collision is detected is 2T
- As T increases, probability of collision increases, more bits can be lost during a collision
  - Imposes maximum separation between stations
- 802.11b: maximum separation between station and router is 100 M

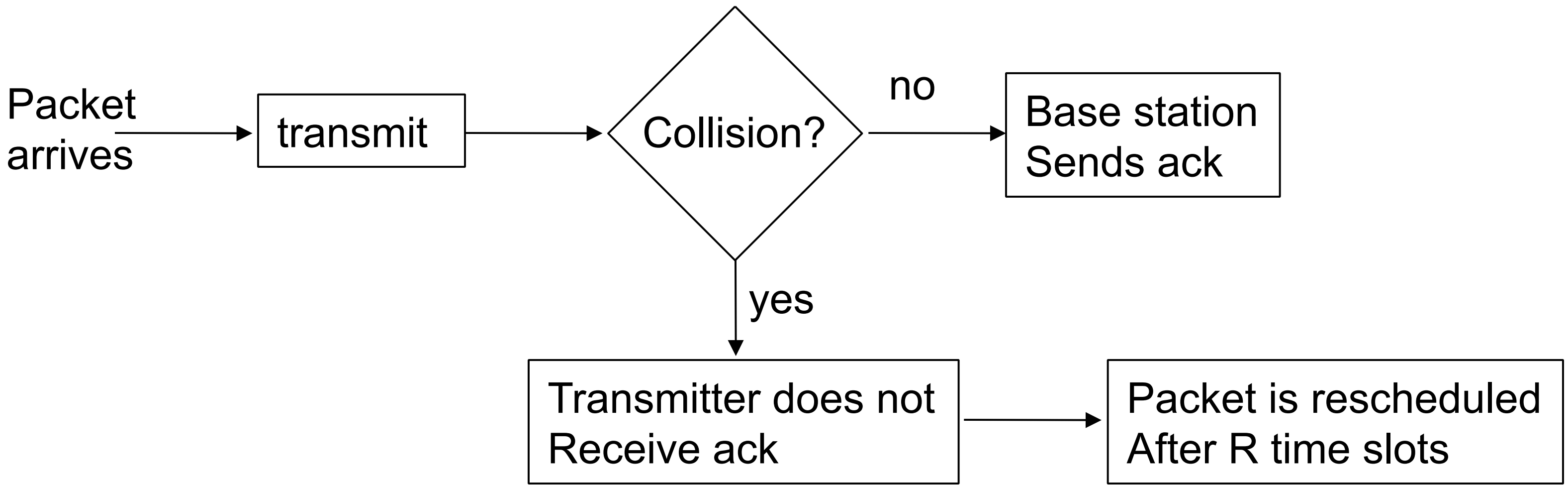
  T = 200/c = 2/3 microsecond

  Data rate 11 Mbps ➔ maximum of 8 bits are lost in collision

Carrier Sensing

- Nonpersistent: After sensing a busy channel, the terminal senses the channel after a random waiting period
- Persistent: The terminal senses the channel until the channel becomes free.
  - 1-Persistent: After the channel becomes free, the terminal transmits immediately.
  - p-Persistent: The terminal transmits with probability p.

Binary Exponential Backoff



- R is random
- Maximum of 16 retries
- Time slot ≥ 2 x (maximum round trip delay)

After 1st collision:
R=0 or 1 with equal probability

After 2nd collision:
R=0,1,2, or 3 with equal probability

After i^{th} collision (i=1,…,10):
R is selected between 0 and 2^i-1

Performance

- Throughput (S): Average number of successful packet transmissions per unit time.
  - Normalized throughput: Percentage of successful packet transmissions (per time slot or time unit)
- Average Delay (D): Average waiting time before successful transmission
- Offered Traffic (G): Number of packet transmission attempts per packet time slot – includes both new arrivals and retransmissions.
- Performance depends on the propagation delay across the network relative to the packet duration.

Throughput vs. Offered Load

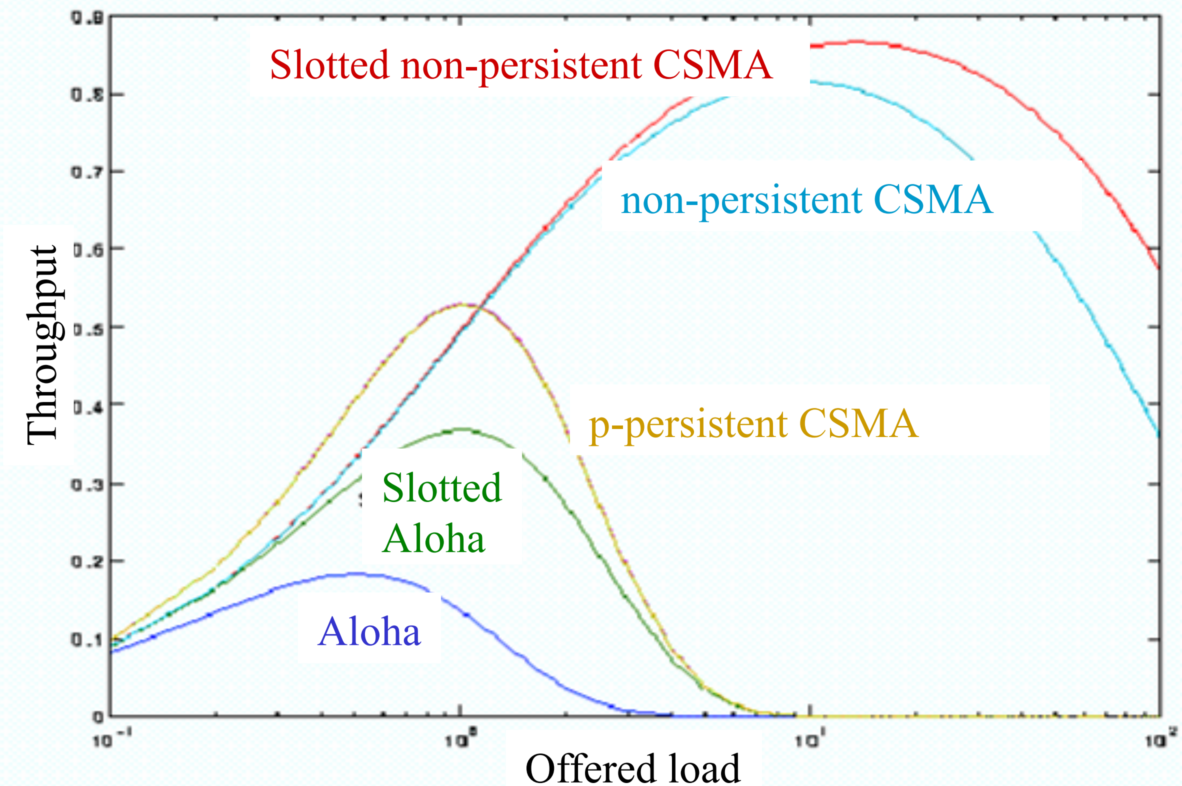


Figure 18: Throughput S versus offered traffic load G for various random access protocols

Throughput vs. Offered Load

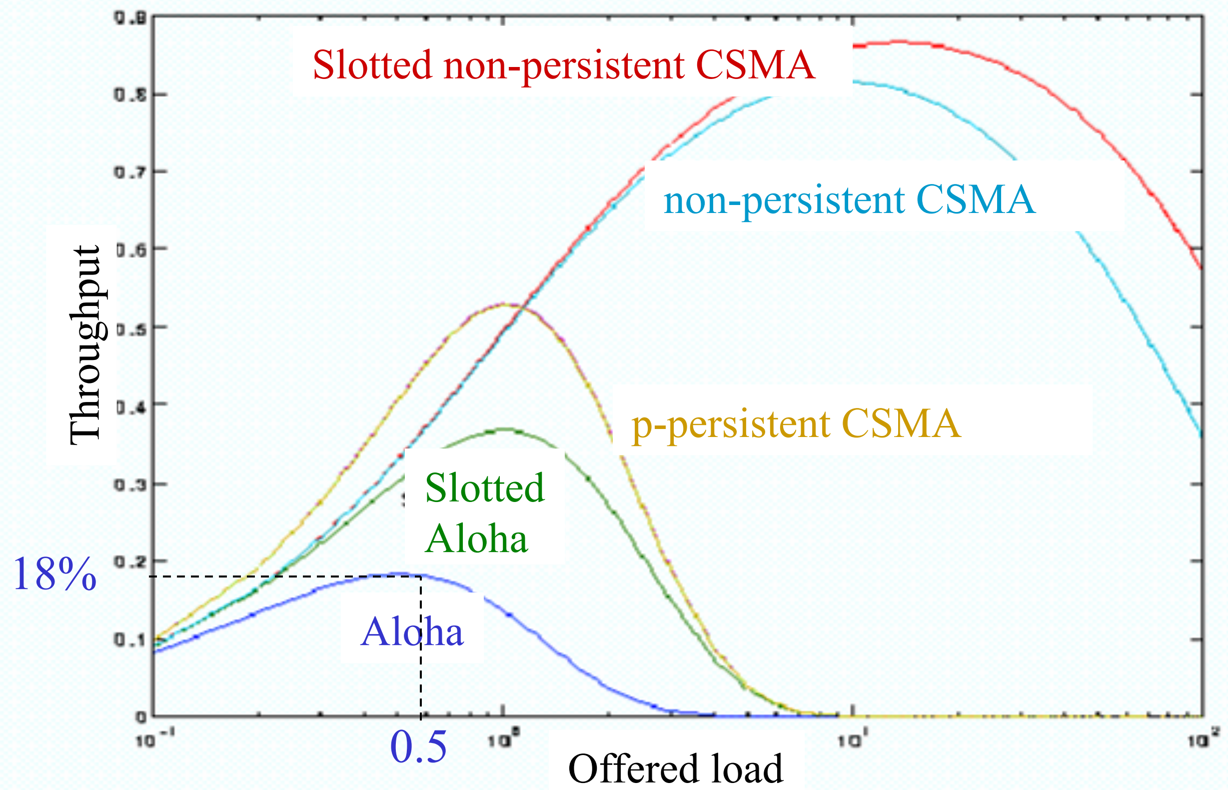


Figure 18: Throughput *S* versus offered traffic load *G* for various random access protocols

Delay vs. Throughput

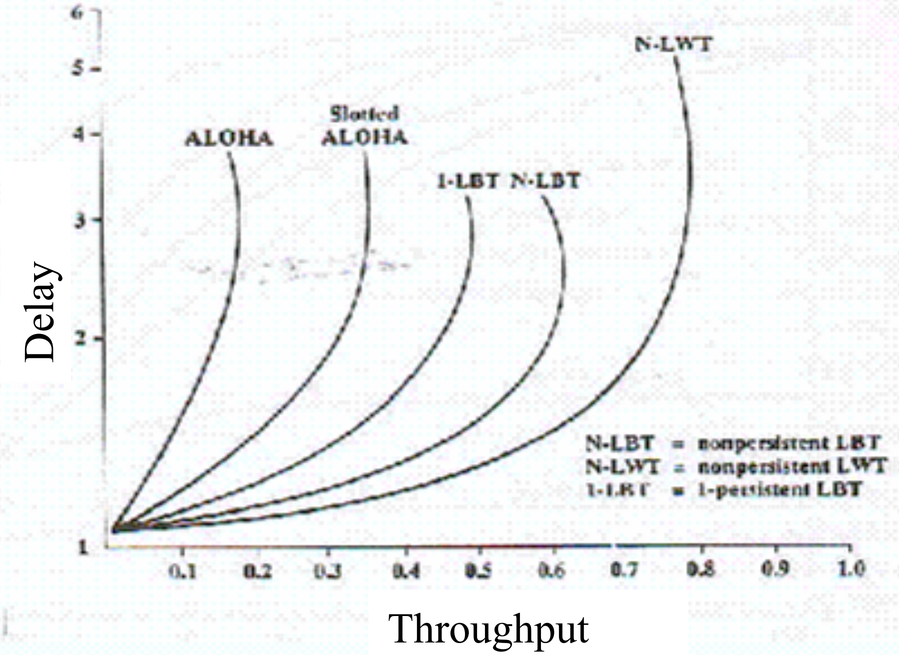


Figure 20: Delay versus throughput for various random access protocols