EE206A Lecture #4
Sharing the Wireless Link: Part I

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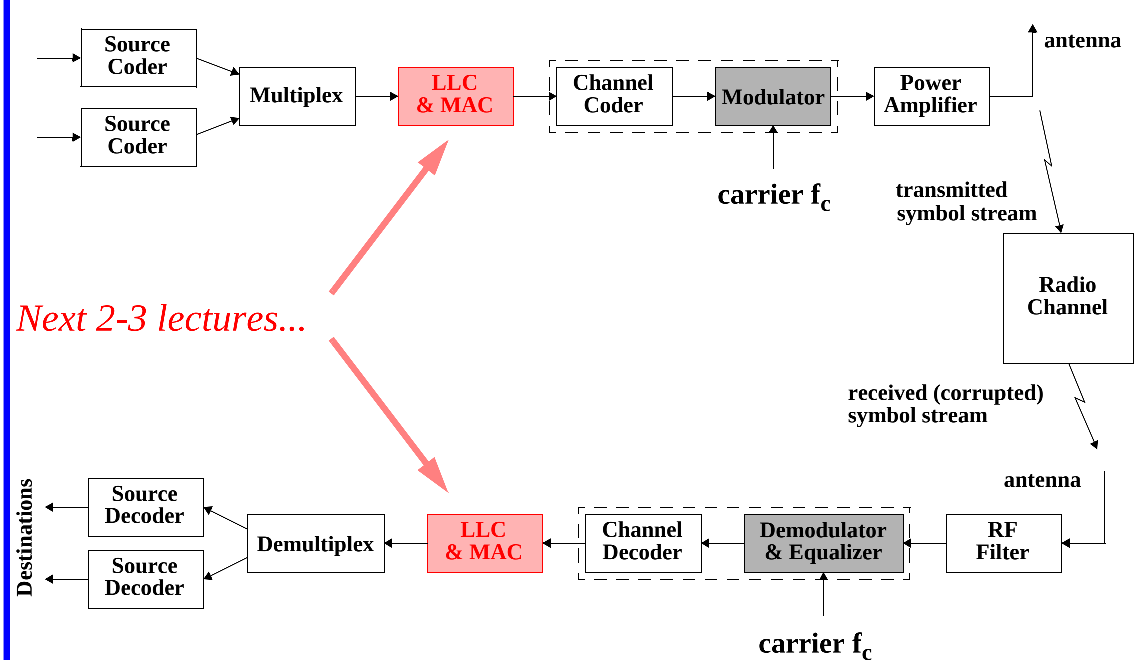
Simplified View of a Wireless Link



Reading List for This Lecture

MANDATORY READING:

None

RECOMMENDED READING:

[van99] van Nee, R.; Awater, G.; Morikura, M.; Takanashi, H.; Webster, M.; Halford, K.W. New high-rate wireless LAN standards. IEEE Communications Magazine, vol.37, (no.12), IEEE, Dec. 1999. p.82-8.

[Goodman89] Goodman, D.J.; Valenzuela, R.A.; Gayliard, K.T.; Ramamurthi, B. Packet reservation multiple access for local wireless communications. IEEE Transactions on Communications, vol.37, (no.8), Aug. 1989. p.885-90.

OTHER READING:

[Chen94], [Falconer95], [Kohno95]

Student Presentations: To Be Scheduled

- **Mon April 29: MAC protocols for sensor networks**

  Based on:

  Alec Woo and David Culler. A transmission control scheme for media access in sensor networks. Mobicom 2001.

  Wei Ye, John Heidemann, and Deborah Estrin. Am energy-efficient MAC protocol for wireless sensor networks. Infocom 2002.

- **Mon April 29: MAC enhancements to 802.11a**

  Based on:

  Daji Qiao, and Sunghyun Choi. Goodput enhancement of IEEE 802.11a wireless LAN via link adaptation. ICC 2001.

  Daji Qiao, Sunghyun Choi, Amjad Soomoro, and Kang G. Shin. Energy-Efficient PCF Operation of IEEE 802.11a Wireless LAN. INFOCOM 2002.

- **Mon April 29: Real-time traffic over 802.11**

  Based on:

  Joao L. Sobrinho and A. S. Krishnakumar. Real-Time Traffic Over the IEEE 802.11 Medium Access Control Layer. Bell Labs Technical Journal, Autumn 1996.

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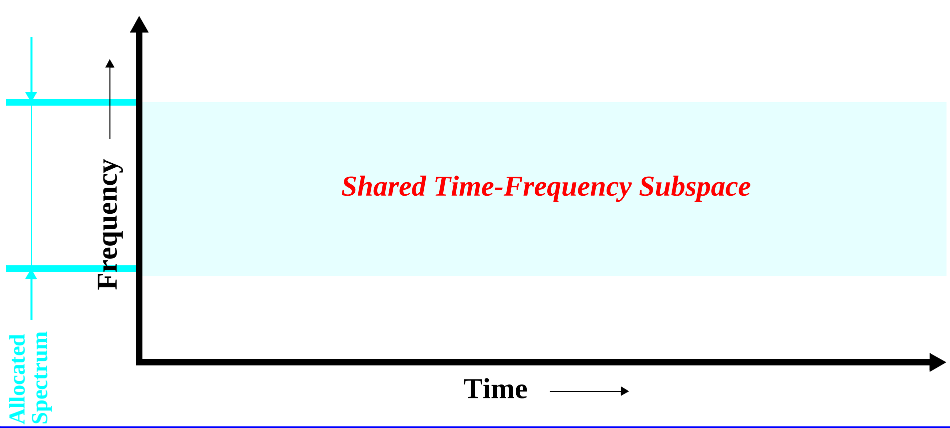
Sharing the Wireless Channel

- **Shared medium**
  - channel resource sharing in time, frequency, and code dimension
- **Impairments**
  - techniques such as ARQ, FEC to cope with impairments
- **Impairments are time varying**
  - need adaptive techniques
  - makes "fair" sharing of channel hard
- **Asymmetric**
  - need protocols that are asymmetric

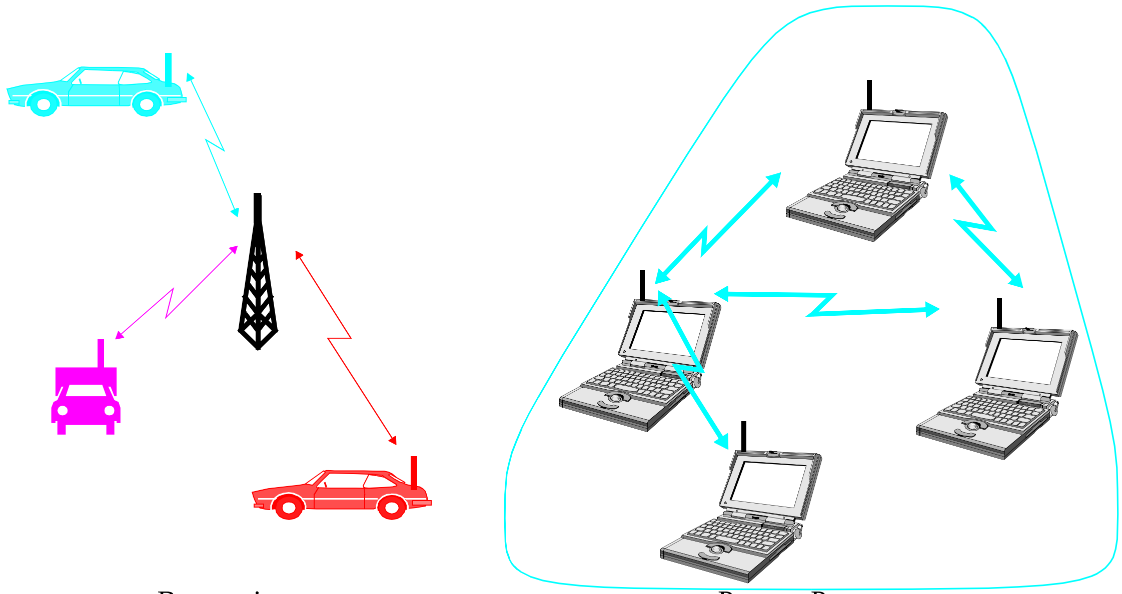
Multiple Access

- **Fundamental problem**

How to share the Time-Frequency space among multiple co-located transmitters?



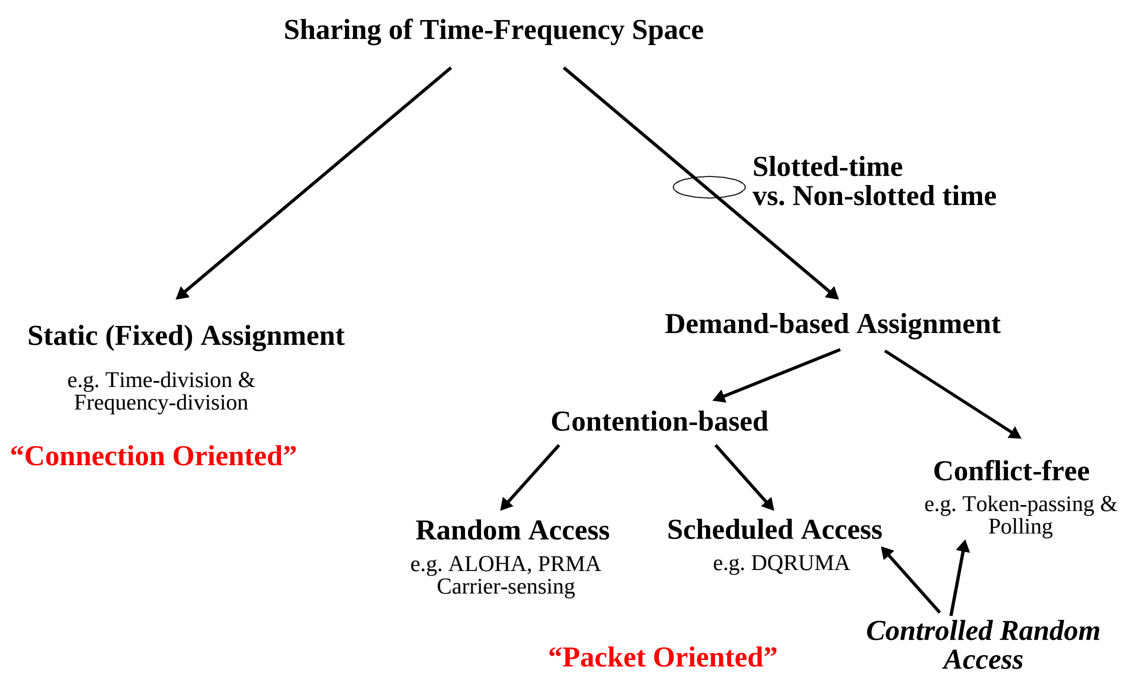
Basestation versus Peer-to-Peer Models



Basestation
(infrastructure - centralized)

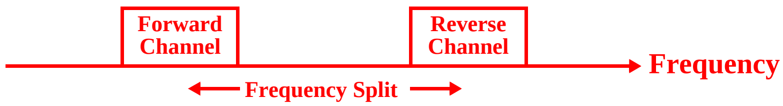
Peer-to-Peer
(ad hoc network - fully-connected vs. multihop)

Approaches to Wireless Multiple Access

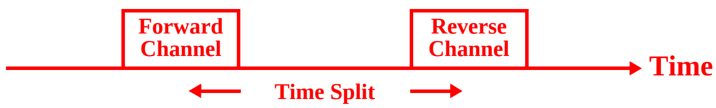


Frequency Division & Time Division Duplexing

- **Frequency Division Duplexing (FDD)**
  - two distinct frequencies at the same time for the two directions
  - frequency separation must be coordinated to allow cheap RF technology
  - coordinate with out-of-band users between the two bands
  - geared towards providing individual frequencies for each user

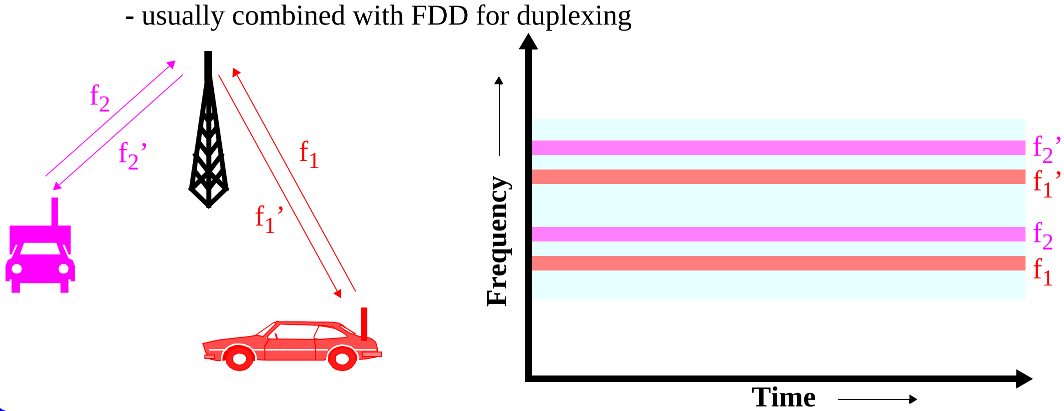


- **Time Division Duplexing (TDD)**
  - two distinct sets of time slots on the same frequency for the two directions
  - time latency because only quasi-duplex
  - no need for RF duplexer



Frequency Division Multiple Access (FDMA)

- **Assign different frequency bands to individual users or circuits**
  - frequency band ("channel") assigned on demand to users who request service
  - no sharing of the frequency bands: idle if not used
  - usually available spectrum divided into number of "narrowband" channels
    symbol time >> average delay spread, little or no equalization required
  - continuous transmission implies no framing or synchronization bits needed
  - tight RF filtering to minimize adjacent band interference
  - costly bandpass filters at basestation to eliminate spurious radiation
  - usually combined with FDD for duplexing



Example - AMPS Cellular System

- **Uses FDMA/FDD**
  - a *channel* is a pair of frequency duplexed simplex channels
  - each simplex channel is 30 KHz
  - simplex channels are separated by 45 MHz (allows cheap RF duplexers)
  - forward link 869-894 MHz, reverse link 824-849 MHz
  - two carriers per market share the channels

- **Number of supported channels in AMPS**

$$N = \frac{B_{total} - 2B_{guard}}{B_{channel}} = \frac{12.5MHz - 2(10kHz)}{30kHz} = 416$$

- **Problem: set of active users is not fixed**

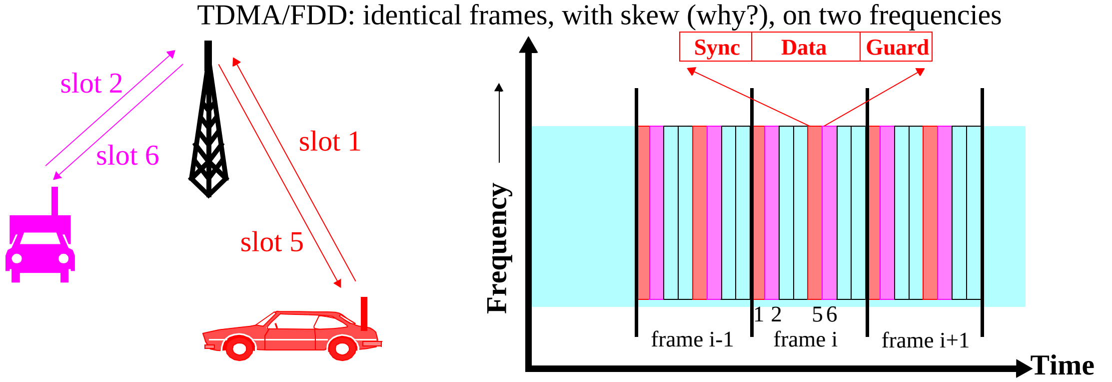
  How is the FDMA/FDD channel allocated to a user who becomes active?

  - static multiple access is not a complete solution... need a separate *signalling channel* with “demand-access”!

- **Pure FDMA is basically “dead” in the digital world...**

Time Division Multiple Access (TDMA)

- **Multiple users share frequency band via cyclically repeating “time slots”**
  - “channel” == particular time slot reoccurring every frame of N slots
  - transmission for any user is non-continuous: buffer-and-burst
    digital data & modulation needed, lower battery consumption
  - adaptive equalization is usually needed due to high symbol rate
  - larger overhead - synchronization bits for each data burst, guard bits
    guard bits for variations in propagation delay and in delay spread
  - usually combined with either TDD or FDD for duplexing
    TDMA/TDD: half the slots in a frame used for uplink, half downlink
    TDMA/FDD: identical frames, with skew (why?), on two frequencies



TDMA (contd.)

- **More features**
  - simplify mobility & link control... snoop for other BSs during idle slots
  - pulsating power envelope: interference with devices such as hearing aids

- **Possible enhancements to basic TDMA to integrate non-voice services**
  - different # of slots per frame to different users (variable bit rate)
  - dynamically reassign time slots for “bandwidth on demand”

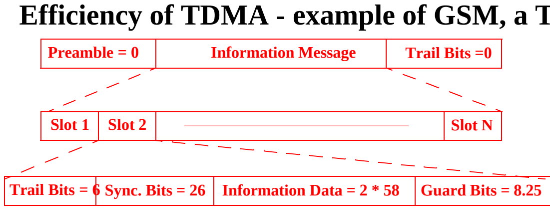
TDMA Frame and Slot Sizes

- **Slot size must be:**
  - much longer than equalizer training sequence to have low overhead
  - short enough so that channel is stationary between two training sequences

- **Frame size (T) affects the delay encountered by the data**

$$D_{TDMA} = \frac{T}{2}\left(1 - \frac{1}{M}\right) + \frac{T}{M} = D_{FDMA} - \frac{T}{2}\left(1 - \frac{1}{M}\right)$$

- **Efficiency of TDMA - example of GSM, a TDMA/FDD system**



In GSM:

8 time slots/frame
156.25 bits/slot (6+26+2*58+8.25)
data sent at 270.833 kbps
bit duration T_b = 1/270.833 kbps = 3.692 us
slot duration T_s = 156.25 x T_b = 0.577 ms
frame duration T_f = 8 x T_s = 4.615 ms

# of bits/slot = 156.25
# of bits/frame = 8x156.25 = 1250
# of overhead bits/frame = 8x(6+26+8.25) = 322
GSM frame efficiency = (1-322/1250) x 100 = 74.24%
# of simultaneous users in GSM = 25 MHz/(200 kHz x 8) = 1000

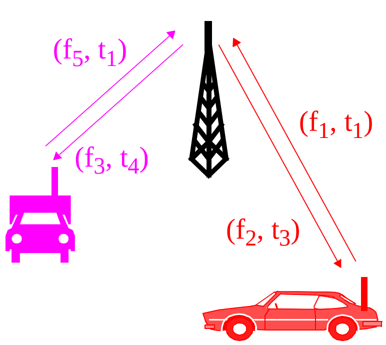
Some TDMA Systems...

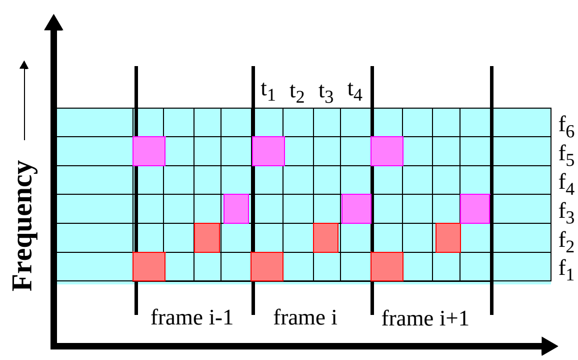
	GSM	IS-54	DECT	PHS
Bit rate	270.8 kbps	48.6 kbps	1.152 Mbps	384 kbps
Carrier spacing (b/w)	200 kHz	30 kHz	1.728 MHz	300 kHz
Time slot duration	0.577 ms	6.7 ms	0.417 ms	0.625 ms
Slots/frame	8 (or 16)	3 (or 6)	12	4
FDD or TDD?	FDD	FDD	TDD	TDD
% payload in time slot	73% adaptive equalizer training overhead	80% adaptive equalizer training overhead	67% system control overhead	71%
Modulation	GMSK	π/4 DQPSK	GMSK	π/4 DQPSK
Adaptive equalizer	required	required	none	none

- **GSM handles time dispersion widths up to 18-20 µs... i.e. 5 bits of ISI**
  - transmission bandwidth >> channel coherence bandwidth
- **IS-54 handles time dispersion up to 40 µs... i.e. 2 symbols might interfere**
  - less complex equalizer needed than GSM|
- **Need equalization indoors at rates > 2 Mbps (DECT is only 1.152 Mbps)**

Hybrid FDMA/TDMA

- **“Pure” TDMA with single frequency band is undesirable**
  - require tight timing tolerances
- **Most TDMA systems actually employ hybrid FDMA/TDMA**
  - multiple carriers with multiple channels per carrier
  - channel == (frequency band, time slot) tuple
  - may do “frequency hopping” on a frame-by-frame basis to combat multipath interference (Time Division Frequency Hopping: TDFH) increases system capacity





Problems with FDMA & TDMA

- **Connection-oriented - can't accommodate traffic variability easily**
- **This is not just a packet data networking problem...**
- **Even in speech-only wireless networks there is variability**

  - set of active transmitters is not fixed
    need "signalling" - e.g. to set up a call (assign a TDM/FDM channel)
    "signalling" traffic is bursty - e.g. SS7 signalling network is a packet
    data network that overlays the voice network in the PSTN

  - even the speech traffic from each transmitter is intermittent
    speech separated into "talkspurts", "silent gaps", and "listen" modes
    e.g. mean talkspurt is 1.0 s, silent gap is 1.35 s, speech duty factor = 0.43

- **Common solution: DAMA... demand assigned multiple access**

  - one or more *common signalling channels* used to reserve data channels
  - large set-up delay... okay for long connections and transactions
  - multiple access problem shifted to the signalling channel
    this becomes the capacity/throughput bottleneck!

Enhancing TDMA: Packet Reservation Multiple Access

- **Combines elements of TDMA and "Demand-based" access**

  - make TDMA handle variable mix of voice and data traffic
  - specifically, combines TDMA with "slotted-ALOHA" (next lecture!)
  - sort of related to "reservation-ALOHA" (next lecture!)

- **Assumptions & design choices**

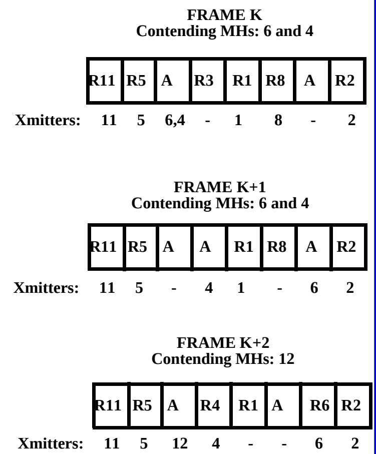
  - centralized network with basestation BS and mobile hosts BS
  - short-range radio channels (i.e. short propagation delays)
    allows rapid acknowledgment of a packet
  - possible wide variations in path loss... near/far phenomenon
    colliding packets may still lead to "capture" of strongest packet
  - BS-to-MHs downstream traffic done in a separate contention-free channel
    could be a frequency band or by time sharing a single band

- **Organization of upstream (MH-to-BS) bit transmissions**

  - TDMA-like fixed-size time slots grouped into frames (N slots/frame)
  - MHs recognize slots as "reserved" or "available" (bitmap registers at MH)
    on the basis of feedback from BS in the previous frame
  - slots sized for one MH-to-BS packet + one broadcast ACK from BS
  - frame duration such that one speech packet per frame during talkspurts

The PRMA Protocol

- **Two types of packets (labelled in header)**
  1. "periodic" speech packets
  2. "random" information (data) packets
- **Speech packets: contention & reservation**
  - MHs contend for idle slot with *permission prob.*
  - permission prob. = 1 for first idle slot
  - permission prob. = p for future idle slots
  - if successful, BS broadcasts an immediate ACK
    - successful MH uses this slot in future frames
    - all MHs mark the slot as "reserved"
  - if no ACK from BH, retry in future idle slots
  - MH drops a speech packet after D_{max}
    - implemented as a FIFO buffer at MH with *front drop* policy - leads to front clipping of talkspurts... perceptually superior?
    - echo canceller needed if D_{max} is large
  - adapt packet size (adaptive codec) vs. dropping?
  - at end of talkspurt, MH releases reservation by leaving the slot empty (wasted bandwidth!)



The PRMA Protocol (contd.)

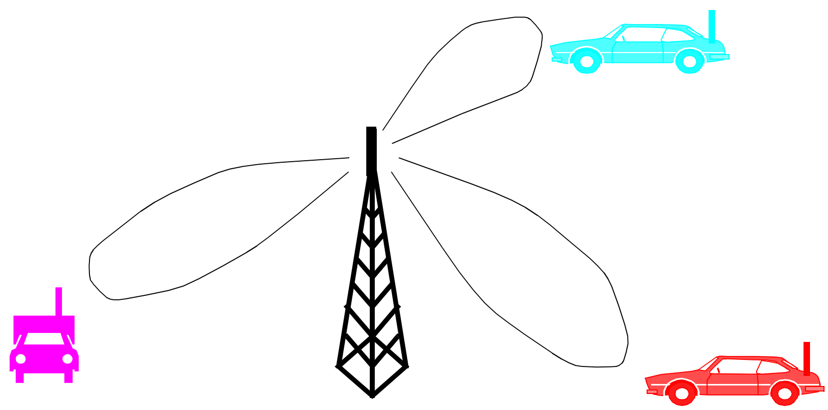
- **Data packets: contention but no reservation**
  - MHs contend for idle slot with *permission prob.*
  - permission prob. = 1 for first idle slot, and = r for future idle slots
    - $p > r$ to give speech packets priority
  - if successful, BS broadcasts an immediate ACK
    - but no reservation is obtained!
  - packet is not dropped but delayed (large buffer)... effectively, $D_{max} = \infty$
  - a PRMA variant: IPRMA ("Integrated PRMA")
    - MH with data packets allowed to reserve *(k-M-1)* from the *k* idle slots in the next N slots (frame-long sliding window)
    - parameter *M* serves as a *speech priority*
- **PRMA performance metrics**

  Quality of service: speech packet drop probability P_{drop}, data packets delay
  System capacity: # of speech and data users for, say, $P_{drop} \le 0.01$
- **PRMA acts a statistical multiplexer**

  e.g. in PRMA with GSM-like system, with D_{max}= 32 ms, one gets
  1.2-1.3 MH per channel for $P_{drop} \le 0.01$

Space Division Multiple Access (SDMA)

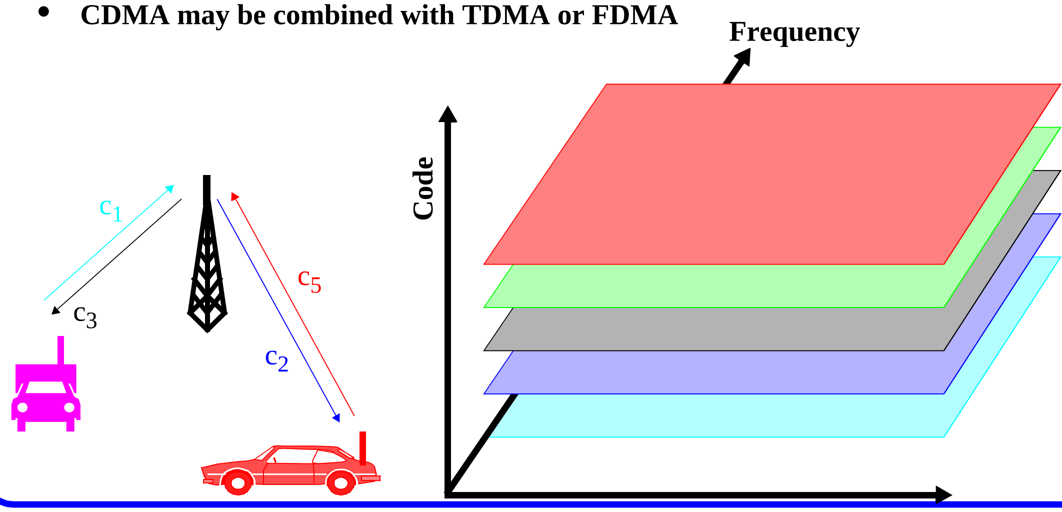
- **Control radiated energy for each user in space**
  - spot beam antennas (sectorized antennas)
  - different areas served by different antenna beams may use same frequency (CDMA, TDMA) or different frequencies (FDMA)
  - in future, adaptive antennas



Code Division Multiple Access (CDMA)

- **Multiplexing in the Code Space**
  - multiple transmitters occupy the same frequency-time space
  - transmissions encoded with *codes* with very low cross-correlation
  - receiver retrieves a specific transmission with its corresponding code

- **CDMA may be combined with TDMA or FDMA**

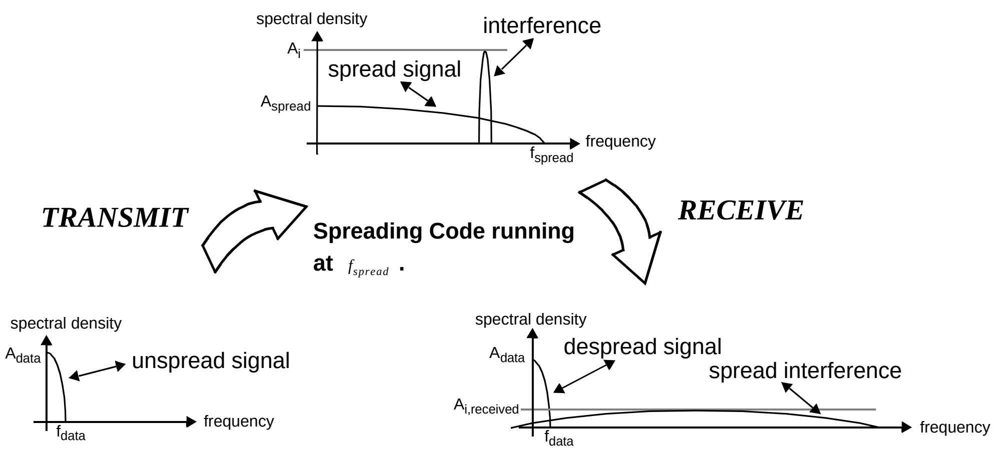


Spread Spectrum Signalling

- **Spread Spectrum is the most common CDMA encoding technique**
  - originally developed for military communication systems
  - “spread” the signal over a much larger bandwidth than the minimum
  - signal appears pseudo-random with noise like properties
  - uniform small energy (W/Hz) over a large bandwidth hides the signal

  ⇒ *Note: use of spread-spectrum does not imply use of CDMA*
- **Spreading is done using a unique code**
- **Receiver does the “despreading” by using a time-synchronized duplicate of the spreading code**
- **Inefficient for a single user, but multiple users can share band**
- **Inherent interference rejection capabilities (e.g. narrowband interferers)**
- **Resistant to multipath effects**
  - delayed versions appear as uncorrelated noise
  - can even exploit multipath signals by combining them
- **Processing Gain: $G_p = B_{spread} / B_{signal}$**
  - indicates improvement in signal-to-interference ratio due to spreading

Spread Spectrum Communications



Wide Band
Anti-jam -> high capacity CDMA
Combats multipath -> diversity
LPI -> Privacy
LPD -> low power density

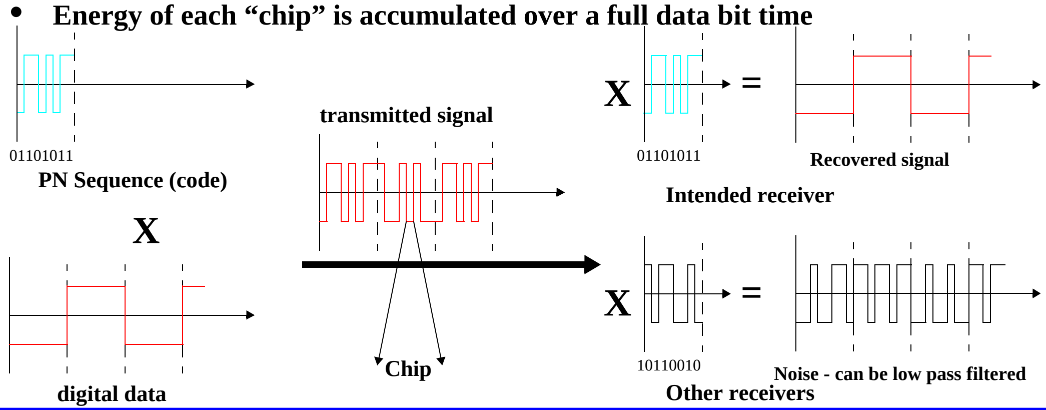
$$PG = \frac{B_{spread}}{B_{signal}}$$

CDMA Using Direct Sequence (DS) Spread Spectrum

- **Spread the narrowband data by multiplying with a wideband pseudo-random code sequence**

  - bits sampled, or "chipped", at a higher frequency (e.g. 1.228 Mcps in IS-95)
  - signal energy is "spread" over a wider frequency (e.g. 1.25MHz in IS-95)
  - code sequences have little cross-correlation (orthogonal)
  - code sequences have little correlation with shifted versions of self

- **Received signal multiplied by synchronized replica of the code sequence**
- **Energy of each "chip" is accumulated over a full data bit time**

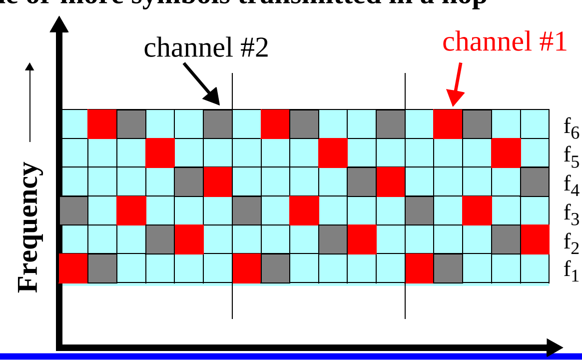


CDMA Using Frequency Hopping Spread Spectrum

- **Transmission frequency is periodically changed**

  - available spectrum divided into bands with central frequencies as carriers
  - sequence of data bursts with time-varying pseudo-random carrier frequencies
  - time duration between hops is the hop duration or hopping period T_h
  - bandwidth of a frequency band in the hopset is the instantaneous b/w B
  - bandwidth of spectrum over which hopping occurs is total hopping b/w W_{ss}
  - processing gain is W_{ss}/B

- **Fast frequency hopping: more than one hop during each transmitted symbol**
- **Slow frequency hop: one or more symbols transmitted in a hop**



Strengths of CDMA

- **Allows frequency reuse of one-in-one in cellular systems**
  - unlike FDMA and TDMA, same frequencies can be used in all cells

  $\Rightarrow$ no frequency planning!
- **Naturally allows exploitation of speech activity (talkspurts)**
  - hard to do with FDMA and TDMA

  $\Rightarrow$ higher system capacity!
- **"Soft" system capacity - allows capacity vs. quality trade-off**
- **Combats interference**
  - reject multipath interference
  - use in ISM band communication devices
- **FHSS vs. DSSS - which is superior?**
  - religious and marketing war in the ISM-band wireless LAN market!

Problems in CDMA

- **DSSS**
  - self-jamming
    - spreading sequences of different users are not exactly orthogonal
    - there are non-zero contributions from undesired users
    - effect gets worse as the number of users increases
  - cannot preserve code orthogonalization unless synchronized
    - problem in MH-to-BS links, and in multipaths
  - near-far problem
    - occurs when an undesired user has a high detected power
    - as compared to a desired user... problem in MH-to-BS links
  - power control is crucial
  - requires contiguous spectrum... problem with large spreading
- **FHSS**
  - "collisions" when more than one transmitter at the same frequency
    - error control and interleaving help
  - deep fades may occasionally occur
    - error control and interleaving help
  - bad interaction of collisions with higher layer ARQ protocols

Multi-access Performance of DSSS

- **Assuming BPSK modulation, with K users of activity factor α, with N chips per information symbol, and $E_b/N_0 = (S/N)(B/R)$ ratio of *signal energy per bit* to *noise power spectral density* at the receiver**

$$P_e = Q\left(1/\left(\sqrt{\frac{\alpha(K-1)}{3N} + \frac{N_0}{2E_b}}\right)\right) = Q\left(\sqrt{2\left(\frac{E_b}{N_0}\right)_{eff}}\right) \text{ where } Q(x) = \frac{1}{2}erfc\left(\frac{x}{\sqrt{2}}\right)$$

- **For interference limited case where thermal noise is not a factor, $E_b/N_0 \to \infty$, and the BER is:**

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

$\Rightarrow$ irreducible error floor due to multiple access interference (assumes that all interferers provide equal power, same as desired user)

- **Example, with ISM-band DSSS devices, for $\alpha = 1$, $N = 11$ & $K = 5$:**

$$P_e = Q\left(\sqrt{\frac{33}{4}}\right) = 0.002 \text{ or, } 0.2\%$$

Multi-access Performance of FHSS

A collision, or “hit”, happens if >2 users transmit simultaneously in the same slot

Let, P_e be the BER for the no collision case.

Also, let p_h be the probability of a hit. Then,

$$P_{e,hop} = P_e(1-p_h) + \frac{1}{2}p_h$$

If there are M slots, there is a $1/M$ probability of a given interferer being in the desired user’s slot.

If there are $K-1$ interfering users, the probability of at least one colliding is:

$$p_h = 1-(1-1/M)^{K-1} \approx (K-1)/M \text{ for large } M$$

On substituting:

$$P_{e,hop} = P_e\left(1-\frac{K-1}{M}\right) + \frac{1}{2}\left(\frac{K-1}{M}\right)$$

For K=1, $P_{e,hop} = P_e$

If $E_b/N_0 \to \infty$, we get: $\lim_{E_b/N_0 \to \infty} P_{e,hop} = \frac{1}{2}\left(\frac{K-1}{M}\right)$

- **This is the irreducible error rate due to multiple access interference.**

Multi-access Performance of Asynchronous FHSS

- **Synchronous (slotted) frequency hopping is often not the case**
  - clocks not synchronized
  - propagation delays in radio signals
- **The probability of hit is larger for the asynchronous case:**

$$p_h = 1 - \left\{1 - \frac{1}{M}\left(1 + \frac{1}{N_b}\right)\right\}^{K-1}$$

where N_b is the number of bits per hop.

- **Consider 2.4 GHz ISM band, IEEE 802.11 physical layer specification...** $M = 79$**. Also, let** $P_e = 10^{-5}$**. Then, for synchronous case, with 5 users**

$$P_{e,\,hop} \approx 2.5\%$$

- **Burst error correcting codes can help with collisions**

System Capacity: SFHSS vs. DSSS in the ISM band

- **Slow frequency hopping**

K = number of collated systems
M = # of frequency slots
B = total band
$C = B/M$ = bandwidth of each channel
Assume 1 bps/Hz

$$\text{Aggregate capacity} = \frac{KB}{M}\left(1 - \frac{(K-1)}{2M}\right)$$

What is the maximum aggregate capacity?

- **Direct sequence**

FCC requires at least 10 dB (x10) of spreading, which is not enough for CDMA

$$\text{Aggregate capacity} = \frac{B}{10}$$

Effect of Frequency Hopping Radios on Performance

- **Slow frequency hopping radios in the 2.4 GHz ISM band**
  - 83 frequency slots of 1 MHz width
  - maximum 0.4 second in any slot every 30 seconds
  - cycle through at least 75 slots in a pseudo-random hopping sequence
  - not allowed coordinate multiple transmitters
- **Channels disrupted due to frequency collisions with each other**
  - hopping patterns chosen to minimize collision probability
- **Weakly orthogonal hopping sequence families**
  - minimize number of collisions with other sequences in the family (irrespective of the phase)
- **3 families of 22 weakly orthogonal hopping sequences of length p=79**

$F_j = \{ f_j(0), \ldots f_j(p-1)\}$
$f_j(i) = (i*j)mod(p) + 2$
Set 1: j = 7, 10, 13, 16,..., 67, 70
Set 2: j = 8, 11, 14, 17,..., 68, 71
Set 3: j = 9, 12, 15, 18,..., 69, 72

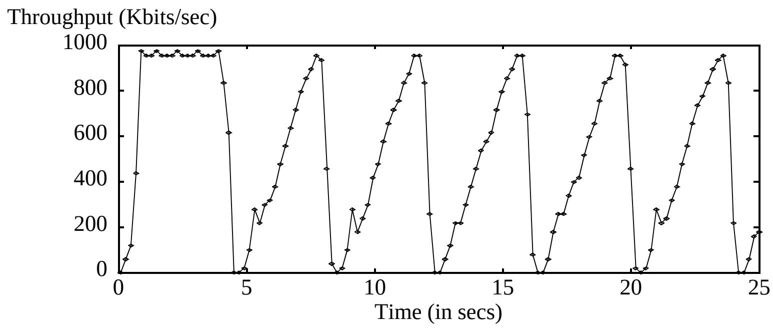
Theoretical Loss of Performance Due to Collisions

- **Family of 22 weakly orthogonal asynchronous sequences of length 79**
  - at most one collision irrespective of the phase

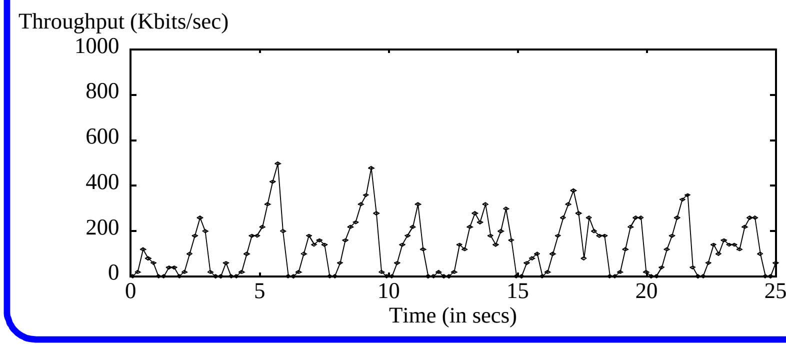
# of Transmitters	% Time in collision		
	Best	Worst	Average
2	**1.27**	**1.27**	**1.27**
3	**1.27**	**2.53**	**2.52**
10	**1.27**	**11.39**	**10.81**
22	**1.27**	**26.58**	**23.47**

- **Real life is much worse...**
  - interference from adjacent slots
  - interaction with retransmission control mechanisms (e.g. TCP)
  - lost of ACKs

Oscillating TCP Throughput due to Frequency Collision



One TCP connection:
- Channel Data Rate = 1 Mbps
- Hopping Interval = 50 ms
- TCP Packet = 500 bytes
- TCP Window = 32 Kbytes
- TCP time-out = 500 ms
- Mean Throughput = 515 Kbps
- (50% loss with TCP vs. 1.27%)



11x2 TCP connection:
- Channel Data Rate = 1 Mbps
- Hopping Interval = 50 ms
- TCP Packet = 500 bytes
- TCP Window = 32 Kbytes
- TCP time-out = 500 ms
- Mean Throughput = 129 Kbps
- (87% loss with TCP vs. 27%)