EE206A Lecture #4
Sharing the Wireless Link: Part I

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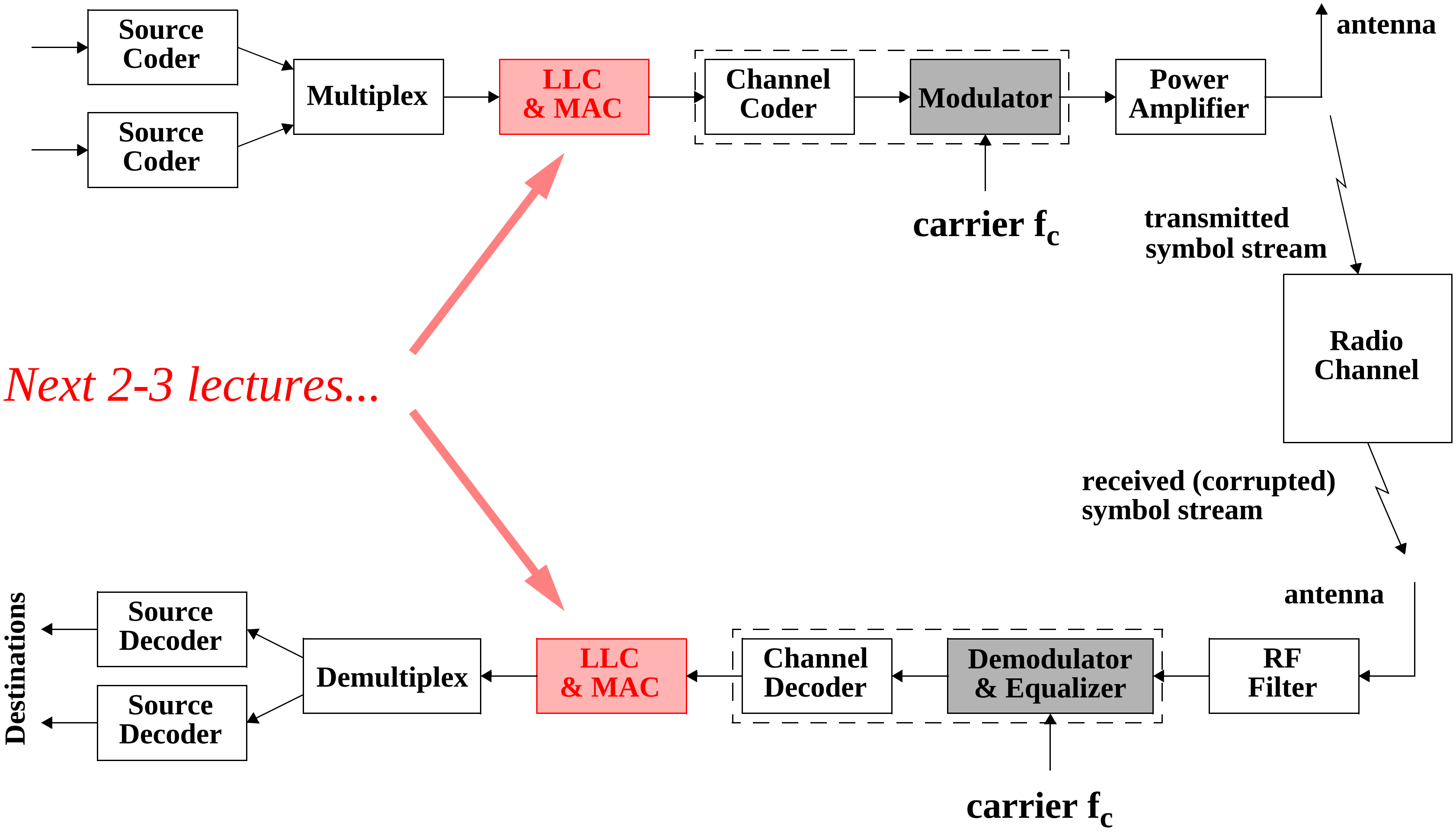
Simplified View of a Wireless Link



Next 2-3 lectures...

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

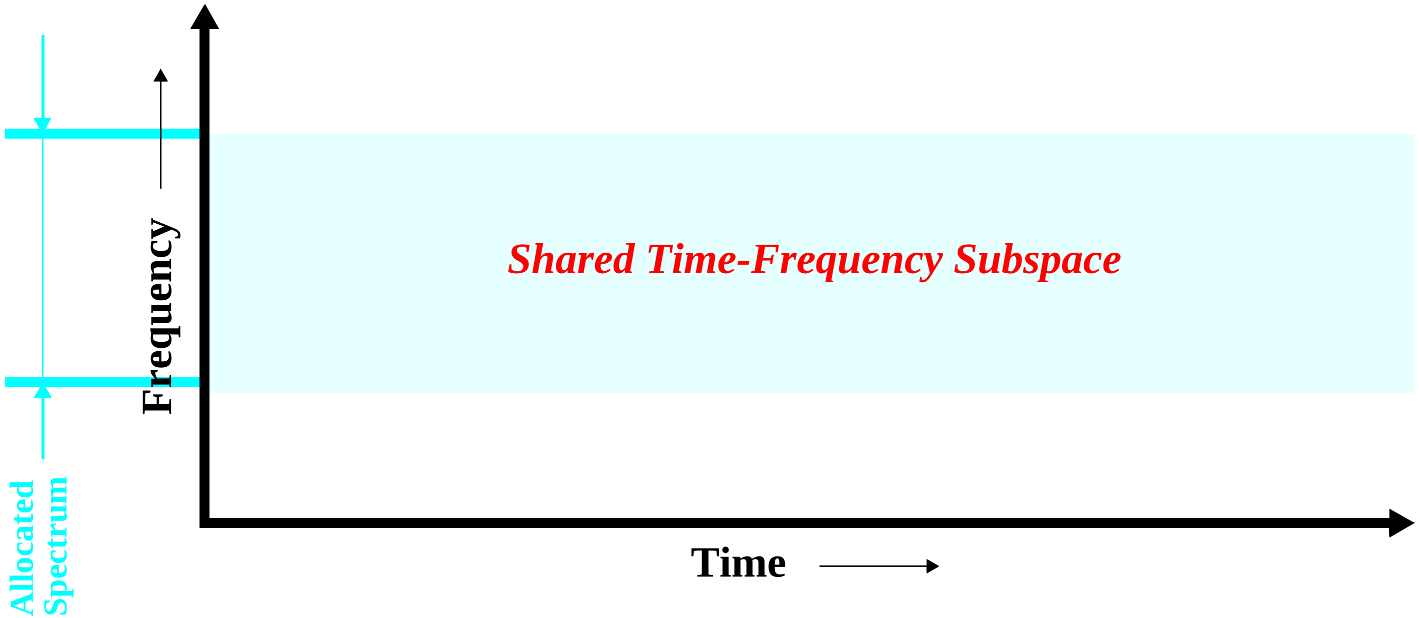
- **Asymmetric**

  - need protocols that are asymmetric

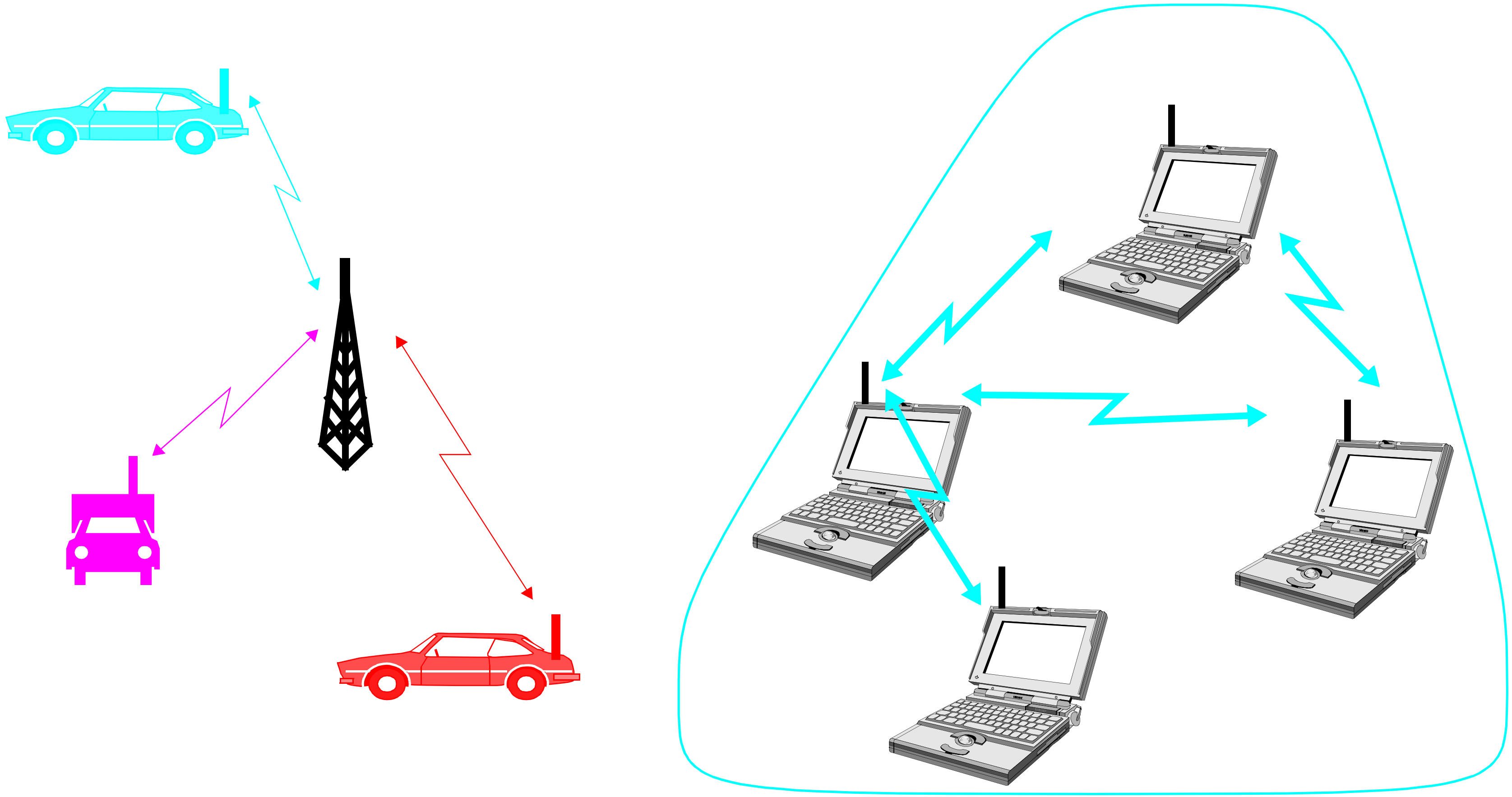
Multiple Access

- **Fundamental problem**

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



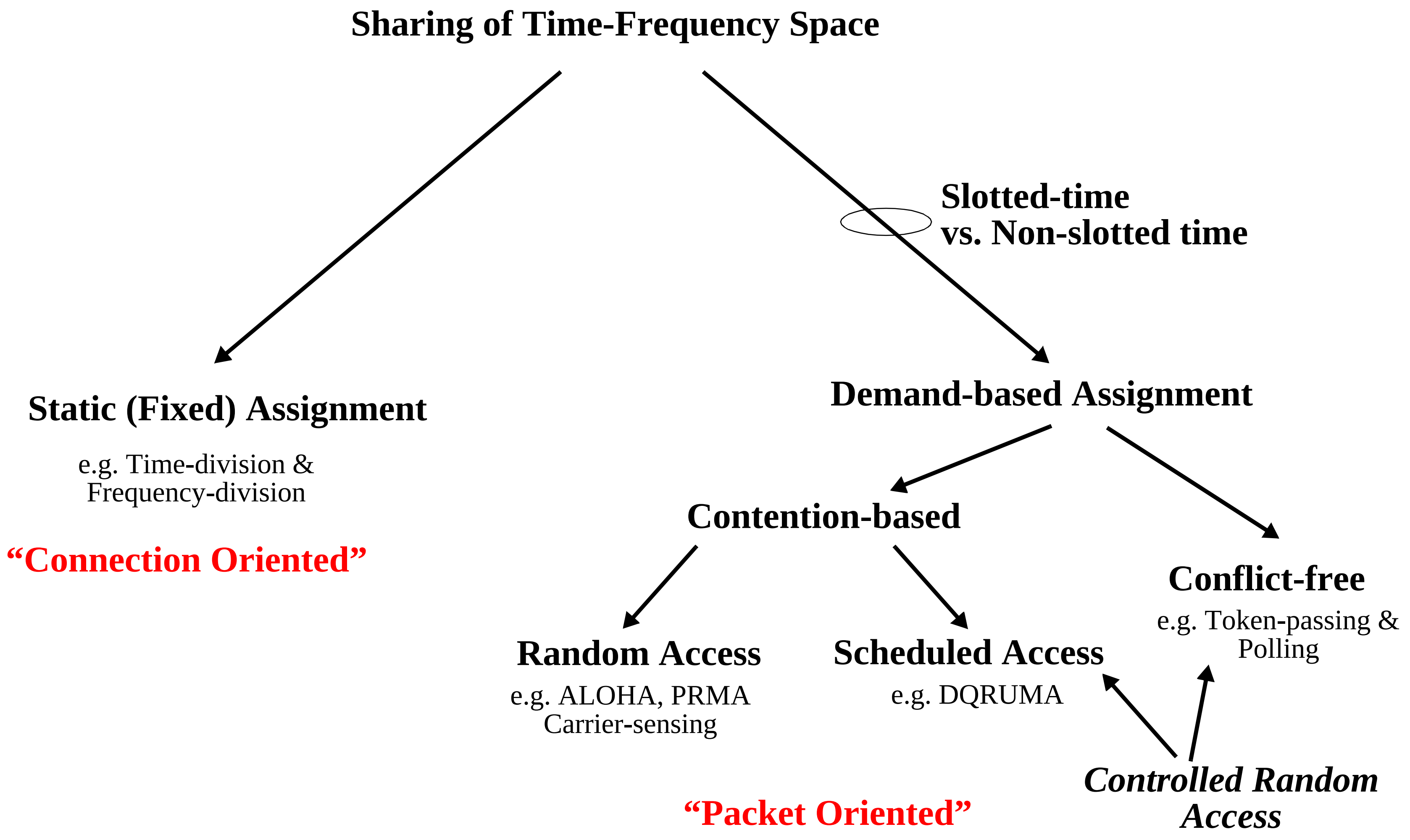
Basestation versus Peer-to-Peer Models



Basestation
(infrastructure - centralized)

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

Approaches to Wireless Multiple Access



Sharing of Time-Frequency Space

Slotted-time vs. Non-slotted time

Static (Fixed) Assignment

e.g. Time-division & Frequency-division

“Connection Oriented”

Demand-based Assignment

Contention-based

Conflict-free

e.g. Token-passing & Polling

Random Access

e.g. ALOHA, PRMA Carrier-sensing

Scheduled Access

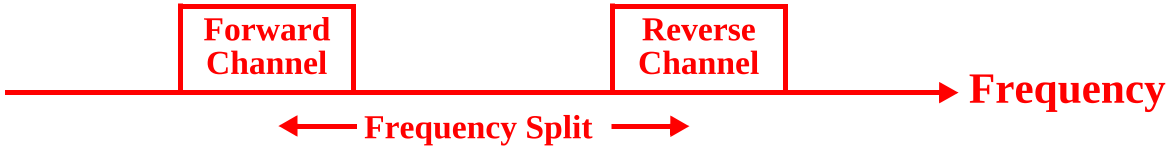
e.g. DQRUMA

Controlled Random Access

“Packet Oriented”

Frequency Division & Time Division Duplexing

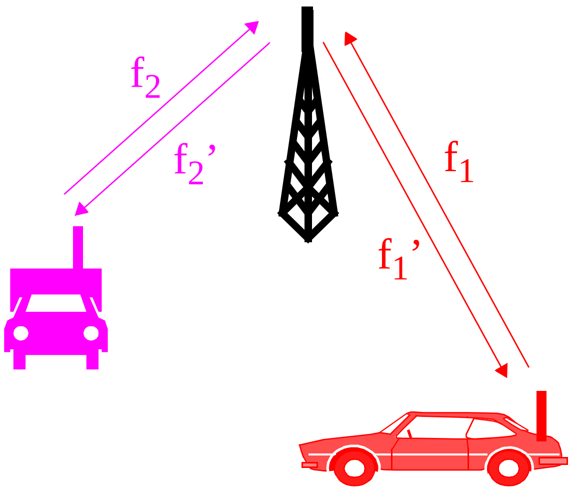
- **Frequency Division Duplexing (FDD)**
  - two distinct frequencies at the same time for the two directions
  - frequency separation must be coordinated to allow cheap RF technology
  - coordinate with out-of-band users between the two bands
  - geared towards providing individual frequencies for each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

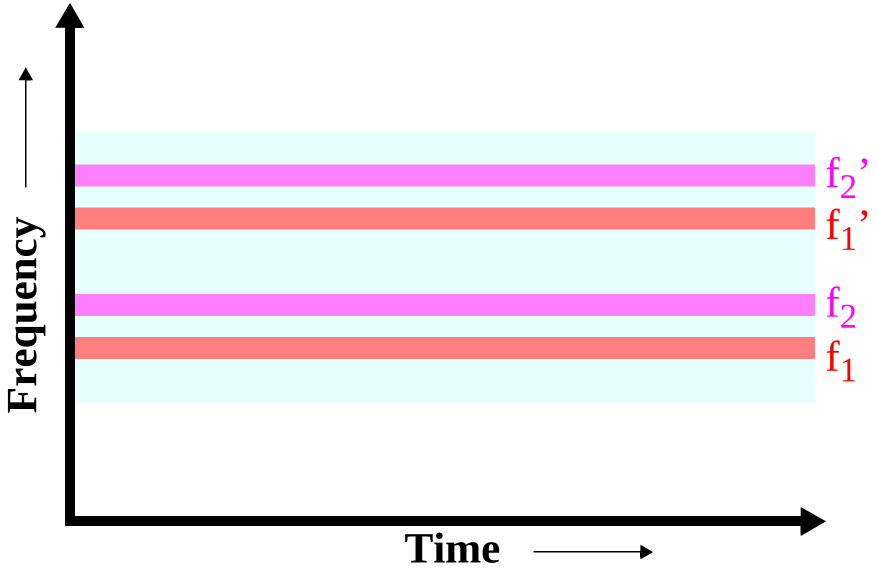


- **Time Division Duplexing (TDD)**
  - two distinct sets of time slots on the same frequency for the two directions
  - time latency because only quasi-duplex
  - no need for RF duplexer

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?

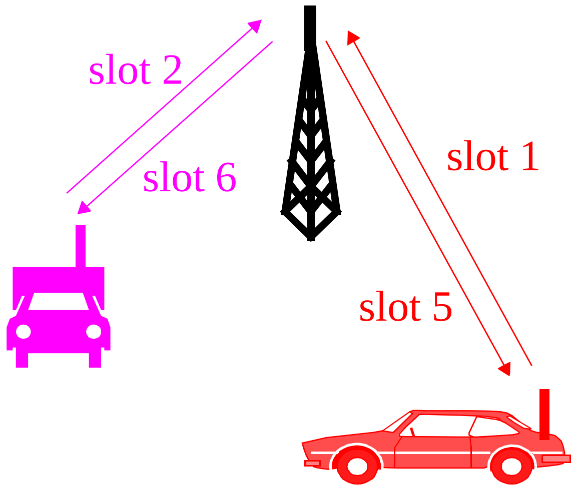
  - static multiple access is not a complete solution... need a separate *signalling channel* with "demand-access"!

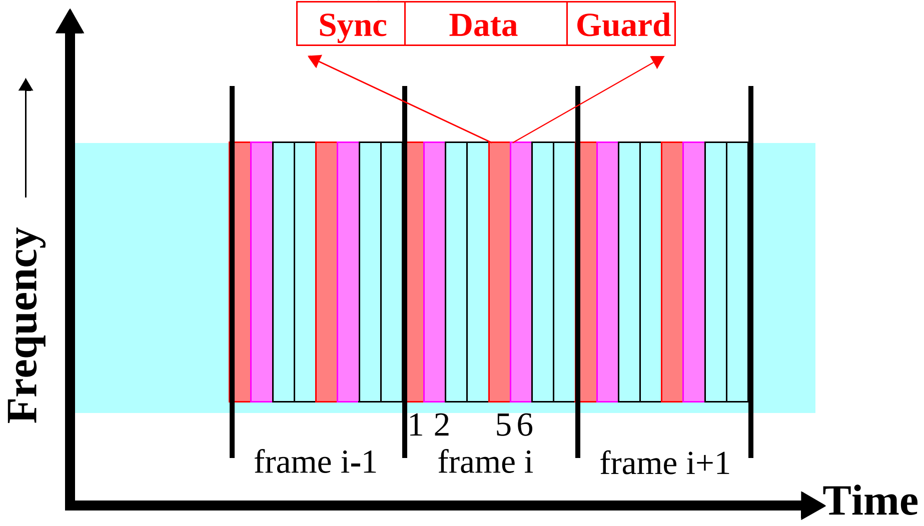
- **Pure FDMA is basically "dead" in the digital world...**

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

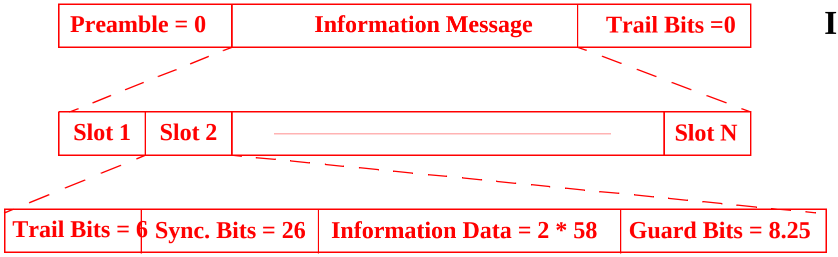
- **Slot size must be:**

  - 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**

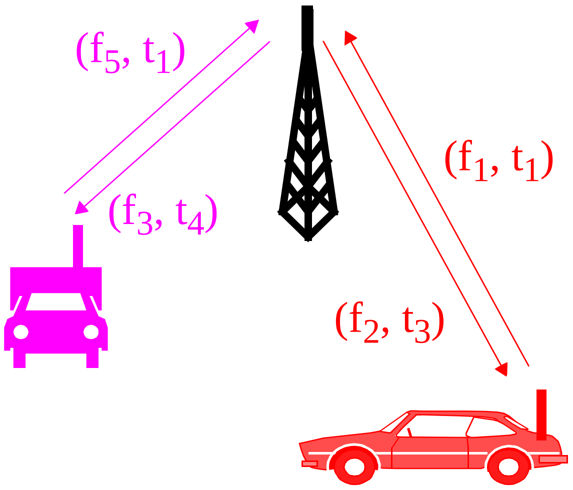
  - transmission bandwidth >> channel coherence bandwidth
- **IS-54 handles time dispersion up to 40 μs... i.e. 2 symbols might interfere**

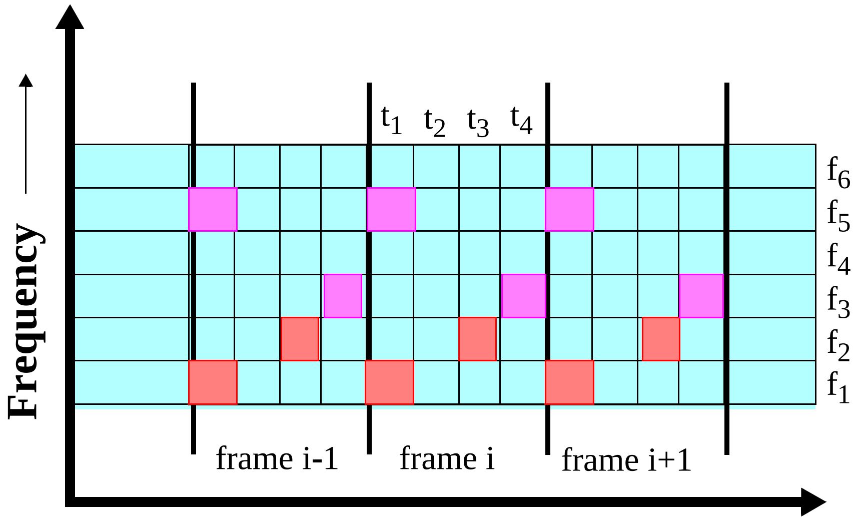
  - less complex equalizer needed than GSM|
- **Need equalization indoors at rates > 2 Mbps (DECT is only 1.152 Mbps)**

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!)

FRAME K
Contending MHs: 6 and 4

	R11	**R5**	**A**	**R3**	**R1**	**R8**	**A**	**R2**
Xmitters:	**11**	**5**	**6,4**	**-**	**1**	**8**	**-**	**2**

FRAME K+1
Contending MHs: 6 and 4

	R11	**R5**	**A**	**A**	**R1**	**R8**	**A**	**R2**
Xmitters:	**11**	**5**	**-**	**4**	**1**	**-**	**6**	**2**

FRAME K+2
Contending MHs: 12

	R11	**R5**	**A**	**R4**	**R1**	**A**	**R6**	**R2**
Xmitters:	**11**	**5**	**12**	**4**	**-**	**-**	**6**	**2**

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 $(k\text{-}M\text{-}1)$ from the k idle slots in the next N slots (frame-long sliding window)
    - parameter M serves as a *speech priority*

- **PRMA performance metrics**

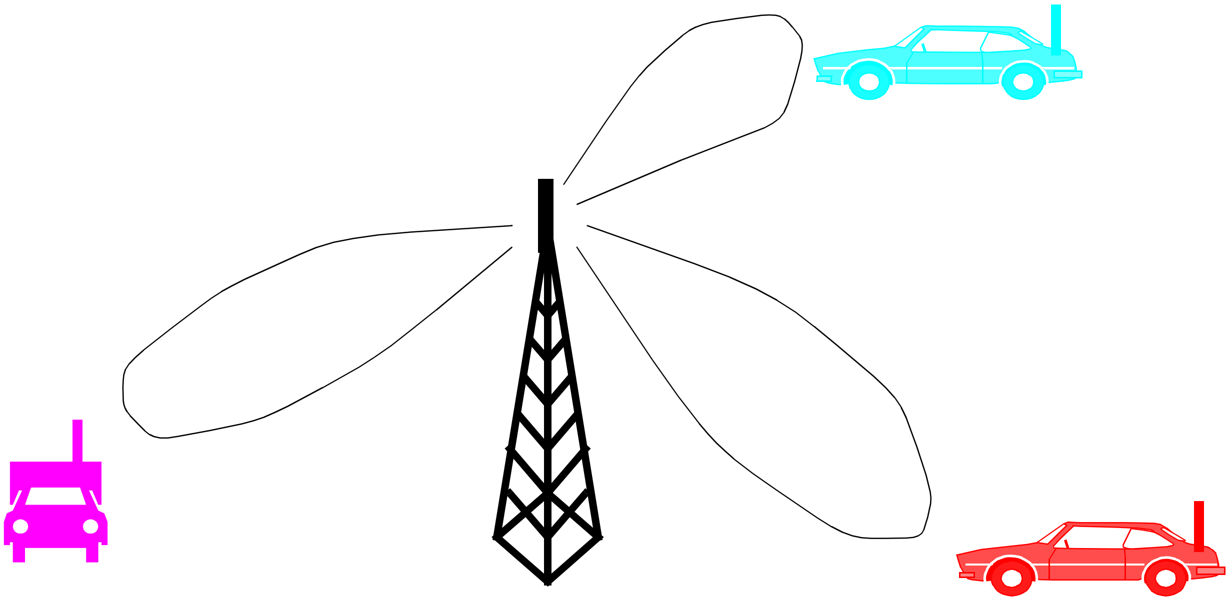
  Quality of service: speech packet drop probability P_{drop}, data packets delay
  System capacity: # of speech and data users for, say, $P_{drop} <= 0.01$

- **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 $P_{drop} <= 0.01$

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

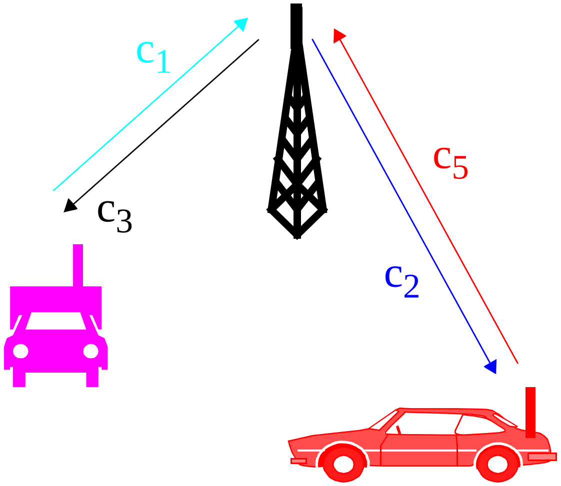


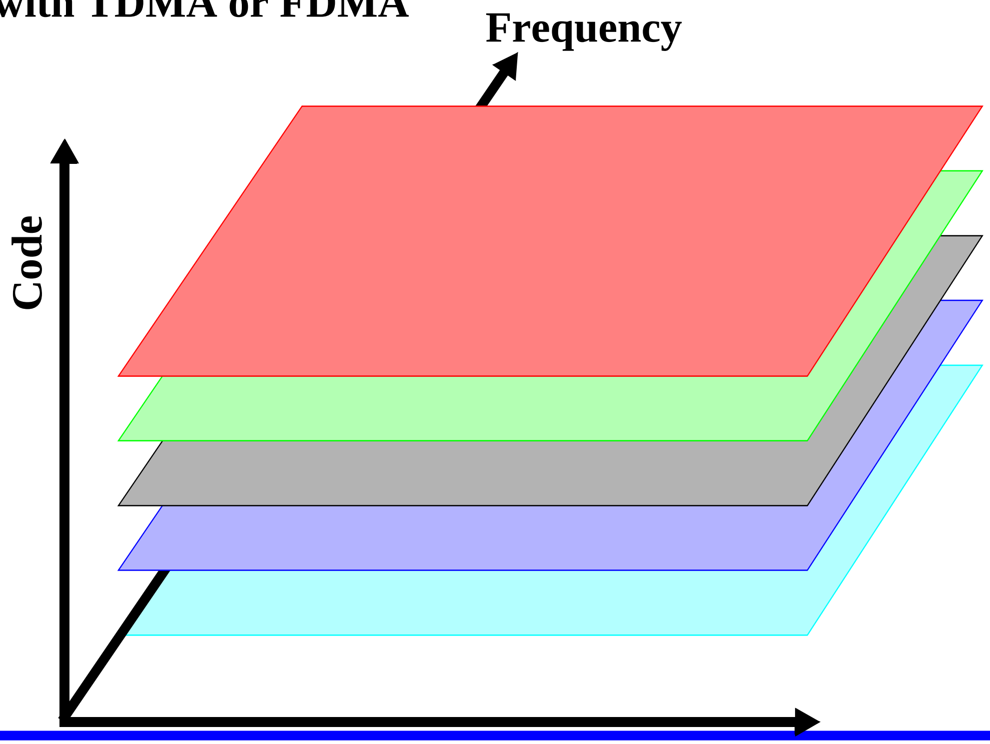
Code Division Multiple Access (CDMA)

- **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*

l **Spreading is done using a unique code**

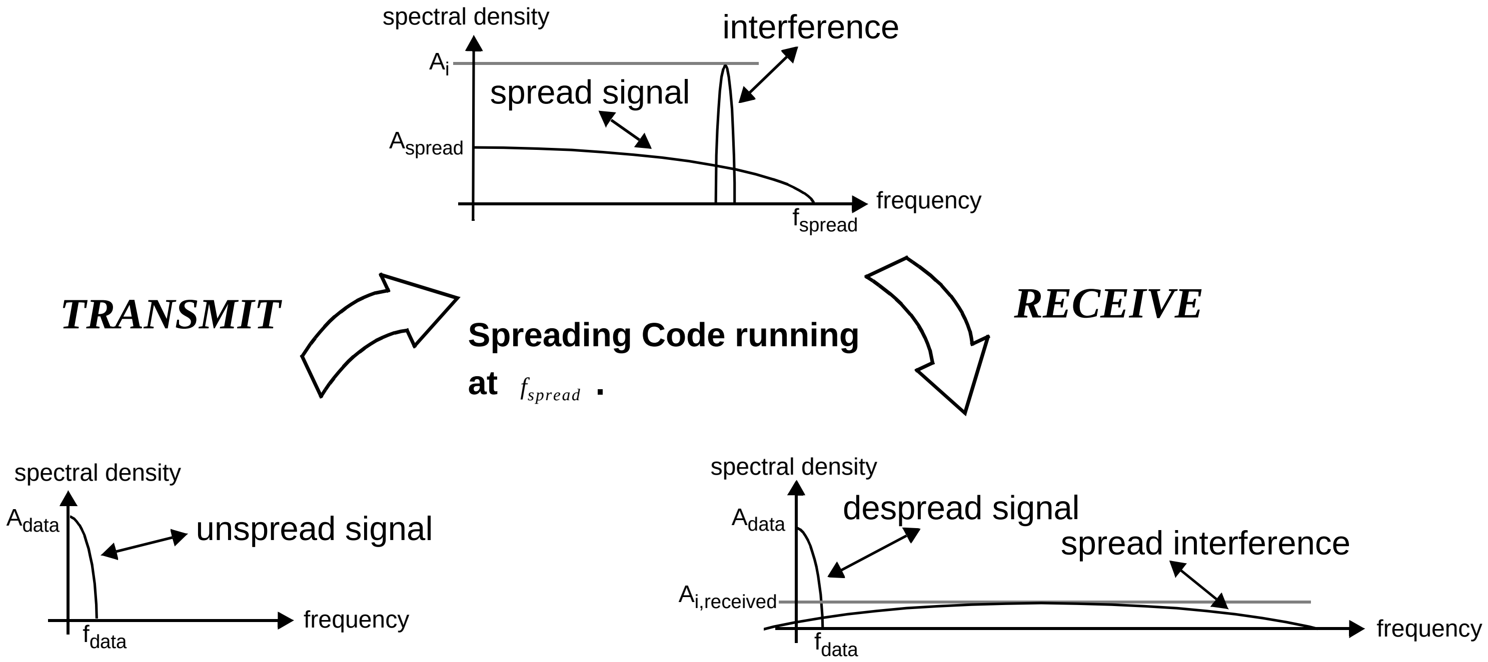
- **Receiver does the "despreading" by using a time-synchronized duplicate of the spreading code**
- **Inefficient for a single user, but multiple users can share band**
- **Inherent interference rejection capabilities (e.g. narrowband interferers)**
- **Resistant to multipath effects**

  - 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



TRANSMIT

Spreading Code running at f_{spread} .

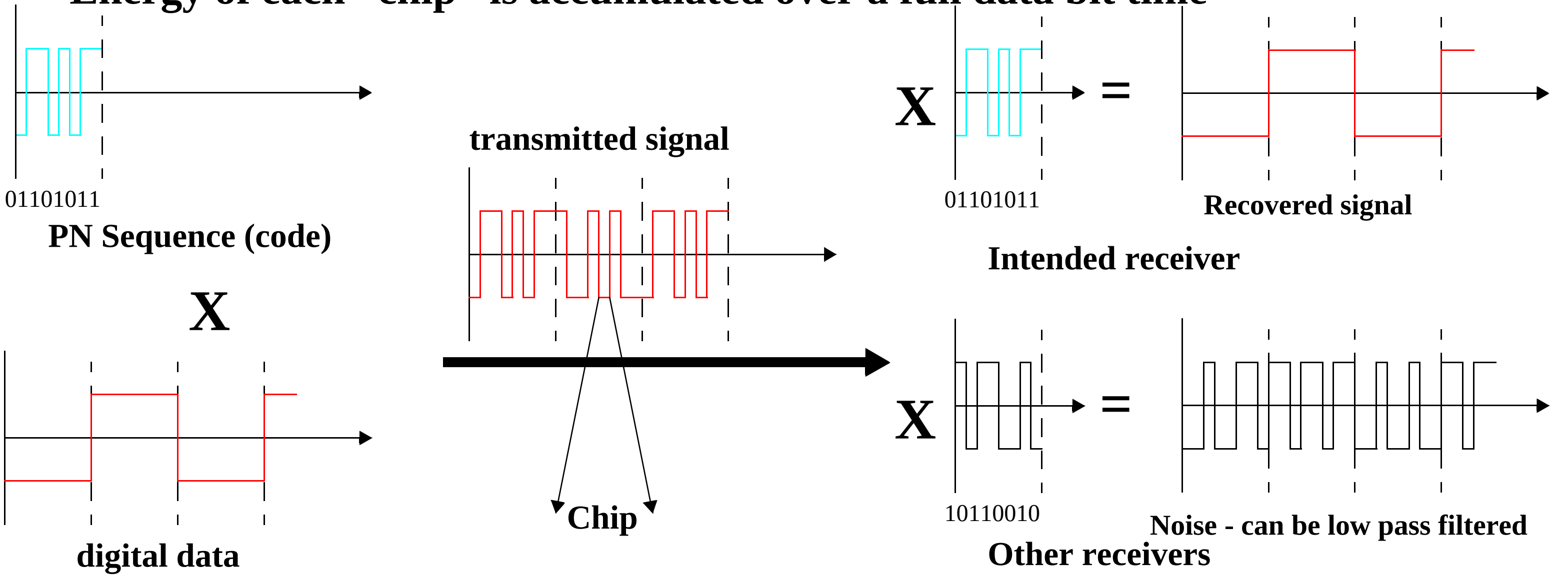
RECEIVE

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

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

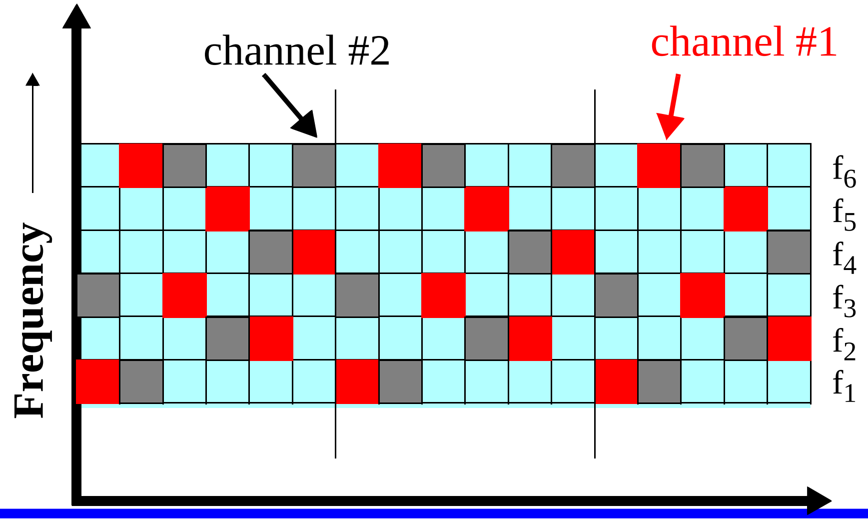
CDMA Using Direct Sequence (DS) Spread Spectrum

- **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

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

  ⇒ 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**

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

Theoretical Loss of Performance Due to Collisions

- **Family of 22 weakly orthogonal asynchronous sequences of length 79**

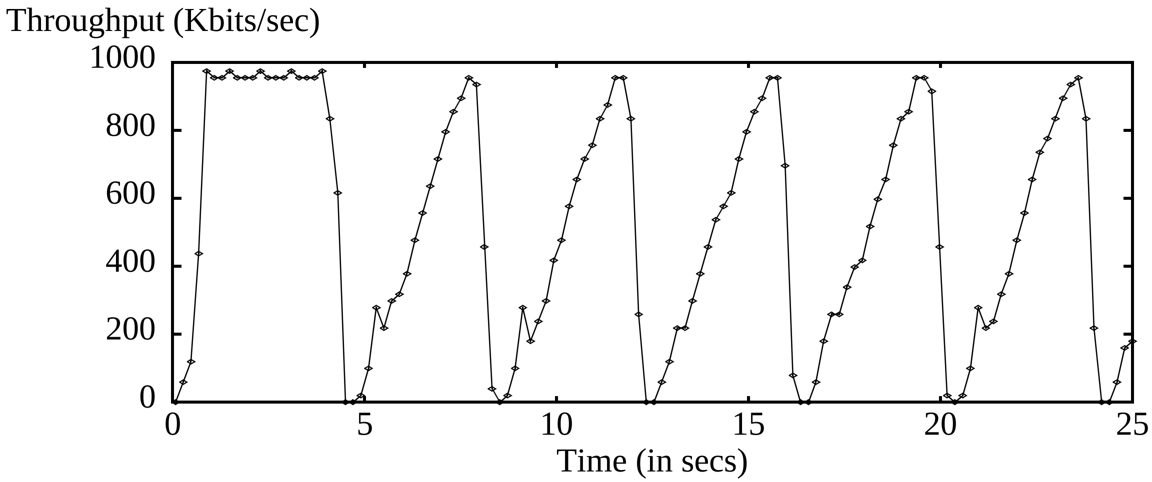
  - at most one collision irrespective of the phase

# 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...**

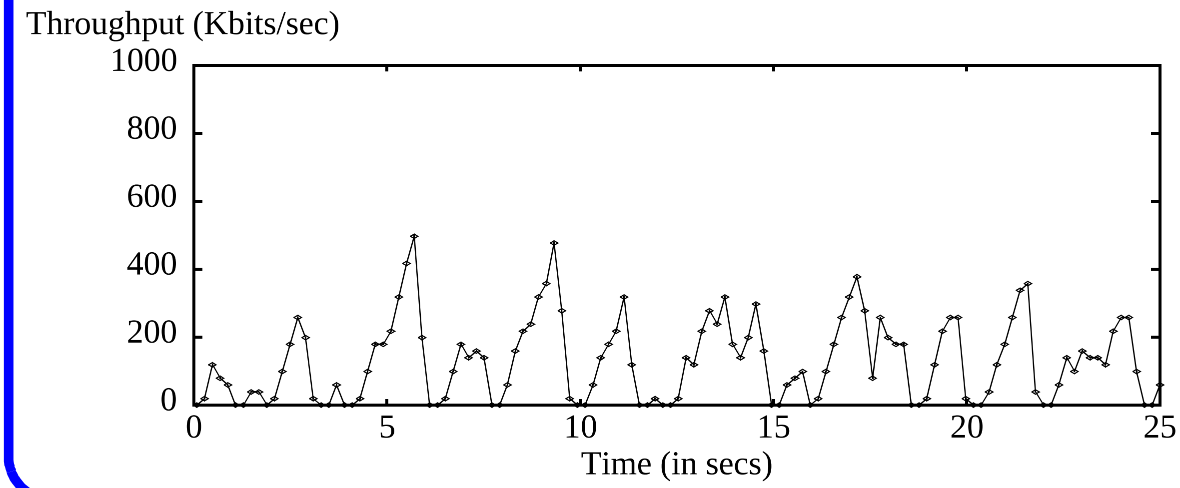
  - interference from adjacent slots
  - interaction with retransmission control mechanisms (e.g. TCP)
  - lost of ACKs

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%)