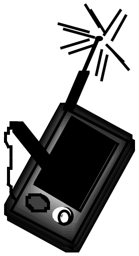
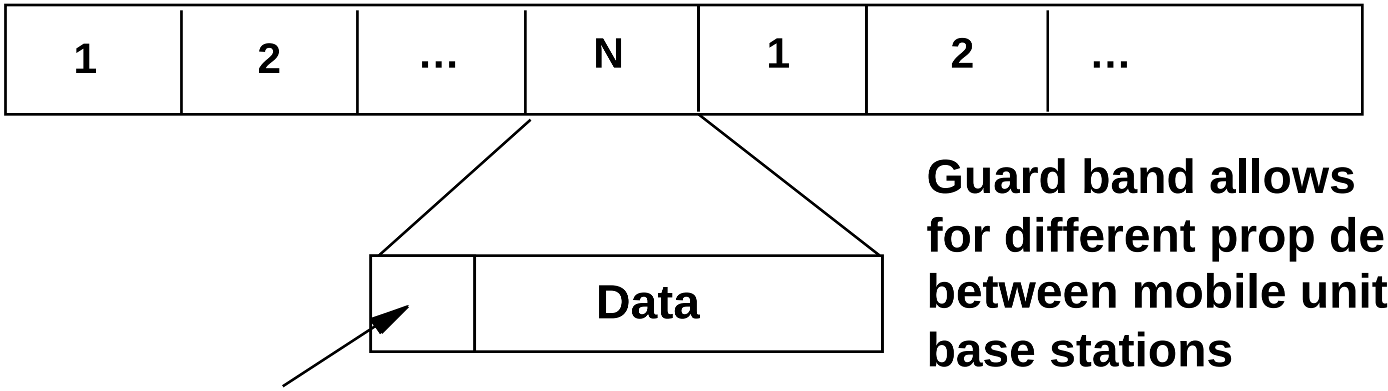
CS 294-7: Media Access— TDMA and CDMA

Prof. Randy H. Katz
CS Division
University of California, Berkeley
Berkeley, CA 946720-1776



Time Division Multiple Access

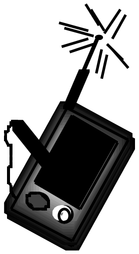
- Multiple users share channel through time allocation scheme



Guard band allows for different prop delays between mobile units and base stations

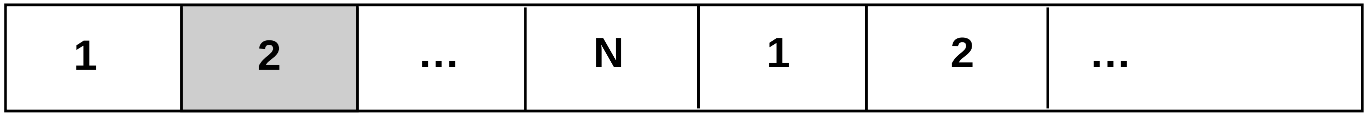
Guard Band & Sync Sequence

- Time Division Duplexing (TDD): DECT, PHP
  Frequent Division Duplexing (FDD): GSM, IS-54, PACS



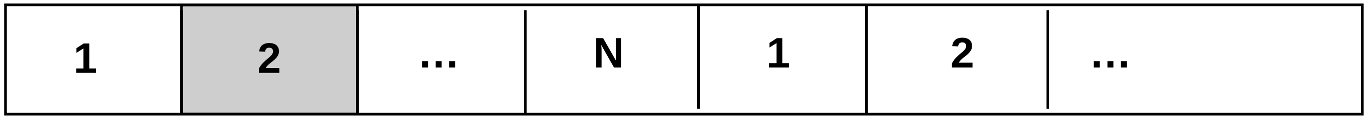
Time Division Multiple Access

- **Downstream: BS broadcasts to mobile units**



1	2	…	N	1	2	…

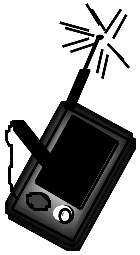
- **Upstream: Mobile units to BS based on assigned slots, transmitted on different freq.**



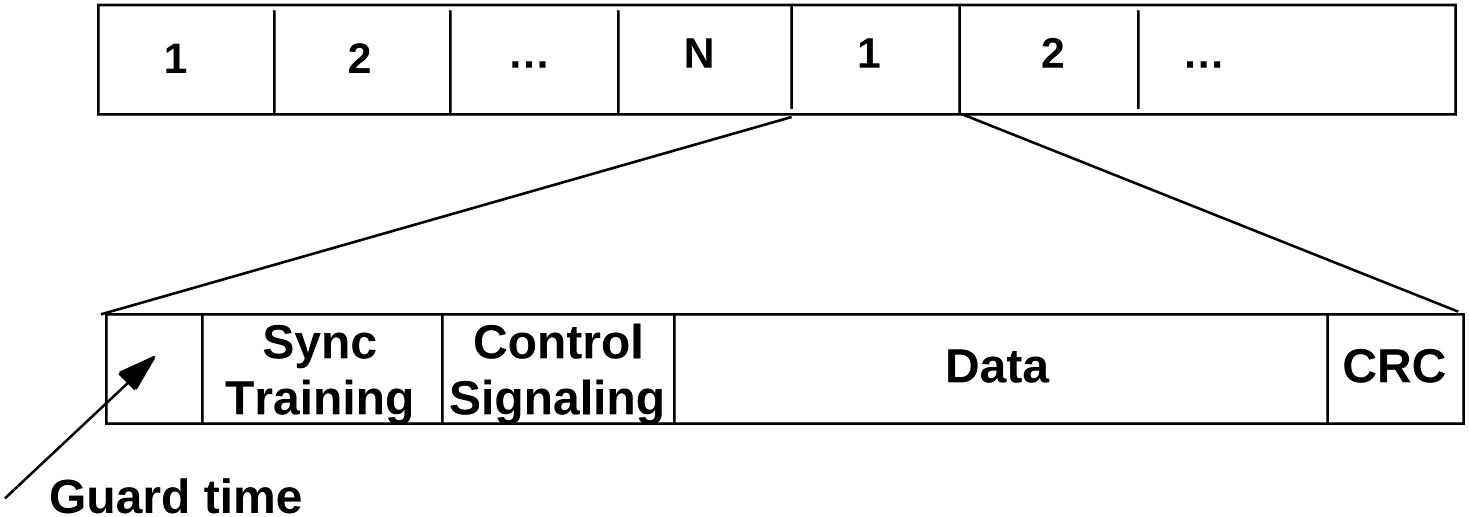
1	2	…	N	1	2	…

Logically, upstream and downstream slots are the same

In reality, these are offset in time to allow mobile unit time to process downstream requests before responding on upstream

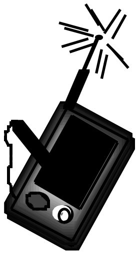


Time Division Multiple Access



Guard time
Ramp, Flag

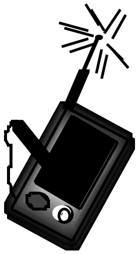
GSM, PHS, DECT: 30% of data rate is overhead
IS-54: 20% overhead
IS-54, GSM: long adaptive equalization training sequences



Tradeoffs in overhead, size of data payload, and latency

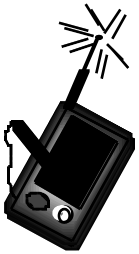
TDMA Systems

	GSM	IS-54	DECT
Bit Rate	270.8 kbps	48.6 kbps	1.152 Mbps
Bandwidth (Carrier Spacing)	200 KHz	30 KHz	1.728 MHz
Time Slot Duration	0,577 ms	6.7 ms	0.417 ms
Upstream slots per frame	8/16	3/6	12
Speech Coding	13 kbps RPE-LTP	7.95 kbps VSELP	32 kbps ADPCM
FDD or TDD	FDD	FDD	TDD
% Payload in Time Slot	73%	80%	67%
Modulation	GMSK	π/4 DQPSK	GMSK
Coding	Coded/Convol Coded+CRC Uncoded	Coded/Convol Coded+CRC Uncoded	CRC Only
Adaptive Equalizer	Mandatory	Mandatory	None



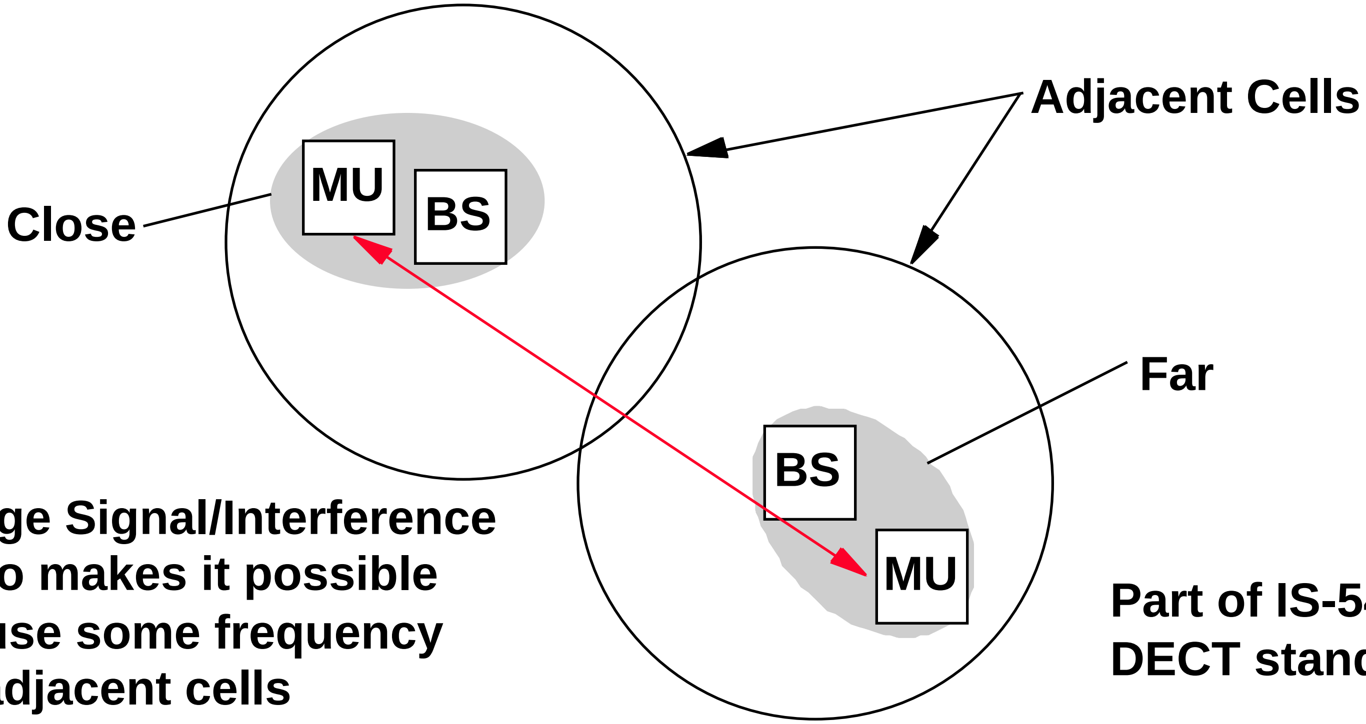
TDMA Advantages/ Disadvantages

- Advantages
  - Sharing among N users
  - Variable bit rate by ganging slots
  - Less stringent power control due to reduced interuser interference—dedicated frequencies and slots
  - Mobile assisted/controlled handoff enable by available measurement slots
- Disadvantages
  - Pulsating power envelop—interference with devices like hearing aids have been detected
  - Complexity inherent in slot/frequency allocation
  - High data rates imply need for equalization



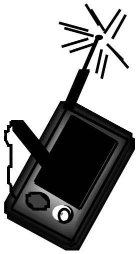
TDMA Capacity Improvements

- Adaptive Channel Allocation
  - in conventional cellular systems, adjacent cells do not use the same frequencies



Large Signal/Interference
ratio makes it possible
to use some frequency
in adjacent cells

Part of IS-54,
DECT standards



A form of dynamic frequency reuse/frequency borrowing

TDMA Capacity Improvements

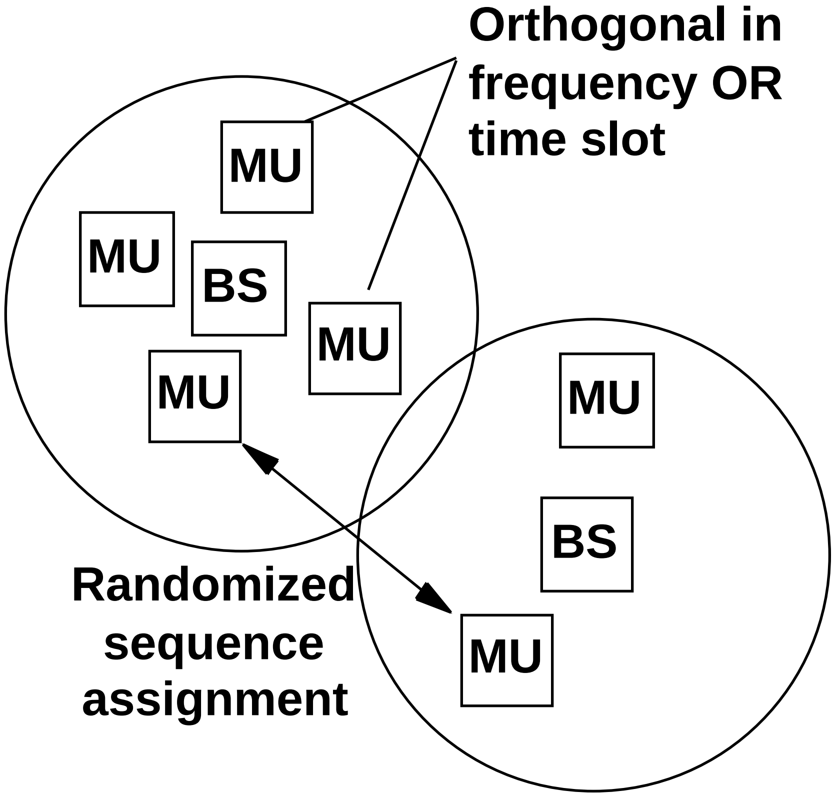
- Frequency Hopping

Users within cell perform slow frequency hopping

Each user at different offset in hopping sequence—frequencies are orthogonal

Randomized sequences in different cells to average intercell interference

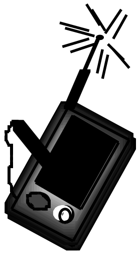
Hopping has the inherent frequency diversity advantages of spread spectrum systems



Orthogonal in frequency OR time slot

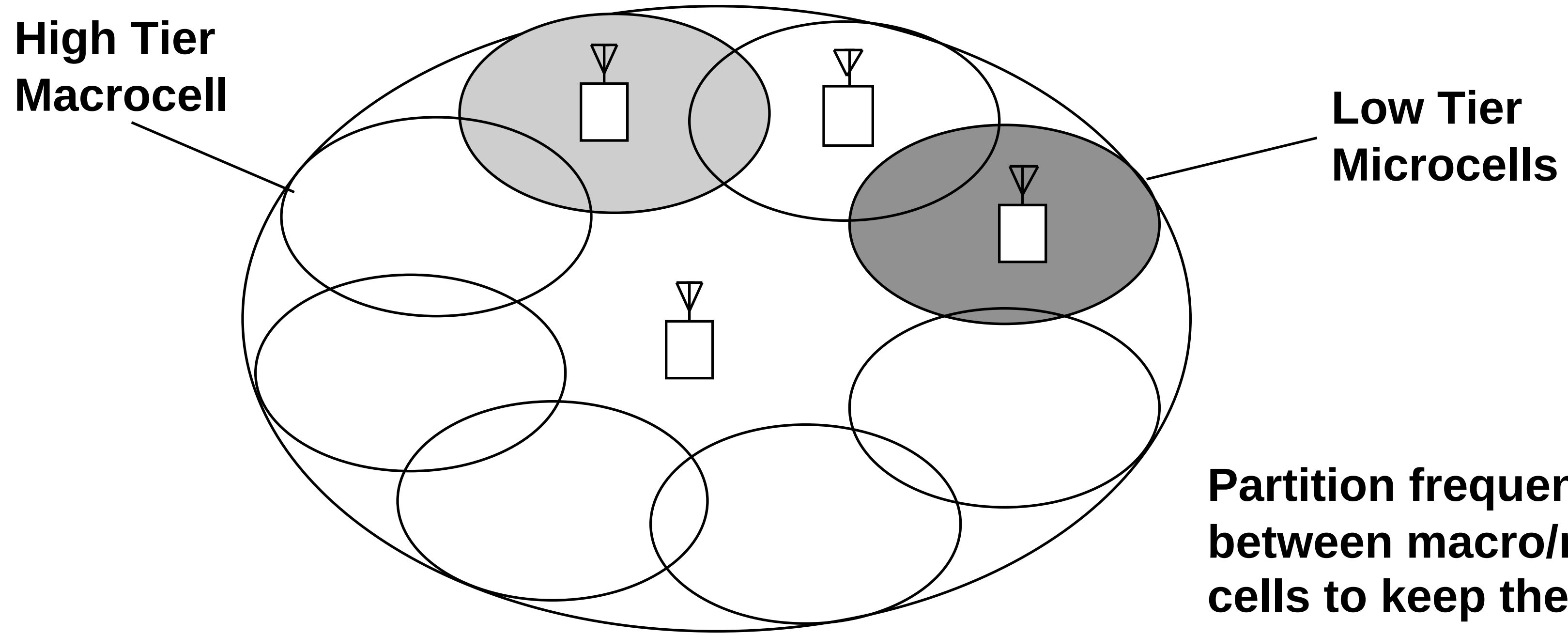
Randomized sequence assignment

Part of GSM

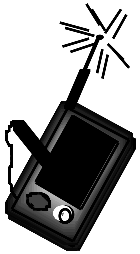


TDMA Capacity Improvements

- Hierarchical Cell Structure



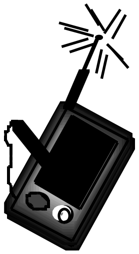
Partition frequencies between macro/micro cells to keep them orthogonal



Mobile Assisted Handoff (MAHO): Measure signal strength in other frequencies during non-slot times

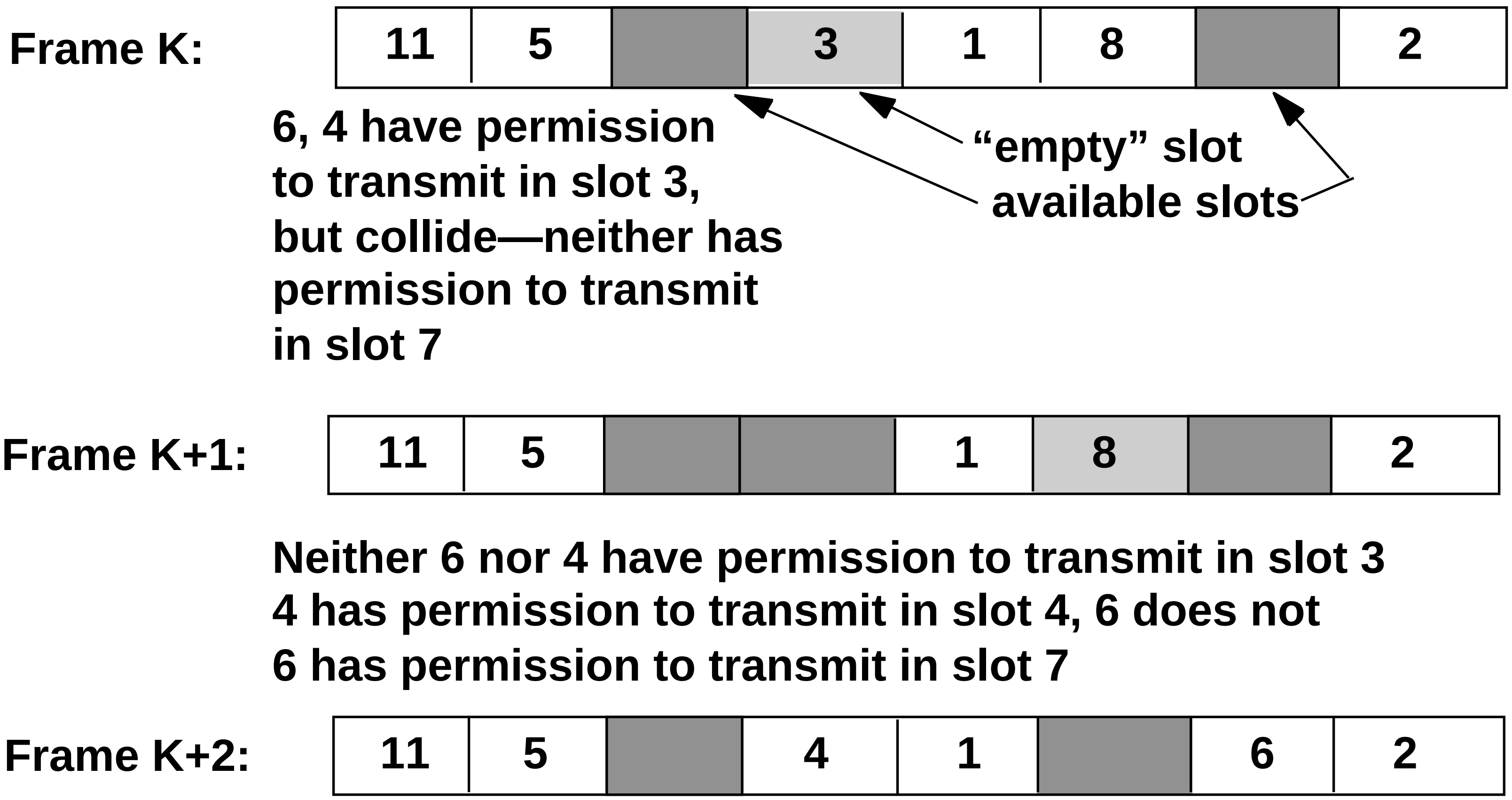
Packet Reservation Multiple Access

- Combines TDMA with elements of slotted ALOHA
  - BS to MH channel + shared MH to BS channel
  - Transmissions are organized into slots, one packet per slot
  - Frames
    - A group of slots
    - Slots within frame may be available or reserved
    - Information about slot status broadcast from BS to mobile units in previous frame
  - Reservation scheme
    - Mobile units with new data contend for an available slot
    - BS indicates whether slot contents was received correctly
    - MH that succeeded in getting its data through reserves that slot in subsequent frames
    - BS detects when their is no data in a reserved slot: the MH loses its reservation



Packet Reservation Multiple Access

State at Frame K-1: Terminals 11, 5, 3, 1, 8, and 2 have reservations



Frame K:

11	5	▨	░ 3	1	8	▨	2

6, 4 have permission to transmit in slot 3, but collide—neither has permission to transmit in slot 7

“empty” slot

available slots

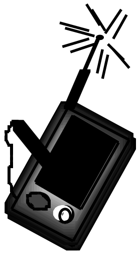
Frame K+1:

11	5	▨	▨	1	░ 8	▨	2

Neither 6 nor 4 have permission to transmit in slot 3
4 has permission to transmit in slot 4, 6 does not
6 has permission to transmit in slot 7

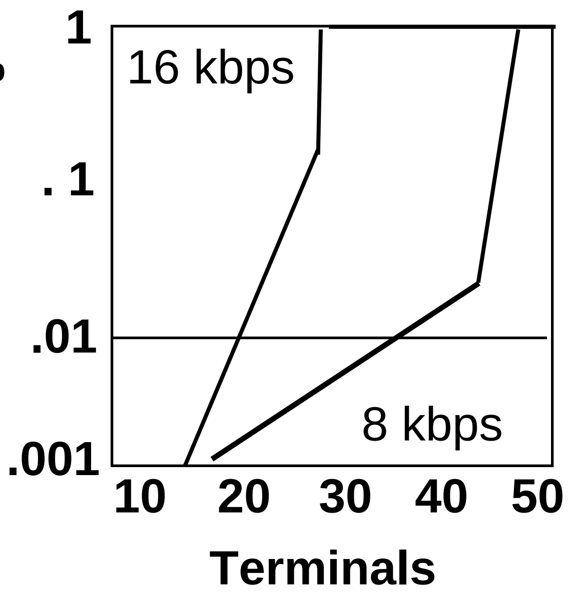
Frame K+2:

11	5	▨	4	1	▨	6	2

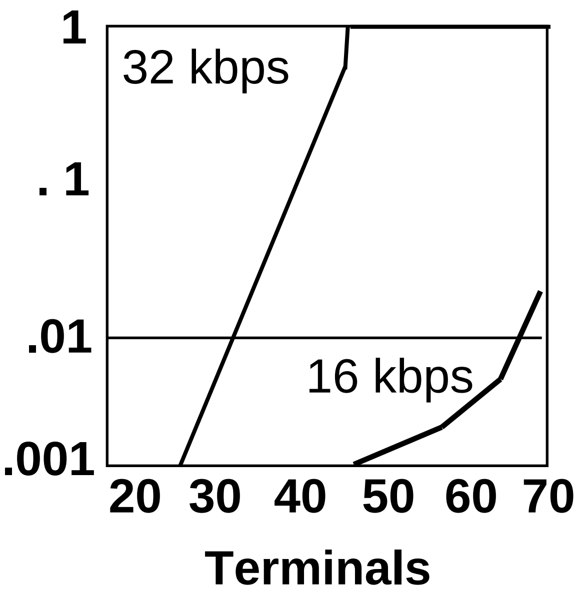


Packet Reservation Multiple Access

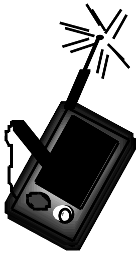
- **Packet Dropping Probability**
  - Packets held beyond D_{max} time are dropped at terminal
  - This is important for real time/latency sensitive applications like packet voice and video
  - P_{drop} set at ≤ 0.01, how many terminals can be supported?



GSM (270 kbps, 28/14 slots per frame)

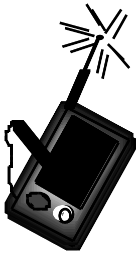


DECT (672 kbps, 35/17 slots per frame)



Spread Spectrum

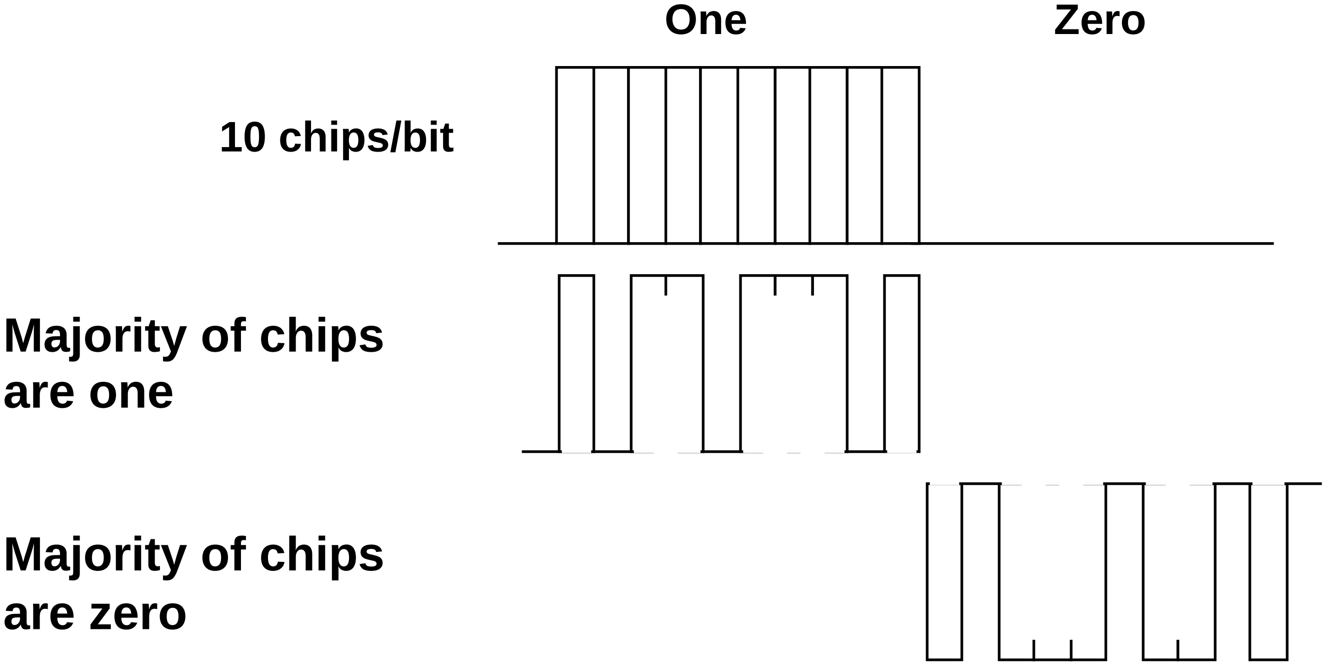
- Techniques known since 1940s and used in military communications systems since 1950s
- Basic idea:
  - “Spread” the radio signal over a wide frequency range by modulating it with a code word unique to the radio
  - Receiver’s correlator distinguishes sender’s signal from other signals by examining the wide spectrum band with a time synchronized duplicate of the spreading code word
  - The sent signal is recovered by a despreading process at the receiver
  - Spread spectrum waveform is more resistant to multipath effects and more tolerant of interference (leading to higher capacity?)



- Spread spectrum systems are *power* rather than bandwidth limited

Spread Sprectrum

- **Direct Sequence SS**
  - Bits sampled (“chipped”) at higher frequency
  - Signal energy “spread” over wider frequency
  - Advantageous diversity recombination (“correlation”) at receiver



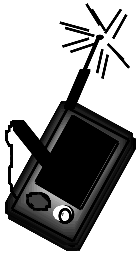
One

Zero

10 chips/bit

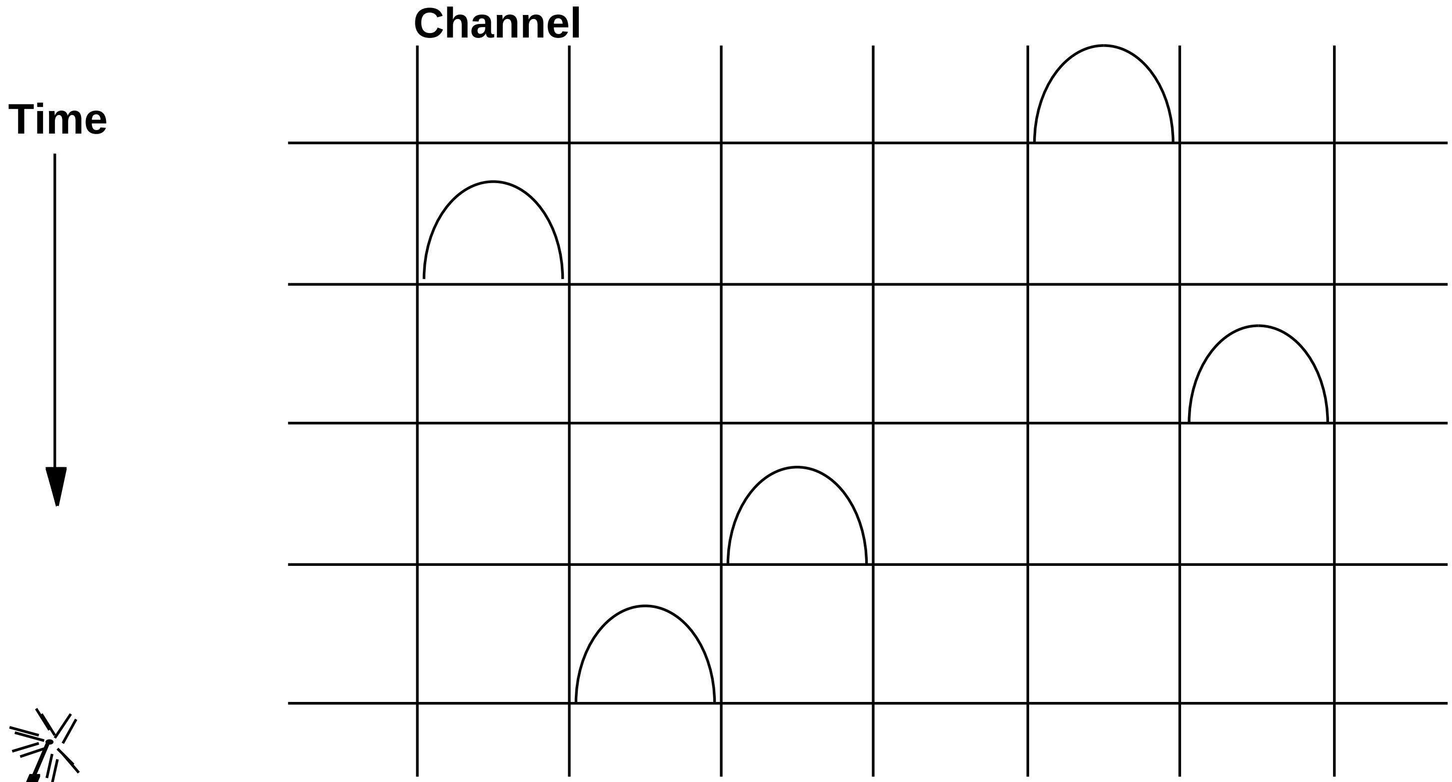
Majority of chips are one

Majority of chips are zero



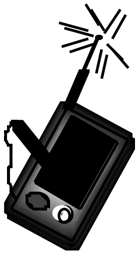
Spread Spectrum

- Frequency Hopping SS
  - Slow hopping: multiple bits before frequency hop
  - Fast hopping: multiple frequency hops per bit



Interference Tolerant: Anti-Jam

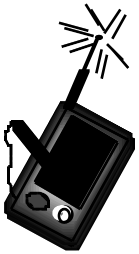
Can learn about interferers and avoid them



Note that TDMA-based GSM also uses FH techniques to give low power mobiles some dB diversity gain at edge of cells

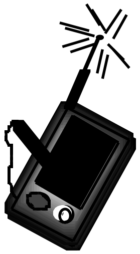
Spread Spectrum

- **Processing Gain: $G_p = B_{spread} / R$ where**
  - B_{spread} is the pseudo noise (PN) code rate
  - R is the information rate
  - PN spreading code aka chipping code
  - $G_p = R_{chip} / R$ where R_{chip} is the chipping rate
- **Energy of each "chip" is accumulated over a full data bit time**
  - For high values of G_p (>1000), information can be transmitted at power levels below ambient noise
  - "Low probability of intercept/detect" (LPI/LPD) and narrowband jamming or interference
  - Commercially available SS systems typically implement processing gains in the 10-100 range (e.g., IS-95 is 64)
  - Purpose is media access via code division rather than lowering error rates in presence of noise

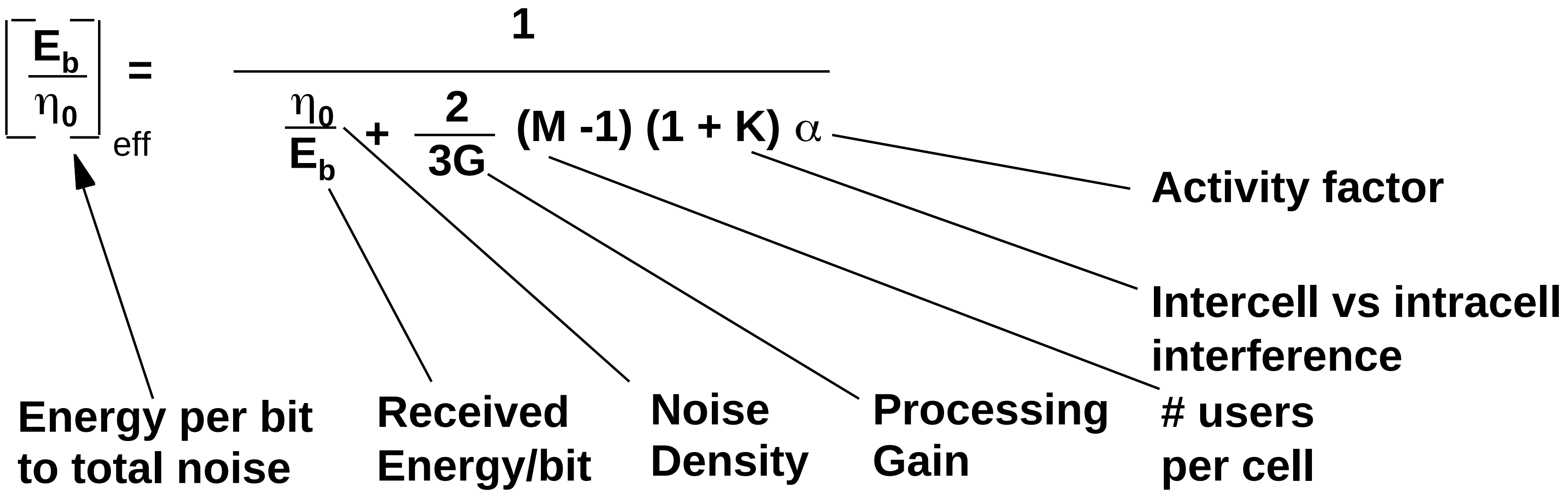


Spread Spectrum

- Power-Limited System: Cocktail party analogy
  - Band playing “random noise” while people talking
  - Need to extract conversation from the background din
  - If people speak in different languages, G_p is high, easier to distinguish individual speakers
  - If G_p is low, more difficult to distinguish between individuals
  - Now image that the Band starts playing even louder!
    - » If becomes too loud, nobody can speak
    - » Speakers try to talk more loudly, increasing the noise
  - How to increase the # of attendees (capacity) at party:
    - » Band agrees to play at low level (background noise)
    - » Participants agree to speak MORE softly as new guests arrive
    - » Host (base station) centralizes all conversations, requiring all guests to speak to him/her at the same relative sound level, no matter how far they are from the host



Interference Limited Performance



$$\left[\frac{E_b}{\eta_0}\right]_{eff} = \frac{1}{\frac{\eta_0}{E_b} + \frac{2}{3G}\,(M-1)\,(1+K)\,\alpha}$$

Activity factor

Intercell vs intracell interference

Energy per bit to total noise

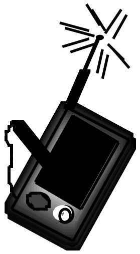
Received Energy/bit

Noise Density

Processing Gain

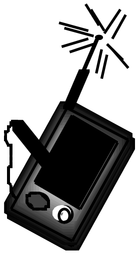
\# users per cell

- BER related to E_b/η_0
- As M, α, K increase, so does the BER
- As G increases, BER decreases
- Trade decreased M for increased coverage, useful at fringe cells
- K depends on cell isolation and user geographic separation
- K becomes larger when the propagation law exponent is smaller
- K is larger when soft handoff is used (same link in adjacent cells)
- To exploit multipath resolution via RAKE receiver, delay spread should be greater than chip rate, which implies wide bandwidth

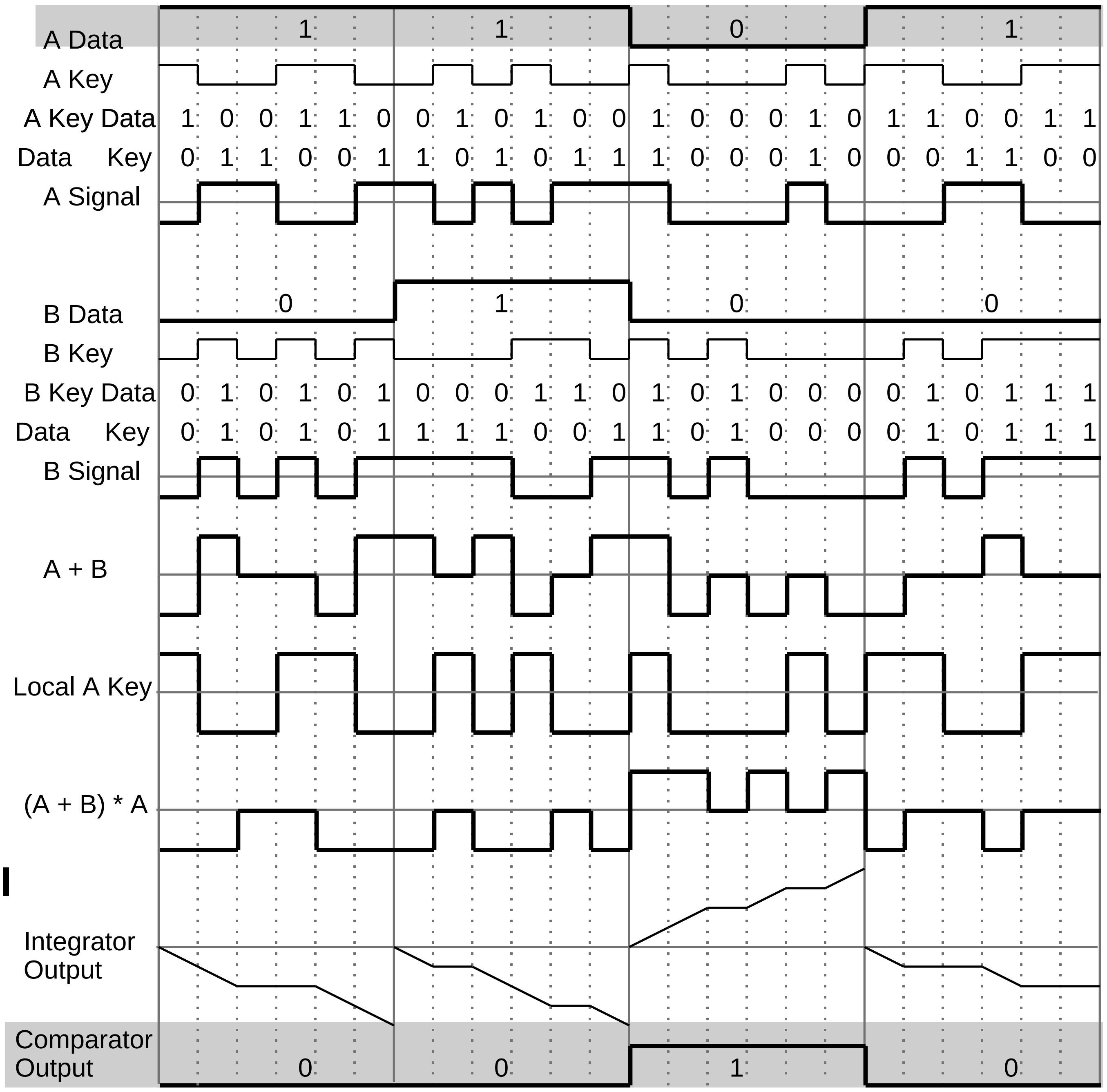


Code Division Multiple Access

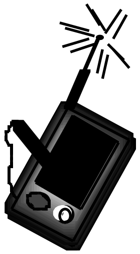
- A strategy for multiple users per channel based on orthogonal spreading codes
  - Multiple communicators simultaneously transmitting using direct sequence techniques, yet not conflicting with each other
  - Pilot tone on BS to mobile unit forward channel used to time synchronize and equalize the channel (coherent detection)
  - Reverse channel is contention based, dynamically power controlled to eliminate the near-far problem
- Developed by Qualcomm as IS-95
  - Special soft handoff capability
  - "Narrowband CDMA": 1.228 MHz chipping rate, 1.25 MHz spread bandwidth
  - Contrast with Broadband CDMA proposal: 10 MHz spread bandwidth
    - » Multipath: Can leverage frequency diversity better
    - » Interference tolerance: Can overlay existing analog user better



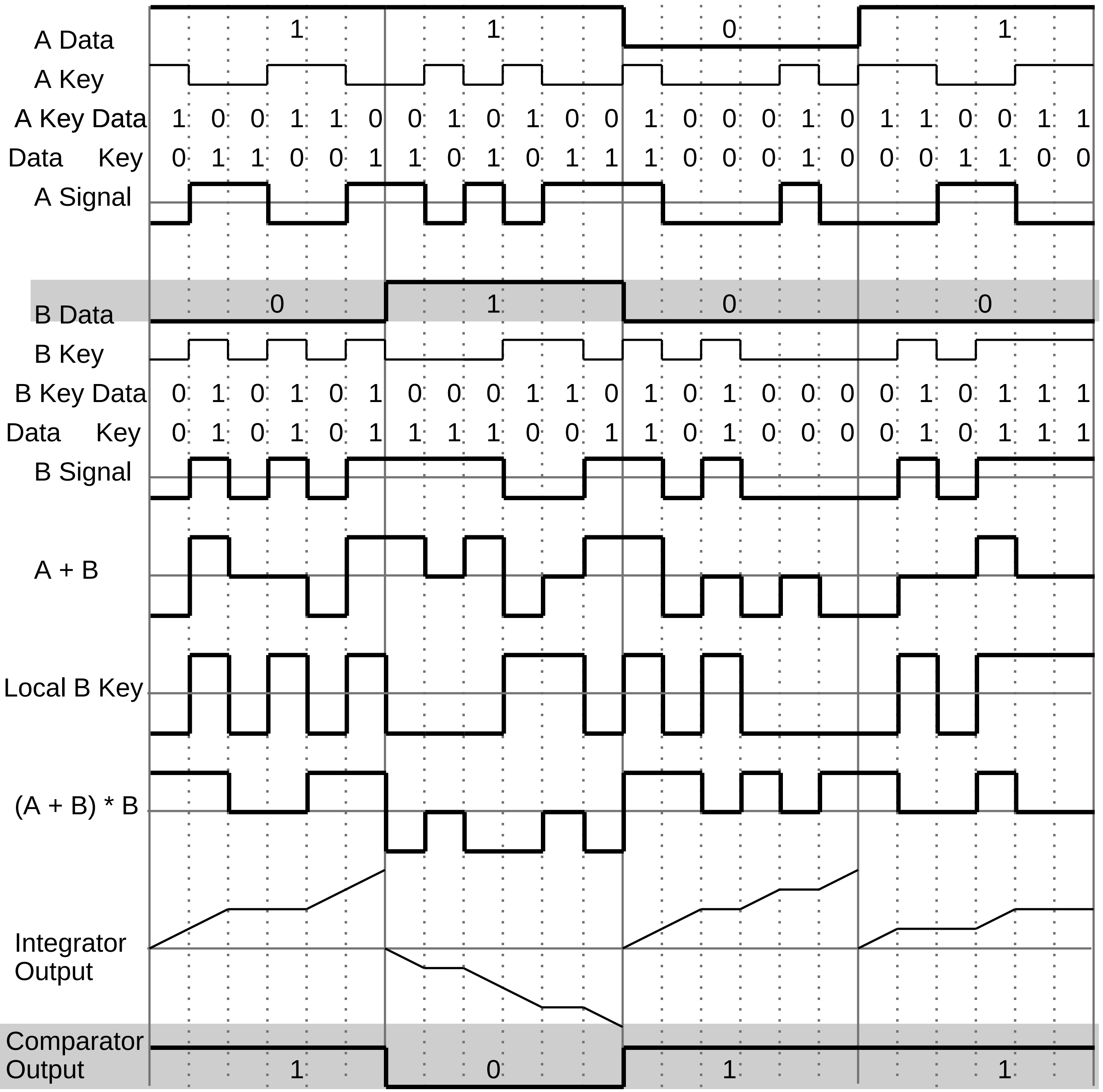
CDMA



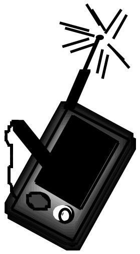
Recovery of A Channel



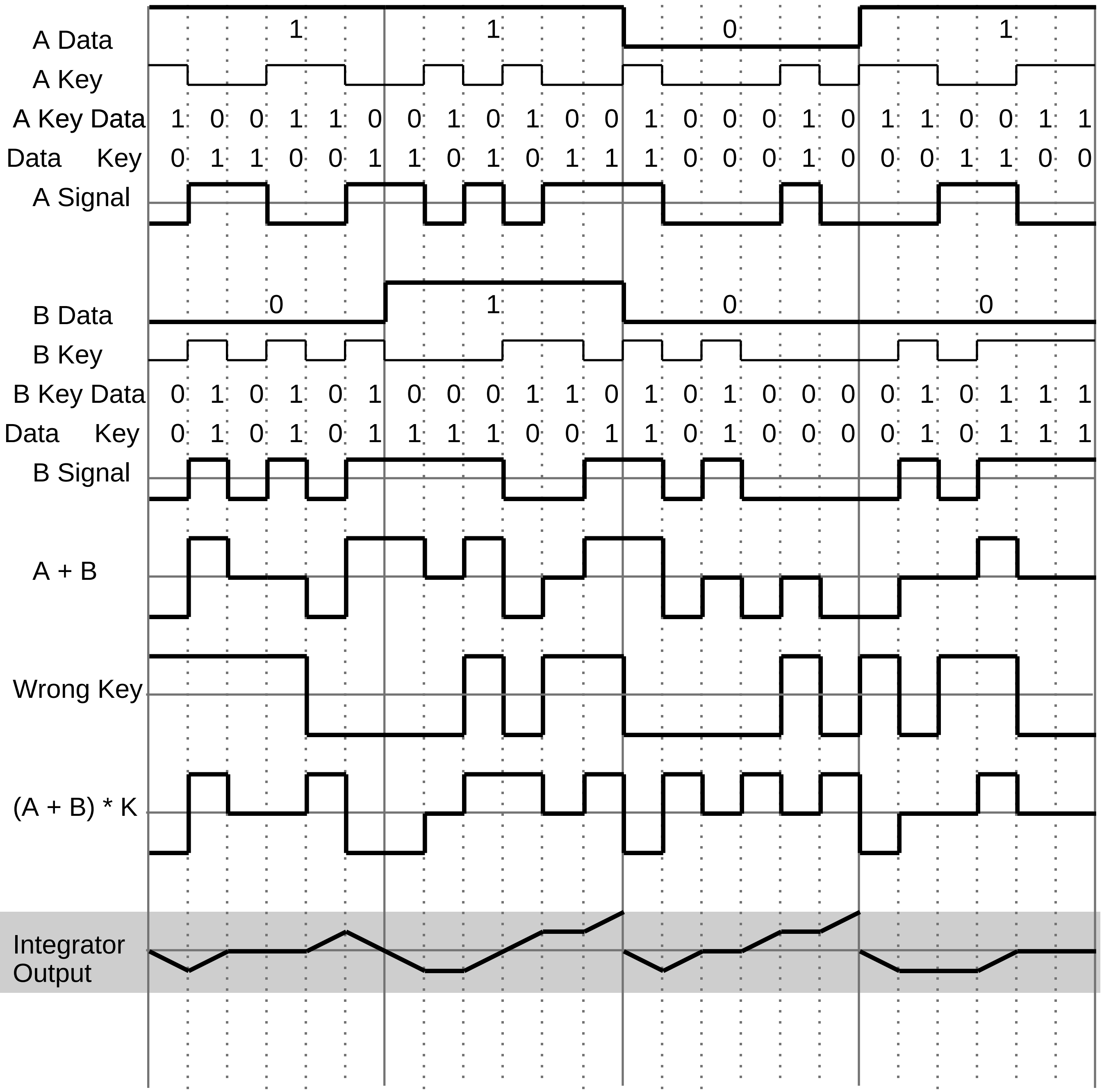
CDMA

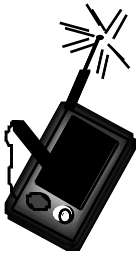


Recovery of B Channel



CDMA

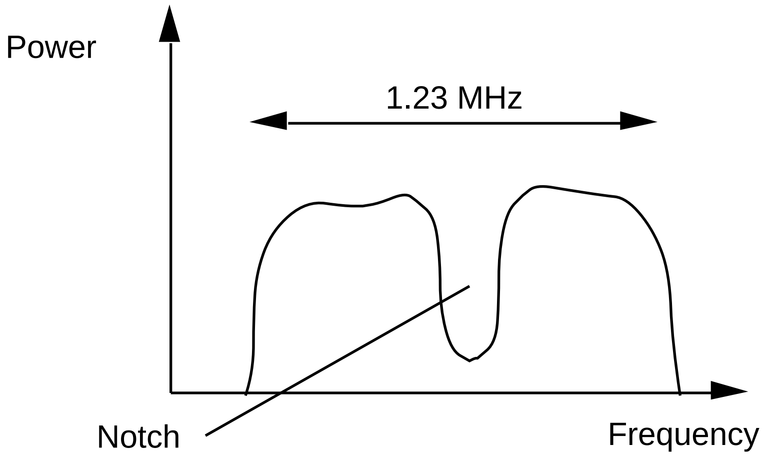




Wrong Key yields noisy output

Diversity in CDMA

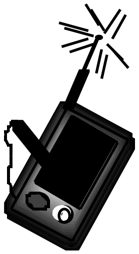
- **Frequency Diversity**
  - **Signal spread over wide band, helps to mitigate multipath effects**
  - **Recall multipath arrises because of different delays on different paths between transmitter and receiver**



IS-95 channel is relatively narrow!

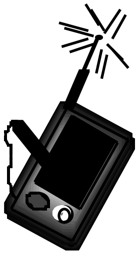
Notch corresponds to a fade

Width of notch approximately equal to 1/(delay between paths)
E.g., 1 µs delay translates into a 1 MHz notch
delays < 1 µs yield deep fades
delays > 1 µs cause power reduction in receiver signal

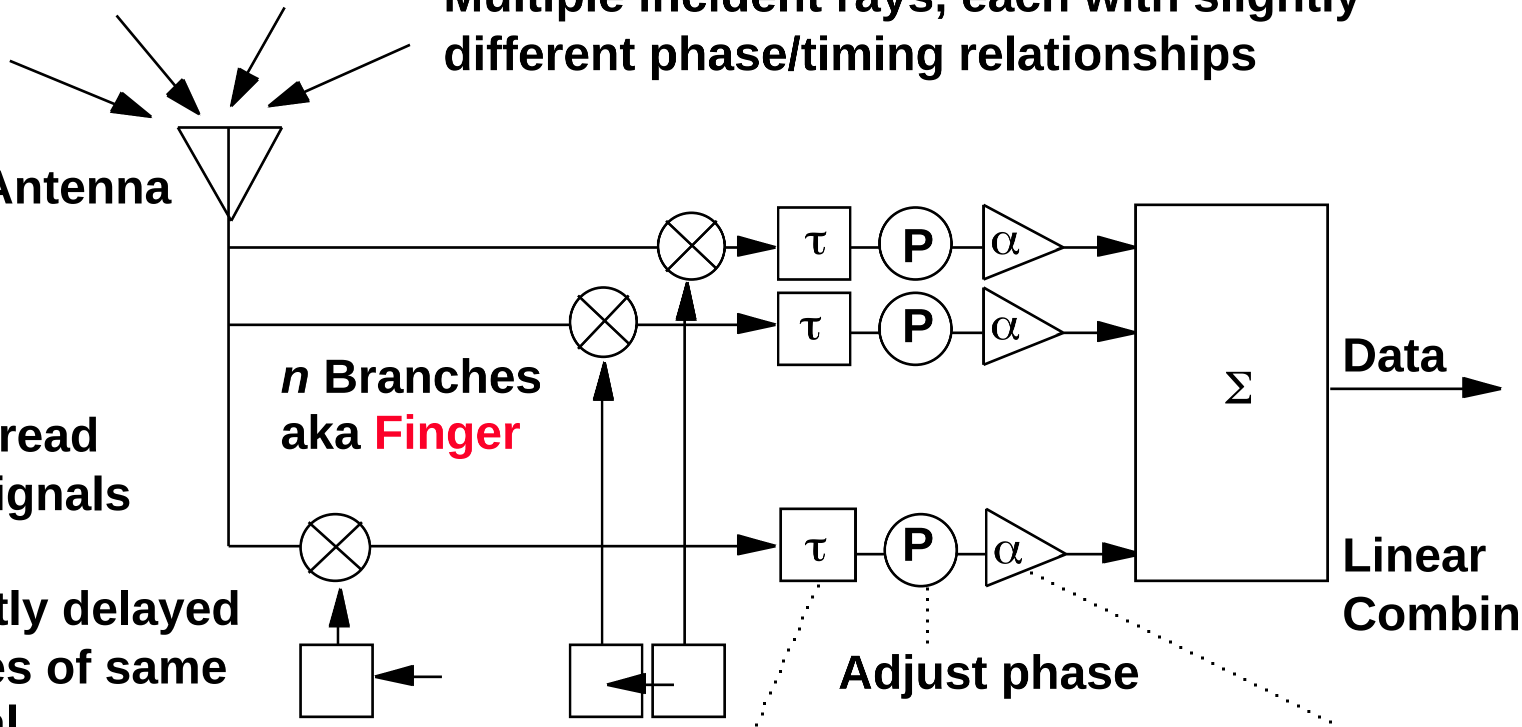


Diversity in CDMA

- Spatial Diversity
  - Multiple antennas at the base station sufficiently far apart to mitigate fades
  - Soft handoff capability
    - Multiple base station signals overlaid on each other makes it possible for mobile to listen to more than one at a time
    - Reduces the probability that a mobile will not be able in contact with some base station
    - Enables “make before break” handoff
    - Contrast with TDMA systems: break before make
- Time Diversity
  - Qualcomm CDMA system makes extensive use of convolutional redundancy codes (1/2 rate on forward channel, 1/3 rate reverse channel) and interleaving in time
  - These techniques can be used in any communications system



CDMA Rake Receiver



Multiple incident rays, each with slightly different phase/timing relationships

Antenna

Despread the signals

slightly delayed copies of same signal

n Branches aka Finger

PN Generators

Data

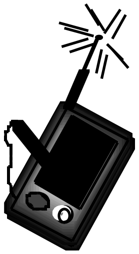
Linear Combiner

Adjust phase

Adaptively equalize

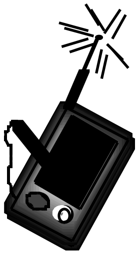
Adaptively cancel delay spread among each of the despread rays

τ dither tracking



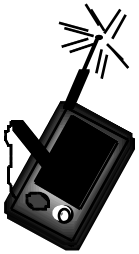
CDMA Rake Receiver

- Assists implementation of soft handoff
  - Mobile moves towards edge of cell
  - BS detects low RF power
  - MTSO assigns mobile’s spreading code to adjacent BS
  - Both BS transmit same data to mobile
  - Rays from both BSs are combined by the rake receiver
  - Mobile moves further into new cell
  - All fingers correlate with rays from new site
  - MTSO instructs old BS to drop mobile’s spreading code



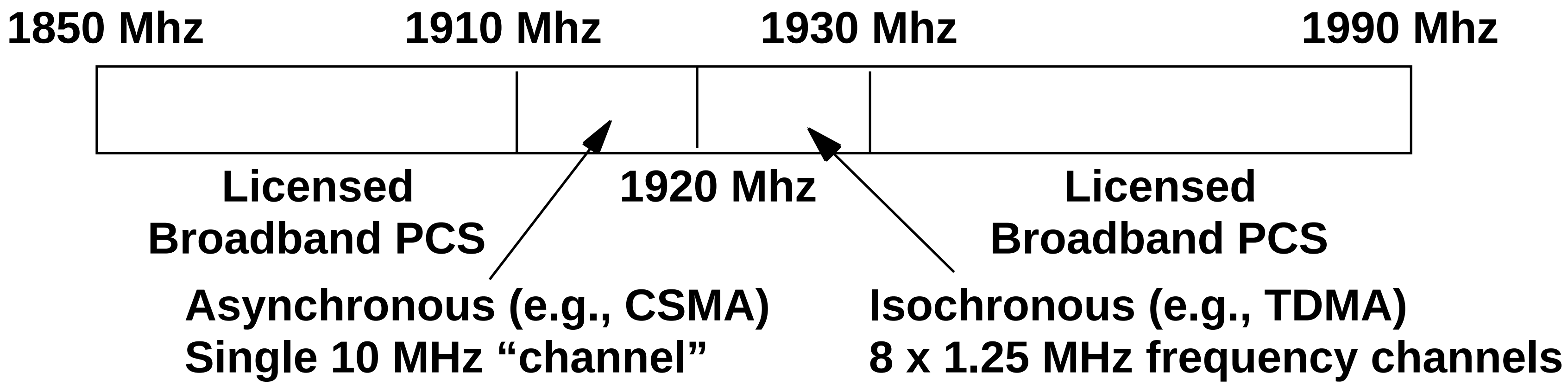
Performance Issues

- Indoor environment
  - Delay spreads 100-300 ns implies coherence b/w ≈ 2 - 5 MHz (large open spaces) to 10 MHz (smaller room): spread over 10 MHz
- Outdoor environment
  - Rural areas: Much larger multipath delay spread (>> 1 µs) implies coherence bandwidth much smaller: spread over 1 MHz
  - Urban areas: Smaller multipath delay spread implies larger coherence bandwidth and a larger spreading b/w is needed
- Satellites
  - Delay spread typically 100 ns yields coherence b/w of 10 MHz, much LESS than the proposed spreading b/w (1.5 MHz)! Dual satellite diversity needed to resolve multipath.
  - Power control also a challenge: fades are shorter than round trip propagation times (10s of ms)!
  - Interleaving and BER: fading channel yields correlated errors. Velocity sensitive: fast mobiles experience more fades per unit time. Interleaver is effective. But if stationary, then interleaving is ineffective.
  - At slow speeds, power control works but interleaving doesn't, at high speeds the reverse is true



Etiquette Rules

- Unlicensed PCS Band 1910 MHz to 1930 MHz



1850 Mhz 1910 Mhz 1930 Mhz 1990 Mhz

Licensed
Broadband PCS

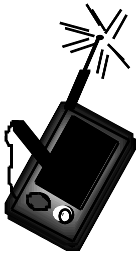
1920 Mhz

Licensed
Broadband PCS

Asynchronous (e.g., CSMA)
Single 10 MHz “channel”

Isochronous (e.g., TDMA)
8 x 1.25 MHz frequency channels

- Basic Principles:
  - Listen before transmit
  - Limited transmitter power
  - Limited time duration of transmissions



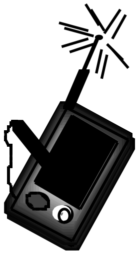
Etiquette Rules

- Transmitter Power and Thresholds

Emission B/W (MHz)	MaxTx Pwr (mW)	MaxTx Pwr (dBm)	Async Thres (dBm)	Isoc Lower Thres (dBm)	Isoc Higher Thres (dBm)
0.1	32	+15		-94	-74
0.5	70	+18	-85	-87	-67
1.0	100	+20	-82	-84	-64
5.0	224	+24	-75		
10.0	315	+25	-72		

Power chosen for 50 foot diameter cells

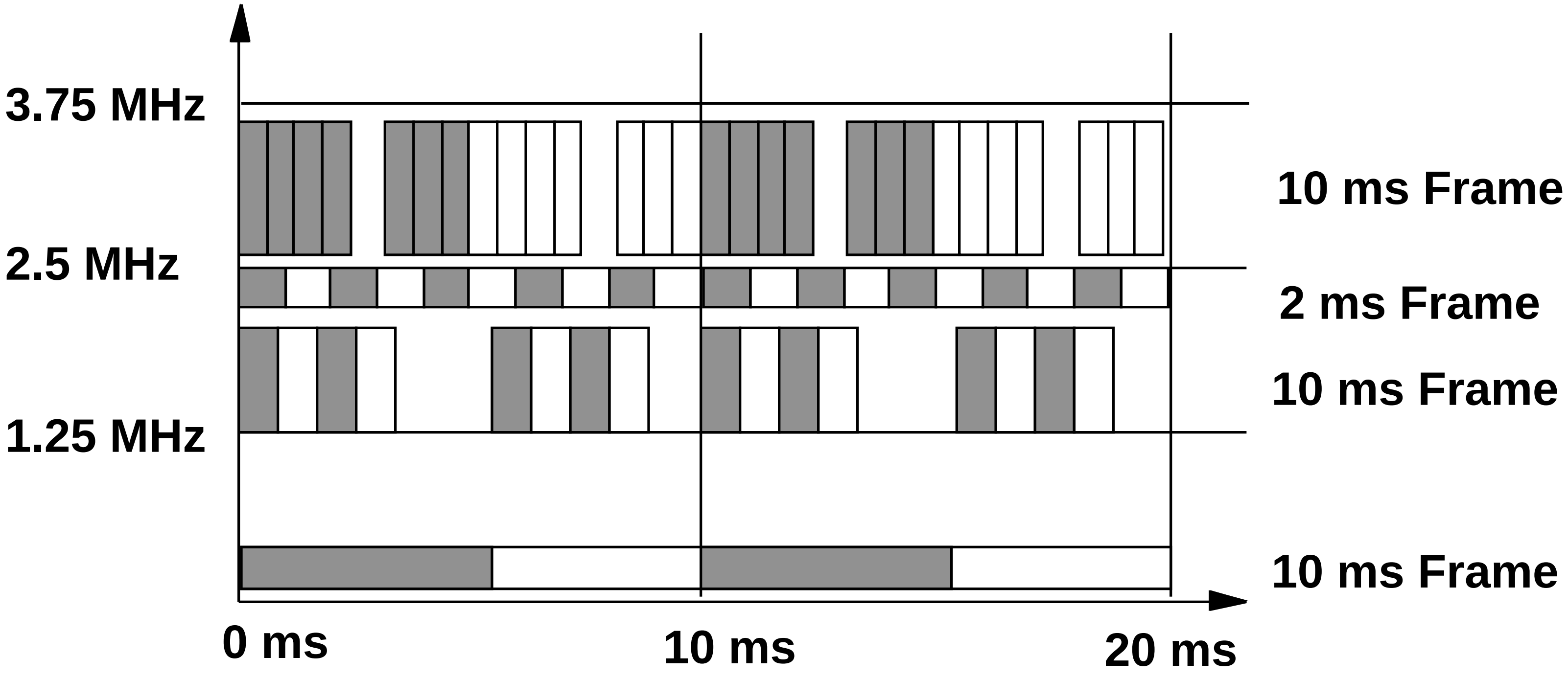
Async Band: Narrow band transmitters placed at channel edges
Wider band transmitters placed at center frequencies

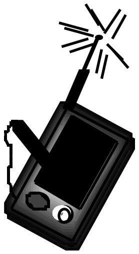


Isoc Band: Narrow band transmitters start at bottom end,
Wider band transmitters start at top end

Etiquette Rules

- **Isochronous Channel Allocation**

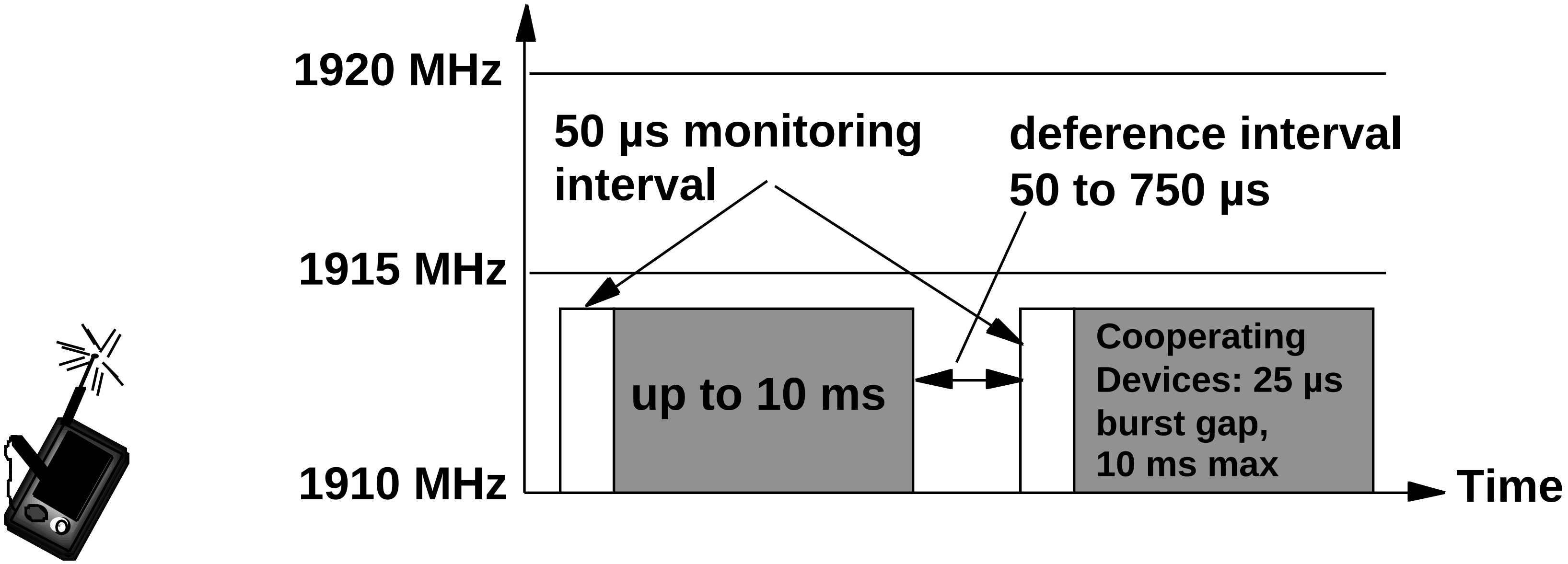




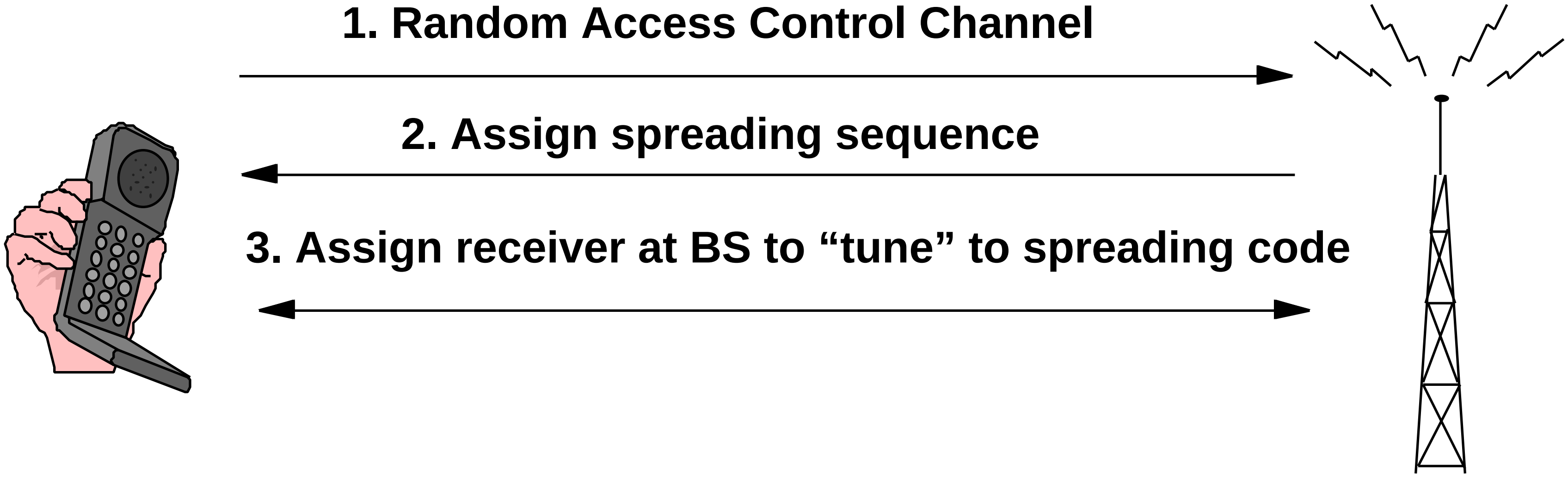
Sense for 10 ms before acquiring the channel
If below power threshold for this time, listening device may transmit
No more than 1 second transmission w/o acknowlegement
8 hour conversation limit

Etiquette Rules

- **Asynchronous Band**
  - If bandwidth < 2.5 MHz, use edges of channel region
    If bandwidth > 2.5 MHz, use middle frequencies
  - Device monitors its desired band for activity for 50 µs
    32 dB above thermal noise indicates band is not in use
  - Once acquired, transmission bursts can last up to 10 ms
  - After burst, defer use for random interval between 50 and 750 µs



Spread Aloha

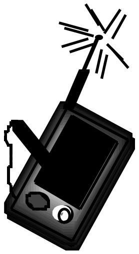


1. Random Access Control Channel

2. Assign spreading sequence

3. Assign receiver at BS to “tune” to spreading code

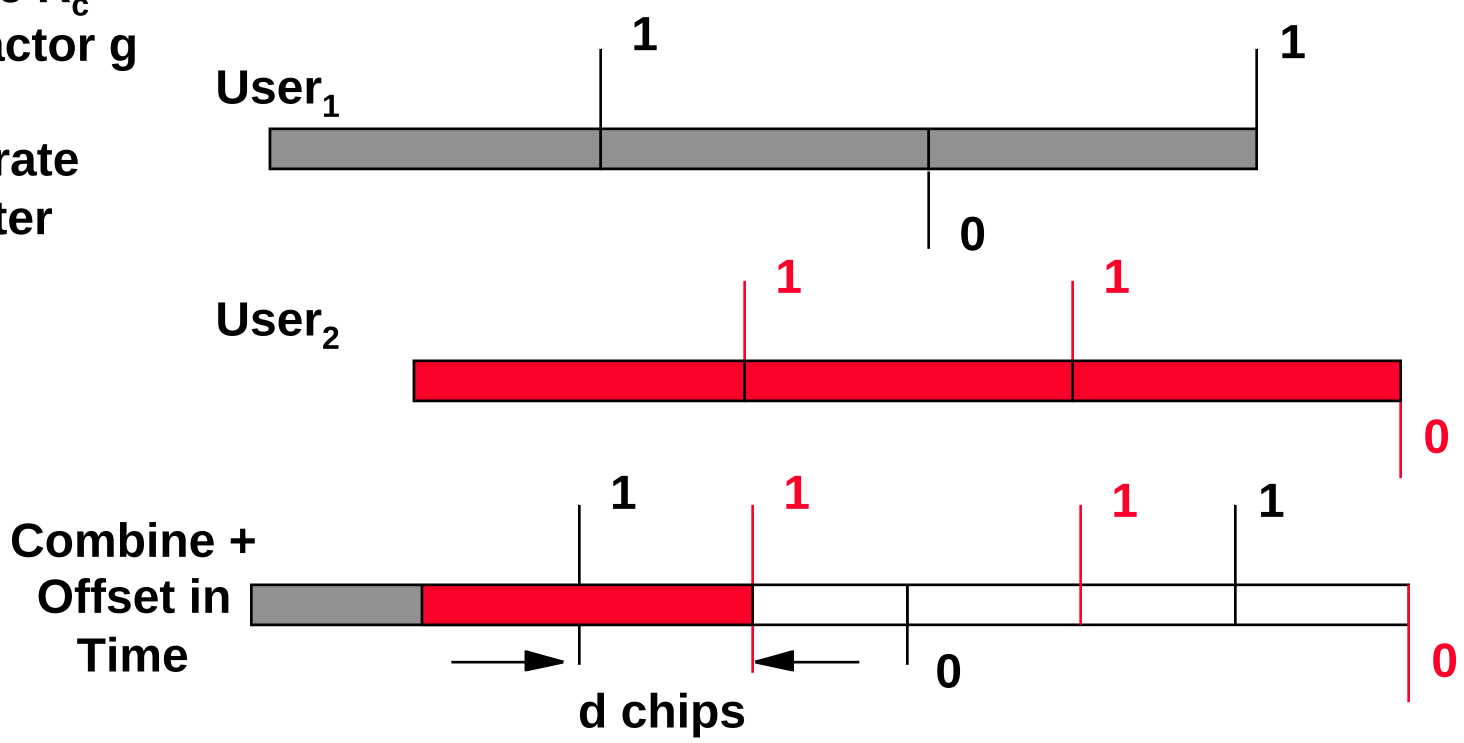
Scheme requires a separate receiver for each active spreading sequence
Qualcomm IS-95: 64 assignments are possible
Overhead associated with set-up



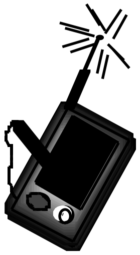
Could you get adequate access sharing a single spreading code among many users, exploiting wide band transmission and Aloha channel ideas?

Spread Aloha

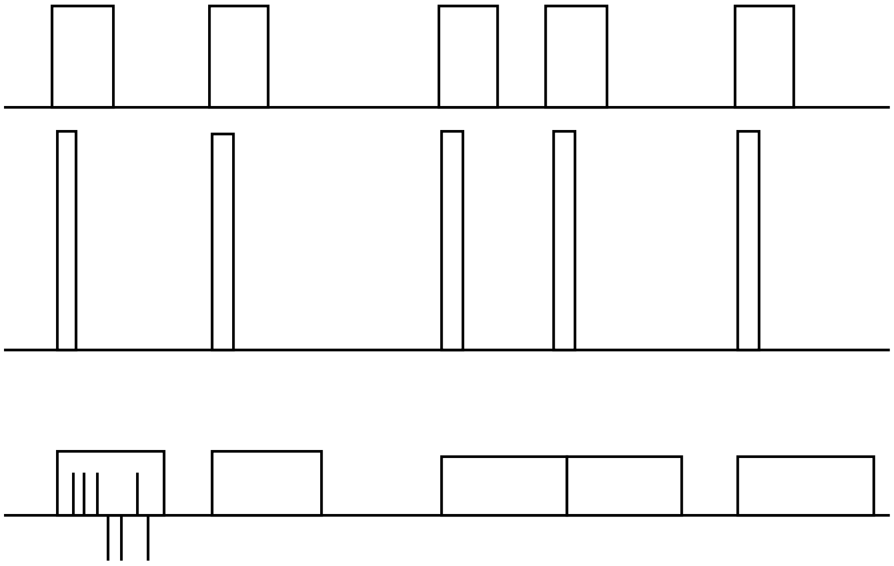
Chipping rate R_c
Spreading factor g
$R_b = R_c / g$
R_b is the bit rate
per transmitter



Limited by self-interference terms of single spreading code
Assumes *no user overlaps* with another -- just like Aloha
Max throughput: ≈18%, very similar to Aloha



Spread Aloha



High Bandwidth Aloha Channel

Narrowband

Increase frequency resources

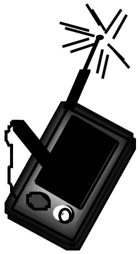
Each packet transmitted in shorter time, at greater power w/ same ave pwr

Spread signal to reduce peak pwr

1110010
spreading
sequence

Stretched packet encoded as spreadspectrum waveform

Time spreading of packets to decrease average burst power, keeping average power the same while exploiting higher bandwidth of the channel



The trick is finding the right single spreading sequence!