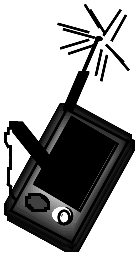
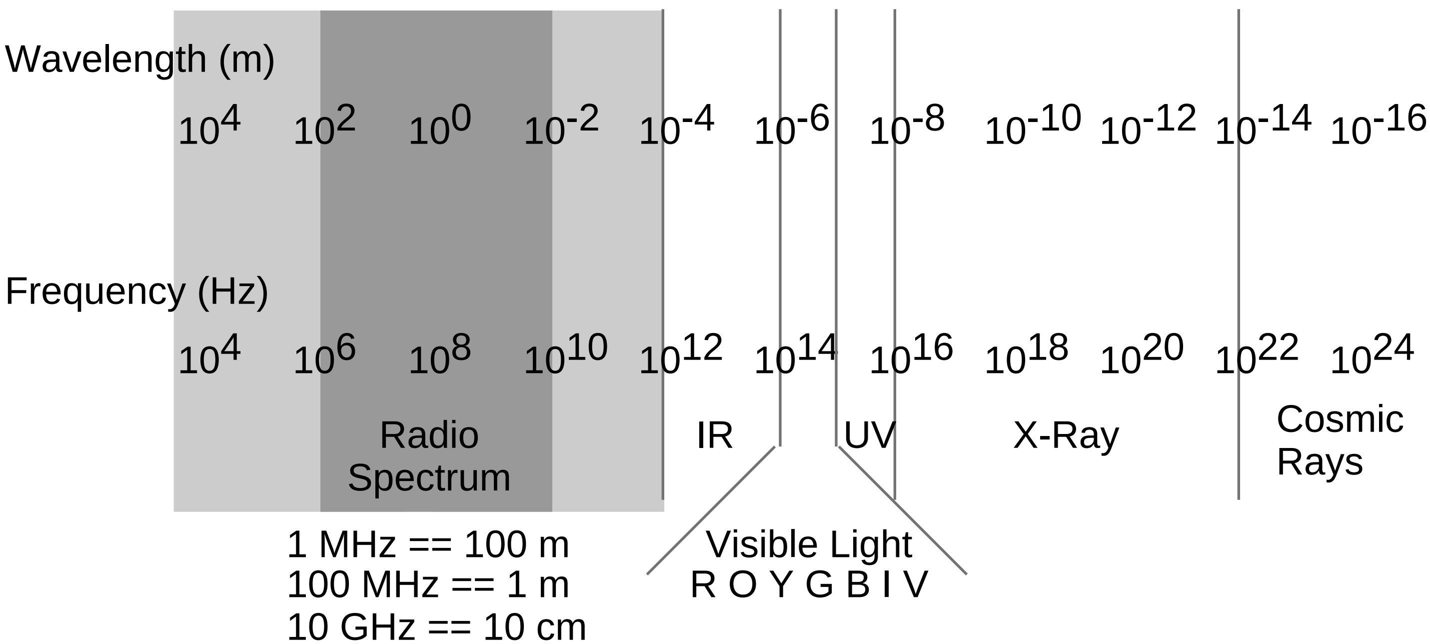
Presentation Outline

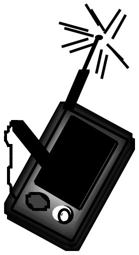
- Historical Overview
- **Radio Fundamentals**
- US Developments in PCS
- Mobile Data
- Satellite Systems
- Problems with existing schemes
- Wireless Overlay Networks
- US Government Research Initiatives



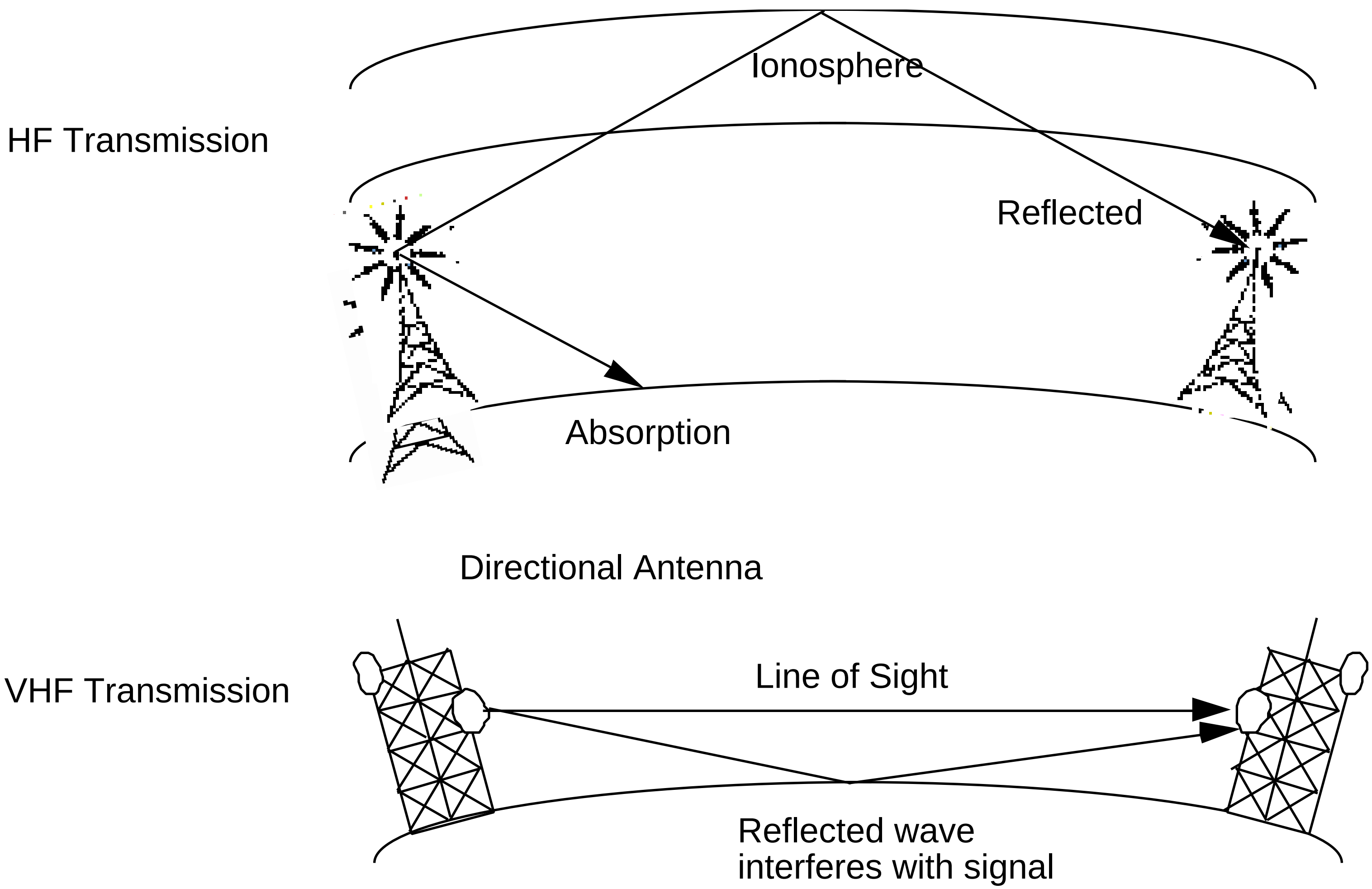
Radio Basics

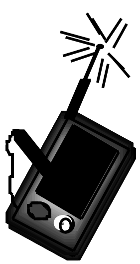


< 30 KHz	VLF
30 - 300 KHz	LF
300 KHz - 3 MHz	MF
3 - 30 MHz	HF
30 - 300 MHz	VHF
300 MHz - 3 GHz	UHF
3 - 30 GHz	SHF
> 30 GHz	EHF



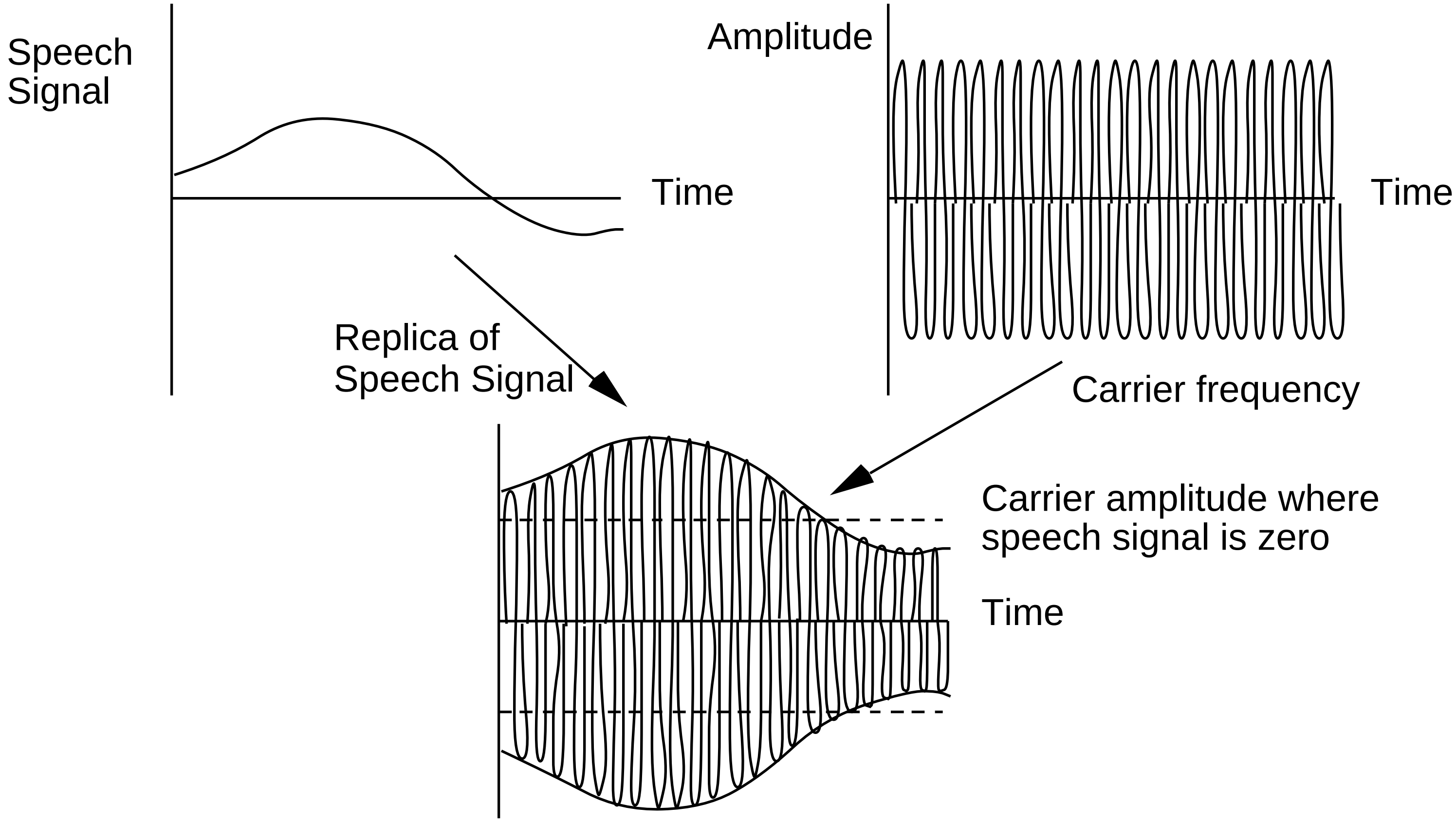
Radio Basics

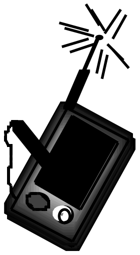




Radio Basics

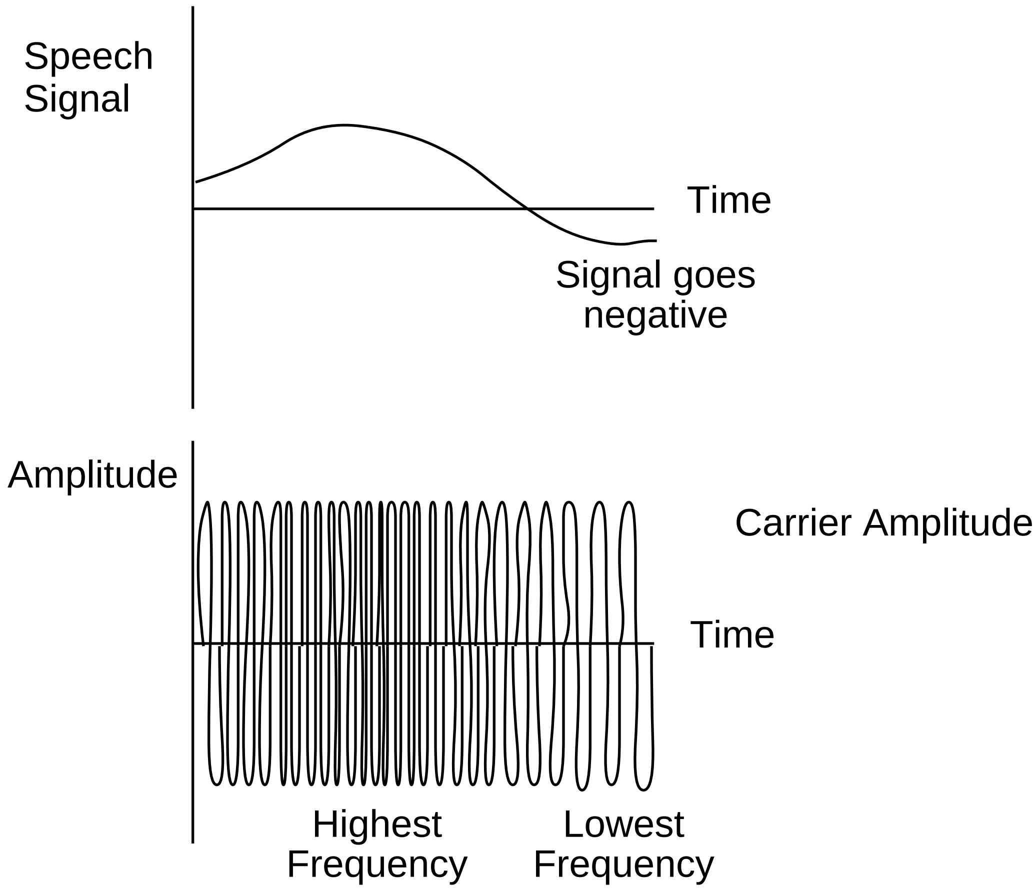
Amplitude Modulation (AM)

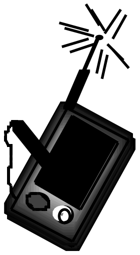




Radio Basics

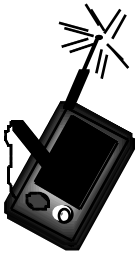
Frequency Modulation (FM)





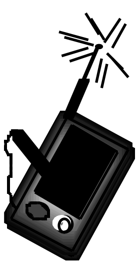
Digital Modulation Techniques

- **Carrier wave s:**
  - **$s(t) = A(t) * \cos[\Theta(t)]$**
  - **Function of time varying amplitude A and time varying angle Θ**
- **Angle Θ rewritten as:**
  - **$\Theta(t) = \omega_0 + \varphi(t)$**
  - **ω_0 radian frequency, phase $\varphi(t)$**
- **$s(t) = A(t) \cos[\omega_0 t + \varphi(t)]$**
  - **ω radians per second**
  - **relationship between radians per second and hertz**
    - » $\omega = 2 \pi f$



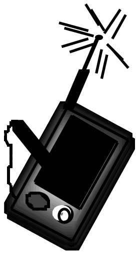
Digital Modulation Techniques

- **Demodulation**
  - Process of removing the carrier signal
- **Detection**
  - Process of symbol decision
  - Coherent detection
    - » Receiver users the carrier phase to detect signal
    - » Cross correlate with replica signals at receiver
    - » Match within threshold to make decision
  - Noncoherent detection
    - » Does not exploit phase reference information
    - » Less complex receiver, but worse performance



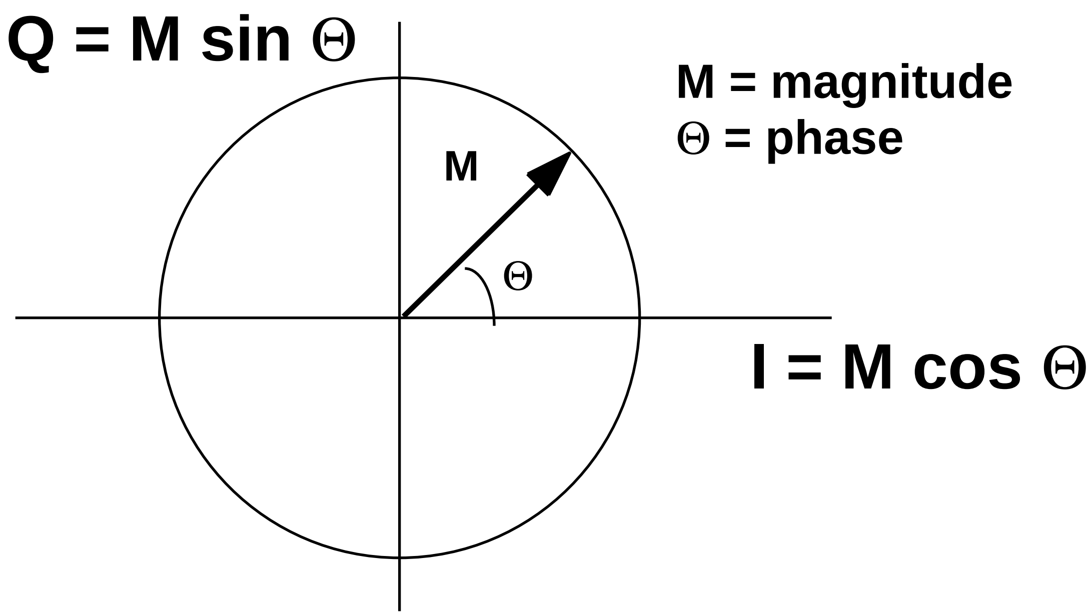
Digital Modulation Techniques

Coherent	Noncoherent
Phase shift keying (PSK)	FSK
Frequency shift keying (FSK)	ASK
Amplitude shift keying (ASK)	Differential PSK (DPSK)
Continuous phase modulation (CPM)	CPM
Hybrids	Hybrids



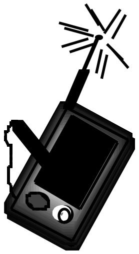
Digital Modulation Techniques

- **Modify carrier's amplitude and/or phase (and frequency)**
- **Vector notation/polar coordinates:**



Considerations in Choice of Modulation Scheme

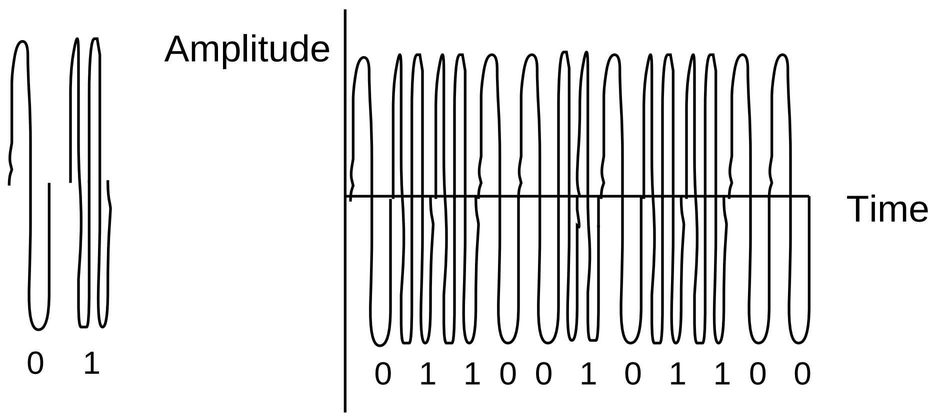
- High spectral efficiency
- High power efficiency
- Robust to multipath effects
- Low cost and ease of implementation
- Low carrier-to-cochannel interference ratio
- Low out-of-band radiation
- Constant or near constant envelope
  - Constant: only phase is modulated
  - Non-constant: phase and amplitude modulated

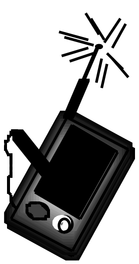


Binary Modulation Schemes

- **Amplitude Shift Keying (ASK)**
  - Transmission on/off to represent 1/0
  - Note use of term “keying,” like a telegraph key
- **Frequency Shift Keying (FSK)**
  - 1/0 represented by two different frequencies slightly offset from carrier frequency

Frequency Shift Keying (FSK)

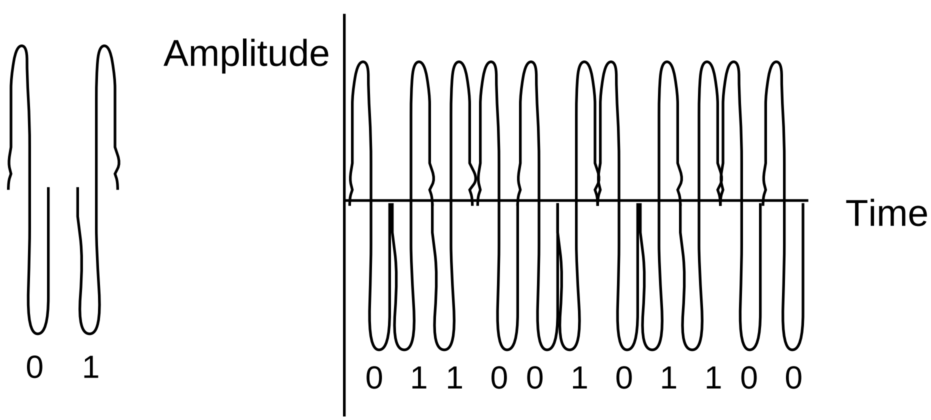


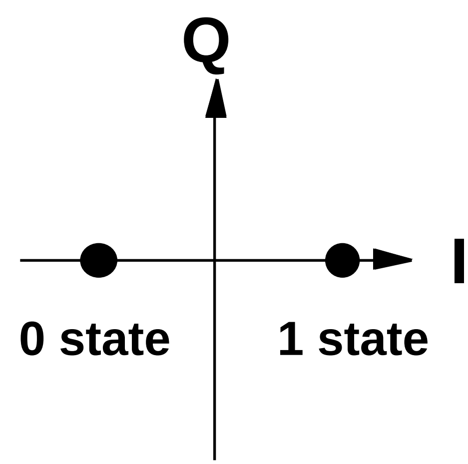


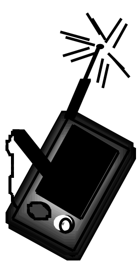
Phase Shift Keying

- **Binary Phase Shift Keying (BPSK)**
  - **Use alternative sine wave phase to encode bits**
  - **Simple to implement, inefficient use of bandwidth**
  - **Very robust, used extensively in satellite communications**

Binary Phase Shift Keying (BPSK)



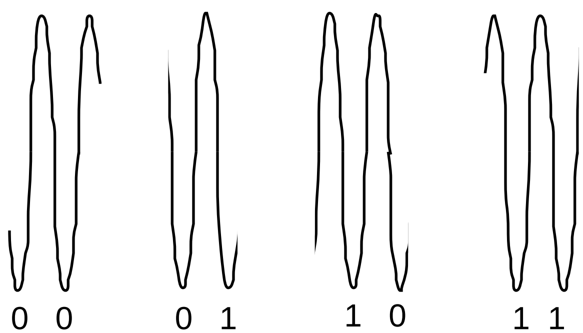


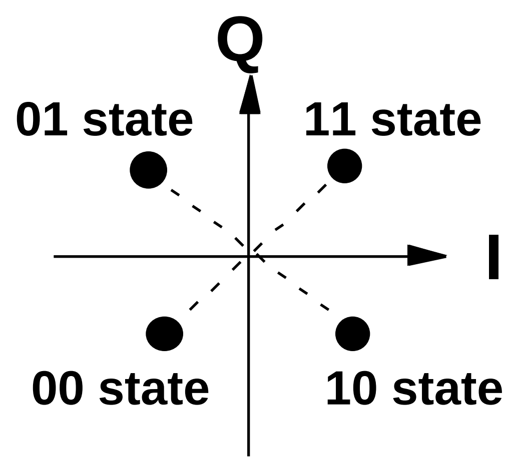


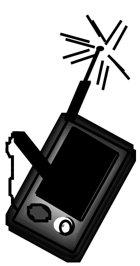
Phase Shift Keying

- **Quarternary Phase Shift Keying (QPSK)**
  - **Multilevel modulation technique: 2 bits per symbol**
  - **More spectrally efficient, more complex receiver**

Quarternary Phase Shift Keying (QPSK)



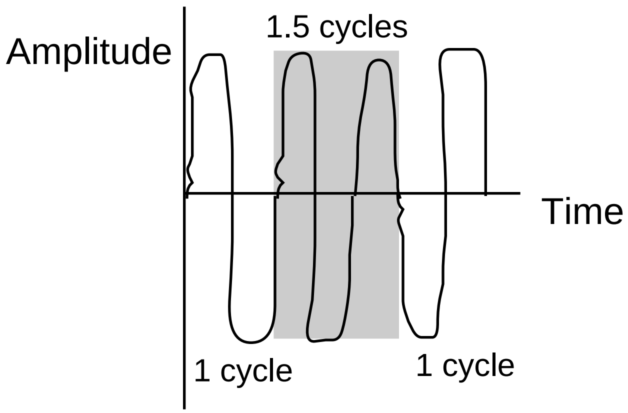


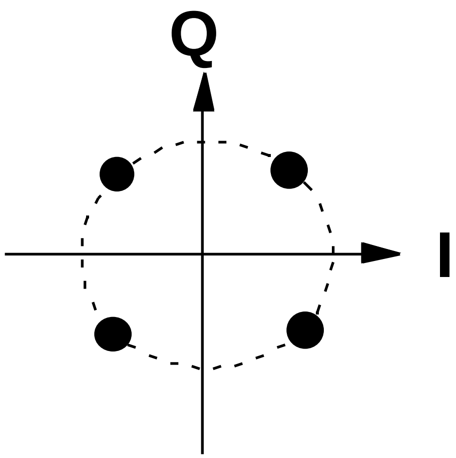


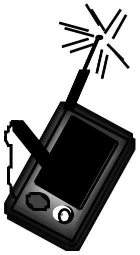
Minimum Shift Keying

- **Special form of frequency shift keying**
  - **Minimum spacing that allows two frequencies states to be orthogonal**
  - **Spectrally efficient, easily generated**

Minimum Shift Keying (MSK)

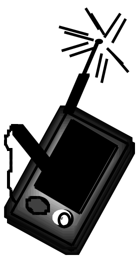






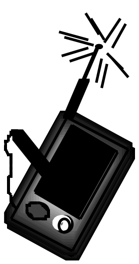
Gaussian Minimum Shift Keying (GMSK)

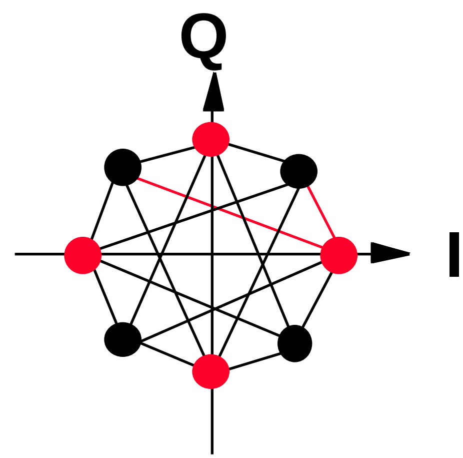
- MSK + premodulation Gaussian low pass filter
- Increases spectral efficiency with sharper cutoff
- Used extensively in second generation digital cellular and cordless telephone applications
  - GSM digital cellular: 1.35 bps/Hz
  - DECT cordless telephone: 0.67 bps/Hz
  - RAM Mobile Data



π/4-Shifted QPSK

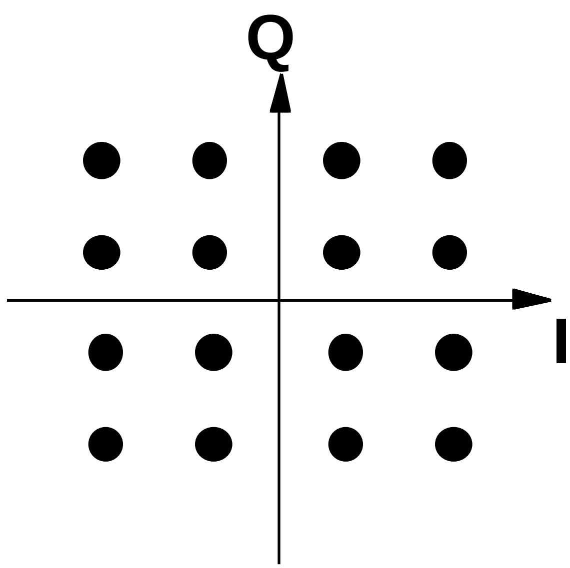
- **Variation on QPSK**
  - Restricted carrier phase transition to +/- π/4 and +/- π/4
  - Signaling elements selected in turn from two QPSK constellations, each shifted by π/4
- **Popular in Second Generation Systems**
  - North American Digital Cellular (IS-54): 1.62 bps/Hz
  - Japanese Digital Cellular System: 1.68 bps/Hz
  - European TETRA System: 1.44 bps/Hz
  - Japanese Personal Handy Phone (PHP)



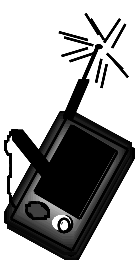


Quadrature Amplitude Modulation

- Quadrature Amplitude Modulation (QAM)
  - Amplitude modulation on both quadrature carriers
  - 2^n discrete levels, n = 2 same as QPSK
- Extensive use in digital microwave radio links



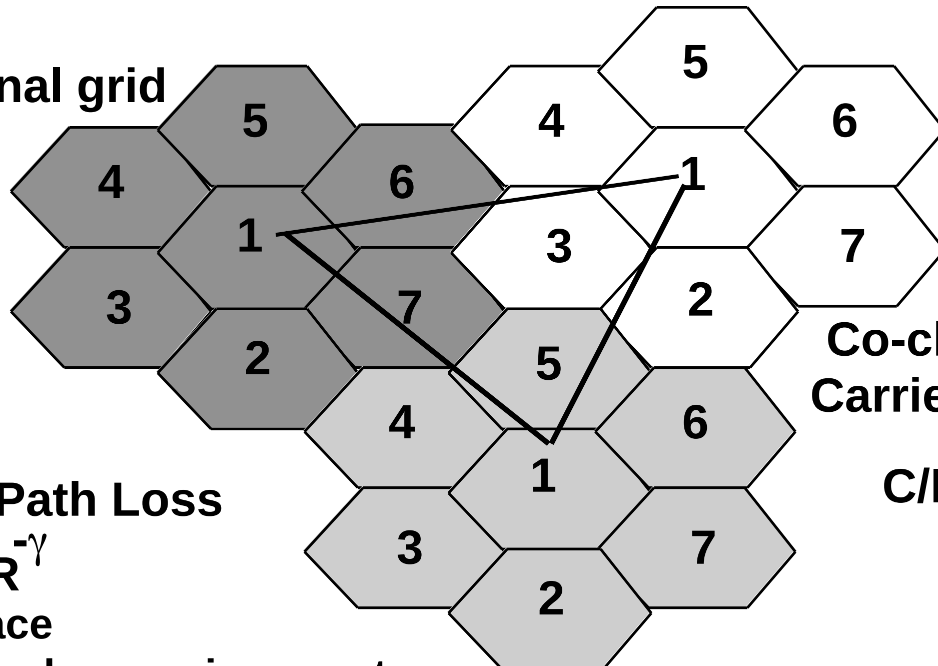
16 Level QAM



Cellular Concept

- **Frequency Reuse (N = 7)**

Ideal hexagonal grid

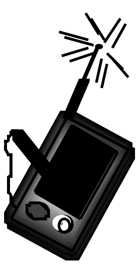


Propagation Path Loss

$$C \approx R^{-\gamma}$$

γ = 2, free space

γ = 5.5, dense urban environment



Co-channel Interference

Carrier-Interference Ratio

$$C/I = \frac{1}{\sum_{k=1}^{N} \left[\frac{D_k}{R}\right]^{-\gamma}}$$

Reuse Radius (D_k) **Cell Radius** (R)

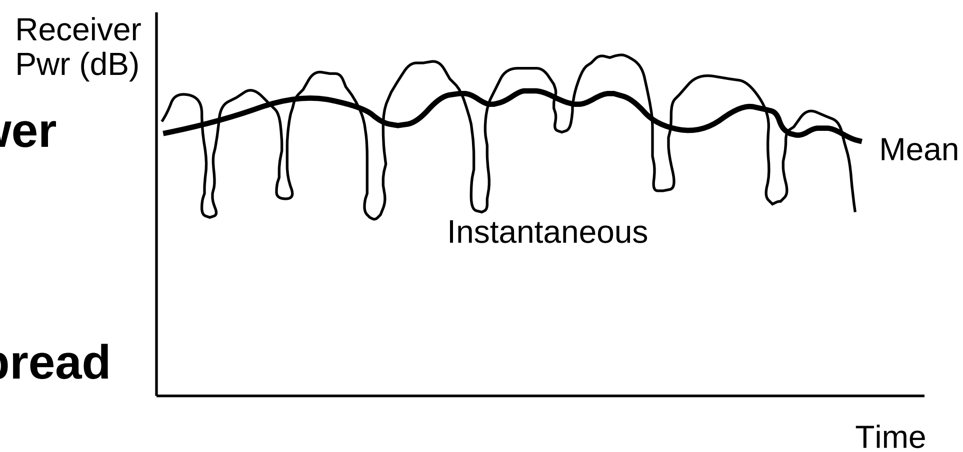
18 dB rule of thumb

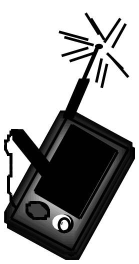
Effect of Mobility on Communications Systems

- **Physical Layer**
  - **Channel varies with user location and time**
  - **Radio propagation is very complex**
    - » **Multipath scattering from nearby objects**
    - » **Shadowing from dominant objects**
    - » **Attenuation effects**
    - » **Results in rapid fluctuations of received power**

Less variation the slower you move

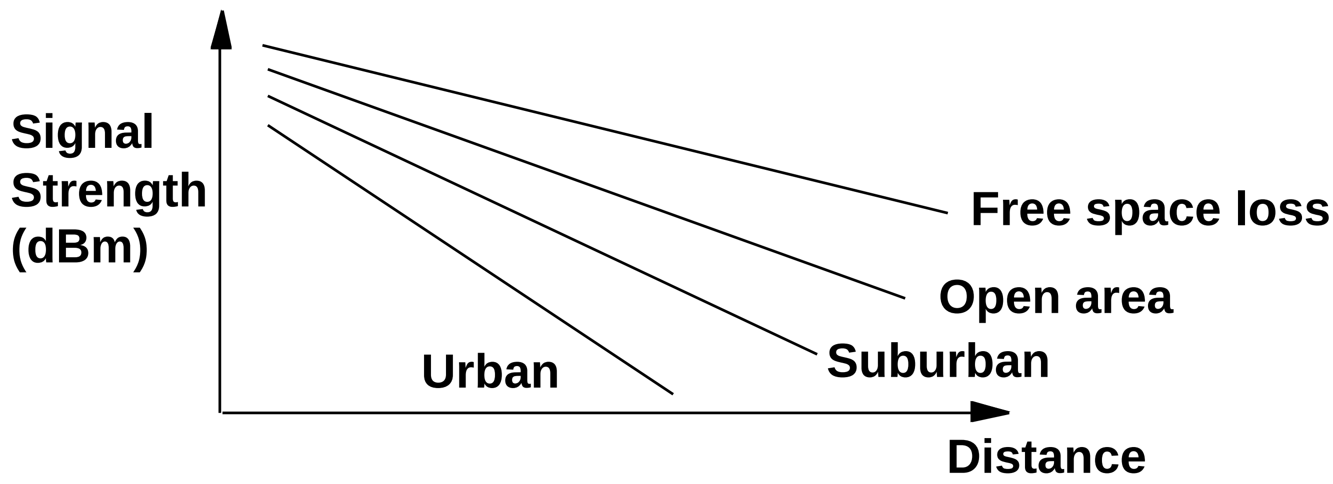
For cellular telephony:
-30 dB, 3 μsec delay spread





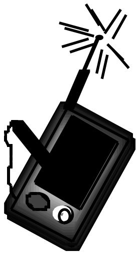
Effect of Mobility on Communications Systems

- **Outdoor Radio Propagation**



BER = *f*(signal stength)

Error rates increase as SNR decreases



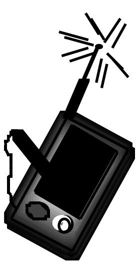
Effect of Mobility on Communications Systems

- Indoor Propagation
  - Signal decays much faster
  - Coverage contained by walls, etc.
  - Walls, floors, furniture attenuate/scatter radio signals
- Path loss formula:

Path Loss = Unit Loss + 10 n log(d) = k F + I W

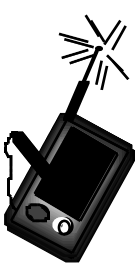
where:

Unit loss = power loss (dB) at 1m distance (30 dB)
n = power-delay index (between 3.5 and 4.0)
d = distance between transmitter and receiver
k = number of floors the signal traverses
F = loss per floor
I = number of walls the signal traverses
W = loss per wall



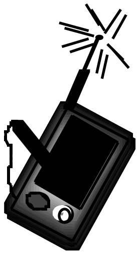
Outdoor Propagation Measurements

- Urban areas
  - RMS delay spread: 2 μsec
  - Min 1 μsec to max 3 μsec
- Suburban areas
  - RMS delay: 0.25 μsec to 2 μsec
- Rural areas
  - RMS delay: up to 12 μsec
- GSM example
  - Bit period 3.69 μsec
  - Uses adaptive equalization to tolerate up to 15 μsec of delay spread (26-bit Viterbi equalizer training sequence)



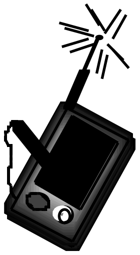
Outdoor-to-Indoor Measurements

- **Penetration/"Building Loss"**
  - Depends on building materials, orientation, layout, height, percentage of windows, transmission frequency
- **Rate of decay/distance power law: 3.0 to 6.2, with average of 4.5**
- **Building attenuation loss: between 2 dB and 38 dB**



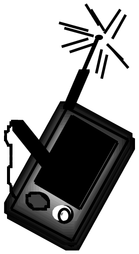
Indoor Measurements

- **Signal strength depends on**
  - Open plan offices, construction materials, density of personnel, furniture, etc.
- **Path loss exponents:**
  - Narrowband (max delay spread < bit period)
    - » Vary between 2 and 6, 2.5 to 4 most common
    - » Wall losses: 10 dB to 15 dB
    - » Floor losses: 12 dB to 27 dB
  - Wideband (max delay spread > bit period)
    - » Delay spread varies between 15 ns and 100 ns
    - » Can vary up to 250 ns



Error Mechanisms

- **Error Burst**
  - Results of fades in radio channels
    - » Doppler induced frequency/phase shifts due to motion can also cause loss of synchronization
    - » Errors increase as bit period approaches delay spread
  - Region of consecutive errors followed by stream of consecutive error-free bits
    - » Voice communication: 10^{-3} BER, 1 error bit in 1000
    - » Data communications: 10^{-6} BER, 1 error in 1,000,000



Error Mechanisms

- **Average Duration of a Fade**

$$\text{ADF} = \frac{\sqrt{2\pi}\,[e^{R^2} - 1]}{\beta\, v\, R}$$

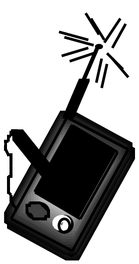
Fade depth (ratio of RMS in dB)

Depends on *f*

Speed of mobile (m/s)

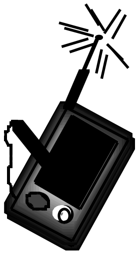
- **Some examples:**
  - 900 MHz, 50 km/hr -- undergoes ave fade depth of 20 dB
  - ADF = 0.962 ms

  - 0.5 m/s, ADF becomes 26.7 ms
  - Portables reside in fades for much longer time periods
  - Renders FEC techniques inoperative



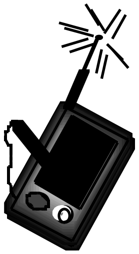
Error Mechanisms

- **Strategies for Overcoming Errors**
  - Antenna diversity (+10 dB)
    - » Dual antennas placed a λ / 2 separation
  - Forward error correction (FEC)
    - » Improve fade margin through coding gain
    - » Coding gain = signal energy per bit-to-noise ratio required to attain a particular error rate with and without coding
    - » Not very effective in slowly varying radio channels
    - » Block vs. Convolutional Codes, Interleaved vs. Non-Interleaved
  - Automatic Repeat Request (ARQ)
    - » Retransmission protocol for blocks in error
    - » Stop and Wait, Go Back N, Selective Repeat



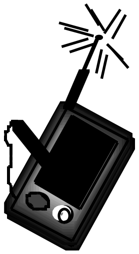
Effect of Mobility on Communications Systems

- **Data Link Layer**
  - Fading radio channels, characterized by burst errors
  - Reliable communications interrupted by fades
- **Network Layer**
  - Rerouting due to movement
- **Presentation Layer**
  - Source coding for better spectrum efficiency
- **Application Layer**
  - Location dependent applications



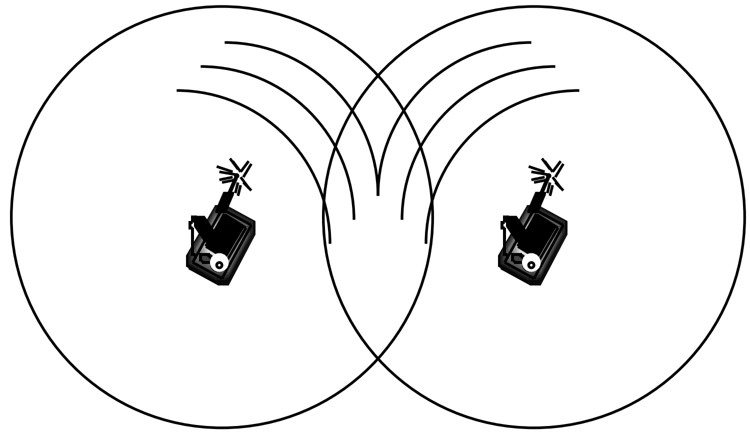
Media Access

- **Aloha**
  - Transmit when desired
  - Positive ACK from receiver on independent link
  - Back off and retransmit if timeout
  - Slotted scheme reduces chance of collision
- **Carrier Sense/Multiple Access (CSMA)**
  - Listen before transmit
  - Back off and retransmit if collision detected
- **Inhibit Sense/Multiple Access**
  - Base station transmits busy tone
  - Transmit when not busy
  - Back off and retransmit if collision

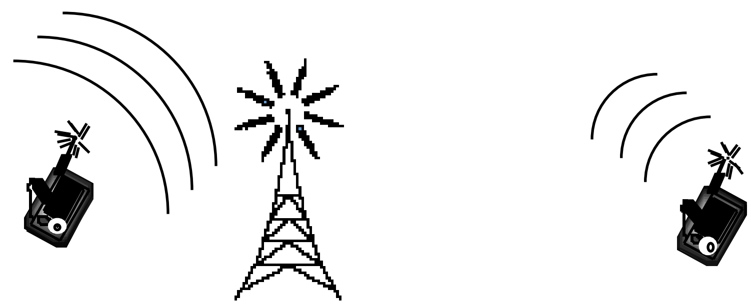


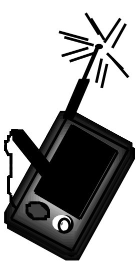
Media Access

- **Hidden Terminals**
  - Cannot hear each other
  - Adds complexity to carrier sense methods



- **Near-Far Problem**
  - Near-by terminal over powers signal from the far-away terminal
  - Unfair access to channel



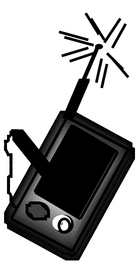


Time Division Multiple Access

- **Multiple users share channel through time allocation scheme**

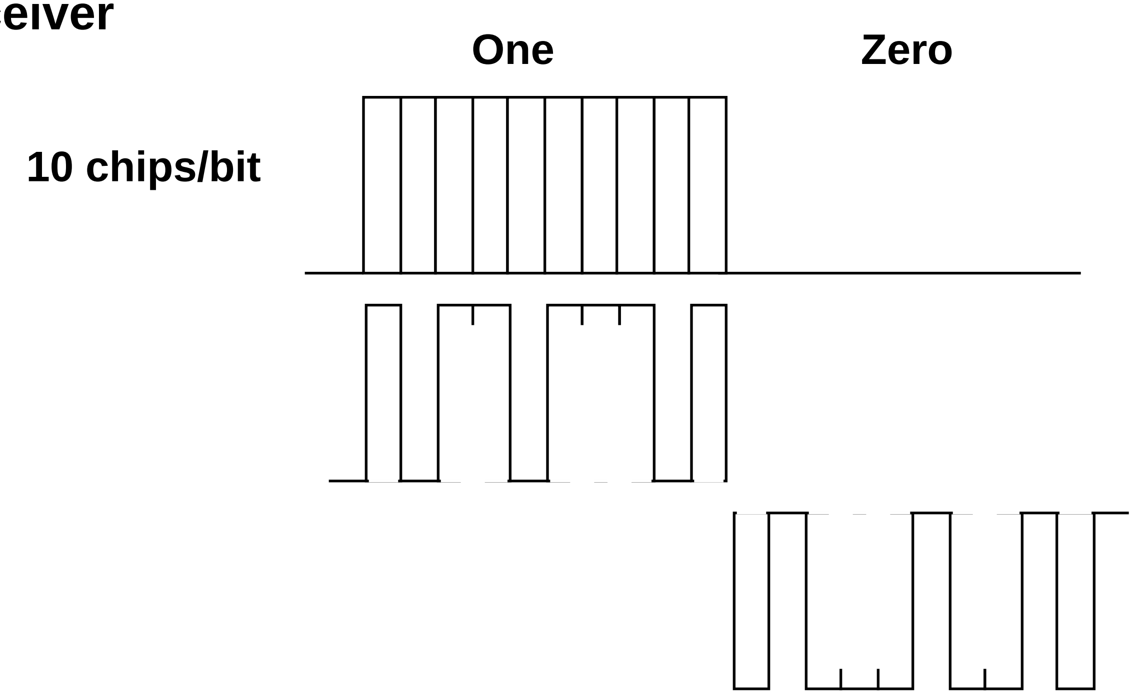
1	2	…	N	1	2	…

- **Reuse in time, often combined with reuse in frequency (e.g., GSM, IS-54)**



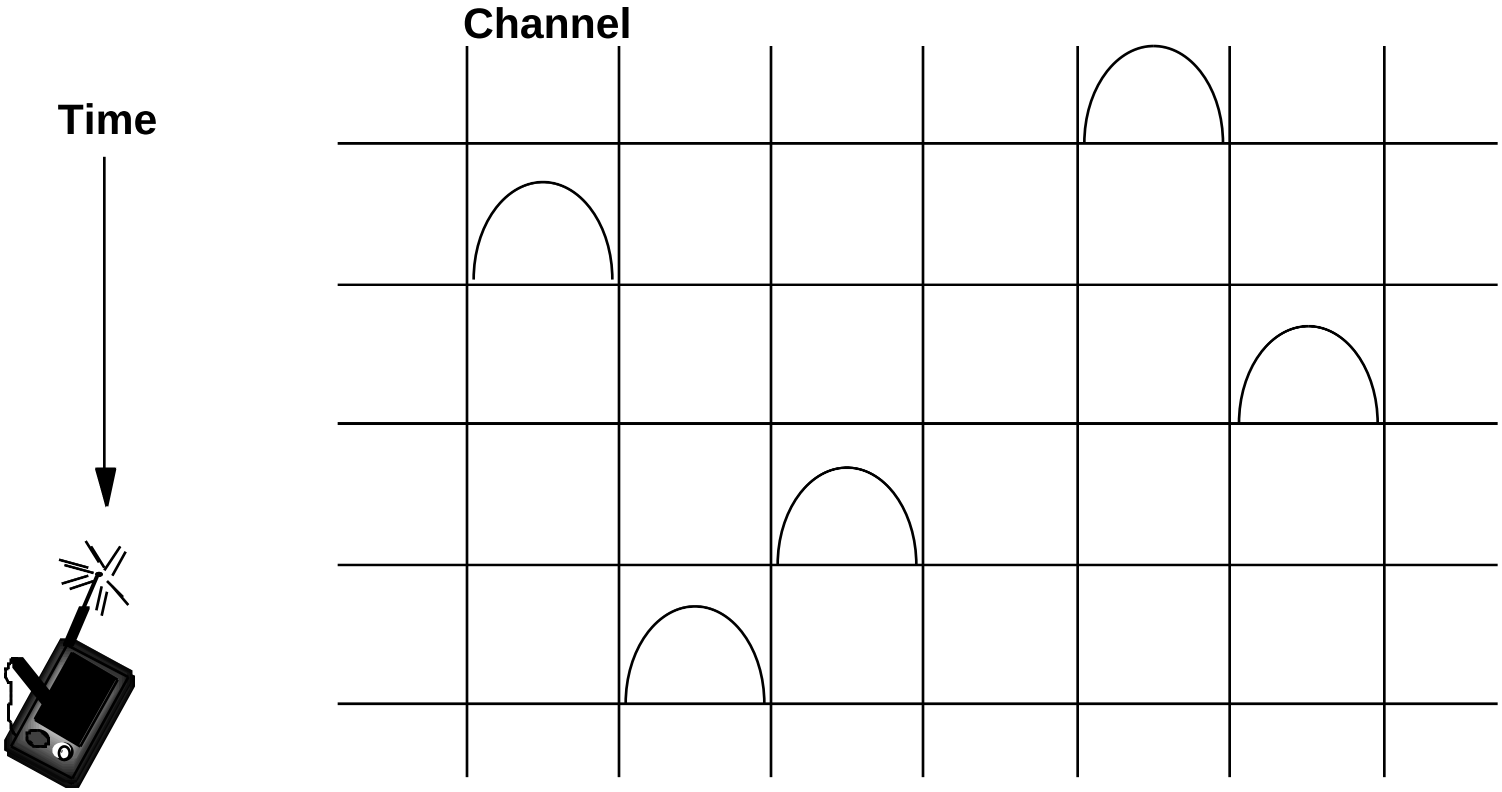
Spread Sprectrum

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



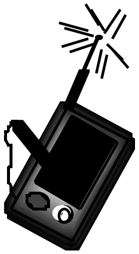
Spread Spectrum

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

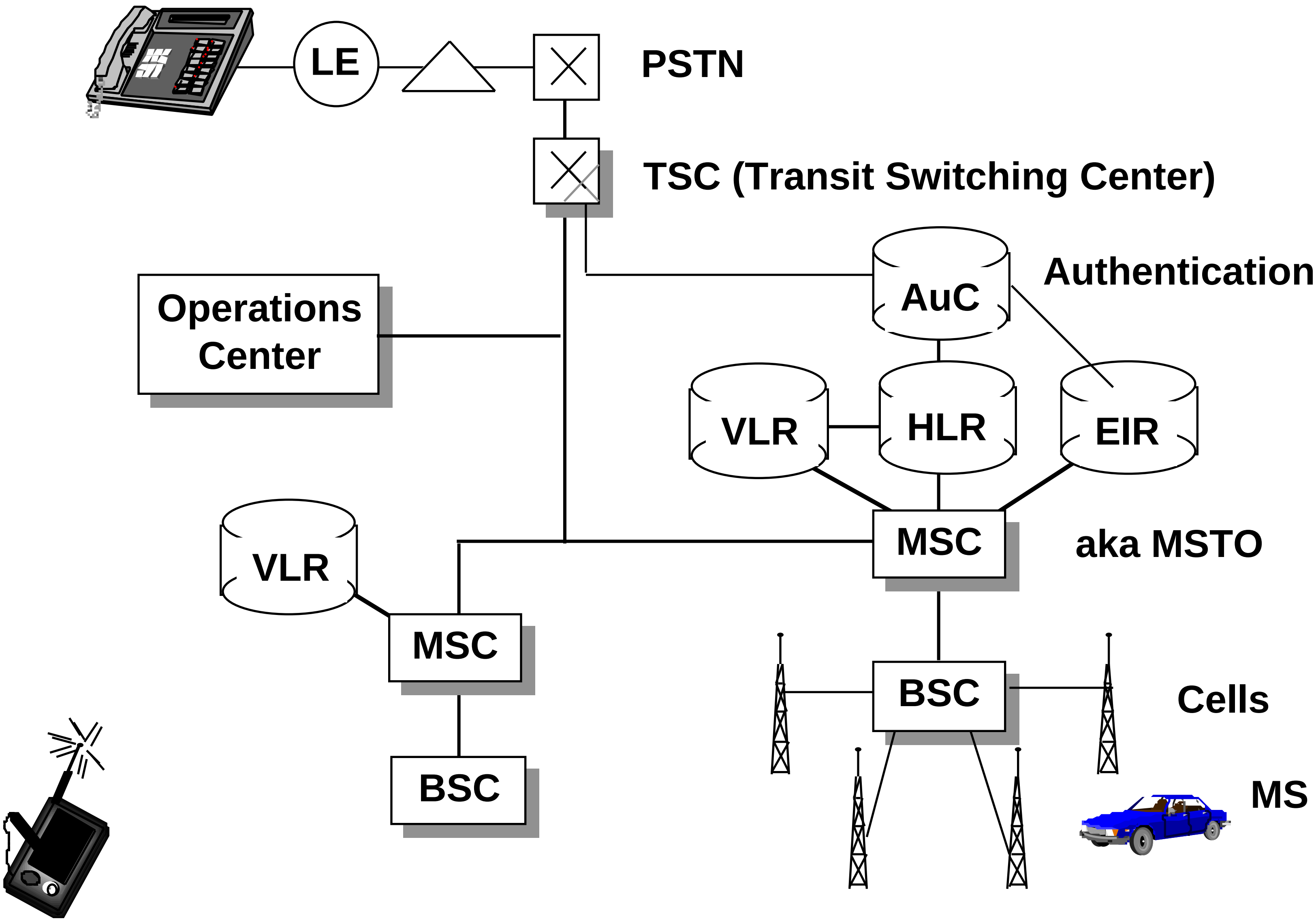


Code Division Multiple Access

- 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
- Developed by Qualcomm as IS-95
  - Special soft handoff capability



Cellular Phone Systems



North American Analog Cellular System (AMPS)

Mobile XMIT

824.04 825.03 835.02 845.01 846.51

A' 33 CHs	A 333 Channels	A Cntl	B Cntl	B 333 Channels	A' 50 CHs	B' 83 CHs

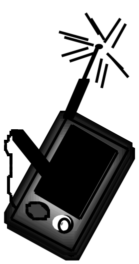
869.04 870.03 880.02 890.01 891.51

Base XMIT

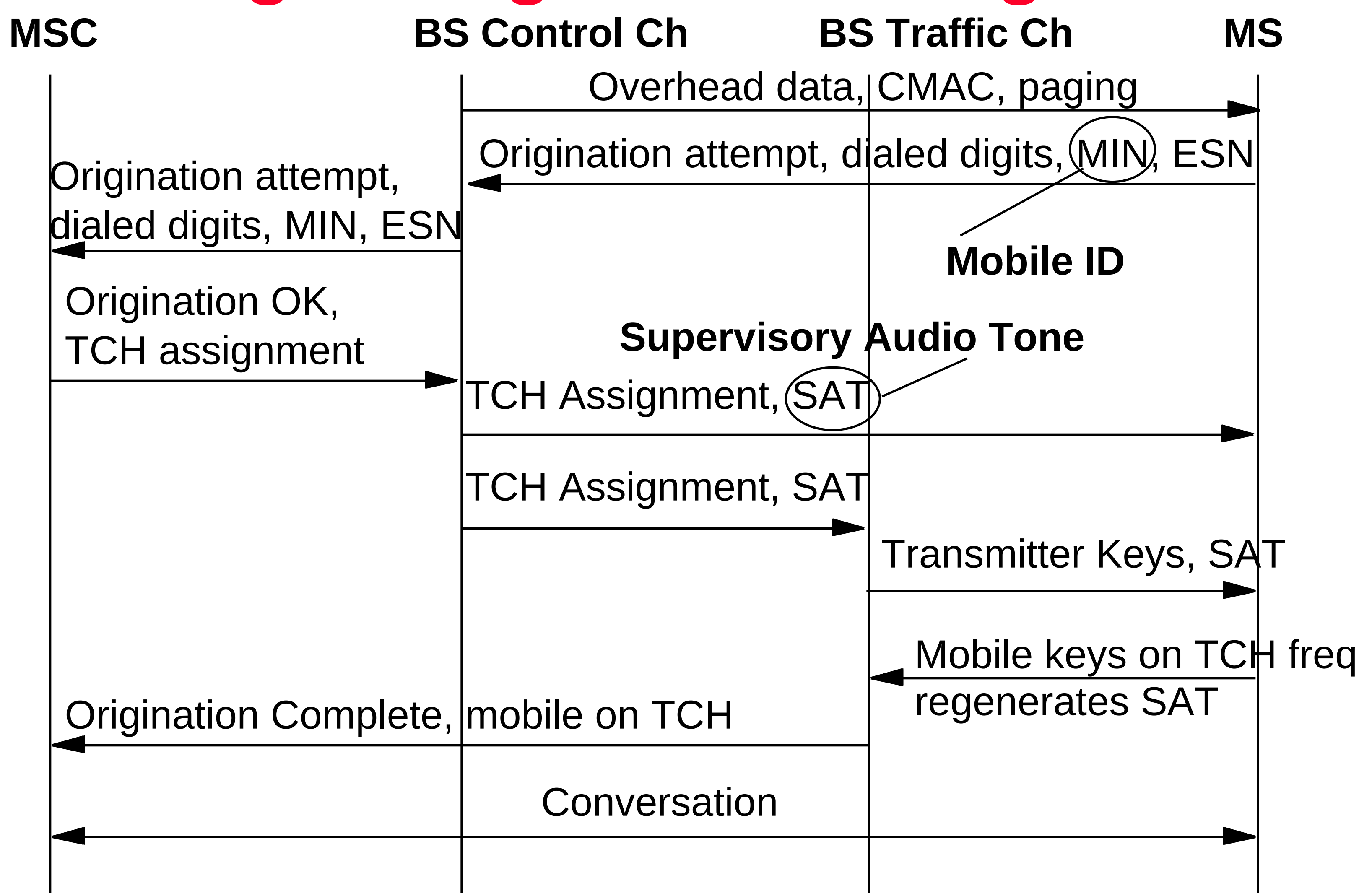
416 30 KHz channels for each of two operators (B wireline)

Traffic Control Channels (TCH):
21 reserved control channels in each band

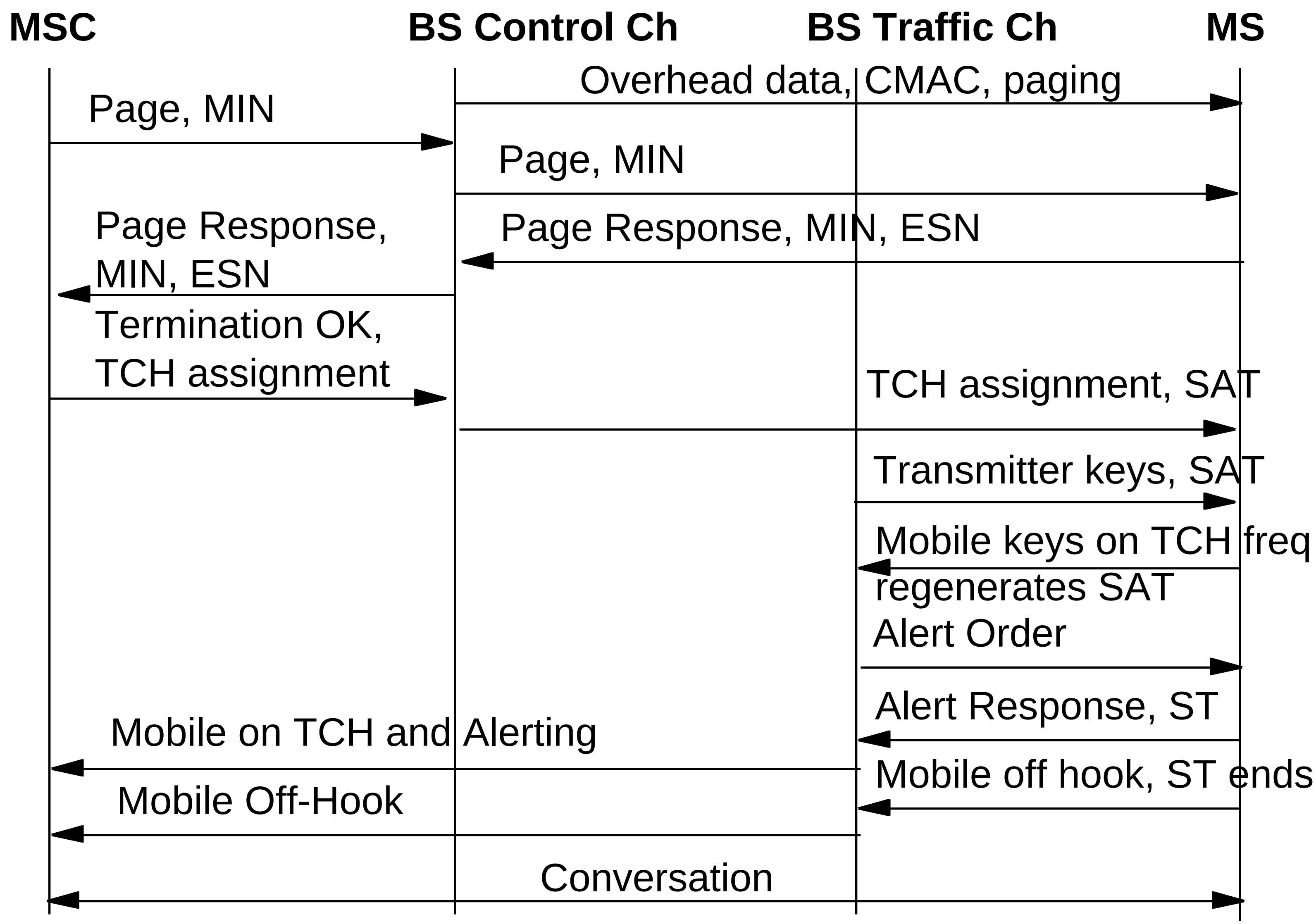
In-band Signaling Tones (e.g., disconnect, RTS dialed digits, Ack handoff order, Alert, measured in 50-1800 ms)

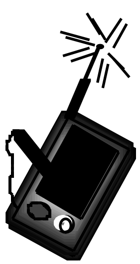


AMPS Signalling: Mobile Origination

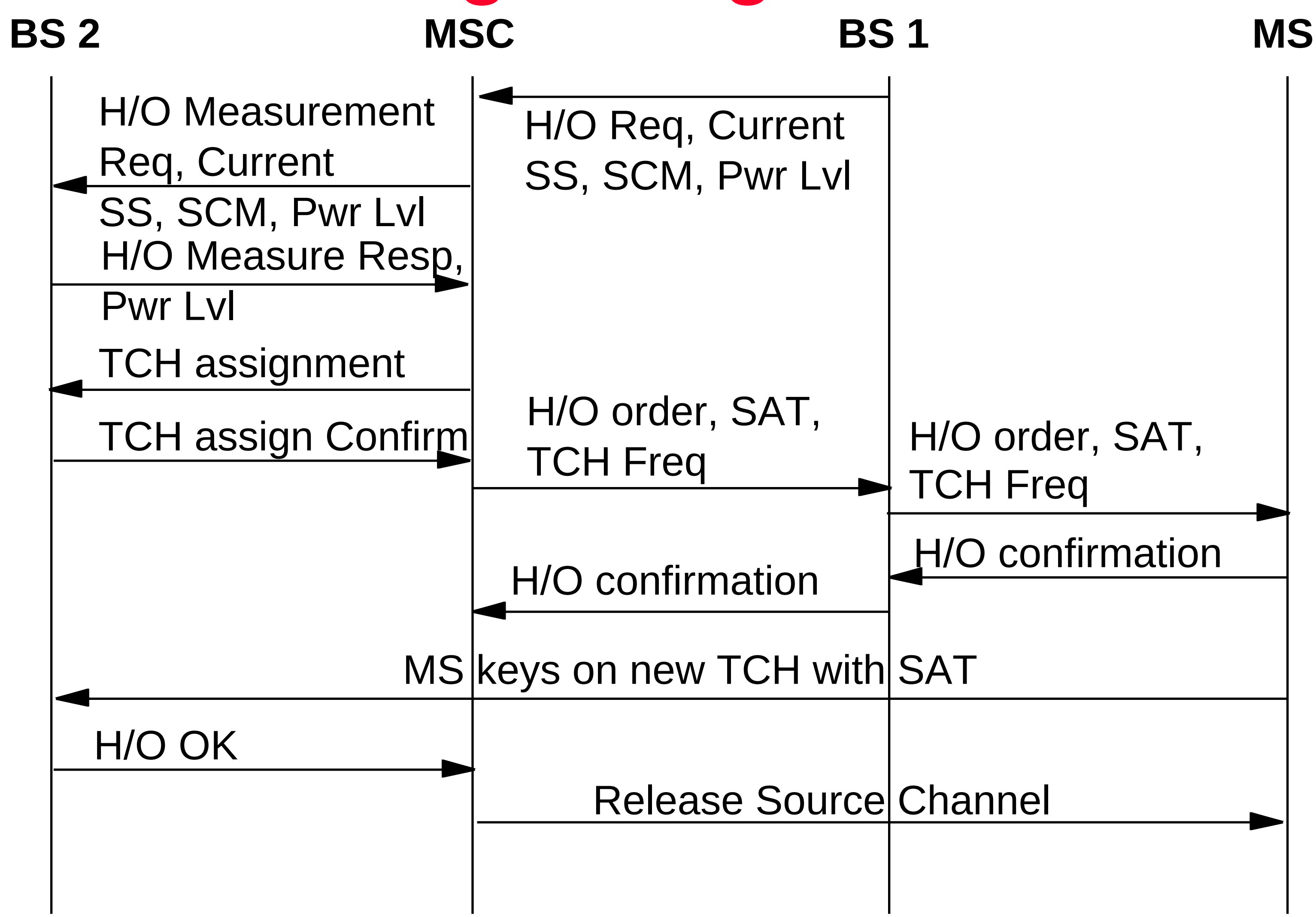


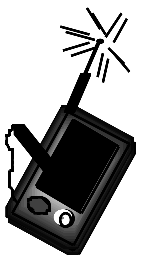
AMPS Signalling: Mobile Termination



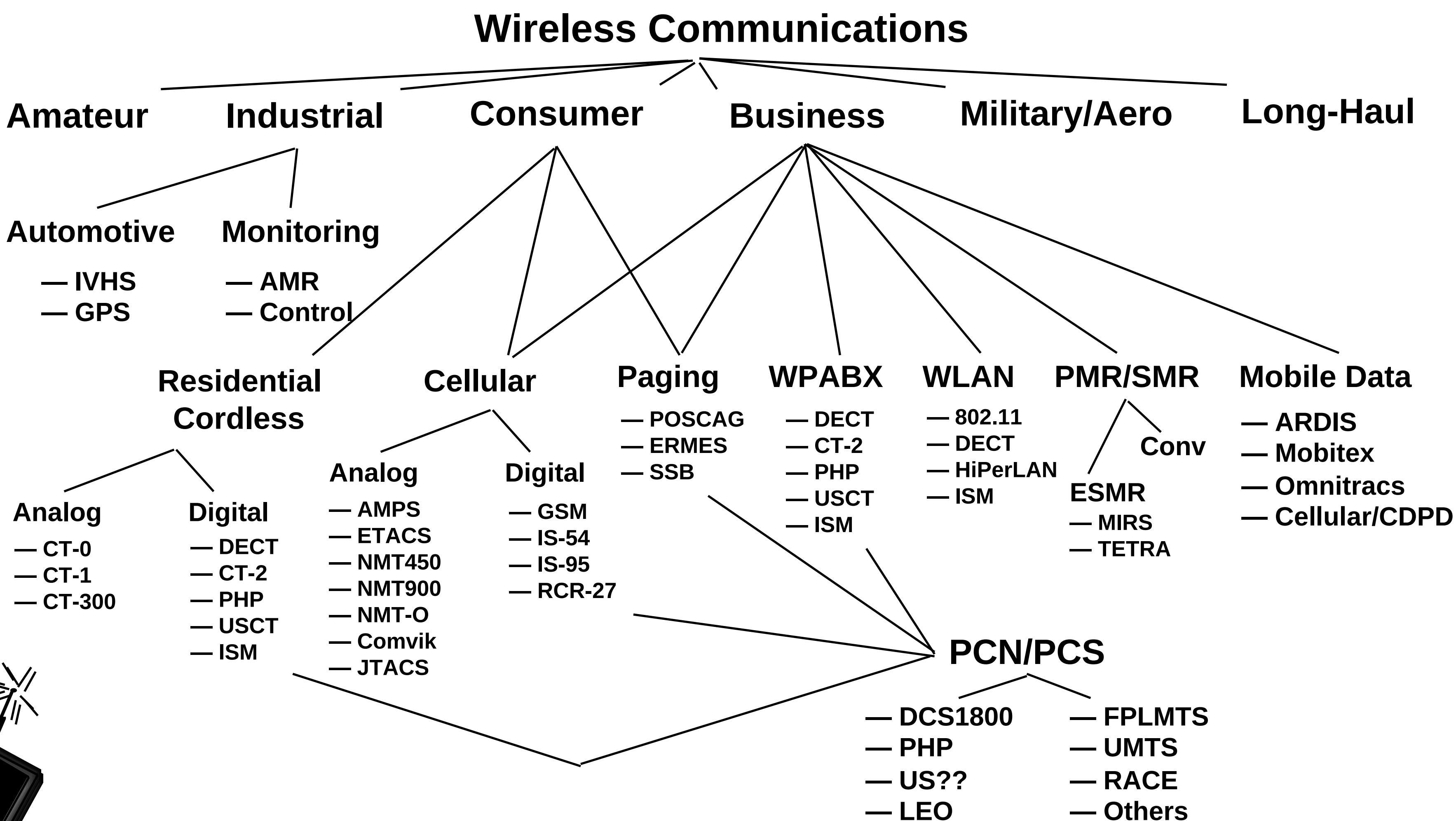


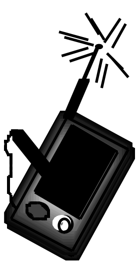
AMPS Signalling: Handoff





The Wireless Universe





Wireless Spectrum