Mobile Communication Systems

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September 1999

Summary of Course

- Overview of Wireless/Mobile Communications
- Physical Layer
- Multiple Access & Cell-Planning
- Overview of Existing/Developing Systems

OVERVIEW OF WIRELESS/MOBILE COMMUNICATIONS

Overview: Topics

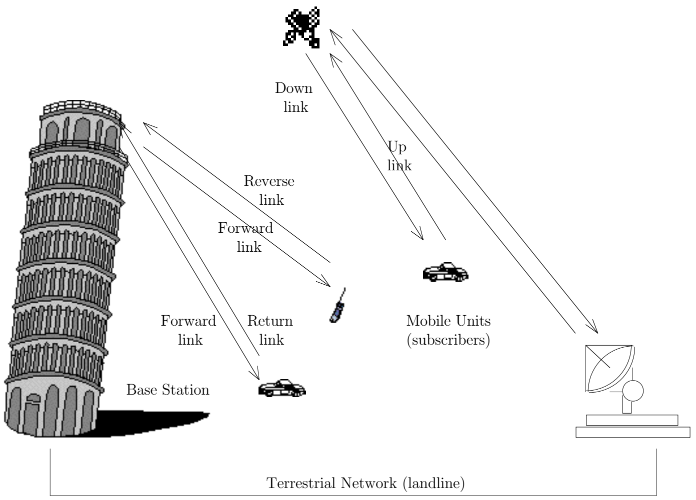
- Characteristics to Specify a System
- Summary of Wireless Systems
- Special Challenges:
  - Mobility
  - Multiple Access
  - Multimedia Sources
- Characterizing the Efficiency (capacity) of a system

Characteristics

- **Carrier Frequency:**
  - Cellular: ∼ 900 MHz
  - Personal Communication Systems: ∼ 2 GHz
  - Wireless LAN: ∼ 2.4 GHz, 5.2 GHz
  - Fixed-Point Wireless (LMDS): ∼ 30-40 GHz
  - Satellite: ∼ 15 GHz
- **RF Channel Bandwidth**
- **Services Provided**
  - Paging
  - High-rate video/data (delay tolerant)
  - Interactive services (*e.g.*, Voice)

Characteristics

- **Simplex vs. Duplex**
  - Time Division Duplexing (TDD)
  - Frequency Division Duplexing (FDD)



Characteristics: Mobility vs. Fixed-Point

- **Primary Challenges of Mobility**
  - *Physical Layer:* Channel impairments (*i.e.*, the SNR, distortion effects, interference characteristics, etc.) will all vary significantly with time/location
    - ∗ *e.g.*, Dense multipath fading can yield fluctuations in received power of 20-30 dB (100 to 1000) in several meters of motion for a 1 GHz carrier.
  - *Network Layer:* Tracking user locations for incoming/outgoing calls, spatial traffic loading is highly nonuniform and time-dependent
    - ∗ *e.g.*, Bulk of urban users are located on highways/railways during commuting hours

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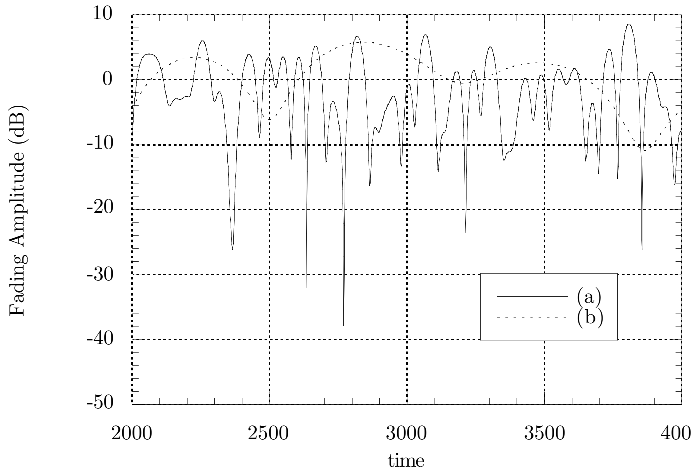
Effect of Mobility on SNR

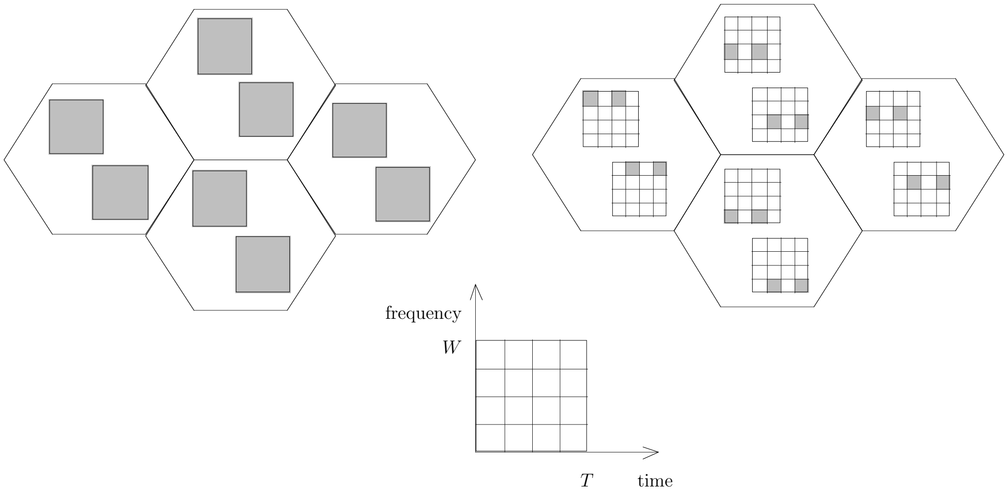


- Two reasonable SNR variations of a GSM user (in symbol times)

Characteristics: Multiple Access vs. Single-User

- **General View of Multiple Access**
  - *Dimensionality of a Signaling Format:* $d = 2WT$
    - W is the bandwidth used in Hz
    - T is the time duration (*e.g.*, symbol time) used
    - *Increasing d:* improved performance against non-AGWN channel impairments: multipath fading, like-signal interference, etc.
  - *Spatial Component:* In most systems of interest, total system resources can be **re-used** in space
- **Challenge:** Design signals, protocols, and spatial cell plans that maximize the "capacity"

Two Approaches to using T-F Dimensions in Space



- Left is comparable to CDMA, right is comparable to TDMA/FDMA

Measuring Multiple Access Capacity/Efficiency

- **Bandwidth Efficiency:** η_W
  - How many bits/sec in each Hz is achieved for each individual user?
- **Spatial Efficiency:** η_S
  - How often are the available resources (*i.e.*, bandwidth) re-used in a large area?
- **Trunking (Traffic) Efficiency:** η_T
  - How well are the system resources allocated/matched to the user requirements?
- **Overall Efficiency:** $\eta = \eta_W \eta_S \eta_T$ in Erlangs/sq-m/Hz
  - For a given total system bandwidth W_{sys} and system area A_{sys}, then the total capacity is

$$C_{sys} = \eta W_{sys} A_{sys}$$

Capacity/Efficiency Improvement Methods

- **Bandwidth Efficiency:**
  - Bandwidth efficient modulation, coding, and diversity techniques
- **Spatial Efficiency:**
  - Smaller cells and tighter reuse
- **Trunking (Traffic) Efficiency:**
  - Dynamic channel allocation
- **Related Issues:**
  - Coverage vs. capacity
  - Infrastructure cost
  - Overhead for processing (*i.e.*, mobility management, cell coordination, etc.)
  - Power consumption

Classes of Wireless/Mobile Services

- **Fixed Point Wireless Systems:**
  - Wireless Local Loop (WLL)
  - Broadband services (last mile solution) (*e.g.*, LMDS)
  - HDTV
  - Geosynchronous satellite services
  - *Typical characteristics*
    - **Mobility:** Low or none
    - **Sources:** High rate, high reliability, delay tolerant

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Classes of Wireless/Mobile Services

- **Mobile Radio Services**
  - Cellular/PCS
  - Mobile Satellite (LEO/MEO)
  - Paging/text massaging services*
  - *Typical characteristics*
    - **Mobility:** Moderate to high
    - **Sources:** Low rate, low reliability, delay intolerant (except *)

Trend Toward Digital

- **Drivers**
  - Better spectral efficiency
  - More flexible multiple accessing
  - Store and forward capabilities
  - Better security (*i.e.*, encryption)
  - Compact, low-power digital processing
  - Simpler integration of multimedia services

PHYSICAL LAYER

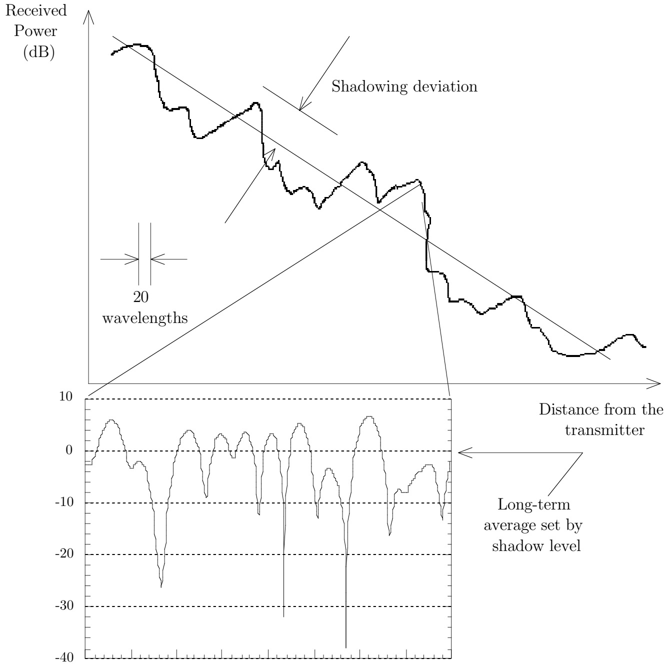
Physical Layer Topics

- **Channel Modeling**
  - Path Loss, Shadowing, and Fading
  - Parameters of channel models
  - Effects of signaling scheme: relative parameters
- **Signaling and Diversity**
  - Modulation
  - Effects of fading & diversity
  - Coding/Interleaving
  - Spreading
- **Receiver Processing**
  - The optimal receiver
  - Multipath combining

Typical 3-Level Channel Models

- **Path Loss**
  - Deterministic propagation loss model
  - Large scale
  - Empirically determined from field measurements
- **Shadowing**
  - Statistical model for the deviation from the path loss model
  - Long-term fading – *e.g.*, 10-100 wavelengths
  - Empirically determined from field measurements
- **Fading**
  - Statistical model for short-term (sub-wavelength) power fluctuations
  - Also characterizes the distortion characteristics of the channel
  - Simple analytical models, verified via measurements

Relation Between Three Levels of Channel Models



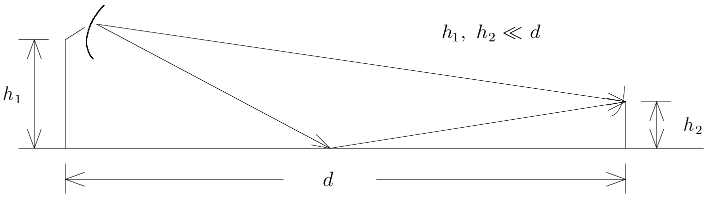
Path Loss Models

- **Free Space:**

$$\frac{P_r(d)}{P_r(d_0)} = \left(\frac{d}{d_0}\right)^{-2}$$

  - Power spread evenly over sphere of radius d

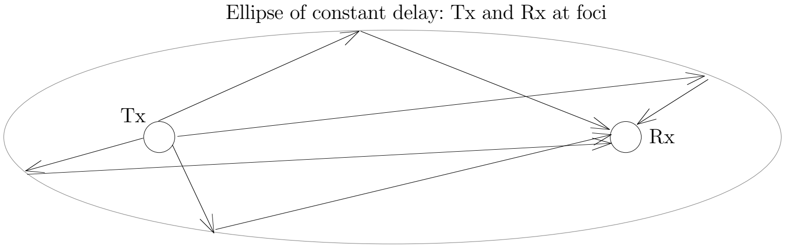
- **Single Ground Reflection:**



$$\frac{P_r(d)}{P_r(d_0)} = \left(\frac{d}{d_0}\right)^{-4}$$

Path Loss Models

- **Multipath Reflection Environments:**



$$\frac{P_r(d)}{P_r(d_0)} = \left(\frac{d}{d_0}\right)^{-\beta}$$

$$\left[\frac{P_r(d)}{P_r(d_0)}\right]_{dB} = -10\beta \log_{10}\left(\frac{d}{d_0}\right)$$

  - β is the *path loss exponent*
    - Typical macrocellular: $\beta \sim 3$ to 4
    - Typical microcellular: $\beta \sim 2$ to 8

Path Loss Models

- **Models are Roughly Frequency Independent**
  - Weak dependency described in more detailed model
  - More difficult to predict in smaller regions (*e.g.*, indoor)
  - Environment specific models: ray-tracing, Manhattan pico cells, etc.
- **Power decays linearly (in dB) with delay**
  - Free space ⇒ 20 dB per decade
  - $\beta \Rightarrow 10\beta$ dB per decade
- **Utility of path loss models:**
  - rough cell planning (*e.g.*, cell size, reuse factors)

Shadowing Models

- Random deviation from path loss model:

$$\frac{P_{r,S}(d;u)}{P_r(d_0)} = \epsilon(u)\frac{P_r(d)}{P_r(d_0)}$$

$$\begin{aligned}\left[\frac{P_{r,S}(d;u)}{P_r(d_0)}\right]_{dB} &= \left[\frac{P_r(d)}{P_r(d_0)}\right]_{dB} + 10\log_{10}\left[\epsilon(u)\right] \\ &= -10\beta\log_{10}\left(\frac{d}{d_0}\right) + \epsilon_{dB}(u)\end{aligned}$$

- **Common Model:** Log-Normal Shadowing

$$\epsilon_{dB}(u) \sim \mathcal{N}(\cdot;0;\sigma^2_{\epsilon_{dB}})$$

  - The received power in dB may be thought of as Gaussian with mean given by the path loss model and variance $\sigma^2_{\epsilon_{dB}}$

- **Shadowing deviation:** $\sigma_{\epsilon_{dB}}$
  - Macrocellular systems have values in the range 5 to 12, with 8 being typical

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Shadowing Models

- **Example:** What's the probability that the received power is less than half the value predicted by the path loss model if $\sigma_{\epsilon_{dB}} = 8$?
  - factor of 1/2 is -3 dB ⇒

$$\begin{aligned}\mathrm{PR}\left\{\epsilon(u) < 1/2\right\} &= \mathrm{PR}\left\{\epsilon_{dB}(u) < -3\right\} \\ &= \mathrm{Q}\left(\frac{3}{8}\right) = 0.35\end{aligned}$$

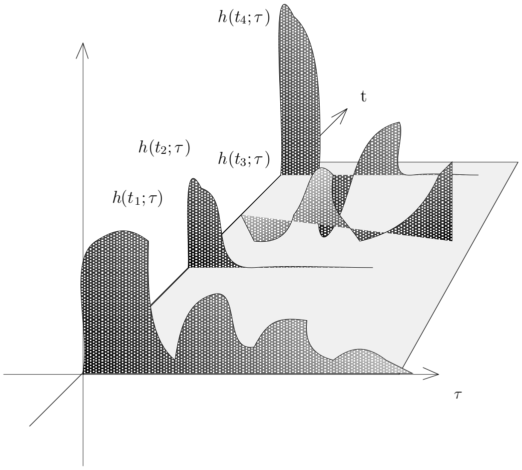
  - 35% of the time, the received power is 3 dB down from the path loss model!

- **Spatial correlation:**
  - Fade level is highly correlated in space
  - Simple first-order Markov models are often used to characterize this correlation

Short-term (multipath) Fading Models

- **Common Model:** random, time-varying linear system
  - Impulse response from a delta applied at time t is $h(u;t;\tau)$

$$y(u,\tau) = h(u;t;\tau) * x(\tau) \quad z(u,\tau) = h(u;t+\delta;\tau) * x(\tau)$$
$$z(u,\tau) \neq y(u,\tau)$$



Short-term (multipath) Fading Models

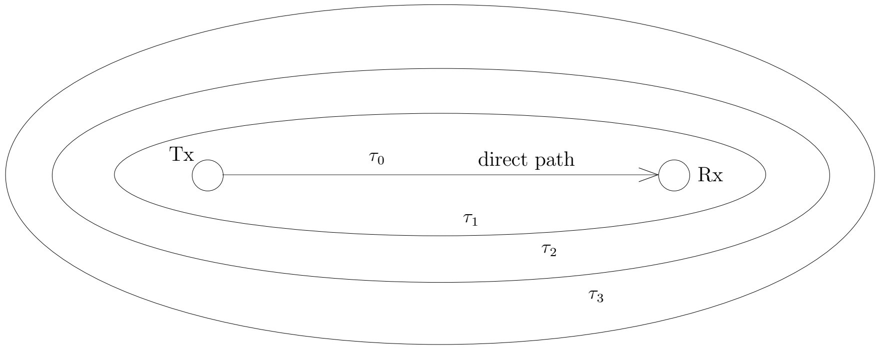
- **Characterizing Distortion:** What is the shape of the impulse response $h(u;t;\tau)$ wrt τ?
  - τ_d: *Delay Spread* – how long does the channel ring from a time impulse?
  - B_c: *Coherence Bandwidth* – over what range of frequencies is the gain of the channel flat?
- **Characterizing Time-variation:** How does $h(u;t;\tau)$ change with t?
  - t_c: *Coherence time* – for what value of Δ are the responses at t and $t+\Delta$ uncorrelated?
  - f_d: *Doppler Spread* – how much will the spectrum of an input tone (*i.e.*, frequency impulse) be spread in frequency?

Short-term (multipath) Fading Models

	Time-variation Properties	Distortion Properties
	variation in t	variation inτ
Time Domain	Coherence Time	Delay Spread
Frequency Domain	Doppler Spread	Coherence Bandwidth

- **Distortion Properties:** $B_c \propto \frac{1}{\tau_d}$
- **Time-variation Properties:** $f_d \propto \frac{1}{t_c}$

Delay Spread



Ellipses of constant delay: Tx and Rx at foci

- **Rule of Thumb:** 1 nanosecond per foot
- **Typical RMS values:**
  - outdoors: 1 to 5 μsec; up to 20 μsec in areas with mountains
  - indoors: $<$ 100 nanosec

WSSUS Assumption

- **Wide Sense Stationary (WSS):**
  - Statistics of $h(u;\tau;t)$ are independent of t
- **Uncorrelated Scatter (US):**
  - Paths with different delays are uncorrelated
- **Gaussian** assumptions also typically follow from dense multipath environments

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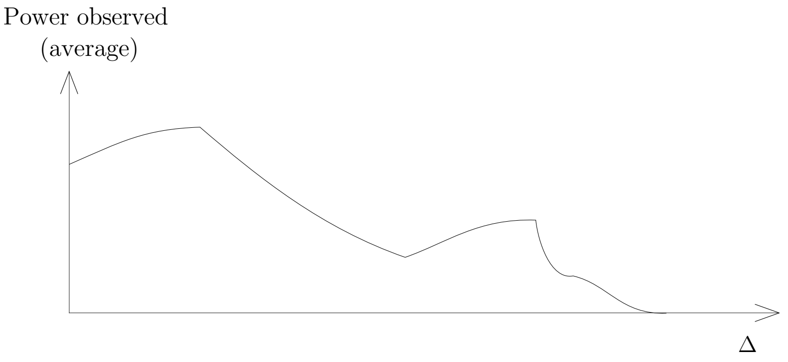
Delay Spread: Details

- **Power Delay (aka Multipath Intensity) Profile:**

$$R_d(\Delta) = \mathbb{E}\left\{h(u;\tau+\Delta;t)h^*(u;\tau;t)\right\}$$

  - RMS value of the delay spread often used
  - B_c is the BW of the spectrum of this process



Time Variations

- **Time correlation:**

$$R_c(\Delta) = \mathbb{E}\left\{h(u;\tau;t)h^*(u;\tau;t+\Delta)\right\}$$

  - $\Delta = t_c$ implies this is zero

- **Doppler Spectrum:** frequency domain version:

$$S_c(f) = \mathbb{E}\left\{H(u;\tau;\nu)H^*(u;\tau;\nu+f)\right\}$$

  - $f > f_d$ implies this is zero

- **Maximum Doppler Spread:**

$$f_d = \frac{v}{c} f_c$$

  - *Example:* at $f_c = 900$ MHz, and 100 Kph, $f_d = 83$ Hz

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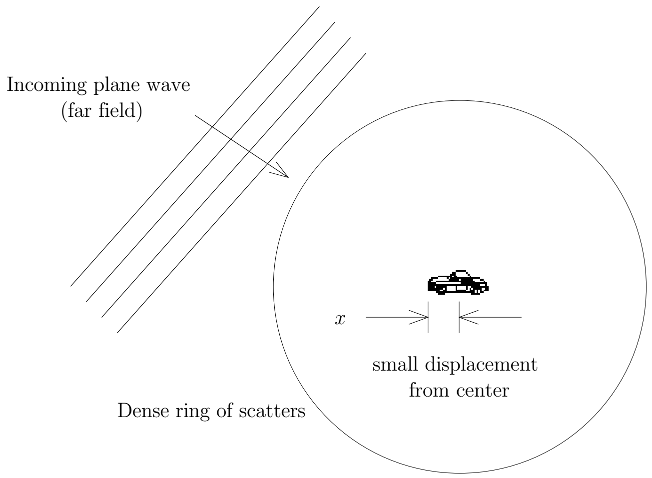
Measures Relative to Signals

- **Does the channel distort the signal?**
  - $W \ll B_c \Rightarrow$ NO $\Rightarrow$ *Flat Fading*
  - $W \geq B_c \Rightarrow$ YES $\Rightarrow$ *Frequency-Selective Fading*
    - **Note:** If $W \cong \frac{1}{T}$, then frequency selective fading implies that $T \leq \tau_d \Rightarrow$ time dispersion or *intersymbol interference (ISI)*
    - Not so for wideband systems – $W \gg \frac{1}{T}$
    - Flat Fading $\Longleftrightarrow$ amplitude and phase distortion only!
- **Does the channel remain constant over many channel uses?**
  - $T \ll t_c \Rightarrow$ YES $\Rightarrow$ *Slow Fading*
  - $T \geq t_c \Rightarrow$ NO $\Rightarrow$ *Fast Fading*
    - Slow fading may still require frequent training and/or adaptive tracking

Measures Relative to Signals

- **Two important relative measures:**
  - $L = \lfloor \tau_d / T + 0.75 \rfloor$ *relative delay spread*
    - $L = 0$ implies no ISI
    - 0.75 bias depends on sensitivity of modulation format to delay spread!
  - $\nu_d = f_d T$ *Normalized Doppler spread*
    - $\nu_d \ll 1$ implies slow fading
- **Example:** GSM has $T = 3.7$ μsec and IS-54 has $T = 42$ μsec
  - $\tau_d = 5$ μsec in GSM yields ISI in GSM but no ISI in IS-54
  - a velocity of 100 kph yields $\nu_d = 3 \times 10^{-4}$ for GSM and $\nu_d = 3.3 \times 10^{-3}$

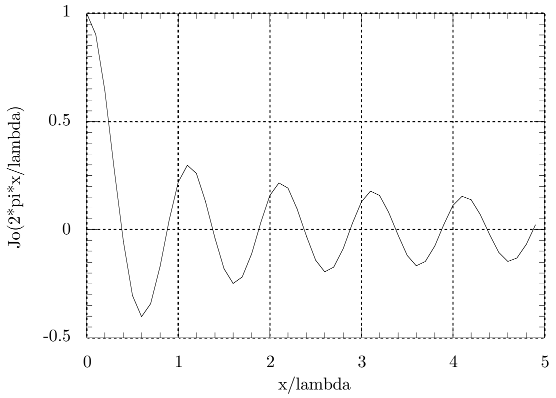
Clarke's Doppler Model: Isotropic (flat) Rayleigh



- **Spatial correlation:**

$$R_h(x) = \mathbb{E}\left\{h(u;x)h^*(u;0)\right\} = J_0\left(\frac{2\pi x}{\lambda}\right)$$

Clarke's Doppler Model: Isotropic Rayleigh



- First zero at $x = 0.38\lambda$
- *Rule of Thumb:* $x > \lambda/2$ is roughly uncorrelated
- $\lambda = \frac{c}{f_c} \Rightarrow \lambda = 0.15$ meters at $f_c = 2$ GHz

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Clarke's Doppler Model: Isotropic (flat) Rayleigh

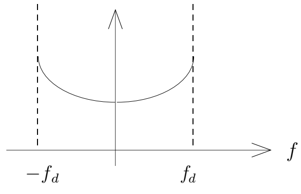
- **Translation to Time Variation:** $x = v * \tau \Rightarrow$

$$R_h(\tau) = \mathbb{E}\left\{h(u; v\tau)h^*(u;0)\right\} = J_0\left(\frac{2\pi v\tau}{\lambda}\right) = J_0(2\pi f_d \tau)$$

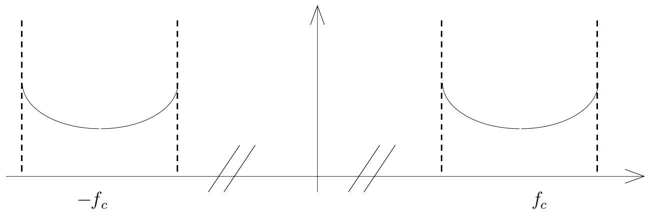
  - *Note:* the $\lambda/2$ decorrelation spacing translates into a coherence time of $t_c = 1/(2f_d)$

- *Doppler Spectrum:*

$$S(f) = \frac{1}{2\pi\sqrt{1-(f/f_d)^2}} \quad |f| \leq f_d$$



Complex Baseband Equivalent Channel



Real Bandpass Channel

Clarke's Doppler Model: Meaning (flat fading)

- **I/Q carrier modulated inputs:**

$$\begin{aligned} x(t) &= x_I(t)\sqrt{2}\cos(2\pi f_c t) - x_Q(t)\sqrt{2}\sin(2\pi f_c t) \\ &= \Re\left\{\bar{x}(t)\sqrt{2}e^{j2\pi f_c t}\right\} \\ &= |\bar{x}(t)|\cos(2\pi f_c t + \angle\bar{x}(t)) \\ \bar{x}(t) &= x_I(t) + jx_Q(t) \end{aligned}$$

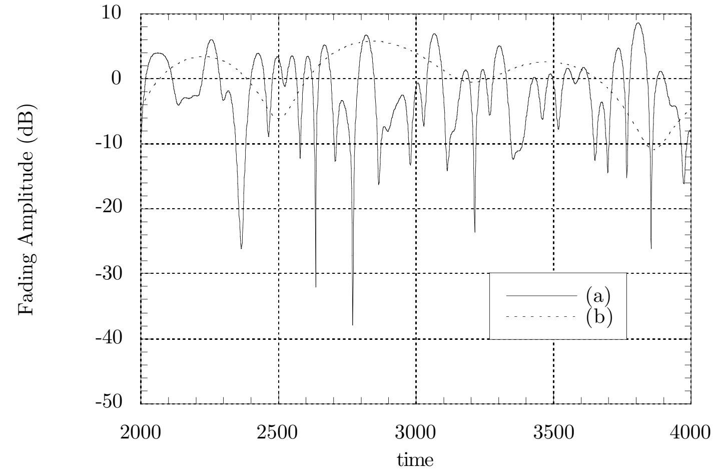
- **Output:**

$$\begin{aligned} y(u;t) &= [h_I(t)x_I(t) - h_Q(t)x_Q(t)]\sqrt{2}\cos(2\pi f_c t) \\ &\quad -[h_I(t)x_Q(t) + h_Q(t)x_I(t)]\sqrt{2}\sin(2\pi f_c t) \\ &= \Re\left\{\bar{y}(t)\sqrt{2}e^{j2\pi f_c t}\right\} \\ &= |\bar{y}(t)|\cos(2\pi f_c t + \angle\bar{y}(t)) \\ \bar{y}(t) &= y_I(t) + jy_Q(t) = \bar{x}(t)\bar{h}(t) \end{aligned}$$

Clarke's Doppler Model: Meaning

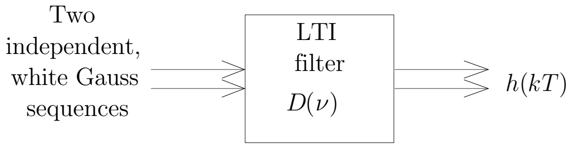
- $h(u;t)$ is a complex circular Gaussian process – I/Q channel gains are iid Gaussian
- Amplitude distribution $|h(u;t)|$ at any time t is a Rayleigh random variable – *Diffuse Multipath*
- If there is an additional direct path, then the amplitude is a Ricean random variable

Power in Sample Realizations



Simulation Methods

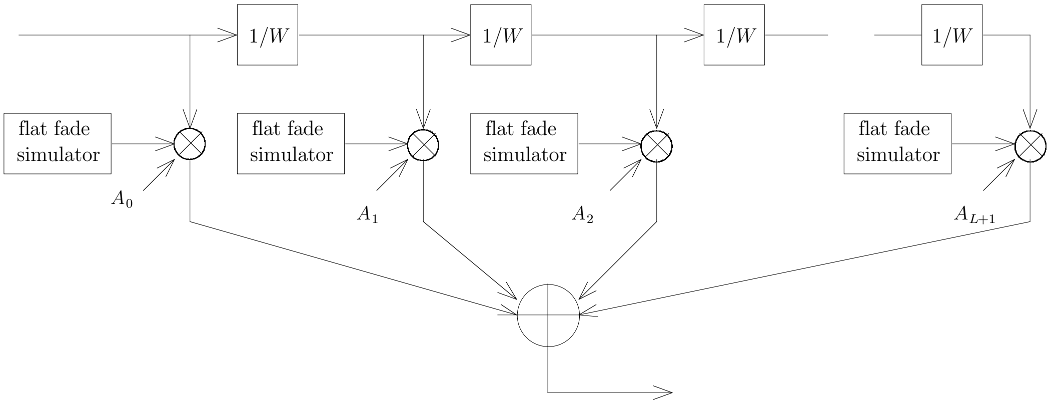
- **Filtered Gaussian Noise:**



$|D(\nu)|^2$ = Normalized Doppler Spectrum

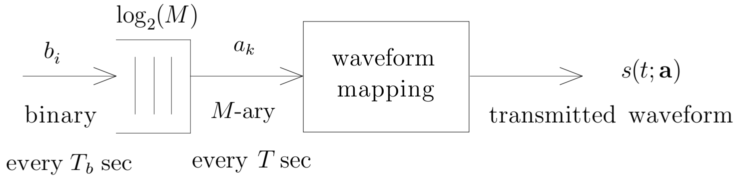
- **Jakes' Method:** Summing cosine and sin waves
- **Relative Advantages:**
  - *Jakes':* very simple and accurate; difficult to generate several independent processes
  - *FGN:* simple to generate independent processes, complicated filter design

Simulation: Frequency-Selective WSSUS



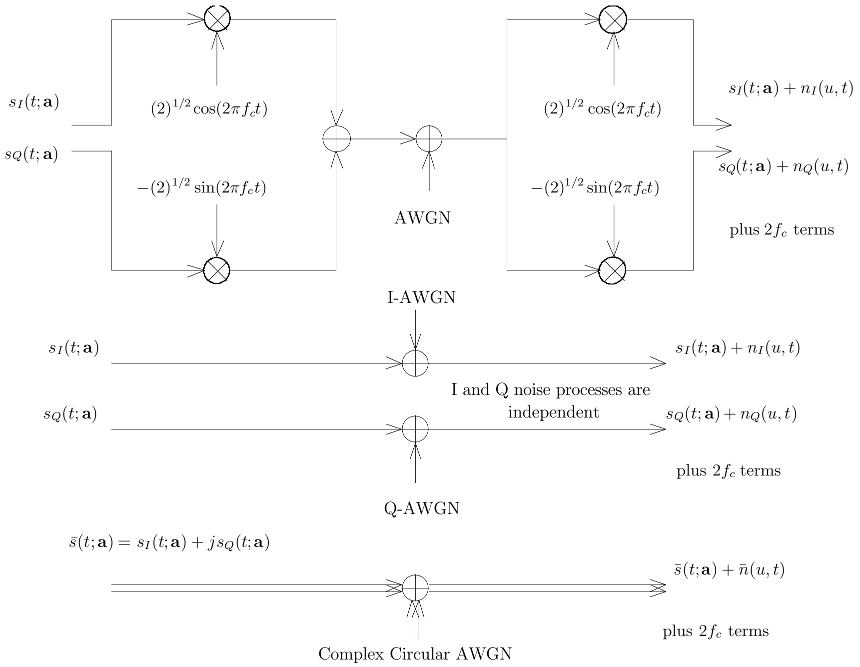
- Valid for an input signal with frequency content $|f| < W/2$
- Number of taps determined by normalized delay spread
- Power in each tap A_i^2 determined by power delay profile
- Taps generated independently (US)

Digital Modulation Formats



- **Definitions:**
  - Mapping from a sequence of digital symbols $\{a_k\}$ drawn from an alphabet of size $M = 2^k$ to a waveform
  - *Bit time:* $T_b = T_s/\log_2(M)$
  - *Bit rate:* $R_b = T_b^{-1}$, *Symbol rate:* $R_s = T^{-1}$
  - *Memoryless Modulation:* for $t \in [kT, (k+1)T)$, $s(t;\mathbf{a}) = s(t;a_k)$ depends only on current symbol
  - *Linear Modulation:* mapping is linear

I/Q Modulation Formats



Modulation Formats

- **Amplitude Phase Representation:**

$$\begin{aligned} A(t;\mathbf{a}) &= \sqrt{s_I^2(t;\mathbf{a}) + s_Q^2(t;\mathbf{a})} \\ \theta(t;\mathbf{a}) &= \tan^{-1}\left(\frac{s_Q(t;\mathbf{a})}{s_I(t;\mathbf{a})}\right) \\ \bar{s}(t;\mathbf{a}) &= A(t;\mathbf{a})\exp[j\theta(t;\mathbf{a})] \\ s(t;\mathbf{a}) &= \sqrt{2}A(t;\mathbf{a})\cos(2\pi f_c + \theta(t;\mathbf{a})) \end{aligned}$$

  – *pure AM:* $\theta(t;\mathbf{a}) = \theta(t)$

  – *pure PM:* $A(t;\mathbf{a}) = A(t)$

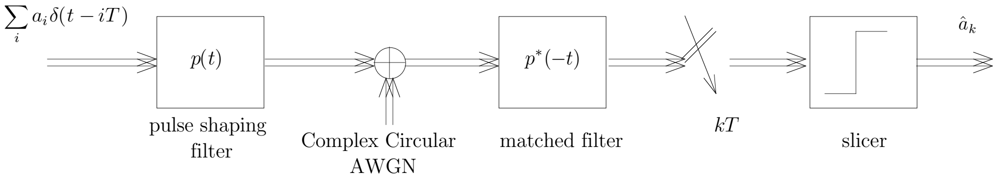
Modulation Formats: General QASK

$$\bar{s}(t;\mathbf{a}) = \sum_i a_k p(t - iT)$$

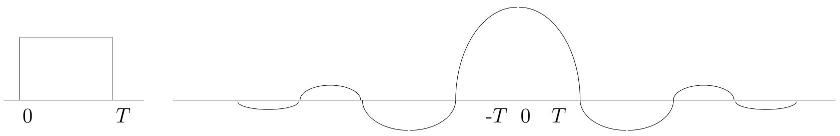
- *Pulse shape:* typically selected to satisfy the Nyquist criterion for no ISI on a memoryless channel

$$p(t) * p^*(-t)\big|_{kT} = E_p \delta_K(k)$$

- *Constellation:* M-ary alphabet for a_k



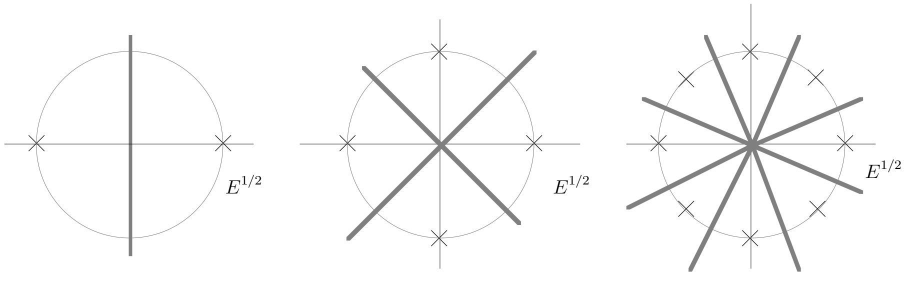
Modulation Formats: General QASK



rect pulse

root-raised cosine pulse

- *Example Pulse shapes*



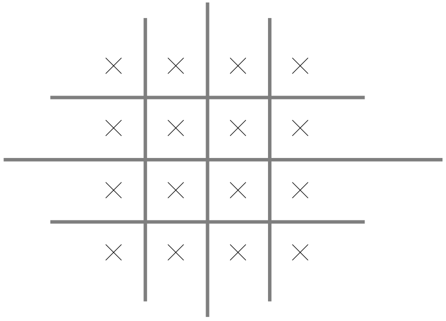
$M = 2$ (BPSK)

$M = 4$ (QPSK)

$M = 8$ (8PSK)

- *Example Constellations*

Modulation Formats: General QASK



16QAM

- Better performance than PSK

M	Advantage of QAM over PSK in dB of E_b/N_0
8	1.7
16	4.2
32	7.0
64	10.0

- Non-constant envelope – *i.e.*, PSK is pure phase modulation

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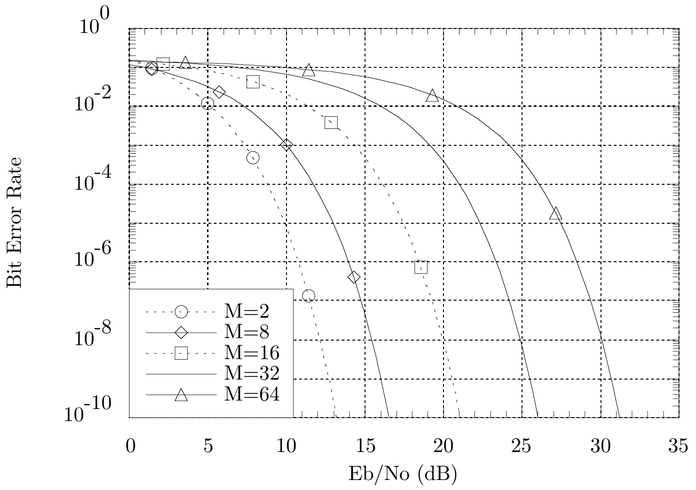
Modulation Formats: PSK Performance (AWGN)



$$P_b \cong \frac{1}{\log_2(M)} \mathrm{Q}\left(\sqrt{\frac{2E_b \log_2(M)}{N_0}\sin^2(\pi/M)}\right)$$

QASK Trade-offs

- **Spectrum (BW):**
  - Determined by $p(t)$ and T only – *i.e.*, independent of M and constellation
- **Basic Trade-off:**
  - Holding the BW fixed, one can increase throughput by increasing the transmit power
  - Costly as M increases

Higher Dimensional (Memoryless) Modulations

- **Basic Idea:**
  - Increase the BW with increasing M
- **Primary Example:** M-ary orthogonal

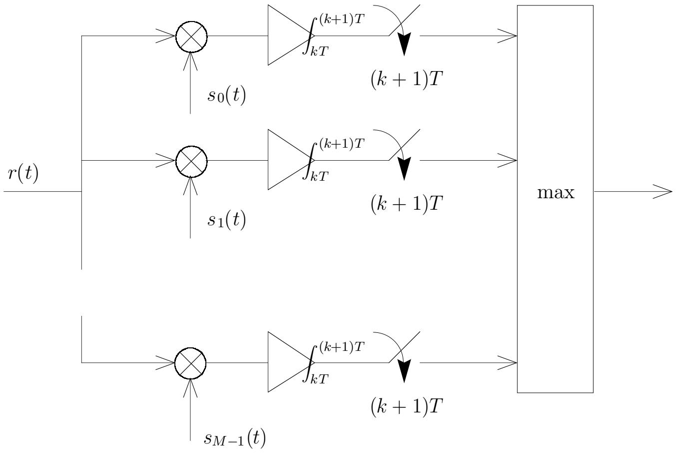
$$\begin{aligned} s(t;\mathbf{a}) &= \sum_i s_{a_i}(t-iT) \\ s_m(t) &= \text{message waveforms } t \in [0,T] \; m = 0,1\ldots M-1 \\ a_i &= \text{sequence in } \{0,1,\ldots M-1\} \\ \int_0^T s_i(t)s_j(t)dt &= \Re\left\{\int_0^T \bar{s}_i(t)\bar{s}_j^*(t)dt\right\} = 0 \quad (i \neq j) \end{aligned}$$

  - *Example:* Orthogonal Frequency Shift Keying (FSK)

$$s_m(t) = \sqrt{\frac{2E}{T}}\cos(2\pi(f_c + m\Delta)t) \;\; t \in [0,T]$$

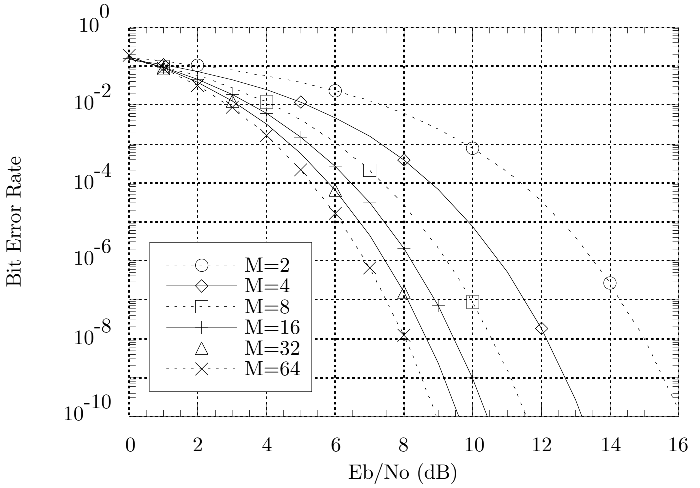
    - Minimum tone spacing for orthogonality $\Delta = 1/(2T)$

Coherent Orthogonal Receiver



- Optimal for AWGN channel

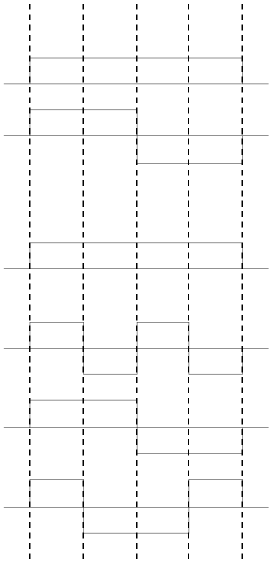
Orthogonal Performance (AWGN)



$$P_b \cong \frac{M/2}{M-1}\left(1-\left[1-\mathrm{Q}\left(\sqrt{\frac{E_b\log_2(M)}{N_0}}\right)\right]^{M-1}\right)$$

Another Orthogonal Format

$$H_2 = \begin{bmatrix} +1 & +1 \\ +1 & -1 \end{bmatrix}$$



Hadamard-ordered Walsh functions can be used to generate orthogonal sequences

$$H_4 = \begin{bmatrix} +H_2 & +H_2 \\ +H_2 & -H_2 \end{bmatrix} = \begin{bmatrix} +1 & +1 & +1 & +1 \\ +1 & -1 & +1 & -1 \\ +1 & +1 & -1 & -1 \\ +1 & -1 & -1 & +1 \end{bmatrix}$$

$$s_m(t) = \sum_{j=0}^{M-1} h_m(j) p(t - jT_h) \quad T_h = T/M$$

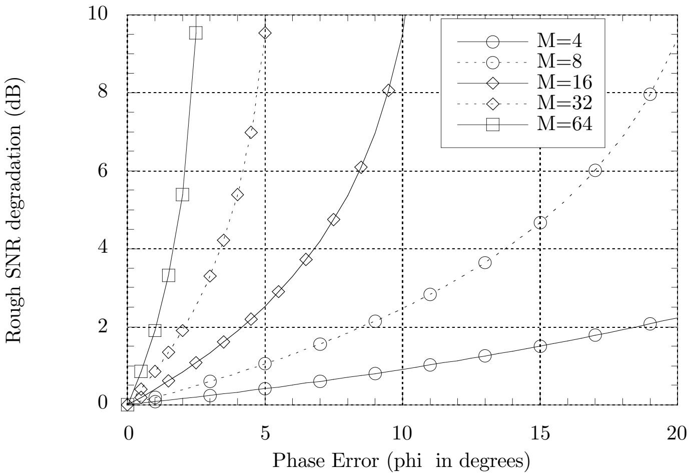
Practical Properties of Modulation Formats

- **Bandwidth Efficiency:**
  - Bits/sec/Hz – largest M possible for a given TW product
  - BW measures and sidelobe roll-off
- **Robustness:**
  - *Nonlinearities*
    - Ideal Constant Envelope: $A(t; \mathbf{a}) = A$
    - Sidelobe re-growth: sidelobes after filter-NL
  - *Like-signal interference:* low cross correlation

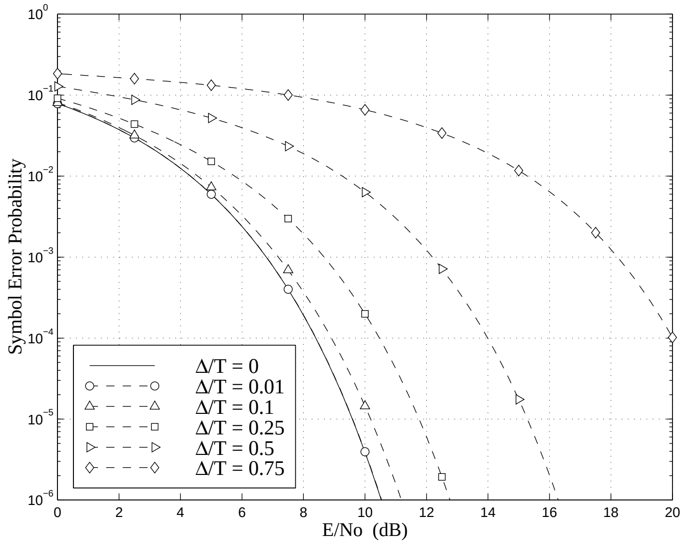
$$\int \bar{s}_1(t) \bar{s}_2^*(t) dt$$

  - *Channel mismatch:* poor estimates of channel impulse response (*i.e.*, phase jitter, imperfect AGC, symbol synchronization, etc.)
  - *Unexpected delay spread:* fractional of a symbol time

MPSK Sensitivity to Phase Error (AWGN)



MPSK Sensitivity to Delay Spread (AWGN)



- BPSK, square pulse, equal power tap at Δ

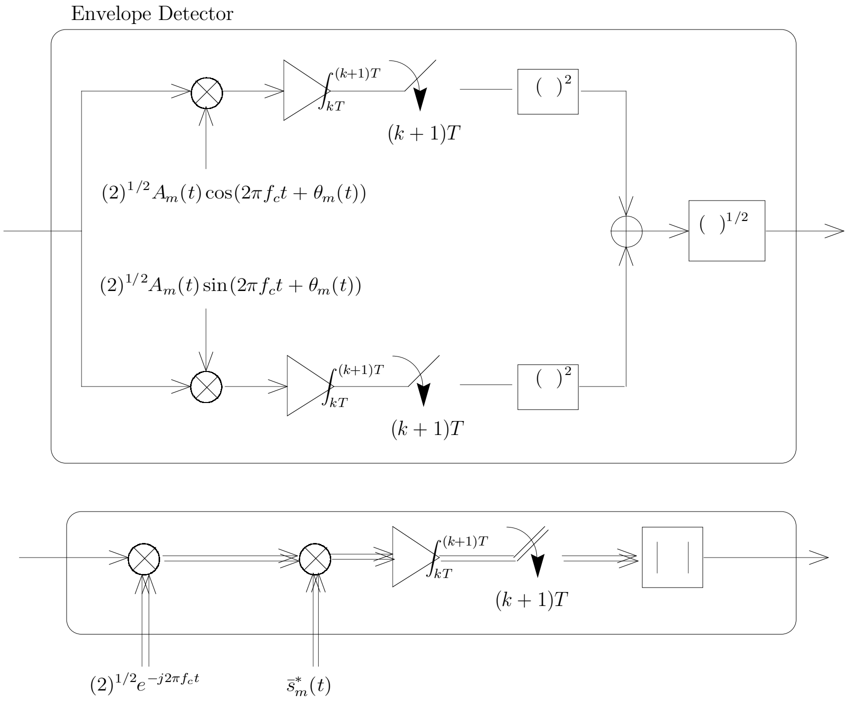
Combating Phase Sensitivity

- **Noncoherent Detection:** average over unknown phase possibilities
  - QASK cannot be detected noncoherently w/o modification
  - Orthogonality condition for noncoherent detection is

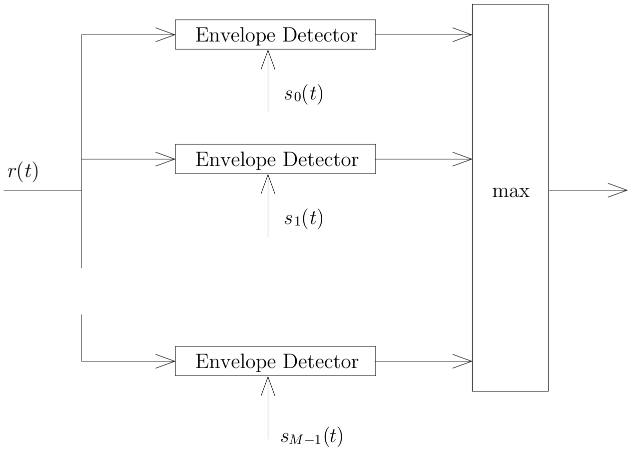
$$\int_0^T \bar{s}_i(t)\bar{s}_j^*(t)dt = 0 \quad (i \neq j)$$

  - *e.g.*, for noncoherent FSK, minimum spacing is $\Delta = 1/T$

Noncoherent Detection

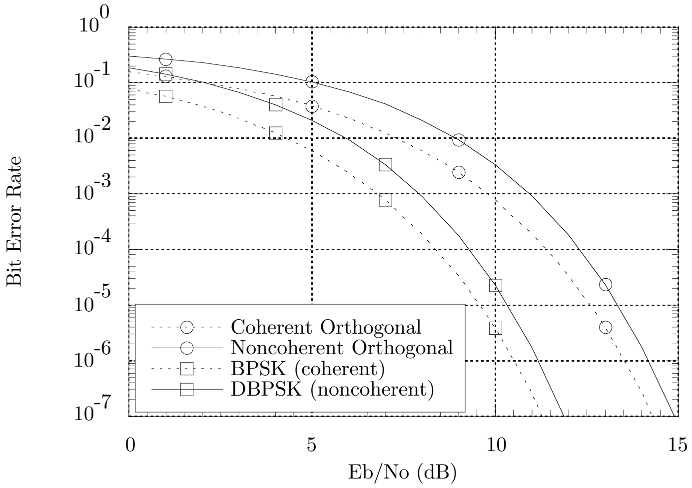


Noncoherent Receiver – Orthogonal M-ary



- Equal energy signals in AWGN (optimal)

Performance Comparison (AWGN)

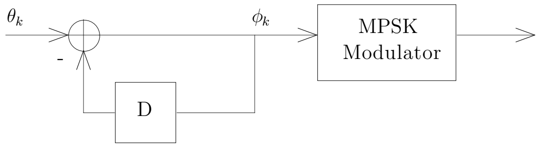


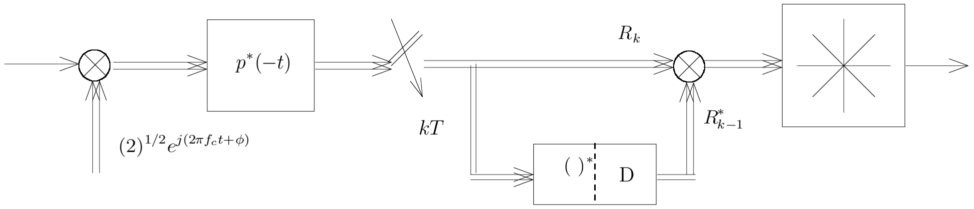
Differential PSK

- **Information phase sequence:** $\theta_k \in \{0, \frac{2\pi}{M}, \ldots \frac{2\pi(M-1)}{M}\}$
- **Transmitted phase sequence:**

$$\phi_k = \phi_{k-1} + \theta_k$$

  - *Note:* ϕ_k is in the same MPSK constellation

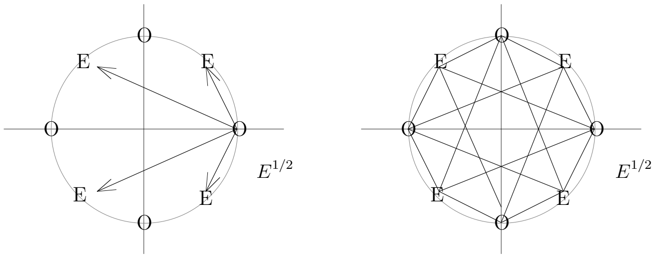




$\pi/4$-Shifted, DQPSK

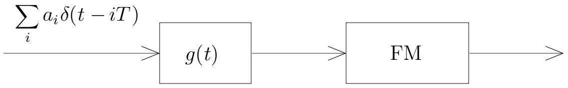
- **Combine differential encoding with $\pi/4$ rotation**

$$\phi_k = \phi_{k-1} + \theta_k + \pi/4$$



- Good robustness to filtered/nonlinearities and symbol synchronization properties

Continuous Phase Modulation



- **Constant envelope:**

$$s(t;\mathbf{a}) = \sqrt{\frac{2E}{T}} \cos(2\pi f_c T + \theta(t;\mathbf{a}))$$

- **Continuous Phase:**

$$\begin{aligned} \theta(t;\mathbf{a}) &= 2\pi h_f \int_{-\infty}^{t} \sum_i a_i g(\tau - iT) d\tau \\ &= 2\pi h_f \sum_i a_i q(t - iT) \\ &= 2\pi h_f a_k q(t - kT) + 2\pi h_f \sum_{i<k} a_i q(t - iT) \\ &= 2\pi h_f a_k q(t - kT) + \phi(s_k) \end{aligned}$$

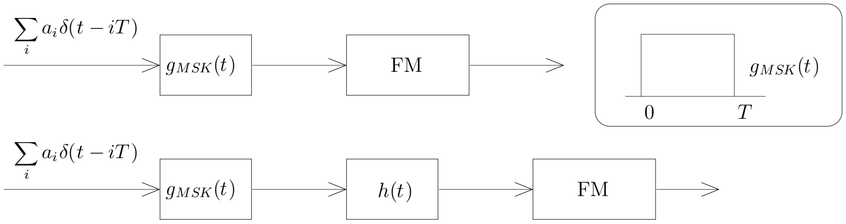
  - *Frequency Pulse:* $g(t)$ – full response if supported on $[0, T]$

Continuous Phase Modulation

- **Advantage:**
  - Good spectral efficiency
- **Drawbacks:**
  - In general, has memory, which implies complicated receiver
  - Optimal receiver is based on the Viterbi algorithm (dynamic programming)

Gaussian (Filtered) MSK

Minimum Shift Keying (MSK)



Gaussian Minimum Shift Keying (GMSK)

- The filter $h(t)$ (bell-shaped) adds memory
  - $B_n = BT$ controls the degree of frequency pulse spreading
  - $B_N \rightarrow \infty \Rightarrow$ MSK
  - $B_N \ll 1 \Rightarrow$ Significant memory
- Increasing memory improves spectral properties, but complicates the receiver

---

Effects of Fading

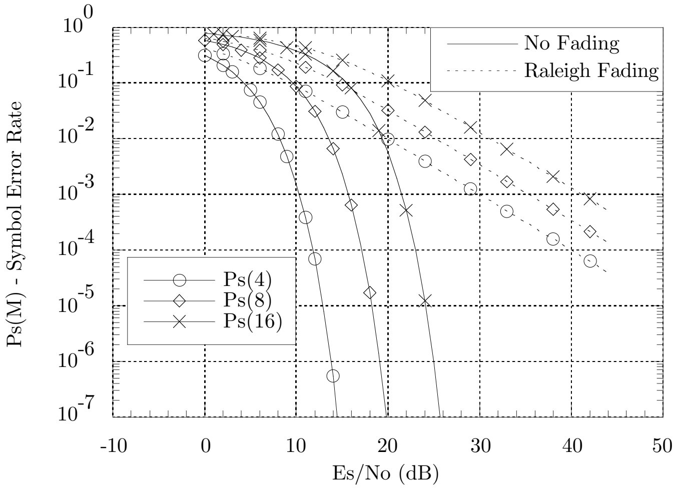
- **Recall:** for the AWGN channel, for all modulations considered, the error performance decays exponentially in SNR

$$P_b \cong K_1 e^{-K_2 \frac{E_b}{N_0}}$$

- **Fading:**
  - Random variations in received power
  - Average the AWGN performance over the statistics E_b/N_0
  - Consider the performance as a function of average E_b/N_0
  - Performance decays only inverse linearly with Rayleigh (flat) fading

$$P_b \cong K \left[\frac{E_b}{N_0}\right]^{-1}$$

Effects of Fading – PSK



- **Intuition:** worst case dominates!

$$\alpha 10^{-1} + (1-\alpha)10^{-6} \cong \alpha 10^{-1} \gg 10^{-6}$$

Combating Fading: Diversity

- **Intuition:** combining multiple independent copies of the received signal will reduce the *variance* of the SNR

$$\bar{r}^{(d)}(t) = \bar{h}^{(d)} s(t; \mathbf{a}) + \bar{n}^{(d)}(t) \quad d = 1, 2 \ldots D$$

  - *Diversity Order: D* – number of effectively independent replicas
  - *Impact on Performance:* Increases BER decay

$$P_b \cong K \left[\frac{E_b}{N_0}\right]^{-D}$$

  - As D increases, the performance approaches that of no-fading!

How to Obtain Diversity

- **Spatial Diversity:**
  - *e.g.*, Space two antennas farther than $\lambda/2$ in dense scattering
- **Time Diversity:**
  - *e.g.*, Repeat the transmission after waiting longer than the coherence time
- **Frequency Diversity:**
  - *e.g.*, Transmit the signal on two carriers spaced further than the coherence BW
- Which type if best?
  - Performance gains are the same regardless (nominally)
  - Effort required to combine the diversity effectively may differ greatly with the type and the exact signal format

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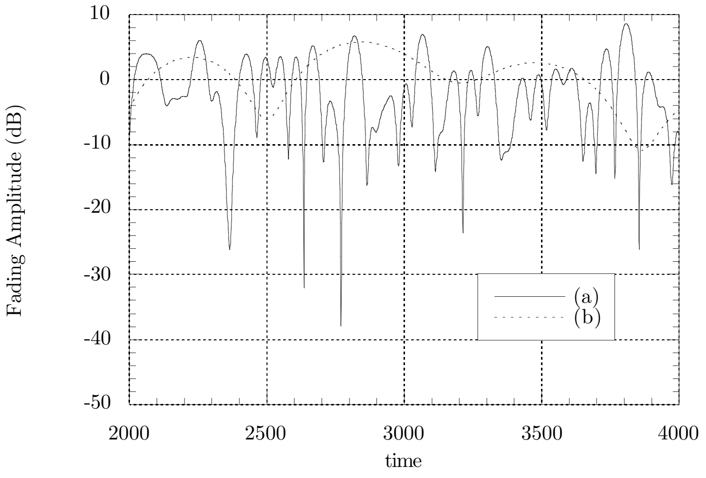
Intuitive View of Diversity



Optimal Diversity Combining

- **Optimal Digital Communication Receiver:**
  - Consider all possible versions of the received signal (including distortion, interference, etc.) that arise from possible **a**
  - Correlate with each of these possibilities
  - Adjust correlation for energy difference
  - Maximize over possibilities
- This yields **Maximum (Signal-to-Noise) Ratio Combining:**

$$z_d(\tilde{\mathbf{a}}) = \int \bar{r}^{(d)}(t) s(t;\tilde{\mathbf{a}}) dt$$

$$Z(\tilde{\mathbf{a}}) = \sum_{d=1}^{D} \left(\bar{h}^{(d)}\right)^* z_d(\tilde{\mathbf{a}})$$

  - If each signal $s(t;\tilde{\mathbf{a}})$ has equal energy, then

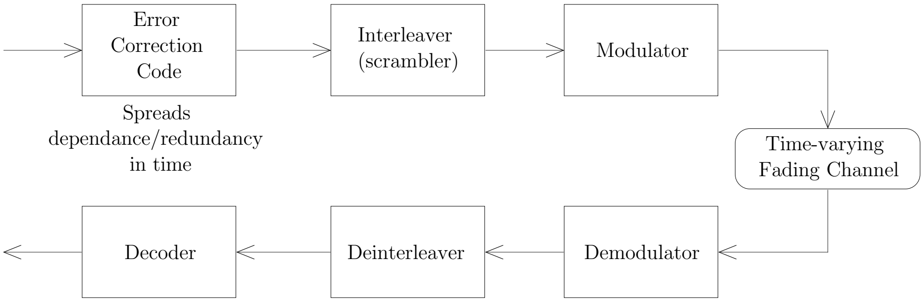
$$\max_{\tilde{\mathbf{a}}} Z(\tilde{\mathbf{a}})$$

Suboptimal Diversity Combining Techniques

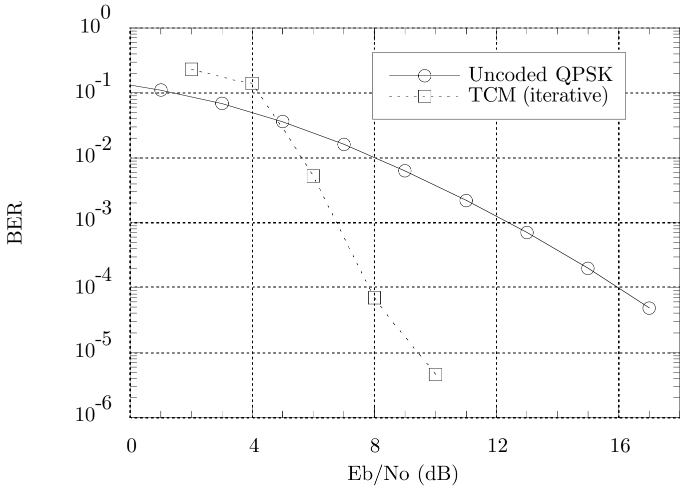
- **Selection Combining:**
  - Use only the branch with maximum energy
- **Equal Gain Combining:**
  - Combine with equal gain and only account for phase
- These result in an SNR loss (lost energy), but not diversity
  - BER vs. E_b/N_0 decays at roughly same rate as MRC
- Nocoherent and hybrid techniques...

Practical Time Diversity: Interleaving and Coding

- **Forward Error Correction Coding:**
  - Provides an SNR gain (*i.e.*, coding gain) on AWGN channel
  - Also provides (small) diversity gain on a time-varying fading channel
- **Interleaving:**
  - Greatly improves the diversity gain associated with coding
  - Useless without coding



Interleaving and Coding



- Note both SNR and diversity gain

Block Interleaver Design

- **Decoding depth of the code:**
  - Delay in decoding a given bit
  - *e.g.*, for a convolutional code with constraint length ν

$$D_{code} \cong 7\nu$$

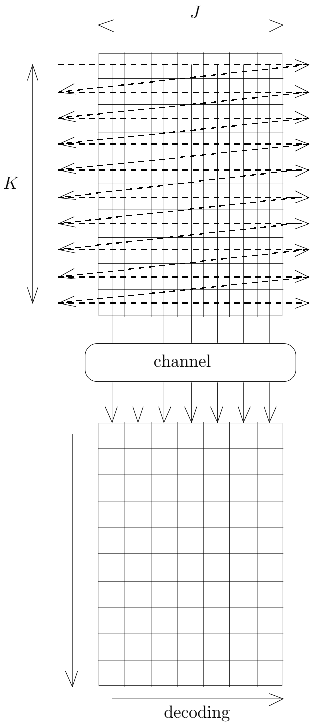
- **Desired Design:**
  - Each coded symbol suffers uncorrelated fading

$$\text{Readout size: } K > \frac{1}{2\nu_d} \text{ symbols}$$

  - All D_c deinterleaved code symbols experience uncorrelated fading

$$\text{Write-in size: } J > D_c \text{ symbols}$$

Block Interleaver Design



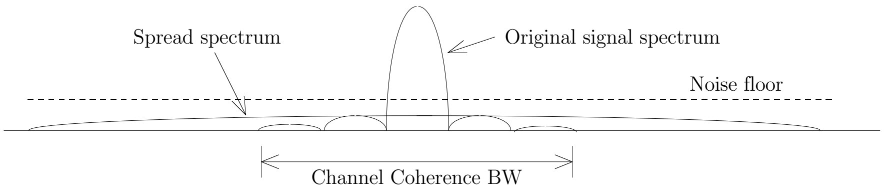
Block Interleaver Design

- **Introduces Delay:** $2KJT$ seconds
- Interactive applications require a delay of less than 50 msec for good quality
- This typically limits the interleaver size for voice systems
- If the mobile unit does not move – no time diversity!!
- *Example:* ideal interleaver sizes for 65 mph

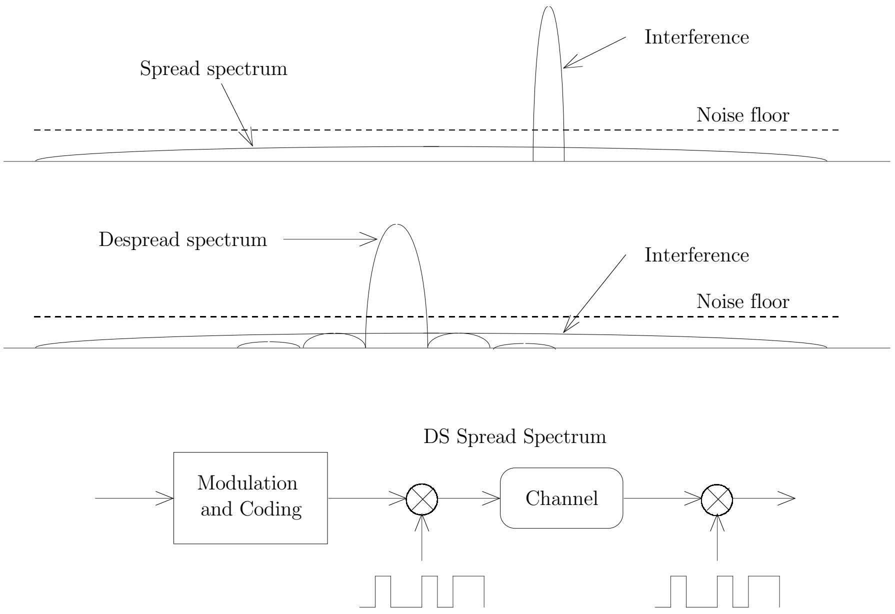
System	ν_D	T_s	K	J	Delay
GSM 900 MHz	$3.2 \cdot 10^{-4}$	3.7 μs	1563	35	0.4 s
1800 MHz	$6.4 \cdot 10^{-4}$	3.7 μs	782	35	0.2 s
IS-54 850 MHz	$3.4 \cdot 10^{-3}$	41 μs	145	42	0.5 s
1800 MHz	$7.1 \cdot 10^{-3}$	41 μs	71	42	0.25 s
IS-95 850 MHz	$4.3 \cdot 10^{-3}$	52 μs	117	63	0.77 s
1800 MHz	$9.1 \cdot 10^{-3}$	52 μs	55	63	0.36 s
Satellite system	$1.1 \cdot 10^{-2}$	3.9 μs	46	49	17.6 ms
Paging system	$2.1 \cdot 10^{-2}$	1 ms	24	49	2.35 s

Practical Frequency Diversity: Spreading

- **Use more bandwidth than required:**
  - provides frequency diversity $\Longleftrightarrow$ frequency-selectivity
  - spectrally inefficient (single-user)
- **Techniques:**
  - *Direct Sequence:* mix with a pseudorandom squarewave carrier
  - *Frequency Hopping:* change f_c according to a pseudorandom pattern
  - *Time Hopping:* change signal epoch of narrow pulse in pseudorandom manner



DS Spread Spectrum



DS Spread Spectrum

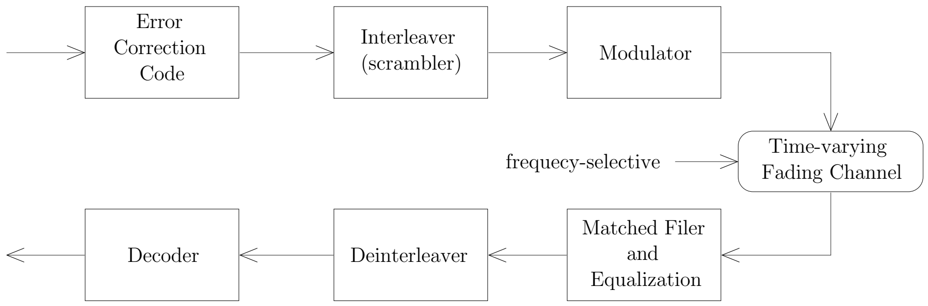
- **Spreading Ratio:** $\eta = T_b/T_c$; T_c = chip time
  - Also called *processing gain* since an interferer's in-band power is reduce by η^{-1} after despreading
- **Frequency Diversity Combining:** RAKE receiver

–

Frequency Diversity in “Unspread” Systems

- **Frequency-selectivity yields diversity:**
  - For a spread spectrum system $D \cong \tau_d/T_c$
  - For a narrowband system $D \cong \tau_d/T$
- **Diversity Combining**
  - Spread spectrum ⇒ RAKE with memoryless post-processor
    - Signal and delayed version are very weakly correlated!
  - Narrowband systems ⇒ matched filter (RAKE) with complex post-processor
    - Equalization

Time/Frequency Diversity in Narrowband Systems



Error Correction Code

Interleaver (scrambler)

Modulator

Time-varying Fading Channel

frequecy-selective

Matched Filer and Equalization

Deinterleaver

Decoder

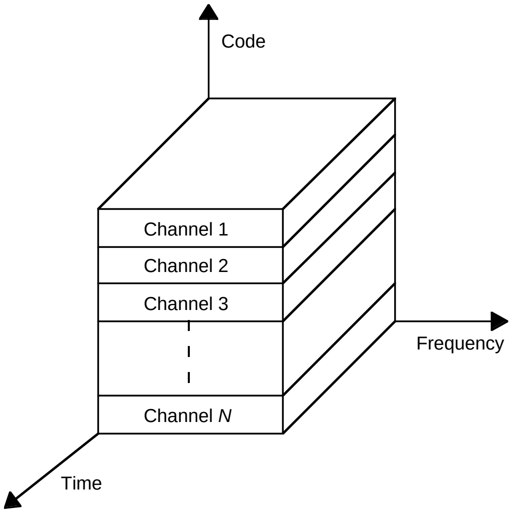
- Viterbi-based Equalization is typically required
- Adaptive channel tracking
- Soft decision decoding is more difficult due to memory in FS channel

MULTIPLE ACCESS & CELL-PLANNING

Methods of Sharing the Channel

- **Channelized systems vs. Random access**
  - Most interactive systems are dedicated channel systems
  - Orderwire/set-up channels may be random access
- **Channelized Methods**
  - Code Division Multiple Access (CDMA)
  - Time Division Multiple Access (TDMA)
  - Frequency Division Multiple Access (FDMA)
- Most practical systems use a combination of these approaches

CDMA



- Requires signals with low cross-correlation: spread spectrum

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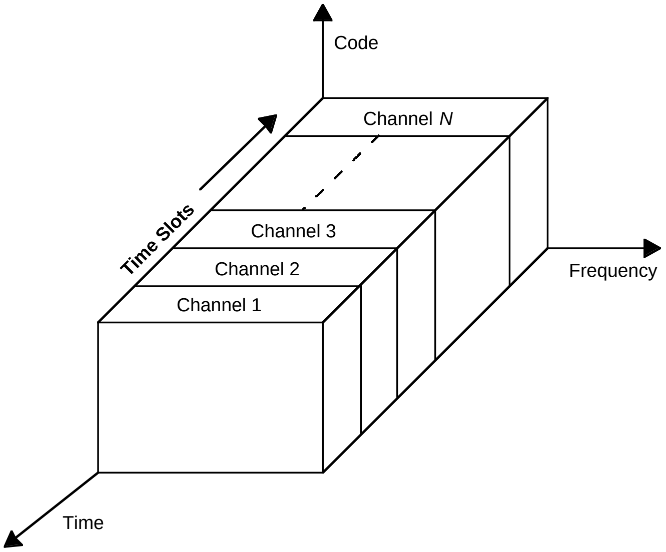
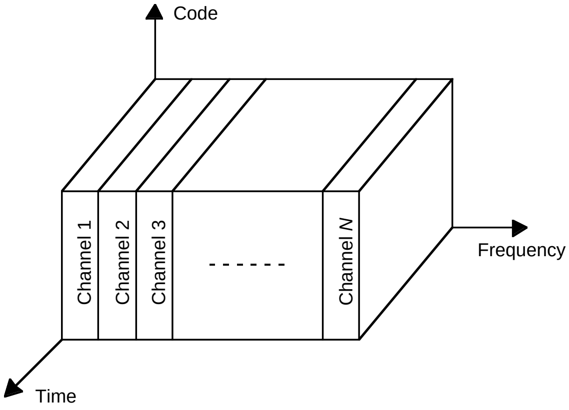
TDMA



- Orthogonality in time: synchronization and time-guard bands

FDMA

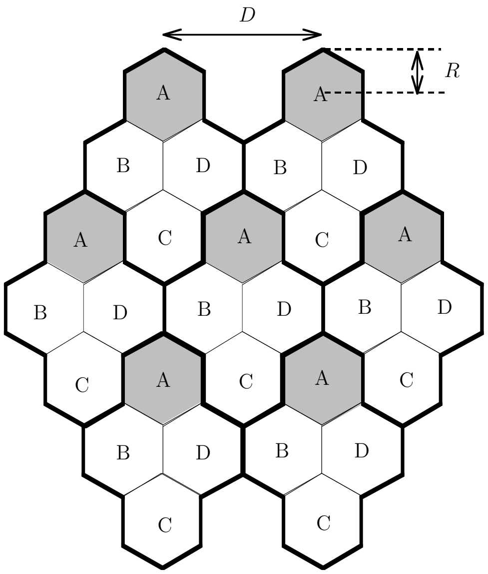


- Orthogonality in frequency: frequency-guard bands

Channel Reuse

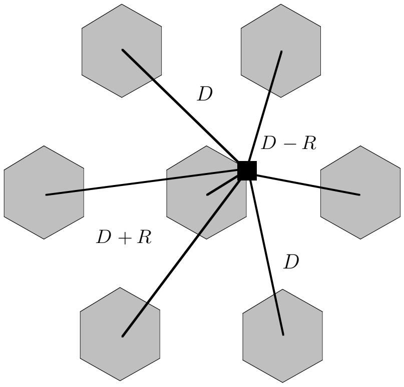
- Users can be on same channels if they are separated by enough distance
- Sufficient distance is determined by: path loss, and signal correlation
- Capacity is increased by "tighter" reuse patterns
- **Hexagonal cell models:**
  - *Reuse Factor:* $N = i^2 + ij + j^2 = 1, 3, 4, 7, 9, 12, \ldots$
  - *Reuse Distance:* $D =$ distance between cells using same channels
  - *Cell Radius:* R
  - *Reuse Ratio:* $D/R = \sqrt{3N}$

Channel Reuse ($N = 4$)



- A, B, C, and D are sets of channels

Worst Case Forward Channel CCI



- **Based only on path loss model:**

$$\frac{C}{I} = \frac{1}{2}\frac{R^{-\beta}}{(D-R)^{-\beta} + D^{-\beta} + (D+R)^{-\beta}}$$
$$= \frac{1}{2}\left[(\sqrt{3N}-1)^{-\beta} + (\sqrt{3N})^{-\beta} + (\sqrt{3N}+1)^{-\beta}\right]^{-1}$$

Sectoring

- Partitioning of channels within a cell
- Requires directional antennas
- Reduces the number of first tier interferers
  - 120 degree sectoring ⇒ at most 2 interferers

$$\frac{C}{I} = \left[(\sqrt{3N}+0.7)^{-\beta} + (\sqrt{3N})^{-\beta}\right]^{-1}$$

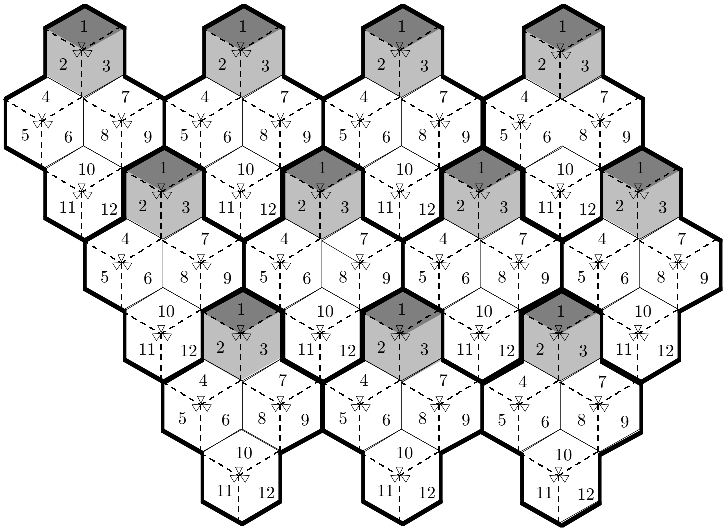
  - 60 degree sectoring ⇒ at most 1 interferers

$$\frac{C}{I} = (\sqrt{3N})^{\beta}$$

- *Example:* $N = 7$ and $\beta = 4$

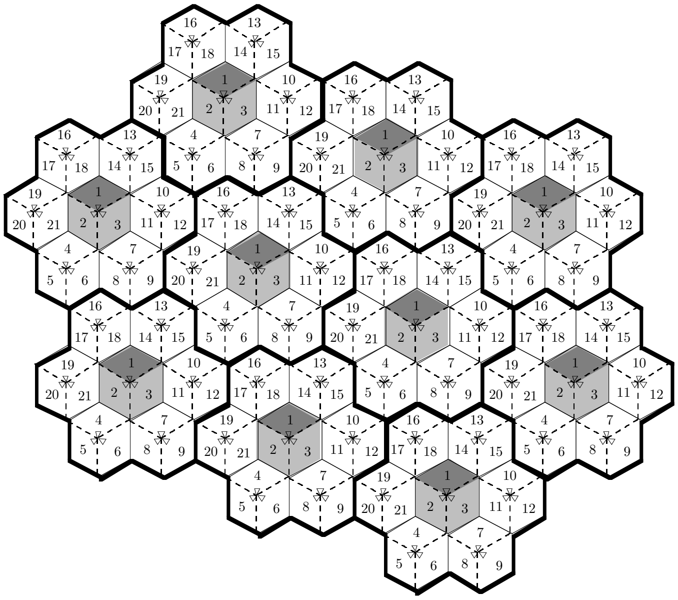
Sectoring	worst case C/I in dB
none	17
120 degree	24.5
60 degree	26.6

Channel Reuse and Sectoring



4/12 Reuse Pattern (reuse factor 4, with 120 degree sectoring)

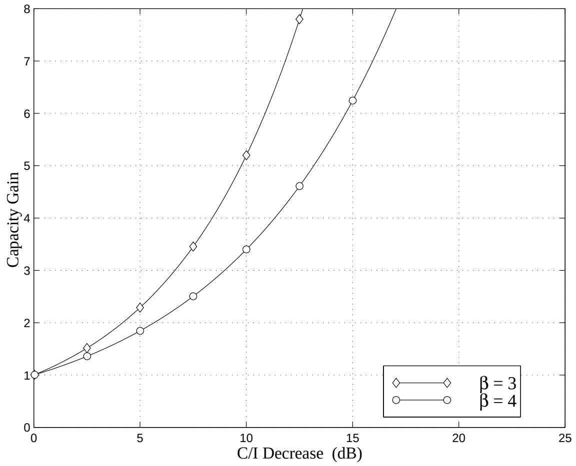
Channel Reuse



7/21 Reuse Pattern (reuse factor 7, with 120 degree sectoring)

Capacity and Reuse

- **Area Efficiency:**
  - Proportional to $(NA)^{-1}$
- **Tolerating more CCI yields capacity gains**



Capacity for Reuse 1 Systems

- **CDMA Systems:** $N = 1$ is commonly used
  - Systems are purely interference limited

$$\begin{aligned} \left[\frac{E}{N_0}\right]_{eff} &= \frac{E}{N_0 + \eta^{-1}\zeta(K-1)E} \\ &\cong \eta\zeta^{-1}\frac{1}{K-1} \\ K_{max} &= \left[\frac{E}{N_0}\right]_{reqd}^{-1}\eta\zeta^{-1} + 1 \end{aligned}$$

  - Sectoring increases capacity proportionally since it reduces the number of interferers
  - *Traffic Activity Factor:* $\zeta \sim [0.3, 0.5]$
  - All of the above assumes perfect power control – *i.e.*, all users are received at equal power

---

Capacity for Reuse 1 Systems

- **Near-Far Problem:** signal of interest is at lower power than other CDMA users
  - *Power differentials:* 80 to 100 dB
  - Good power control is $\pm 1 - 2$ dB with lock times less than 1 sec
  - Even with this power control, ideal capacity is reduced 30-70 %

OVERVIEW OF EXISTING/DEVELOPING SYSTEMS

System Comparisons

System	MA	Freq. band	Modulation	RF Channel BW
AMPS	FDMA	824-894 MHz	FM	30 KHz
DAMPS (USDC, IS-54)	FDMA/TDMA	824-894 MHz 1.8-2.0 GHz	$\pi/4$-DQPSK	30 KHz
IS-95	CDMA	824-894 MHz 1.8-2.0 GHz	QPSK/BPSK 64-Orthogonal	1.25 MHz
GSM	FDMA/TDMA	824-894 MHz 1.8-2.0 GHz	GMSK	200 KHz

System Comparisons

Parameter	AMPS	GSM	USDC	PDC
Bandwidth (MHz)	25	25	25	25
Voice Channels	833	1000	2500	3000
Frequency Reuse (Cluster sizes)	7	4 or 3	7 or 4	7 or 4
Channels/Site	119	250 or 333	357 or 625	429 or 750
Traffic (Erlangs/sq.km)	11.9	27.7 or 40	41 or 74.8	50 or 90.8
Capacity Gain	1.0	2.3 or 3.4	3.5 or 6.3	4.2 or 7.6

IS-54 System Parameters

Parameter	**USDC IS-54 Specification**
Multiple Access	TDMA/FDD
Modulation	$\pi/4$ DQPSK
Channel Bandwidth	30 kHz
Reverse Channel Frequency Band	824-849 MHz
Forward Channel Frequency Band	869-894 MHz
Forward and Reverse Channel Data Rate	48.6 kbps
Spectrum Efficiency	1.62 bps/Hz
Equalizer	Unspecified
Channel Coding	7 bit CRC and rate 1/2 convolutional coding of constraint length 6
Interleaving	2 slot interleaver
Users per Channel	3 (full-rate speech coder of 7.95 kbps/user) 6 (with half-rate speech coder of 3.975 kbps/user)

GSM System Parameters

Parameter	**Specifications**
Reverse Channel Frequency	890-915 MHz
Forward Channel Frequency	935-960 MHz
ARFCN Number	0 to 124 and 975 to 1023
Tx/Rx Frequency Spacing Tx/Rx Time Slot Spacing	45 MHz 3 Time slots
Modulation Data Rate	270.833333 kbps
Frame Period	4.615 ms
Users per Frame (Full Rate)	8
Time slot Period	576.9 μs
Bit Period	3.692 μs
Modulation	0.3 GMSK
ARFCN Channel Spacing	200 kHz
Interleaving (max. delay)	40 ms
Voice Coder Bit Rate	13.4 kbps

IS-95 System Parameters

Parameter	Data Rate (bps)			
User data rate	9600	4800	2400	1200
Coding Rate	1/2	1/2	1/2	1/2
User Data Repetition Period	1	2	4	8
Baseband Coded Data Rate	19,200	19,200	19,200	19,200
PN Chips/Coded Data Bit	64	64	64	64
PN Chip Rate (Mcps)	1.2288	1.2288	1.2288	1.2288
PN Chips/Bit	128	256	512	1024

Reference Mobile Radio Systems

Standard	Service Type	Speech Coder Type Used	
			Bit Rate (kbps)
GSM	Cellular	RPE-LTP	13
CD-900	Cellular	SBC	16
USDC (IS-54)	Cellular	VSELP	8
IS-95	Cellular	CELP	1.2, 2.4, 4.8, 9.6
IS-95 PCS	PCS	CELP	14.4
PDC	Cellular	VSELP	4.5, 6.7, 11.2
CT2	Cordless	ADPCM	32
DECT	Cordless	ADPCM	32
PHS	Cordless	ADPCM	32
DCS-1800	PCS	RPE-LTP	13
PACS	PCS	ADPCM	32

Reference Mobile Radio Systems

Quality Scale	Score	Listening Effort Scale
Excellent	5	No effort required
Good	4	No appreciable effort required
Fair	3	Moderate effort required
Poor	2	Considerable effort required
Bad	1	No meaning understood with reasonable effort

Coder	MOS
64 kbps PCM	4.3
14.4 kbps QCELP13	4.2
32 kbps ADPCM	4.1
8 kbps ITU-CELP	3.9
8 kbps CELP	3.7
13 kbps GSM Codec	3.54
9.6 kbps QCELP	3.45
4.8 kbps CELP	3.0
2.4 kbps LPC	2.5

Wideband CDMA Proposal

Bandwidth	1.25/5/10/20 MHz
Chip Rate	1.024/4.096/8.192/16.384 Mcps
Modulation	QPSK Spreading; QPSK/BPSK (coherent)
Channel Coding	Voice: convolutional ($R = 1/3$, $K = 9$) Data:concatenated RS-CC
Diversity	Rake/Antenna