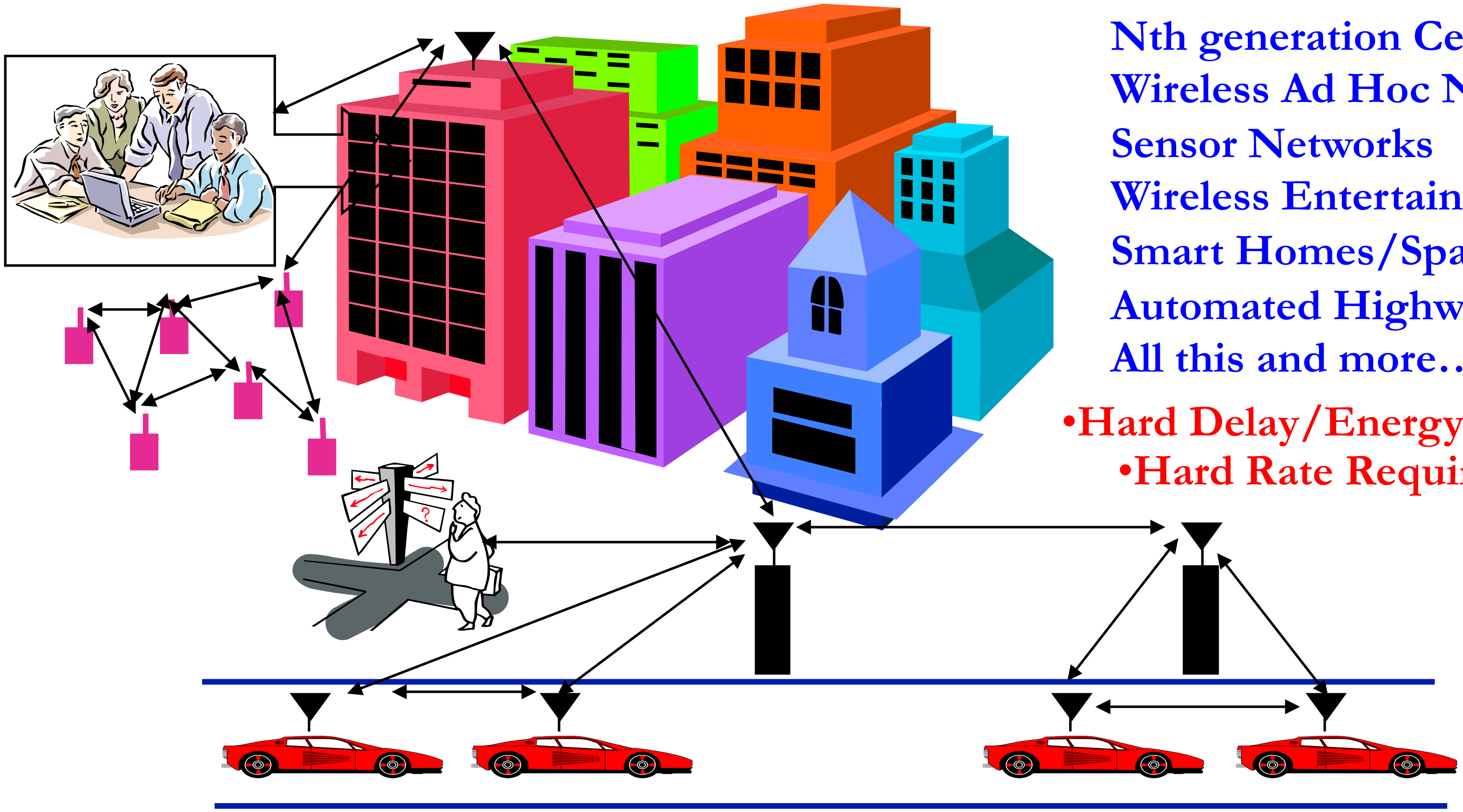
# Midterm Review

- Overview of Wireless Systems
- Signal Propagation and Channel Models
- Modulation and Performance Metrics
- Impact of Channel on Performance
- Fundamental Capacity Limits
- Diversity Techniques

# Future Wireless Networks

## *Ubiquitous Communication Among People and Devices*



Wireless Internet access
Nth generation Cellular
Wireless Ad Hoc Networks
Sensor Networks
Wireless Entertainment
Smart Homes/Spaces
Automated Highways
All this and more…

- Hard Delay/Energy Constraints
- Hard Rate Requirements

# Design Challenges

- Wireless channels are a difficult and capacity-limited broadcast communications medium
- Traffic patterns, user locations, and network conditions are constantly changing
- Applications are heterogeneous with hard constraints that must be met by the network
- Energy, delay, and rate constraints change design principles across all layers of the protocol stack

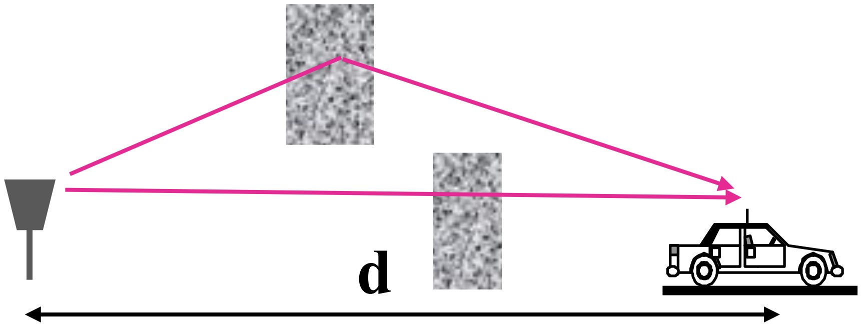
# Current Wireless Systems

- Cellular Systems
- Wireless LANs
- Wimax
- Satellite Systems
- Paging Systems
- Bluetooth
- Zigbee radios

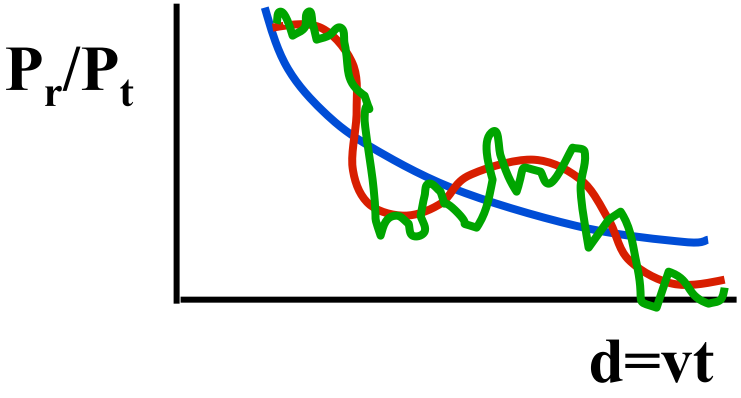
# Signal Propagation

- Path Loss
  - Free space, 2-path,…
  - Simplified model

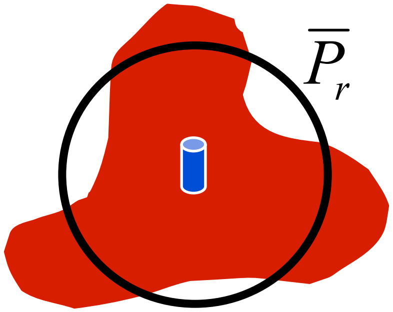
$$P_r = P_t K \left[ \frac{d_0}{d} \right]^{\gamma}, \; 2 \le \gamma \le 8$$



- Shadowing
  - dB value is Gaussian
  - Find path loss exponent and shadow STD by curve fitting
- Multipath
  - Ray tracing
  - Statistical model

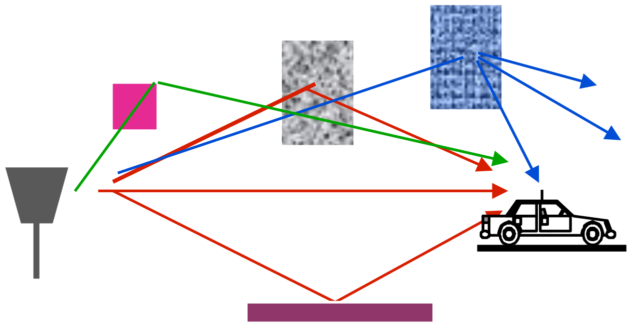


# Outage Probability and Cell Coverage Area



- Path loss: circular cells
- Path loss+shadowing: amoeba cells
  - Tradeoff between coverage and interference
- Outage probability
  - Probability received power below given minimum
- Cell coverage area
  - % of cell locations at desired power
  - Increases as shadowing variance decreases
  - Large % indicates interference to other cells

# Statistical Multipath Model



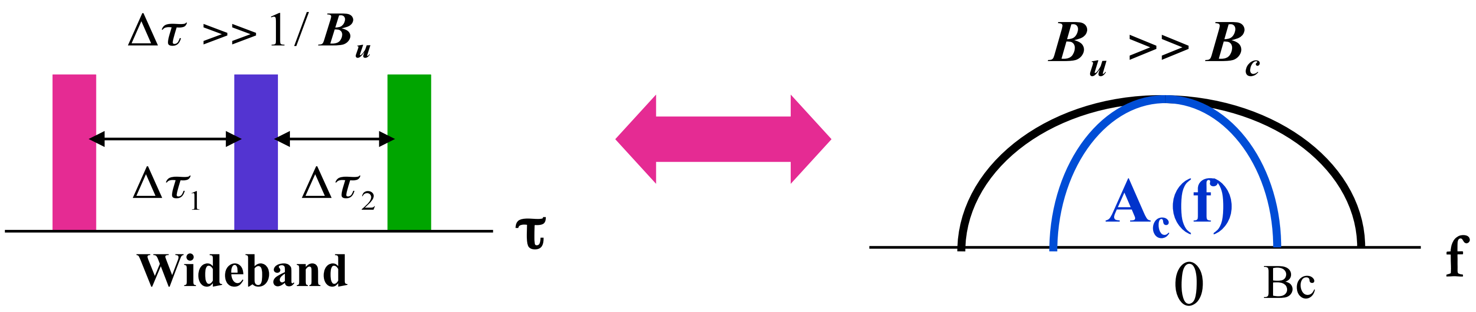
- Random # of multipath components, each with varying amplitude, phase, doppler, and delay
- Leads to time-varying channel impulse response

$$c(\tau,t)=\sum_{n=1}^{N}\alpha_n(t)e^{-j\varphi_n(t)}\delta(\tau-\tau_n(t))$$

- Narrowband channel
  - No signal distortion, just a complex amplitude gain
  - Signal amplitude varies randomly (Rayleigh, Ricean, Nakagami).
  - $2^{nd}$ order statistics (Bessel function), Average fade duration
  - Can also model amplitude variations via a Markov model

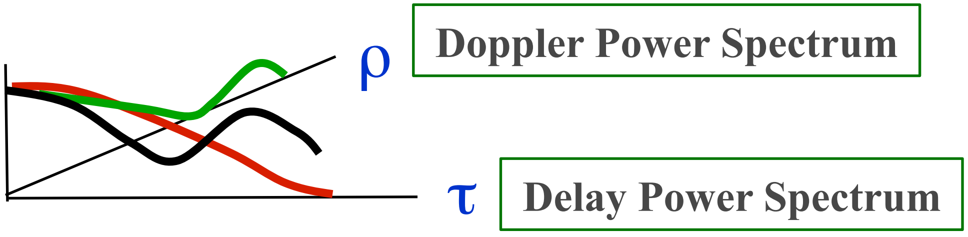
# Wideband Channels

- Individual multipath components resolvable
- True when time difference between components exceeds signal bandwidth



- Scattering function

  $s(\tau,\rho)=\mathcal{F}_{\Delta t}[A_c(\tau,\Delta t)]$



Doppler Power Spectrum

Delay Power Spectrum

  - Yields delay spread/coherence BW ($\sigma_\tau \sim 1/B_c$)
  - Yields Doppler spread/coherence time ($B_d \sim 1/T_c$)

# Capacity of Flat Fading Channels

- Three cases
  - Fading statistics known
  - Fade value known at receiver
  - Fade value known at receiver and transmitter

- Optimal Adaptation with TX and RX CSI
  - Vary rate and power relative to channel
  - Goal is to optimize ergodic capacity

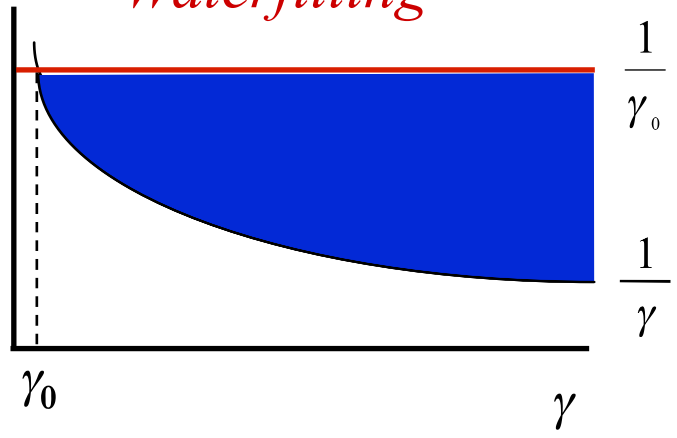
$$C = \max_{P(\gamma):E[P(\gamma)]=\overline{P}} \int_0^\infty B\log_2\left(1+\frac{\gamma P(\gamma)}{\overline{P}}\right)p(\gamma)d\gamma$$

# Optimal Adaptive Scheme

- **Power Adaptation**

$$\frac{P(\gamma)}{\overline{P}} = \begin{cases} \frac{1}{\gamma_0} - \frac{1}{\gamma} & \gamma \geq \gamma_0 \\ 0 & else \end{cases}$$

Waterfilling



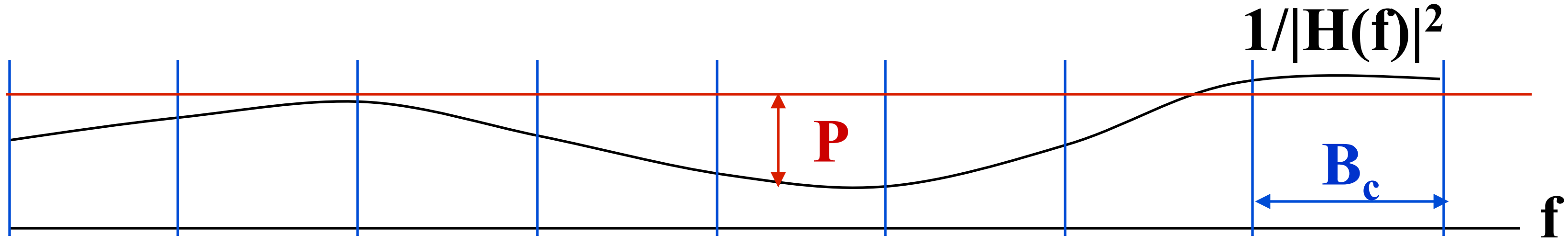
- **Capacity**

$$\frac{R}{B} = \int_{\gamma_0}^{\infty} \log_2\left(\frac{\gamma}{\gamma_0}\right) p(\gamma)d\gamma.$$

- **Alternatively can use channel inversion (poor performance) or truncated channel inversion**

# Frequency Selective Fading Channels

- For time-invariant channels, capacity achieved by water-filling in frequency
- Capacity of time-varying channel unknown
- Approximate by dividing into subbands
  - Each subband has width $B_c$ (like MCM).
  - Independent fading in each subband
  - Capacity is the sum of subband capacities

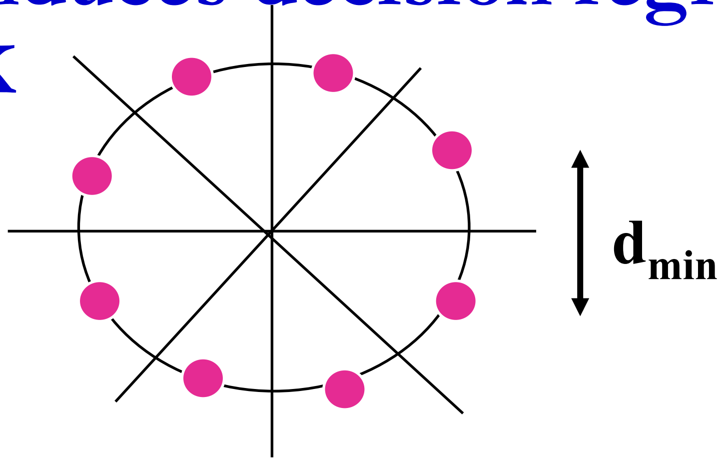


# Modulation Considerations

- **Want high rates, high spectral efficiency, high power efficiency, robust to channel, cheap.**
- **Linear Modulation (MPAM,MPSK,MQAM)**
  - **Information encoded in amplitude/phase**
  - **More spectrally efficient than nonlinear**
  - **Easier to adapt.**
  - **Issues: differential encoding, pulse shaping, bit mapping.**
- **Nonlinear modulation (FSK)**
  - **Information encoded in frequency**
  - **More robust to channel and amplifier nonlinearities**

# Linear Modulation in AWGN

- ML detection induces decision regions
  - Example: 8PSK

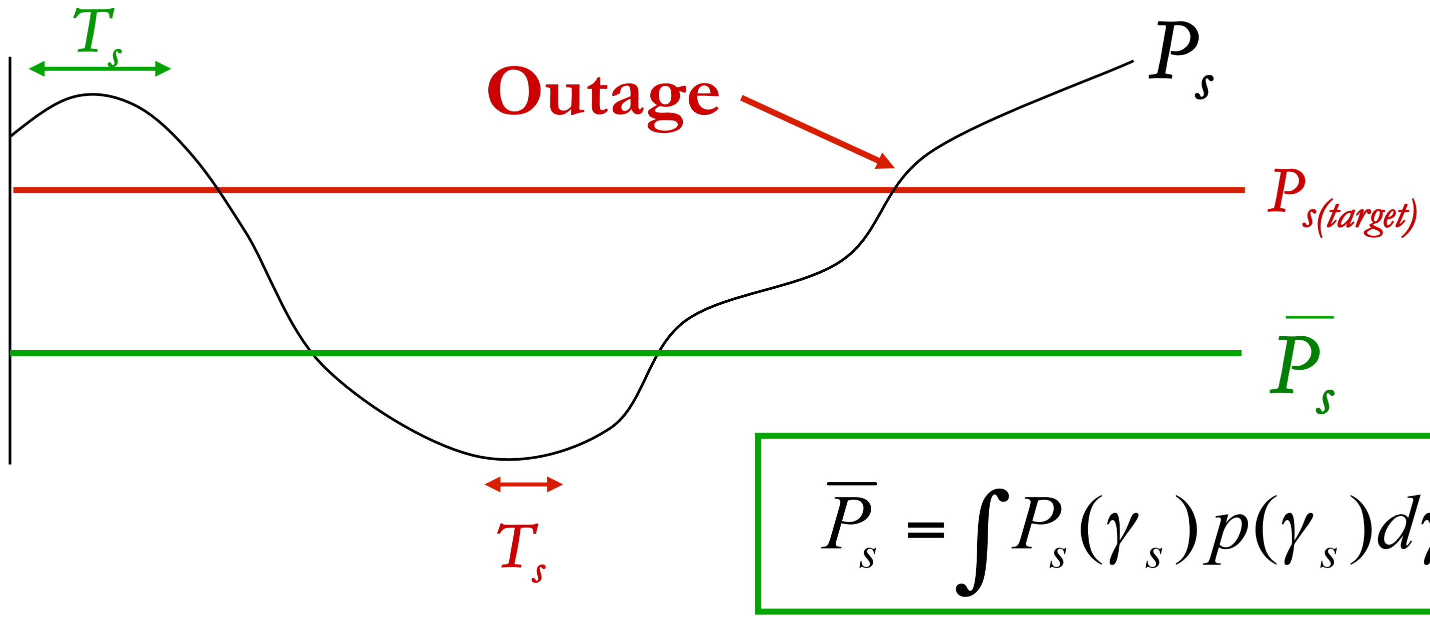


- $P_s$ depends on
  - # of nearest neighbors
  - Minimum distance $d_{min}$ *(depends on* $\gamma_s$*)*
  - Approximate expression

$$P_s \approx \alpha_M Q\left(\sqrt{\beta_M \gamma_s}\right)$$

# Linear Modulation in Fading

- **In fading $\gamma_s$ and therefore $P_s$ random**
- **Metrics: outage, average $P_s$ , combined outage and average.**



$$\overline{P}_s = \int P_s(\gamma_s)\,p(\gamma_s)\,d\gamma_s$$

# Moment Generating Function Approach

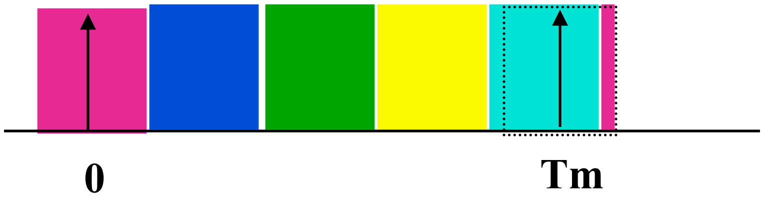
- Simplifies average $P_s$ calculation
- Uses alternate Q function representation
- $\overline{P_s}$ reduces to MGF of $\gamma_s$ distribution
- Closed form or simple numerical calculation for general fading distributions
- Fading greatly increases average $P_s$ .

# Doppler Effects

- High doppler causes channel phase to decorrelate between symbols
- Leads to an irreducible error floor for differential modulation
  - Increasing power does not reduce error
- Error floor depends on $B_d T_s$

# ISI Effects

- Delay spread exceeding a symbol time causes ISI (self interference).



- ISI leads to irreducible error floor
  - Increasing signal power increases ISI power
- ISI requires that $T_s >> T_m$ ($R_s << B_c$)

# Diversity

- Send bits over independent fading paths
  - Combine paths to mitigate fading effects.
- Independent fading paths
  - Space, time, frequency, polarization diversity.
- Combining techniques
  - Selection combining (SC)
  - Equal gain combining (EGC)
  - Maximal ratio combining (MRC)
- Can have diversity at TX or RX
  - In TX diversity, weights constrained by TX power

# Selection Combining

- Selects the path with the highest gain
- Combiner SNR is the maximum of the branch SNRs.
- CDF easy to obtain, pdf found by differentiating.
- Diminishing returns with number of antennas.
- Can get up to about 20 dB of gain.

# MRC and its Performance

- With MRC, $\gamma_\Sigma = \Sigma\gamma_i$ for branch SNRs $\gamma_i$
  - Optimal technique to maximize output SNR
  - Yields 20-40 dB performance gains
  - Distribution of $\gamma_\Sigma$ hard to obtain
- Standard average BER calculation

$$\overline{P}_b = \int P_b(\gamma_\Sigma) p(\gamma_\Sigma) d\gamma_\Sigma = \int\int \dots \int P_b(\gamma_\Sigma) p(\gamma_1) * p(\gamma_2) * \dots * p(\gamma_M) d\gamma_1 d\gamma_2 \dots d\gamma_M$$

  - Hard to obtain in closed form
  - Integral often diverges
- MGF Approach

$$\overline{P}_b = \frac{1}{\pi} \int_0^{.5\pi} \prod_{i=1}^{M} \mathcal{M}_i \left[ \frac{-g}{\sin^2 \varphi} ; \gamma_i \right] d\varphi$$

# Main Points

- Wireless channels introduce path-loss, shadowing and multipath fading
  - Shadowing introduced outage
  - Flat-fading causes large power fluctuations
  - ISI causes self-interference
- Performance of digital communications in wireless channels random
  - Characterized by outage probability and average probability of error in flat-fading
  - Characterized by irreducible error floors in ISI
- Need mechanisms to compensate for multipath
- Diversity compensates for effects of flat fading.