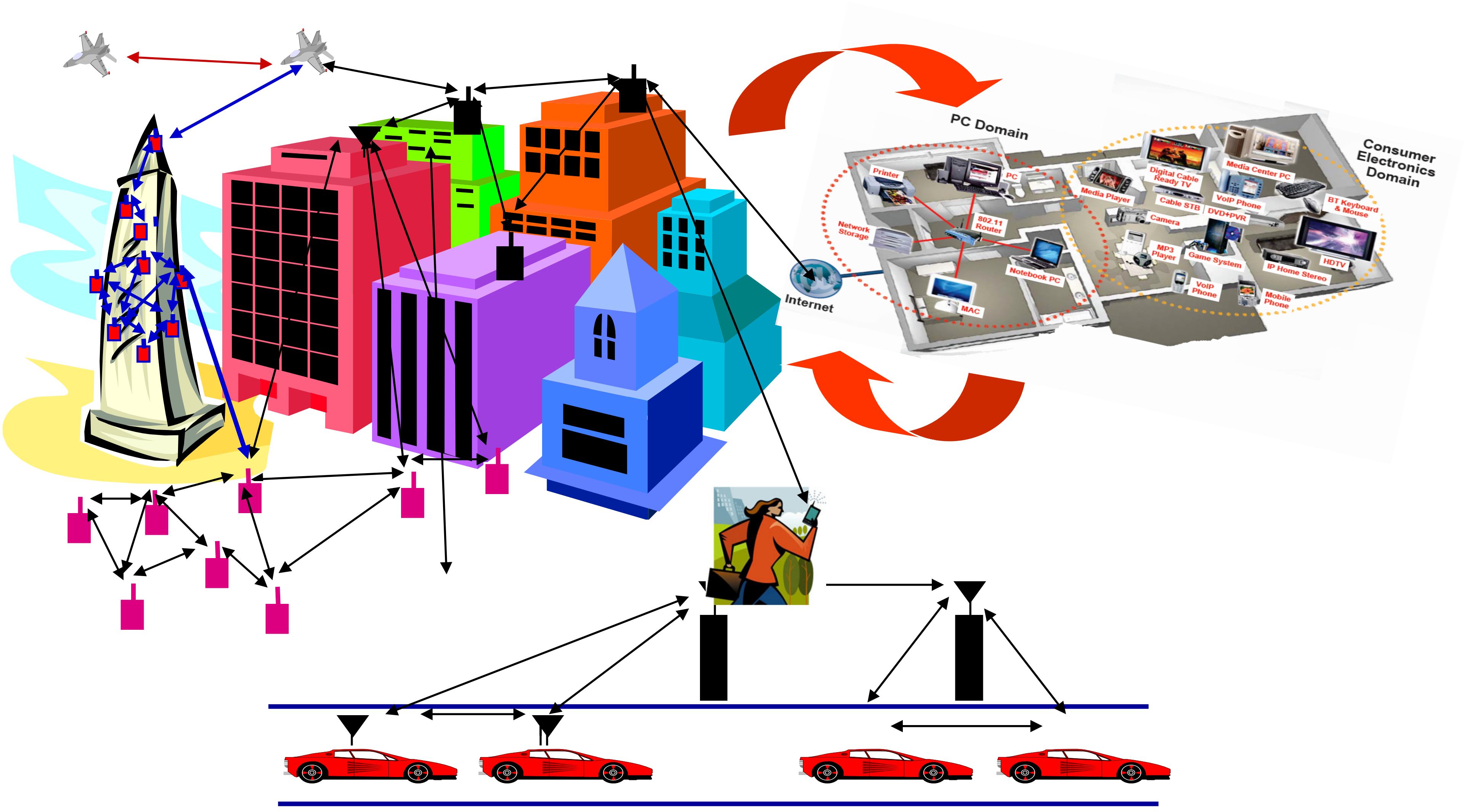
EE 359: Wireless Communications

Announcements and Course Summary



Announcements

- Last HW and bonus HW questions due Sunday 12/10 at 4 pm (no late HWs).
- Final projects must be posted 12/9 (Sat) at midnight.
- 25 bonus points for course evaluations (online)
- Final 12/13/2017, 12:15-3:15pm in Thornton 102 (here)
  - Covers Chapters 9, 10, 12, 13.1-13.2, 13.4, 14.1-14.4, 15.1-15.4 (+ earlier chps)
  - Similar format to MT, but longer: open book, notes.
  - If you need a book or calculator, let us know by 12/8 (Fri)
  - Practice finals posted (10 bonus points). Turn in for solns, by exam for bonus pts
  - Final review and discussion section: Monday, 12/11, 2-4pm, Packard 364.

OHs leading up to final exam

- Mine
  - This week: today after class, Fri 12-1pm & by appt.
  - Next week: Sun 12/10: 5-6pm, Tue 12/11 10:30-12 & by appt.

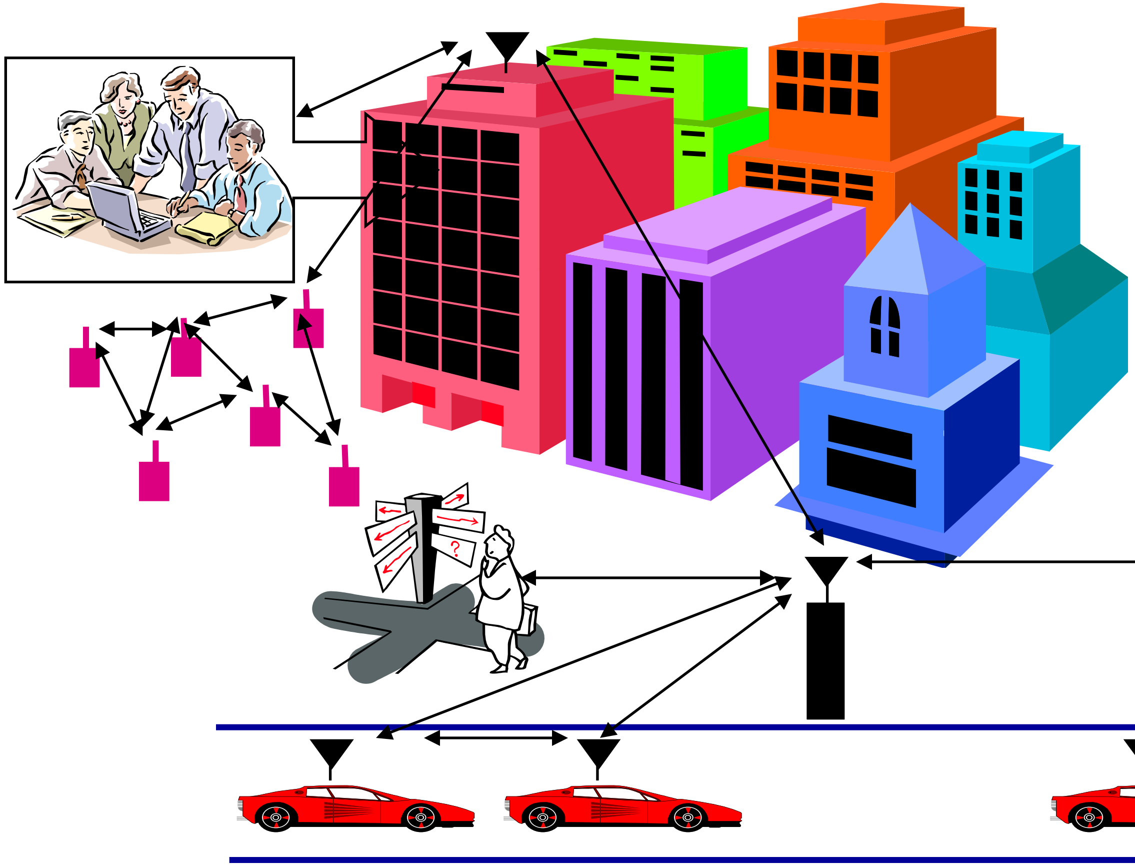
- TAs:
  - Thursday, 12/7, 5-6pm Milind OH
  - Thursday, 12/7, 6-7pm Milind Email OH
  - Saturday, 12/9, 2-4pm Tom OH (HW8 + Exam questions)
  - Monday, 12/11, 2-4pm Final review
  - Monday, 12/11, 4-6pm Tom OH
  - Tuesday, 12/12 2-4pm Milind OH
  - Wednesday, 12/13, 9:30am-11:30am, Tom OH

Course Summary

- Signal Propagation and Channel Models
- Modulation and Performance Metrics
- Impact of Channel on Performance
- Fundamental Capacity Limits
- Flat Fading Mitigation: Diversity and Adaptive Modulation
- ISI Mitigation
  - Equalization (not covered)
  - Multicarrier Modulation/OFDM
  - Spread Spectrum
- Multiuser Systems
  - Multiple access: time/frequency/code/space division
  - Random access
- Cellular Systems
  - Multiuser Detection
  - Area Spectral Efficiency

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

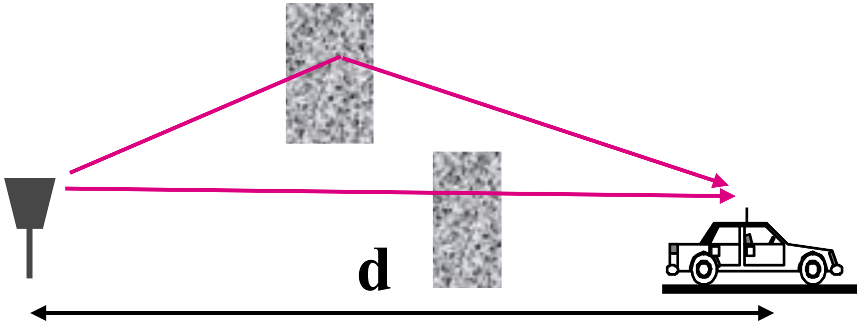
Design Challenges

- 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

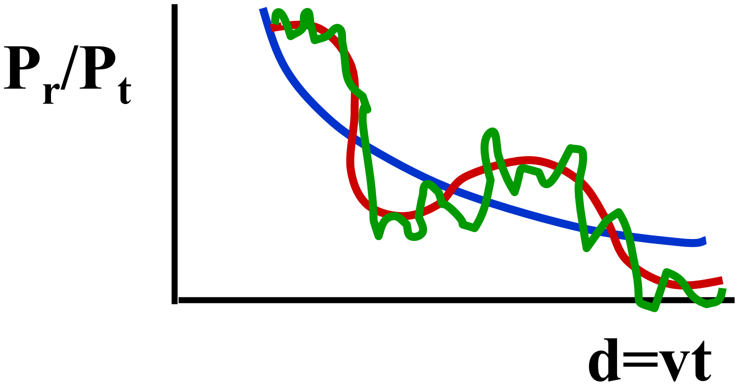
Signal Propagation

- Path Loss
  - Free space, 2-path, general ray tracing, mmwave
  - Simplified model

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

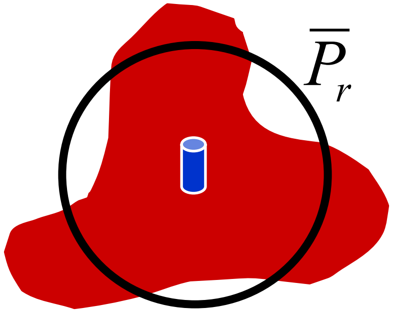


- Shadowing
  - dB value is Gaussian
  - Find path loss exponent and shadow STD by curve fitting



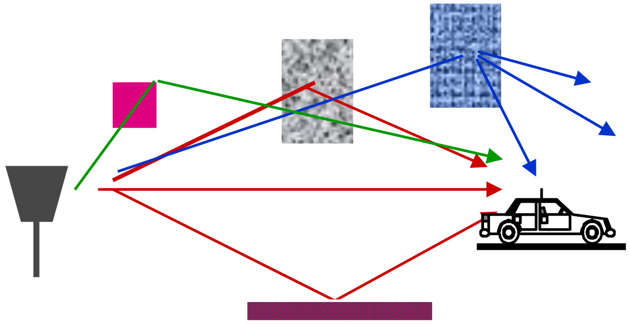
- Multipath
  - Ray tracing
  - Statistical model

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



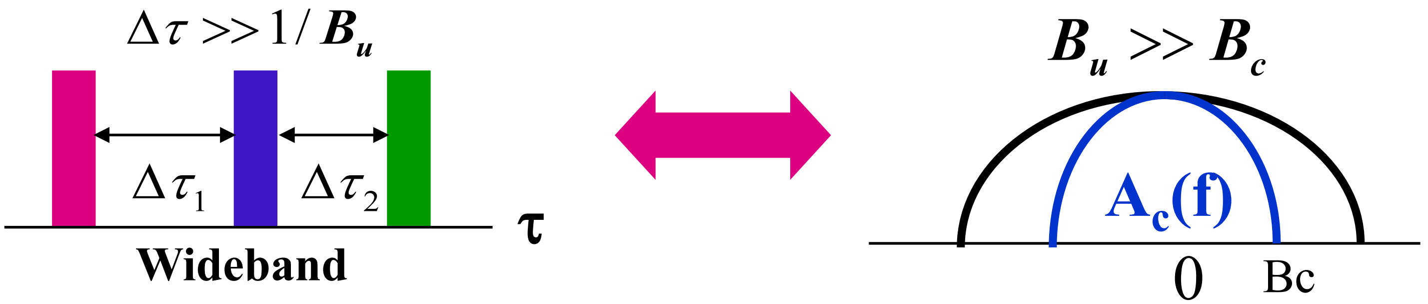
- Random # of multipath components, each with varying amplitude, phase, doppler, and delay
- Leads to time-varying channel impulse response

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

- Narrowband channel
  - No signal distortion, just a complex amplitude gain
  - Signal amplitude varies randomly (Rayleigh, Ricean, Nakagami).
  - 2nd order statistics (Bessel function), Average fade duration

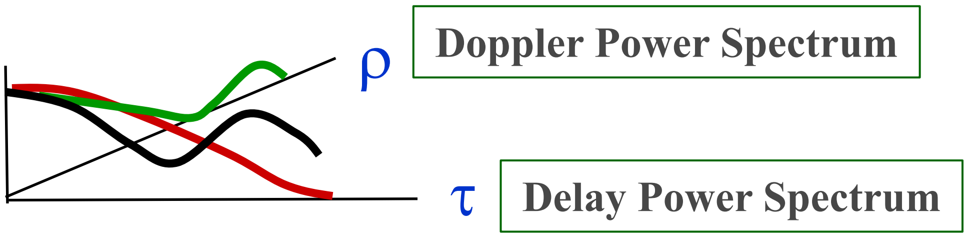
Wideband Channels

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



- Scattering function

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



  - 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

- Channel Capacity
  - Maximum data rate that can be transmitted over a channel with arbitrarily small error
- Capacity of AWGN Channel: $B\log_2[1+\gamma]$ bps
  - $\gamma=P_r/(N_0B)$ is the receiver SNR
- Capacity of Flat-Fading Channels
  - Nothing known: capacity typically zero
  - Fading Statistics Known (few results)
  - Fading Known at RX (average capacity)

$$C=\int_0^\infty B\log_2(1+\gamma)p(\gamma)d\gamma \le B\log_2(1+\bar{\gamma})$$

- **Capacity in Flat-Fading: γ known at TX/RX**

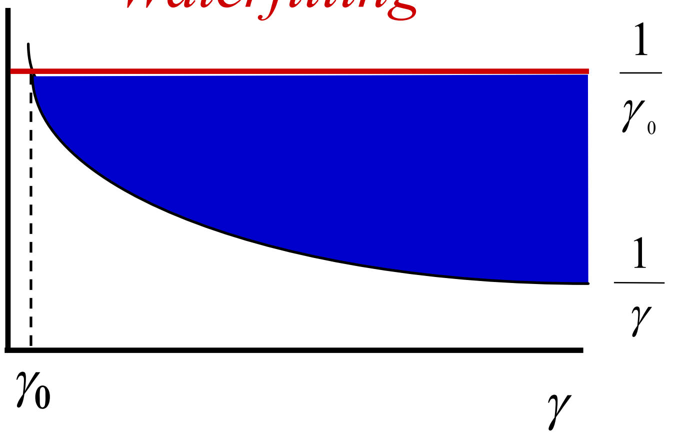
$$C = \max_{P(\gamma):E[P(\gamma)]=\overline{P}} \int_0^\infty B\log_2\left(1+\frac{\gamma P(\gamma)}{\overline{P}}\right)p(\gamma)d\gamma$$

- **Optimal Rate and Power Adaptation**

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

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

Waterfilling



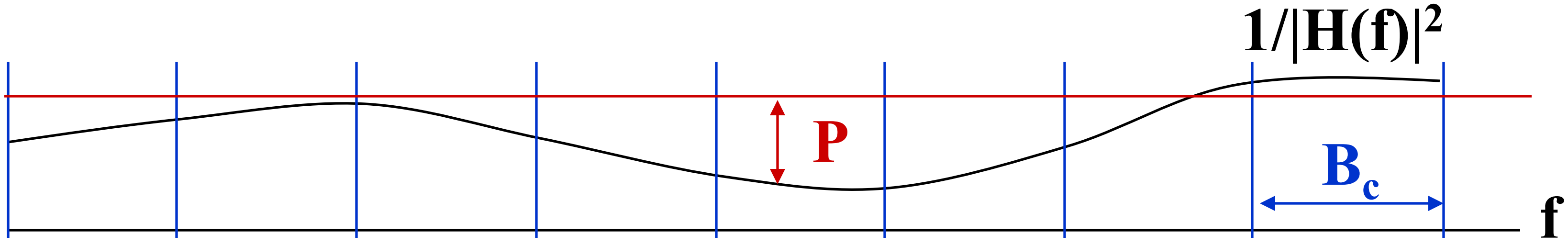
- **The instantaneous power/rate only depend on p(γ) through γ_0**

Channel Inversion

- Fading inverted to maintain constant SNR
- Simplifies design (fixed rate)
- Greatly reduces capacity
  - Capacity is zero in Rayleigh fading
- Truncated inversion
  - Invert channel above cutoff fade depth
  - Constant SNR (fixed rate) above cutoff
  - Cutoff greatly increases capacity
    - Close to optimal

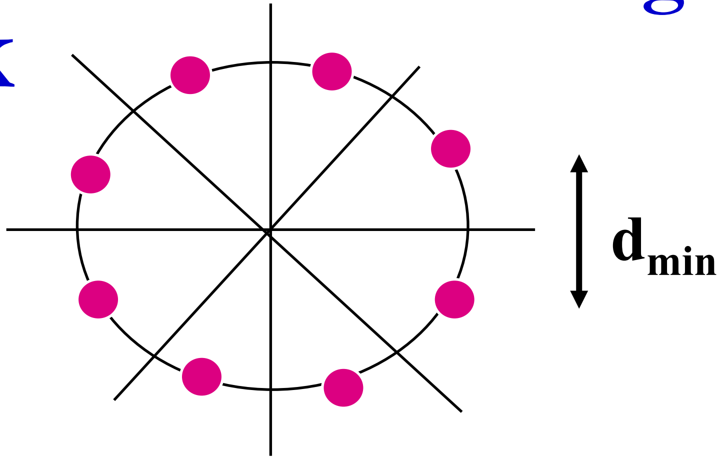
Frequency Selective Fading Channels

- 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
  - Independent fading in each subband
  - Capacity is the sum of subband capacities



Linear Modulation in AWGN: MPSK and MQAM

- ML detection induces decision regions
  - Example: 8PSK

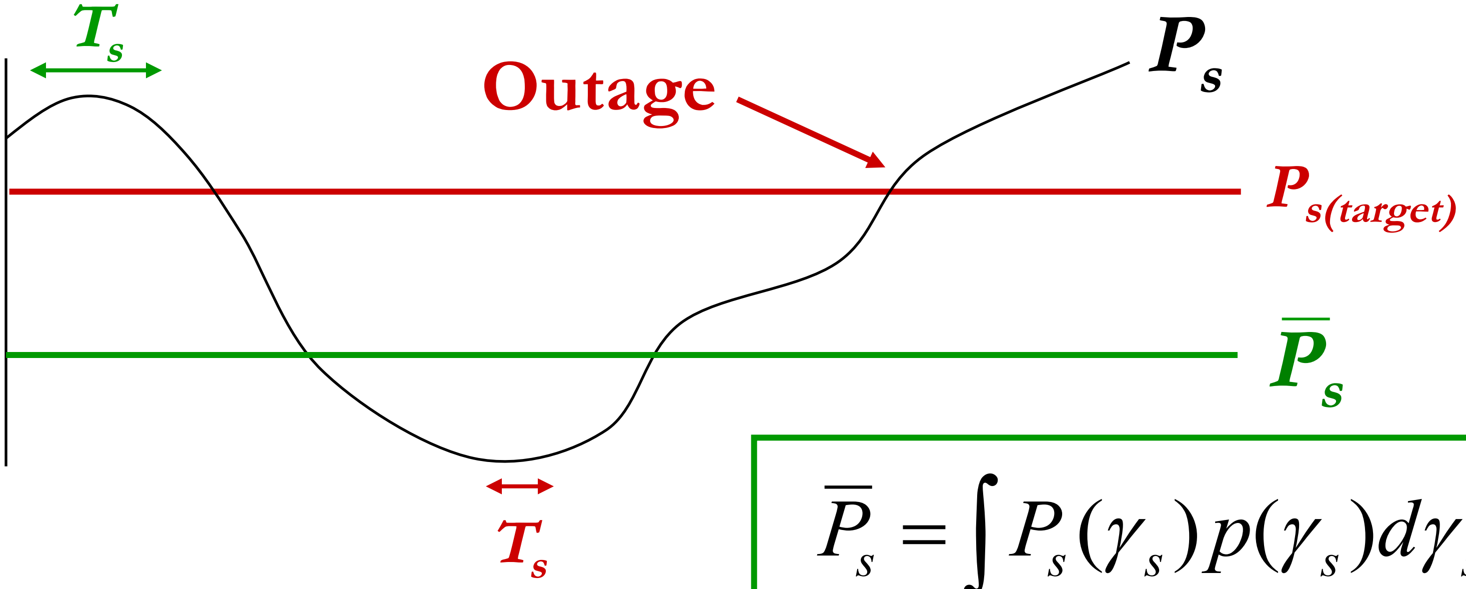


- P_s depends on
  - # of nearest neighbors
  - Minimum distance d_{min} *(depends on γ_s)*
  - Approximate expression

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

Linear Modulation in Fading

- In fading γ_s and therefore P_s random
- Metrics: outage, average P_s , combined outage and average.



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

Moment Generating Function Approach

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

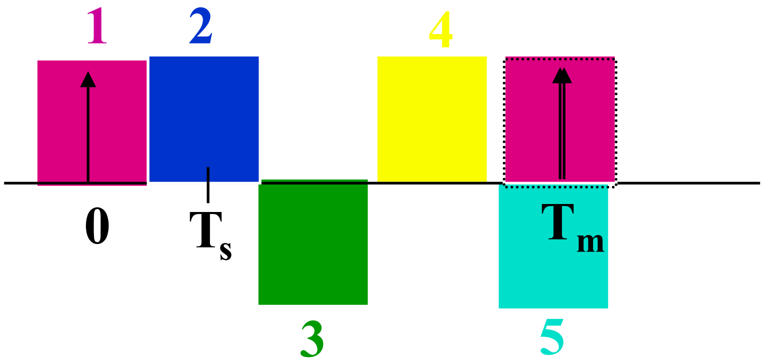
Doppler Effects

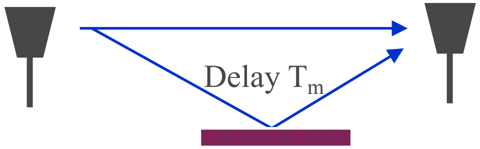
- High doppler causes channel phase to decorrelate between symbols
- Leads to an irreducible error floor for differential modulation
  - Increasing power does not reduce error
- Error floor depends on $f_D T_b$ as

$$P_{floor} = \frac{1 - J_0(2\pi f_D T_b)}{2} \approx .5(\pi f_D T_b)^2$$

Delay Spread (ISI) Effects

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





- ISI leads to irreducible error floor: $\overline{P}_{b,floor} \approx (\sigma_{T_m}/T_s)^2$
  - Increasing signal power increases ISI power
- ISI imposes data rate constraint: $T_s >> T_m$ ($R_s << B_c$)

$$R \leq \log_2(M) \times \sqrt{\overline{P}_{b,floor}/\sigma^2_{T_m}}$$

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)
  - 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.

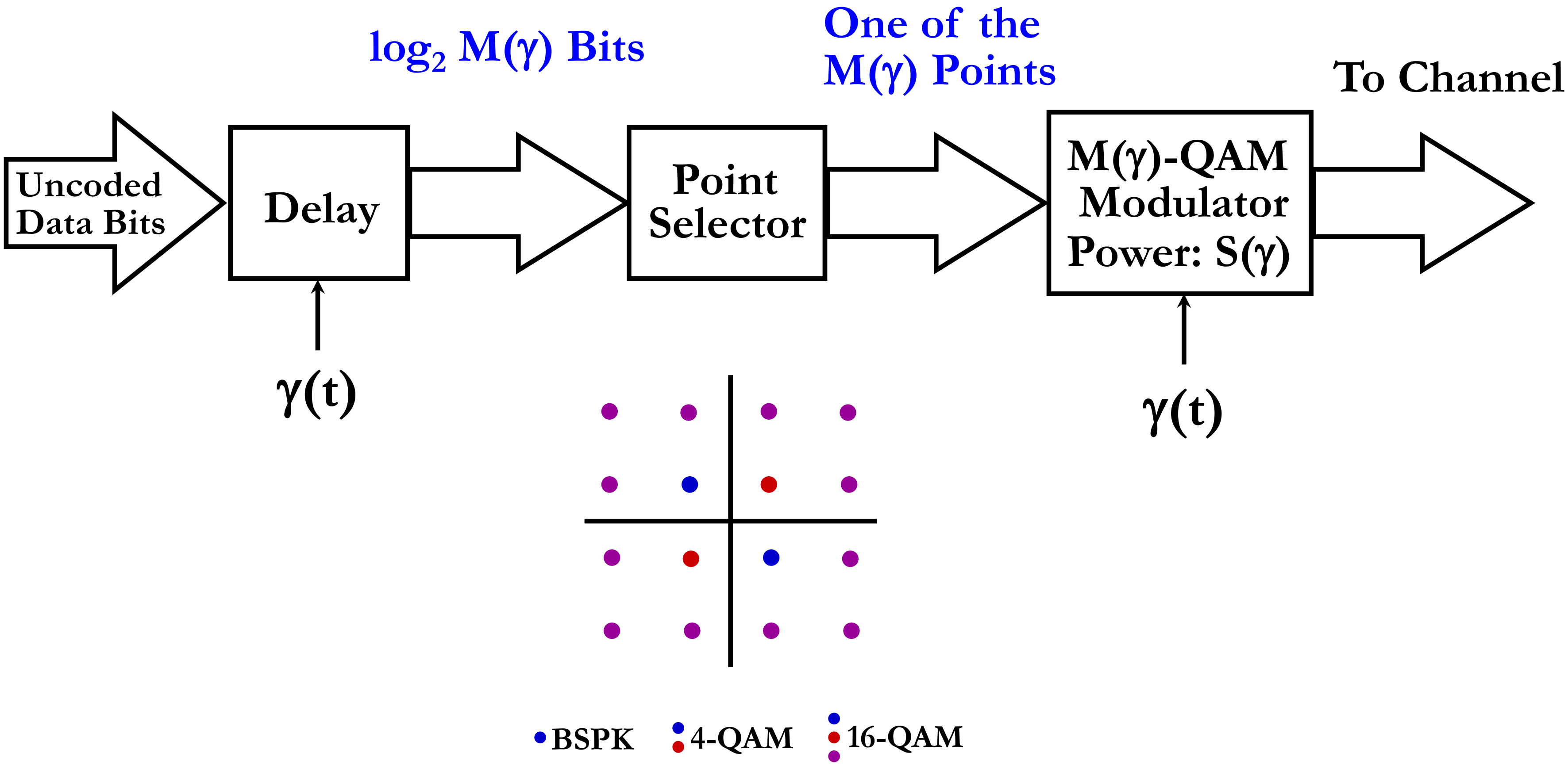
MRC and its Performance

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

$$\overline{P}_s = \int P_s(\gamma_\Sigma)\, p(\gamma_\Sigma)\, d\gamma_\Sigma = \int\int \ldots \int P_s(\gamma_\Sigma)\, p(\gamma_1) * p(\gamma_2) * \ldots * p(\gamma_M)\, d\gamma_1 d\gamma_2 \ldots d\gamma_M$$

  - Hard to obtain in closed form
  - Integral often diverges
- MGF Approach: $\overline{P}_s = \frac{\alpha_M}{\pi} \int_0^{\pi/2} \prod_{i=1}^{M} \mathcal{M}_{\gamma_i}\left[\frac{-.5\beta_M}{\sin^2\phi}\right] d\phi$
- TX diversity has same gains as RX diversity

Variable-Rate Variable-Power MQAM



Uncoded Data Bits

Delay

$\gamma(t)$

$\log_2 M(\gamma)$ Bits

Point Selector

One of the $M(\gamma)$ Points

$M(\gamma)$-QAM Modulator Power: $S(\gamma)$

$\gamma(t)$

To Channel

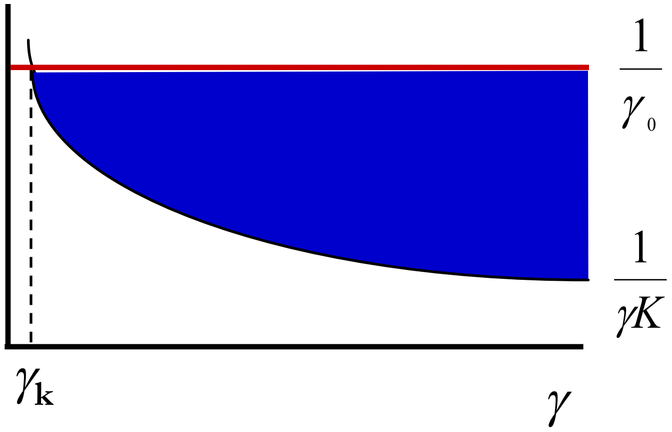
● BSPK ● 4-QAM ● 16-QAM

Goal: Optimize $S(\gamma)$ and $M(\gamma)$ to maximize $EM(\gamma)$

Optimal Adaptive Scheme

- **Power Water-Filling**

$$\frac{S(\gamma)}{\bar{S}} = \begin{cases} \frac{1}{\gamma_0} - \frac{1}{\gamma K} & \gamma \geq \frac{\gamma_0}{K} = \gamma_K \\ 0 & \textbf{else} \end{cases}$$

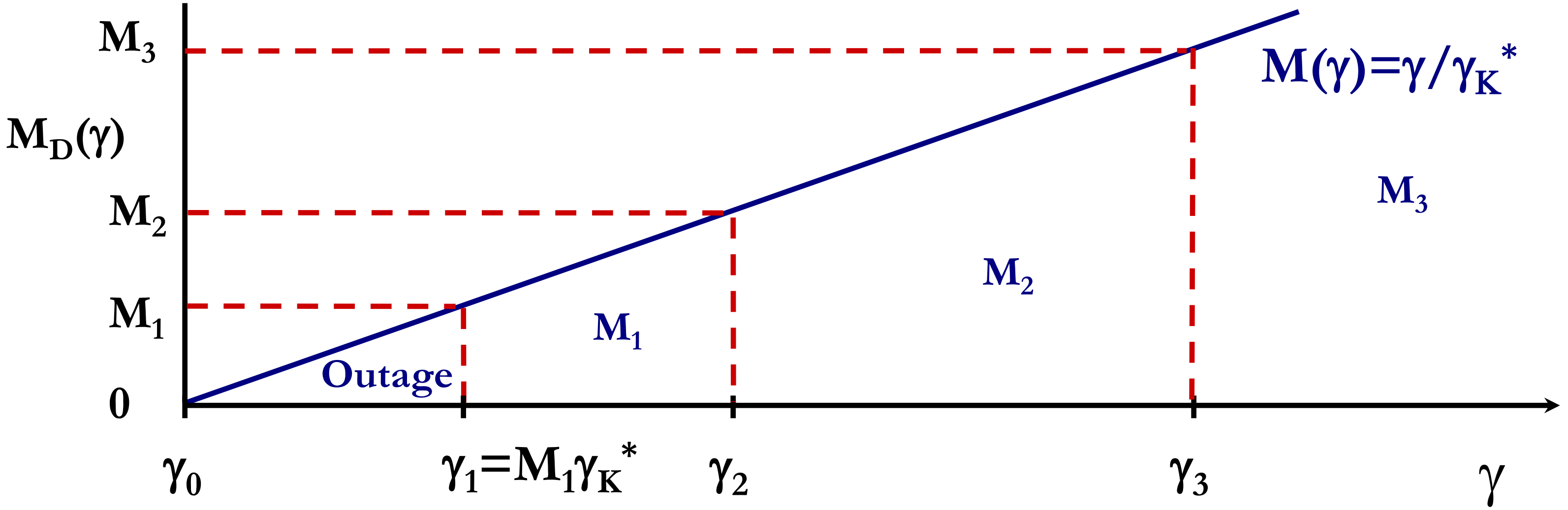


- **Spectral Efficiency**

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

Equals Shannon capacity with an effective power loss of K.

Constellation Restriction



- **Power adaptation:**

$$\frac{P_j(\gamma)}{P} = \begin{cases} (M_j-1)/(\gamma K) & \gamma_j \le \gamma < \gamma_{j+1}, j>0 \\ 0 & \gamma < \gamma_1 \end{cases}$$

- **Average rate:**

$$\frac{R}{B} = \sum_{j=1}^{N} \log_2 M_j p(\gamma_j \le \gamma < \gamma_{j+1})$$

Performance loss of 1-2 dB

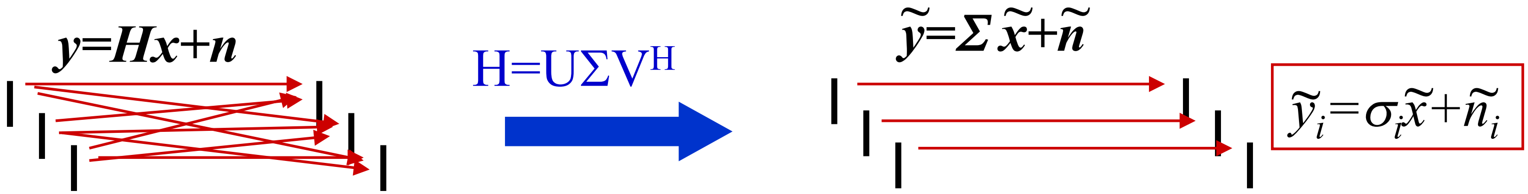
Practical Constraints

(not on final)

- Constant power restriction
  - Another 1-2 dB loss
- Constellation updates
  - Need constellation constant over 10-100T_s
- Estimation error and delay
  - Lead to imperfect CSIT (assume perfect CSIR)
  - Causes mismatch between channel and rate
  - Leads to an irreducible error floor

Multiple Input Multiple Output (MIMO)Systems

- MIMO systems have multiple (*M*) transmit and receiver antennas
- Decompose channel through transmit precoding ($x=V\tilde{x}$) and receiver shaping ($\tilde{y}=U^H y$)



$y=Hx+n$

$H=U\Sigma V^H$

$\tilde{y}=\Sigma\tilde{x}+\tilde{n}$

$\boxed{\tilde{y}_i=\sigma_i\tilde{x}+\tilde{n}_i}$

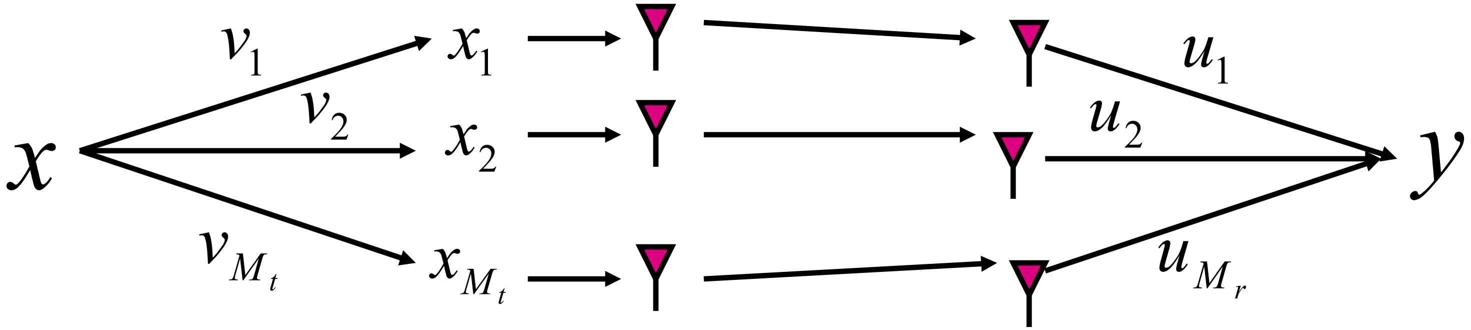
- Leads to $R_H \le \min(M_t,M_r)$ independent channels with gain σ_i (ith singular value of H) and AWGN
- Independent channels lead to simple capacity analysis and modulation/demodulation design

Capacity of MIMO Systems

- Depends on what is known at TX and RX and if channel is static or fading
- For static channel with perfect CSI at TX and RX, power water-filling over space is optimal:
  - In fading waterfill over space (based on short-term power constraint) or space-time (long-term constraint)
- Without transmitter channel knowledge, capacity metric is based on an outage probability
  - P_{out} is the probability that the channel capacity given the channel realization is below the transmission rate.
- Massive MIMO: in high SNR, singular values converge to a constant: $C=\min(M_t,M_r)B\log(1+\rho)$

Beamforming

- Scalar codes with transmit precoding

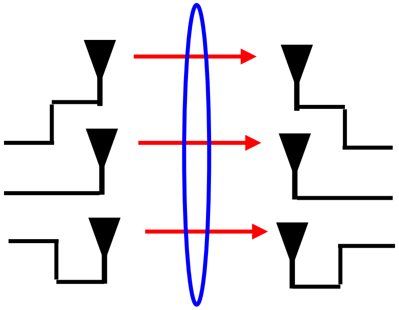


$$\boxed{y=\boldsymbol{u}^H\boldsymbol{H}\boldsymbol{v}x+\boldsymbol{u}^H\boldsymbol{n}}$$

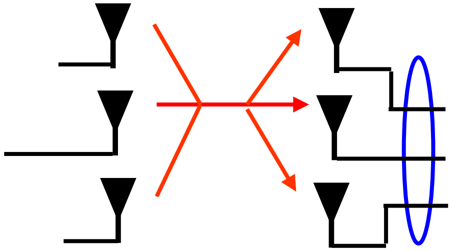
- Transforms system into a SISO system with diversity.
  - Array and diversity gain
  - Greatly simplifies encoding and decoding.
  - Channel indicates the best direction to beamform
  - Need "sufficient" knowledge for optimality of beamforming
- Precoding transmits more than 1 and less than R_H streams
  - Transmits along some number of dominant singular values

Diversity vs. Multiplexing

- Use antennas for multiplexing or diversity



Error Prone



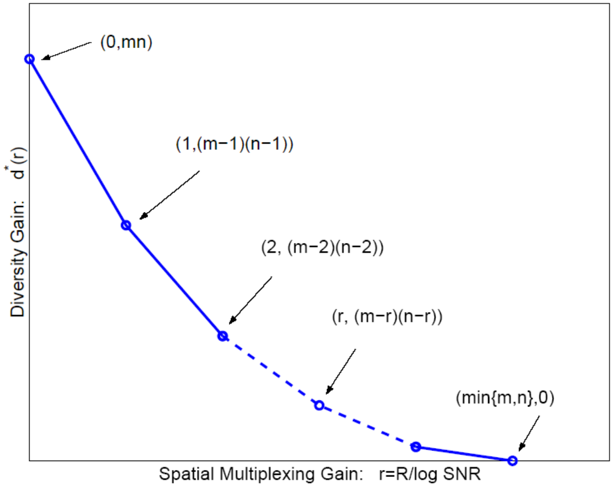
Low P_e

- Diversity/Multiplexing tradeoffs (Zheng/Tse)

$$\lim_{SNR\to\infty}\frac{\log P_e(SNR)}{\log SNR} = -d$$

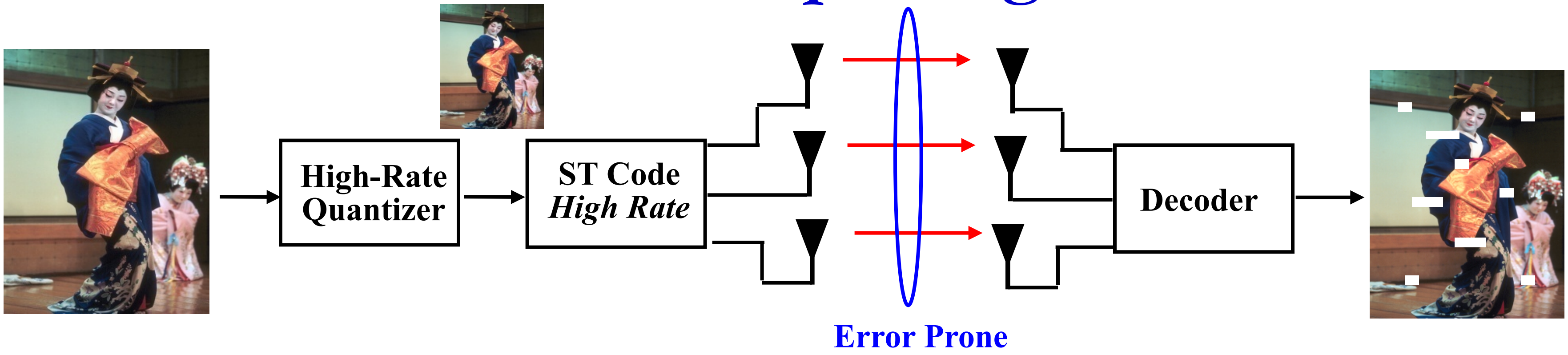
$$\lim_{SNR\to\infty}\frac{R(SNR)}{\log SNR} = r$$

$$\boxed{d^*(r) = (M_t - r)(M_r - r)}$$

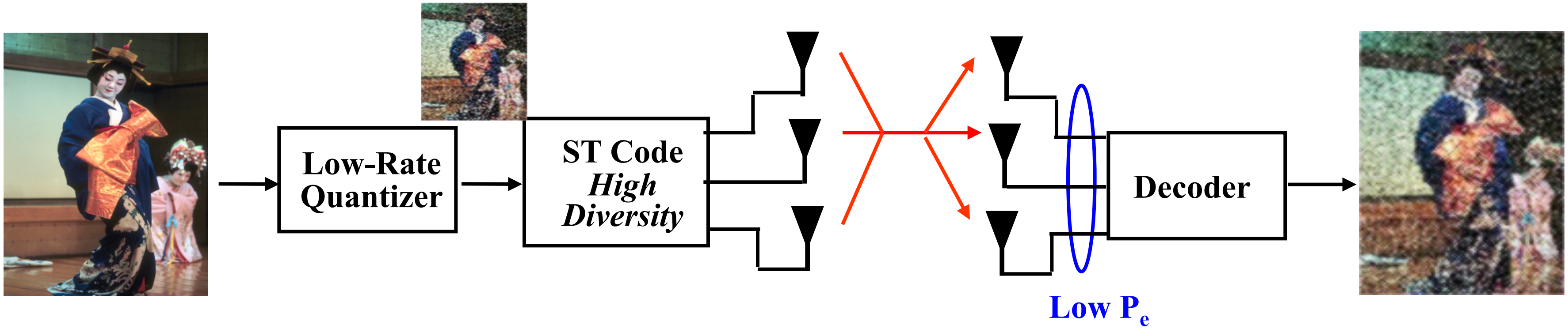


How should antennas be used?

- Use antennas for multiplexing:



- Use antennas for diversity



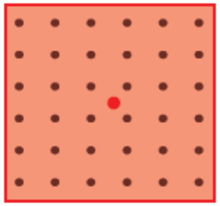
Depends on end-to-end metric: *Solve by optimizing app. metric*

MIMO Receiver Design

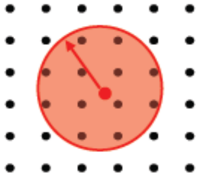
- Optimal Receiver:
  - Maximum likelihood: finds input symbol most likely to have resulted in received vector
  - Exponentially complex # of streams and constellation size
- Linear Receivers
  - Zero-Forcing: forces off-diagonal elements to zero, enhances noise
  - Minimum Mean Square Error: Balances zero forcing against noise enhancement
- Sphere Decoder:
  - Only considers possibilities within a sphere of received symbol.
    - If minimum distance symbol is within sphere, optimal, otherwise null is returned

$$\hat{x} = \arg\min |y - Hx|^2$$

ML Decoding



Sphere Decoding



$$\hat{x} = \arg\min_{x:|y-Hx|<r} |y - Hx|^2$$

Other MIMO Design Issues
Not covered in lecture/HW/exams

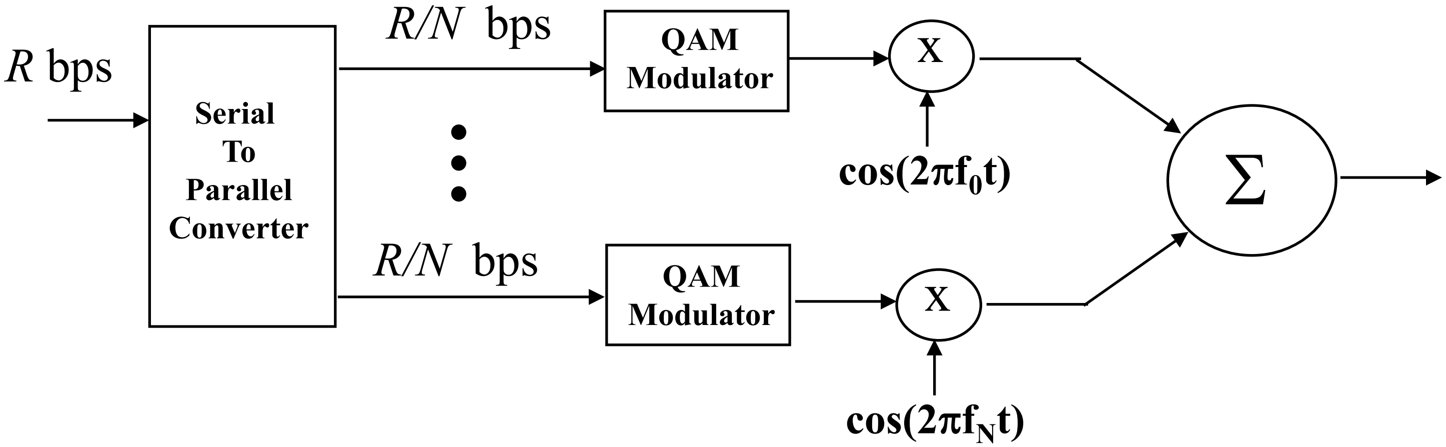
- Space-time coding:
  - Map symbols to both space and time via space-time block and convolutional codes.
  - For OFDM systems, codes are also mapped over frequency tones.
- Adaptive techniques:
  - Fast and accurate channel estimation
  - Adapt the use of transmit/receive antennas
  - Adapting modulation and coding.
- Limited feedback transmit precoding:
  - Partial CSI introduces interference in parallel decomp: can use interference cancellation at RX
  - TX codebook design for quantized channel

ISI Countermeasures

- Equalization
  - Signal processing at receiver to eliminate ISI
  - Complex at high data rates, performs poorly in fast-fading
  - Not used in state-of-the-art wireless systems
- Multicarrier Modulation
  - Break data stream into lower-rate substreams modulated onto narrowband flat-fading subchannels
- Spread spectrum
  - Superimpose a fast (wideband) spreading sequence on top of data sequence, allows resolution for combining or attenuation of multipath components.
- Antenna techniques (Massive MIMO)
  - (Highly) directional antennas reduce delay spread/ISI

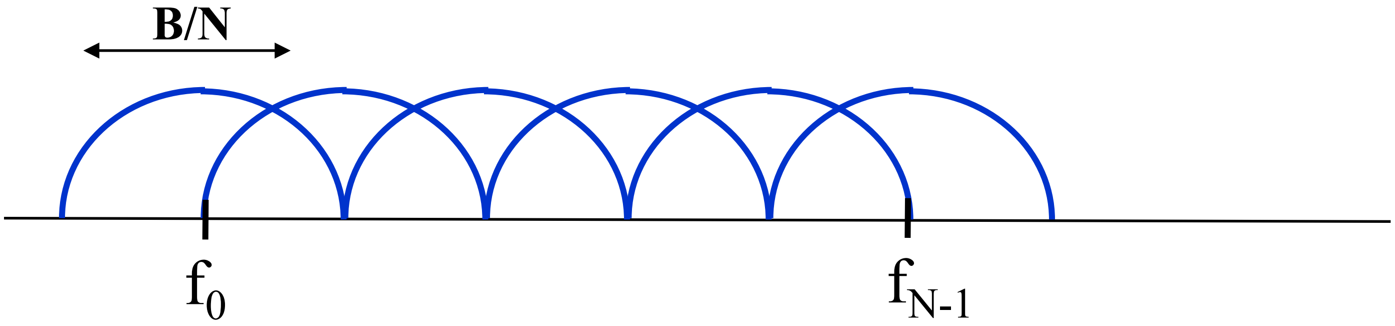
Multicarrier Modulation

- Divides bit stream into N substreams
- Modulates substream with bandwidth B/N
  - Separate subcarriers
  - $B/N<B_c \Rightarrow$ flat fading (no ISI)
- Requires N modulators and demodulators
  - Impractical: solved via OFDM implementation



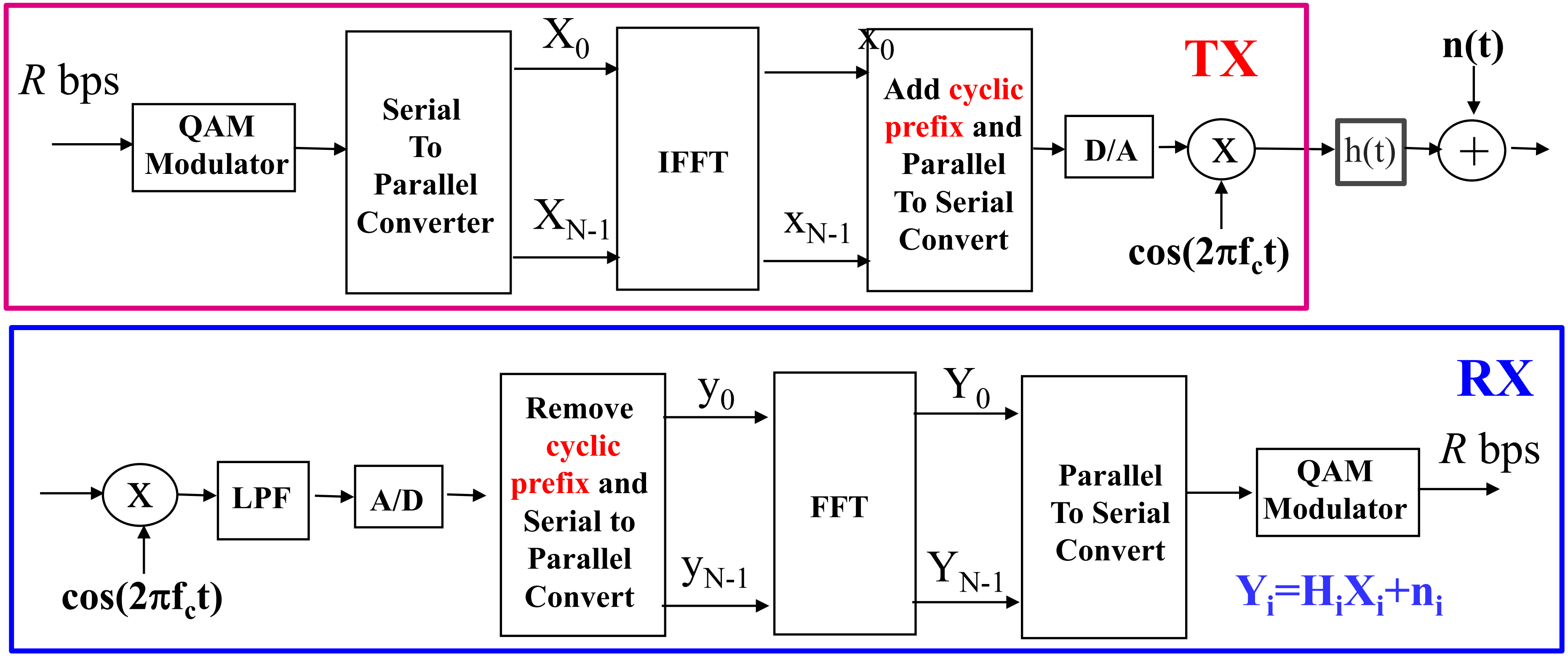
Overlapping Substreams

- Can have completely separate subchannels
  - Required passband bandwidth is B.
- OFDM overlaps substreams
  - Substreams (symbol time T_N) separated in RX
  - Minimum substream separation is B_N.
  - Total required bandwidth is B/2 (for $T_N=1/B_N$)



FFT Implementation of OFDM

- Use IFFT at TX to modulate symbols on each subcarrier
- Cyclic prefix makes linear convolution of channel circular, so no interference between FFT blocks in RX processing
- Reverse structure (with FFT) at receiver



TX

R bps

QAM Modulator

Serial To Parallel Converter

X_0

X_{N-1}

IFFT

x_0

x_{N-1}

Add cyclic prefix and Parallel To Serial Convert

D/A

X

$\cos(2\pi f_c t)$

h(t)

n(t)

+

RX

X

$\cos(2\pi f_c t)$

LPF

A/D

Remove cyclic prefix and Serial to Parallel Convert

y_0

y_{N-1}

FFT

Y_0

Y_{N-1}

Parallel To Serial Convert

QAM Modulator

R bps

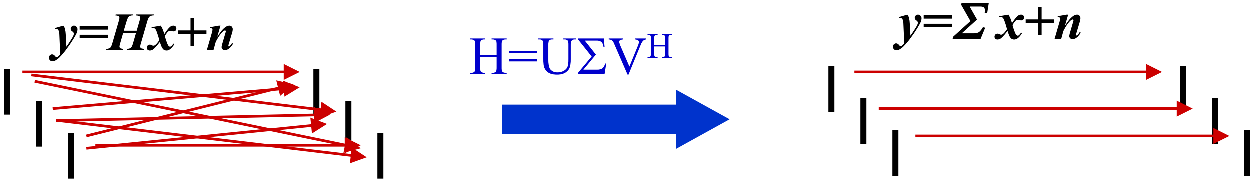
$Y_i = H_i X_i + n_i$

OFDM Design Issues

- Timing/frequency offset:
  - Impacts subcarrier orthogonality; self-interference
- Peak-to-Average Power Ratio (PAPR)
  - Adding subcarrier signals creates large signal peaks
  - Solve with clipping or PAPR-optimized coding
- Different fading across subcarriers
  - Mitigate by precoding (fading inversion), adaptive modulation over frequency, and coding across subcarriers
- MIMO-OFDM
  - Apply OFDM across each spatial dimension
  - Can adapt across space, time, and frequency
  - MIMO-OFDM represented by a matrix, extends matrix representation of OFDM alone (considered in HW)

MIMO-OFDM

- Send OFDM symbol along each spatial dimension
  - MIMO diversity-capacity benefits, OFDM removes ISI
  - Can adapt across time, space, and frequency

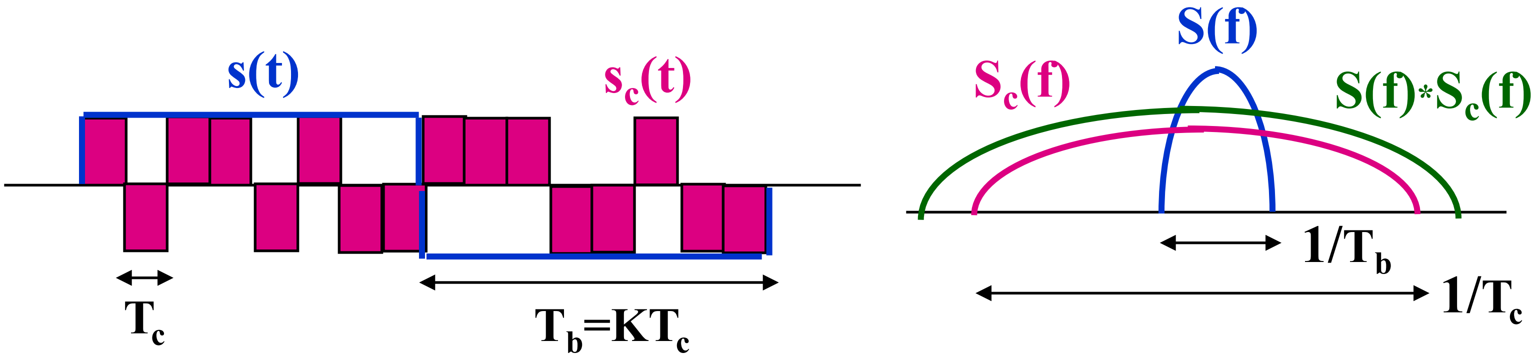


- OFDM can be represented by a matrix:
  - Represents DFT as a matrix: $y=\hat{H}x+\nu$, $\hat{H}$ circulant
  - Then vector $Y=\Lambda X+\nu_Q$ for Λ an NxN diagonal matrix
  - Cyclic prefix added after DFT

- MIMO-OFDM matrix representation: $y=Hx+\nu$
  - Dimensions are H: $NM_r x(N+\mu)M_t$; x: $(N+\mu)M_t$; y,ν: M_rN
  - Extends matrix representation of OFDM (example in HW)

Direct Sequence Spread Spectrum

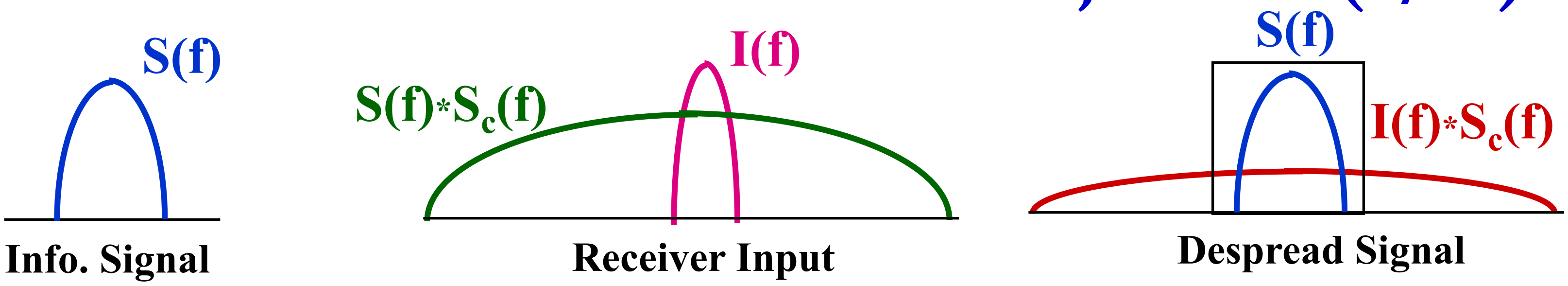
- Bit sequence modulated by chip sequence



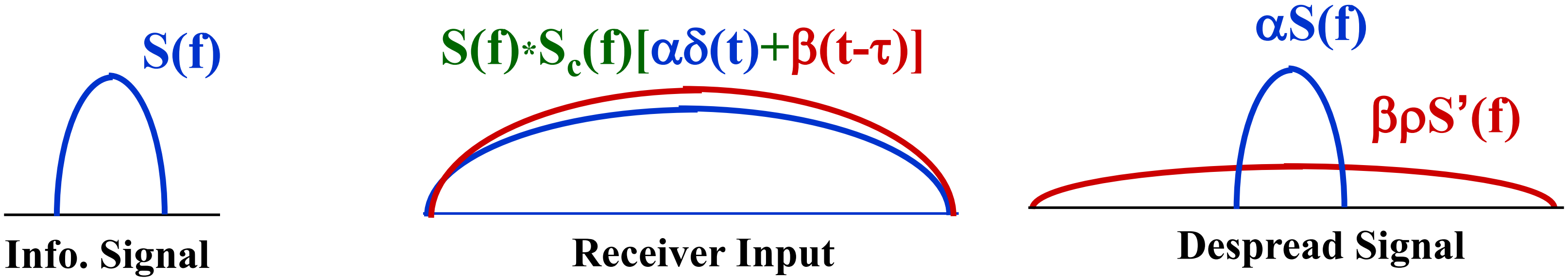
- Spreads bandwidth by large factor (K)
- Despread by multiplying by $s_c(t)$ again $(s_{c_{2}}(t)=1)$
- Mitigates ISI and narrowband interference
  - ISI mitigation a function of code autocorrelation
- Must synchronize to incoming signal

ISI and Interference Rejection

- Narrowband Interference Rejection (1/K)



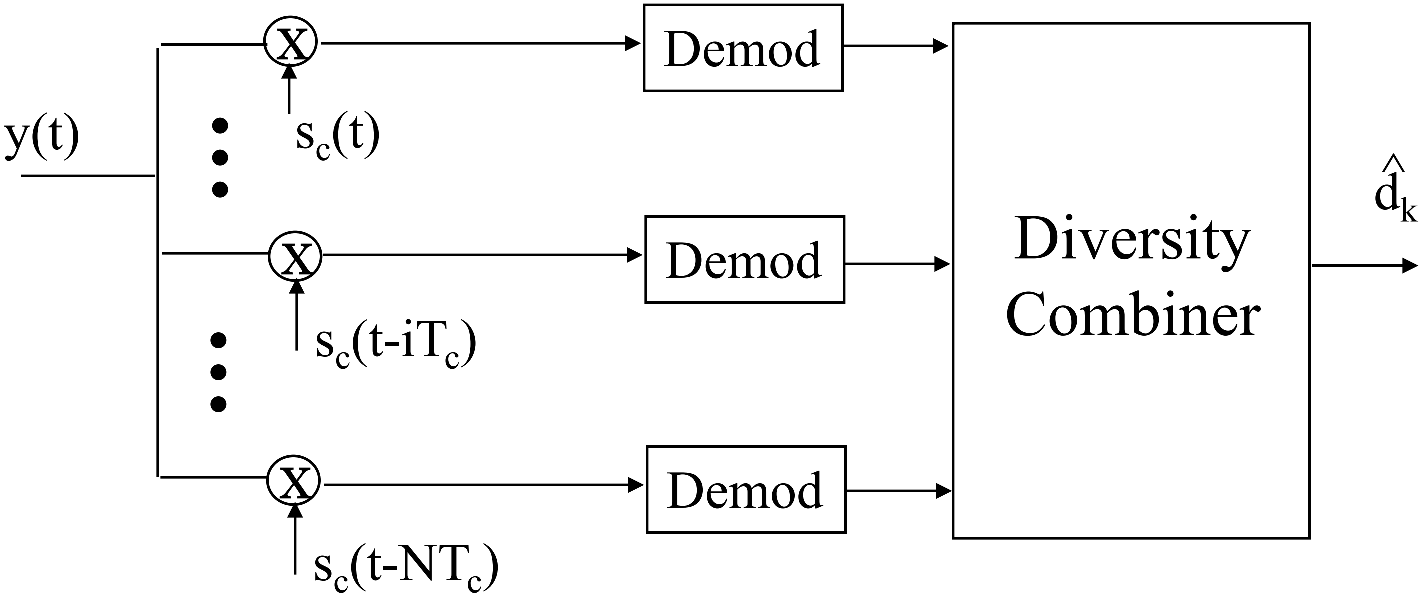
- Multipath Rejection (Autocorrelation ρ(τ))



  - Short codes repeat every Ts, so poor multipath rejection at integer multiples of Ts
  - Otherwise take a partial autocorrection

RAKE Receiver

- **Multibranch receiver**
  - **Branches synchronized to different MP components**



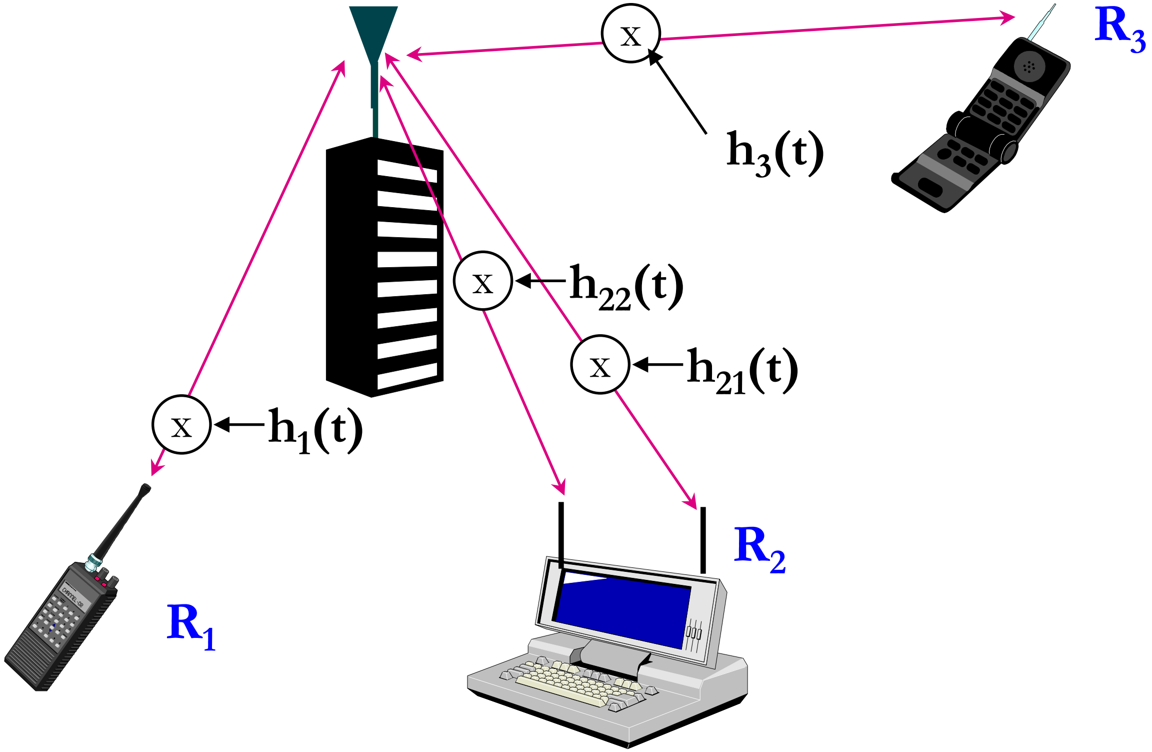
- **These components can be coherently combined**
  - **Use SC, MRC, or EGC**

Multiple Access

Sharing system resources across multiple users

Uplink:
Many Transmitters
to One Receiver.

Downlink:
One Transmitter
to Many Receivers.

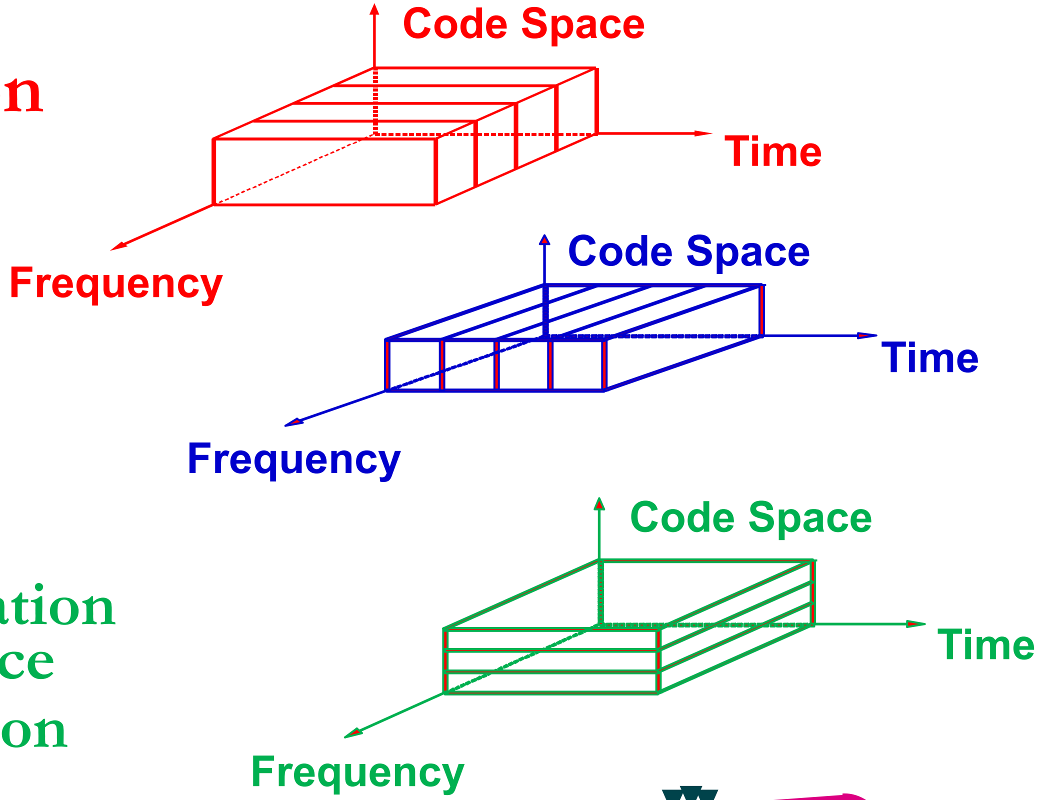


Uplink and Downlink typically duplexed in time or frequency

Full-duplex radios are being considered for 5G systems

Creating Multiple Channels

- Frequency Division
  - OFDMA
- Time Division
- Code Division
  - Code cross-correlation dictates interference
  - Multiuser Detection
- Space (MIMO Systems)
- Hybrid Schemes

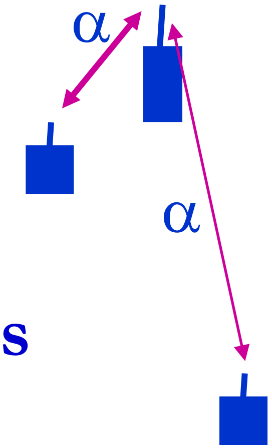


Code Division via DSSS

- Interference between users mitigated by code cross correlation

$$\hat{x}(t)=\int_0^{T_b}\alpha_1 s_1(t)s_{c1}^2(t)\cos^2(2\pi f_c t)+\alpha_2 s_2(t-\tau)s_{c2}(t-\tau)s_{c1}(t)\cos(2\pi f_c t)\cos(2\pi f_c(t-\tau))dt$$

$$=.5\alpha_1 d_1+.5\alpha_2 d_2\int_0^{T_b}s_{c1}(t)s_{c2}(t)dt=.5d_1+.5d_2\cos(2\pi f_c\tau)\rho_{12}(\tau)$$

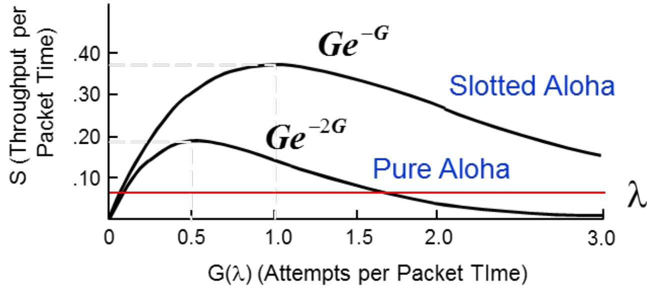


- In downlink, signal and interference have same received power
- In uplink, “close” users drown out “far” users (near-far problem)

Random Access

- In multiple access, channels are assigned by a centralized controller
  - Requires a central controller and control channel
  - Inefficient for short and/or infrequent data transmissions
- In random access, users access channel randomly when they have data to send
  - A simple random access scheme will be explored in homework

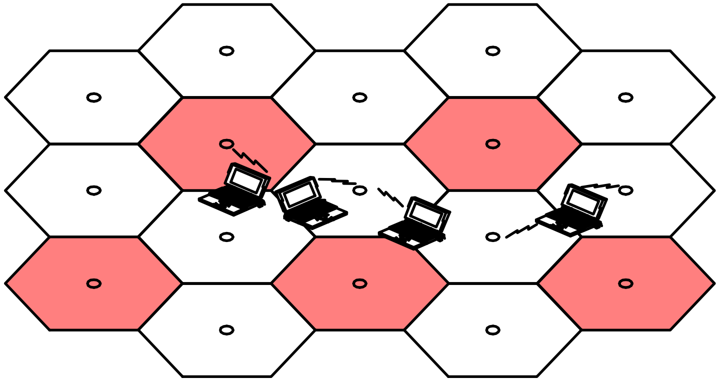
- ALOHA Schemes (not covered on exam)
  - Data is packetized.
  - Packets occupy a given time interval



- Pure ALOHA
  - send packet whenever data is available
  - a collision occurs for any partial overlap of packets (nonorthogonal slots)
  - Packets received in error are retransmitted after random delay interval (avoids subsequent collisions).

- Slotted ALOHA
  - same as ALOHA but with packet slotting
  - packets sent during predefined timeslots
  - A collision occurs when packets overlap, but there is no partial overlap of packets
  - Packets received in error are retransmitted after random delay interval.

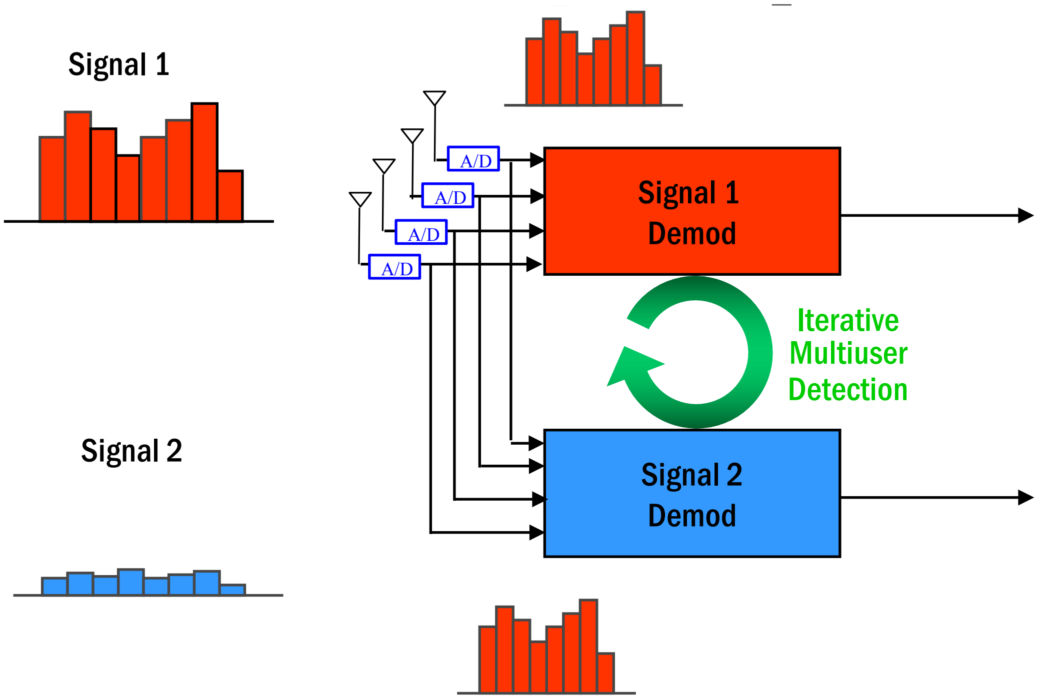
Cellular System Design



- Frequencies/time slots/codes reused at spatially-separated locations
  - Exploits power falloff with distance.
  - Best efficiency obtained with minimum reuse distance
- Base stations perform centralized control functions
  - Call setup, handoff, routing, etc.
- Ideally, interference results in SINR above desired target.
  - The SINR depends on base station locations, user locations, propagation conditions, and interference reduction techniques.
  - System capacity is interference-limited as SINR must be above target
  - MIMO introduces diversity-multiplexing-interference reduction tradeoff
  - Multiuser detection reduces inter/intracell interference: increases capacity

Multiuser Detection

- Multiuser detection (MUD) exploits the fact that the structure of the interference is known
  - Maximum likelihood: exponentially complex in number of users *N*
  - Successive interference cancellation (SIC)

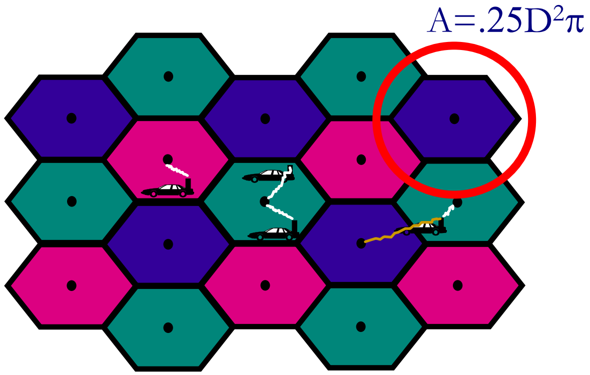


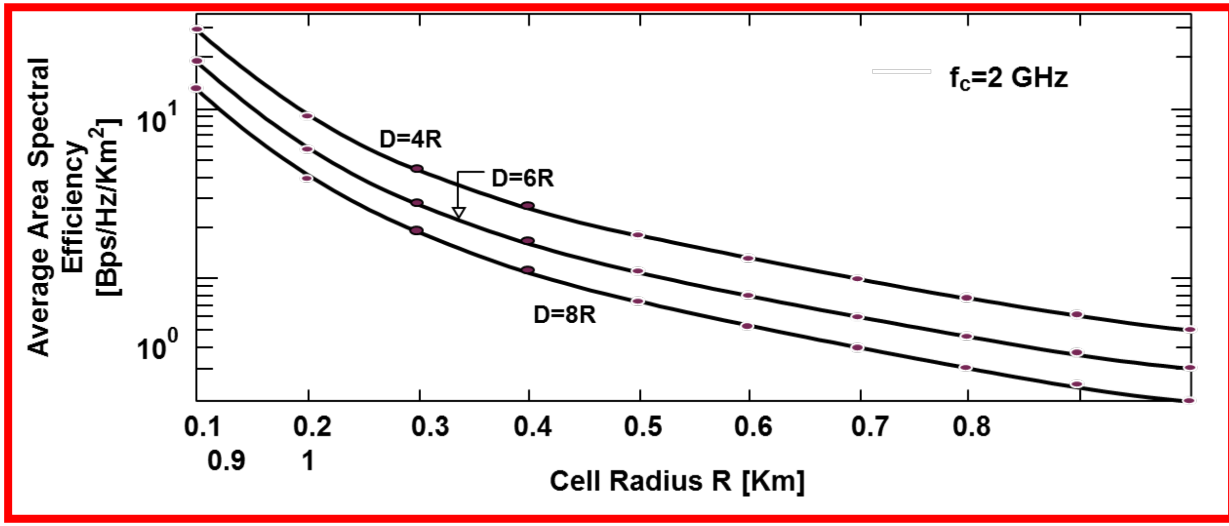
Why not ubiquitous today? Power, A/D Precision, Error propagation

Area Spectral Efficiency (ASE)

- **System capacity due to optimal cell size and/or reuse distance:** $A_e = \Sigma R_i / (.25 D^2 \pi)$ bps/Hz/Km^2.

Area Spectral Efficiency





- S/I increases with reuse distance (increases link capacity).
- Tradeoff between reuse distance and link spectral efficiency (bps/Hz).
- Capacity increases exponentially as cell size decreases
- Future cellular systems will be hierarchical
  - Large cells for coverage, small cells for capacity

Megathemes of EE359

- The wireless vision poses great technical challenges
- The wireless channel greatly impedes performance
  - Low fundamental capacity; Channel is randomly time-varying.
  - Flat fading and ISI must be compensated for.
- Compensate for flat fading with diversity or adaptive mod.
  - MIMO provides diversity and/or multiplexing gain
- A plethora of ISI compensation techniques exist
  - Various tradeoffs in performance, complexity, and implementation.
  - OFDM is the dominant technique; works well with MIMO, basis for 4G/5G Cellular/WiFi due to adaptivity over time/space/frequency
- Sharing spectrum among multiple users a major challenge
- Cellular systems exploit frequency reuse; better physical layer design, flexibility, and interference reduction needed in 5G