EE359 – Lecture 16 Outline

- Announcements:
  - HW due Fri, new HW to be posted, due week after Thanksgiving
  - End-of-Quarter schedule and possible bonus lecture
  - Project comments this week.
- MIMO Receiver Design
  - Linear Receivers, Sphere Decoder
- Other MIMO Design Issues
  - Space-time coding, adaptive techniques, limited feedback
- ISI Countermeasures
- Multicarrier Modulation

End of Quarter Schedule

- Today is last lecture this week
- Lectures week of 11/20: None!
- Thu 11/30 lecture will be Fri 12/1 (10:30, here)
- Normal lectures week of 12/4
  - 12/7 lecture: 10:30am-11:30am (class summary), 11:30am-12:30pm (bonus lecture on advanced topics)
- Final exam is 12/13 from 12:15-3:15pm

Review of last lecture

Capacity of Fading & Massive MIMO Systems

- **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)**

$$C = \mathrm{E}_{\mathbf{H}}\left[\max_{\mathbf{R_x}:\mathrm{Tr}(\mathbf{R_x})=\rho} B\log_2\det\left[\mathbf{I}_{\mathbf{M_r}} + \mathbf{H}\mathbf{R_x}\mathbf{H}^{\mathbf{H}}\right]\right] = \mathrm{E}_{\mathbf{H}}\left[\max_{P_i:\sum_i P_i\le P}\sum_i B\log_2\left(1+\frac{P_i\gamma_i}{P}\right)\right].$$

  - **Or over space-time (long-term constraint)**

$$C = \max_{P_H : E_H[P_H]\le \overline{P}} E_H\left[\max_{P_i:\sum_i P_i \le P_H}\sum_i B\log_2\left(1+\frac{P_i\gamma_i}{P_H}\right)\right]$$

- **Without transmitter channel knowledge, capacity metric is based on an outage probability with respect to transmitted rate C:**

$$p_{out} = p\left(\mathbf{H} : B\log_2\det\left[\mathbf{I}_{M_r} + \frac{\rho}{M_t}\mathbf{H}\mathbf{H}^H\right] < C\right)$$

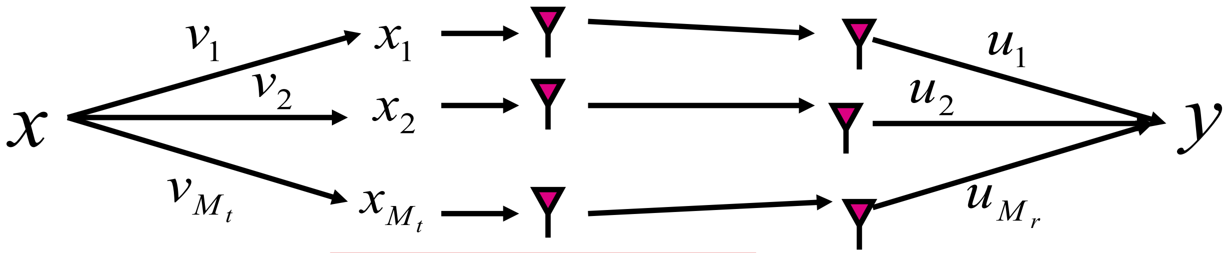
Correction to Lect. 15 ppt slides

- **Massive MIMO: At high SNR, as Mt,Mr→ ∞, by random matrix theory**

$$\mathbf{C=\min(M_t,M_r)B\log_2(1+\rho)}$$

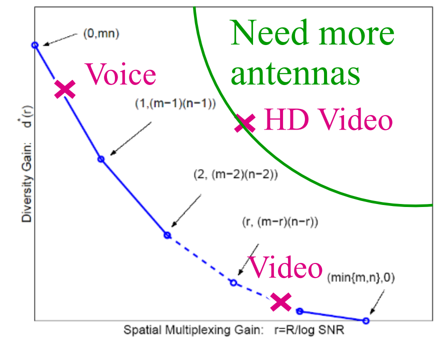
Review of Last Lecture (Cont'd)

- **Beamforming: Scalar transmission**
  - **Principle vectors of U and V are weights: maximizes SNR**



$$y = u^H H v x + u^H n$$

- **Diversity-Multiplexing Tradeoff: high SNR**
  - **Can use some antennas for diversity, some for capacity gain: $d^*(r) = (M_t - r)(M_r - r)$**
  - **How antennas used depends on system metric**
  - **If requirements unmet, need more antennas**

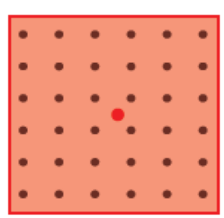


MIMO Receiver Design

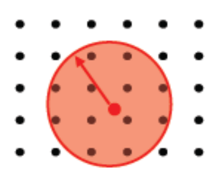
- Optimal Receiver:
  - Maximum likelihood: finds input symbol most likely to have resulted in received vector
  - Exponentially complex # of streams and constellation size
- Linear Receivers
  - Zero-Forcing: forces off-diagonal elements to zero, enhances noise
  - Minimum Mean Square Error: Balances 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

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

ML Decoding



Sphere Decoding



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

Other MIMO Design Issues

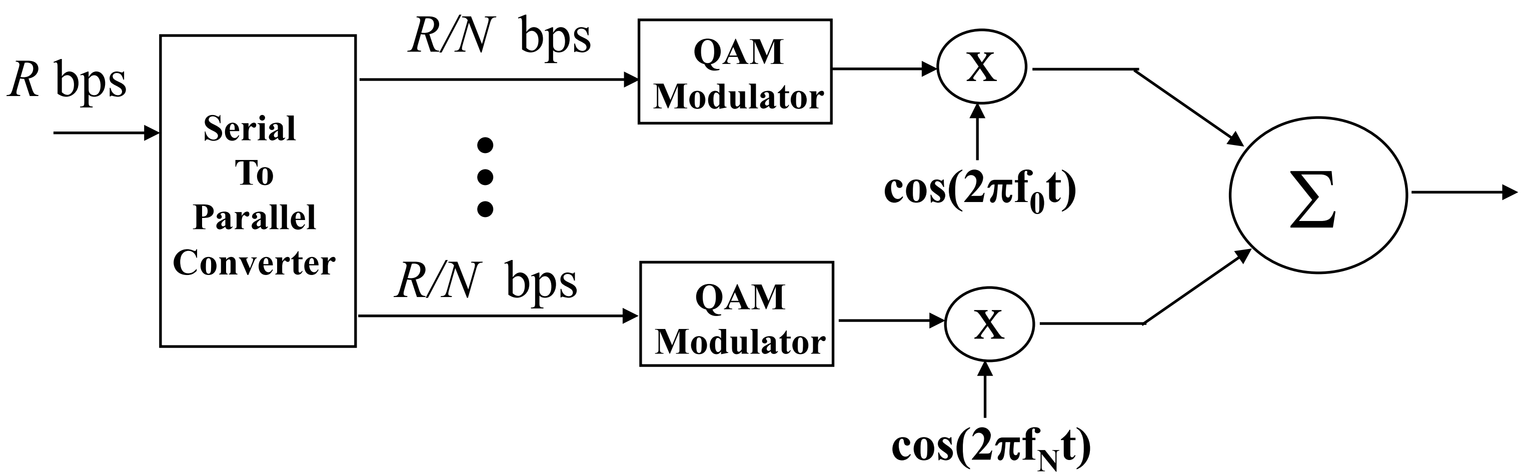
Not covered in lecture/HW/exams

- 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:
  - Need 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

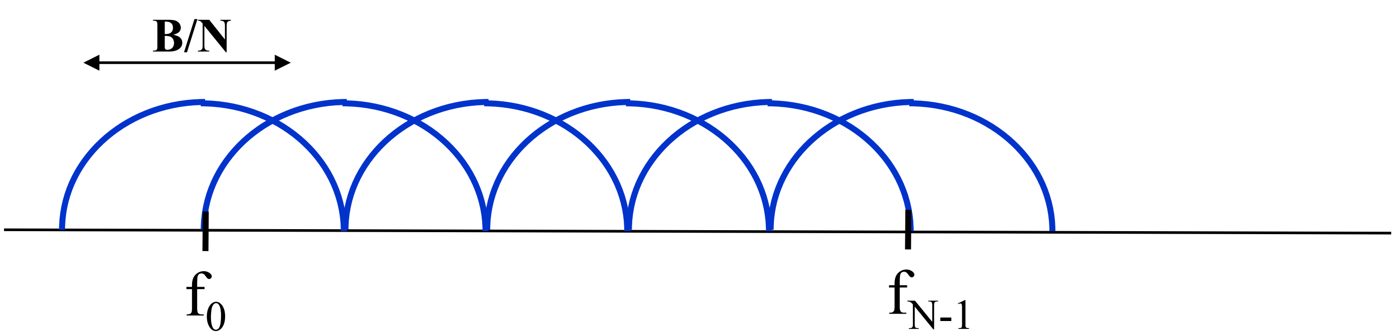
Multicarrier Modulation



- Breaks data into N substreams
- Substream modulated onto separate carriers
  - Substream passband BW is B/N for B total BW
  - $B/N<B_c$ implies flat fading on each subcarrier (no ISI)

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 $1/T_N$ for rectangular pulses
  - Total required bandwidth is B/2



Main Points

- MIMO RX design trades complexity for performance
  - ML detector optimal - exponentially complex
  - DF receivers prone to error propagation
  - Sphere decoders allow performance tradeoff via radius

- Other MIMO design issues include space-time coding, adaptation, codebooks for limited feedback

- ISI mitigated through equalization, multicarrier modulation (MCM) or spread spectrum
  - Today, equalizers often too complex or can't track channel.
  - MCM splits channel into NB flat fading subchannels
  - Can overlap subcarriers to preserve bandwidth