Announcements:
- HW due Fri, new HW to be posted, due week after Thanksgiving
- End-of-Quarter schedule and possible bonus lecture
- Project comments today (I promise). No OHs after class but available by phone and next week in person.

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 11/21: None!
- Normal lectures week of 11/28
- Lectures week of 12/5 (rescheduled):
  - 12/5 (Monday): 12-1:20 in Thorton 102 w/lunch
  - 12/9 (Friday): 9:30-10:30am (class summary), 10:30-11:30am (bonus lecture on advanced topics), w/donuts
- Final exam is 12/15 from 12.15-3.15 pm in this room (Huang 18).
Review of last lecture

Capacity of MIMO Systems

- Depends on what is known at TX/RX and if channel 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)

\[
C = E_H \max_{\mathbf{R}_x: \text{Tr}(\mathbf{R}_x) = \rho} B \log_2 \det [\mathbf{I}_{\mathbf{M}_r} + \mathbf{H}\mathbf{R}_x\mathbf{H}^H] = E_H \max_{\mathbf{P}_i: \sum_i P_i \leq P} \sum_i B \log_2 \left(1 + \frac{P_i \gamma_i}{P}\right) \tag{10.16}
\]

  - Or over space-time (long-term constraint) (correction, Soleil was right)

\[
C = \max_{\mathbf{P}_H: E_H[\mathbf{P}_H] \leq \bar{P}} E_H \max_{\mathbf{P}_i: \sum_i P_i \leq \mathbf{P}_H} \sum_i B \log_2 \left(1 + \frac{P_i \gamma_i}{\mathbf{P}_H}\right) \tag{10.17}
\]

- 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: \(C = \min(\mathbf{M}_t, \mathbf{M}_r) B \log(1+\rho)\)
Review of Last Lecture (Cont’d)

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

  ![Beamforming Diagram]

  \[ y = u^H H v x + u^H n \]

- **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

Need more antennas

Voice
HD Video

HD Video

Spatial Multiplexing Gain: \( nR \log SNR \)
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

\[
\hat{x} = \arg\min_x |y - Hx|^2
\]

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

- 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