EE359 – Lecture 17 Outline

- **Announcements**
  - Thu lecture move to Fri, 10:30-11:50, here; Tom’s Fri OH 9:30-10:30
  - HW due Friday
  - Last HW will be posted Thurs, due Fri of dead week (no late HWs)
  - Last lecture 12/7 will be 10:30-11:30 (course review) and 11:30-12:30 (advanced topics; bonus lecture).

- **Multicarrier Modulation**
- **Overlapping subcarriers in MCM**
- **FFT implementation of MCM (OFDM)**
- **Implementation Challenges in OFDM**
- **Fading across Subcarriers**
- **MIMO-OFDM**
Review of Last Lecture

- **MIMO RX Design** (see supplemental handout):
  - Optimal Receiver is ML: finds input symbol most likely to have resulted in received vector, exponentially complex in $M_t$
  - Linear Receivers: First performs linear equalization: $\hat{x} = Ay$
    then quantizes $\hat{x}$ to nearest constellation point $x \in \mathcal{X}^{M_t}$
  - Zero-Forcing ($A = H^\dagger$, the Moore-Penrose pseudo inverse of $H$): (if $H$ invertible, equals inverse, else $H^\dagger = (H^H H)^{-1} H^H$); forces off-diagonal terms to zero ($\tilde{x}_i = x_i + \tilde{n}_i; \tilde{n} = H^\dagger n$, enhances noise)
  - Minimum Mean Square Error ($A = H^H (H H^H + \lambda I)^{-1}$): $\lambda \propto 1/\text{SNR}$
    Balances zero forcing against noise enhancement

- **Sphere Decoder**: Uses QR decomposition of $H$
  - Considers possibilities within sphere of transformed received symbol.
    - If minimum distance symbol is within sphere, optimal, otherwise null is returned

\[
\hat{x} = \arg \min \left| y - Hx + n \right|^2
\]

ML Decoding

Sphere Decoding

\[
\hat{x} = \arg \min \left| Q^H y - Rx + Q^H n \right|^2
\]

$x:|Q^H y - Rx|<r$
Multicarrier Modulation

- Can mitigate ISI with equalization (not commonly used or covered), multicarrier modulation, or spread spectrum
- Multicarrier Modulation: breaks data into N substreams \( B/N < B_c \); Substreams 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 $B$.

- MCM with overlapping substreams
  - Substreams (symbol time $T_N$) separated in RX
  - Minimum substream separation is $1/T_N$ for rectangular pulses
  - Total required bandwidth is $B/2$
FFT Implementation of MCM (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

\[
x(t) = \cos(2\pi f_c t)
\]

**TX**

- QAM Modulator
- Serial To Parallel Converter
- IFFT (+ pulse shaping)
- Add cyclic prefix and Parallel To Serial Convert
- D/A
- Cos(2πf_c t)

**RX**

- Parallel To Serial Convert
- QAM Modulator
- A/D
- LPF
- Remove cyclic prefix and Serial to Parallel Convert
- FFT
- Y_0
- Y_{N-1}
- X
- Cos(2πf_c t)
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)
Main Points

- MCM splits channel into NB flat fading subchannels
  - Overlapping subcarriers in OFDM reduces BW by 2x
- MCM implemented with IFFTs/FFT (OFDM)
  - Block size depends on data rate relative to delay spread
- OFDM challenges: timing/frequency offset, PAPR
- Subcarrier fading degrades OFDM performance
  - Compensate through precoding (channel inversion), coding across subcarriers, or adaptation
- OFDM naturally combined with MIMO
  - Orthogonal in space/freq; extended matrix representation
  - 4G Cellular and 802.11n/ac/ax all use OFDM+MIMO