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: $\tilde{x} = Ay$**

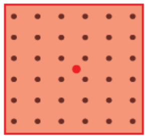
    then quantizes $\tilde{x}$ to nearest constellation point $x \in \mathcal{X}^{M_t}$
    - **Zero-Forcing ($A = \mathbf{H}^\dagger$, the Moore-Penrose pseudo inverse of H): (if H invertible, equals inverse, else $\mathbf{H}^\dagger = (\mathbf{H}^H\mathbf{H})^{-1}\mathbf{H}^H$); forces off-diagonal terms to zero ($\tilde{x}_i = x_i + \tilde{n}_i$; $\tilde{n} = \mathbf{H}^\dagger n$, enhances noise)**
    - **Minimum Mean Square Error ($A = \mathbf{H}^H(\mathbf{H}\mathbf{H}^H + \lambda\mathbf{I})^{-1}$): $\lambda \propto 1/SNR$ 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

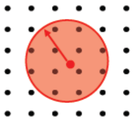
$$\hat{x} = \arg\min |y - Hx|^2$$

$Hx+n$

ML Decoding



Sphere Decoding

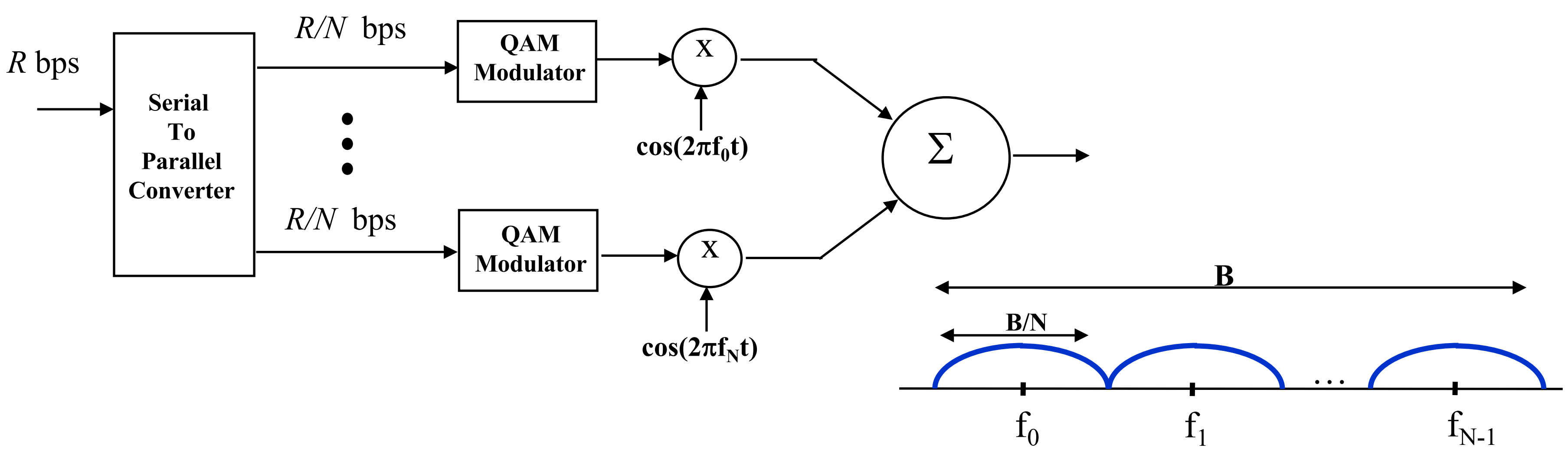


$$\hat{x} = \arg\min_{x:|Q^H y - Rx|<r} |Q^H y - Rx|^2$$

$Q^H y = Rx + Q^H n$

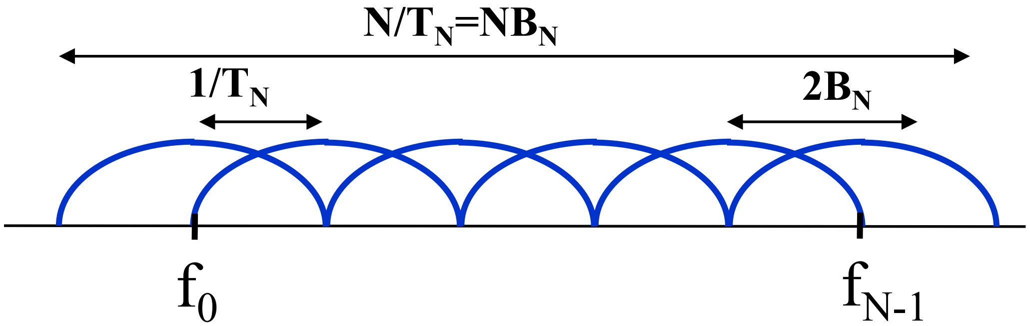
Multicarrier Modulation

- 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)



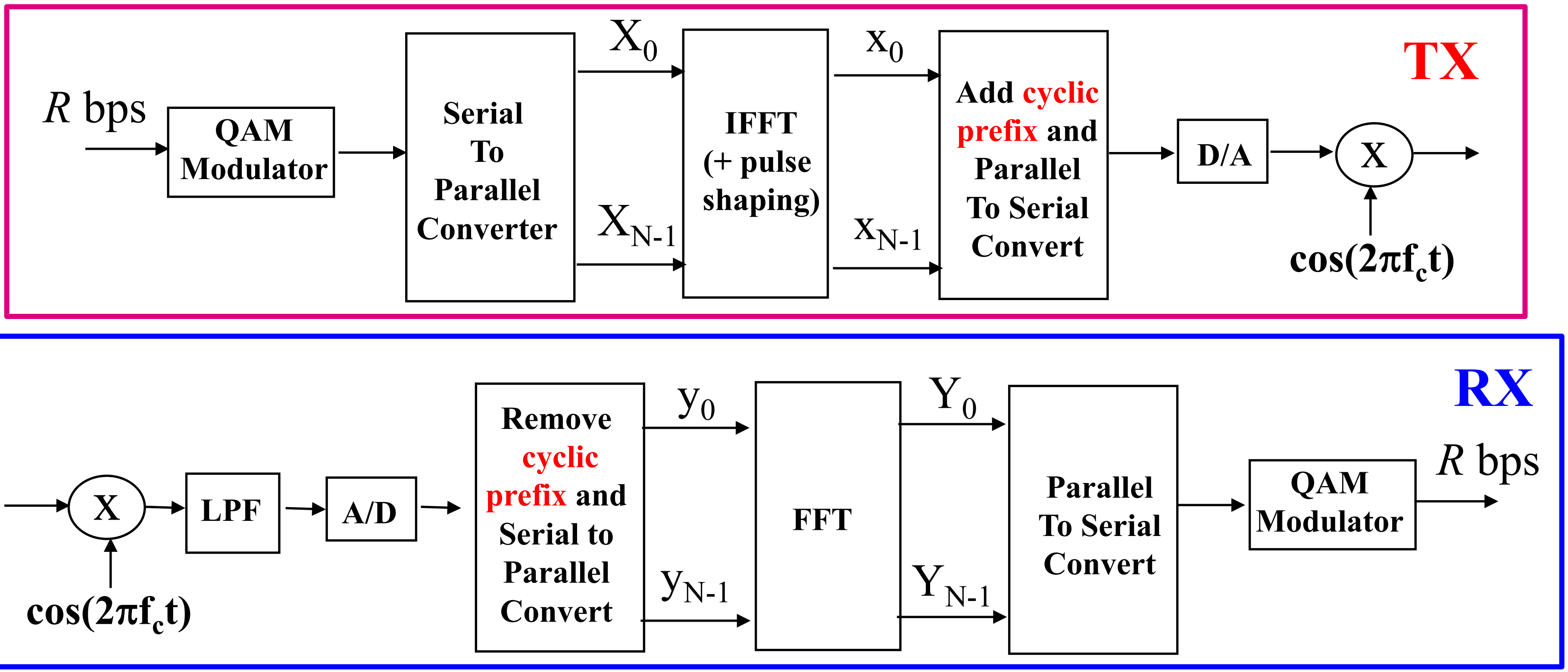
Overlapping Substreams

- 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



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