Link Channels

- Channel is band-limited
  - I.e., dispersive (low pass)
  - Short TX pulses get spread out
  - Low latency
- Also get reflections
  - Z mismatches, connectors, etc.
  - Longer latency

Why ISI Matters

- First sample doesn’t even reach RX threshold
- Suffers ISI from all previous zero bits
- Middle sample hardly different from first
  - 0.2 trailing ISI (from previous symbol) and 0.1 leading ISI (from next symbol)

Inter-Symbol Interference

- Equalization been around for a very long time…
- What makes electrical interfaces unique:
  - Performance
  - Power and area constraints

Equalization

- Basic goal is to “flatten” channel response
  - I.e., in time domain, get back our nice clean pulse
  - For low-pass channel, equalizer boosts high frequencies

History
Equalizer Types

- More alphabet soup...
  - CTLE, ZFE, DFE, RX FIR, MMSE, ...
- Three basic distinctions:
  - Linear vs. Non-Linear
  - Continuous Time vs. Discrete Time
  - Minimize ISI vs. Minimize ISI + Noise

Linear FIR

Continuous Time Linear Equalizer (CTLE)

CTLE Implementation, Limitations

Transmitter FIR Example

Setting the Coefficients

- Assume channel response is known for now
  - See later how to estimate it
- Most basic approach: zero-forcing (ZFE)
ZFE Setting Formulation (Math…)

“Zero-Forcing”: Desired Response

Transmitter FIR Revisited

Final Coefficients: Least Squares

The Fundamental Issue: Noise

An Alternate Approach: MMSE

• Can’t generally use ZFE result directly
  • TX has a peak swing constraint
  • At same max. swing, RX amplitude reduced
  • Is this a problem?

• ZFE eliminates ISI
  • But increases magnitude of noise relative to signal
  • “Noise enhancement”
  • Particularly bad on channels with notches
  • TX/RX eq. needs large atten./gain

• Don’t just cancel ISI
  • Find optimal balance between noise and ISI

• Minimum Mean Squared Equalizer:
**MMSE vs. ZFE, Limitations**

- MMSE allows residual ISI
  - But amplifies noise less

- Unfortunately, MMSE not so straightforward to apply in links
  - Harder to adapt (more later)
  - Noise may not be known

**DFE Issues**

- Only handles post-cursors
  - May still need linear (feedforward) filter for pre-cursors

- What happens when RX makes a mistake?

**Good News: There Is Another Way…**

- Once you know which bit was transmitted
  - You also know exactly what ISI that bit will cause

- Why not directly cancel the ISI you know is coming?

**DFE Issues: Timing**

- Need to do all of the following in at most 1UI:
  - Resolve the (small) bit
  - Scale the bit by the coefficient
  - Sum the new analog value

**Decision Feedback Equalization (DFE)**

- Key advantage: no noise enhancement
  - Feedback signal based on “perfect” digital bits
  - ISI subtracted based on those bits

**Pulse Shape Interaction**

- Ideal DFE would actually settle within 0.5UI
  - Otherwise affects edge position
  - FIR filter can have same issue
  - Fixing it requires an over-sampled (fractional) equalizer
Fractional Equalization

Symbol-spaced
2x Oversampled