Lecture 18: RX FIR & CTLE Equalization
Announcements

• HW5 now due Friday (in class)
  • Any issues?

• Reading
  • Hanumolu equalization overview paper
Agenda

- RX FIR Equalization
- RX CTLE Equalization
Link with Equalization
TX FIR Equalization

- TX FIR filter pre-distorts transmitted pulse in order to invert channel distortion at the cost of attenuated transmit signal (de-emphasis)
RX FIR Equalization

• Delay analog input signal and multiply by equalization coefficients

• Pros
  • With sufficient dynamic range, can amplify high frequency content (rather than attenuate low frequencies)
  • Can cancel ISI in pre-cursor and beyond filter span
  • Filter tap coefficients can be adaptively tuned without any back-channel

• Cons
  • Amplifies noise/crosstalk
  • Implementation of analog delays
  • Tap precision

[Hall]
RX Equalization Noise Enhancement

- Linear RX equalizers don’t discriminate between signal, noise, and cross-talk
  - While signal-to-distortion (ISI) ratio is improved, SNR remains unchanged
Analog RX FIR Equalization Example

• 5-tap equalizer with tap spacing of $T_b/2$

Digital RX FIR Equalization

- Digitize the input signal with high-speed low/medium resolution ADC and perform equalization in digital domain
  - Digital delays, multipliers, adders
  - Limited to ADC resolution
- Power can be high due to very fast ADC

[Hanumolu]
Digital RX FIR Equalization Example

- 12.5GS/s 4.5-bit Flash ADC in 65nm CMOS
- 2-tap FFE & 5-tap DFE
- XCVR power (inc. TX) = 330mW, Analog = 245mW, Digital = 85mW

[Harwood ISSCC 2007]
RX Continuous-Time Linear Equalizer (CTLE)

- Passive R-C (or L) can implement high-pass transfer function to compensate for channel loss
- Cancel both precursor and long-tail ISI
- Can be purely passive or combined with an amplifier to provide gain

Passive CTLE

![Passive CTLE Circuit Diagram]

Active CTLE

![Active CTLE Circuit Diagram]

[Hanumolu]
Passive CTLE

- Passive structures offer excellent linearity, but no gain at Nyquist frequency

\[ H(s) = \frac{R_2}{R_1 + R_2} \frac{1 + R_1 C_1 s}{1 + \frac{R_1 R_2}{R_1 + R_2} (C_1 + C_2) s} \]

\[ \omega_z = \frac{1}{R_1 C_1}, \quad \omega_p = \frac{1}{\frac{R_1 R_2}{R_1 + R_2} (C_1 + C_2)} \]

\[ \text{DC gain} = \frac{R_2}{R_1 + R_2}, \quad \text{HF gain} = \frac{C_1}{C_1 + C_2} \]

\[ \text{Peaking} = \frac{\text{HF gain}}{\text{DC gain}} = \frac{\omega_p}{\omega_z} = \frac{R_1 + R_2}{R_2} \frac{C_1}{C_1 + C_2} \]

[Hanumolu]
Active CTLE

- Input amplifier with RC degeneration can provide frequency peaking with gain at Nyquist frequency
- Potentially limited by gain-bandwidth of amplifier
- Amplifier must be designed for input linear range
  - Often TX eq. provides some low frequency attenuation
- Sensitive to PVT variations and can be hard to tune
- Generally limited to 1st-order compensation

\[
H(s) = \frac{g_m}{C_p} \left( \frac{s + \frac{1}{R_s C_s}}{s + 1 + \frac{g_m R_s}{2}} \right) \left( s + \frac{1}{R_D C_p} \right)
\]

\[
\omega_z = \frac{1}{R_s C_s}, \quad \omega_{p1} = \frac{1 + g_m R_s}{R_s C_s}, \quad \omega_{p2} = \frac{1}{R_D C_p}
\]

DC gain = \( \frac{g_m R_D}{1 + g_m R_s/2} \), Ideal peak gain = \( g_m R_D \)

Ideal Peaking = \( \frac{\text{Ideal peak gain}}{\text{DC gain}} = \frac{\omega_{p1}}{\omega_z} = 1 + \frac{g_m R_s}{2} \)
Active CTLE Example

![CTLE Example Diagram]

Channel Response w/ RX CTLE Eq

6Gb/s Eye - Refined BP Channel w/ No Eq

6Gb/s Eye - Refined BP Channel w/ RX CTLE Eq
Active CTLE Tuning

- Tune degeneration resistor and capacitor to adjust zero frequency and 1st pole which sets peaking and DC gain.

\[ \omega_z = \frac{1}{R_s C_s}, \quad \omega_{p1} = \frac{1 + g_m R_s / 2}{R_s C_s} \]
Next Time

- RX DFE
- Alternate/Future Approaches