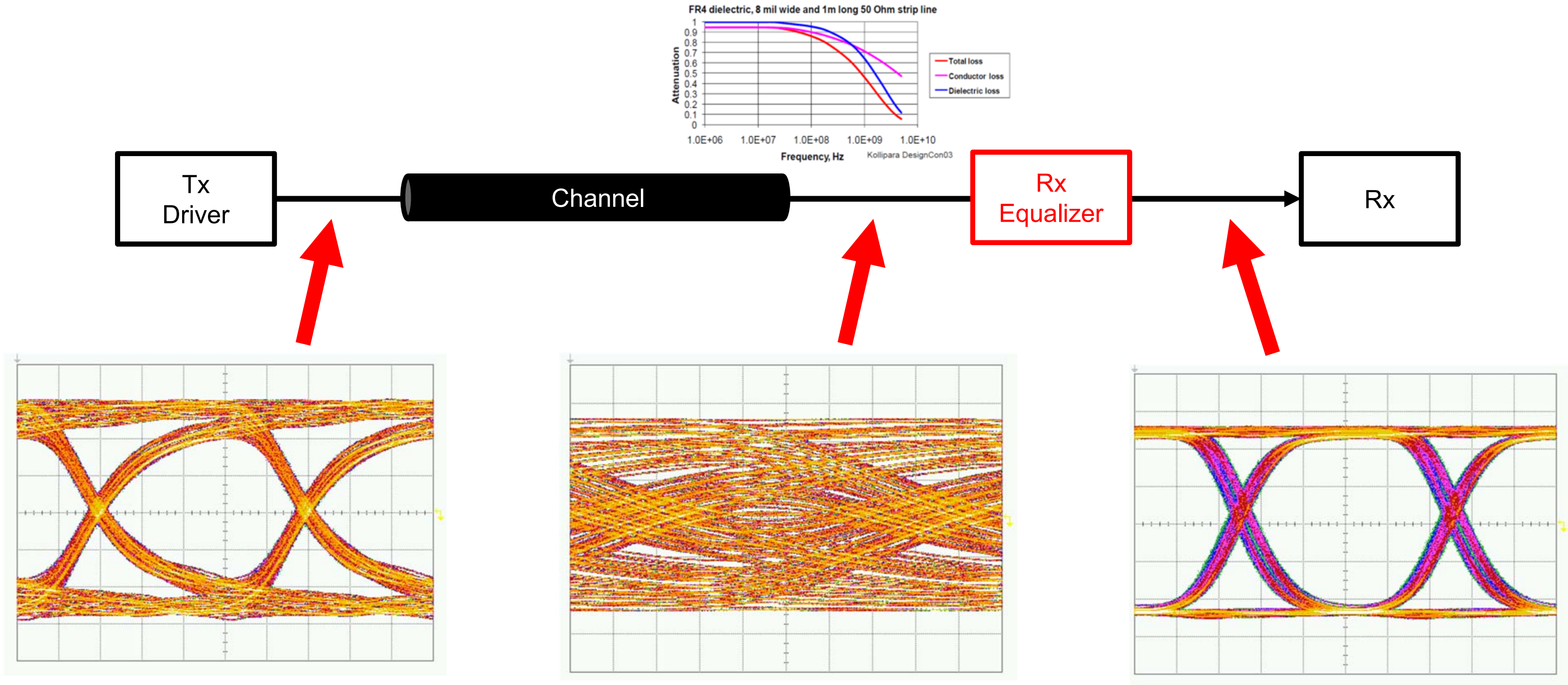
High-speed Serial Interface

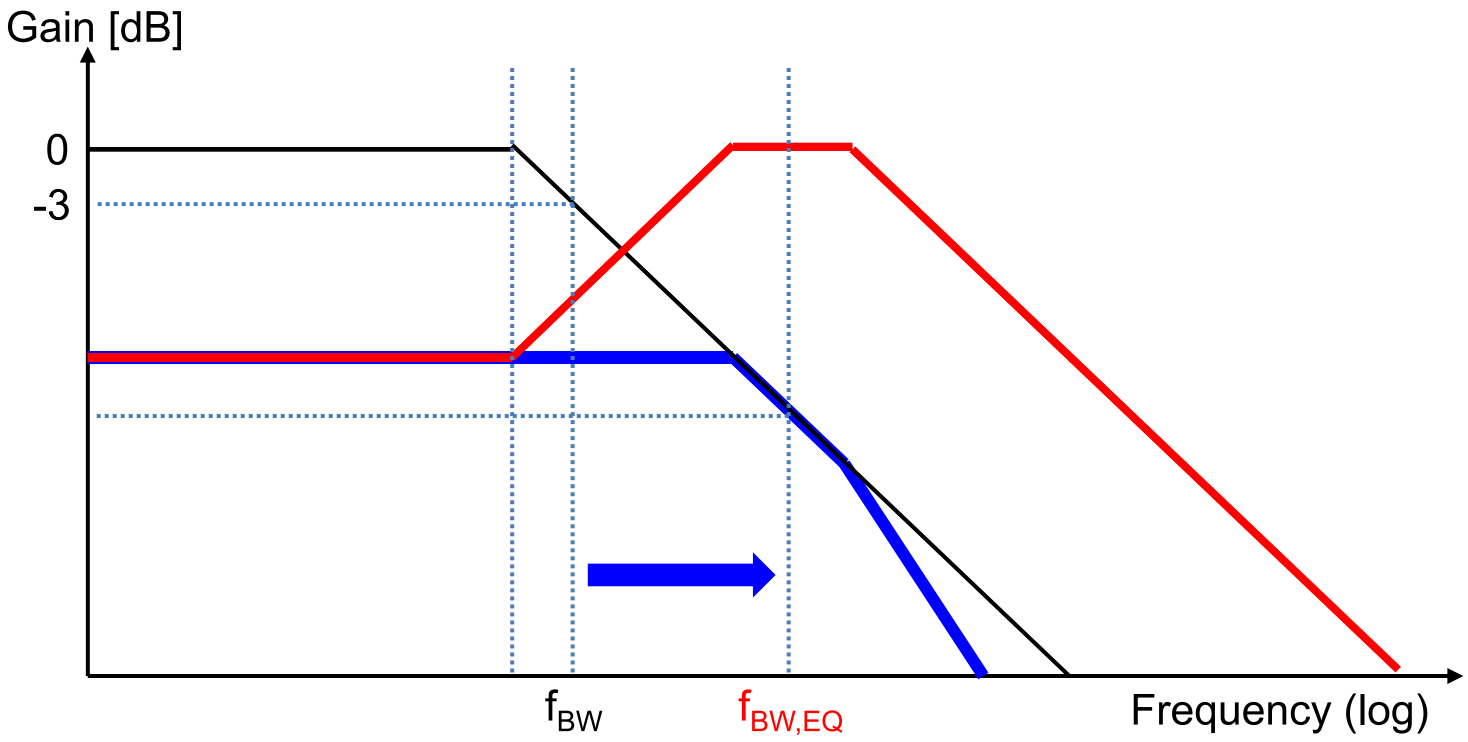
Lect. 8: Linear Equalizers

Why equalization?

- Inter-symbol interference (ISI) caused by frequency-dependent loss of channel



Equalizer Frequency Response



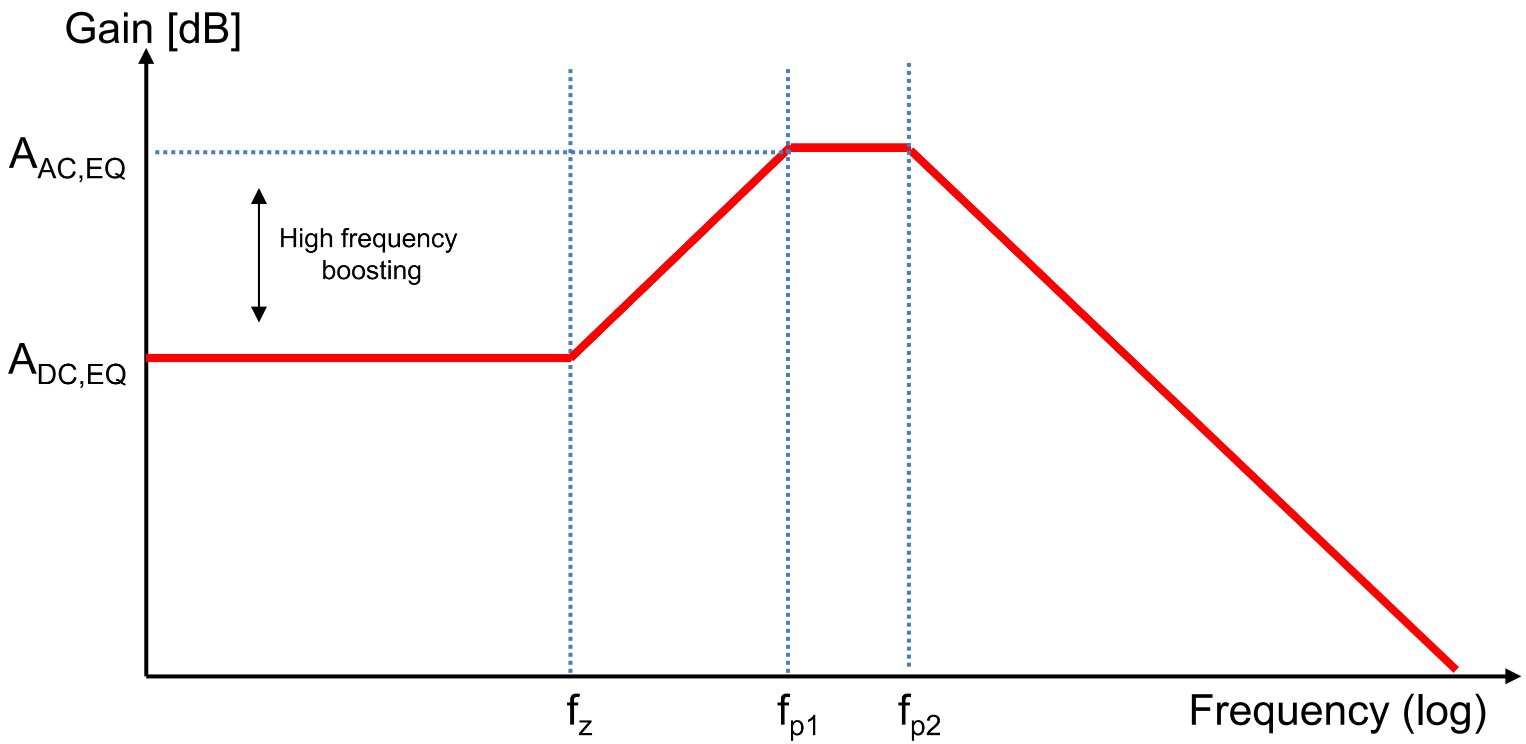
High-pass filter / High-frequency boosting

➔ Continuous Time Linear Equalizer (CTLE)

CTLE Frequency Response

Assuming channel has one pole,

CTLE should provide 1 zero and 2 poles



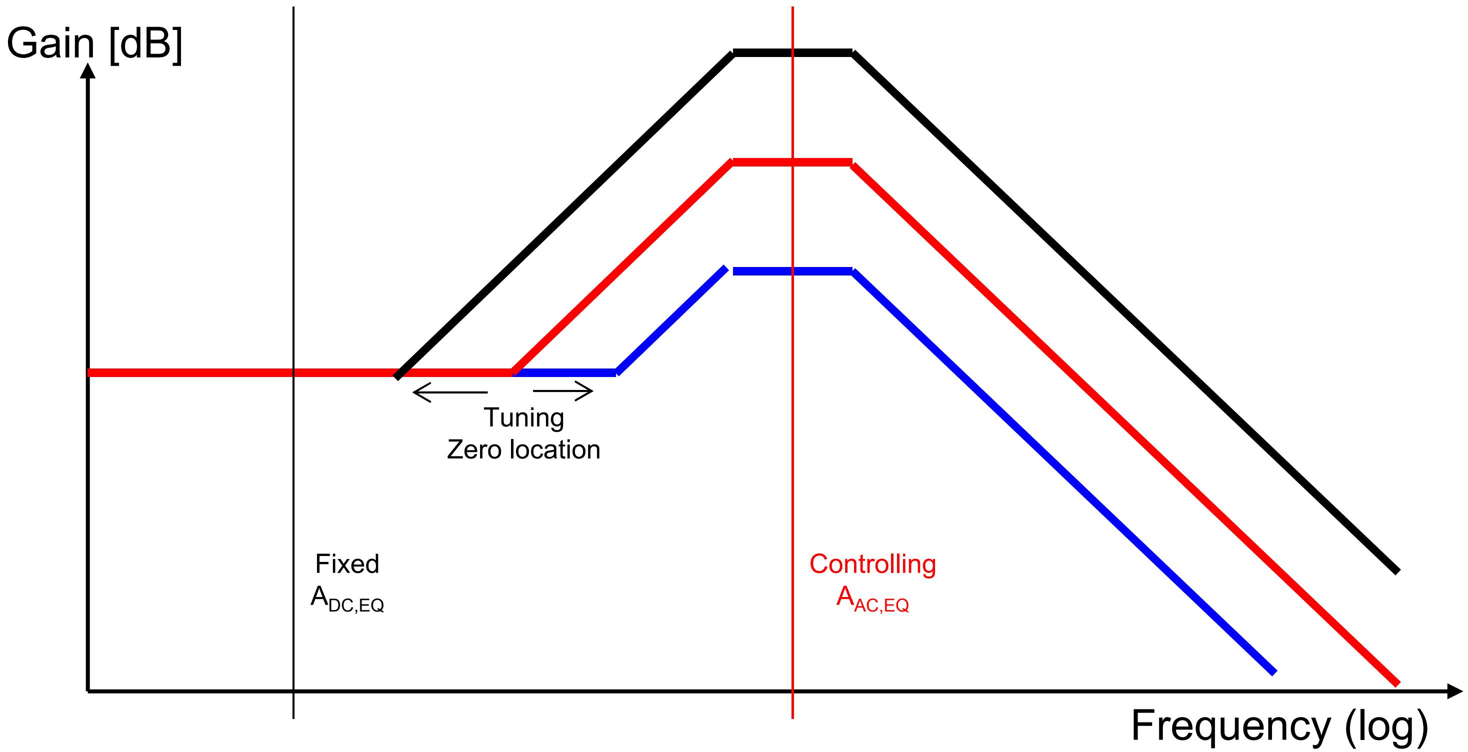
Tunability

- CTLE should be tunable
  - Channel variation
    - Variations in channel fabrication
    - Uncertainty in channel modeling
    - Channel degradation/defect after usage
  - PVT variation of equalizer

➔ Tunability is a must

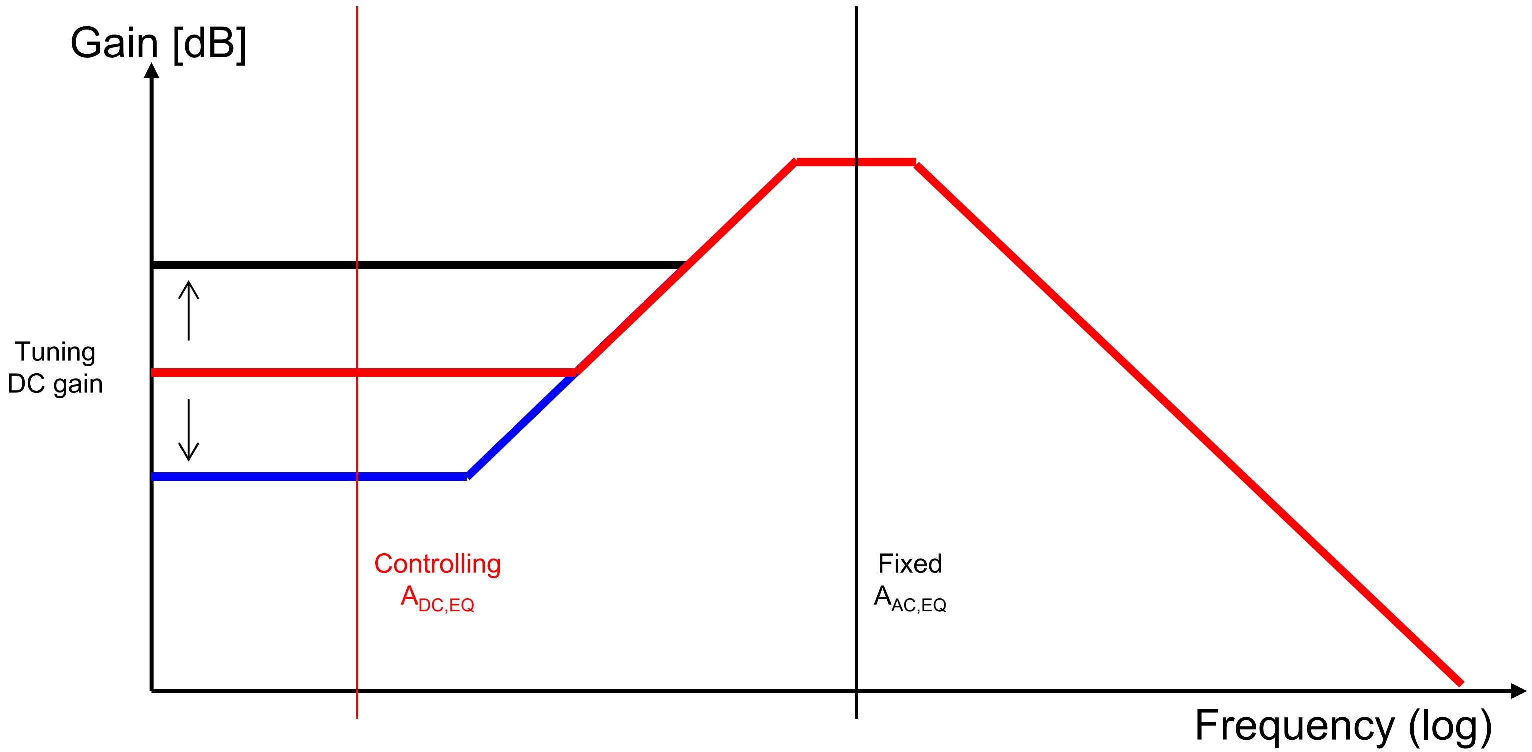
Tunability

- Tuning pole/zero locations



Controllability

- Tuning DC gain



Passive CTLE

– Various passive high-pass filters available

No power consumption

But

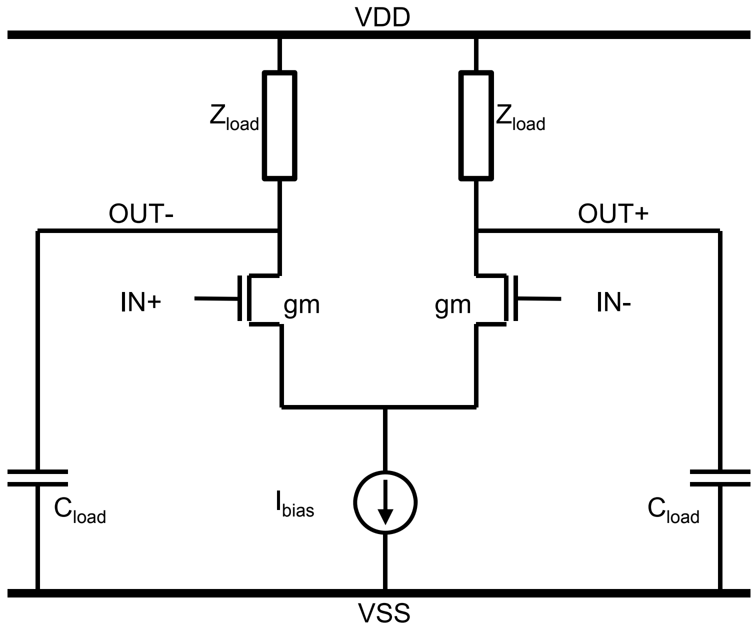
- Lossy
- PVT dependent
- Difficult to achieve 50-ohm matching
- Difficult to tune
- Often large size

Active CTLE

- Differential amplifier
  - Basic differential amp. has 1 pole from load capacitance

$$|H(s)| \sim g_m \left(Z_{load} \, // \, \frac{1}{sC_{load}} \right)$$

$$= \frac{g_m}{\left(sC_{load} + \frac{1}{Z_{load}} \right)}$$



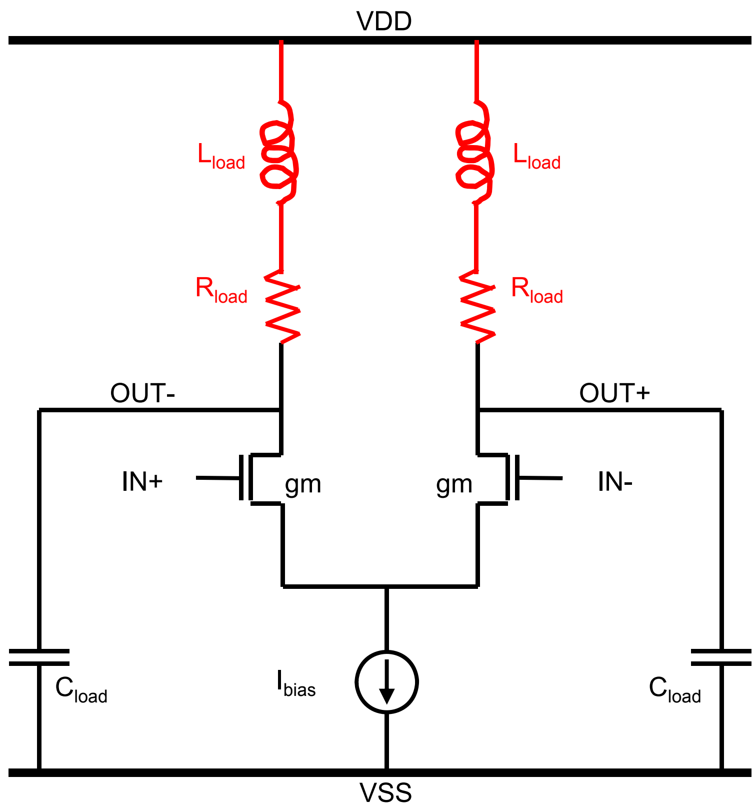
Active CTLE

- Inductive load
  - Shunt inductor provides a pole/zero pair

$$|H(s)| \sim g_m \left(Z_{load} \,//\, \frac{1}{sC_{load}} \right)$$

$$= \frac{g_m}{\left(sC_{load} + \frac{1}{sL_{load} + R_{load}} \right)}$$

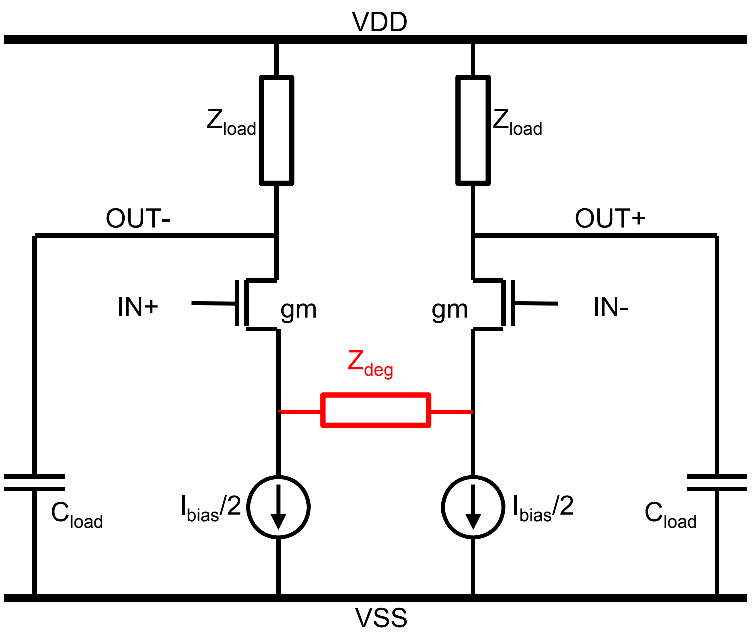
$$= \frac{g_m (sL_{load} + R_{load})}{(s^2 L_{load} C_{load} + sR_{load} C_{load} + 1)}$$



Source Degeneration for CTLE

$$|H(s)| \sim g_m' \left(Z_{load} \, // \, \frac{1}{sC_{load}} \right)$$

$$= \frac{g_m}{1 + \frac{g_m Z_{deg}}{2}} \left(Z_{load} \, // \, \frac{1}{sC_{load}} \right)$$

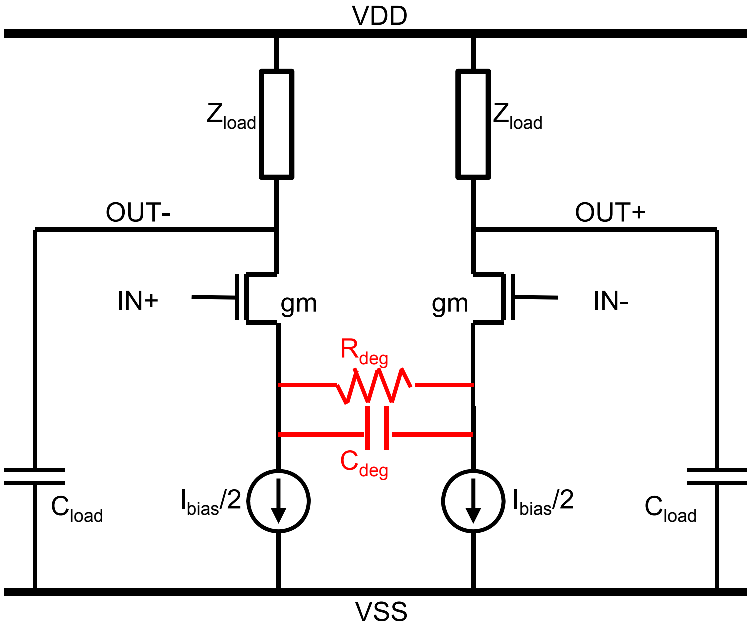


Source Degeneration for CTLE

– Capacitive generation provides high-frequency boosting since a capacitor has lower impedance at high frequency

$$H(s) = \frac{g_m}{1 + \frac{g_m Z_{deg}}{2}} \left(Z_{load} \,//\, \frac{1}{sC_{load}} \right)$$

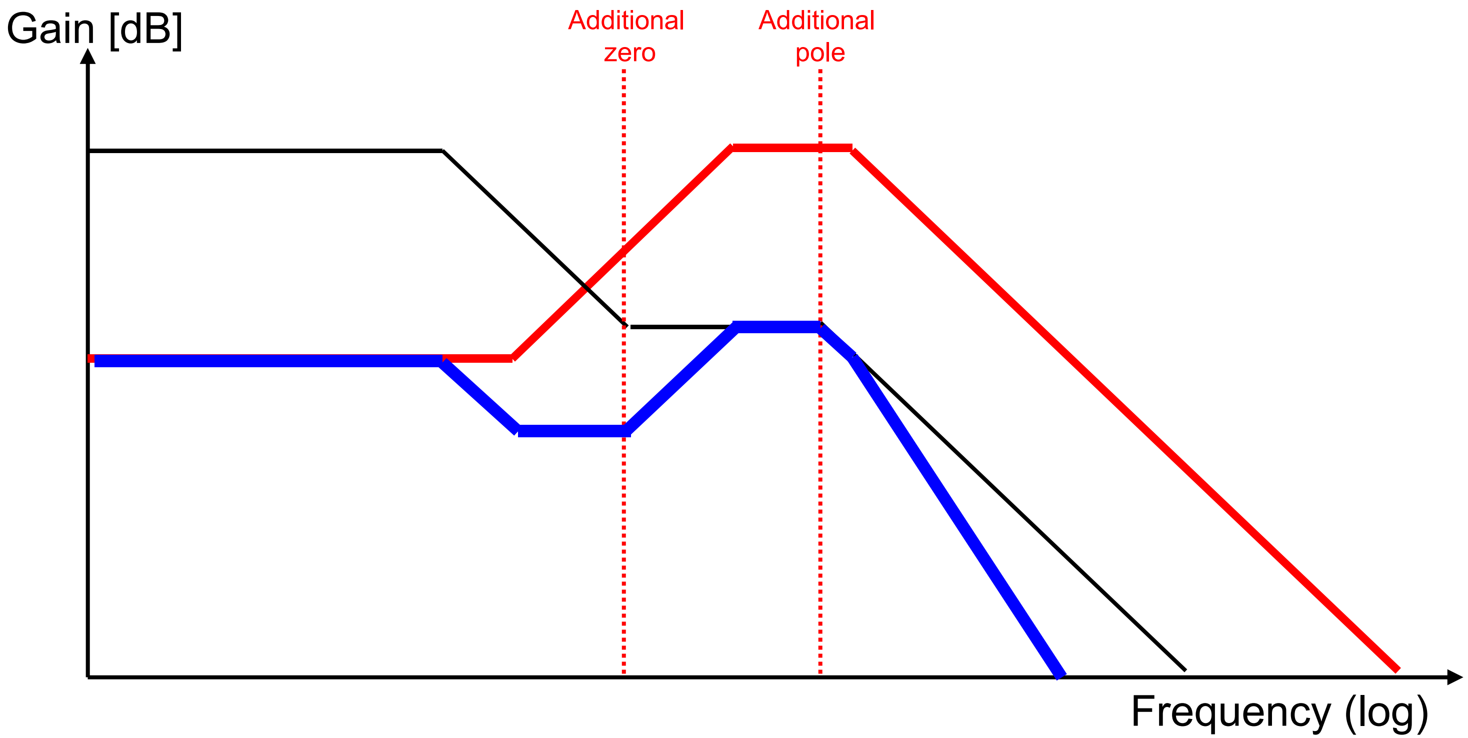
$$= \frac{g_m}{C_{load}} \frac{\left[s + \frac{1}{R_{deg}C_{deg}} \right]}{\left[s + \frac{1 + \frac{g_m R_{deg}}{2}}{R_{deg}C_{deg}} \right] \left[s + \frac{1}{Z_{load}C_{load}} \right]}$$



➔ Design Exercise

Limitations of CTLE

- Channels may not be properly modeled with one pole



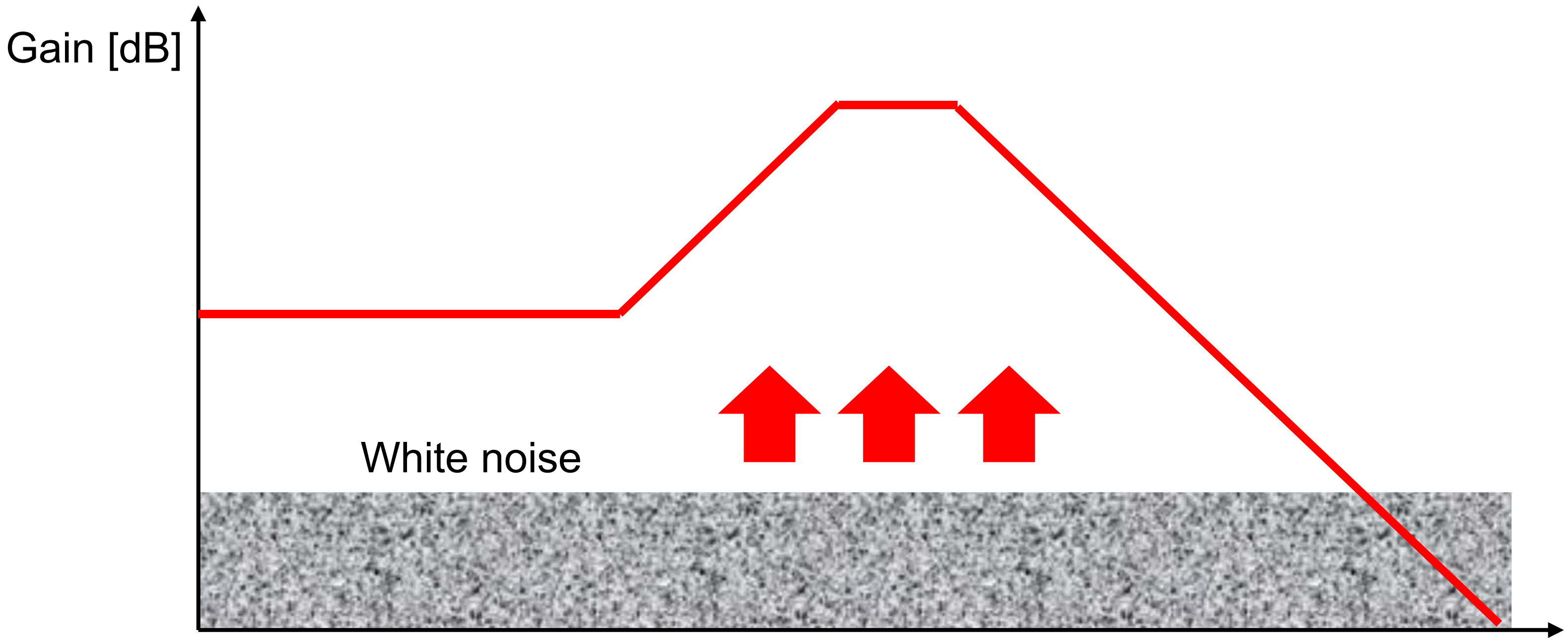
Limitations of CTLE

- Applicable to only ISIs due to linear frequency-dependent loss

- Other causes for ISI are;
  - Impedance mismatching
  - Cross-talk
  - Parasitic poles and zeros (ex: package parasitics)

Limitations of CTLE

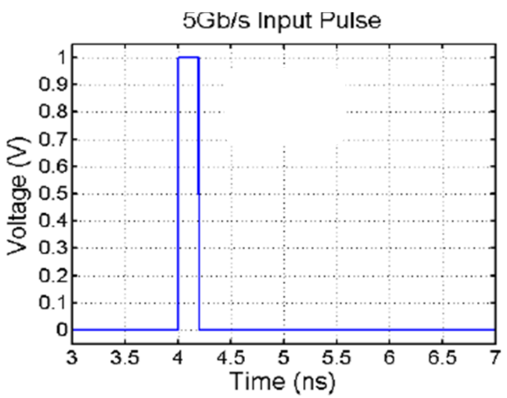
- High-frequency Noise boosting

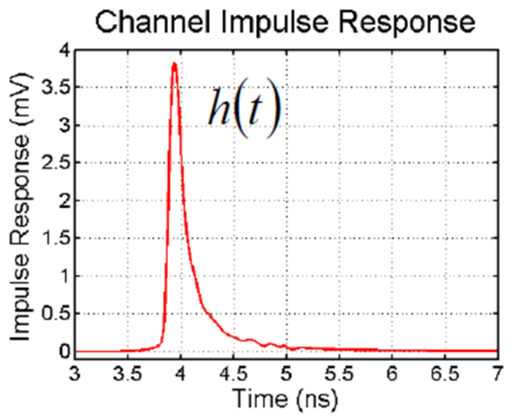


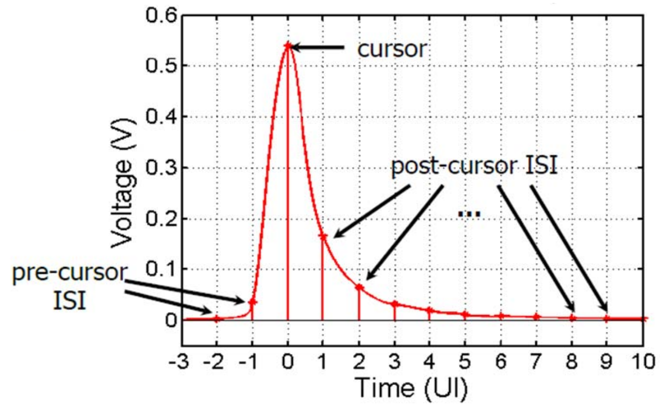
Time-Domain Analysis

– Frequency-Domain Analysis
  - Freq. Response of Input x Freq. Response of Channel x Equalizer
    = Freq. Response of Output

– Time-Domain Analysis

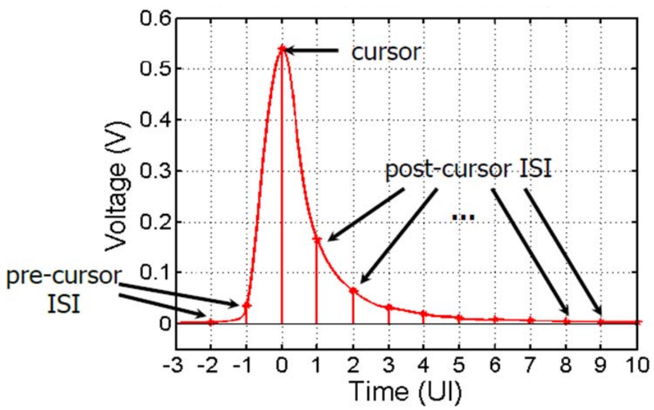


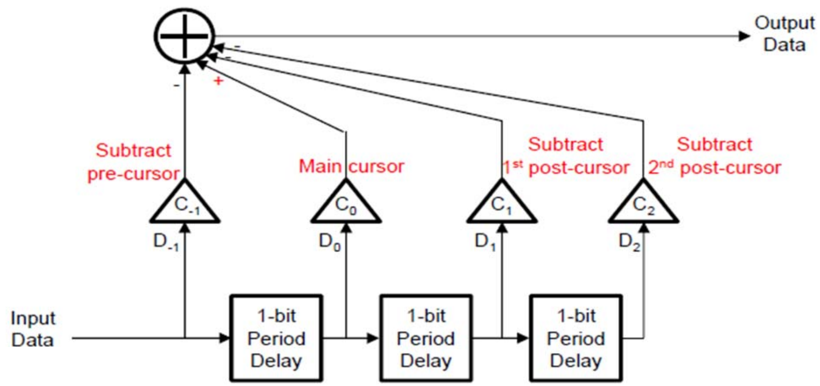




- Equalization: Force pre- and post-cursors to zero

FIR Filter



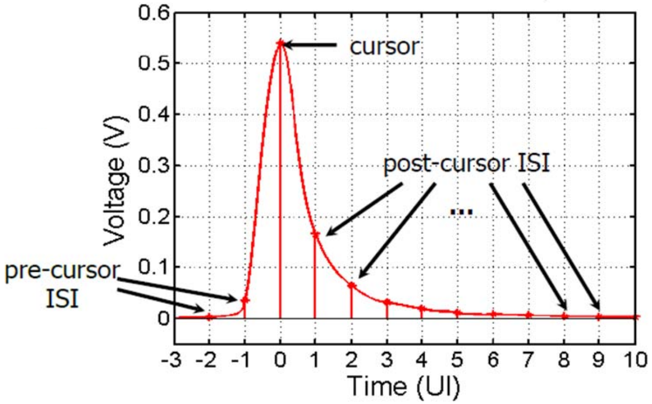


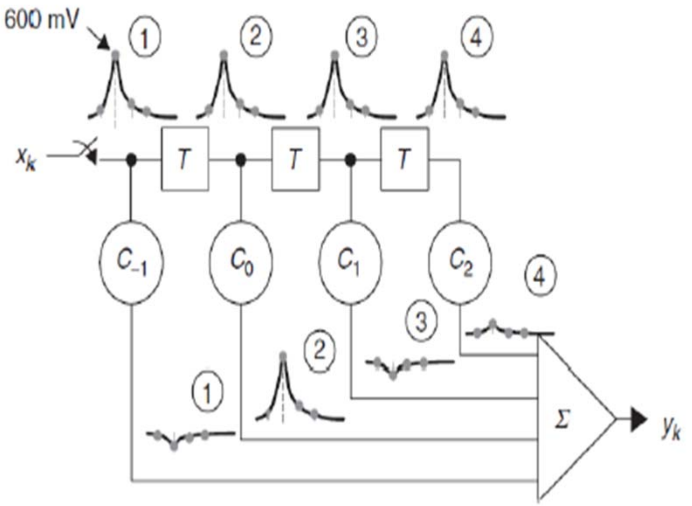
Tap and Delay

➔ FIR (Finite Impulse Response)

IIR (Infinite Impulse Response) for CTLE

FIR Filter

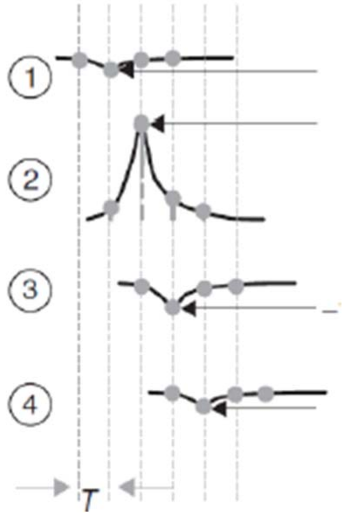




- Difficult to implement Rx FIR filter

Because the precise amount of delay (clock period) is not known in Rx

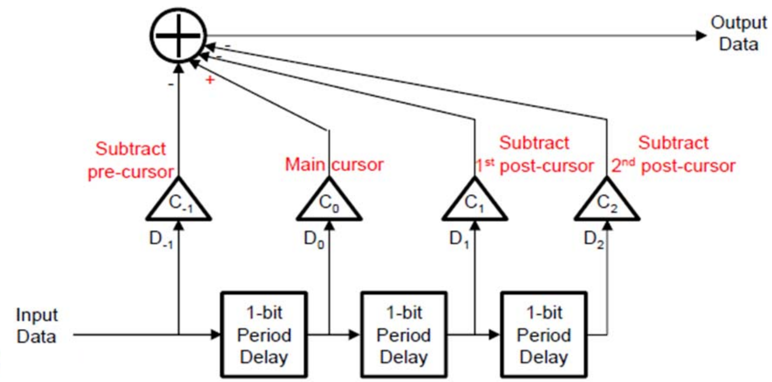
➔ Tx FIR filter



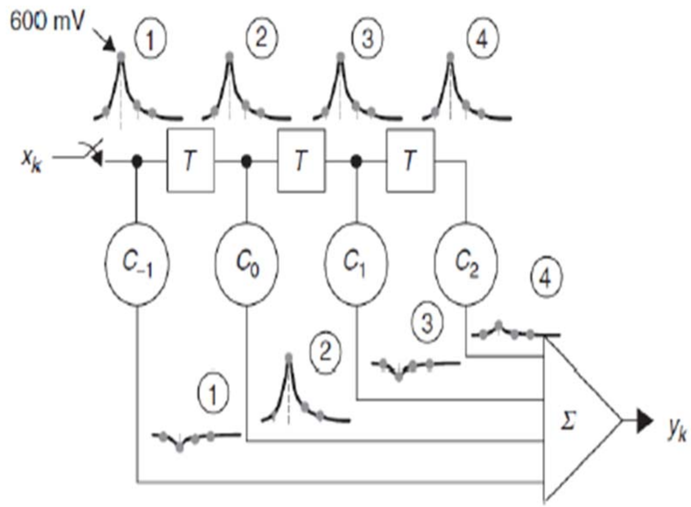
FIR Filter

- Any CTLE filter can be converted into a discrete-time domain filter

- IIR (Infinite Impulse Response) ➔ FIR (Finite Impulse Response)



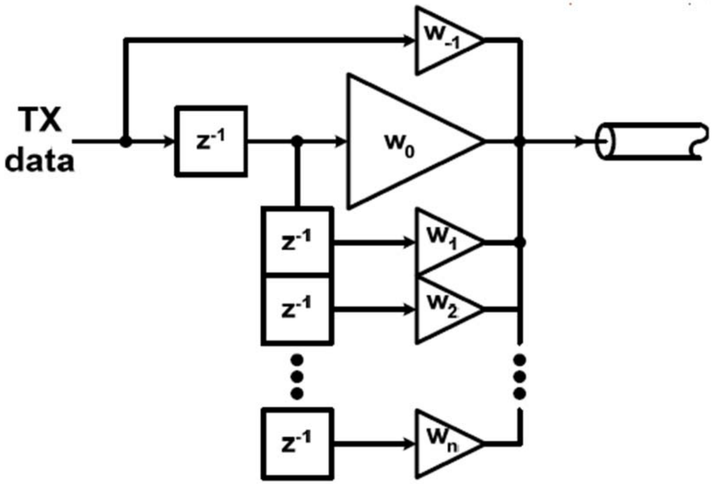
Tap and Delay

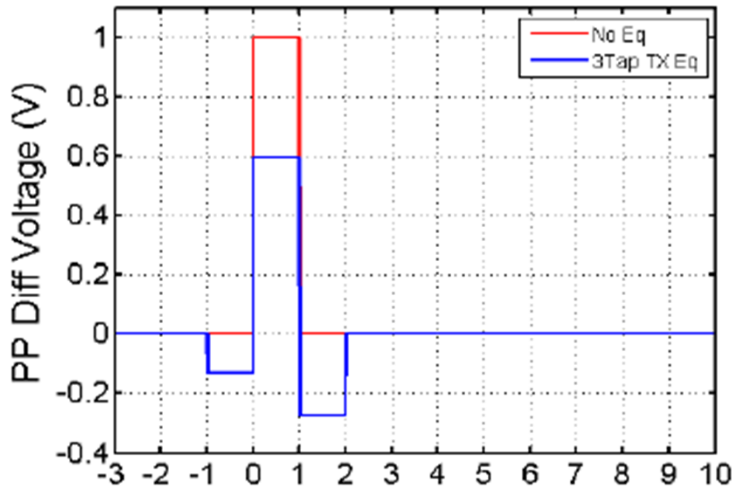


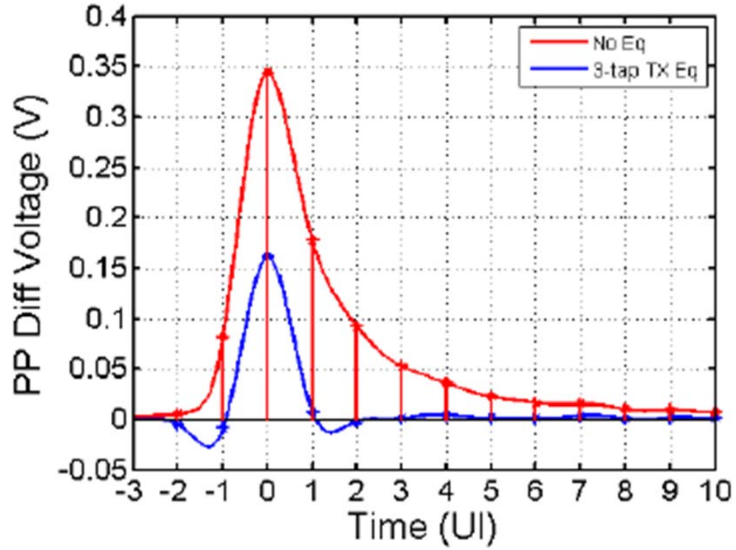
- Hard to implement Rx FIR filter because the precise amount of delay (clock period) is not available in Rx

➔ Tx FIR filter

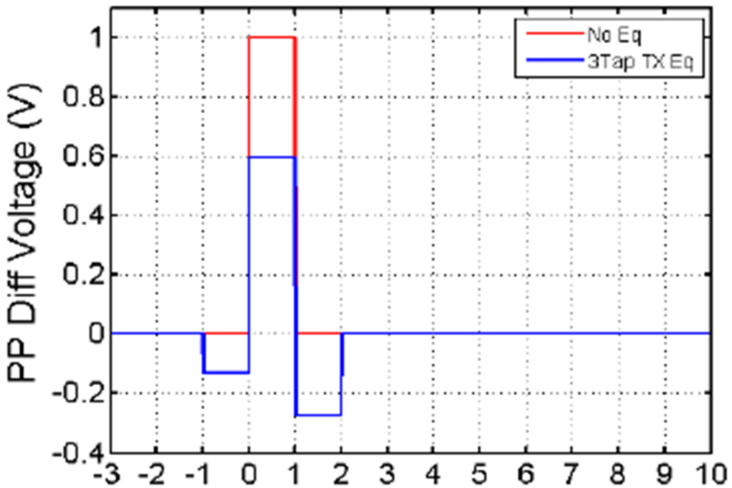
Tx FIR

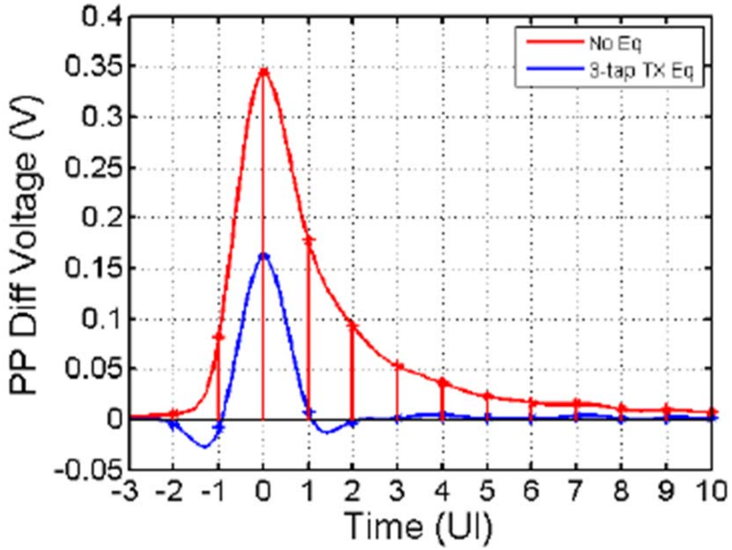

TX
data
z-1
w-1
w0
w1
w2
wn


No Eq
3Tap TX Eq
PP Diff Voltage (V)


No Eq
3-tap TX Eq
PP Diff Voltage (V)
Time (UI)

Frequency-Domain Analysis





$$W(z) = -0.131 + 0.595z^{-1} - 0.274z^{-2}$$

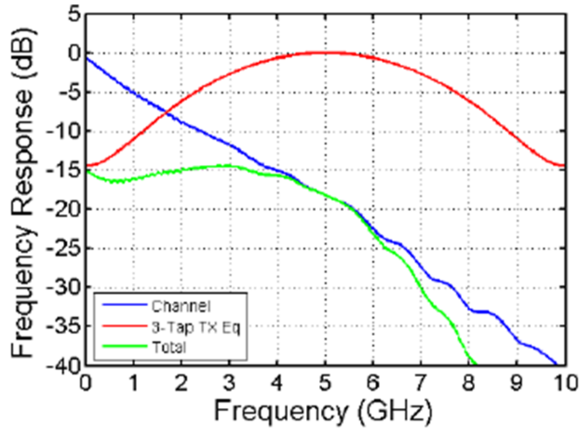
$$z = e^{j2\pi f T_s} = \cos(2\pi f T_s) + j\sin(2\pi f T_s)$$

Low Frequency Response $(f = 0)$

$$z = \cos(0) + j\sin(0) = 1 : W(f = 0) = 0.190 \Rightarrow -14.4dB$$

Nyquist Frequency Response $\left(f = \frac{1}{2T_s}\right)$

$$z = \cos(\pi) + j\sin(\pi) = -1 : \quad W\left(f = \frac{1}{2T_s}\right) = -1 \Rightarrow 0dB$$

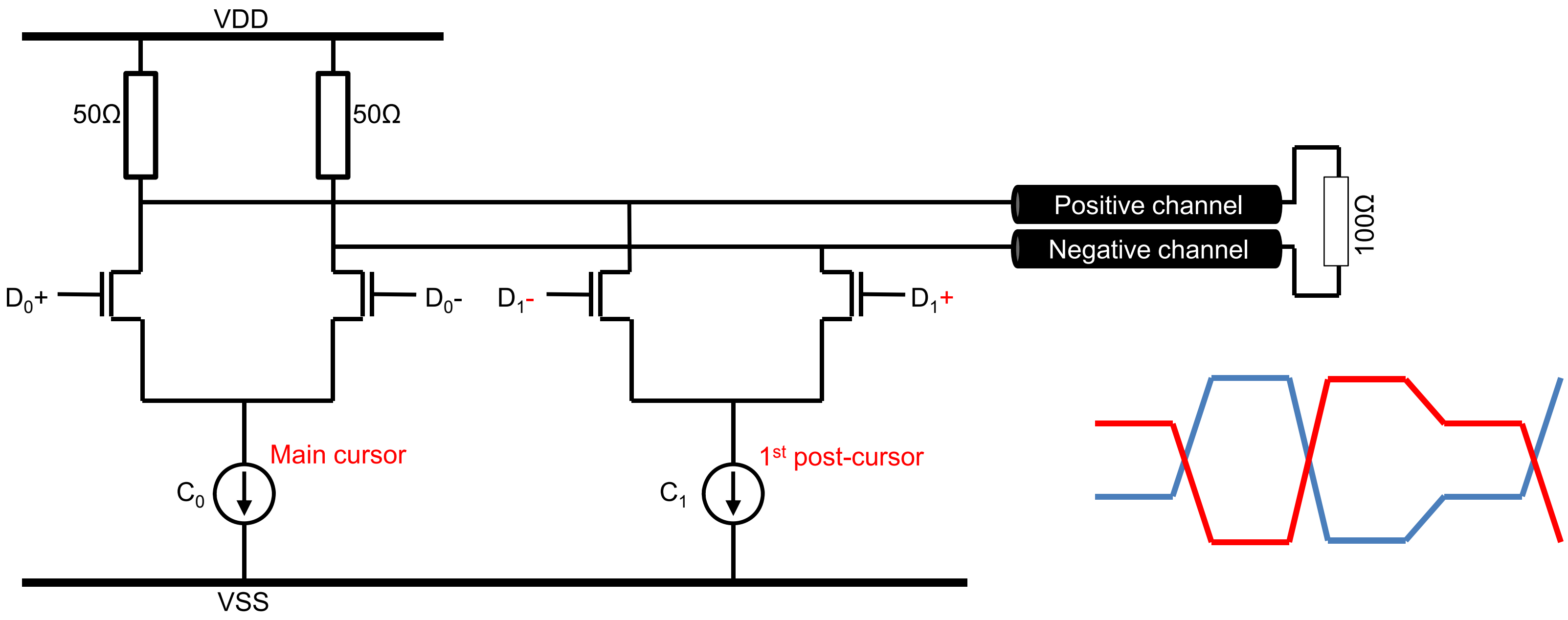


Circuit implementation

- Tx FIR can be easily implemented with current-mode drivers

(For 2-tap Tx FIR)

  - $D_1 = D_0 \rightarrow V_{out,diff}$ = +/- 100 x $(C_0 - C_1)/4$
  - $D_1 \neq D_0 \rightarrow V_{out,diff}$ = +/- 100 x $(C_0 + C_1)/4$
  - By setting C_1/C_0, Tx FIR is achieved



Pre-/De-Emphasis

– Tx FIR is also called Feed-Forward Equalizer (FFE) or Pre-/De-Emphasis
  - Pre-emphasis: to enhance high-frequency components
  - De-emphasis: to reduce low-frequency components