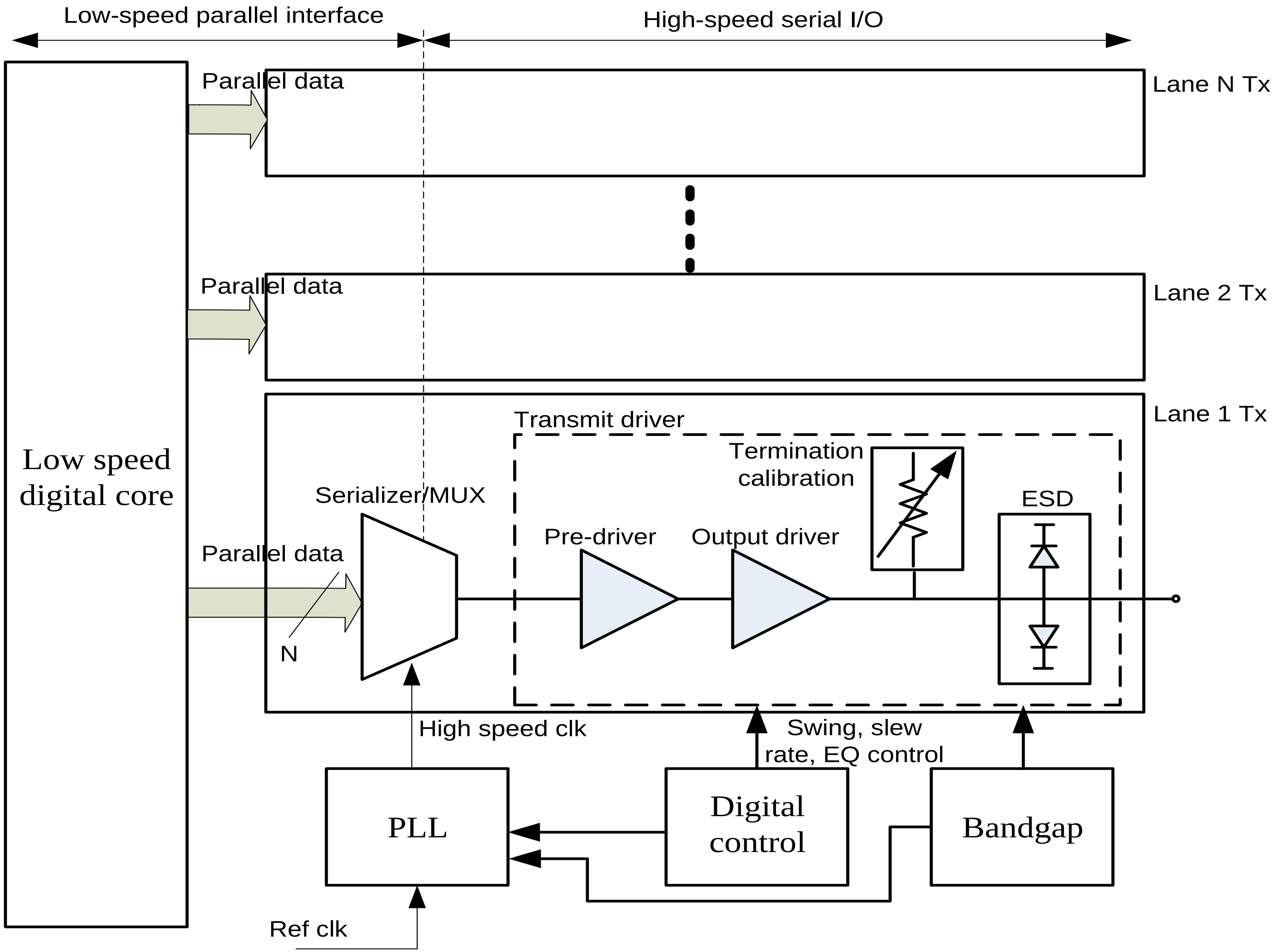
High-Speed Wire Line Transmitters

Lecture 3

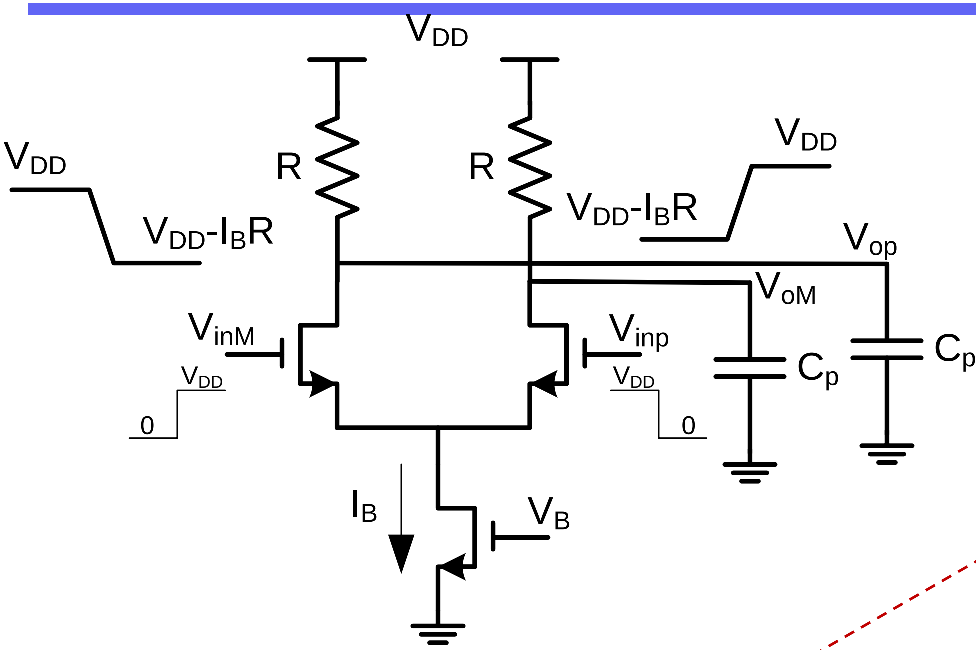
Transmitter Block Diagram

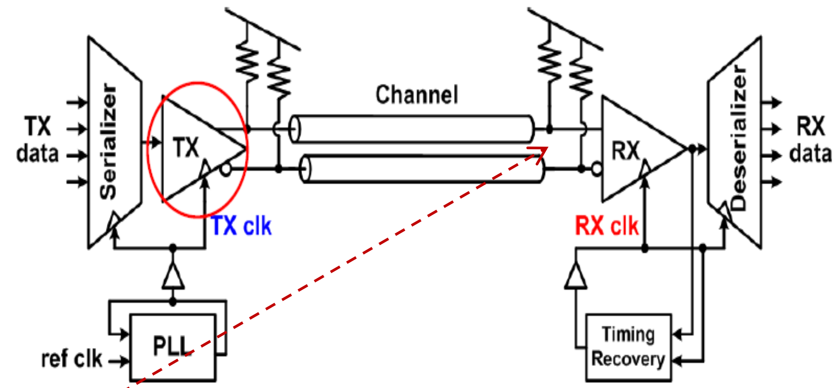


Tx Output Drivers

- Tx output driver needs to deliver a full rate signal with a large differential swing with an on-chip 50Ohm termination
- Serial standards require swings between ~ $0.8V_{ppdiff}$ to $1.2V_{ppdiff}$
- If a current mode driver is used this indicates that a variable current is needed to achieve a programmable swing
- The Tx ESD diodes, output pads & package add to the total output capacitance that the Tx needs to drive which sets the minimum achievable rise and fall times
- Common Tx drivers architectures:
  - Current-mode:
    - CML (current mode logic) driver
    - H-bridge driver
  - Voltage-mode:
    - SST (source series terminated) driver

Current Mode Logic (CML) Output Driver

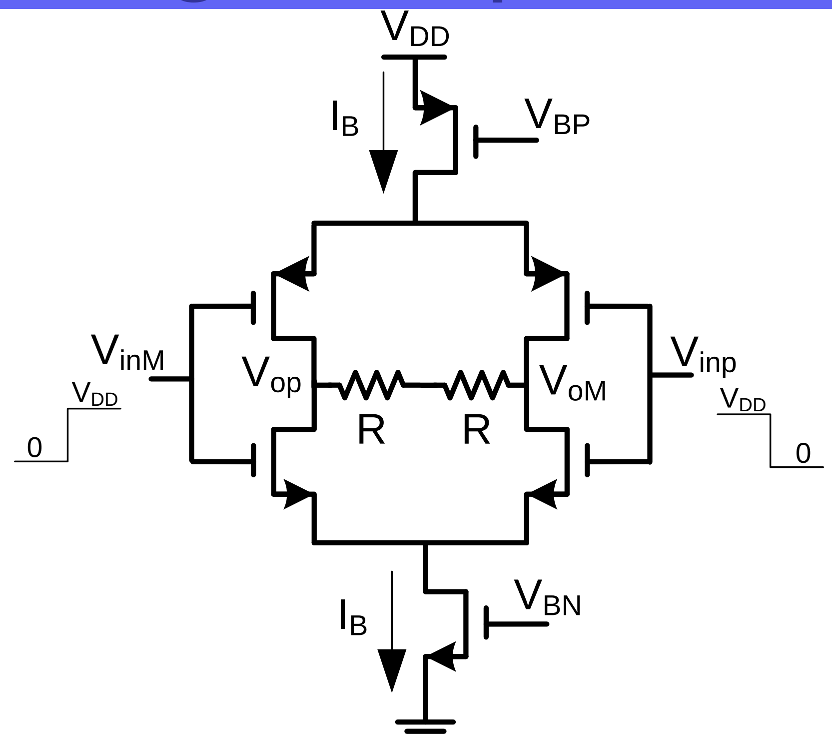




R/2 due to the Rx side termination

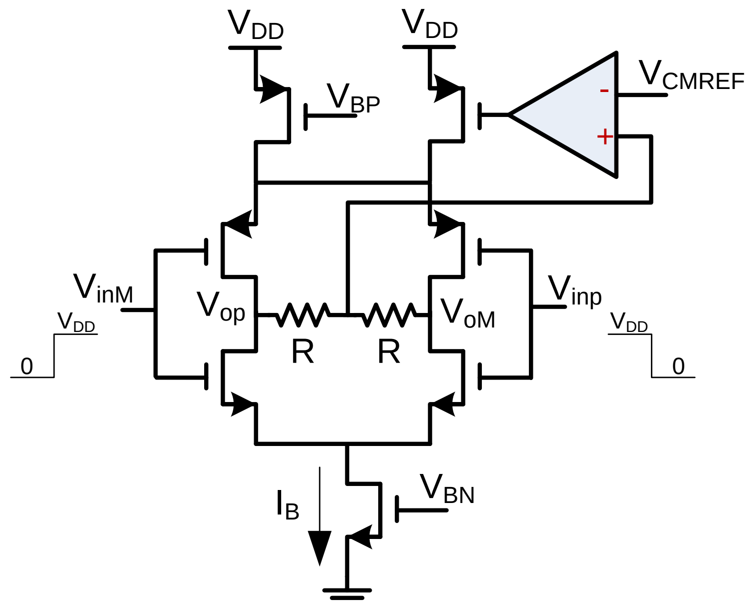
- Differential pp output swing = $2I_BR/2$, where R is 50Ohm, and I_B is the tail bias current
- For example, for a 1.2Vpp swing, I_B=24mA
- The size of the input transistors is usually large in order to handle the necessary current without pushing the current source into triode
- Lower current source in SAT → well controlled swing & good common-mode rejection
- Lower transistor needs to be large to reduce it's Vdsat
- A pre-driver is necessary to drive the large capacitance of the output stage
- Output common mode is well defined $V_{cm\text{-}out}=V_{DD}-I_BR/2$

H-Bridge Output Driver



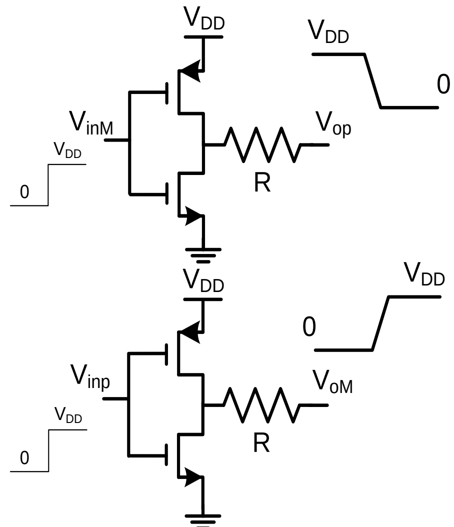
- Differential pp output swing = $4I_BR/2$, where R is 50Ohm, and I_B is the tail bias current
- For example, for a 1.2Vpp swing, I_B=12mA
- The H-bridge offers the same output swing of a CML driver with half the power consumption
- Output common mode voltage is not well defined → needs a CM feedback circuit
- H-bridge has more parasitic capacitance at the output (worst S_{22}) than CML due to the PMOS

H-Bridge Output Driver (Cont’d)



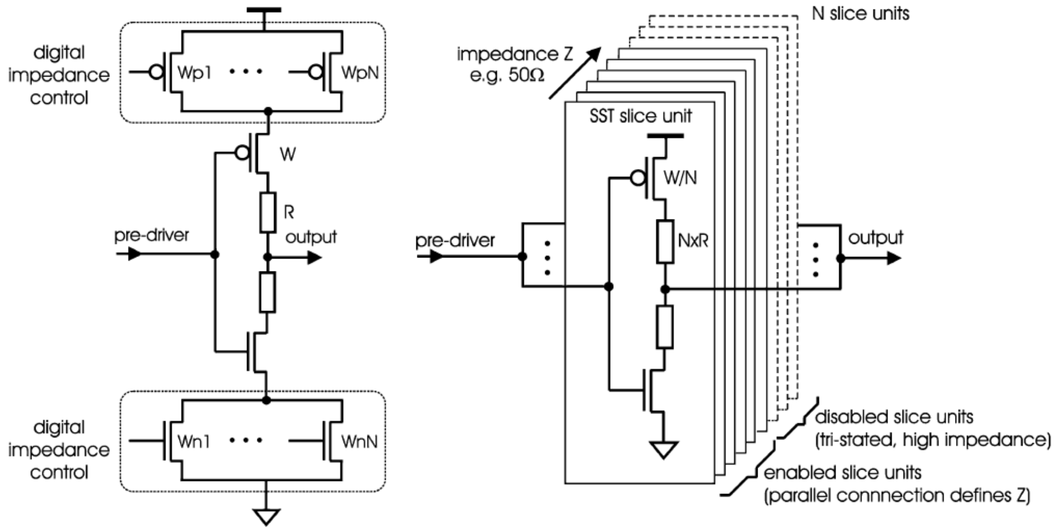
- A common-mode feedback loop senses V_{outcm} and compares it with V_{CMREF} & controls the bias voltage to the PMOS current source
- The common mode feedback loop must have enough phase margin to guarantee stability, note that the package loading might impact the phase margin requiring over designing the feedback loop to guarantee stability
- The large compensation capacitor makes the loop response too slow which might not be acceptable by some standards which puts a spec on the power up time
- To improve the settling speed PMOS current source can be divided into a large fixed portion and a smaller feedback portion

Voltage mode: SST Output Driver



- SST driver consists of inverters driving series termination resistors
- The series resistance provide the 50Ω o/p impedance
- Differential pp output swing = $V_{DD,}$ output common mode voltage ~$V_{DD}/2$
- A programmable swing is not straight forward (no current source to control the swing)
- SST has poor supply sensitivity, any variation in the supply would directly show up as variation in the output swing → supply regulation
- The series resistance isolates the output pins from the drain junctions of the transistors providing some ESD protection & better high frequency S_{22}

JSSC 2008: 8Gb/s High-swing SST Transmitter in 65nm Bulk CMOS

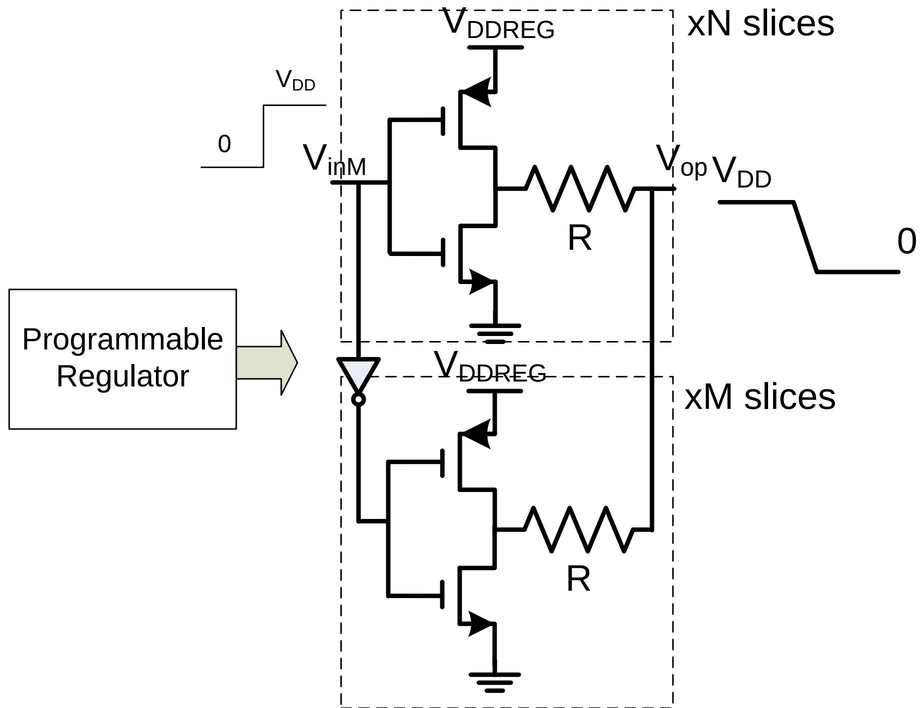


- FET impedance tuning banks at top and bottom of SST stage
- The equivalent resistance of these impedance-tuning FETs is used to adjust the line-drive impedance to the desired value
- Tuning FETs require voltage headroom

- Parallel connection of impedance scaled SST stages
- If the resulting impedance is too low, some of the slice units are disabled to increase the impedance to the desired value
- No voltage headroom penalty if the disablement or tri-stating of the slice units is performed via the data path

M. Kossel et al., "A T-Coil-Enhanced 8.5 Gb/s High-Swing SST Transmitter in 65 nm Bulk CMOS With < -16 dB Return Loss Over 10 GHz Bandwidth," in IEEE Journal of Solid-State Circuits, vol. 43, no. 12, pp. 2905-2920, Dec. 2008

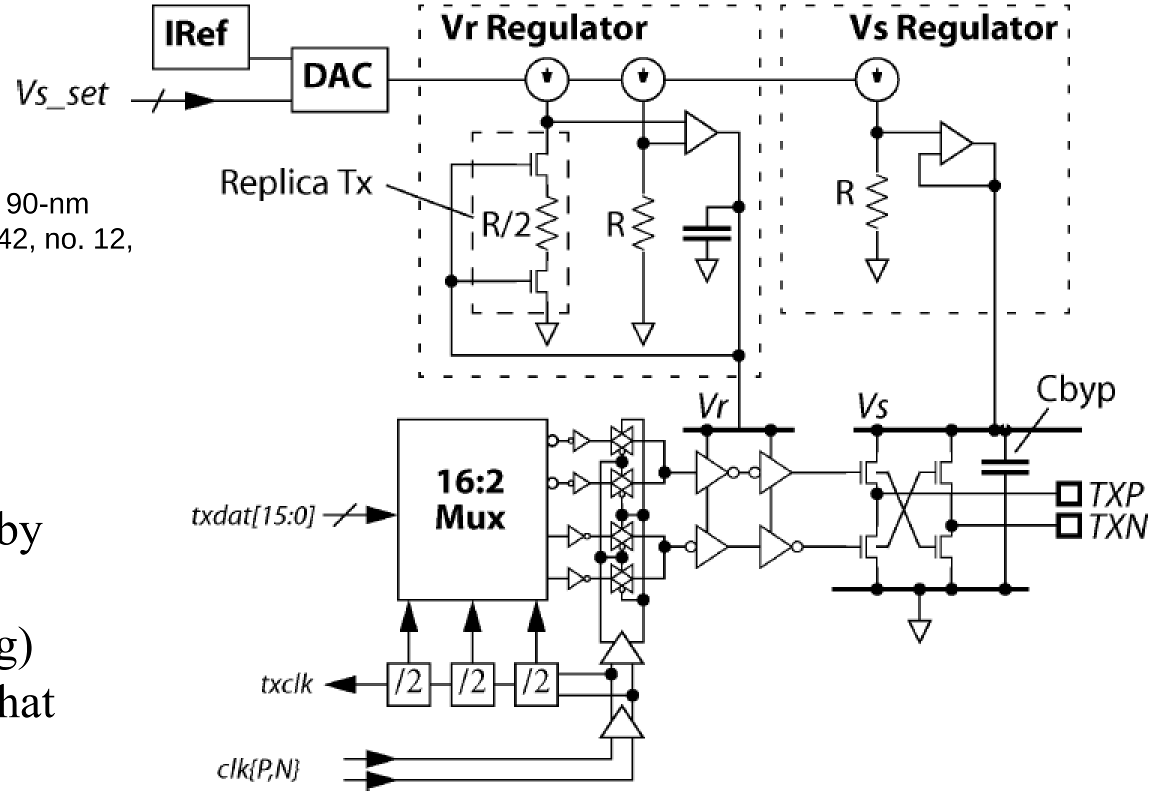
SST Output Driver Swing Control



- To program the swing of the SST driver one of the following techniques can be used:
  - A programmable supply regulator
  - Dividing the driver into multiple slices and deriving them with the opposite polarity input
    - The slices act as a potential divider between V_{DD} and GND and the swing becomes a function of the number of slices N and M: $Vswing=V_{DD}(N-M)/(N+M)$

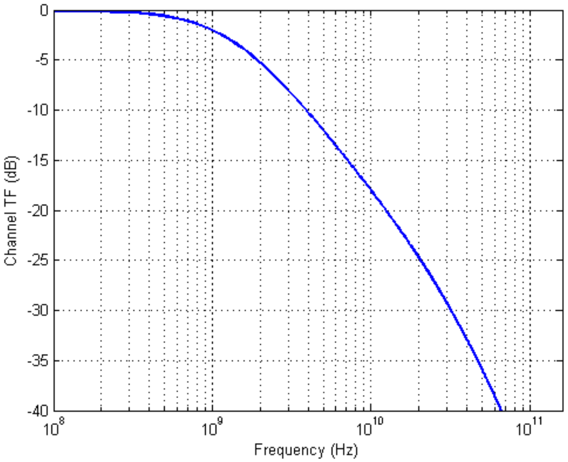
JSSC 2007: 14-mW 6.25-Gb/s Transceiver in 90-nm CMOS

J. Poulton et al., "A 14-mW 6.25-Gb/s Transceiver in 90-nm CMOS," in IEEE Journal of Solid-State Circuits, vol. 42, no. 12, pp. 2745-2757, Dec. 2007.

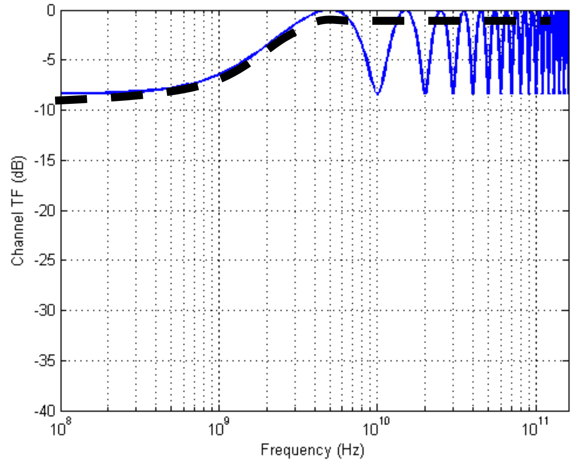


- The output terminals are driven by an NMOS-NMOS driver
- The voltage Vs (the output swing) is adjusted digitally via a DAC that sets the currents
- Vr is generated in a replica-bias circuit that forces a replica transmitter to have the same impedance as a scaled resistor
- This method sets the sum of the pullup and pulldown impedance of the transmitter approximately equal to the line impedance.

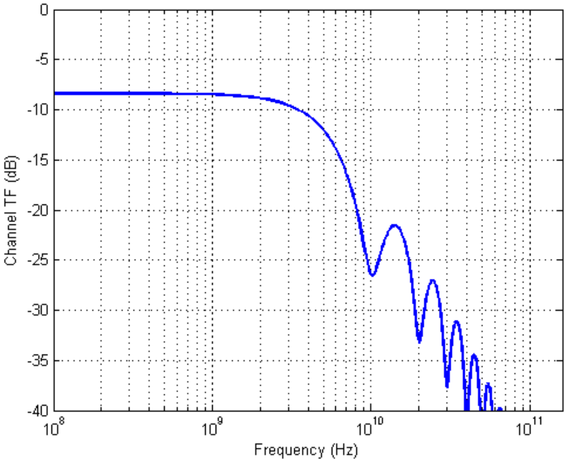
Transmit Driver Equalization



Channel BW_{3dB} ~1.5GHz



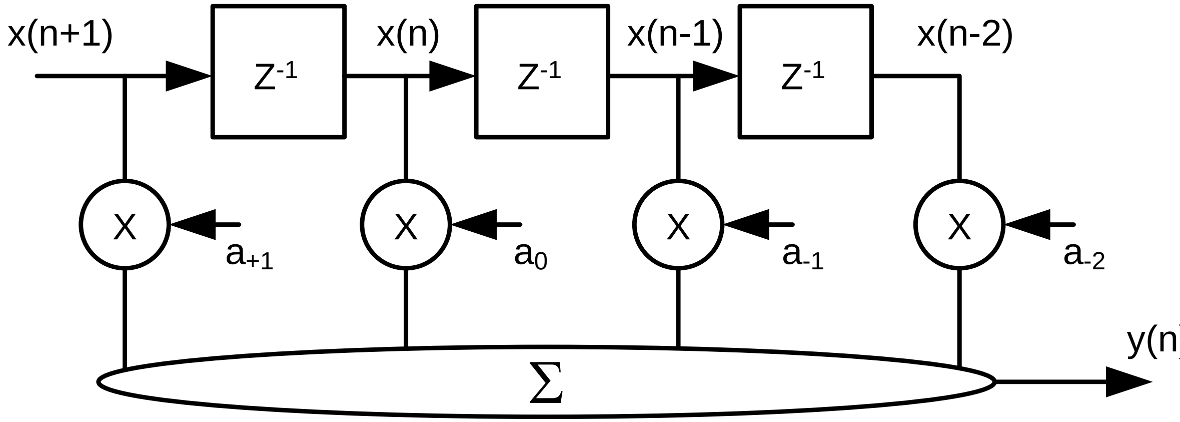
FIR frequency response ~ 9dB high frequency boost



Combined channel and Tx EQ BW_{3dB}~ $F_{Nyquist}$

- To equalize HF loss it is important to flatten the frequency response regardless of the value of the DC gain
- Tx equalization can be used to provide high frequency boost resulting in a higher 3dB bandwidth for the equalized response
- Due to limited supply headroom (limited by the maximum swing), Tx EQ usually de-emphasizes the DC amplitude and leaves the high frequency response at 0dB as opposed to providing high frequency gain
- Tx pre-emphasis intentionally distorts the signal such that an open eye is received at the end of the channel

Transmit FIR



- Tx pre-emphasis can be done using analog or digital techniques, however digital techniques are more popular especially since the clock is available
- The most common approach used for digital Tx pre-emphasis is using a finite impulse response (FIR) filter also called FFE (feed forward equalizer)
- 3 and 4 tap Tx FIRs are the most commonly used
- The number of taps and maximum tap weights determine the allowable de-emphasis value and the quality of equalization (both are usually specified by standards)
- The Tx FIR transfer function is given by:

$$H_{TX}(z) = (a_{+1}z + a_0 + a_{-1}z^{-1} + a_{-2}z^{-2})$$

Transmit FIR (Cont'd)

- **Problem**: Derive an expression for the boost of a 4-tap FIR equalizer at the Nyquist frequency
- **Solution**:

$$4-tap\ FIR: H_{TX}(z) = a_{+1}z + a_0 + a_{-1}z^{-1} + a_{-2}z^{-2}$$

$$Boost\Big|_{Nyquist} = \frac{H_{TX}(f = f_N)}{H_{TX}(f = 0)}$$

$$z = e^{i\omega T_b}$$

$$for\ f = 0 \rightarrow z = 1$$

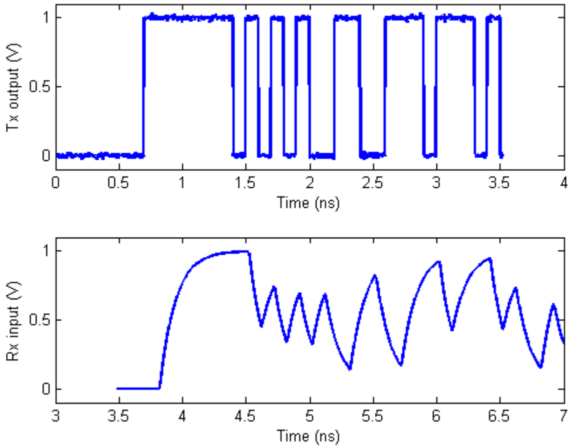
$$H_{TX}(f = 0) = a_{+1} + a_0 + a_{-1} + a_{-2}$$

$$for\ f = f_N \rightarrow z = e^{i(2\pi f_N)T_b} = e^{i(2\pi(1/2T_b))T_b} = -1$$

$$H_{TX}(f = f_N = 1/2T_b) = -a_{+1} + a_0 - a_{-1} + a_{-2}$$

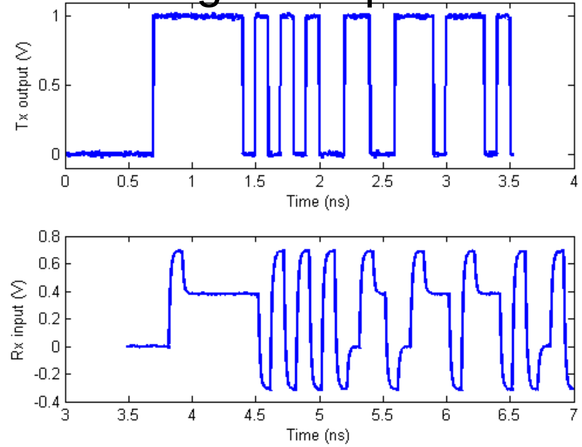
$$Boost\Big|_{Nyquist} = \frac{-a_{+1} + a_0 - a_{-1} + a_{-2}}{a_{+1} + a_0 + a_{-1} + a_{-2}}$$

Transmit FIR (Cont’d)

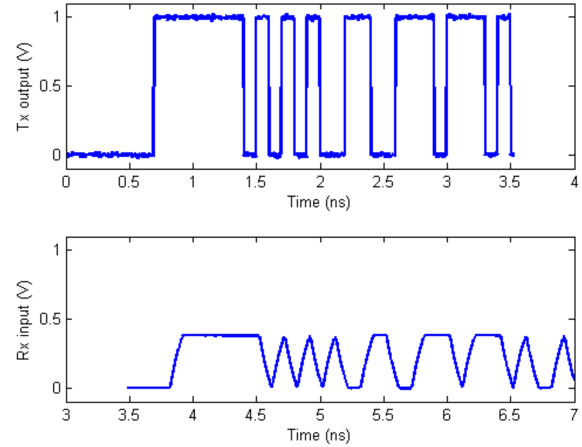


Tx and Rx signals with lossy channel without Tx EQ

Digital sequence



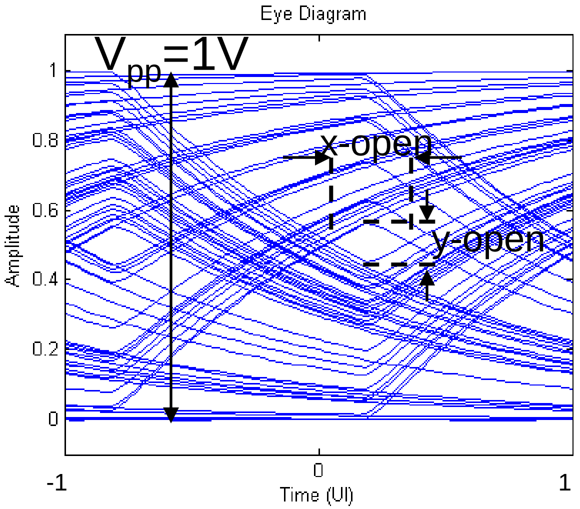
Tx Pre-distorted output to compensate for channel ISI



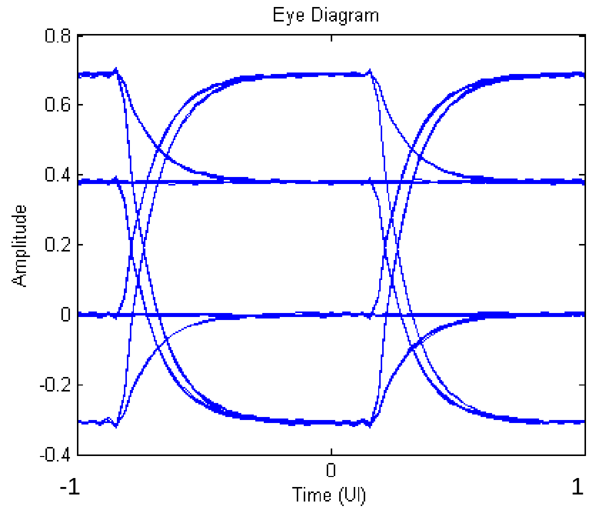
Rx received signal with Tx EQ

- If no Tx pre-emphasis is used the single bit transitions are heavily attenuated compared to CIDs
- When Tx pre-emphasis is used the transition bits are emphasized, non transition but are not emphasized
- The channel attenuates the transition bits more than the non transition bits due to their higher frequency content
- At the receiver input both transition and non transition bits have the same amplitude, i.e. ISI is eliminated

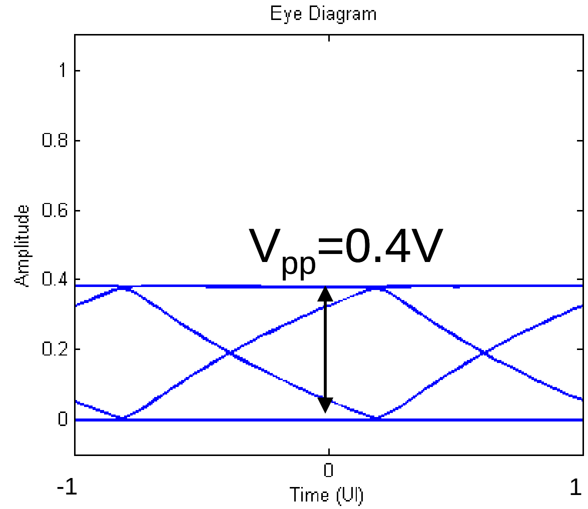
Transmit FIR (Cont'd)



Rx eye diagram with lossy channel without Tx EQ



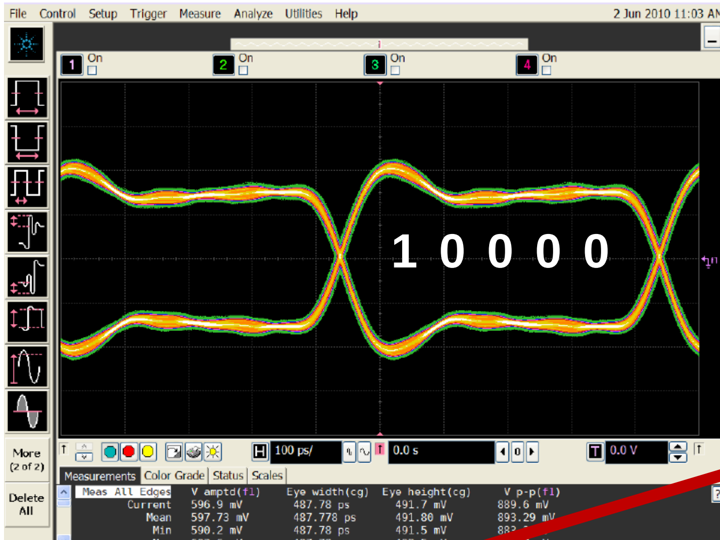
Tx output eye diagram with pre-emphasis (pre-distorted eye)

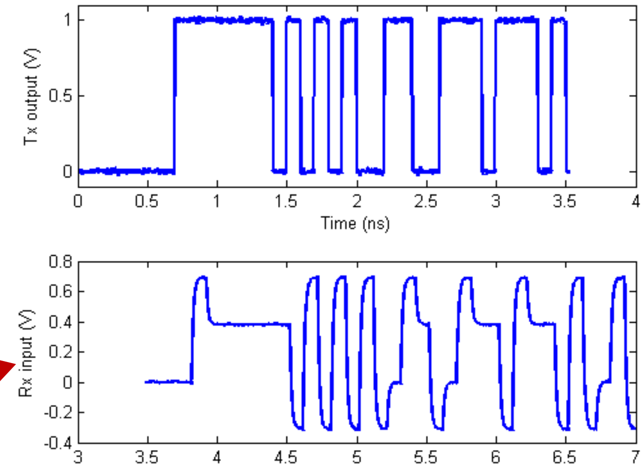


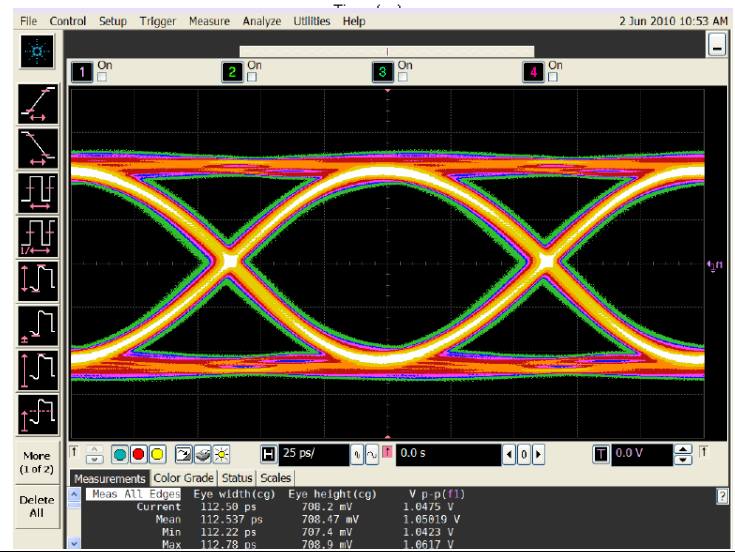
Rx received eye diagram with Tx pre-emphasis

- Receiver eye was nearly closed without using Tx pre-emphasis resulting in high BER
- After applying the right amount of pre-emphasis, ISI can be eliminated from the received eye
- However, pre-emphasis also reduces the outer eye opening, i.e. the non transition bits are de-emphasized, thus a maximum limit is usually set by standards on how much pre-emphasis can be used

PCIe gen 3: 8Gb/s Rx Eye Diagram







Tx Pre-distorted output to compensate for channel ISI

Rx received eye diagram after Tx pre-emphasis has compensated for the channel ISI