# ECEN689: Special Topics in High-Speed Links Circuits and Systems
# Spring 2010

## Lecture 9: Modulation Schemes

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# Announcements

- Exam 1 will be second week of March (3/8-12)

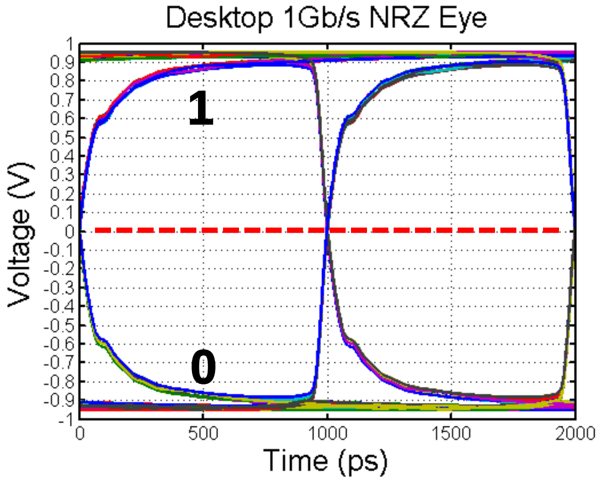
- Reading
  - Papers posted on PAM-4 and duobinary modulation

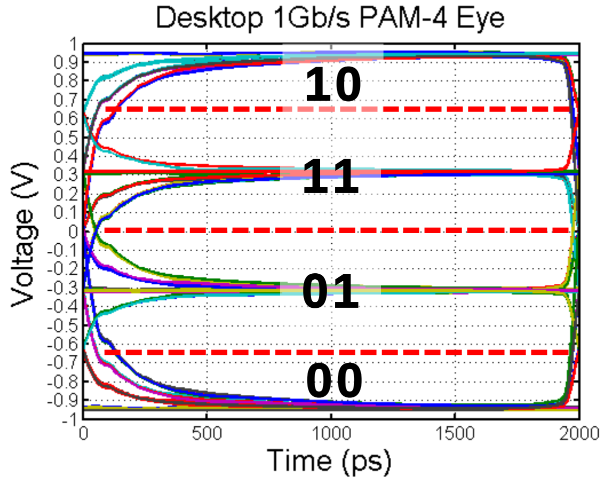
# Agenda

- Compare NRZ, PAM-4, and Duobinary modulation

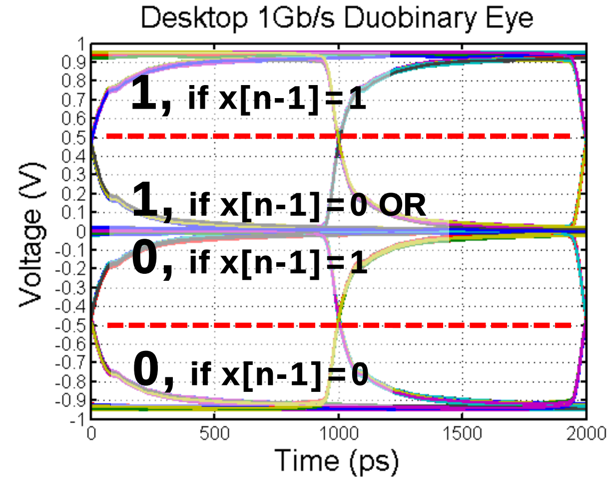
# Modulation Schemes

- Binary, NRZ, PAM-2
  - Simplest, most common modulation format
- PAM-4
  - Transmit 2 bits/symbol
  - Less channel equalization and circuits run ½ speed
- Duobinary $w[n] = x[n] + x[n-1]$
  - Allows for controlled ISI, symbol at RX is current bit plus preceding bit
  - Results in less channel equalization

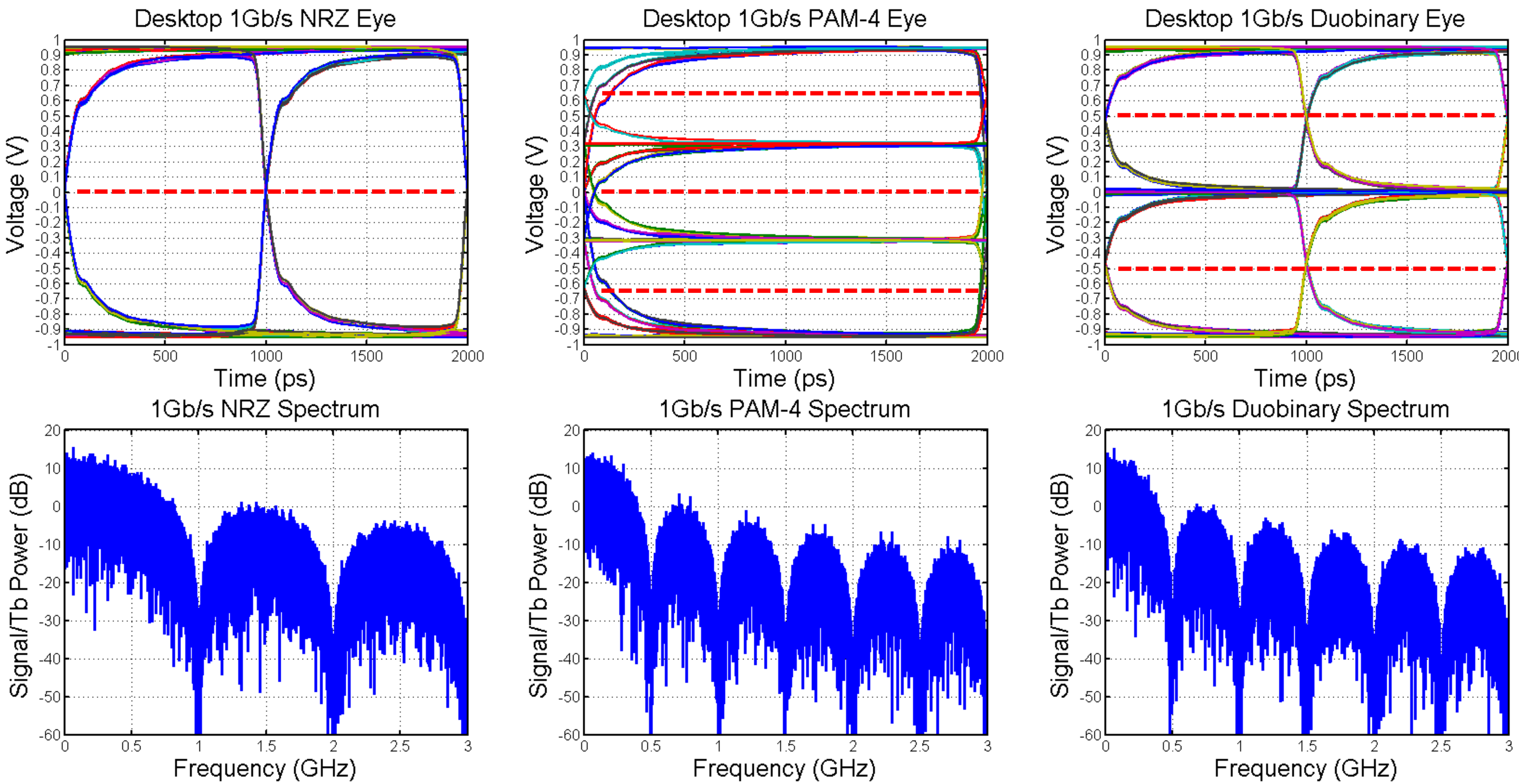



**No Pre-Coding Case**



# Modulation Frequency Spectrum




Majority of signal power in 1GHz bandwidth

Majority of signal power in 0.5GHz bandwidth

Majority of signal power in 0.5GHz bandwidth

# Nyquist Frequency

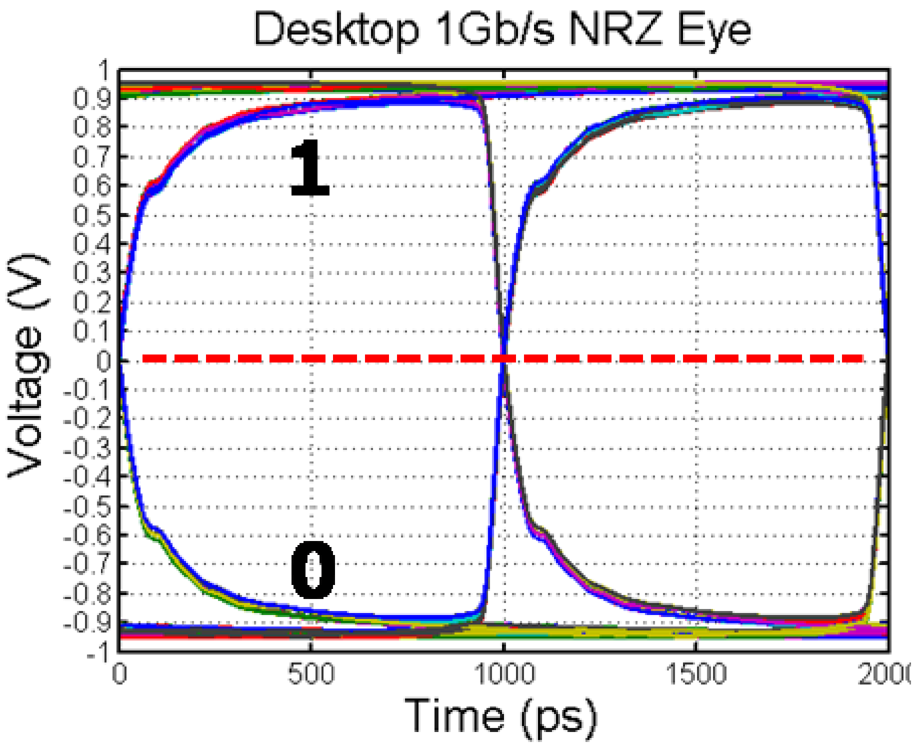
- Nyquist bandwidth constraint:
  - The theoretical minimum required system bandwidth to detect $R_S$ (symbols/s) without ISI is $R_S/2$ (Hz)
  - Thus, a system with bandwidth $W=1/2T=R_S/2$ (Hz) can support a maximum transmission rate of $2W=1/T=R_S$ (symbols/s) without ISI

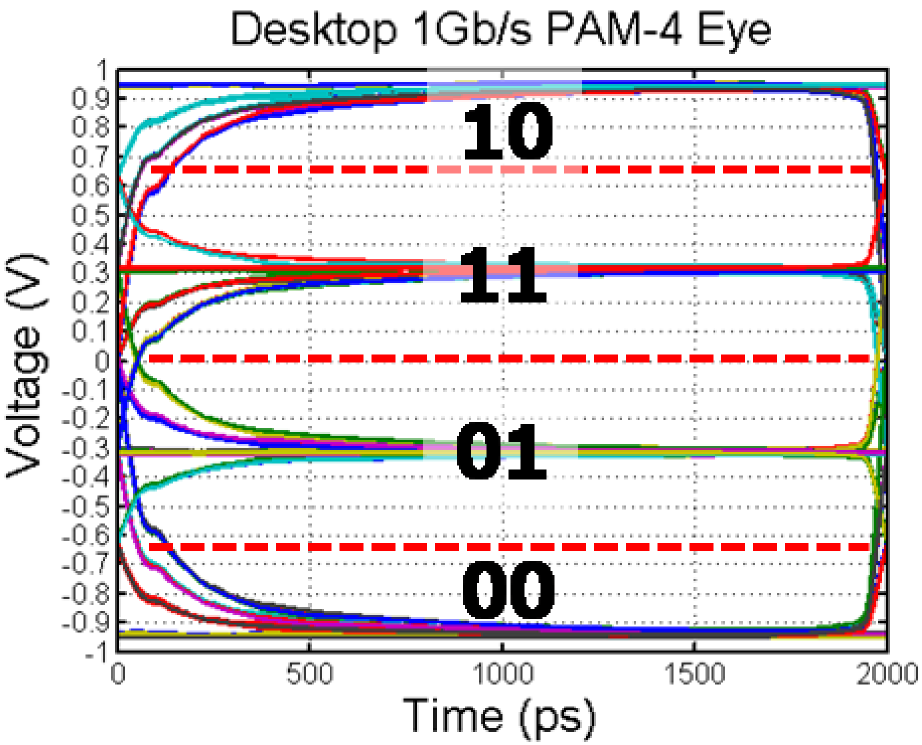
$$\frac{1}{2T} = \frac{R_S}{2} \leq W \Rightarrow \frac{R_S}{W} \leq 2 \quad \text{(symbols/s/Hz)}$$

  - For ideal Nyquist pulses (sinc), the required bandwidth is only $R_S/2$ to support an $R_S$ symbol rate

| **Modulation** | **Bits/Symbol** | **Nyquist Frequency** |
|---|---|---|
| NRZ | 1 | $R_s/2=1/2T_b$ |
| PAM-4 | 2 | $R_s/2=1/4T_b$ |
| Duobinary | 1 (or more) ?? | $1/3T_b$ (not Nyquist signaling) |

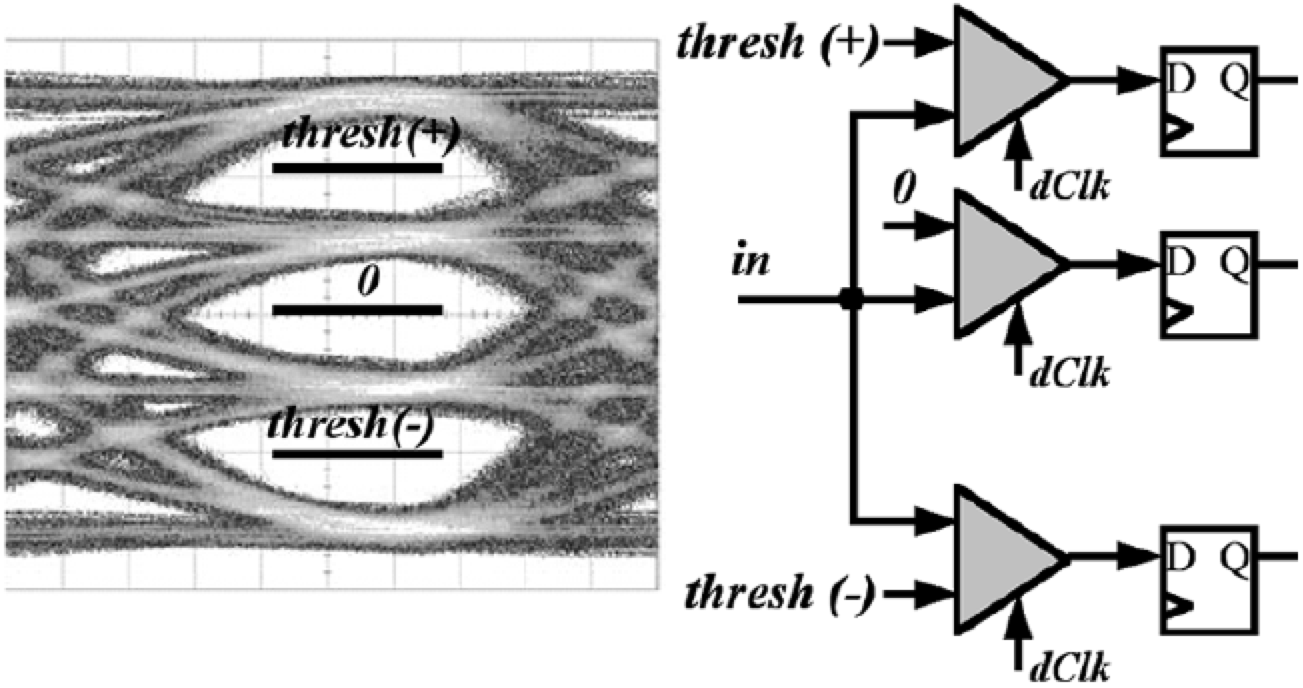
# NRZ vs PAM-4




- PAM-4 should be considered when
  - Slope of channel insertion loss ($S_{21}$) exceeds reduction in PAM-4 eye height
    - Insertion loss over an octave is greater than 20*log10(1/3)=-9.54dB
  - On-chip clock speed limitations

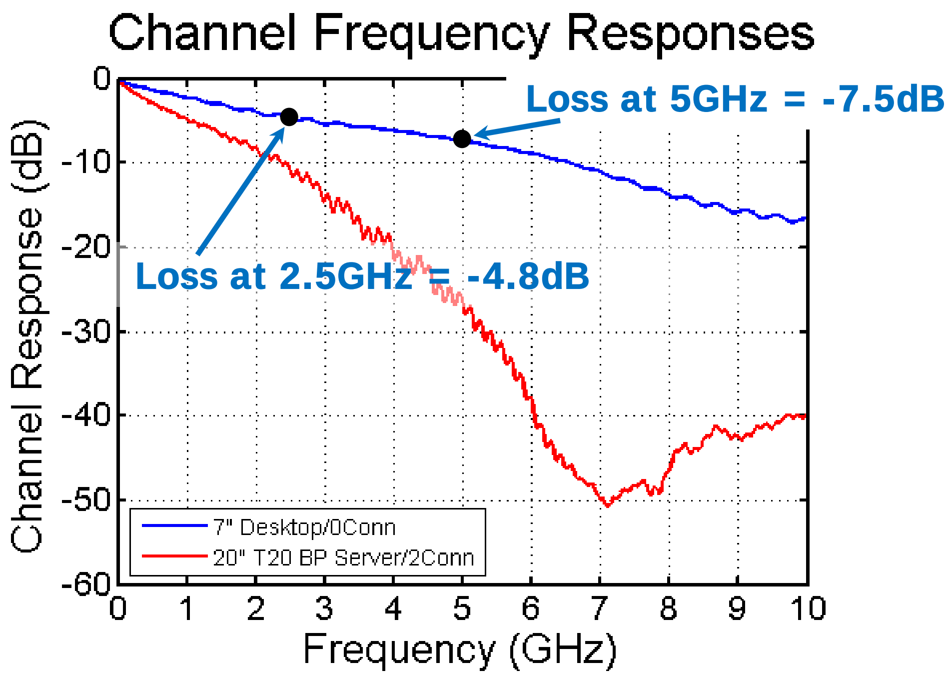
# PAM-4 Receiver

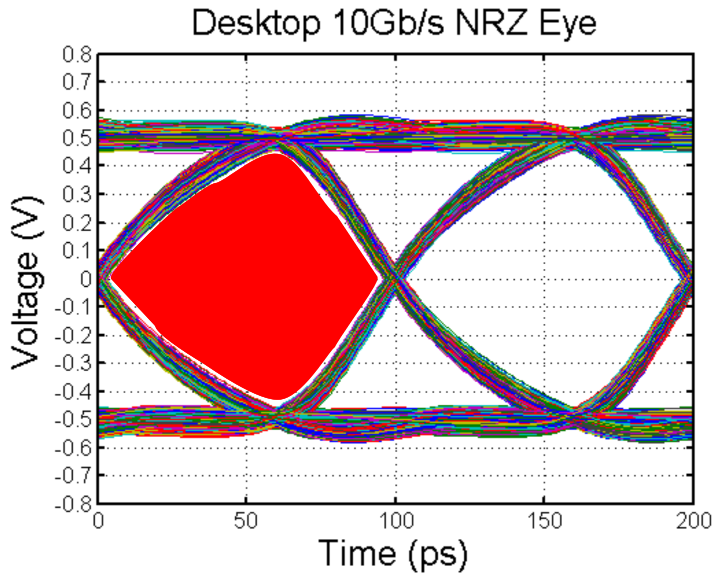


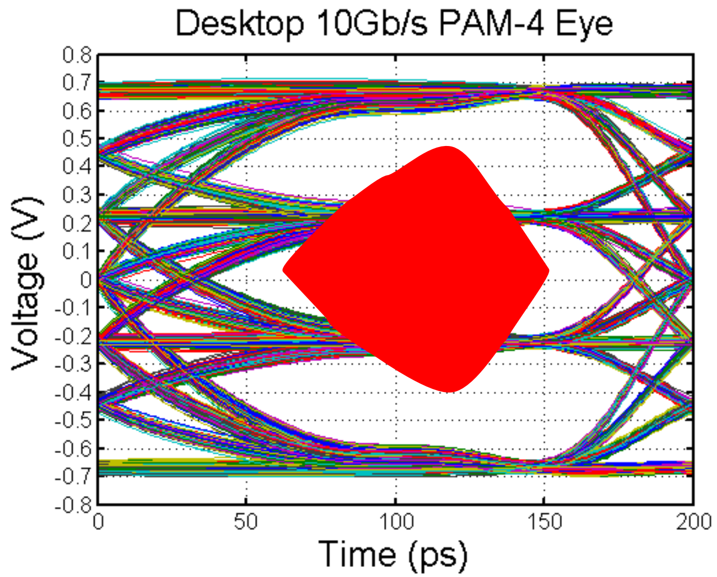

[**Stojanovic JSSC 2005**]

- 3x the comparators of NRZ RX

# NRZ vs PAM-4 – Desktop Channel

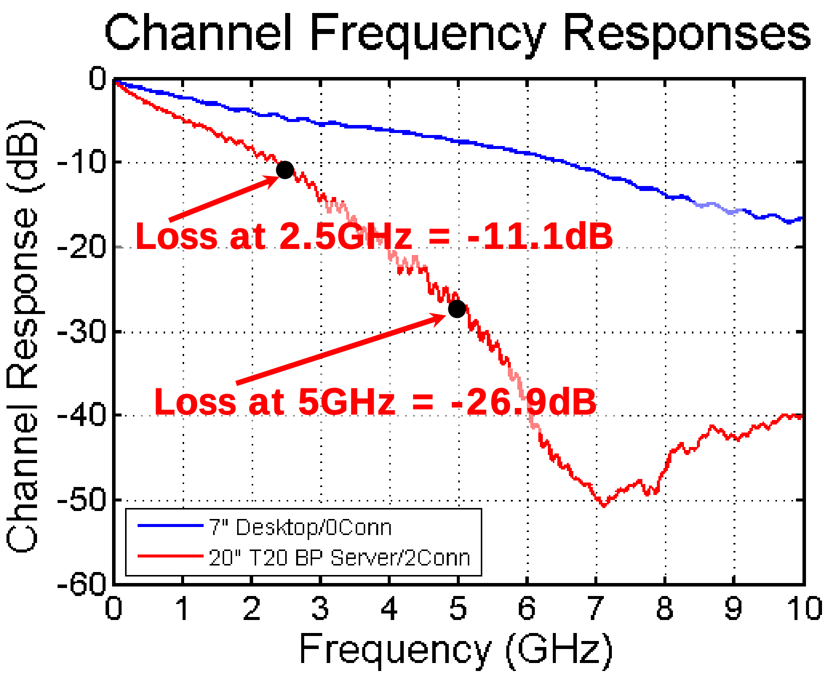


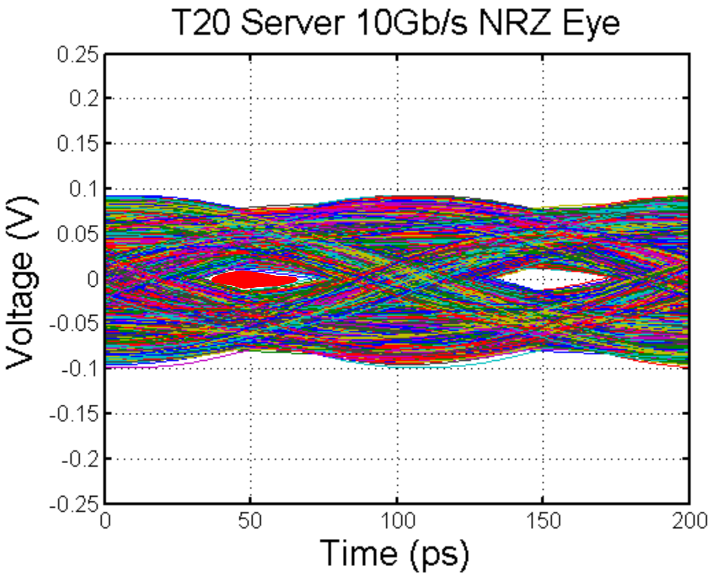



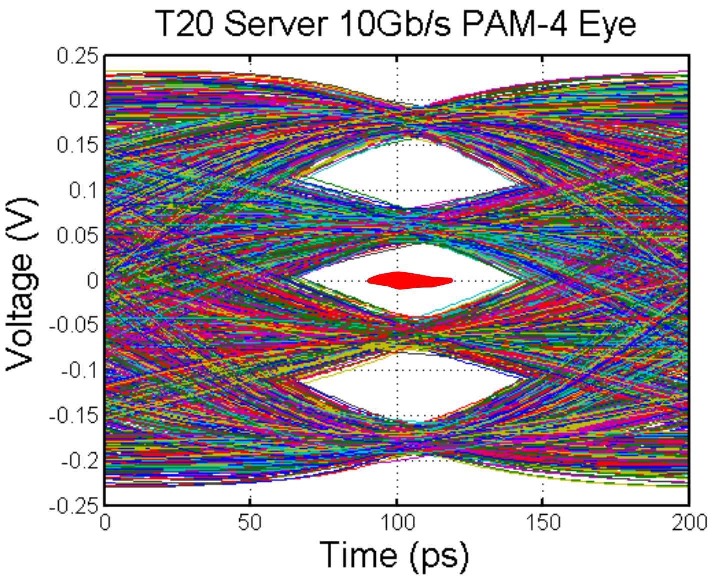

- Eyes are produced with 4-tap TX FIR equalization
- Loss in the octave between 2.5 and 5GHz is only 2.7dB
  - NRZ has better voltage margin

# NRZ vs PAM-4 – T20 Server Channel




- Eyes are produced with 4-tap TX FIR equalization
- Loss in the octave between 2.5 and 5GHz is 15.8dB
  - PAM-4 “might” be a better choice

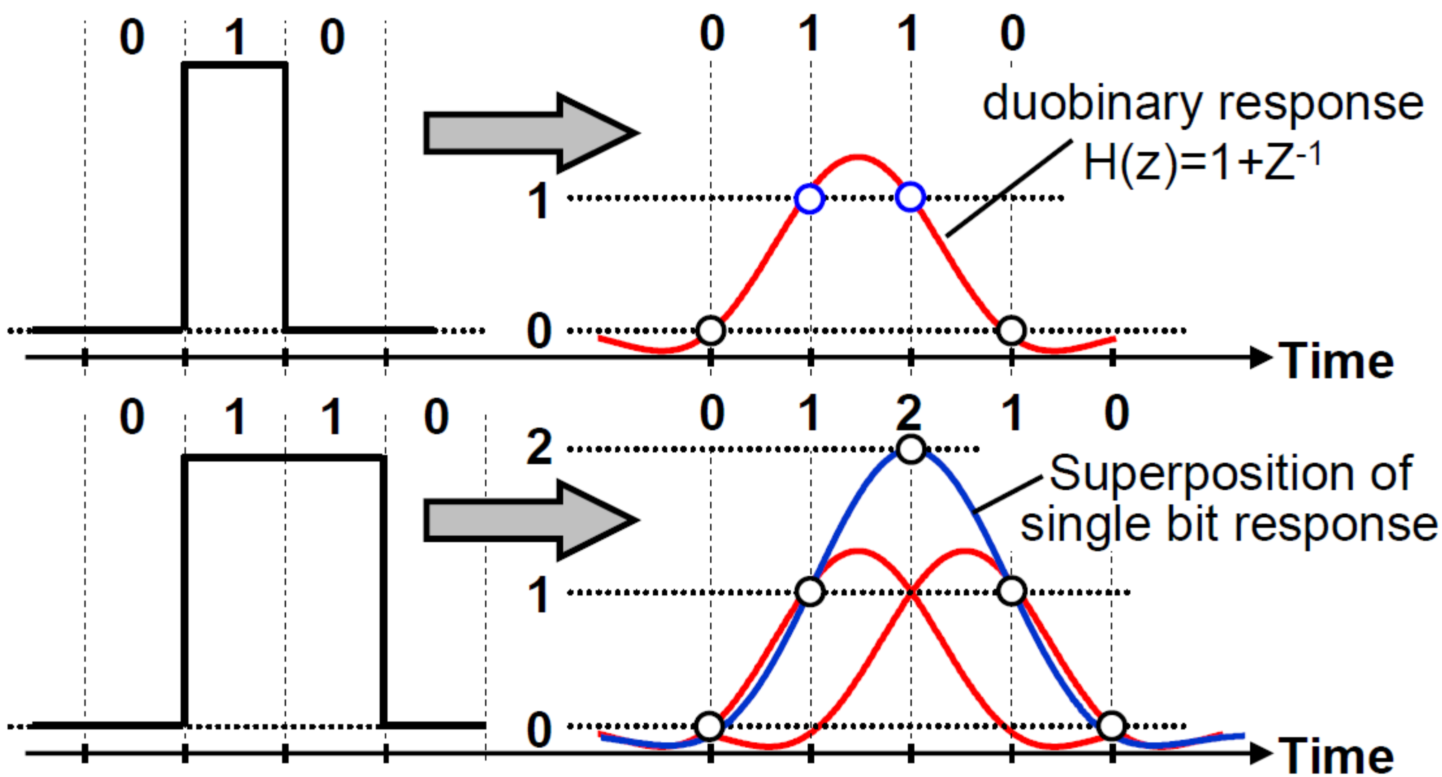


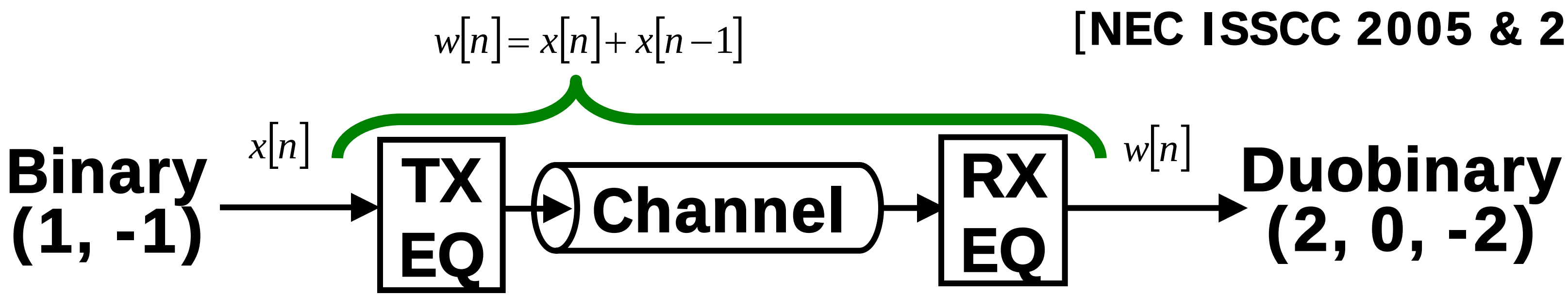
# Multi-Level PAM Challenges

- Receiver complexity increases considerably
  - 3x input comparators (2-bit ADC)
  - Input signal is no longer self-referenced at 0V differential
    - Need to generate reference threshold levels, which will be dependent on channel loss and TX equalization
- CDR can display extra jitter due to multiple “zero crossing” times
- Smaller eyes are more sensitive to cross-talk due to maximum transitions
- Advanced equalization (DFE) can allow NRZ signaling to have comparable (or better) performance even with >9.5dB loss per octave

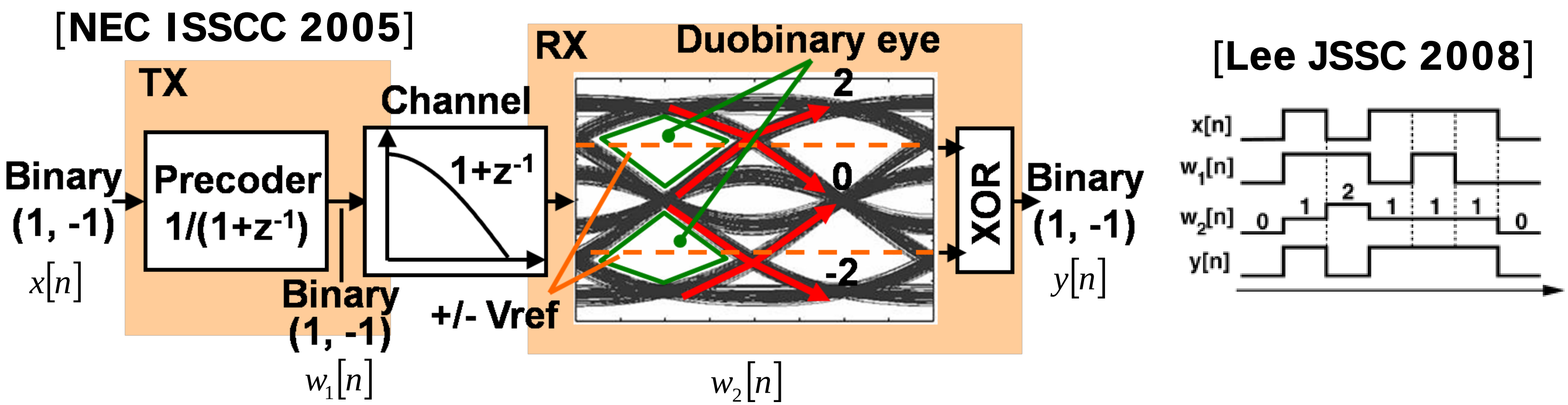
# Duobinary Signaling




[NEC ISSCC 2005 & 2009]

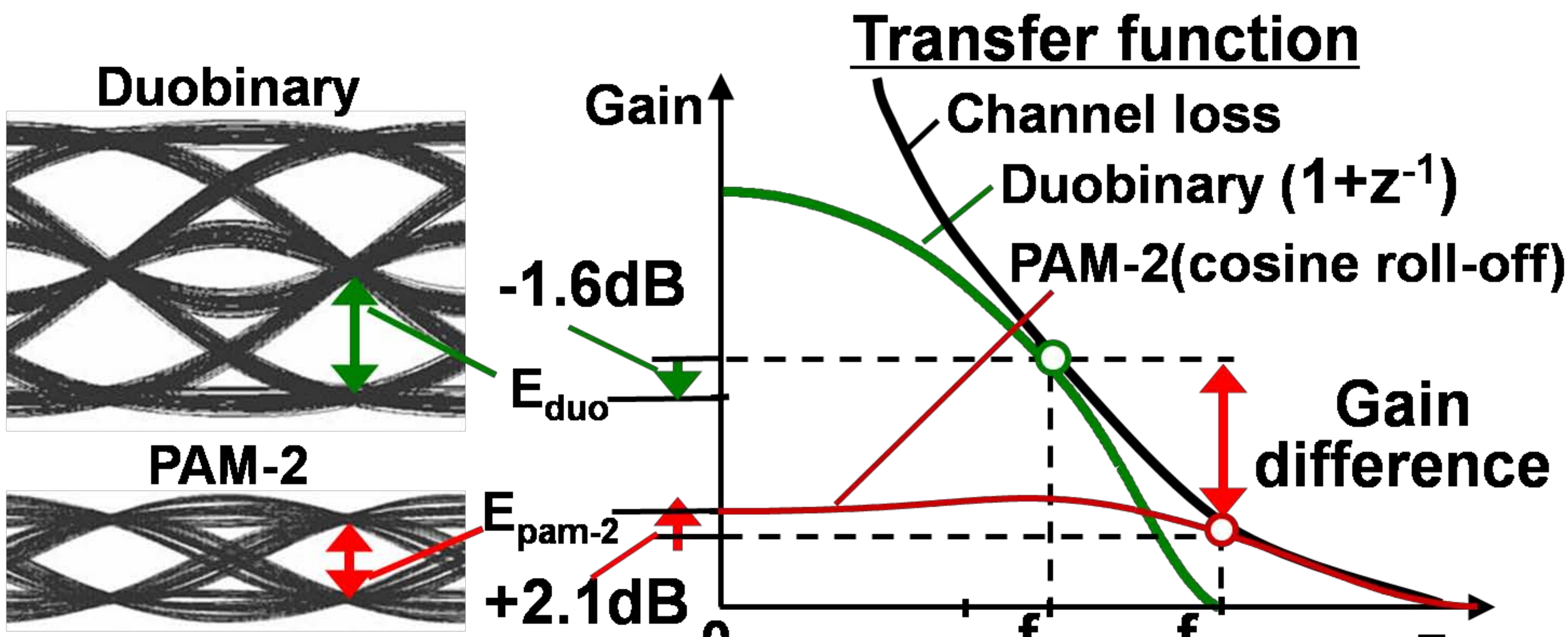


# Duobinary Signaling w/ Precoder




- With precoder, “middle” signal at the receiver maps to a “1” and “high” and “low” signal maps to a “0”
- Precoder allows for binary signal out of transmitter resulting in a power gain
- Channel can be leveraged to aid in duobinary pulse shaping
- Eliminates error propagation at receiver
- Similar performance to using a 1-tap loop-unrolled DFE at RX

# NRZ vs Duobinary



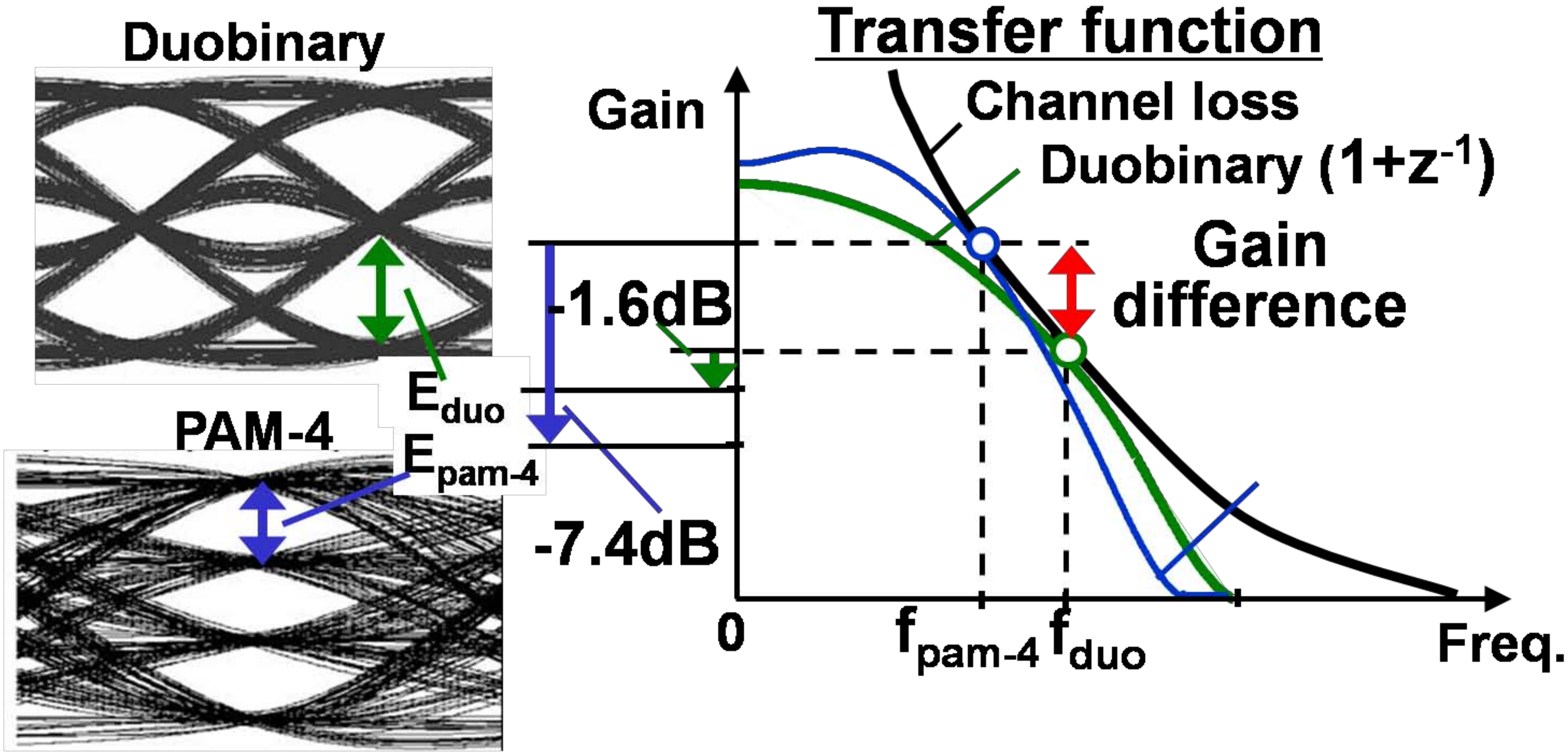

$f_{pam\text{-}2}$: Nyquist freq. of PAM-2

$f_{duo}$: Nyquist freq. of Duobinary, 2/3* $f_{pam\text{-}2}$

**If gain difference is larger than 3.7dB, $E_{duo}$ > $E_{pam\text{-}2}$**

[NEC ISSCC 2005]

# PAM-4 vs Duobinary

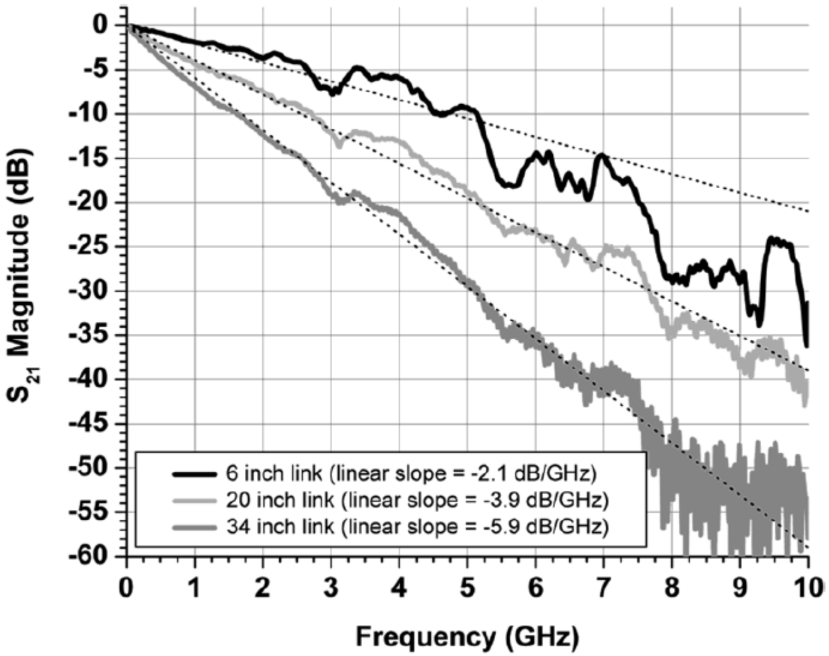



**If gain difference is less than 5.8dB, $E_{duo} > E_{pam-4}$**

[NEC ISSCC 2005]

# 10Gb/s Modulation Comparisons

[**Sinsky MTT 2005**]



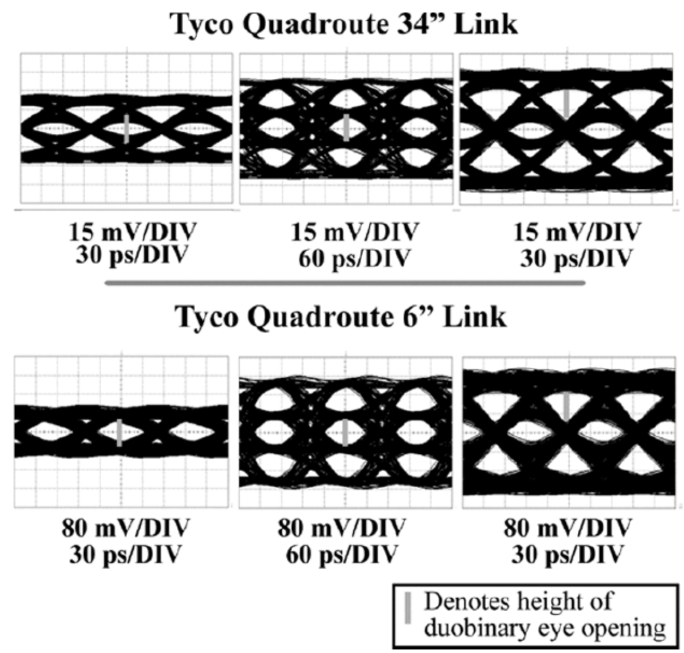




TABLE IV

MINIMUM EYE OPENINGS THROUGH A TYCO QUADROUTE BACKPLANET

| | 6” Link (#1) | 20” Link (#5) | 34” Link (#8) |
|---|---|---|---|
| NRZ | 78.3 $mV_{pp}$ | 37.4 $mV_{pp}$ | 10.2 $mV_{pp}$ |
| ***Duobinary*** | ***125.6 $mV_{pp}$*** | ***82.9 $mV_{pp}$*** | ***24.9 $mV_{pp}$*** |
| PAM-4 | 100.8 $mV_{pp}$ | 53.1 $mV_{pp}$ | 15.3 $mV_{pp}$ |

- Channel input = 600$mV_{pp}$
- 2-tap TX FIR equalization
- Both duobinary and PAM-4 perform better
- With more equalization NRZ will be more competitive

# Modulation Take-Away Points

- Loss-slope guidelines are a good place to start in consideration of alternate modulation schemes
- More advanced modulation trades-off receiver complexity versus equalization complexity
- Advanced modulation challenges
  - Peak TX power limitations
  - Setting RX comparator thresholds and controlling offsets
  - CDR complexity
  - Crosstalk sensitivity (PAM-4)
- Need link analysis tools that consider voltage, timing, and crosstalk noise to choose best modulation scheme for a given channel

# Next Time

- Link Circuits
  - Termination structures
  - Drivers
  - Receivers