

# **EE 437/538B: Integrated Systems**

## **Capstone/Design of Analog Integrated Circuits and Systems**

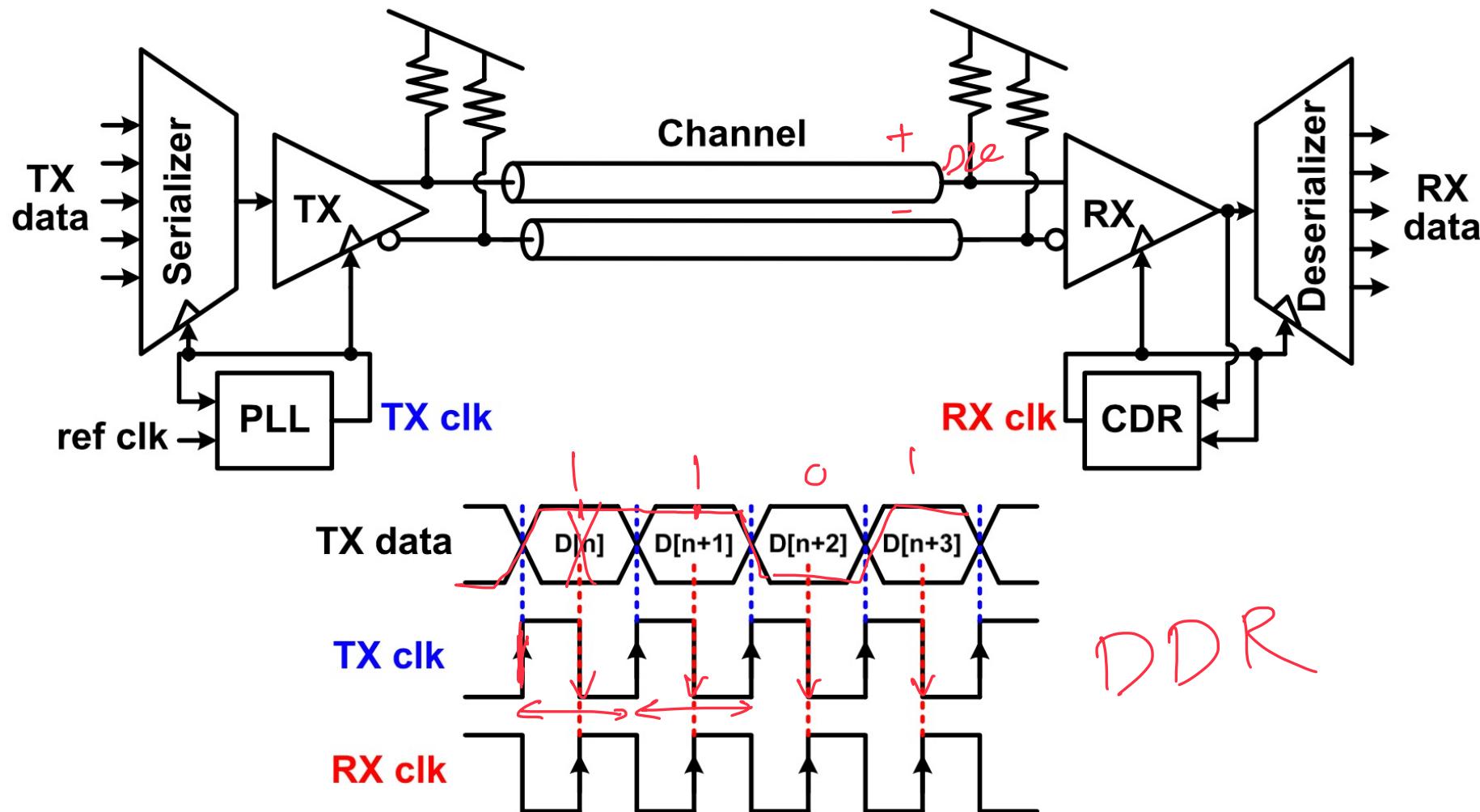
### **Lecture 2: Channel Pulse Model**

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Spring 2022

# High-Speed Electrical Link System

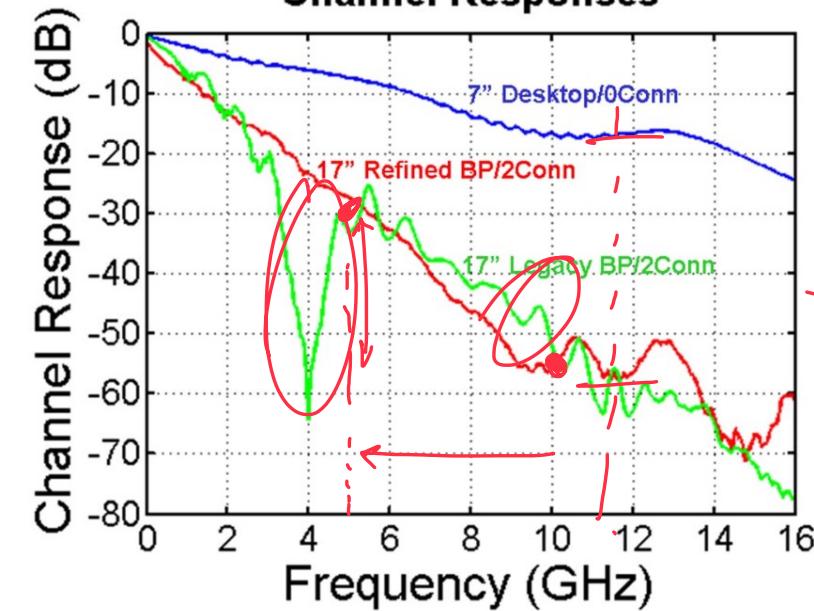


[Sam Palermo]

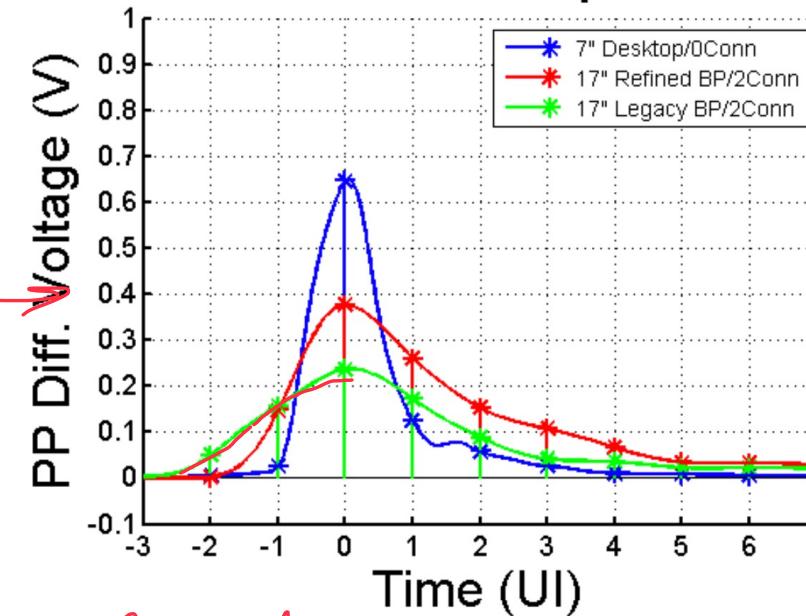
# Channel Example

① BW limiter  
② freq notch

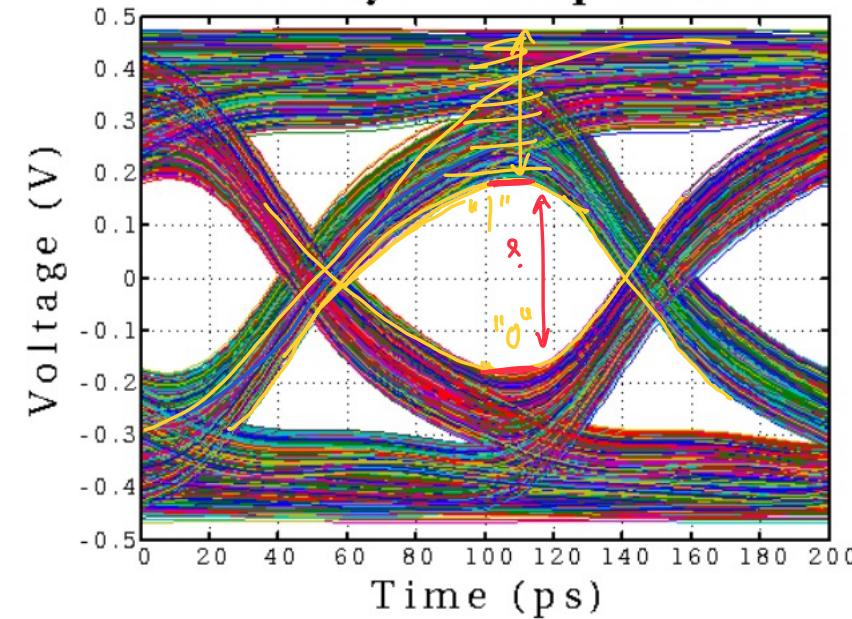
Channel Responses



10Gb/s Pulse Responses



10Gb/s Eye - Desktop Channel

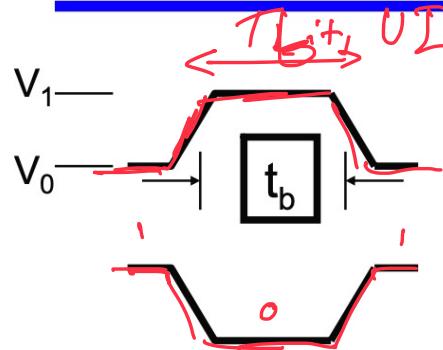


→ Wireline →  
→ Optical →

} Skin depth, dielectric losses  
Gmetas / reflect  
Inter Connect of photonics & elec.  
Modulator & PD

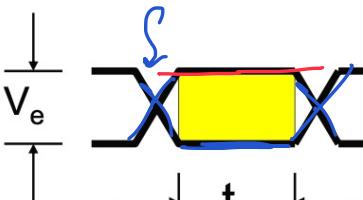
[Sam Palermo]

# Eye Diagrams



This is a “1”

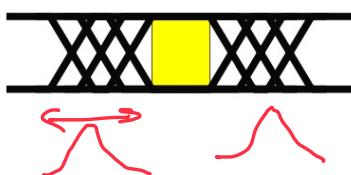
This is a “0”



Eye Opening - space between 1 and 0



With voltage noise

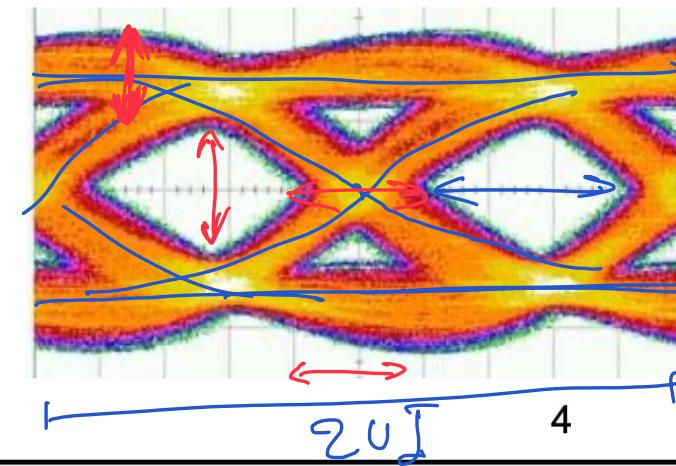


With timing noise

jitter

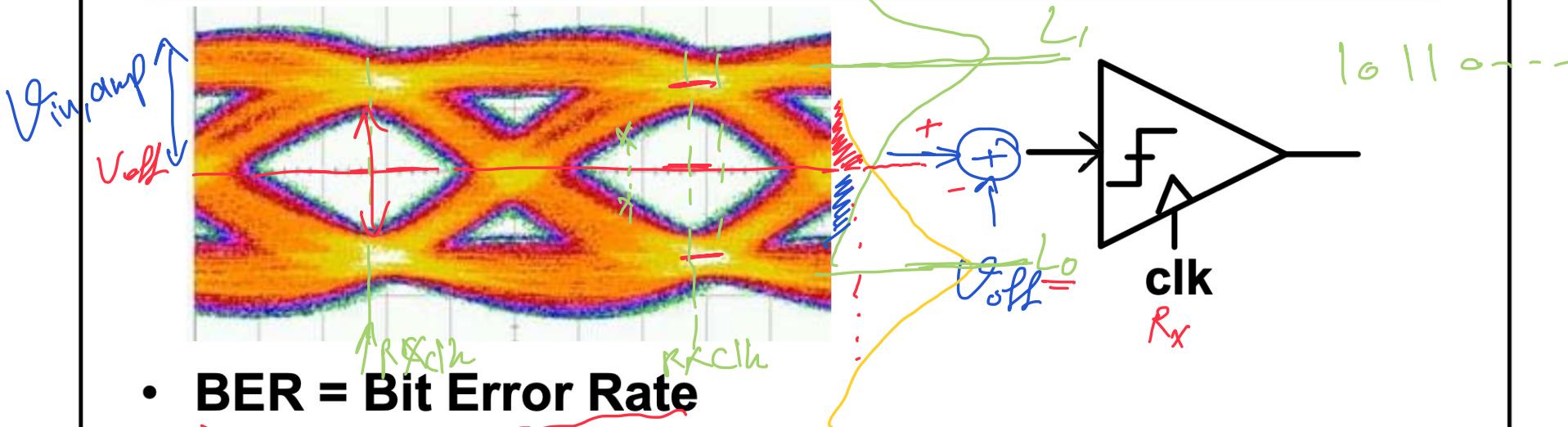
EE290C

Lecture 2



\* Just Consider the voltage noise

# BER



"Error-free!"

$$\underline{\underline{BER}} = \frac{1}{2} erfc \left( \frac{V_{in,ampl} - V_{off}}{\sqrt{2} \sigma_{noise}} \right)$$

- **BER =  $10^{-12}$ :**  $(V_{in,ampl} - V_{off}) = 7\sigma_n$
- **BER =  $10^{-20}$ :**  $(V_{in,ampl} - V_{off}) = 9.25\sigma_n$

total  
eve  
open  
 $\approx 14.8$

from  
applican  
side!

EE290C

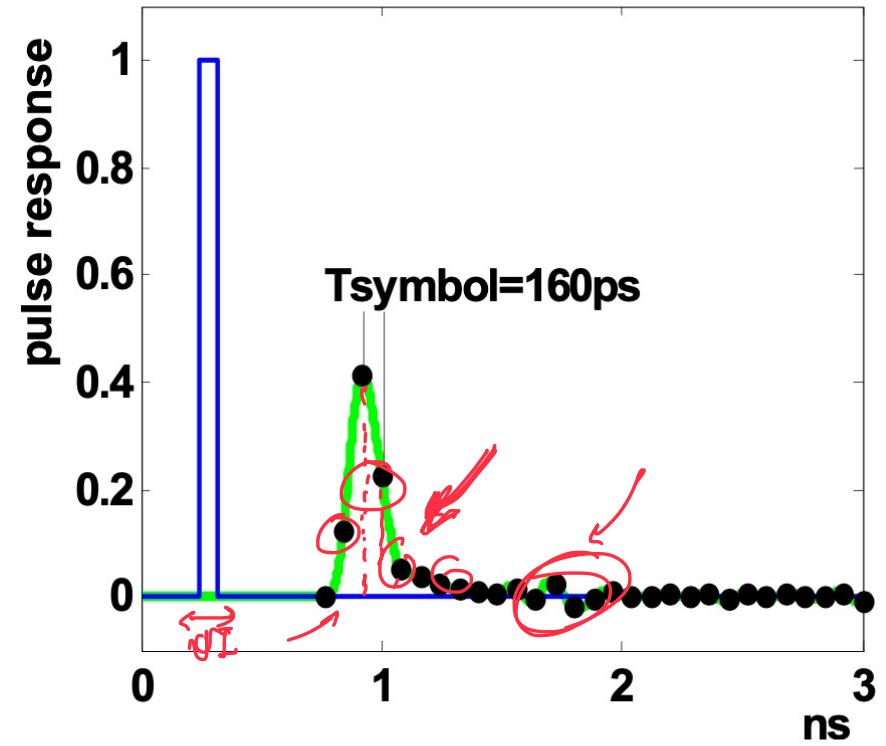
Lecture 2

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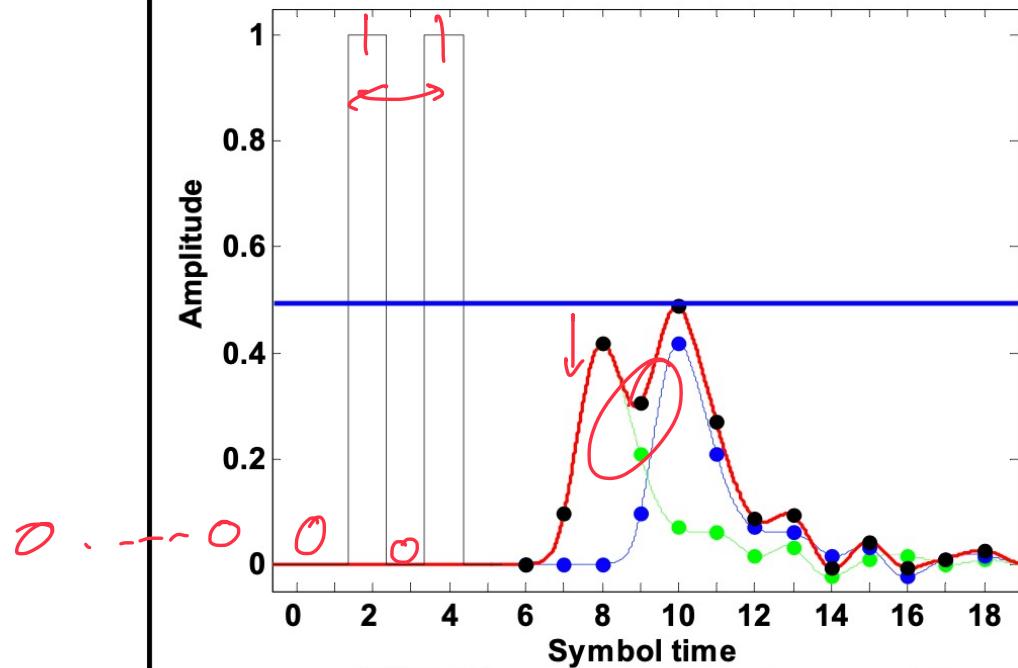
[Elad Alon]

# Inter-Symbol Interference (ISI)

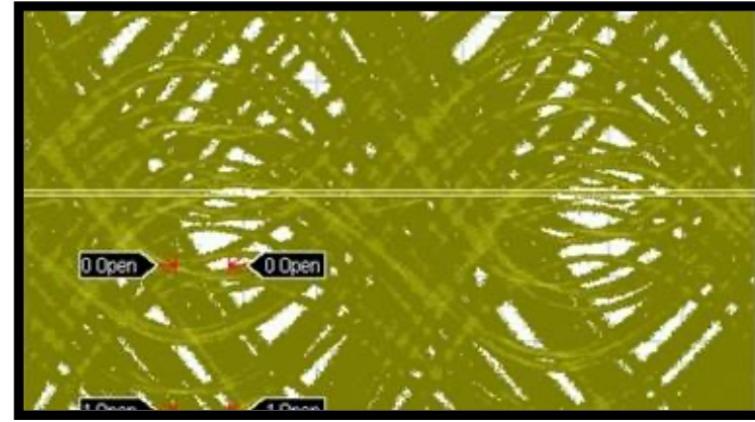
- Channel is band-limited
  - I.e., dispersive (low pass)
  - Short TX pulses get spread out
  - Low latency
- Also get reflections
  - Z mismatches, connectors, etc.
  - Longer latency



# Why ISI Matters



Eye Diagram



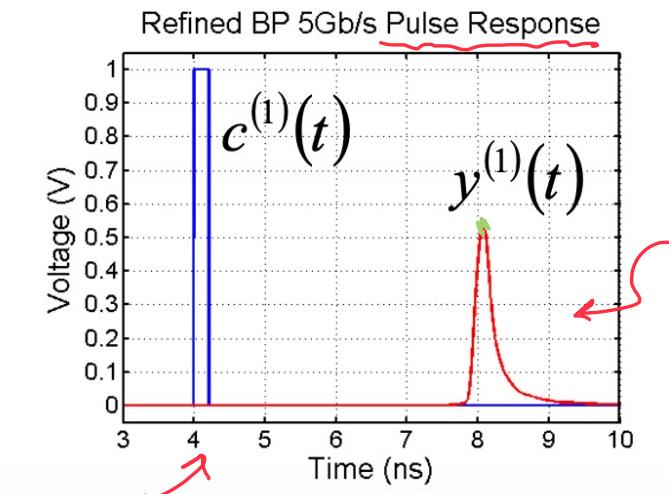
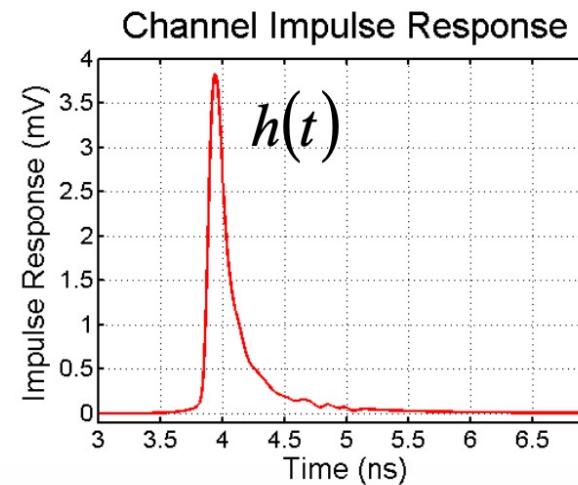
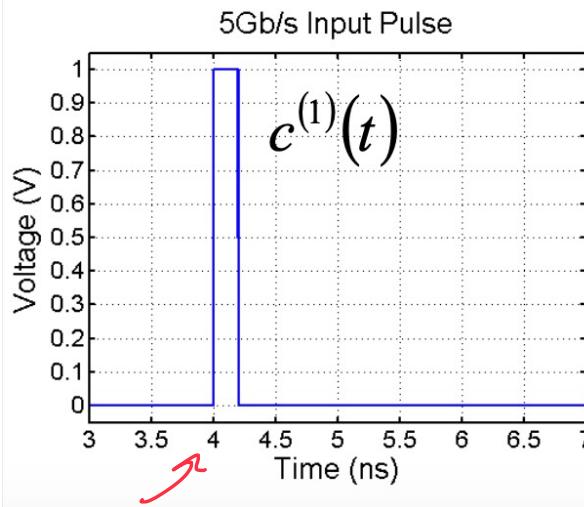
- **First sample doesn't even reach RX threshold**
  - Suffers ISI from all previous zero bits
- **Middle sample hardly different from first**
  - **0.2** trailing ISI (from previous symbol) and **0.1** leading ISI (from next symbol)

# Inter-Symbol Interference (ISI)

(LTI)

- Previous bits residual state can distort the current bit, resulting in inter-symbol interference (ISI)
- ISI is caused by
  - Reflections, Channel resonances, Channel loss (dispersion)
- Pulse Response

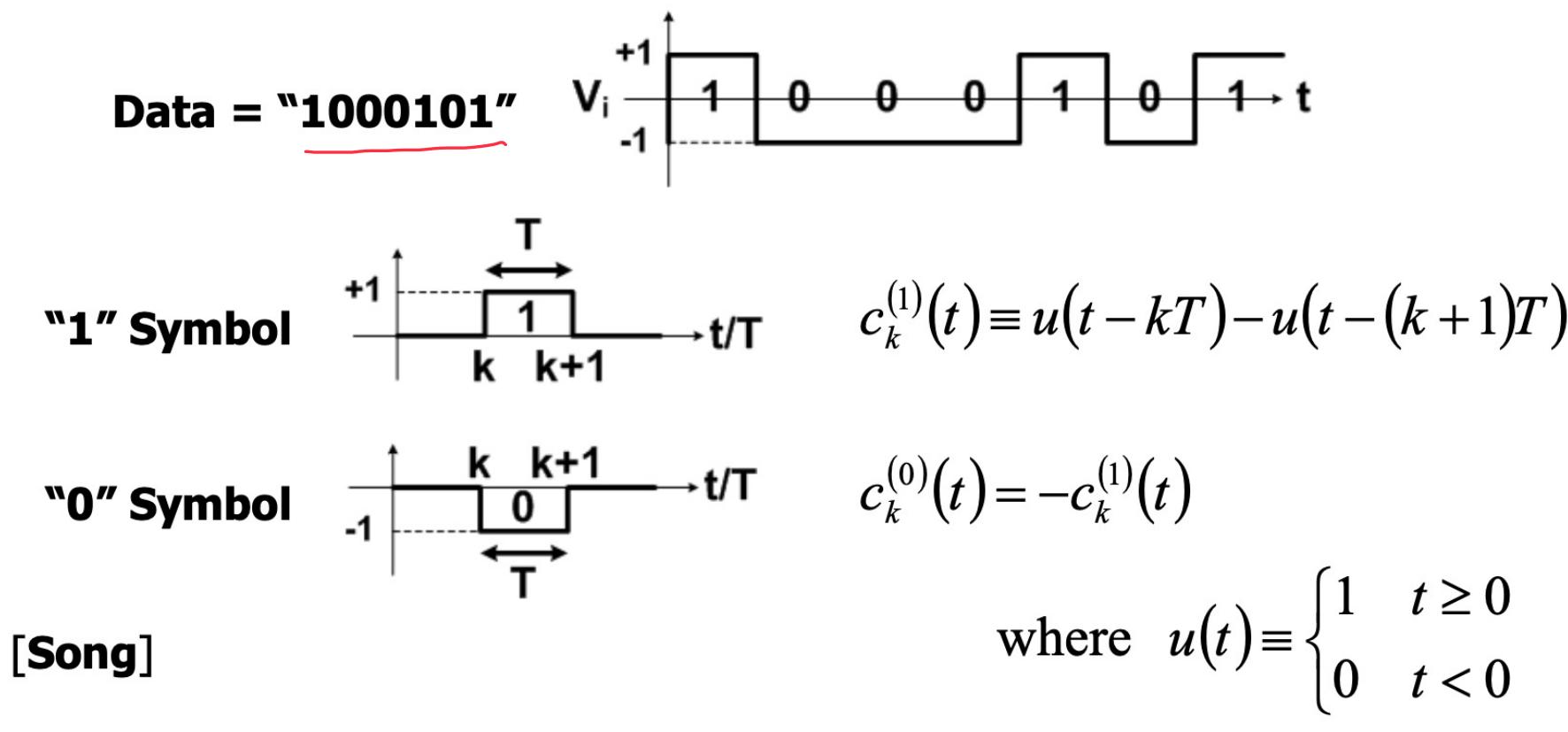
$$y^{(1)}(t) = c^{(1)}(t) * h(t)$$



[Sam Palermo]

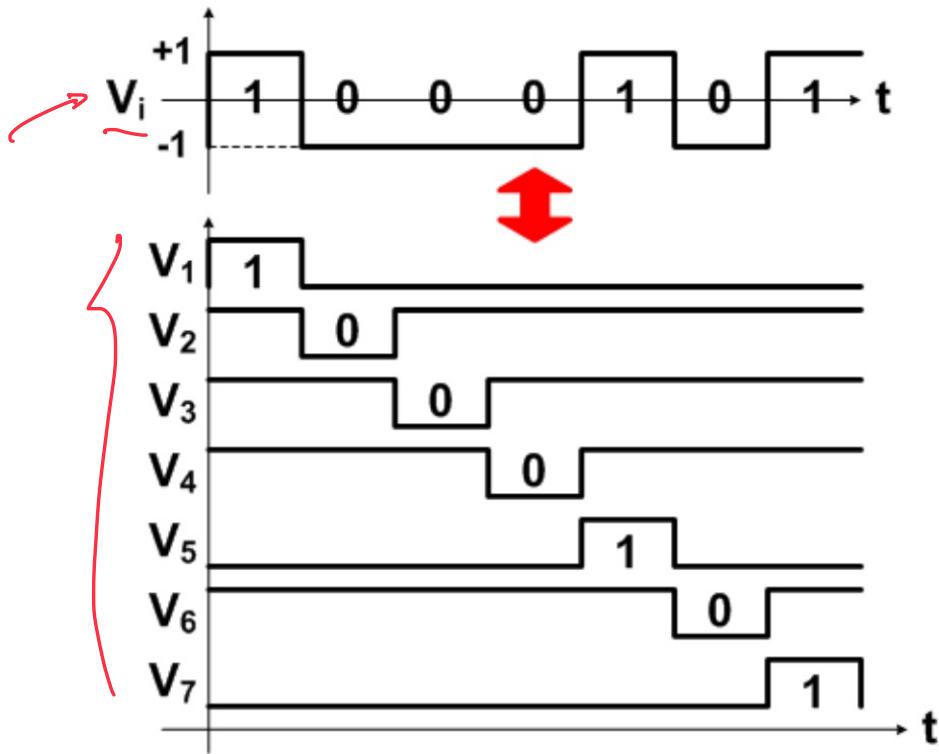
# NRZ Data Modeling

- An NRZ data stream can be modeled as a superposition of isolated "1"s and "0"s

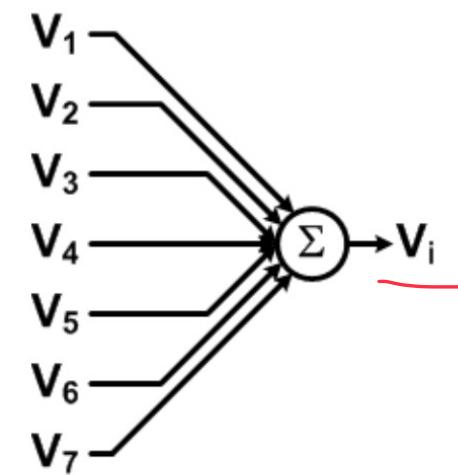


# NRZ Data Modeling

- An NRZ data stream can be modeled as a superposition of isolated “1”s and “0”s



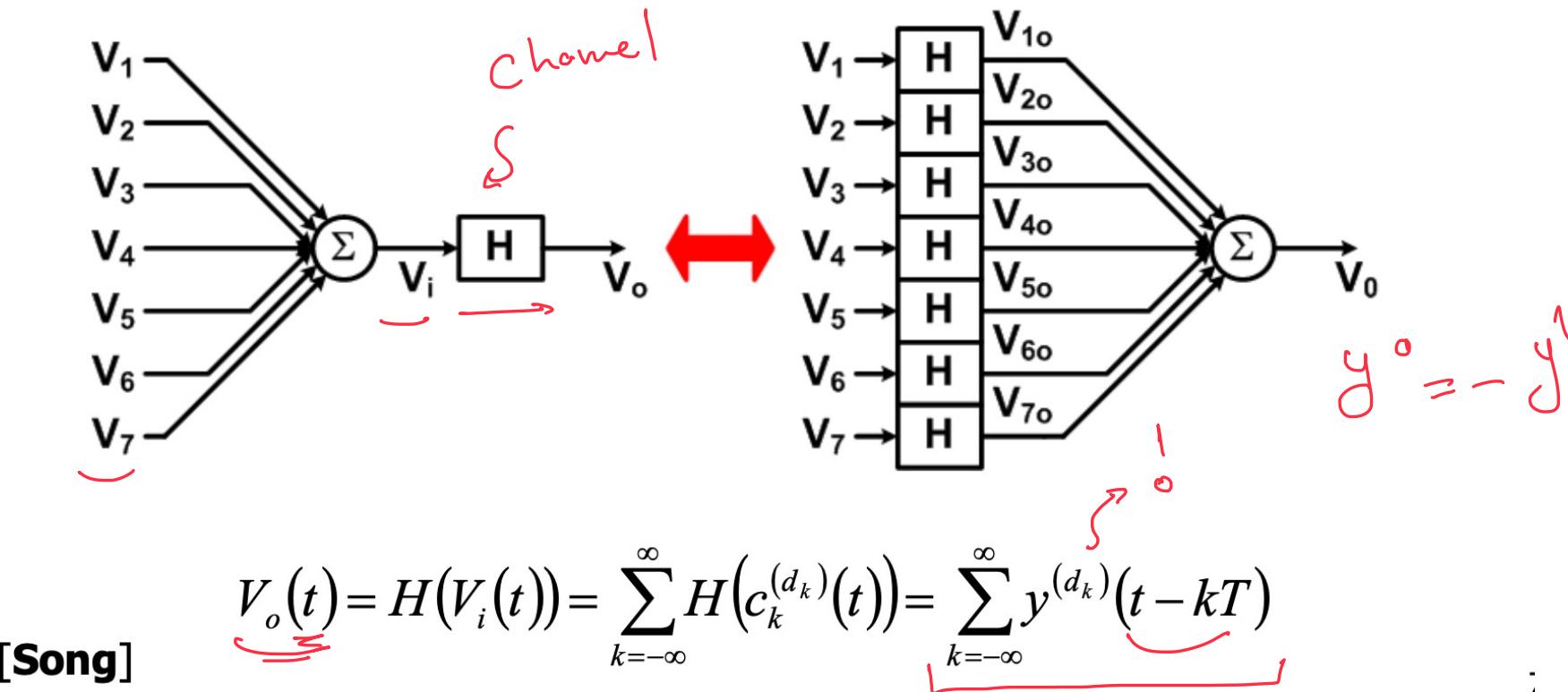
[Song]



$$V_i(t) = \sum_{k=-\infty}^{\infty} c_k^{(d_k)}(t)$$

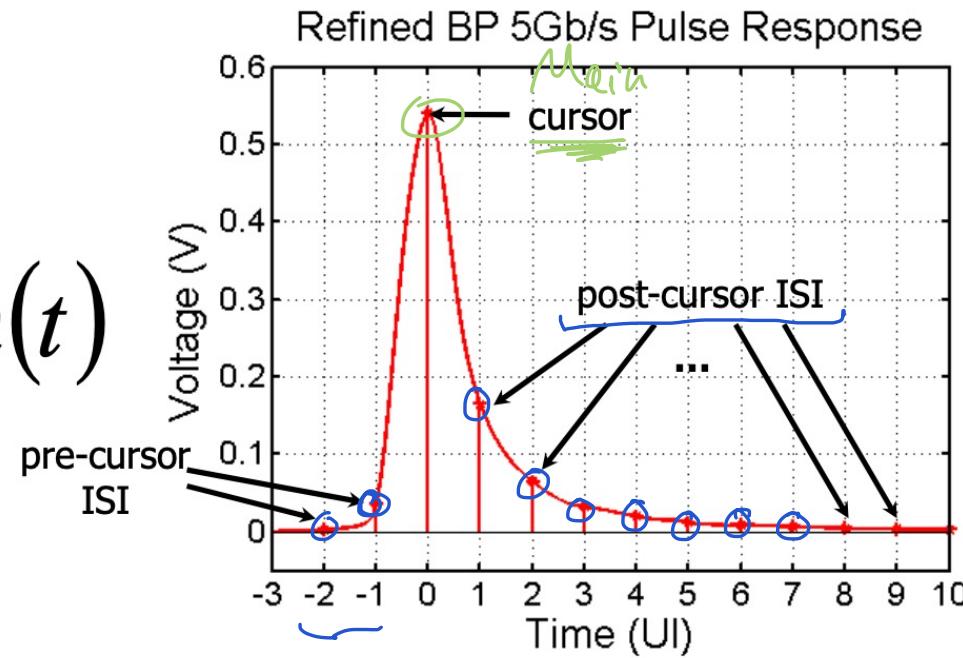
# Channel Response to NRZ Data

- Channel response to NRZ data stream is equivalent to superposition of isolated pulse responses



# Channel Pulse Response

$$y^{(d_k)}(t) = c^{(d_k)}(t) * h(t)$$



$y^{(1)}(t)$  sampled relative to pulse peak:

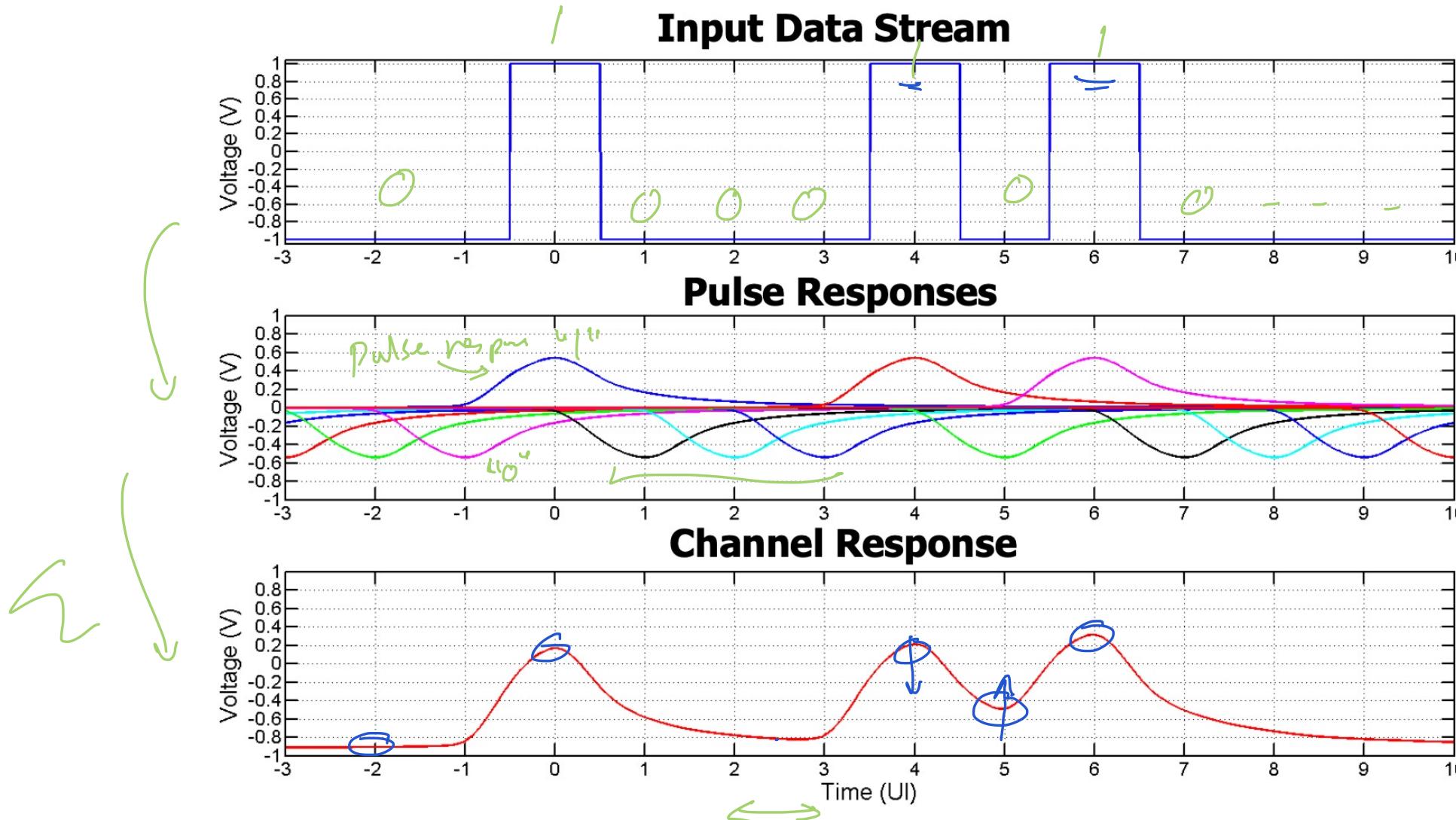
[... 0.003 0.036 0.540 0.165 0.065 0.033 0.020 0.012 0.009 ...]

$k = [ \dots -2 \quad -1 \quad 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad \dots ]$

\* By Linearity:  $y^{(0)}(t) = -1 * y^{(1)}(t)$

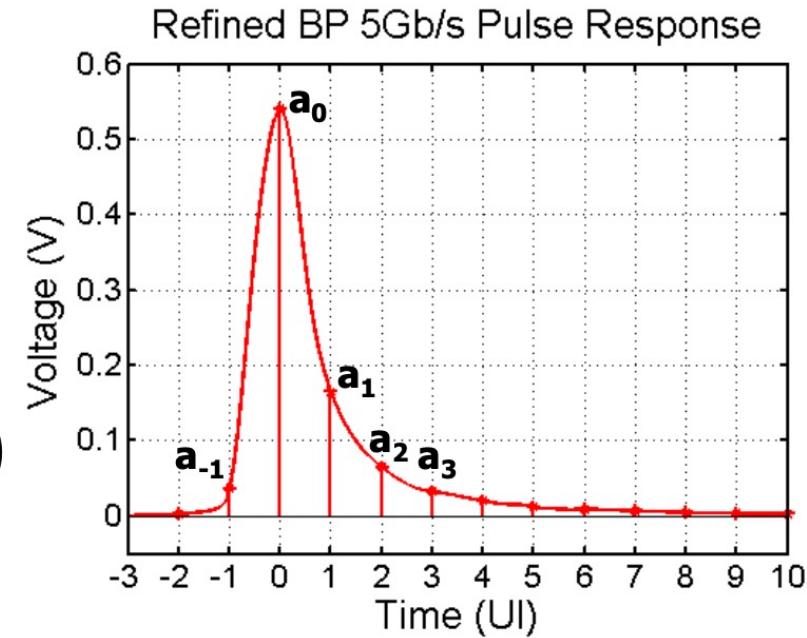
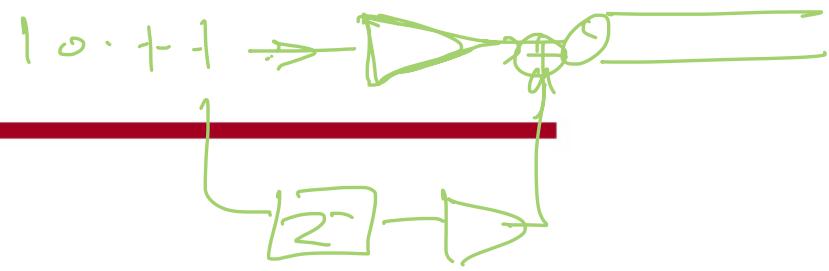
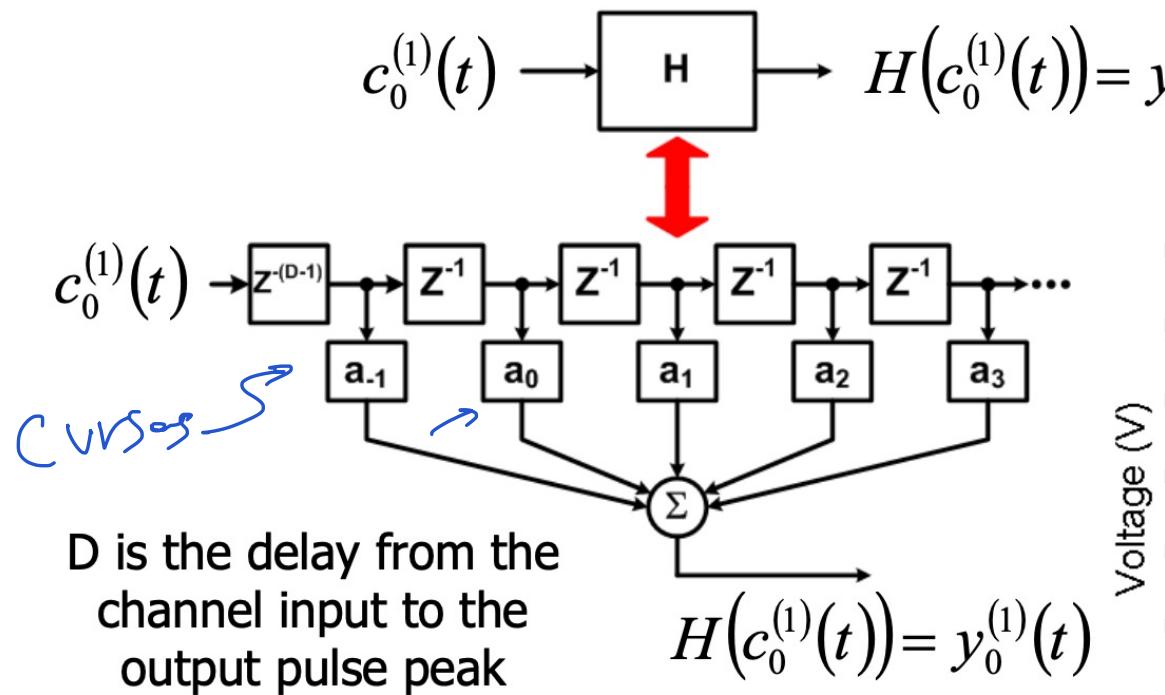
[Sam Palermo]

# Channel Data Stream Response



[Sam Palermo]

# Channel “FIR” Model



$y^{(1)}(t)$  sampled relative to pulse peak:

[... 0.003 0.036 0.540 0.165 0.065 0.033 0.020 0.012 0.009 ...]

$a = [ \dots a_{-2} \quad a_{-1} \quad a_0 \quad a_1 \quad a_2 \quad a_3 \quad a_4 \quad a_5 \quad a_6 \quad \dots ]$

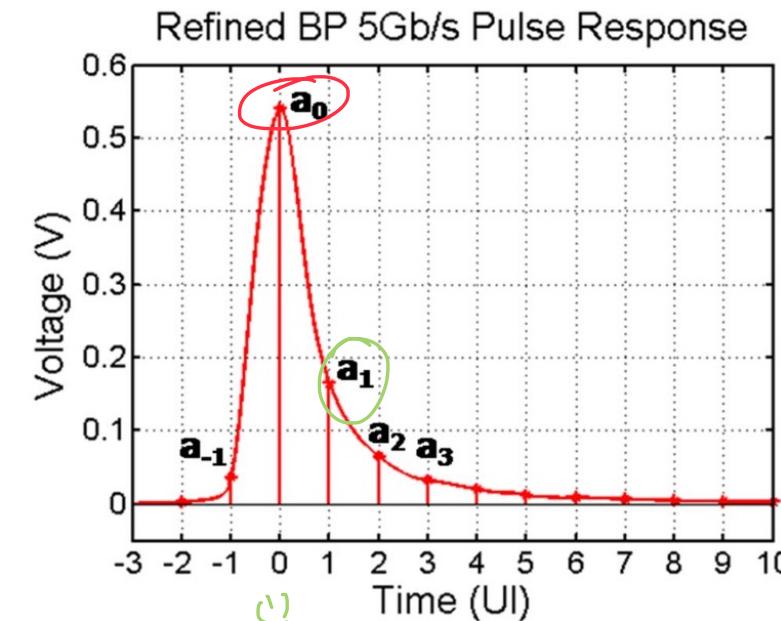
# Peak Distortion Analysis

- Can estimate worst-case eye height and data pattern from pulse response
- Worst-case “1” is summation of a “1” pulse with all negative non  $k=0$  pulse responses

Worst case signal  
amp up for  
sign

$$s_1(t) = y_0^{(1)}(t) + \sum_{k=-\infty}^{\infty} y^{(d_k)}(t - kT) \Big|_{y(t-kT) < 0}$$

- Worst-case “0” is summation of a “0” pulse with all positive non  $k=0$  pulse responses



$$s_0(t) = y_0^{(0)}(t) + \sum_{k=-\infty}^{\infty} y^{(d_k)}(t - kT) \Big|_{y(t-kT) > 0}$$

[Sam Palermo]

# Peak Distortion Analysis

- Worst-case eye height is  $s_1(t) - s_0(t)$

$$s(t) = s_1(t) - s_0(t) = \left( y_0^{(1)}(t) - y_0^{(0)}(t) \right) + \left( \sum_{\substack{k=-\infty \\ k \neq 0}}^{\infty} y^{(d_k)}(t - kT) \Big|_{y(t-kT) < 0} - \sum_{\substack{k=-\infty \\ k \neq 0}}^{\infty} y^{(d_k)}(t - kT) \Big|_{y(t-kT) > 0} \right)$$

Because  $y_0^{(0)}(t) = -1(y_0^{(1)}(t))$

$$s(t) = 2 \left( y_0^{(1)}(t) + \sum_{k=-\infty}^{\infty} y^{(1)}(t - kT) \Big|_{y(t-kT) < 0} - \sum_{k=-\infty}^{\infty} y^{(1)}(t - kT) \Big|_{y(t-kT) > 0} \right) = 2 \left( y_0^{(1)}(t) - \sum_{i \neq 0} 1 a_i \right)$$

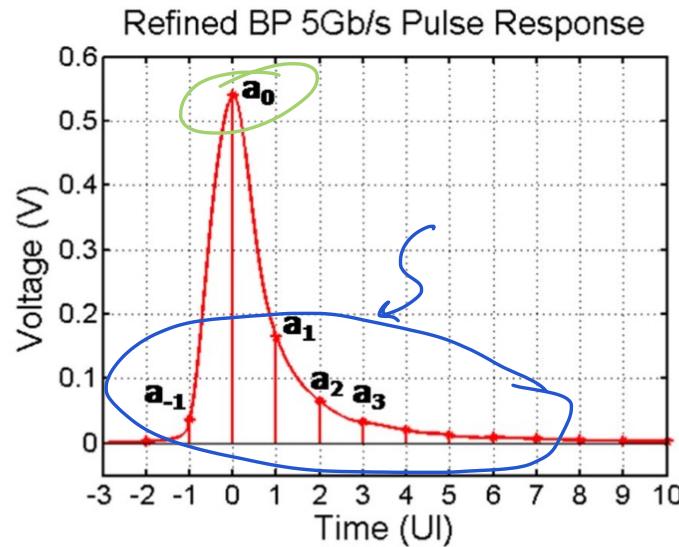
*s<sub>1</sub> - s<sub>0</sub> total eye open*

"1" pulse worst-case "1" edge      "1" pulse worst-case "0" edge

- If symmetric "1" and "0" pulses (linearity), then only positive pulse response is needed

[Sam Palermo]

# Peak Distortion Analysis Example 1

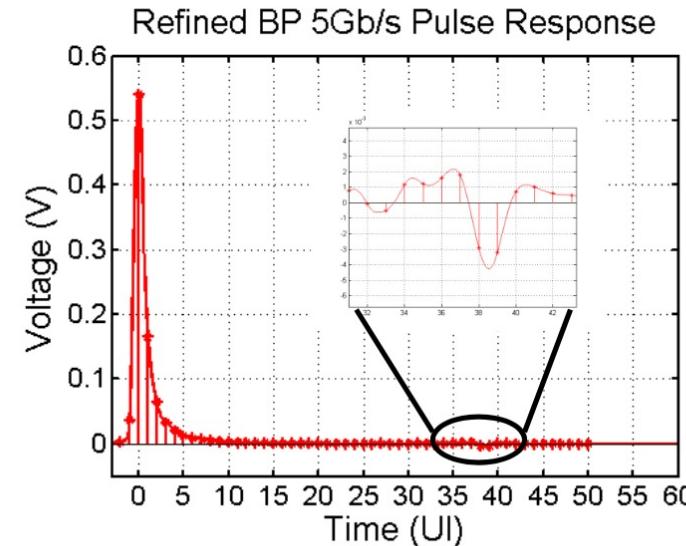


$$y_0^{(1)}(t) = 0.540$$

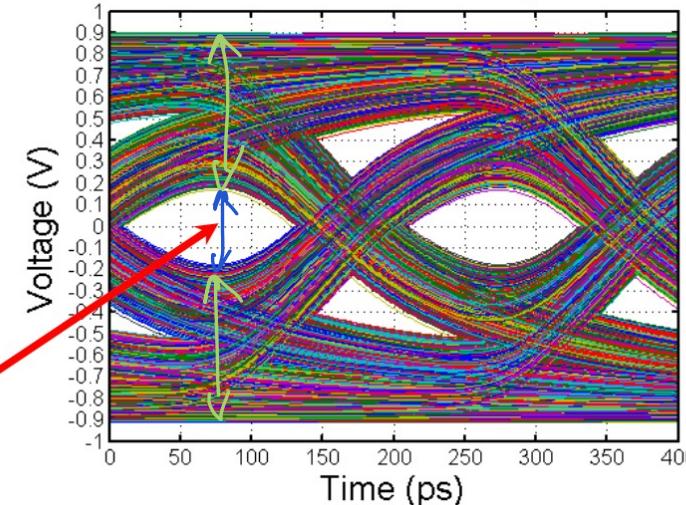
$$\sum_{\substack{k=-\infty \\ k \neq 0}}^{\infty} y^{(1)}(t - kT) \Big|_{y(t-kT) < 0} = -0.007$$

$$\sum_{\substack{k=-\infty \\ k \neq 0}}^{\infty} y^{(1)}(t - kT) \Big|_{y(t-kT) > 0} = 0.389$$

$$s(t) = 2(0.540 - 0.007 - 0.389) = 0.288$$



Refined BP 5Gb/s Eye



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[Sam Palermo]

# Worst-Case Bit Pattern

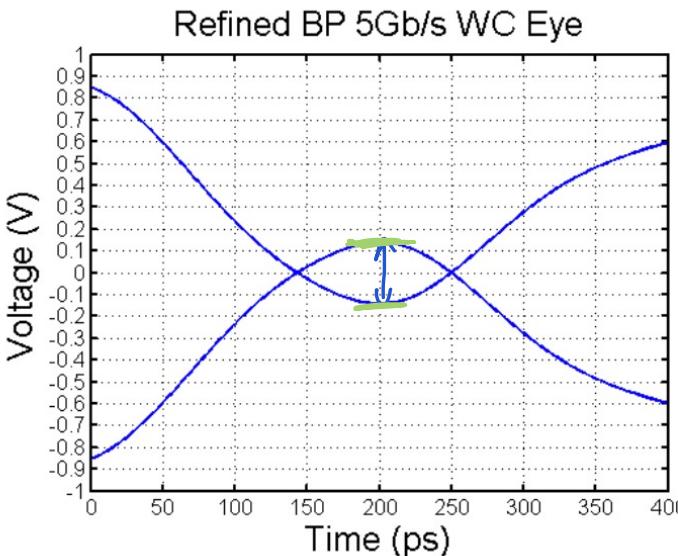
- Pulse response can be used to find the worst-case bit pattern

$$\text{Pulse } a = [\dots \ a_{-2} \quad a_{-1} \quad a_0 \quad a_1 \quad a_2 \quad a_3 \quad a_4 \quad a_5 \quad a_6 \ \dots]$$

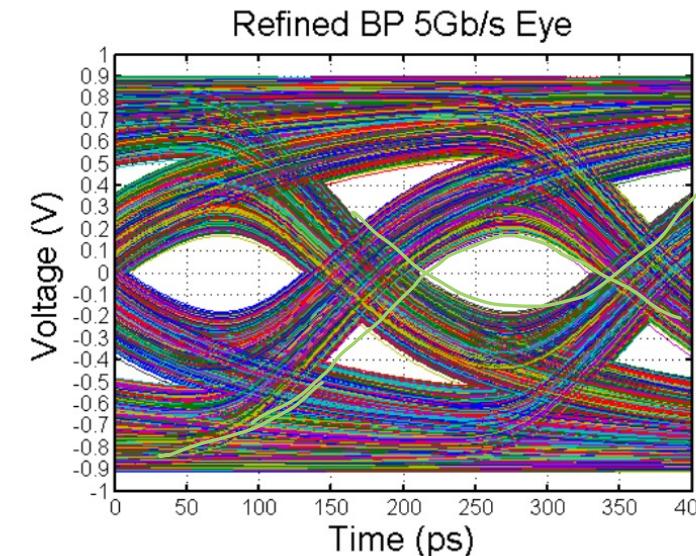
- Flip pulse matrix about cursor  $a_0$  and the bits are the inverted sign of the pulse ISI

  $[\dots -\text{sign}(a_6) \quad -\text{sign}(a_5) \quad -\text{sign}(a_4) \quad -\text{sign}(a_3) \quad -\text{sign}(a_2) \quad -\text{sign}(a_1) \quad \underline{1} \quad -\text{sign}(a_{-1}) \quad -\text{sign}(a_{-2}) \ \dots]$

## Worst-Case Bit Pattern Eye



## **10kbits Eye**

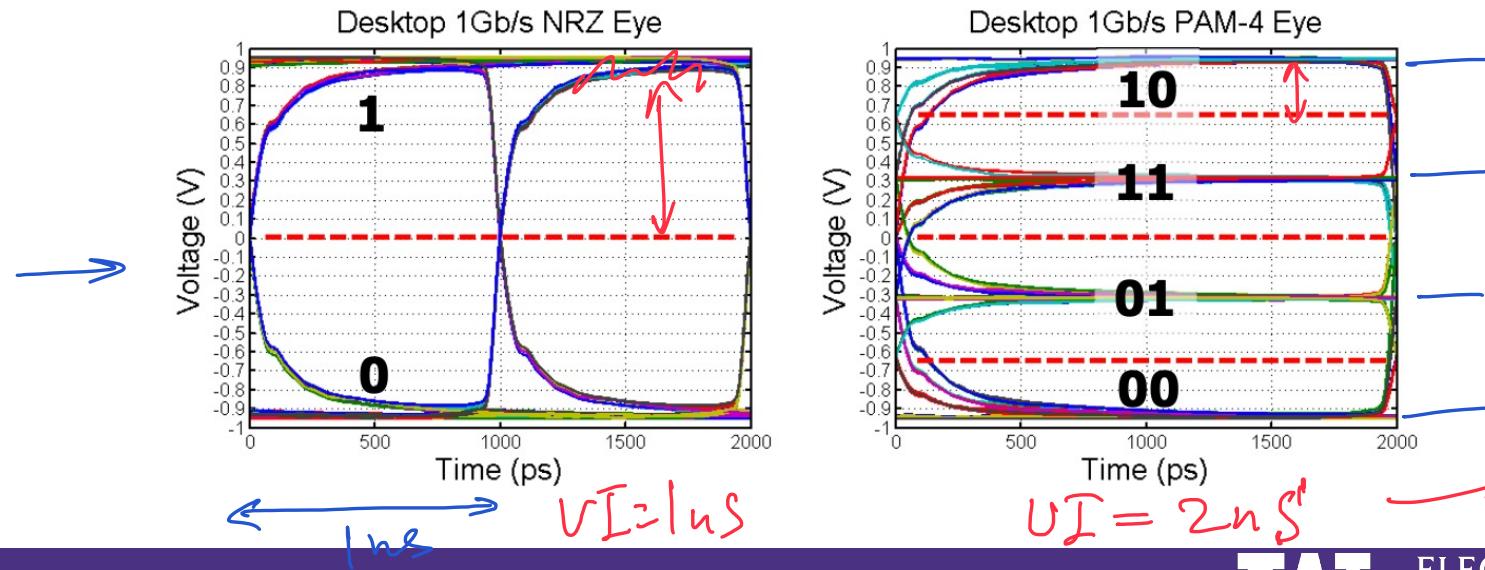


[Sam Palermo]

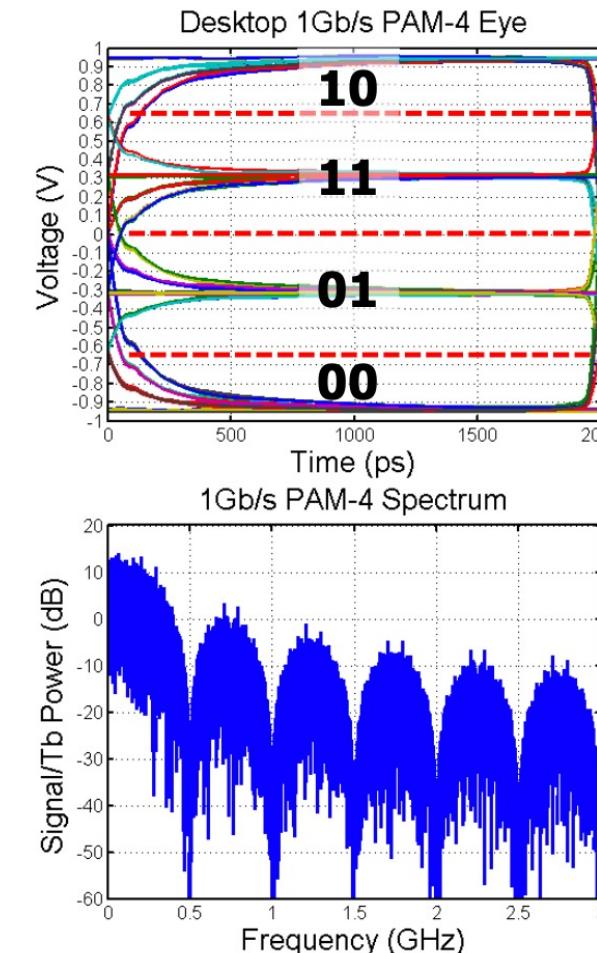
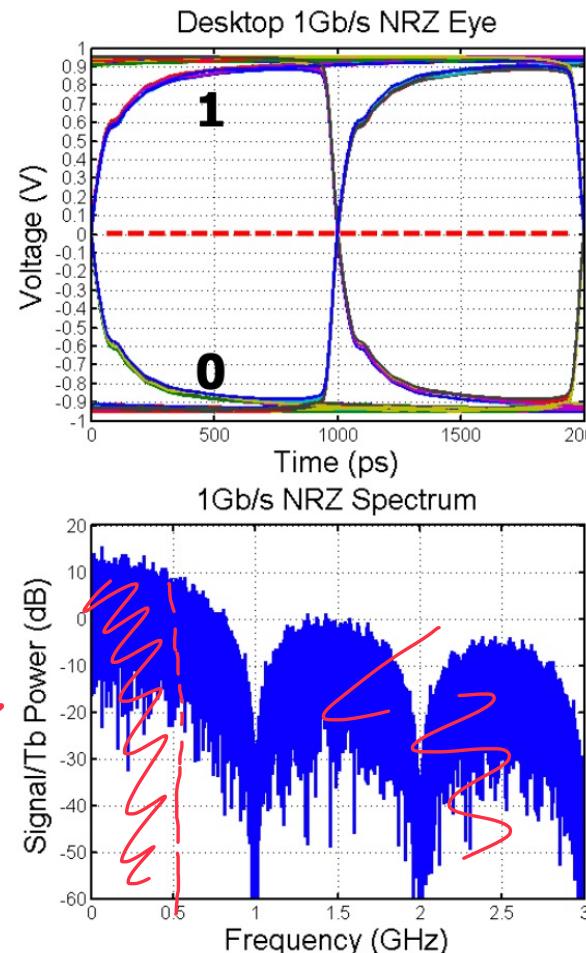
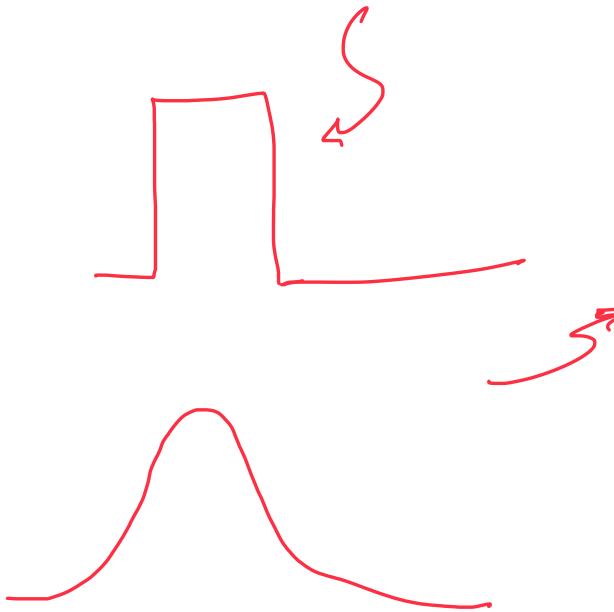
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# PAM-2 (NRZ) vs PAM-4 Modulation

- Binary, NRZ, PAM-2
  - Simplest, most common modulation format
- PAM-4
  - Transmit 2 bits/symbol
  - Less channel equalization and circuits run  $\frac{1}{2}$  speed



# Modulation Frequency Spectrum



[Sam Palermo]

# Nyquist Frequency

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- Nyquist bandwidth constraint:
  - The theoretical minimum required system bandwidth to detect  $\underline{R_s}$  (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

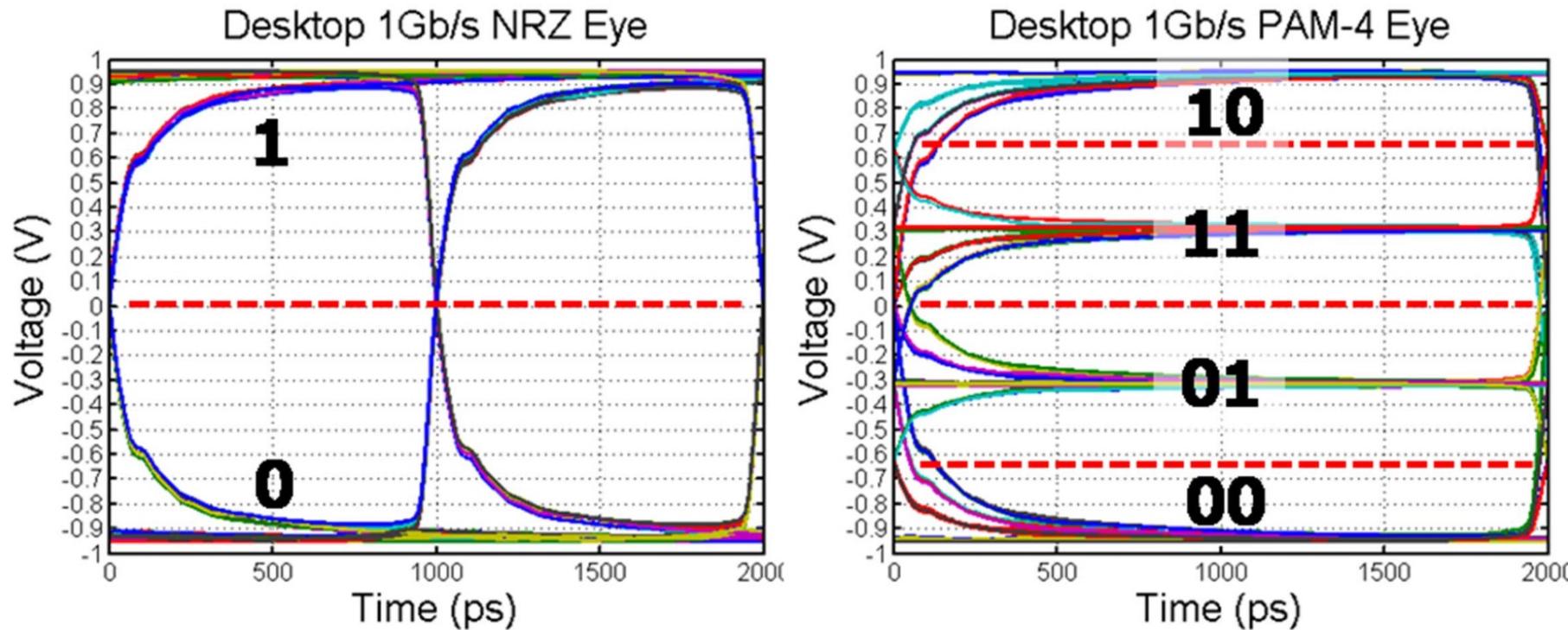
$$\frac{1}{2T} = \frac{R_s}{2} \leq W \Rightarrow \frac{R_s}{W} \leq 2 \text{ (symbols/s/Hz)}$$

- 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	$R_s/2=1/4T_b$

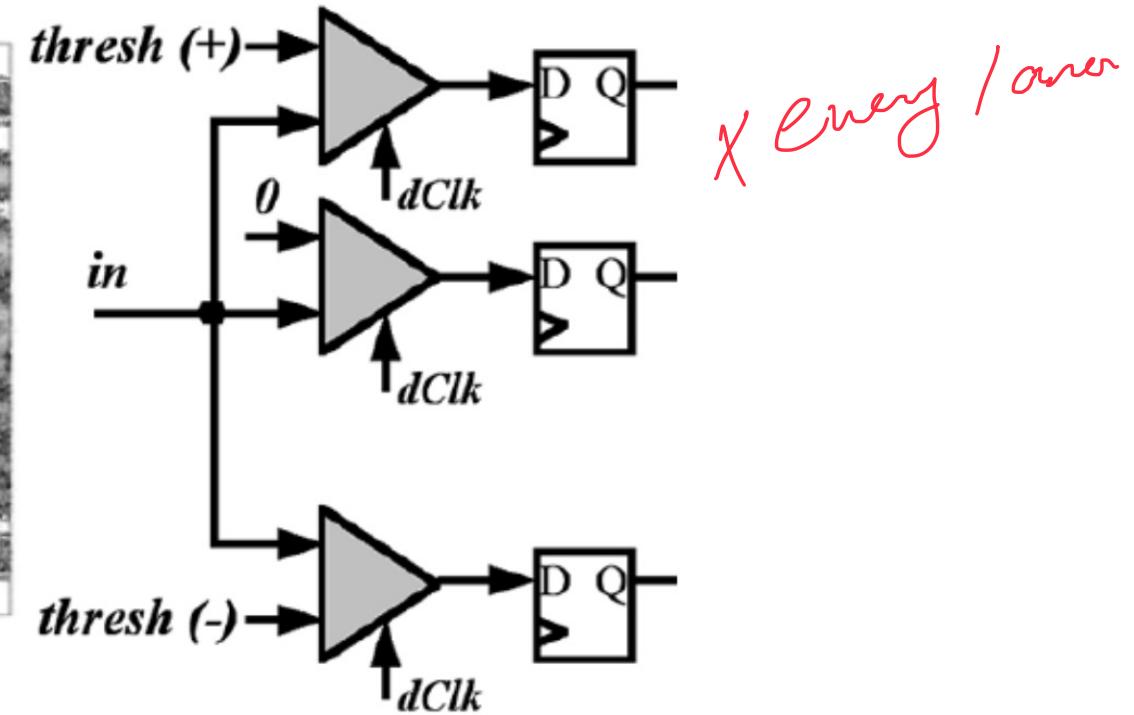
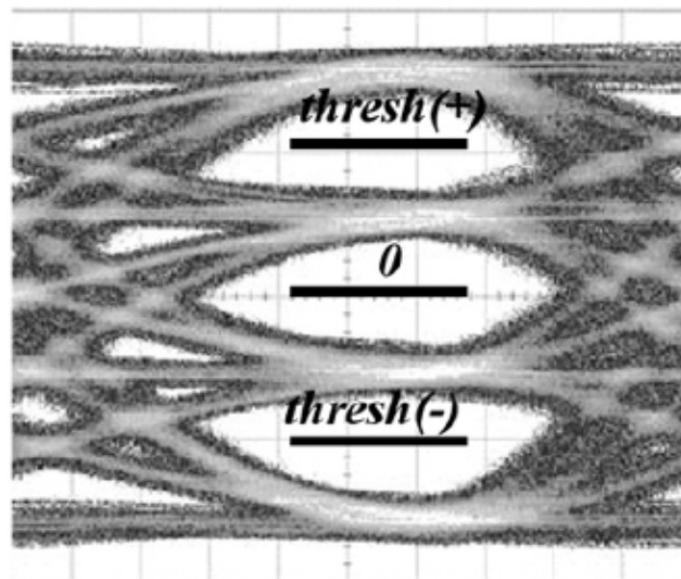
[Sam Palermo]

# 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  $20 \cdot \log_{10}(1/3) = -9.54\text{dB}$
  - On-chip clock speed limitations

# PAM-4 Receiver



[Stojanovic JSSC 2005]

- 3x the comparators of NRZ RX

[Sam Palermo]