

## ECEN 720 High-Speed Links: Circuits and Systems

### Lab2- Channel Models

#### Objective

To learn S-parameters, eye diagram, ISI, modulation techniques and their simulations in MATLAB and Cadence.

#### Introduction

Scattering parameters (S-parameters) are widely used in industry for characterizing the transmission lines, vias, chip sockets, and connectors. A transmission line can be represented by an S-parameter model which can be used during the circuit design and frequency domain simulation. Channel impulse responses can be generated from the S-parameter by performing inverse Fourier transform. Convolution of the channel impulse response with input data, channel output can be produced along with the eye diagram. In this lab, channel S-parameter model, Inter-Symbol Interference (ISI), peak distortion analysis, modulation scheme and termination circuit design are going to be studied. The plotting of channel output eye diagram and S-parameter will be performed through MATLAB and Cadence.

#### S-parameter

ABCD parameters can represent a two-port network as shown in Figure 1, which describe the network in terms of input and output voltage and current. They are suitable for calculating cascaded circuits. Since the ABCD parameters are evaluated with short and open circuits, they are not measured directly; instead they are calculated from the measured S-parameters which can be measured directly by a network analyzer without causing short and open circuit. The conversion between ABCD parameters and S-parameters is shown in Figure 2.



$$A = \left. \frac{v_1}{v_2} \right|_{i_2=0} \quad B = \left. \frac{v_1}{i_2} \right|_{v_2=0} \quad C = \left. \frac{i_1}{v_2} \right|_{i_2=0} \quad D = \left. \frac{i_1}{i_2} \right|_{v_2=0} \quad \begin{bmatrix} v_1 \\ i_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} v_2 \\ i_2 \end{bmatrix} \quad \text{[Hall]}$$

Figure 1 ABCD Parameters

**TABLE 9-3. Relationships Between Two-Port  $S$  and  $ABCD$  Parameters<sup>a</sup>**

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} \frac{B - Z_n(D - A + CZ_n)}{B + Z_n(D + A + CZ_n)} & \frac{2Z_n(AD - BC)}{B + Z_n(D + A + CZ_n)} \\ \frac{2Z_n}{B + Z_n(D + A + CZ_n)} & \frac{B - Z_n(A - D + CZ_n)}{B + Z_n(D + A + CZ_n)} \end{bmatrix}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} \frac{(1 + S_{11})(1 - S_{22}) + S_{12}S_{21}}{2S_{21}} & Z_n \frac{(1 + S_{11})(1 + S_{22}) - S_{12}S_{21}}{2S_{21}} \\ \frac{1}{Z_n} \frac{(1 - S_{11})(1 - S_{22}) - S_{12}S_{21}}{2S_{21}} & \frac{(1 - S_{11})(1 + S_{22}) + S_{12}S_{21}}{2S_{21}} \end{bmatrix}$$

<sup>a</sup> $Z_n$  is the termination impedance at the ports.

[Hall]

Figure 2 Two-Port  $S$  and  $ABCD$  Parameters Conversion

### Channel Impulse Response

A linear, time-invariant (LTI) system as shown in Figure 3 can be completely characterized by its impulse response. Thus, for any input, the output function can be calculated in terms of the input and the impulse response.

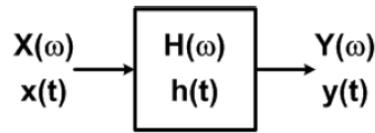


Figure 3 LTI System

The output function in time and frequency domain can be expressed as the following:

$$Y(\omega) = H(\omega)X(\omega) \quad (1)$$

$$y(t) = h(t) * x(t) = \int_{-\infty}^{+\infty} h(t - \tau)x(\tau) d\tau \quad (2)$$

The impulse response of a system can be generated from its  $S$ -parameters by using inverse Fourier transform.

$$h(t) = F^{-1}\{S(\omega)\} \quad (3)$$

In this lab, channel  $S$ -parameters are provided. The impulse response of the channel is calculated through MATLAB. It represents the channel response characteristic. If the input data is given

and the channel impulse response is obtained from S-parameters, the transient channel output can be calculated through convolving input data with impulse response. It is shown in Figure 4.

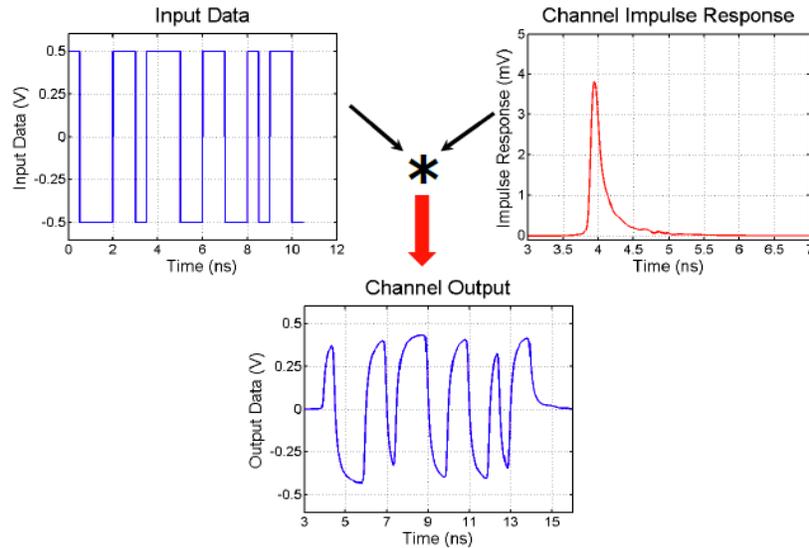


Figure 4 Channel Transient Response

## Eye Diagram

An eye diagram is made of overlaying a signal over many of its unit intervals (UI) as shown in Figure 5. It visually indicates a signal's voltage and timing uncertainty due to various circuit non-idealities (power/ground noise, crosstalk, channel loss, phase noise, etc.). It can be generated using simulation tools or be measured using an oscilloscope. The eye opening in the center of the diagram indicates the voltage and timing margin associated with the signal. The amount of the margin can be used to calculate the receiver's sensitivity requirement. The timing margin is often used to estimate a digital system timing budget or the receiver's aperture time.

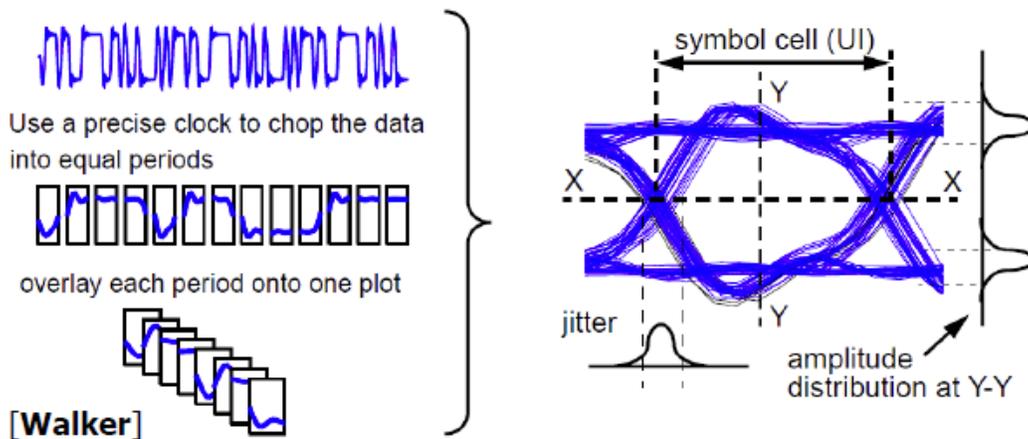


Figure 5 Eye Diagram

## Inter-Symbol Interference

Inter-symbol interference (ISI) is a form of a signal distortion which is caused by reflections, channel resonances and channel loss (dispersion). It is the interference between symbols where the current bit (symbol) could distort its subsequent and previous bits (symbol). An ideal 5Gb/s input pulse is passed through a channel as shown in Figure 6 (blue). Due to the channel characteristic, the pulse is dispersed as shown in Figure 6 (red). The dispersion spreads the pulse energy and distorts other bits, which reduces eye opening.

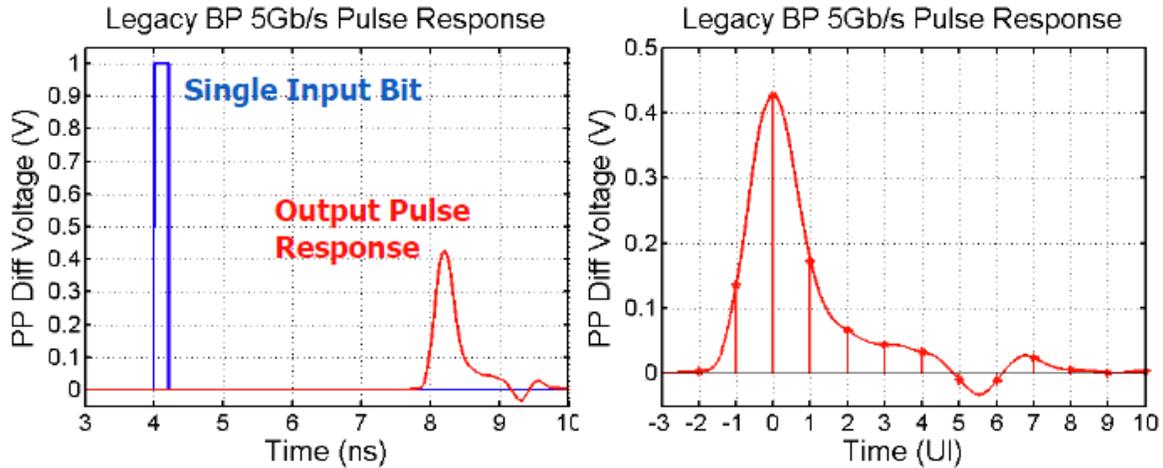


Figure 6 Inter-Symbol Interference

## Peak Distortion Analysis

Peak distortion analysis (PDA) is used to estimate the worst-case eye diagram from pulse response. The worst-case “1” is the summation of a “1” pulse ( $t=0$ ) with all negative (negative pre and post cursor ISI) non  $k=0$  pulse responses ( $t \neq 0$ , can be “1” or “0”). It is shown as the following.

$$S_1(t) = y_o^{(1)}(t) + \sum_{k=-\infty, k \neq 0}^{\infty} y^{(d_k)}(t - KT) |_{y(t-KT) < 0} \quad (4)$$

The worst-case “0” is the summation of a “0” pulse ( $t=0$ ) with all positive (positive pre and post cursor ISI) non  $k=0$  pulse responses ( $t \neq 0$ , can be “1” or “0”). It is shown as the following.

$$S_0(t) = y_o^{(0)}(t) + \sum_{k=-\infty, k \neq 0}^{\infty} y^{(d_k)}(t - KT) |_{y(t-KT) > 0} \quad (5)$$

The worst case eye height can be expressed as

$$\begin{aligned}
 S(t) = 2 \left\{ & y_o^{(1)}(t) \right. \\
 & + \sum_{k=-\infty, k \neq 0}^{\infty} y^{(t)}(t - KT) |_{y(t-KT) < 0} \\
 & \left. - \sum_{k=-\infty, k \neq 0}^{\infty} y^{(t)}(t - KT) |_{y(t-KT) > 0} \right\} \quad (6)
 \end{aligned}$$

### Example:

Give the pulse response as shown in Figure 7, obtain the worst case eye height and worst case bit pattern using the peak distortion analysis.

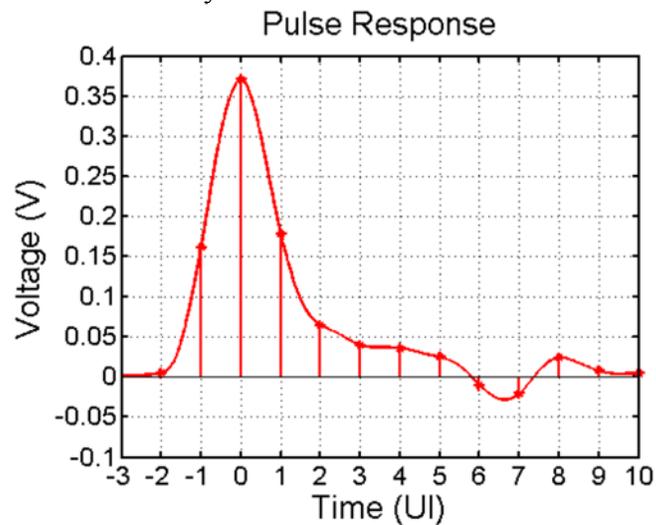


Figure 7 Channel Pulse Response

Table 1 Peak Distortion Analysis and Worst-Case Bit Pattern

UI	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10
volt	0.001	0.005	0.161	0.37	0.178	0.065	0.04	0.03	0.025	-0.01	-0.02	0.025	0.008	0.005
UI	10	9	8	7	6	5	4	3	2	1	0	-1	-2	-3
volt	0.005	0.008	0.025	-0.02	-0.01	0.025	0.03	0.04	0.065	0.178	0.37	0.161	0.005	0.001
Worst Case 1	0	0	0	1	1	0	0	0	0	0	1	0	0	0
Worst Case 0	1	1	1	0	0	1	1	1	1	1	0	1	1	1

$$S(t) = 2 \left\{ y_o^{(1)}(t) + \sum_{k=-\infty, k \neq 0}^{\infty} y^{(t)}(t - KT) |_{y(t-KT) < 0} - \sum_{k=-\infty, k \neq 0}^{\infty} y^{(t)}(t - KT) |_{y(t-KT) > 0} \right\} \quad (7)$$

$$\sum_{k=-\infty, k \neq 0}^{\infty} y^{(t)}(t - KT) |_{y(t-KT) < 0} = -0.03 \quad (8)$$

$$\sum_{k=-\infty, k \neq 0}^{\infty} y^{(t)}(t - KT) |_{y(t-KT) > 0} = 0.543 \quad (9)$$

The worst case eye height can be calculated as

$$S(t) = 2(0.37 - 0.03 - 0.543) = -0.406 \quad (10)$$

## Modulation Schemes

Most channel responses have a low-pass profile. Such a channel attenuates and distorts high frequency components of the input signal. Modulation schemes can be used to reduce signal bandwidth and overcome some of the channel loss problems. NRZ<sup>1</sup>, PAM-4<sup>2</sup> and Duobinary modulation schemes are shown in Figure 8.

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<sup>1</sup> NRZ stands for Non-Return to Zero. NRZ is also sometimes referred as PAM-2 or 2-PAM in the literature.

<sup>2</sup> PAM stands for Pulse Amplitude Modulation. PAM-4 is also sometimes referred as 4-PAM in the literature.

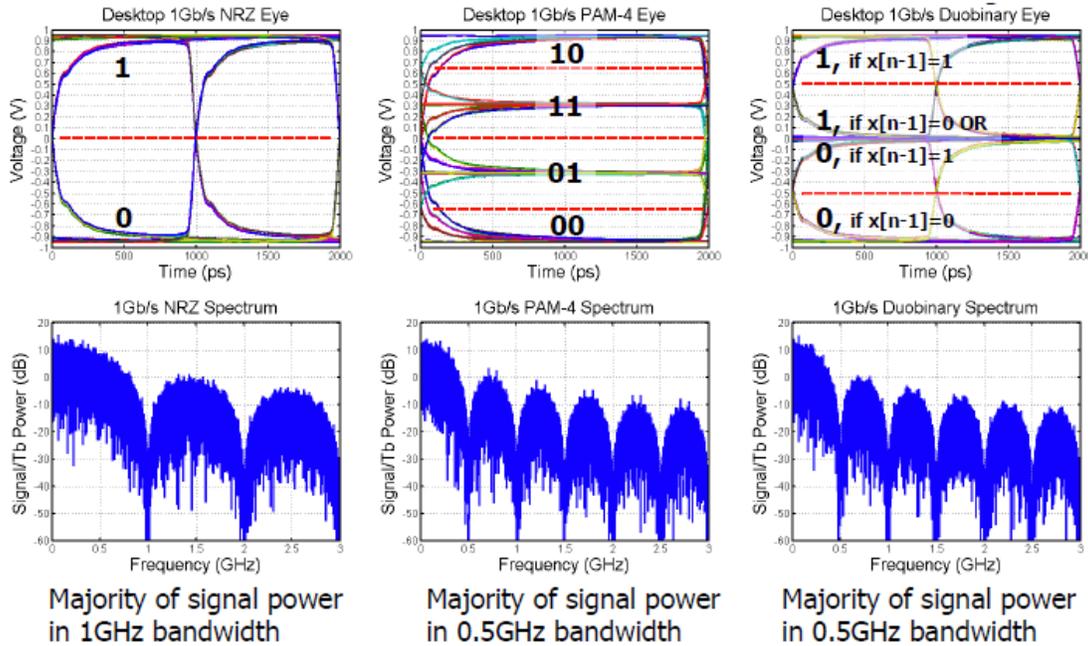


Figure 8 Channel Modulation Schemes

NRZ is the simplest and most common used modulation format. For 1Gb/s data rate, the majority of signal power is within 1GHz. PAM-4 transmits 2 bits/symbol, which runs  $\frac{1}{2}$  NRZ speed. Its signal power concentrates at half of the NRZ bandwidth. Due to its lower frequency characteristic, it is affected less by the channel's high frequency loss. Less channel equalization is needed but with reduction of eye height. When the channel insertion loss at NRZ frequency is greater than -9.54dB ( $\equiv 1/3$ ) than the channel insertion loss at PAM-4 frequency, PAM-4 scheme could be considered. Duobinary is another modulation scheme which also runs at half of the NRZ speed. It takes advantage of the inherent channel roll-off and results in simpler circuit structure. Duobinary data can be generated by sending NRZ data through a “delay and add” filter (Low Pass Filter) which is also shown in Figure 9.

$$w[n] = x[n] + x[n - 1] \quad (11)$$

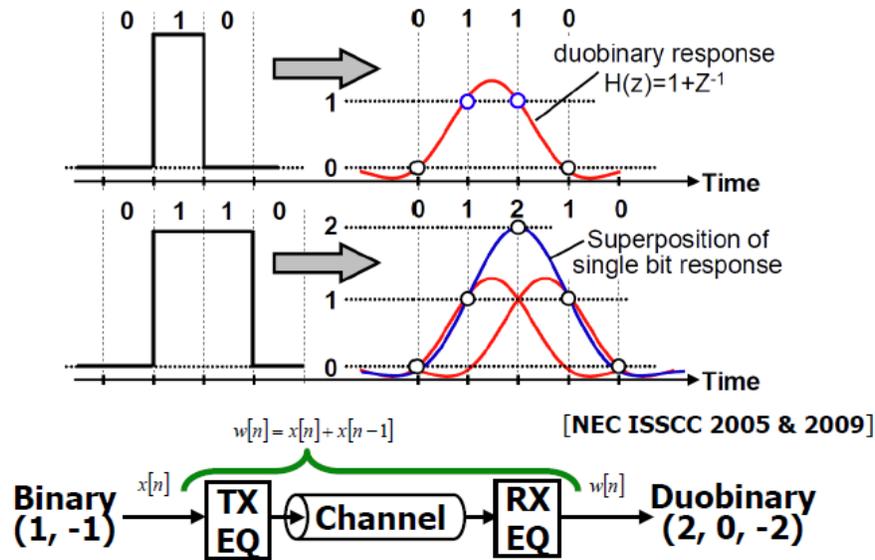


Figure 9 Duobinary Signaling

## Termination Circuits

In high speed link design, it is preferred to use on-chip termination. Off-chip termination may introduce unwanted reflection due to the package parasitics. One way to implement termination resistor is to use transistors. Triode transistor can be used as a termination resistor. Its linear range of operation can be extended by adding a diode connected FET. In differential signaling, pass-gate terminator can be used. This structure provides accurate termination resistance at the extremes of common-mode voltage near power rails. These termination schemes are shown in Figure 10.

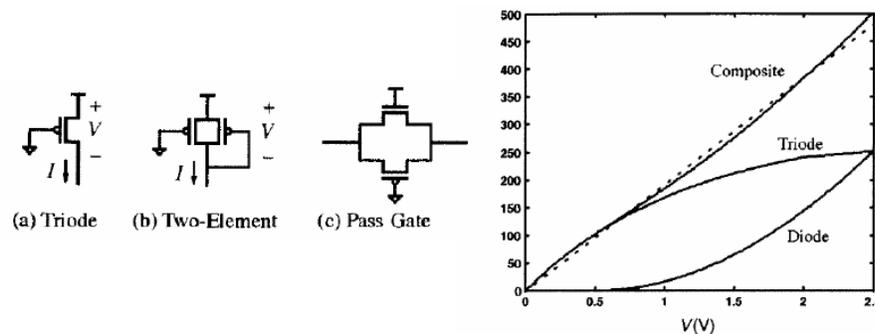


Figure 10 Active Termination Schemes [Dally]

## Pre-Lab

1. Plot  $S_{11}$  and  $S_{21}$  for the circuit shown in Figure 11 using Cadence ( $R_T=50\Omega$ ).
  - a.  $T_d=0\text{ps}$  (no t-line),  $C_1=0\text{pF}$ ,  $L_1=0\text{nH}$ ,  $C_2=1\text{pF}$
  - b.  $T_d=0\text{ps}$  (no t-line),  $C_1=3\text{pF}$ ,  $L_1=2\text{nH}$ ,  $C_2=1\text{pF}$
  - c.  $T_d=300\text{ps}$ ,  $C_1=3\text{pF}$ ,  $L_1=2\text{nH}$ ,  $C_2=1\text{pF}$

Comment on the results.

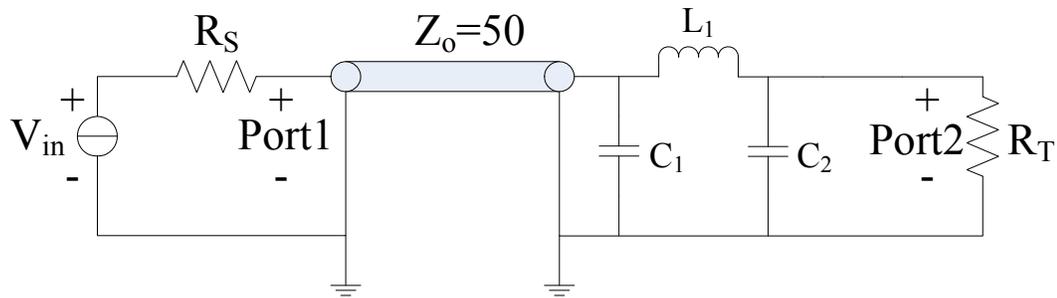


Figure 11 S-parameters Simulation Circuit

2. Briefly compare the difference between AC and DC coupled termination schemes.

## Lab Questions

1. **Channel Transient Simulation.** The objective of this problem is to use measured channel S-parameters data to produce an impulse response and perform a transient simulation in MATLAB involving sending random NRZ data across this channel.
  - a. Download the S-parameters file for a 12" Backplane channel, "peters\_01\_0605\_B12\_thru.s4p"
  - b. Use the MATLAB file "read\_sparam.m" to produce an impulse response. Note this code requires the function "xfr\_fn\_to\_imp.m".
  - c. Use the produced impulse response to perform transient simulations. Plot eye diagrams with 10k random bits at 3, 6, and 8Gbps. Example code for this is the file "channel\_data.m".
  - d. Using peak distortion analysis generate the worst case bit pattern and plot the worst case eye at 6 and 8Gbps. In generating the worst case bit pattern, truncate the pulse response such that there are 10 pre-cursor samples and 100 post-cursor samples.
  
2. Use measured channel S-parameters data to produce a pulse response and perform a transient simulation in Cadence. Use a 12" Backplane channel, "peters\_01\_0605\_B12\_thru.s4p" and transfer the file to ECEN720 directory where you run Cadences. Perform a pulse response simulation using an ideal 1V pulse (differential) with 1ps rise/fall time and 125ps pulse width (for 8Gbps). The channel needs to be terminated at both input and output. The pulse response can be obtained by measuring  $V_{out}$ . The circuit setup is shown in Figure 12. Refer to the Appendix on how to use channel model in Cadence.
  - a. Show your schematic and simulation results.

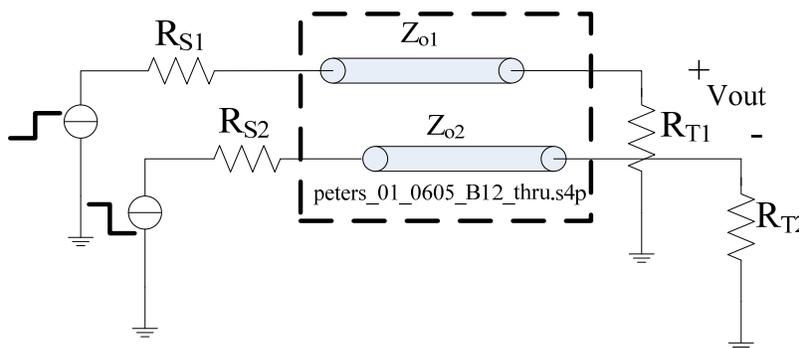


Figure 12 Circuit Setup for Impulse Response

- b. Perform transient simulation using a PRBS input pattern at 3Gbps, 6Gbps, and 8Gbps. Refer to the Appendix for PRBS generation in Cadence.

- c. Plot eye diagrams at these data rates using Cadence's calculator. Refer to the Appendix on how to plot an eye diagram.
3. **Peak Distortion Analysis.** For the 1-bit pulse response shown in Figure 13, find the worst-case input bit pattern, assuming the ISI is ZERO for samples outside the plot range. Also, find the worst-case eye height.

Pulse Response	
Time (UI)	Sample (V)
-3	0.02
-2	-0.03
-1	0.03
0	0.33
1	0.25
2	0.15
3	0.06
4	0
5	-0.05
6	0.03
7	-0.02
8	0.02
9	0.01

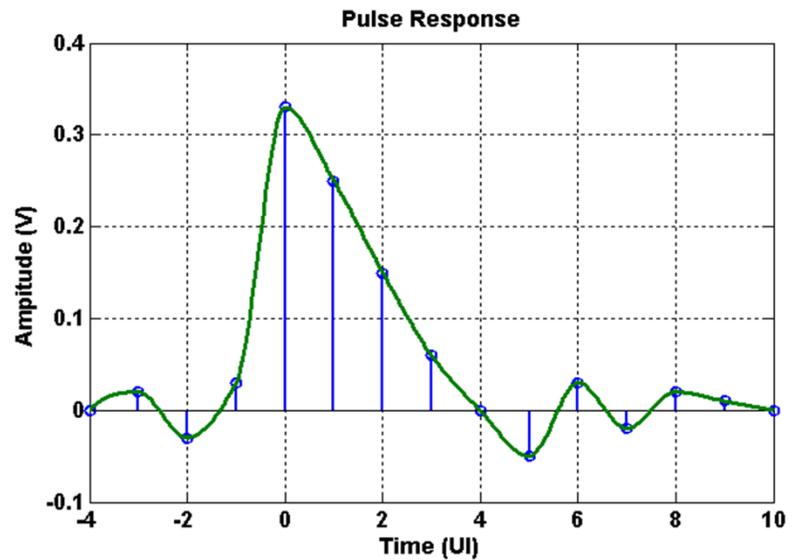


Figure 13 Pulse Response for Peak Distortion Analysis

4. **Modulation Schemes.** NRZ is the most commonly used modulation format. PAM-4 transmits 2 bits/symbol at half the speed. Duobinary allows for controlled ISI resulting in less channel equalization.
- Explain the difference between the NRZ and PAM4 schemes.
  - Assuming the channel loss at 2.5GHz is 7dB and at 5GHz is 14dB, which modulation scheme (NRZ or PAM-4) would have better voltage margin?
  - Solve the code based on the duobinary waveform shown in Figure 15.

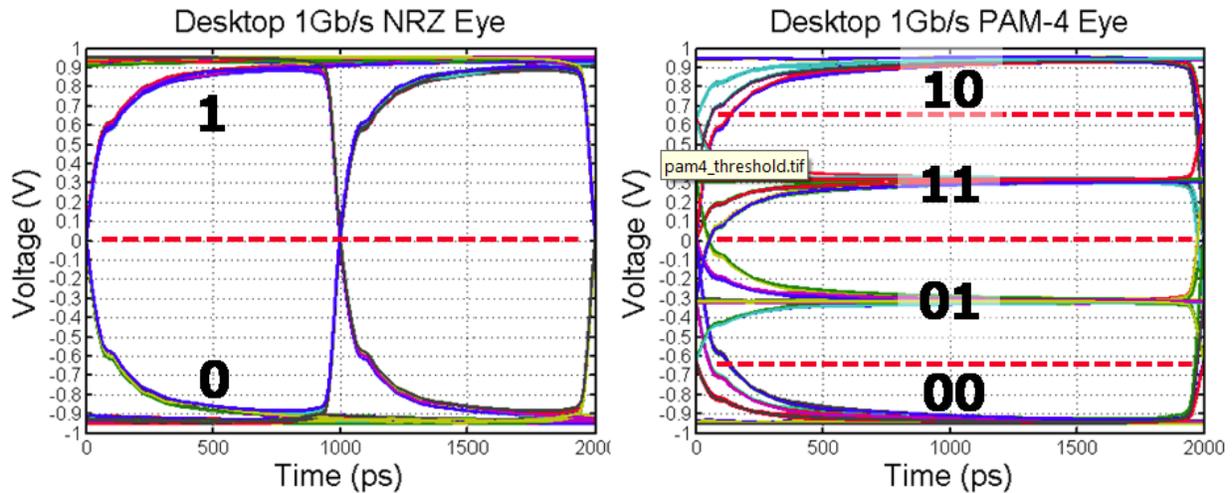


Figure 14 NRZ and PAM-4 Modulation Schemes

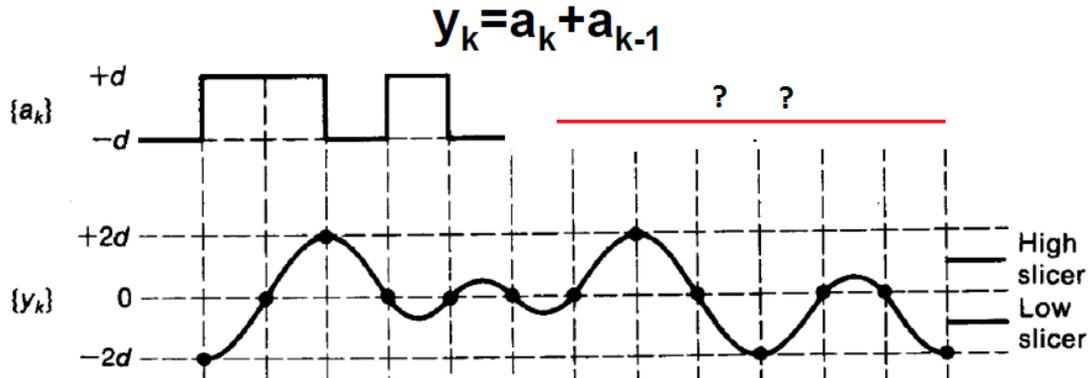


Figure 15 Duobinary Coding [D. R. Smith]

## 5. Termination Circuit.

- Briefly list the pros and cons of these termination schemes: (a) Off-chip vs. on-chip, (b) series vs. parallel, and (c) DC vs. AC coupling.
- Design three  $50\Omega$  active terminations and characterize the resistance of these three active termination schemes as shown in Figure 10. **For configurations in Figures 10(a) and (b) use once only PMOS and then only NMOS transistors.** Sweep the input voltage from GND to VDD and show the resistance curves vs. input voltage. If 90nm CMOS process is used, the nominal supply voltage is 1.2V (use the nominal VDD for any other CMOS process you use as well).

## Appendix

### How to use channel model in Cadence

Channel symbol (n4port) can be found in analogLib. The S-parameter file should be specified including its directory path in S-parameter data file as shown in Figure 16.

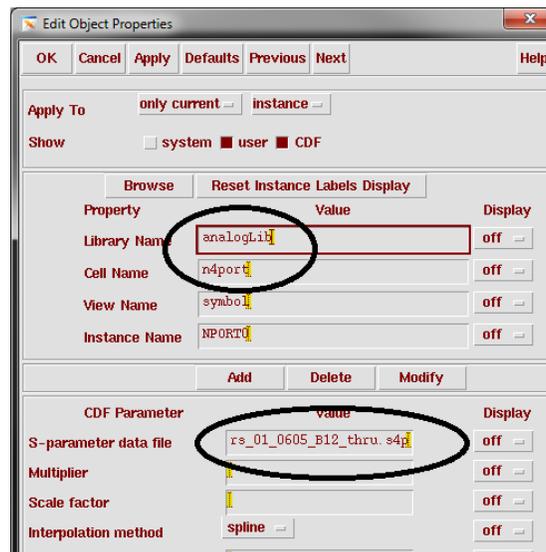


Figure 16 n4port Properties in Cadence

The n4port can be used as shown in Figure 17. Please note that 4 of the 8 ports are return paths.

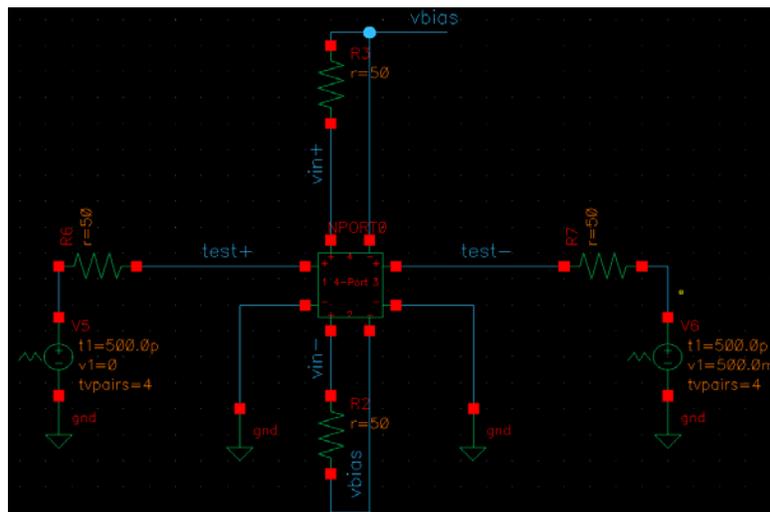


Figure 17 Impulse Response Setup Using n4port Block

## How to use PRBS generator in Cadence

PRBS generator can be found in ahdlLib. It is called rand\_bit\_stream. Please specify a PRBS generator as shown in Figure 18.

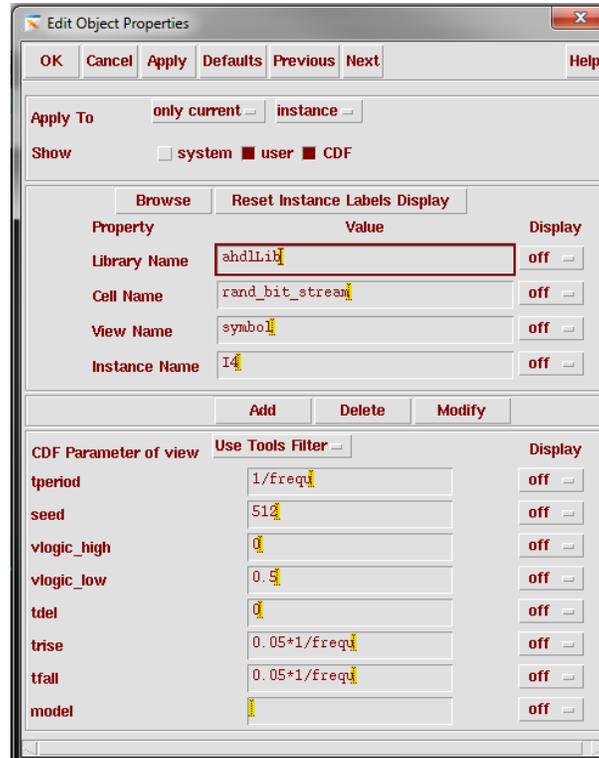


Figure 18 PRBS Generator Properties in Cadence

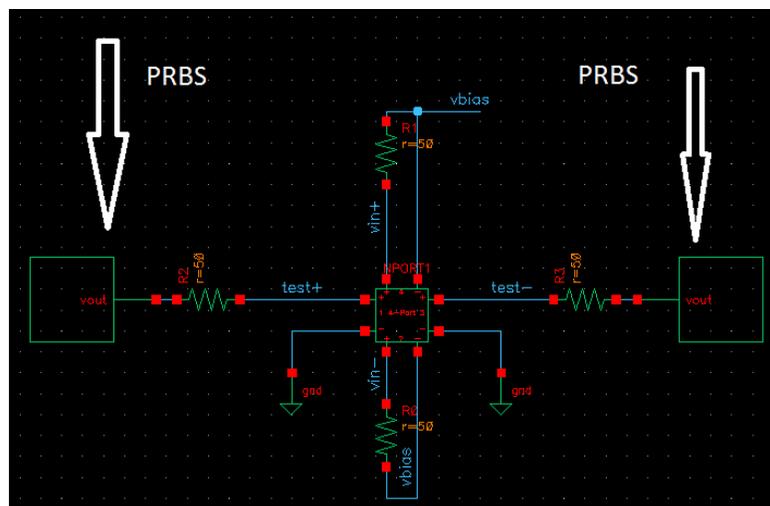


Figure 19 Sample Test Setup for PRBS Generator

## How to plot Eye Diagram in Cadence calculator



Figure 20 How to Plot Eye Diagram in Cadence Using Calculator

## References

- [1] *Digital Systems Engineering*, W. Dally and J. Poulton, Cambridge University Press, 1998.
- [2] *Digital Transmission Systems*, D.R. Smith, Boston Kluwer Academic Publishers, 1985.