ECEN689: Special Topics in High-Speed Links Circuits and Systems Spring 2012

Lecture 3: Time-Domain Reflectometry & S-Parameter Channel Models

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Announcements

- This Thursday lab time will be used for a make-up lecture
- No class next Monday
- Reference Material Posted on Website
  - TDR theory application note
  - S-parameter notes

Agenda

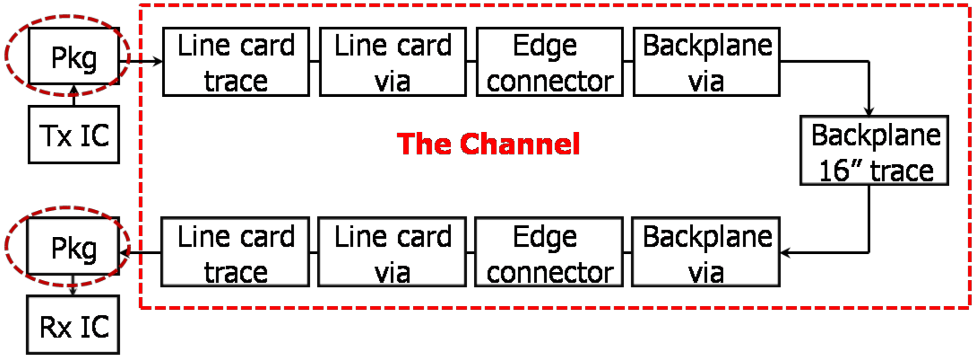
- Interconnect measurement techniques
  - Time-domain reflectometry (TDR)
  - Network analyzer
- S-parameters
- Cascading S-parameter models
- Full S-parameter channel model
- Transient simulations
  - Impulse response generation
  - Eye diagrams
  - Inter-symbol interference

Lecture References

- Majority of TDR material from Dally Chapter 3.4, 3.6 - 3.7

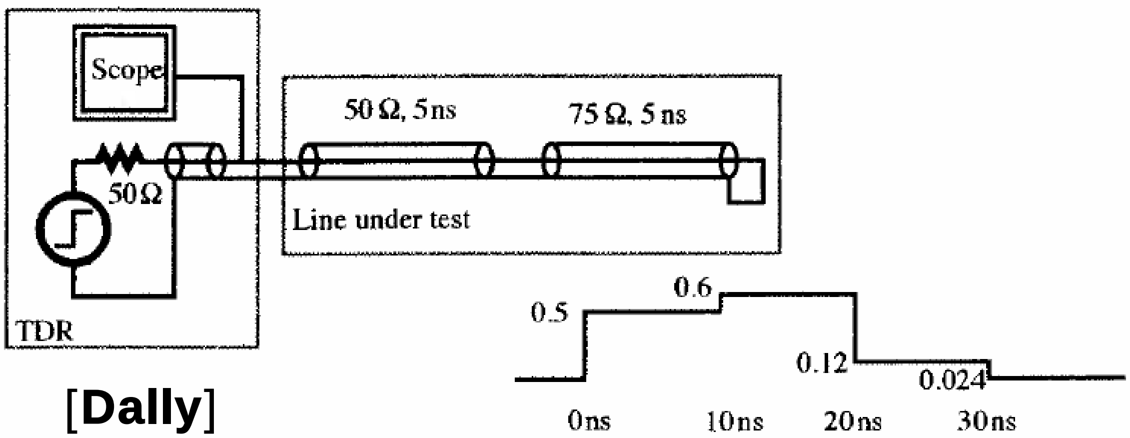
- Majority of s-parameter material from Hall "Advanced Signal Integrity for High-Speed Digital Designs" Chapter 9

Interconnect Modeling

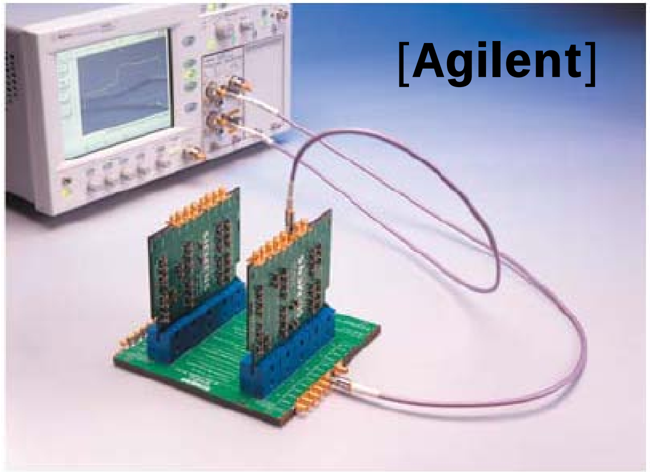


- Why do we need interconnect models?
  - Perform hand calculations and simulations (Spice, Matlab, etc...)
  - Locate performance bottlenecks and make design trade-offs
- Model generation methods
  - Electromagnetic CAD tools
  - Actual system measurements
- Measurement techniques
  - Time-Domain Reflectometer (TDR)
  - Network analyzer (frequency domain)

Time-Domain Reflectometer (TDR)



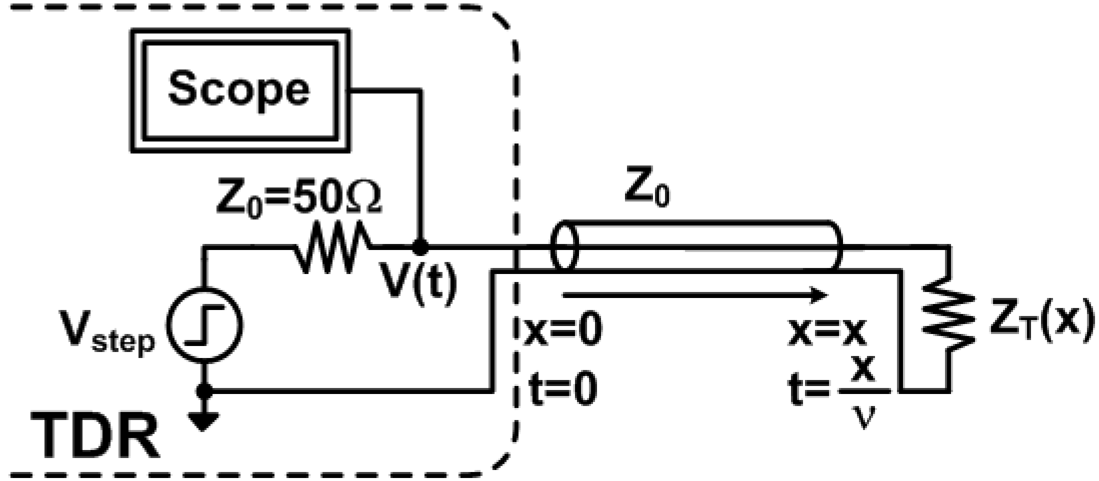
[Dally]



[Agilent]

- TDR consists of a fast step generator and a high-speed oscilloscope
- TDR operation
  - Outputs fast voltage step onto channel
  - Observe voltage at source, which includes reflections
  - Voltage magnitude can be converted to impedance
  - Impedance discontinuity location can be determined by delay
- Only input port access to characterize channel

TDR Impedance Calculation



$$k_r(t) = \frac{V_r(t)}{V_i} = \frac{Z_T(t) - Z_0}{Z_T(t) + Z_0}$$

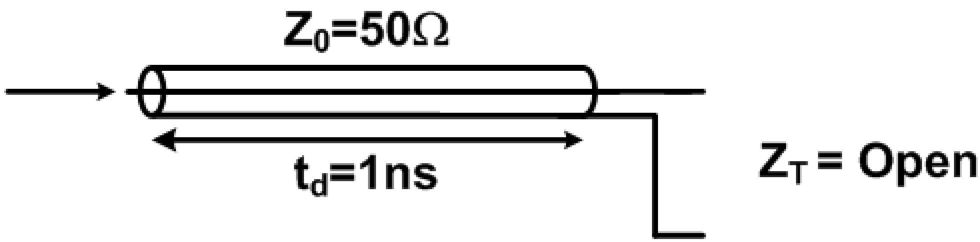
$$Z_T(t) = Z_0\left(\frac{1 + k_r(t)}{1 - k_r(t)}\right) = Z_0\left(\frac{V_i + V_r(t)}{V_i - V_r(t)}\right) = Z_0\left(\frac{V(t)}{2V_i - V(t)}\right)$$

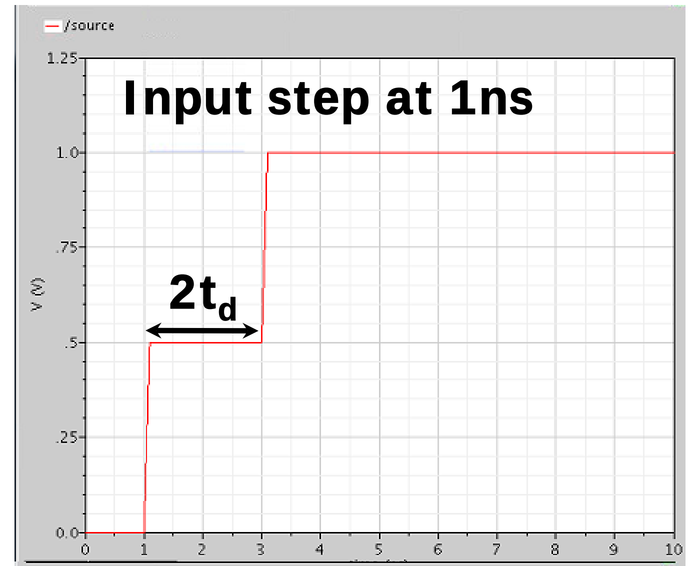
$$\text{If } V_{\text{STEP}} = 1V \Rightarrow V_i = 0.5\text{V}$$

$$\boxed{Z_T(t) = Z_0\left(\frac{V(t)}{1V - V(t)}\right) \qquad Z_T(x) = Z_T\left(t = \frac{2x}{\upsilon}\right)}$$

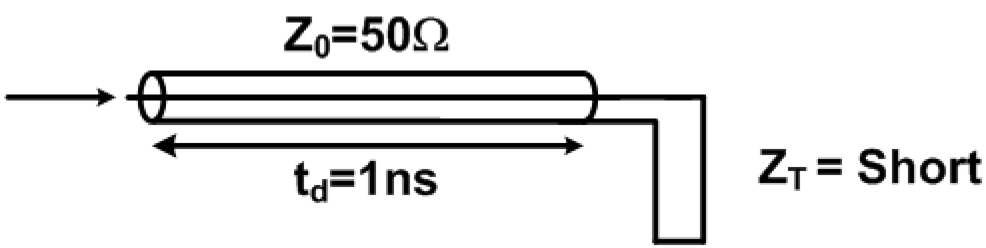
TDR Waveforms (Open & Short)

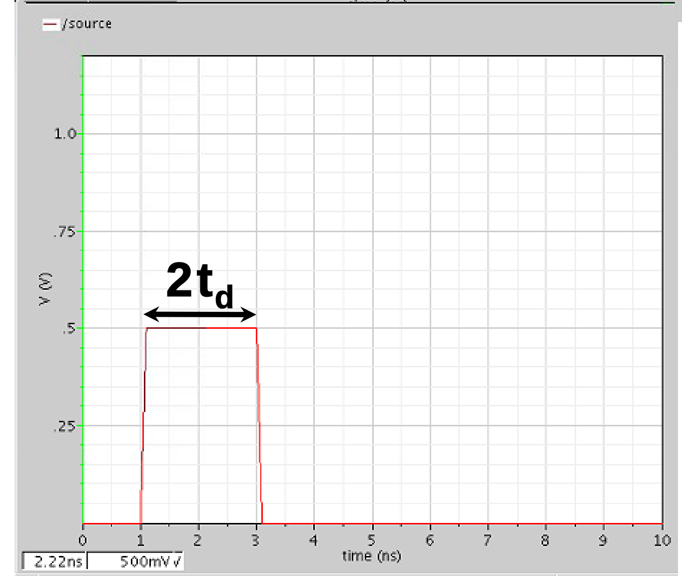
- Open termination





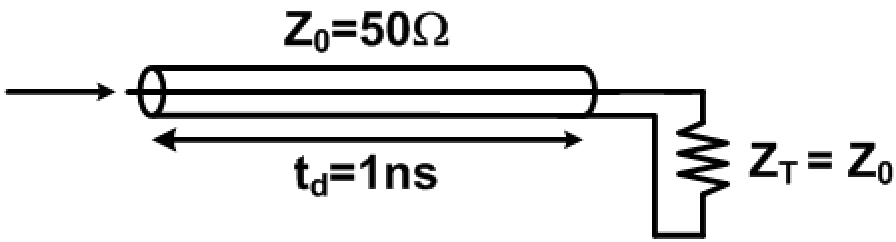
- Short termination

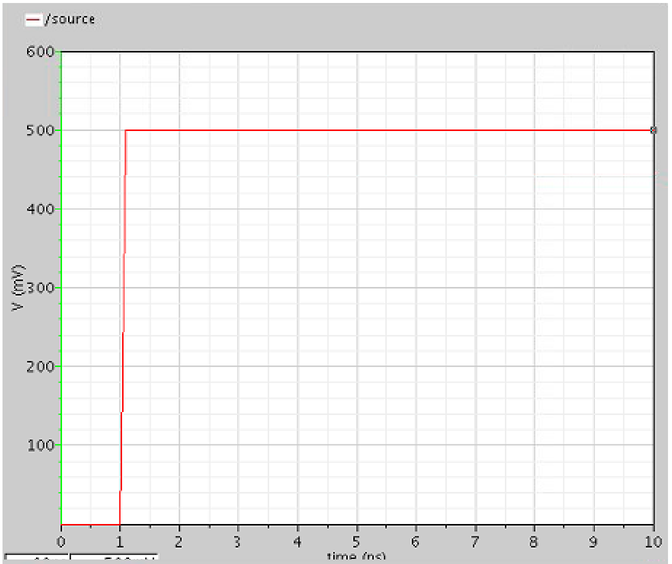




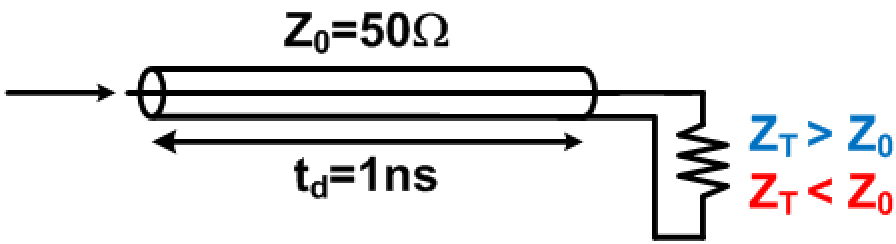
TDR Waveforms (Matched & Mismatched)

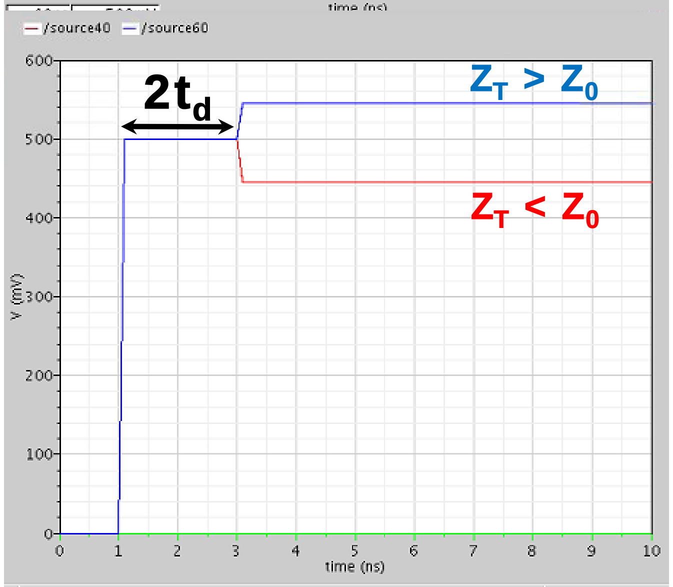
- Matched termination





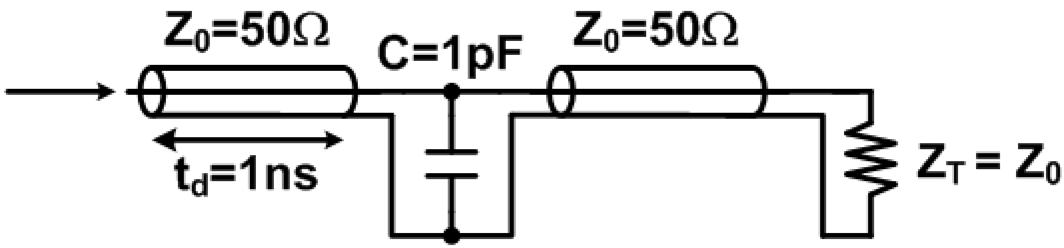
- Mismatched termination



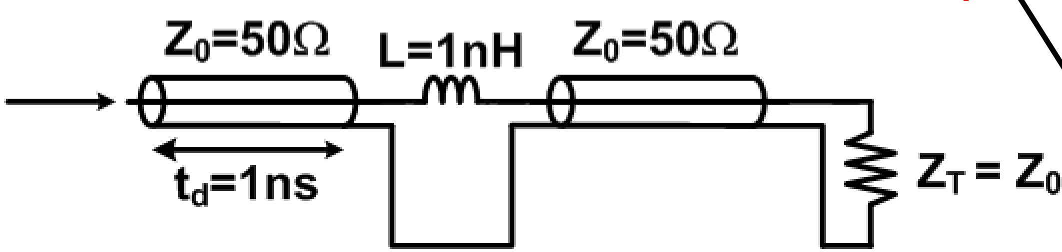


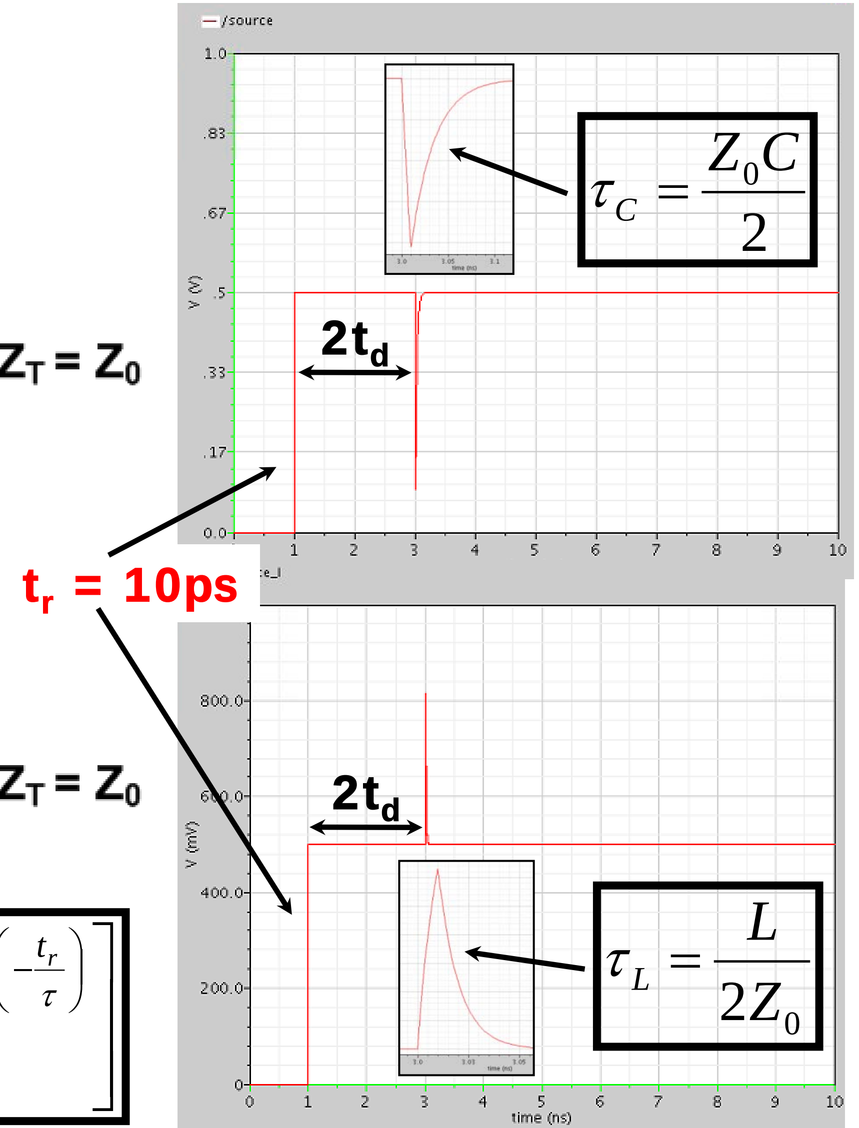
TDR Waveforms (C & L Discontinuity)

- Shunt C discontinuity



- Series L discontinuity





Peak voltage spike magnitude:

$$\frac{\Delta V}{V} = \left(\frac{\tau}{t_r}\right)\left[1 - e^{\left(-\frac{t_r}{\tau}\right)}\right]$$

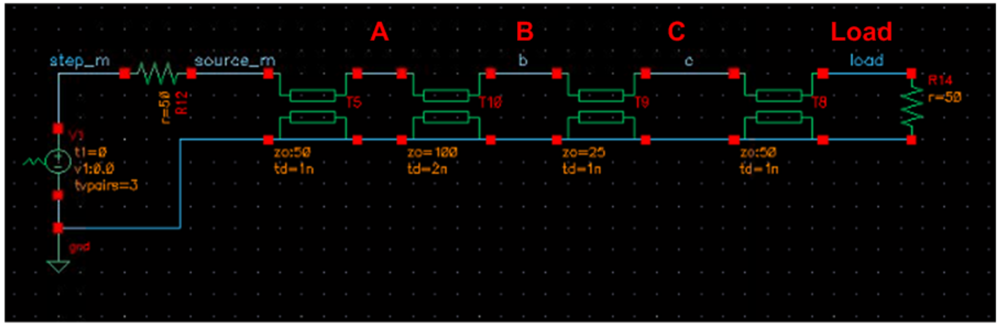
TDR Rise Time and Resolution

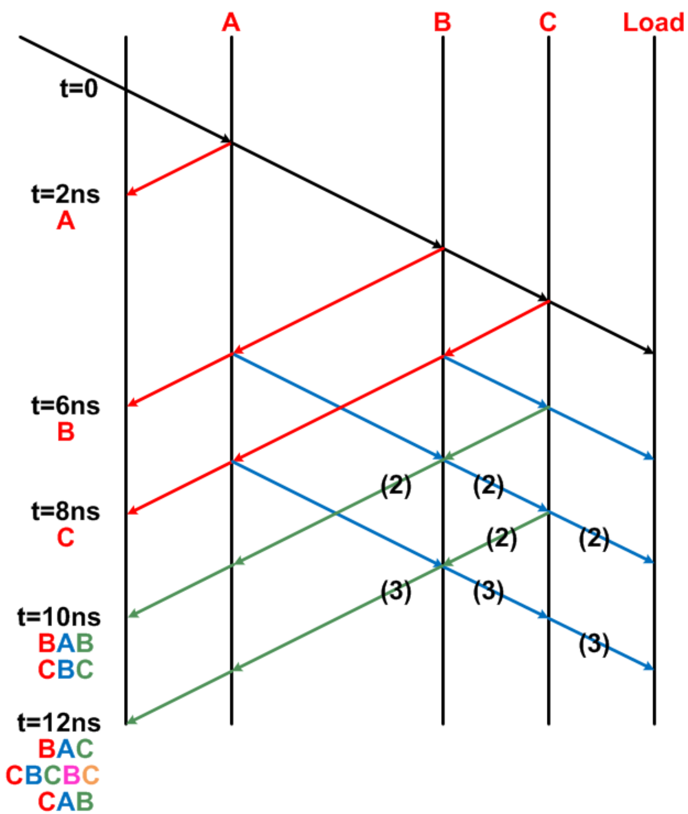
- TDR spatial resolution is set by step risetime

$$\boxed{\Delta x > t_r \upsilon}$$

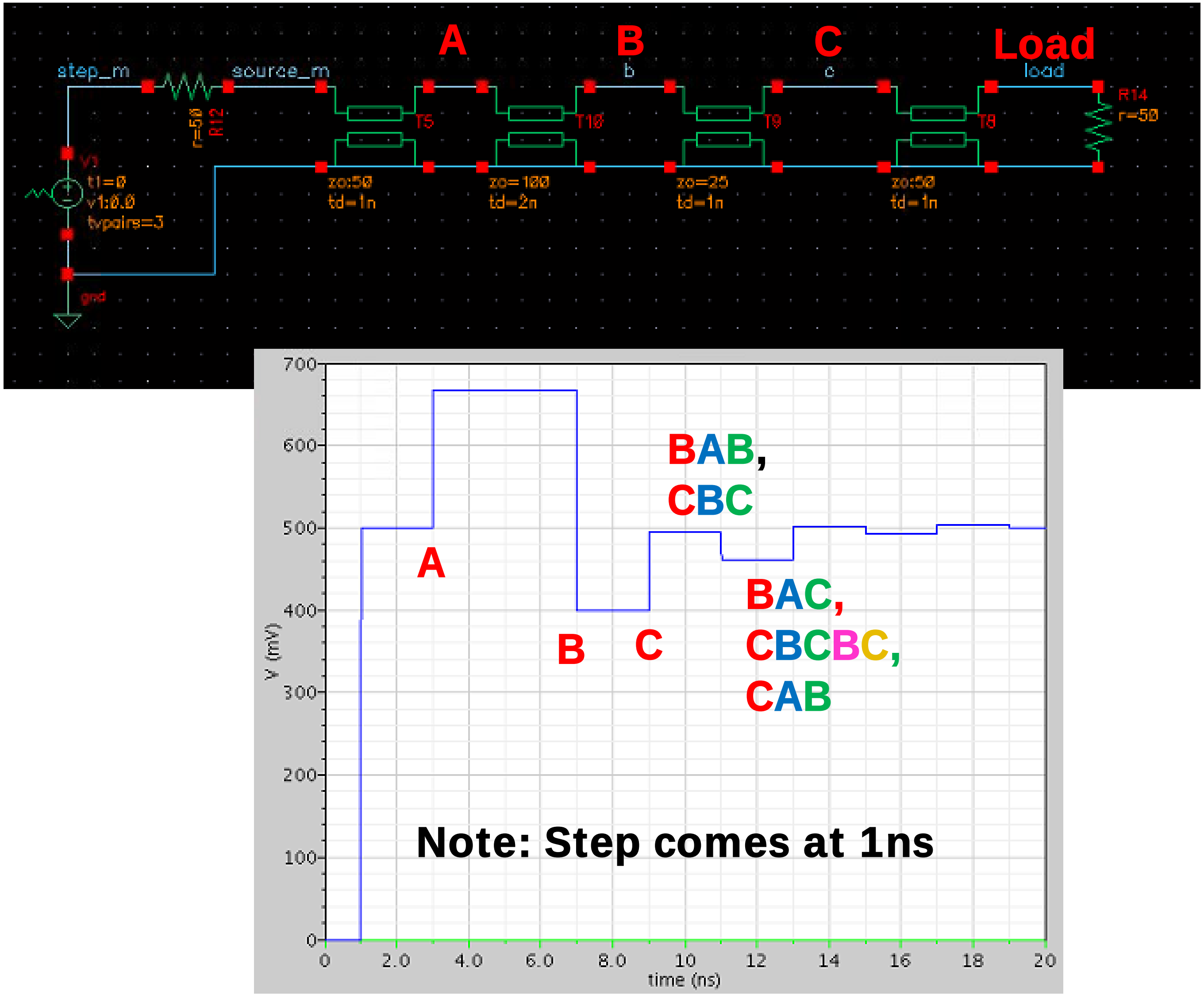
- Step risetime degrades with propagation through channel
  - Dispersion from skin-effect
  - Lump discontinuities low-pass filter the step
- Causes difficulty in estimating L & C values
- Channel filtering can actually compensate for lump discontinuity spikes ☺

TDR Multiple Reflections

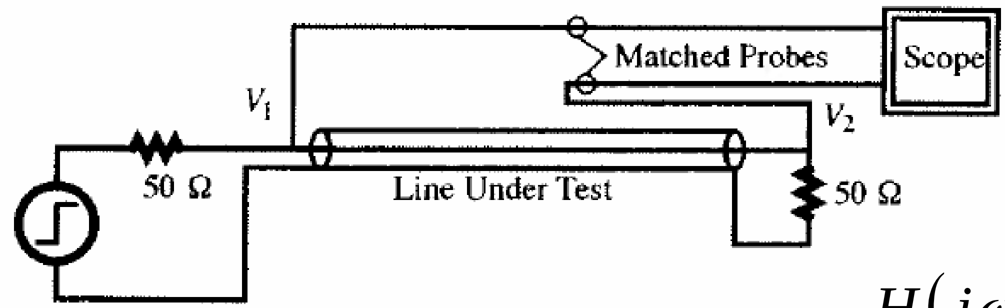




TDR Waveforms (Multiple Discontinuities)



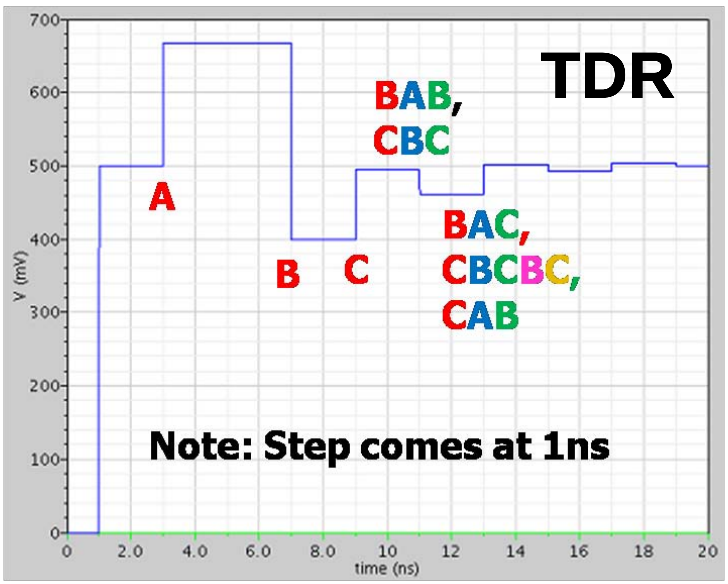
Time-Domain Transmission (TDT)

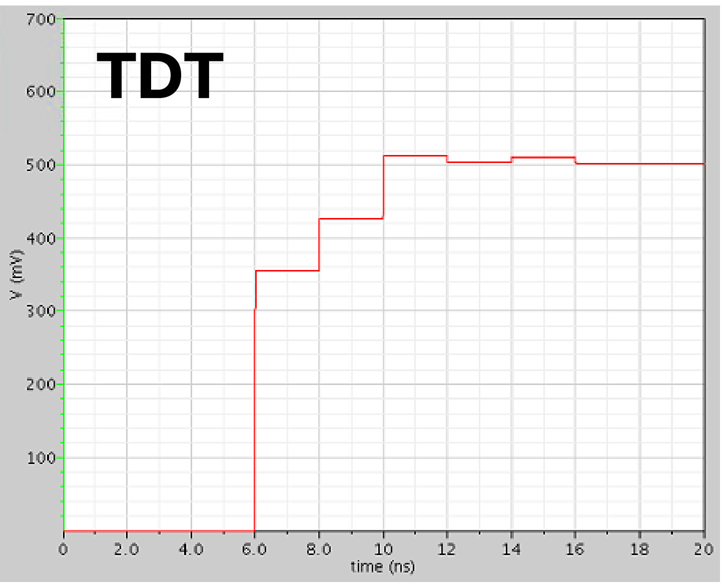


[Dally]

$$H(j\omega)=\frac{V_2(j\omega)}{V_1(j\omega)}$$

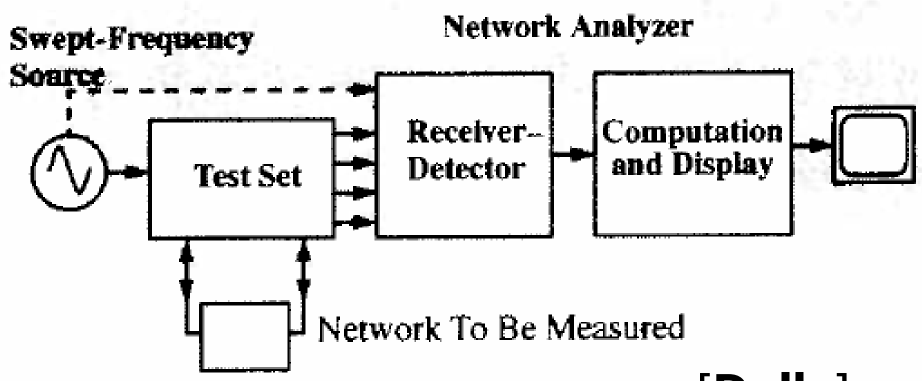
- Can measure channel transfer function
- Hard to isolate impedance discontinuities, as they are superimposed on a single rising edge



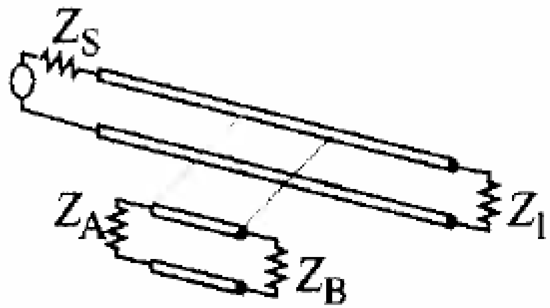


Network Analyzer

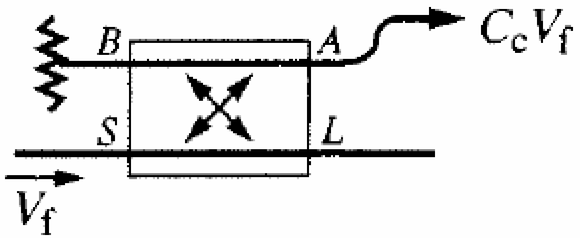
- Stimulates network with swept-frequency source
- Measures network response amplitude and phase
- Can measure transfer function, scattering matrices, impedance, ...



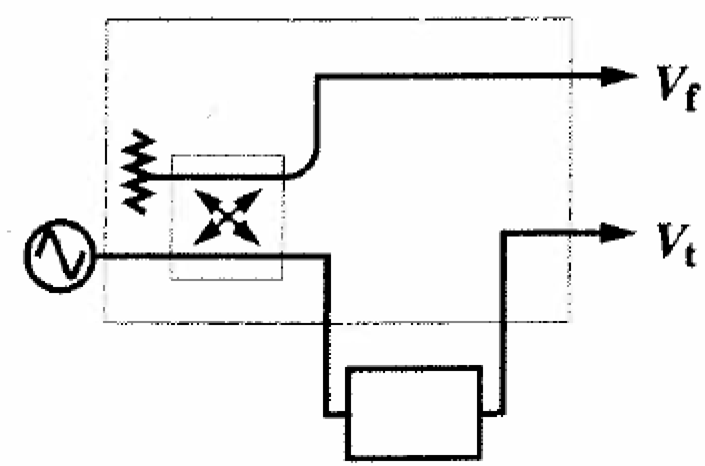
[**Dally**]



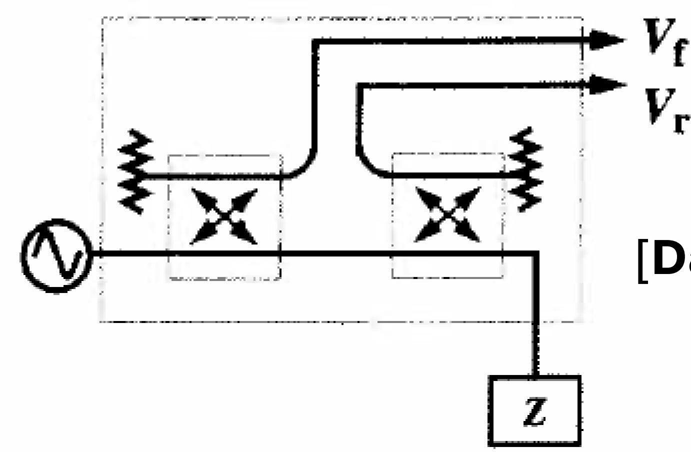
Direction Coupler



Transfer Function & Impedance Measurements



Test Set for Transfer Function

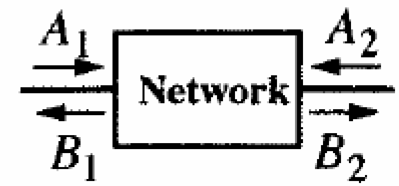


Test Set for Impedance Measurements

[**Dally**]

Scattering (S) Parameters

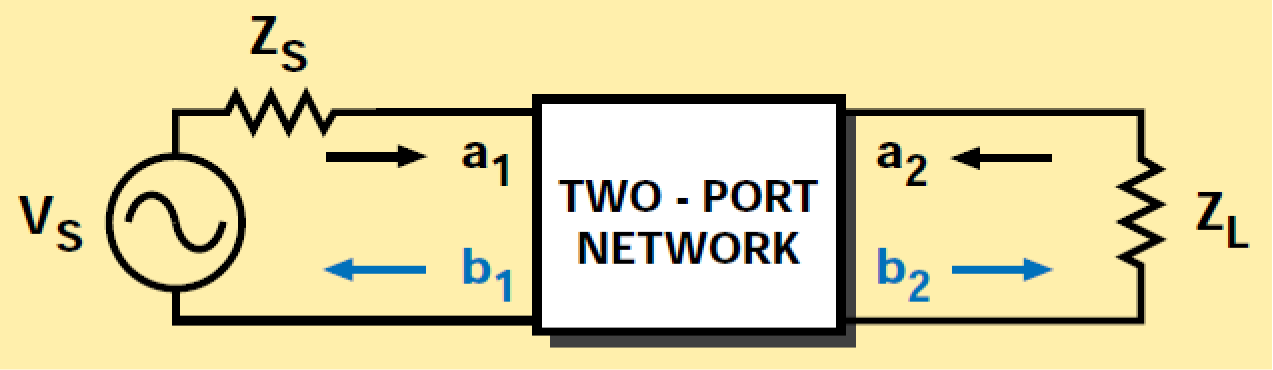
- Why S Parameters?
  - Easy to measure
  - Y, Z parameters need open and short conditions
  - S parameters are obtained with nominal termination
  - S parameters based on incident and reflected wave ratio



$$\begin{bmatrix} B_1 \\ B_2 \end{bmatrix} = \underbrace{\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}}_{\text{S-matrix}} \cdot \begin{bmatrix} A_1 \\ A_2 \end{bmatrix}$$

[**Dally**]

Formal S-Parameter Definitions



[Agilent]

$$s_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0}$$ = Input reflection coefficient with the output port terminated by a matched load (Z_L=Z_0 sets a_2=0)

$$s_{22} = \left.\frac{b_2}{a_2}\right|_{a_1=0}$$ = Output reflection coefficient with the input terminated by a matched load (Z_S=Z_0 sets V_s=0)

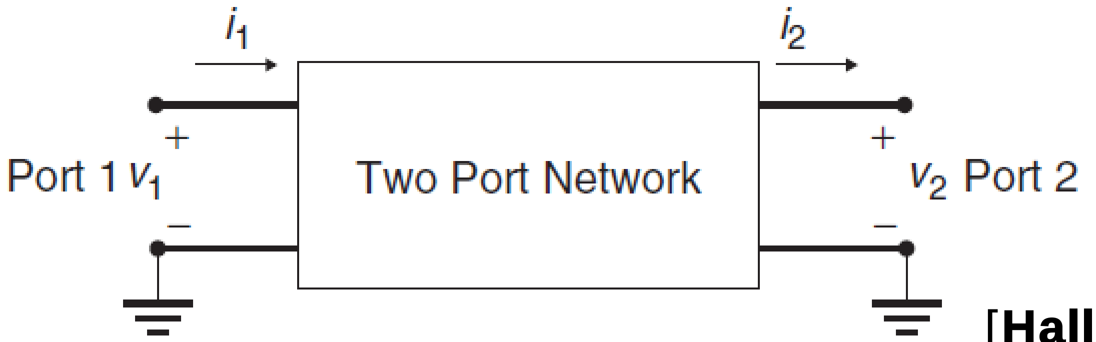
$$s_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0}$$ = Forward transmission (insertion) gain with the output port terminated in a matched load.

$$s_{12} = \left.\frac{b_1}{a_2}\right|_{a_1=0}$$ = Reverse transmission (insertion) gain with the input port terminated in a matched load.

Cascading S-Parameters

- Network analysis allows cascading of independently characterized structures
- However, can’t directly cascade s-parameter matrices and multiply
- Must first convert to an ABCD matrix (or T matrix)

ABCD Parameters



[**Hall**]

$$A = \left.\frac{v_1}{v_2}\right|_{i_{2=0}} \quad B = \left.\frac{v_1}{i_2}\right|_{v_{2=0}} \quad C = \left.\frac{i_1}{v_2}\right|_{i_{2=0}} \quad D = \left.\frac{i_1}{i_2}\right|_{v_{2=0}}$$

$$\begin{vmatrix} v_1 \\ i_i \end{vmatrix} = \begin{vmatrix} A & B \\ C & D \end{vmatrix} \bullet \begin{vmatrix} v_2 \\ i_2 \end{vmatrix}$$

Converting Between S & ABCD Parameters

TABLE 9-3. Relationships Between Two-Port S and $ABCD$ Parameters[a]

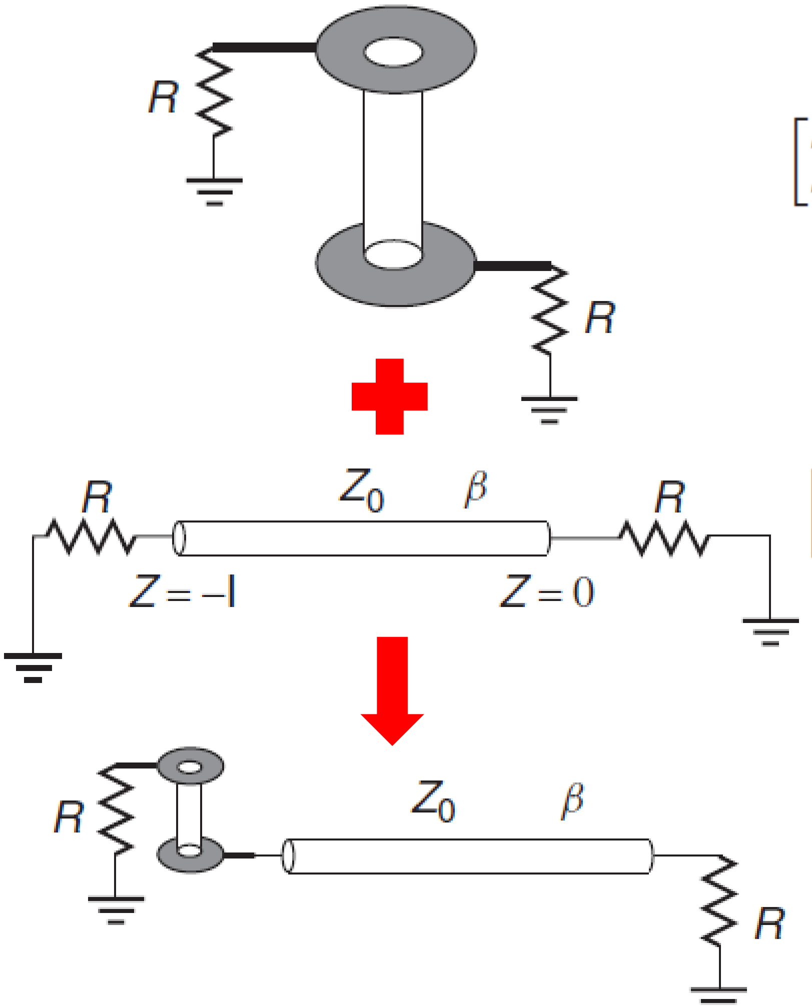
$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \quad \begin{bmatrix} \dfrac{B - Z_n(D - A + CZ_n)}{B + Z_n(D + A + CZ_n)} & \dfrac{2Z_n(AD - BC)}{B + Z_n(D + A + CZ_n)} \\ \dfrac{2Z_n}{B + Z_n(D + A + CZ_n)} & \dfrac{B - Z_n(A - D + CZ_n)}{B + Z_n(D + A + CZ_n)} \end{bmatrix}$$

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

[a] Z_n is the termination impedance at the ports.

[**Hall**]

Example: Cascaded Via & Transmission Line



$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}_{\text{via}} = \begin{bmatrix} -0.1235 - j0.1516 & 0.7597 - j0.6190 \\ 0.7597 - j0.6190 & -0.1235 - j0.1516 \end{bmatrix}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{\text{via}} = \begin{bmatrix} 0.790 & j22.22 \\ j0.01686 & 0.790 \end{bmatrix}$$

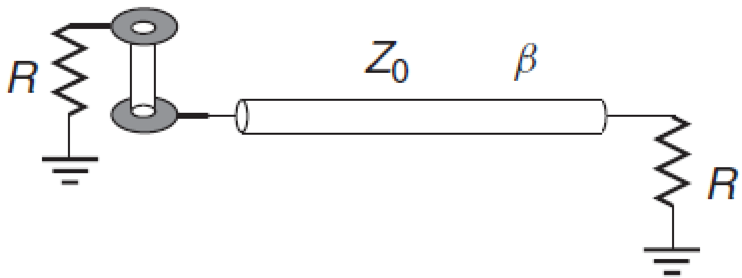
$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}_{\text{t-line}} = \begin{bmatrix} 0.00325 - j0.00323 & -1.00 - j0.003 \\ -1.00 - j0.003 & 0.00325 - j0.00323 \end{bmatrix}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{\text{t-line}} = \begin{bmatrix} -1 & j0.3228 \\ j0.000129 & -1 \end{bmatrix}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{\text{cascade}} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{\text{via}} \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{\text{t-line}}$$

- Taken from “Advanced Signal Integrity for High-Speed Digital Designs” by Hall

Example: Cascaded Via & Transmission Line



$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{\text{cascade}} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{\text{via}} \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{\text{t-line}}$$

$$= \begin{bmatrix} 0.790 & j22.22 \\ j0.01686 & 0.790 \end{bmatrix} \cdot \begin{bmatrix} -1 & j0.3228 \\ j0.000129 & -1 \end{bmatrix}$$

$$= \begin{bmatrix} -0.790 & -j21.965 \\ -j0.01686 & -0.795 \end{bmatrix}$$

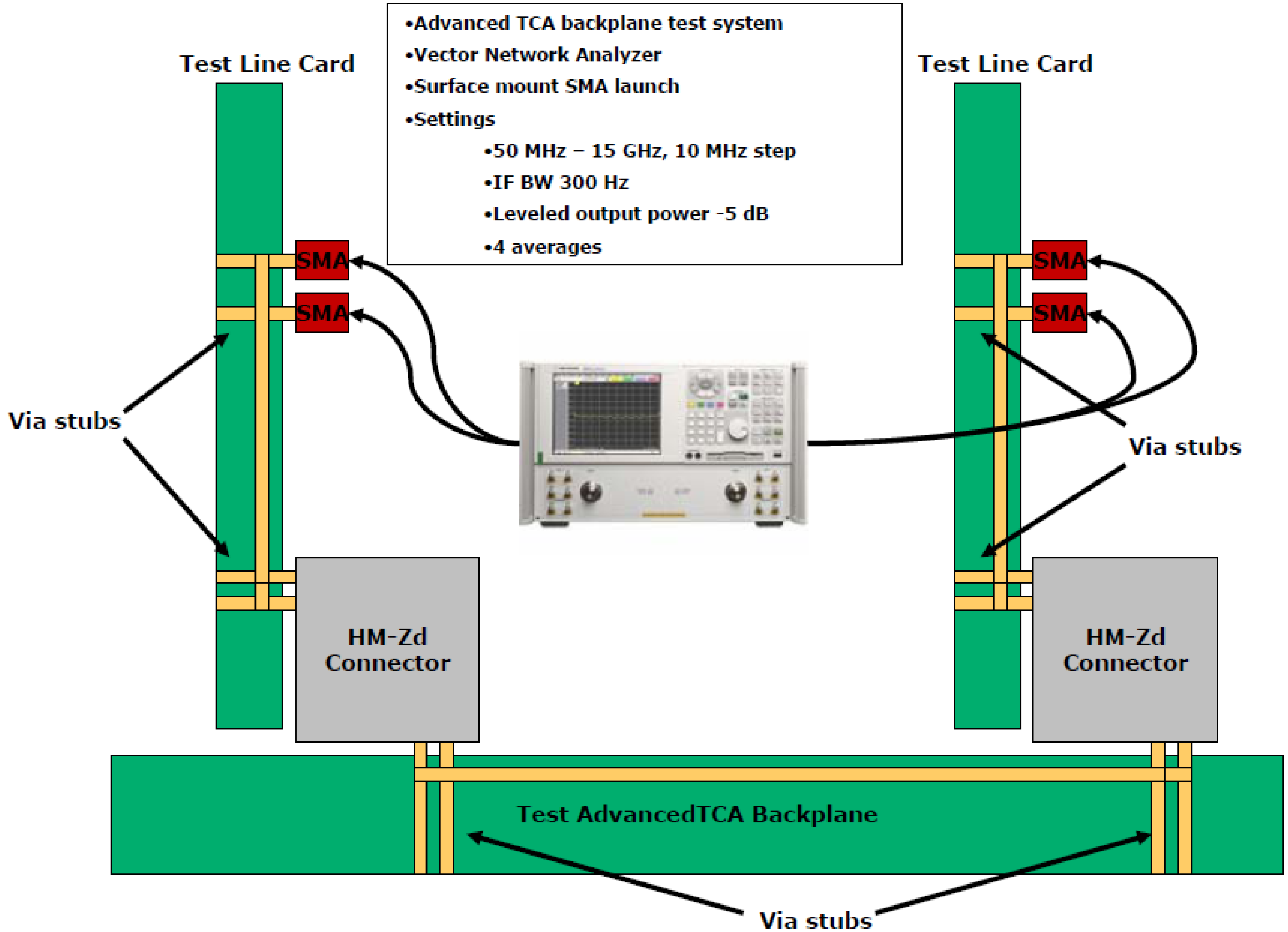
- Using conversion table:

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}_{\text{cascade}} = \begin{bmatrix} -0.1259 - j0.1553 & -0.7635 + j0.6186 \\ -0.7645 + j0.6182 & -0.1200 - j0.1565 \end{bmatrix}$$

- Can also use T matrixes to cascade

- Taken from “Advanced Signal Integrity for High-Speed Digital Designs” by Hall

S-Parameter Channel Example



[Peters, IEEE Backplane Ethernet Task Force]

S-Parameter Channel Example (4-port differential)

```
! peters_01_0605 T20 channel thru response
#       HZ        S              RI          R       50
!
! FREQ                  S11                            S12                            S13                            S14
!                       S21                            S22                            S23                            S24
!                       S31                            S32                            S33                            S34
!                       S41                            S42                            S43                            S44
!                   REAL      IMAG                 REAL      IMAG                 REAL      IMAG                 REAL      IMAG
5.00000000e+007  6.279266901548e-002 -5.256007502766e-002 -1.995363973143e-001 -9.018006169275e-001  7.405252014369e-002 -1.653914717779e-002  4.694410796534e-004  2.855671737566e-003
                -1.993592781969e-001 -9.017752677900e-001  6.847049395661e-002 -3.537762509466e-002  6.592975593456e-004  2.600733690373e-003  7.478976460177e-002 -1.488182269791e-002
                 7.438370524663e-002 -1.650568516548e-002  6.663957537997e-004  2.723661634513e-003  5.641343731365e-002 -5.693035832892e-002 -2.070369894915e-001 -8.986367167361e-001
                 3.380698172980e-004  2.715033111885e-003  7.497765935351e-002 -1.488546535615e-002 -2.063544808970e-001 -9.002700655374e-001  6.856095801756e-002 -3.019606086420e-002
6.00000000e+007  4.829977376755e-002 -6.288238652440e-002 -4.923832497425e-001 -7.721510464035e-001  6.298956599590e-002 -3.938489680891e-002  1.125377257145e-003  1.921732299021e-003
                -4.925547500023e-001 -7.726263821707e-001  6.163450406360e-002 -4.486265928179e-002  1.299644022342e-003  1.492436402394e-003  6.462146347807e-002 -3.736630924981e-002
                 6.308085276969e-002 -3.947655302643e-002  1.386741613180e-003  1.653454474207e-003  4.393874455850e-002 -6.448913049207e-002 -4.992743919180e-001 -7.660808533046e-001
                 1.280875740087e-003  1.936760526874e-003  6.482369657086e-002 -3.743006383763e-002 -4.995203164654e-001 -7.674804458241e-001  6.284893613667e-002 -4.132139739274e-002
```

Data from 50MHz to 15GHz in 10MHz steps

```
1.49900000e+010 -1.884123481138e-001  3.522933794755e-001  9.493645552321e-004  2.735890006358e-004  2.939002692375e-002 -8.676465491258e-003 -2.207496924854e-004  1.236065259912e-004
                 9.463443060684e-004  3.105615146344e-004 -1.742347383703e-001  4.813685271232e-002 -6.152705437030e-004  1.614752661571e-003  6.774475978813e-002  9.617239585695e-003
                 2.953403838205e-002 -8.707827389646e-003 -6.226849675423e-004  1.637610280621e-003 -1.595766021694e-001  3.757605914955e-001 -1.809501624148e-004 -7.061855554470e-004
                -2.613575703191e-004  1.368108929760e-004  6.788329666403e-002  9.551687705500e-003 -2.146293806886e-004 -7.363580847286e-004 -1.199804891859e-001  7.697336952293e-002
1.50000000e+010 -1.883176013184e-001  3.545614742110e-001  9.524680768441e-004 -5.404222971799e-005  2.935126165241e-002 -1.235086132268e-002 -1.616280086909e-004  2.347368458649e-004
                 1.039250921080e-003 -6.032017103742e-005 -1.649137634331e-001  4.966164587830e-002 -6.748937194262e-005  1.689652681670e-003  6.725041473699e-002  1.961009613152e-003
                 2.959693594806e-002 -1.251203706381e-002 -2.927441863297e-005  1.747754847916e-003 -1.531702433245e-001  3.773014940454e-001 -3.769459376261e-004 -5.671620228005e-004
                -2.089293612250e-004  2.303682313561e-004  6.740524959192e-002  1.672663579641e-003 -4.385850073691e-004 -5.810569604703e-004 -1.121319455376e-001  7.458173831411e-002
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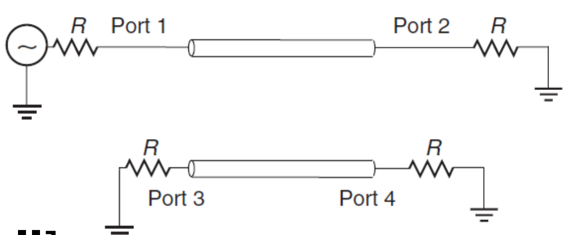


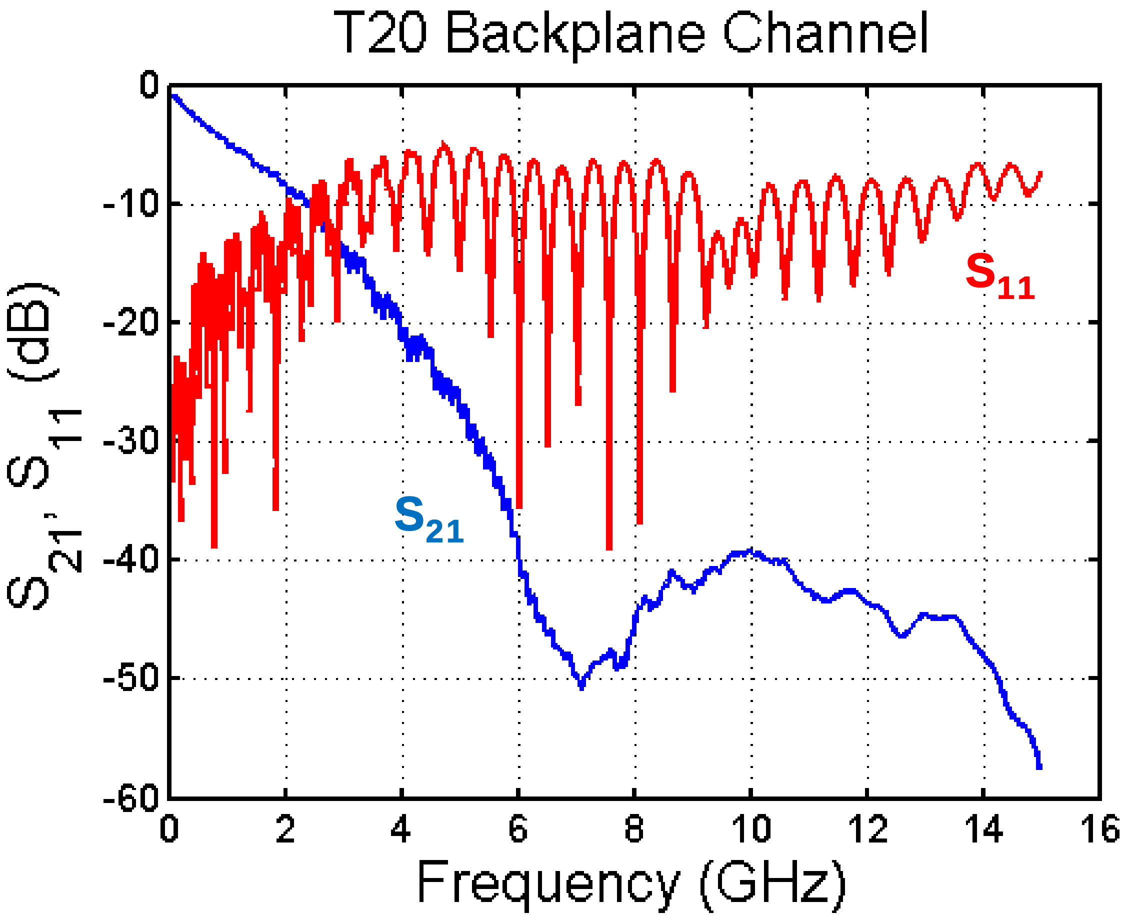
[Hall]

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} \begin{bmatrix} v \\ 0 \\ -v \\ 0 \end{bmatrix}$$

$$S_{dd11} = \left.\frac{b_{d1}}{a_{d1}}\right|_{a_2=a_4=0} = \frac{1}{2}\left(S_{11} + S_{33} - S_{13} - S_{31}\right)$$

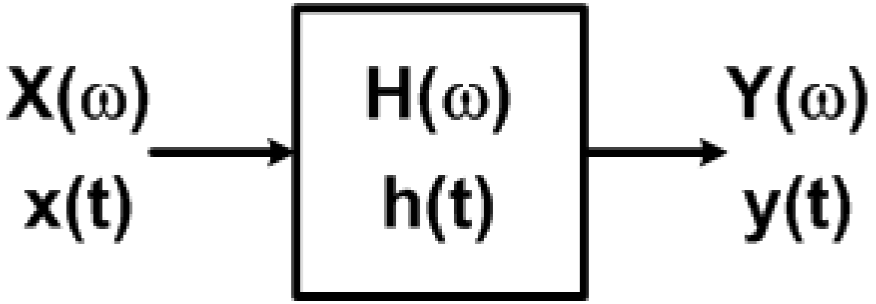
$$S_{dd21} = \left.\frac{b_{d2}}{a_{d1}}\right|_{a_2=a_4=0} = \frac{1}{2}\left(S_{21} + S_{43} - S_{23} - S_{41}\right)$$

S-Parameter Channel Example



Impulse Response

- Channel impulse responses are used in
  - Time domain simulations
  - Link analysis tools



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

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

$$h(t) = F^{-1}\{H(w)\}$$

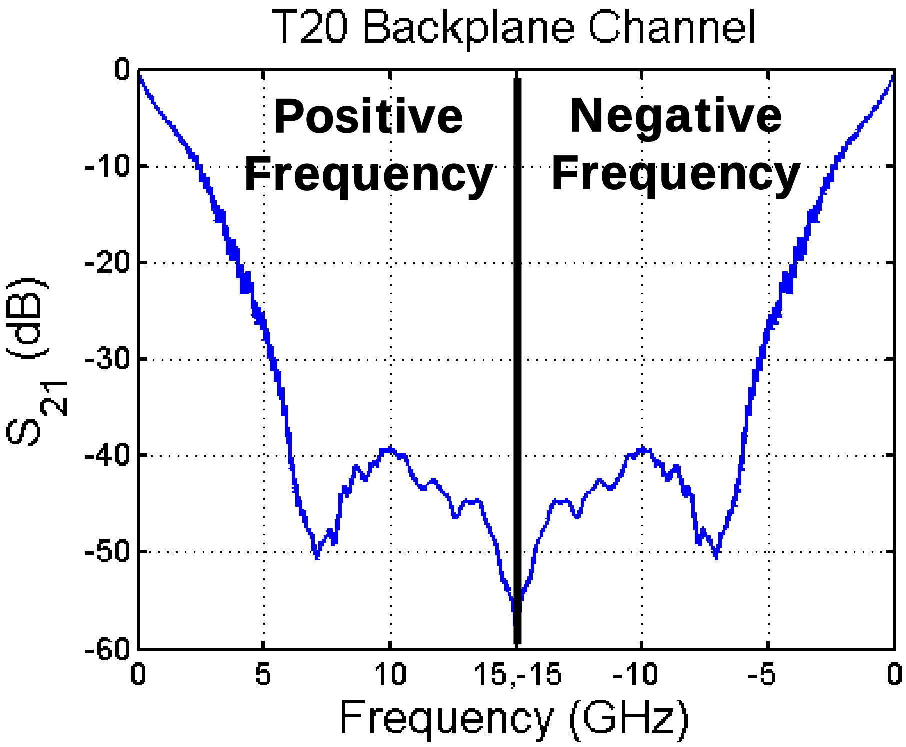
Generating an Impulse Response from S-Parameters

- Perform the inverse Fourier transform on the s-parameter of interest

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

- Step 1: For ifft, produce negative frequency values and append to s-parameter data in the following manner

$$S(-f) = S(f)^*$$



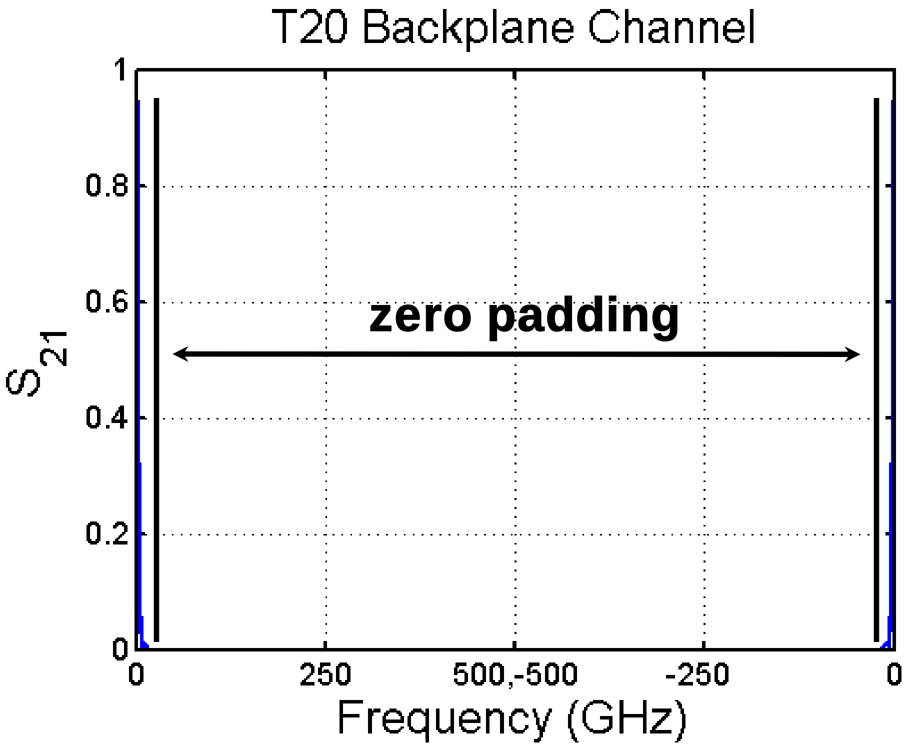
Increasing Impulse Response Resolution

- Could perform ifft now, but will get an impulse response with time resolution of

$$\frac{1}{2f_{max}} = \frac{1}{2(15\text{GHz})} = 33.3\text{ps}$$

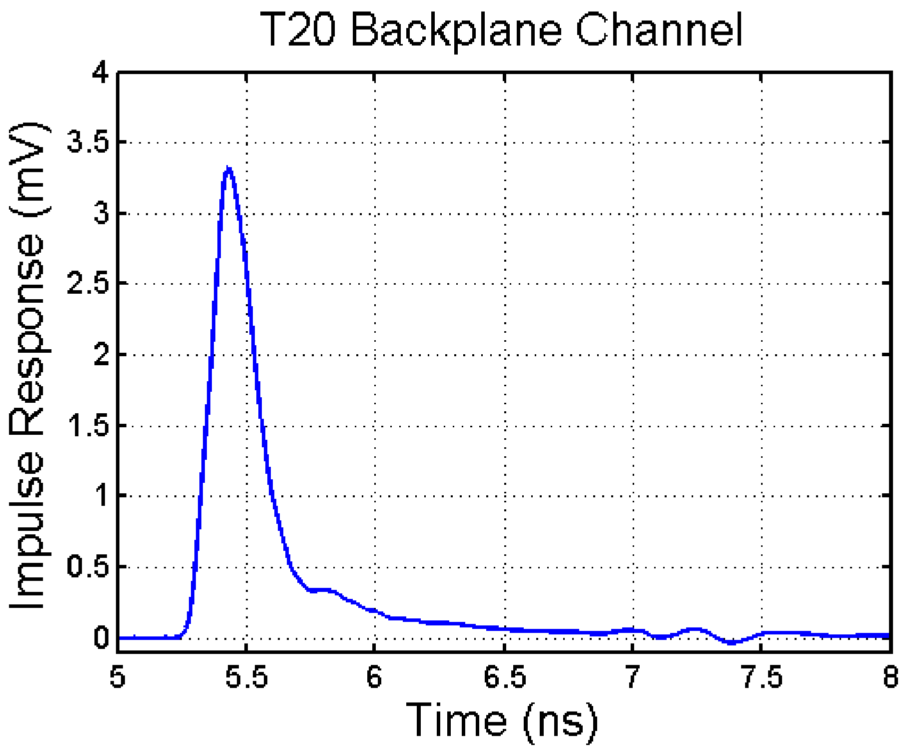
- To improve impulse response resolution expand frequency axis and “zero pad”

For 1ps resolution:
zero pad to +/-500GHz

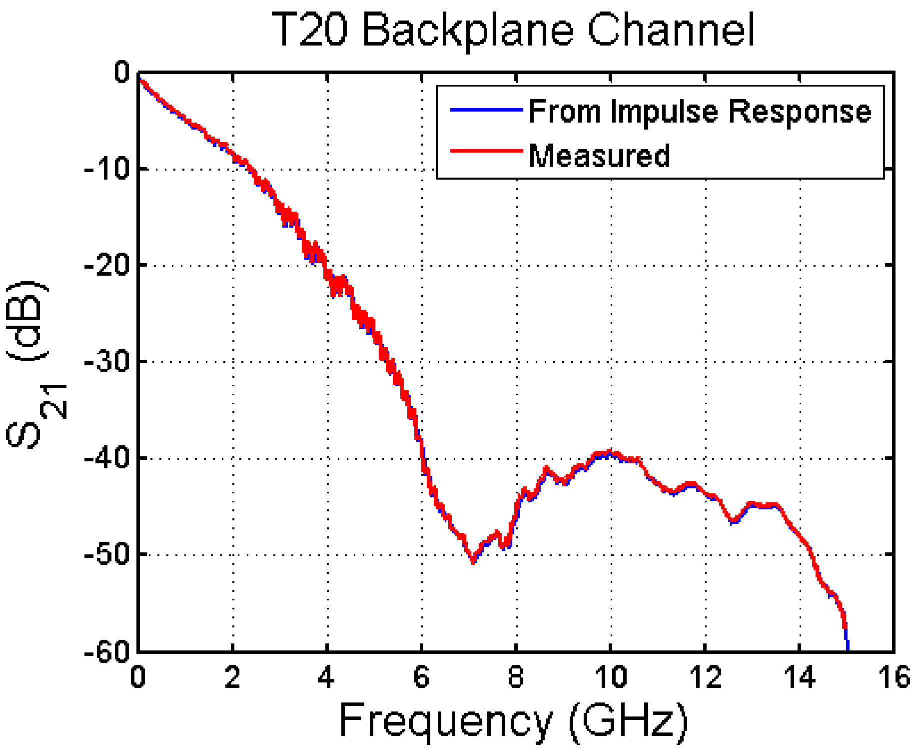


Channel Impulse Response

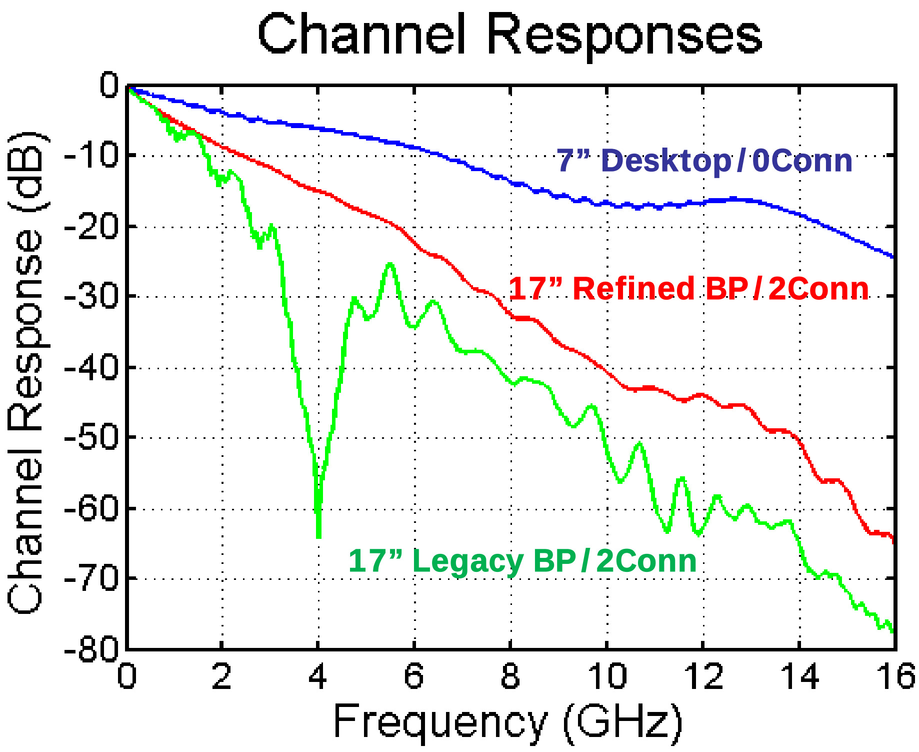
- Now perform ifft to produce impulse response

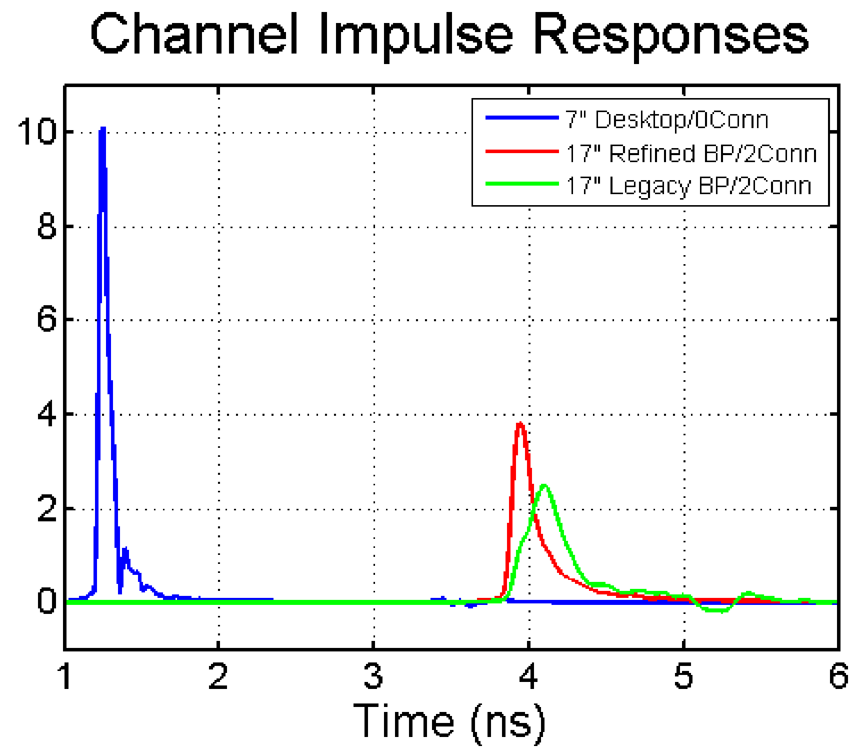


- Can sanity check by doing an fft on impulse response and comparing to measured data

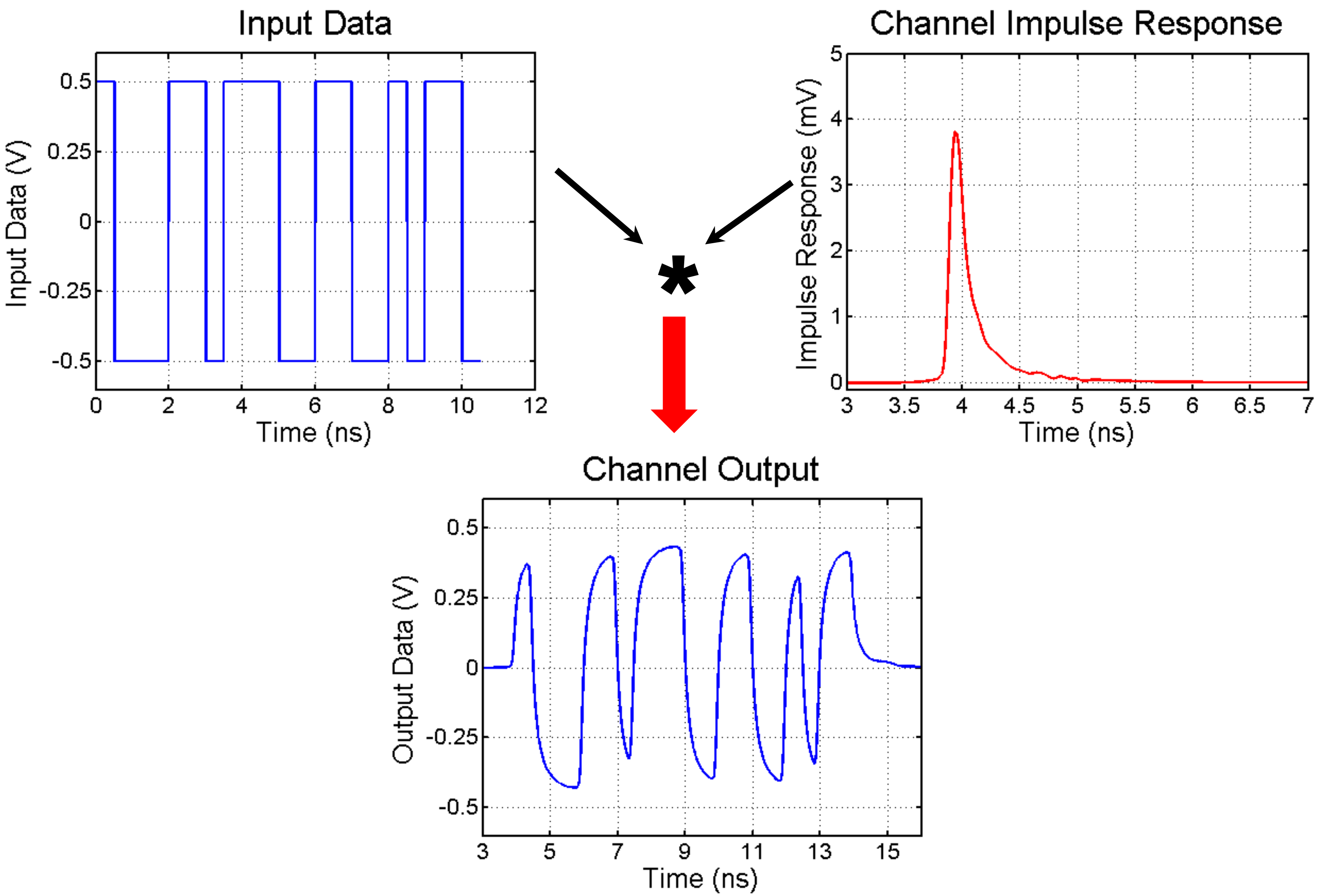


Impulse Response of Different Channels

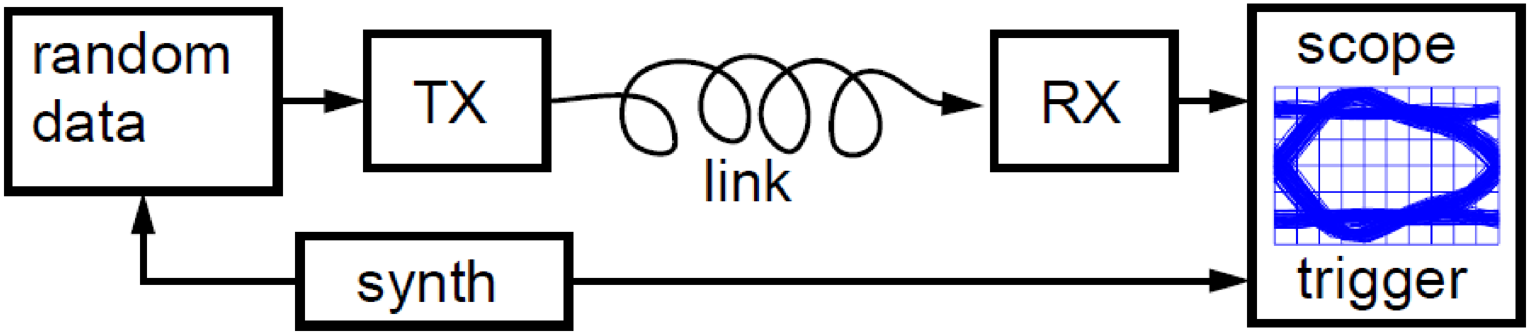


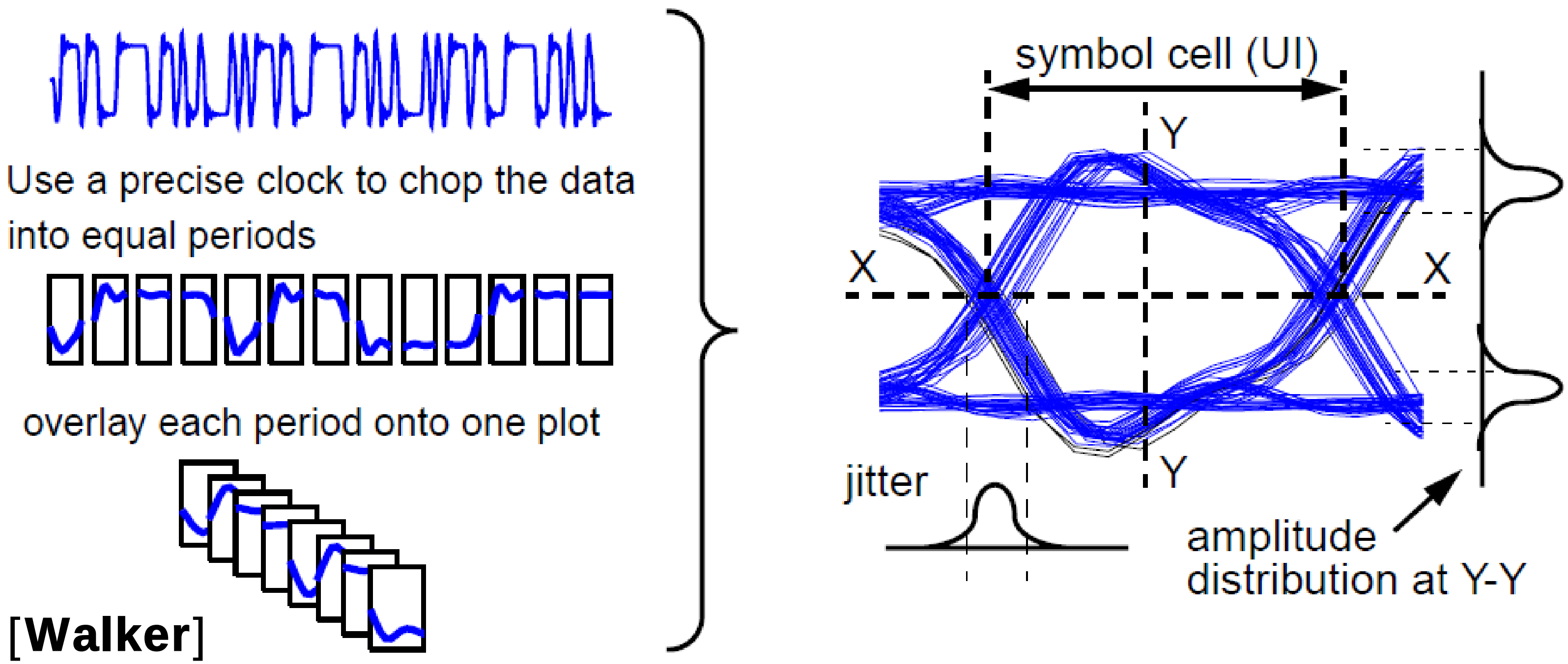


Channel Transient Response

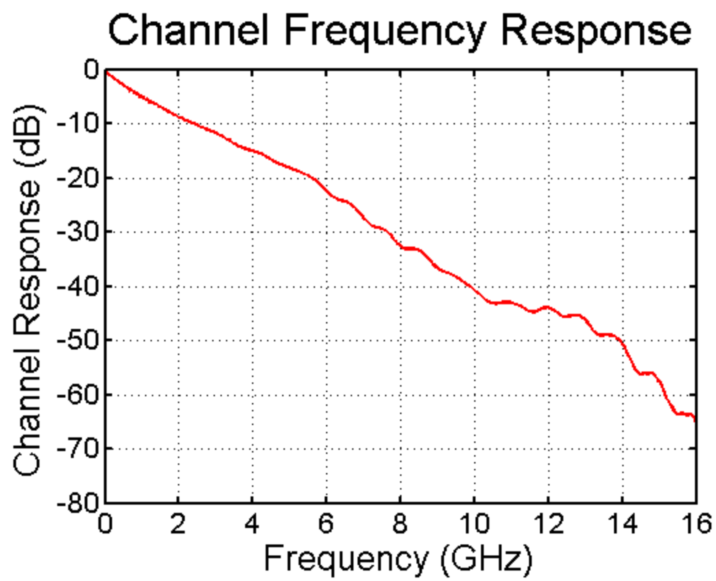


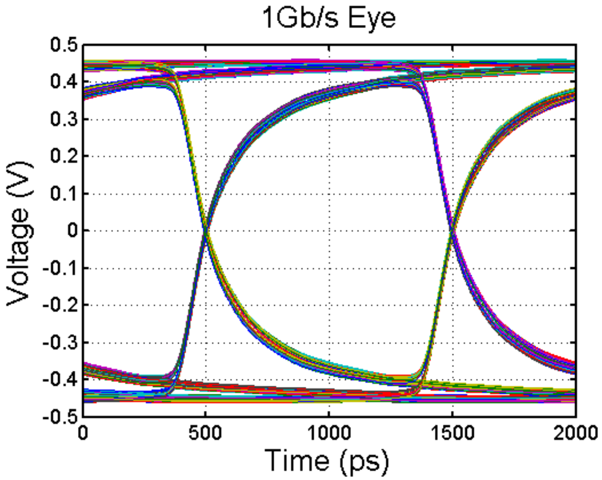
Eye Diagrams

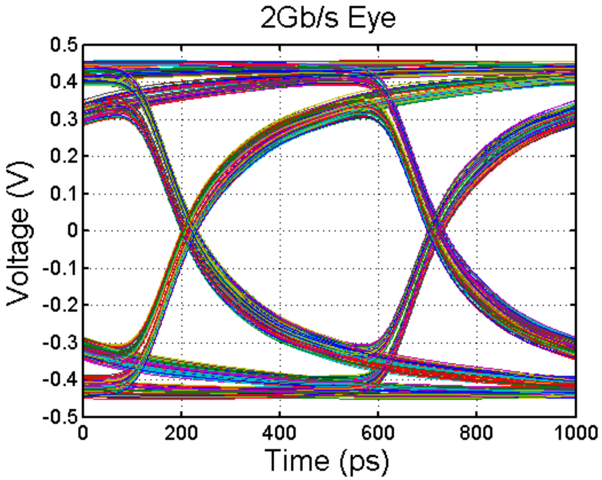


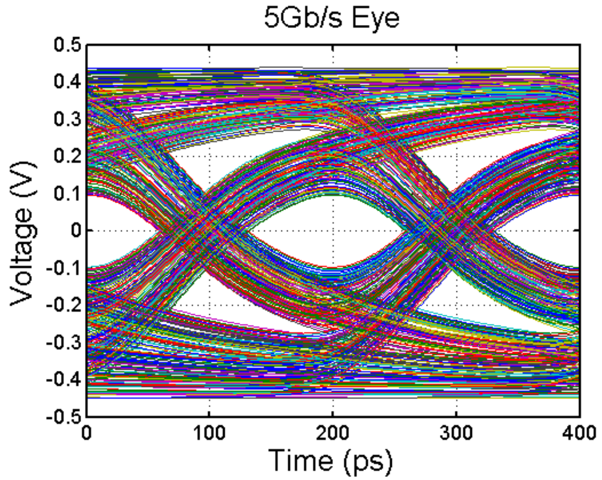


Eye Diagrams vs Data Rate

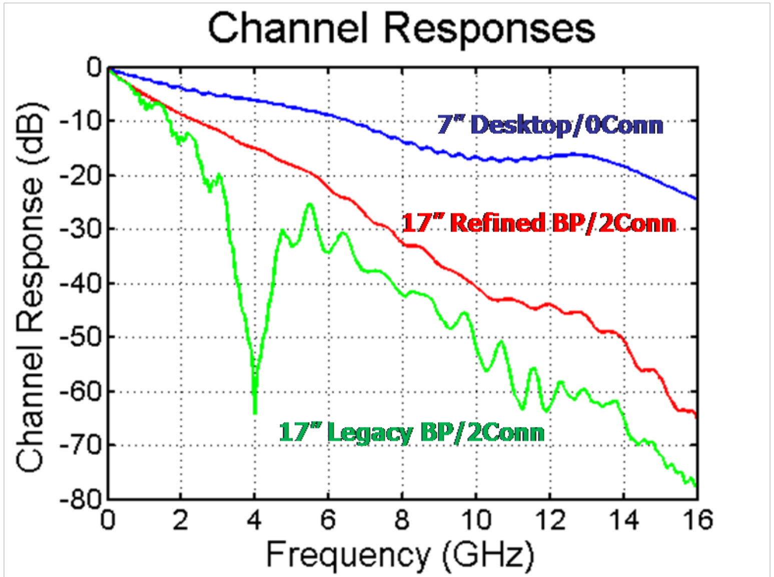


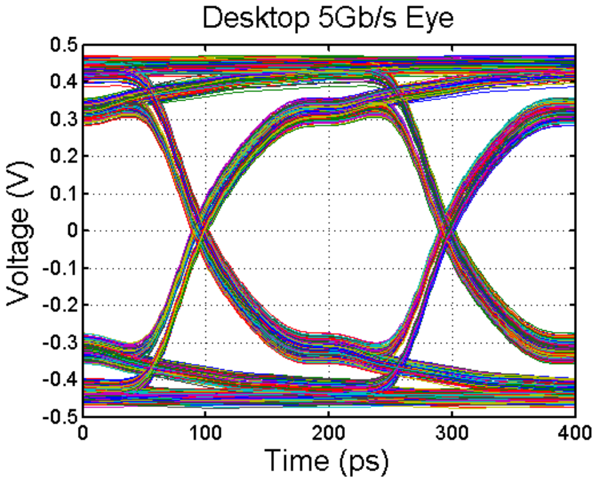


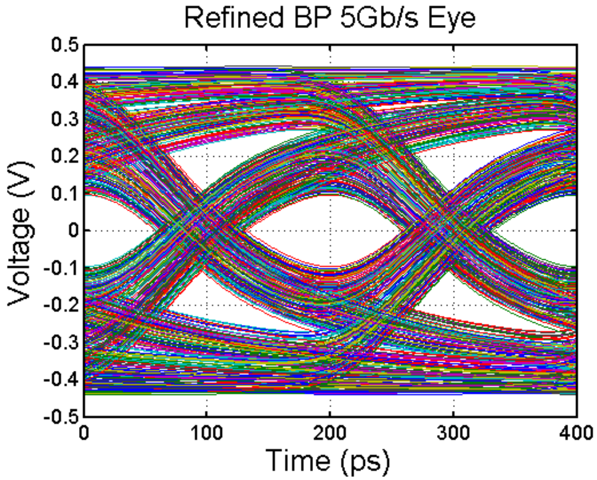


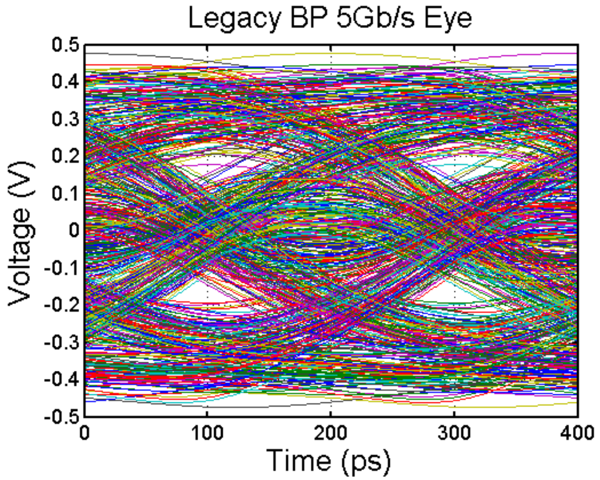


Eye Diagrams vs Channel



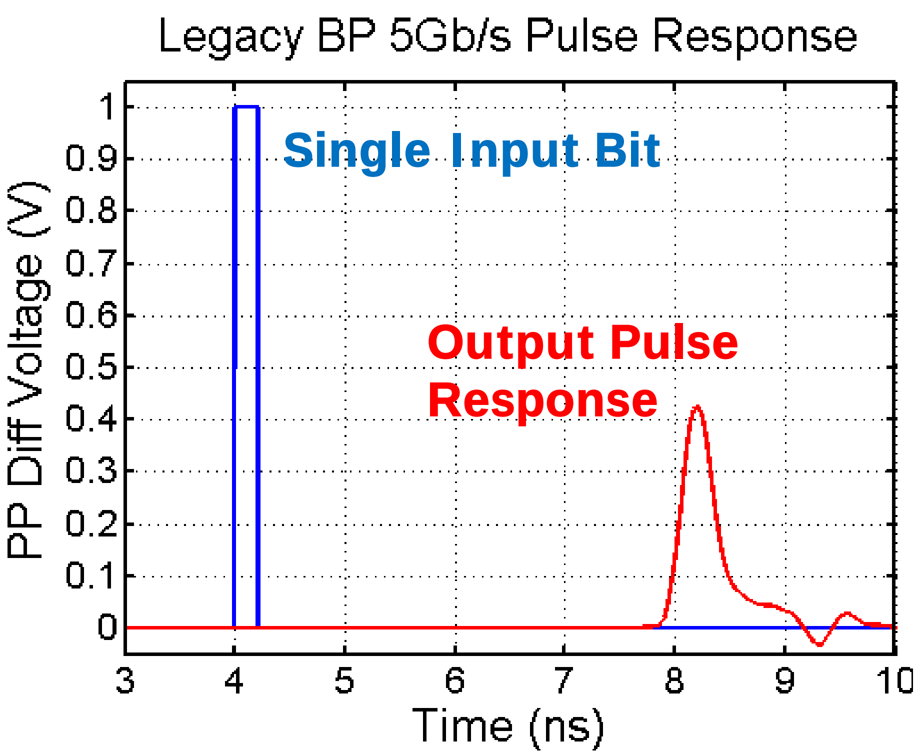


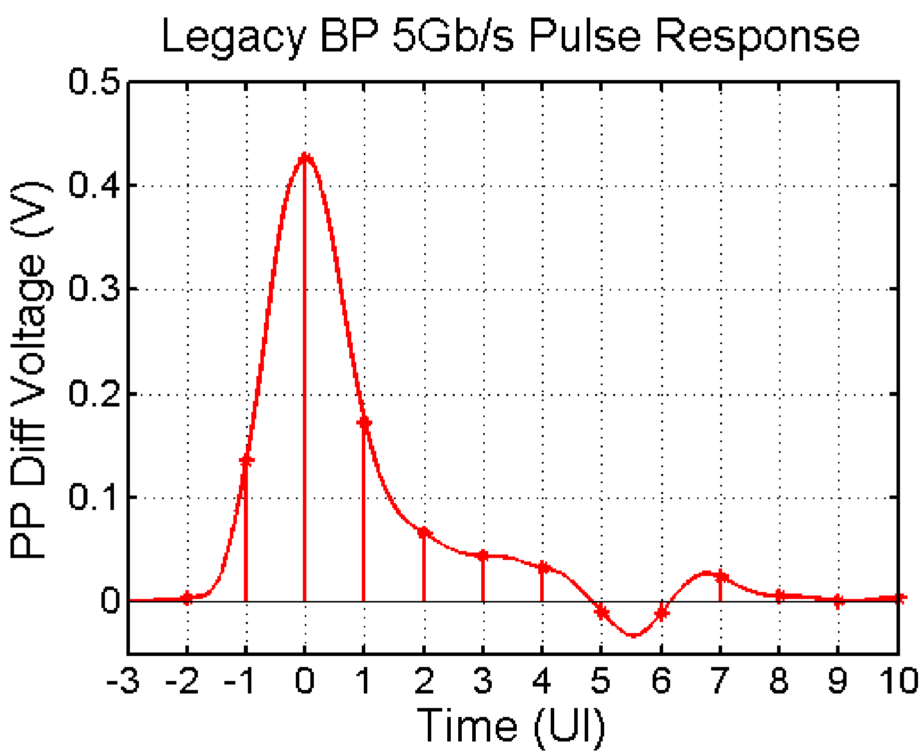




Inter-Symbol Interference (ISI)

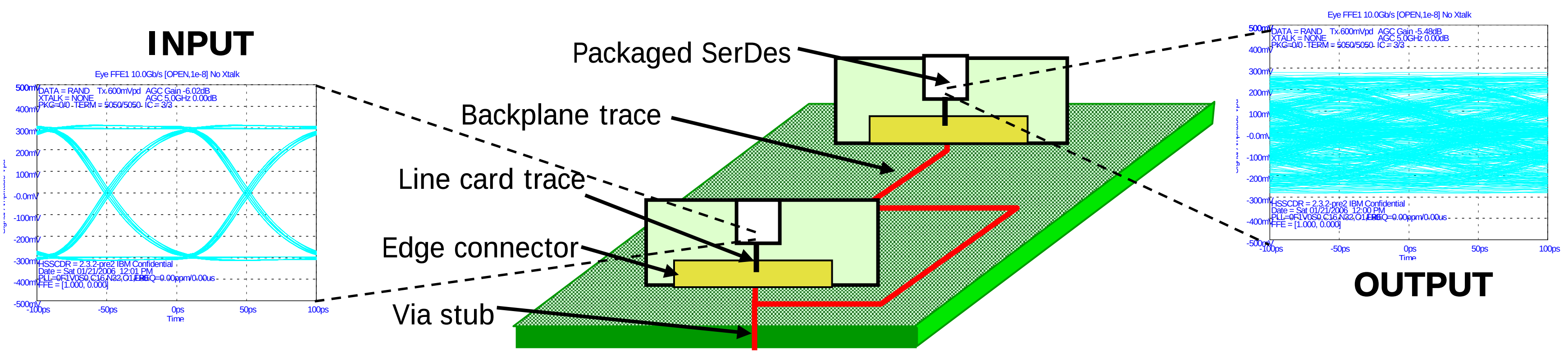
- Previous bits residual state can distort the current bit, resulting in inter-symbol interference (ISI)
- ISI is caused by
  - Reflections, Channel resonances, Channel loss (dispersion)





ISI Impact

- At channel input (TX output), eye diagram is wide open
- As data pulses propagate through channel, they experience dispersion and have significant ISI
  - Result is a closed eye at channel output (RX input)



[Meghelli (IBM) ISSCC 2006]

Next Time

- Channel pulse response model
- Modulation schemes