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

Lecture 7: Channel Time-Domain Response

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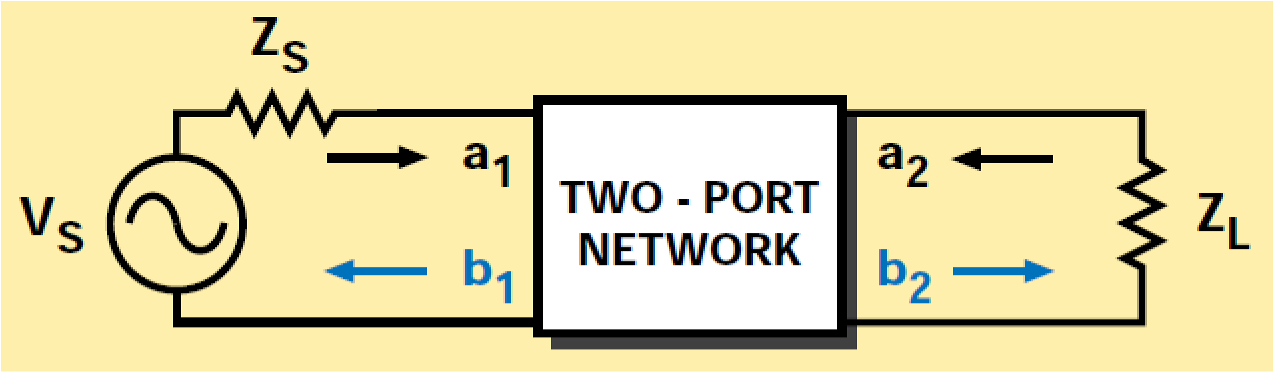
Announcements

- HW2 due 2/5
- **No class next week**
- Reading
  - Will post some material on TDR and network analyzers (S-parameters)
  - Link signaling papers

Agenda

- S-parameters revisited
- Impulse response generation
- Eye diagrams
- Inter-symbol interference (ISI)

Formal S-Parameter Definitions



[Agilent]

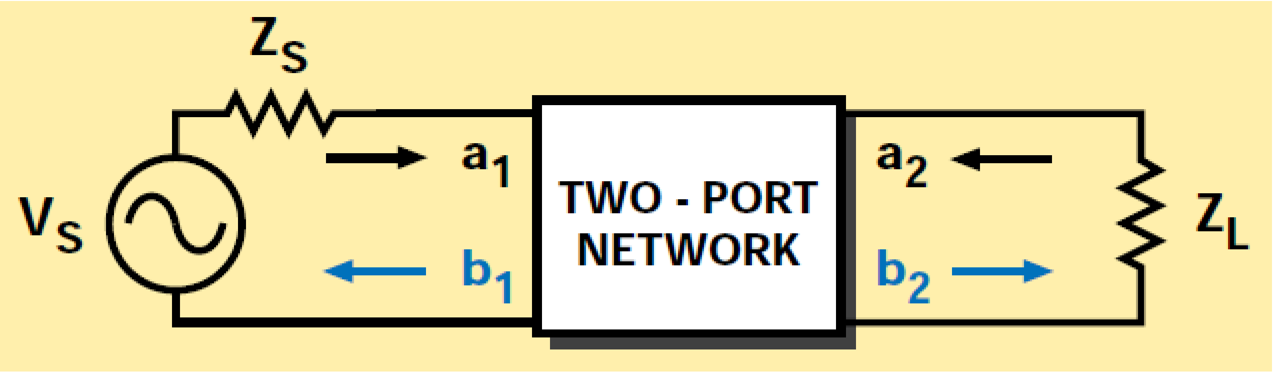
$$s_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0}$$ = Input reflection coefficient with the output port terminated by a matched load ($Z_L = Z_0$ sets $a_2 = 0$)

$$s_{22} = \left.\frac{b_2}{a_2}\right|_{a_1=0}$$ = 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.

S-Parameters with Arbitrary Termination



[Agilent]

Input reflection coefficient with arbitrary Z_L

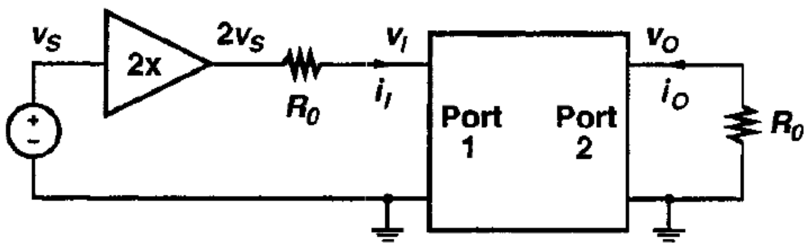
$$s'_{11} = s_{11} + \frac{s_{12}\, s_{21}\, \Gamma_L}{1 - s_{22}\, \Gamma_L} \qquad \mathbf{(a_2 \neq 0)}$$

Output reflection coefficient with arbitrary Z_s

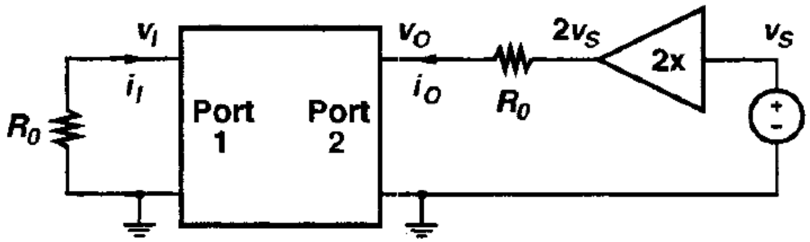
$$s'_{22} = s_{22} + \frac{s_{12}\, s_{21}\, \Gamma_S}{1 - s_{11}\, \Gamma_S} \qquad \mathbf{(a_1 \neq 0)}$$

- I believe this is what the network analyzer reports for s_{11} and s_{22} when a matching network is not used

S-Parameter Test Circuits & Meaning



[**Sackinger**]



$$S_{11}(s)=\frac{V_{i,reflected}}{V_{i,incident}}=\frac{V_i-R_0I_i}{V_i+R_0I_i}=\frac{V_i-V_s}{V_s}$$

$$S_{21}(s)=\frac{V_{o,transmitted}}{V_{i,incident}}=\frac{V_o-R_0I_o}{V_i+R_0I_i}=\frac{V_o}{V_s}$$

$$S_{22}(s)=\frac{V_{o,reflected}}{V_{o,incident}}=\frac{V_o-R_0I_o}{V_o+R_0I_o}=\frac{V_o-V_s}{V_s}$$

$$S_{12}(s)=\frac{V_{i,transmitted}}{V_{o,incident}}=\frac{V_i-R_0I_i}{V_o+R_0I_o}=\frac{V_i}{V_s}$$

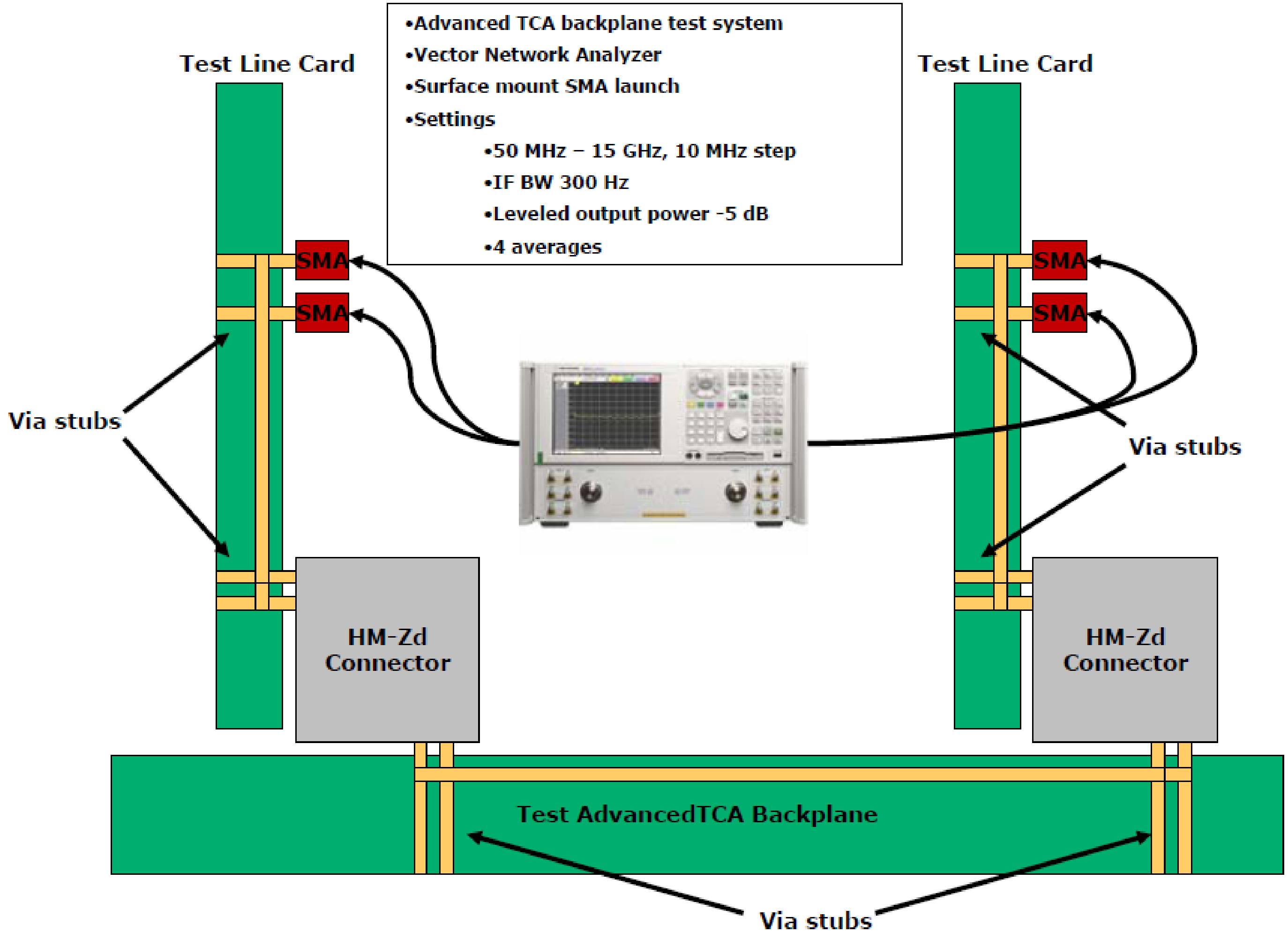
- S_{11} = Input reflection coefficient
  - $1/S_{11}$ = Input return loss
- S_{21} = Forward transmission coefficient
  - Gain w/ input matching dependency
- S_{22} = Output reflection coefficient
  - $1/S_{22}$ = Output return loss
- S_{12} = Reverse transmission coefficient (isolation)

$$S_{21}(s)=[1+S_{11}(s)]A(s)$$

where A(s) is loaded voltage gain

If a1 and a2 are not equal to zero for the appropriate measurements, these are "formally" s_{11}' , s_{21}' , s_{22}' , s_{12}'

S-Parameter Channel Example



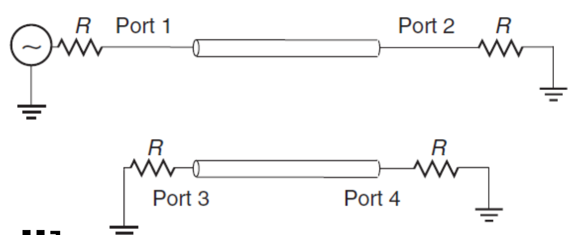
[Peters, IEEE Backplane Ethernet Task Force]

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
```



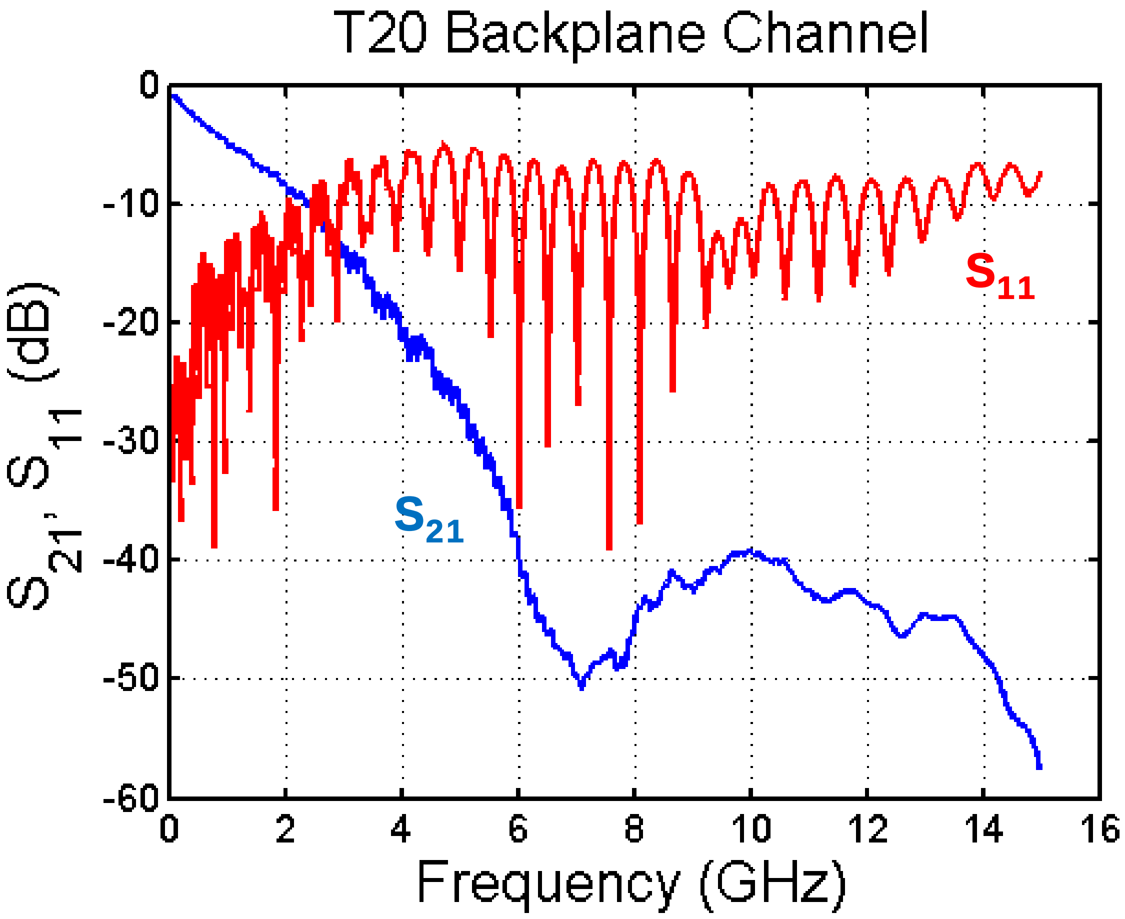
[Hall]

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

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

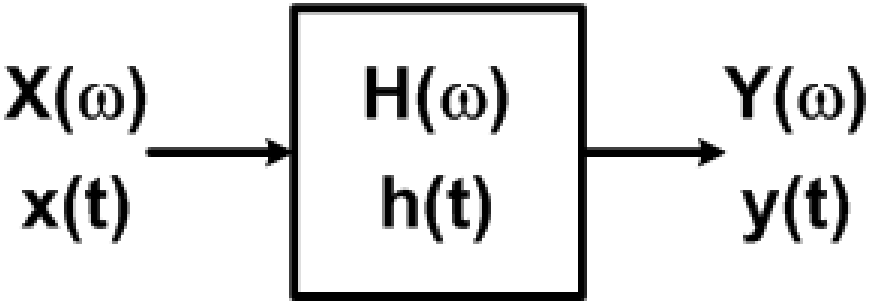
$$S_{dd21} = \left.\frac{b_{d2}}{a_{d1}}\right|_{a_2=a_4=0} = \frac{1}{2}\left(S_{21} + S_{43} - S_{23} - S_{41}\right)$$

S-Parameter Channel Example



Impulse Response

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



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

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

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

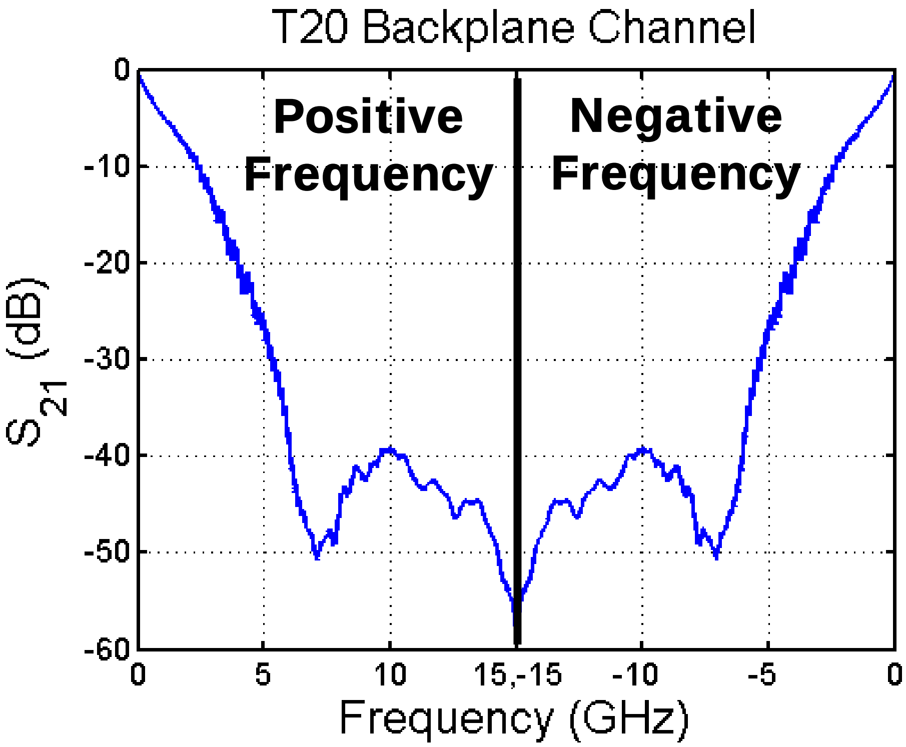
Generating an Impulse Response from S-Parameters

- 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

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



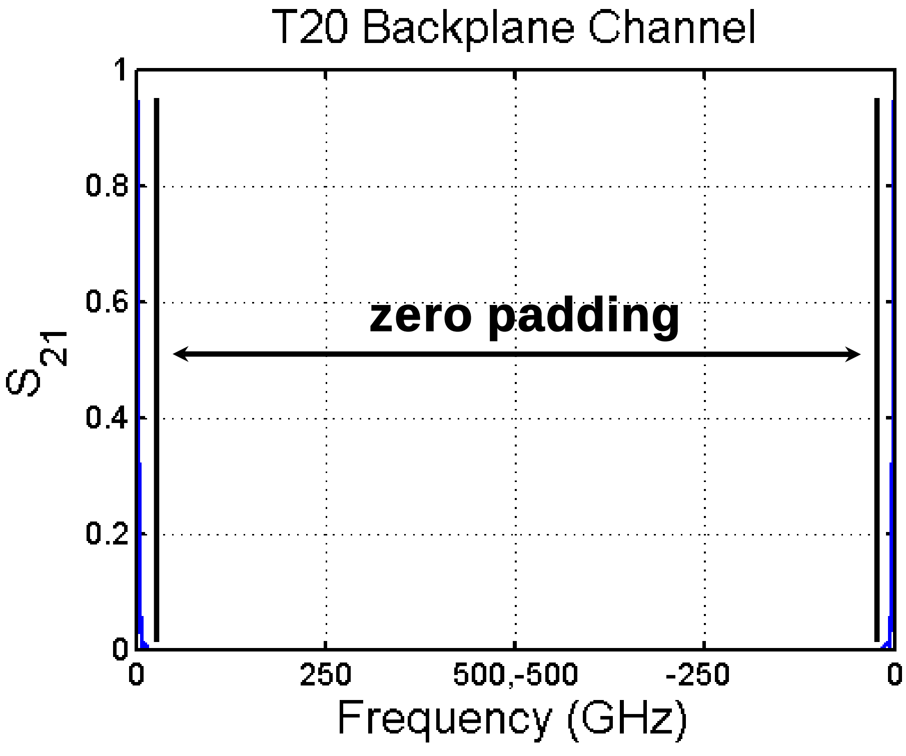
Increasing Impulse Response Resolution

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

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

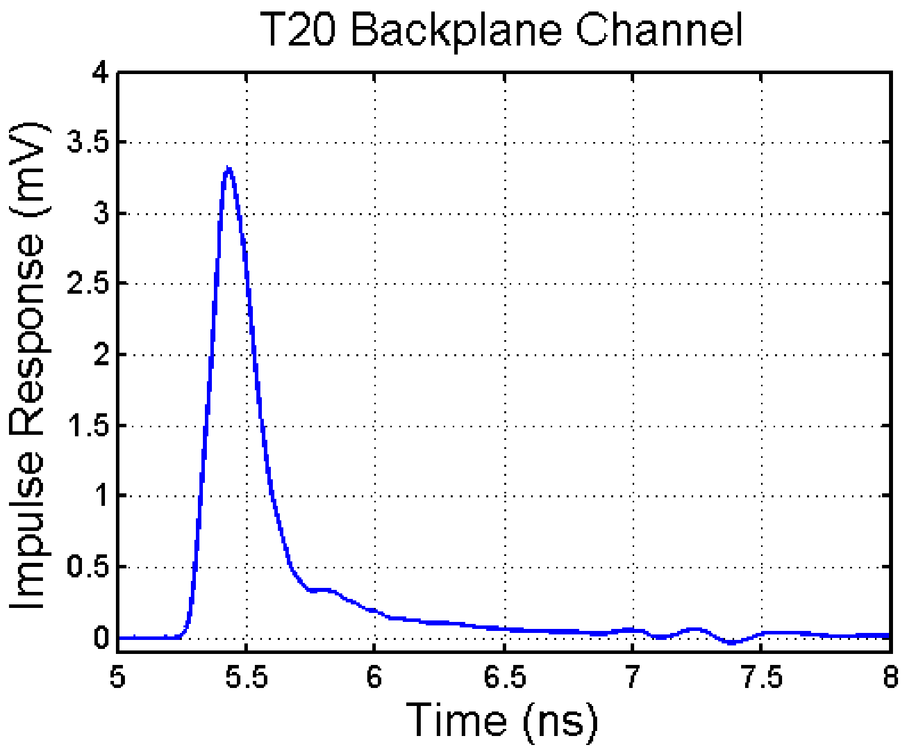
- To improve impulse response resolution expand frequency axis and “zero pad”

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

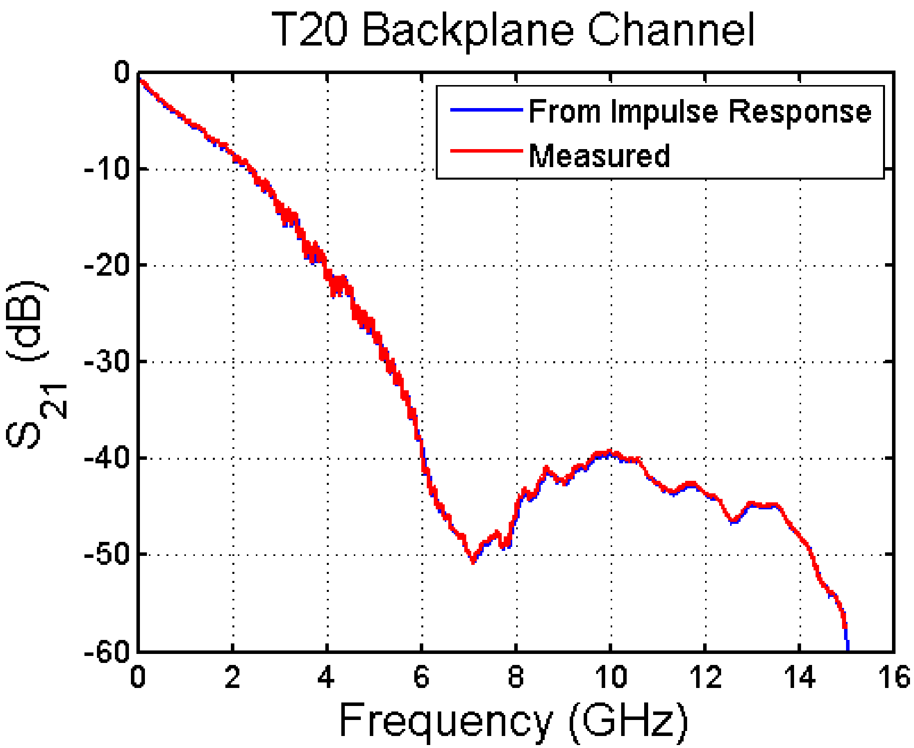


Channel Impulse Response

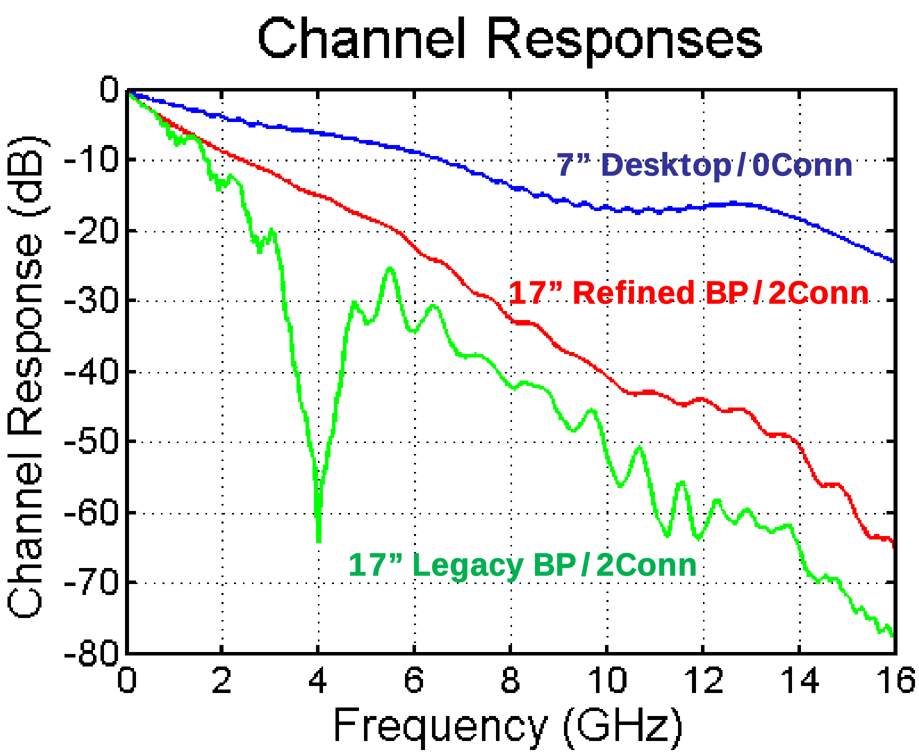
- Now perform ifft to produce impulse response

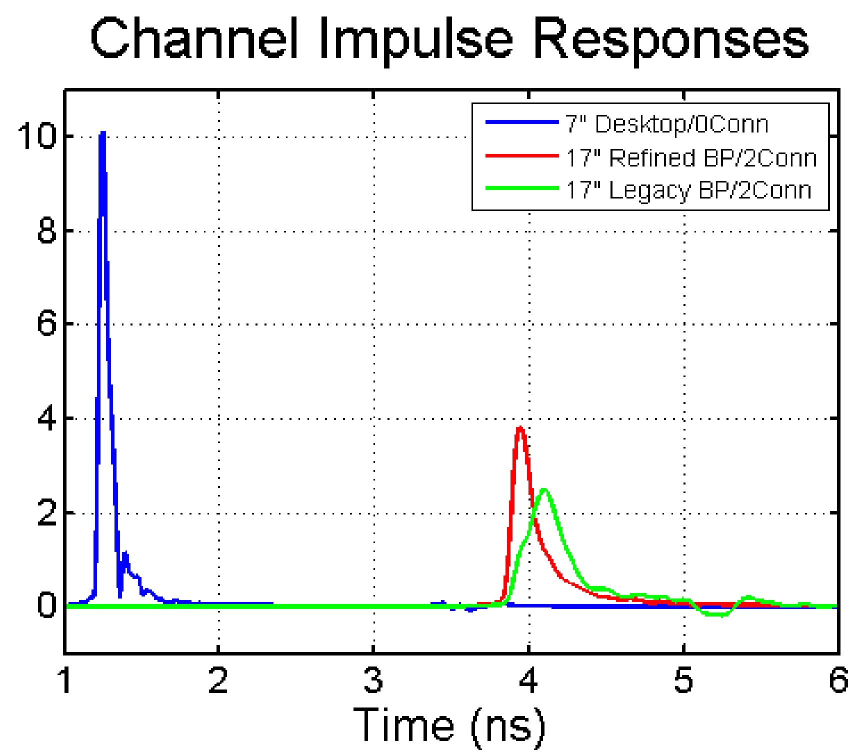


- Can sanity check by doing an fft on impulse response and comparing to measured data

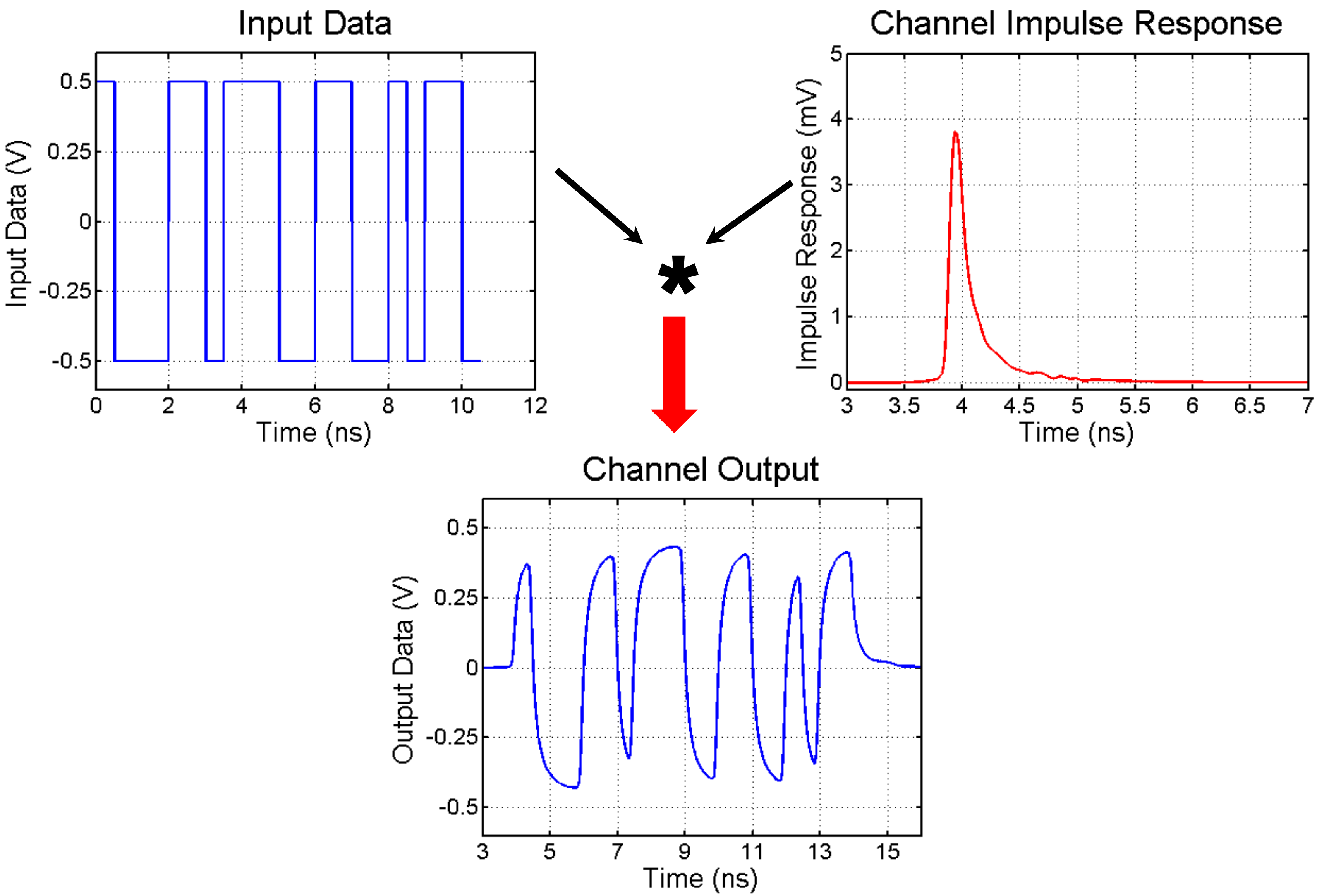


Impulse Response of Different Channels

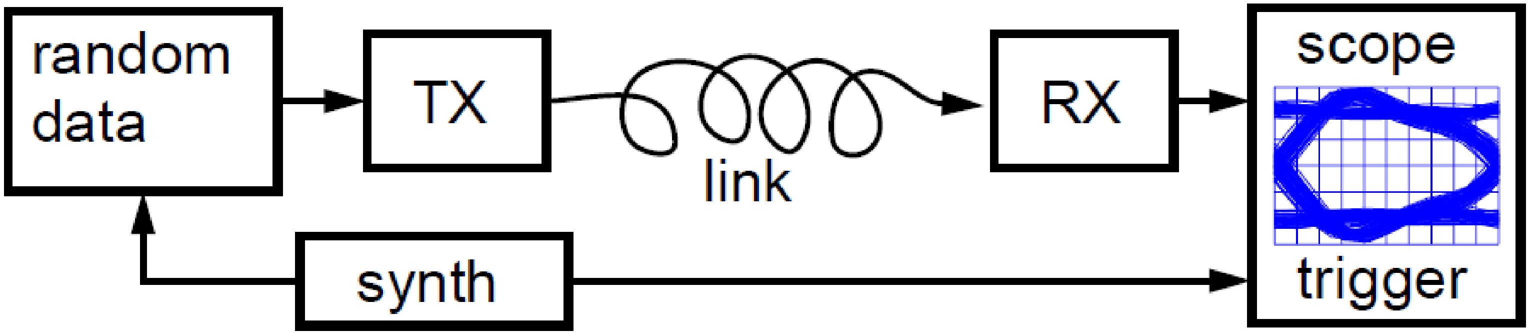


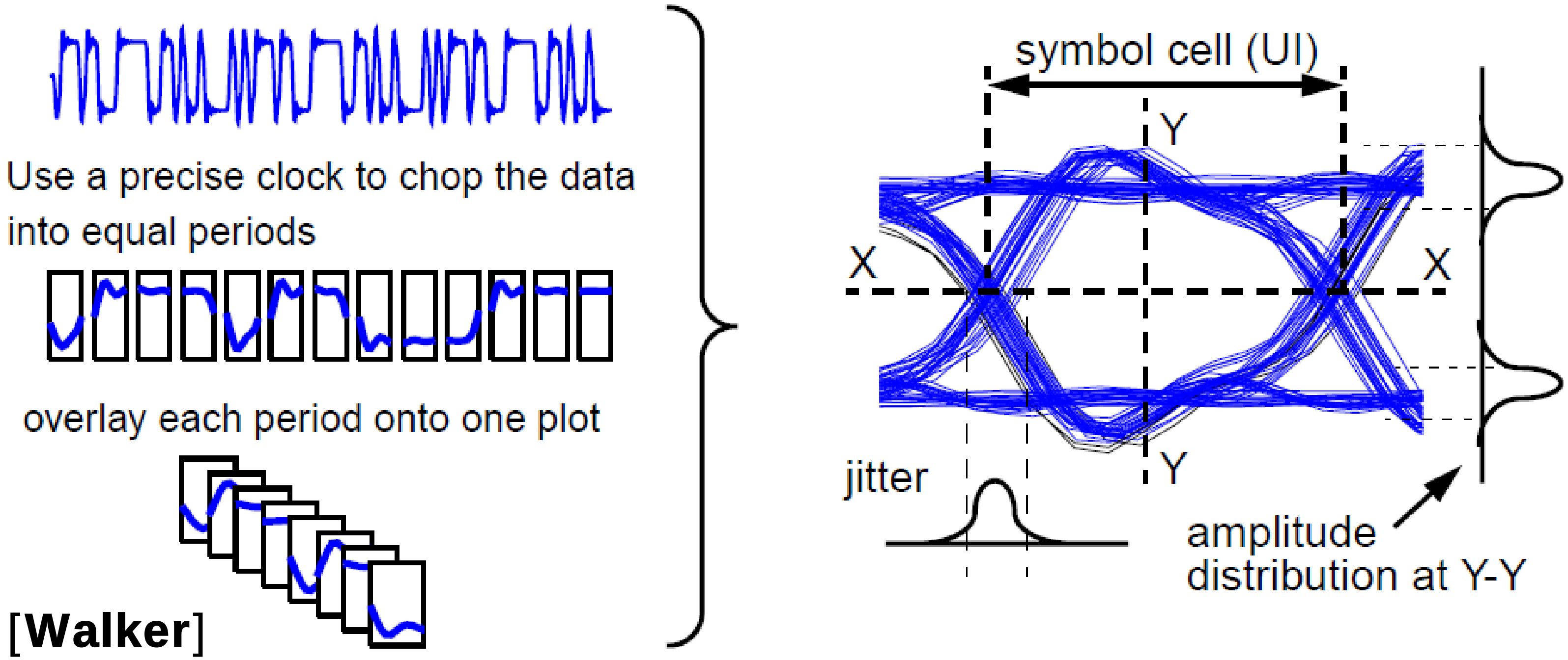


Channel Transient Response

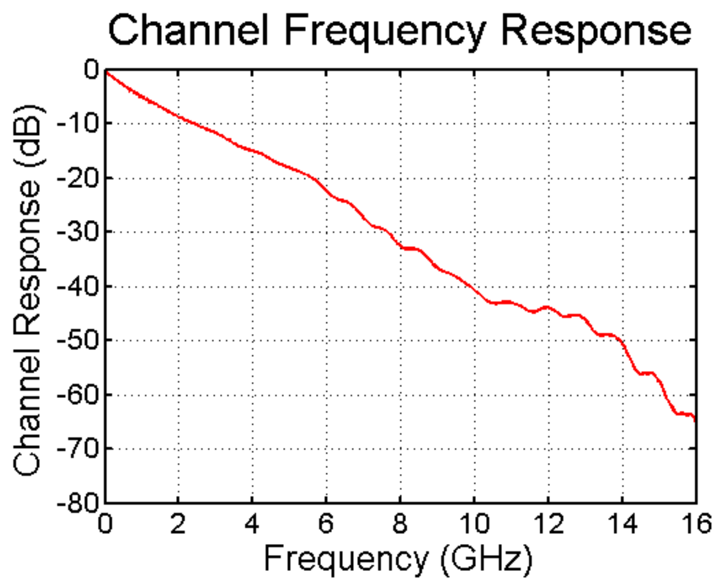


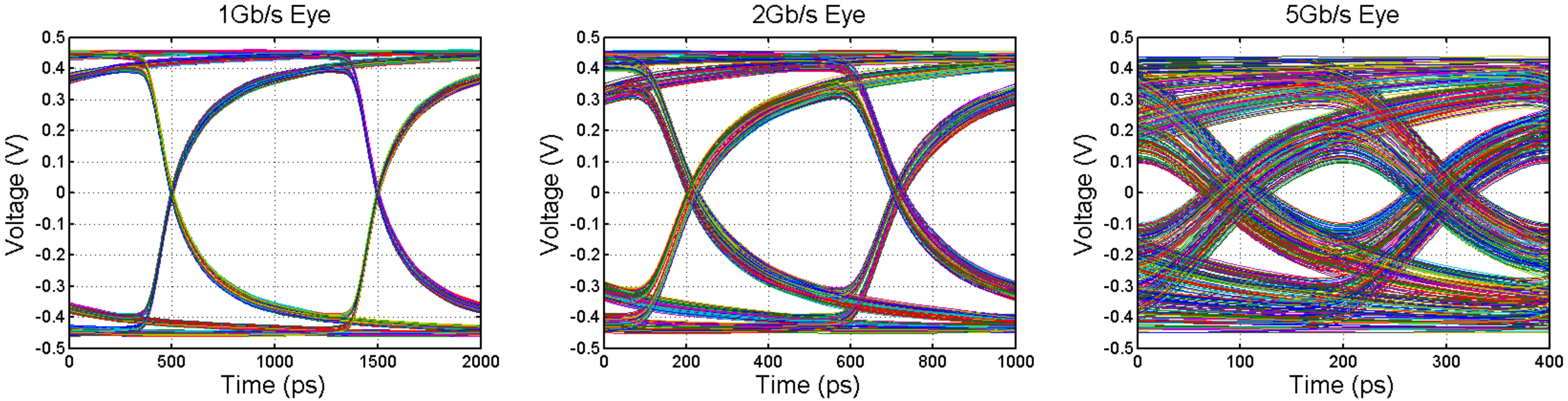
Eye Diagrams



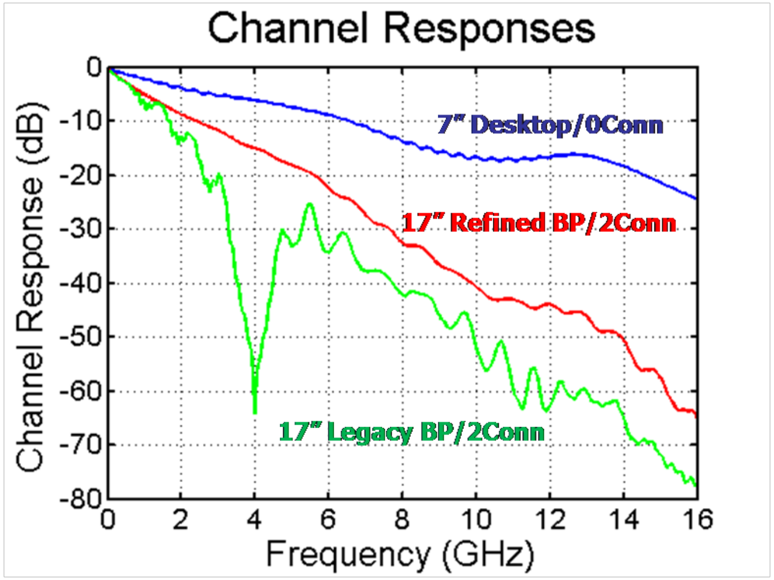


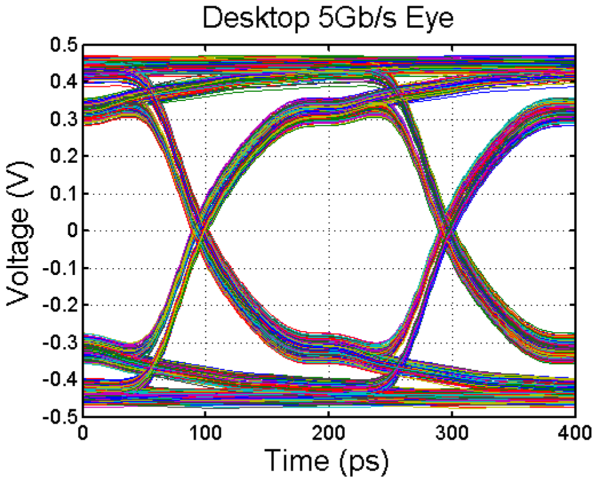
Eye Diagrams vs Data Rate

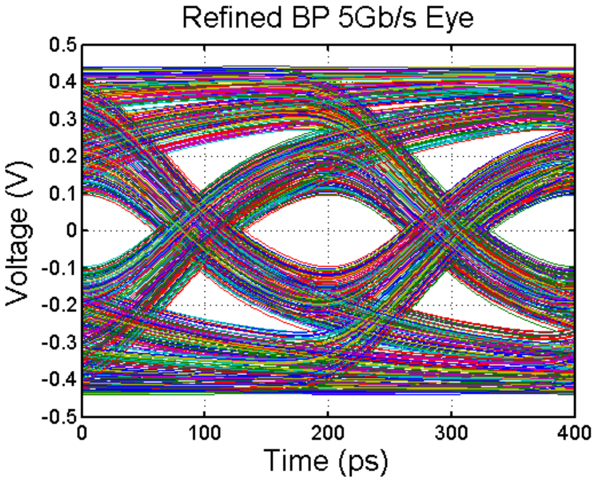


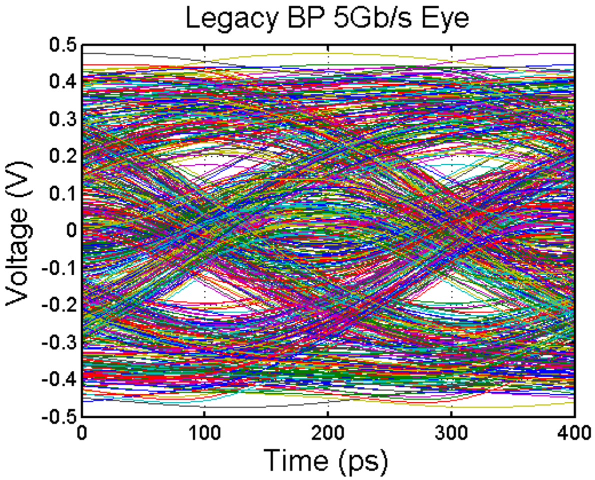


Eye Diagrams vs Channel



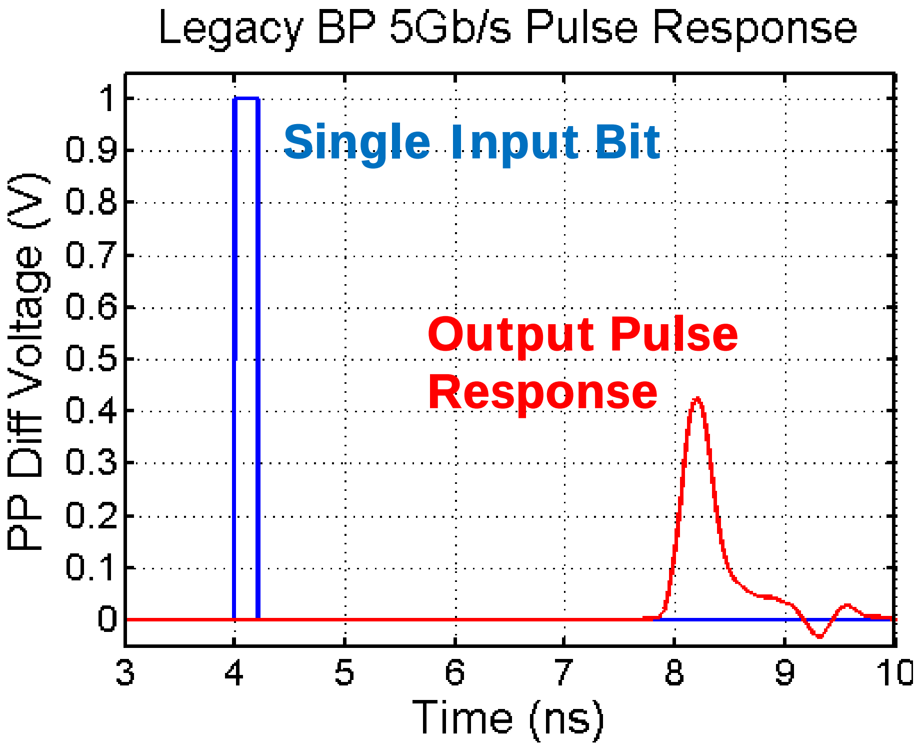


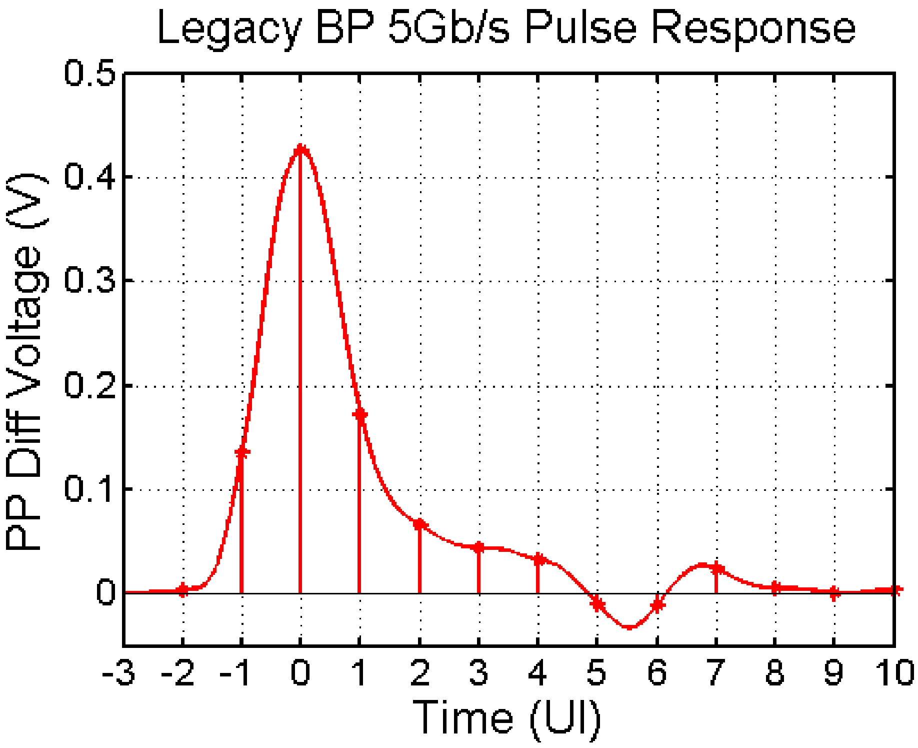




Inter-Symbol Interference (ISI)

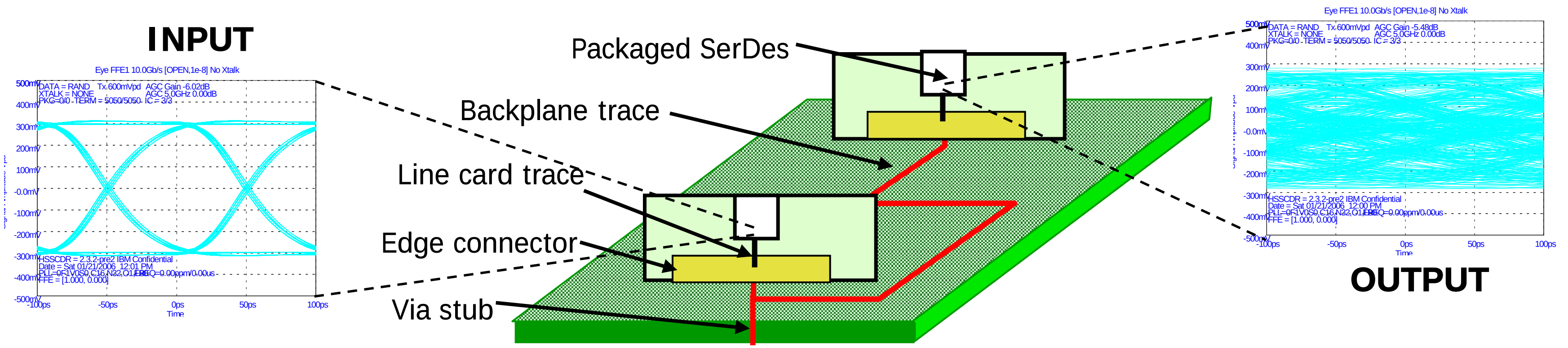
- Previous bits residual state can distort the current bit, resulting in inter-symbol interference (ISI)
- ISI is caused by
  - Reflections, Channel resonances, Channel loss (dispersion)





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