ECE 621
Signaling & Synchronization
Fall 2020

Topic 2
I/O Channel Characteristics

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ICL

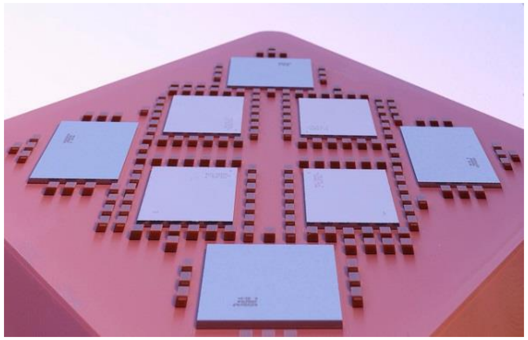
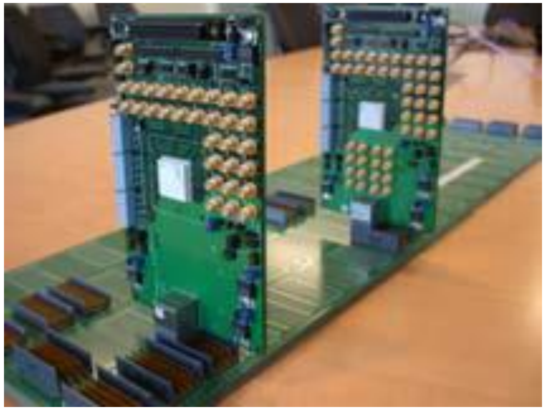
(Courtesy of S. Pamarti – UCLA, S. Palermo – TAMU, E. Alon – UCB, and W. Dally – Stanford)

Outline

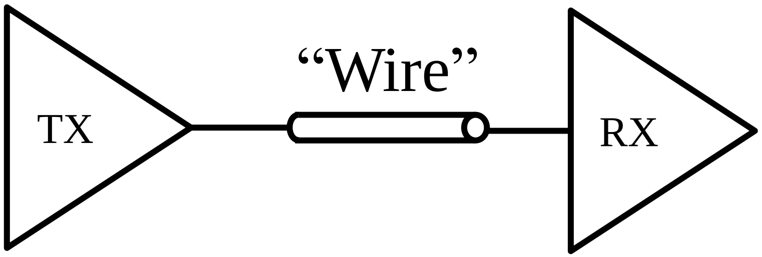
- **Channel Components**
  - Wires (PCB traces, Co-axial cables, twisted pairs, ..etc.)
  - IC Packages
  - Vias
  - Connectors
- **Channel Impairments**
  - Limited Bandwidth - Loss
  - Reflections
  - Cross-Talk
- **Channel Representations**
  - Impulse Response
  - S-Parameters
  - Eye Diagram
  - Time-Domain Reflectometry (TDR)

Chip-to-Chip Communication Channels

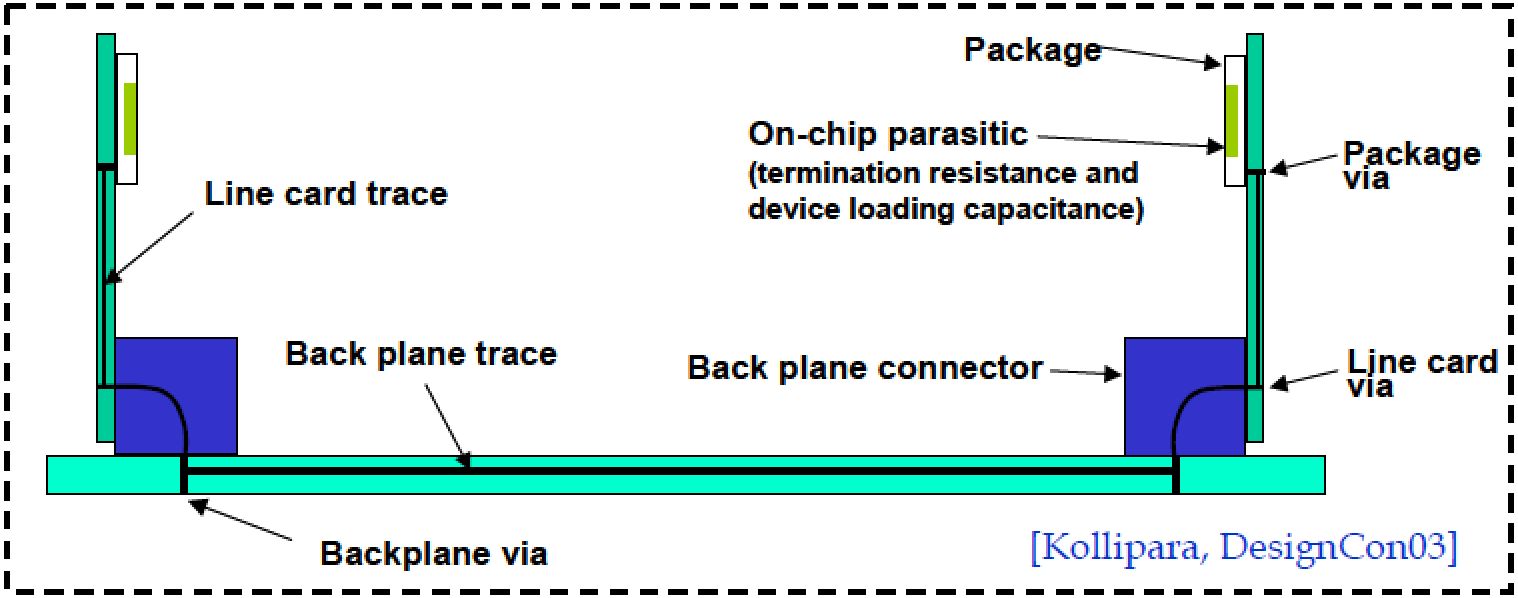
- **Short Range**
  - ICs on the same PCB
  - The PCB could be within a multi-chip module
- **Long Range**
  - ICs on different PCBs
  - PCBs connected through another board or a co-axial cable

Channel Complexity

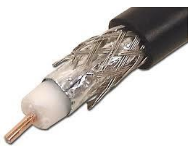


Neglected for low data-rates, short lengths and simple architecture
Otherwise



Example Wires

Cables



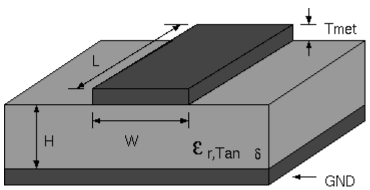
Coaxial

Flat or Ribbon

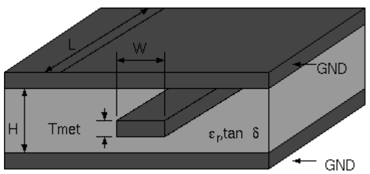
Twisted Pair

Flex Circuit

PCB Traces



Micro-strip



Strip-line

TABLE 2-2 **American Wire Gauges and Their Properties**

Gauge (AWG)	Wire Diameter (mils)	Wire Diameter (mm)	DC Resistance ($\times 10^{-3}$ Ω/m)[a]	Maximum Current (A)	Attenuation at 1 GHz (dB/m)
000	409.6	10.404	0.203	175	0.02
0	324.9	8.252	0.322	125	0.03
4	204.3	5.189	0.815	70	0.04
6	162.0	4.115	1.297	50	0.06
8	128.5	3.264	2.061	35	0.07
10	101.9	2.588	3.277	25	0.09
12	80.81	2.053	5.210	20	0.11
14	64.08	1.628	8.268	15	0.14
18	40.30	1.024	20.95	5	0.22
20	31.96	0.8118	33.31	3	0.28
22	25.35	0.6439	52.95		0.35
24	20.10	0.5105	84.22		0.45
28	12.64	0.3211	213.0		0.71
30	10.03	0.2548	338.2		0.90
32	7.950	0.2019	538.4		1.13
34	6.310	0.1602	854.6		1.42

[a]For annealed copper at 20°C.
[b]Skin-effect frequency.

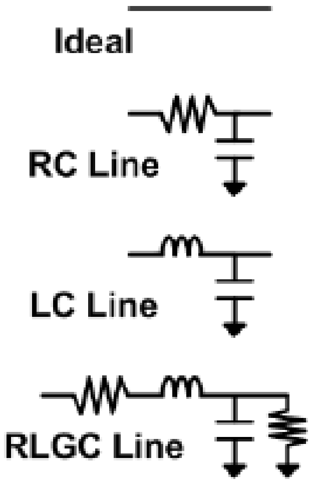
$$AWG = -10\ln\left(\frac{A}{A_0}\right)$$

[Dally]

Type	W	R	C	L
On chip	0.6µm	150kΩ/m	200pf/m	600nH/m
PC Board	150µm	5Ω/m	100pf/m	300nH/m
24AWG pair	511µm	0.08Ω/m	40pf/m	400nH/m

Wire Models

- **Model Types**
  - Ideal
  - Lumped C, R, L
  - RC transmission line
  - LC transmission line
  - RLGC transmission line

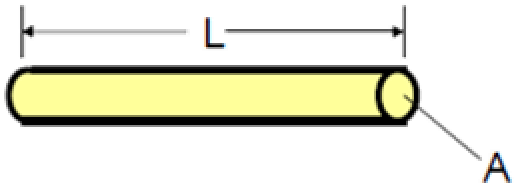


- **Condition for LC or RLGC model (vs RC)**

$$f_0 \geq \frac{R}{2\pi L}$$

Basic Electrical Properties of Wires

- **Resistance**

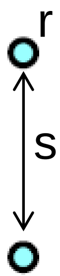


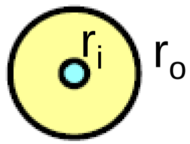
$$R = \frac{\rho L}{A}$$

Material	ρ (nΩ-m)
Ag	16
Cu	17
Au	22
Al	27

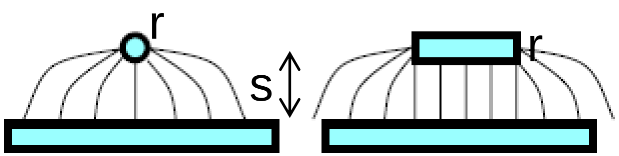
- **Capacitance**

$$C = \frac{\pi\varepsilon}{\log\left(\frac{s}{r}\right)}$$





$$C = \frac{2\pi\varepsilon}{\log\left(\frac{r_o}{r_i}\right)}$$



$$\frac{2\pi\varepsilon}{\log\left(2s/r\right)}$$

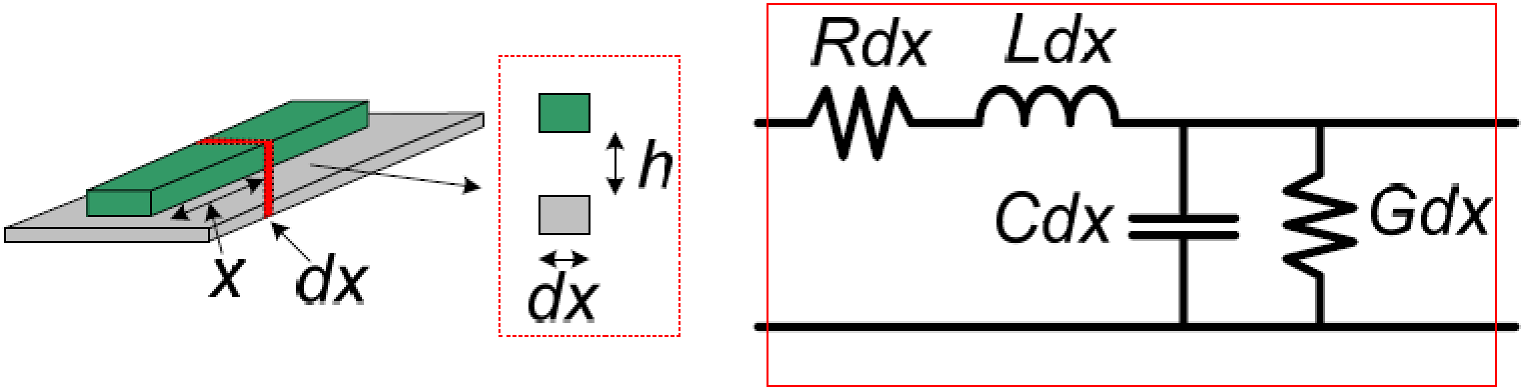
$$C = \frac{w\varepsilon}{s} + \frac{2\pi\varepsilon}{\log\left(4s/r\right)}$$

|| Plate + Fringing

- **Inductance**

$$L = \frac{\varepsilon\mu}{C}$$

Wires/Cables as Transmission Lines



- **Electromagnetic field propagation**
- **Per unit length,**
  - R, L, and C are the resistance, inductance, and capacitance of the conductor structure
  - G represents loss in the dielectric between the conductors
- **For a lossless transmission line, R = 0 and G = 0**

IC Package Types

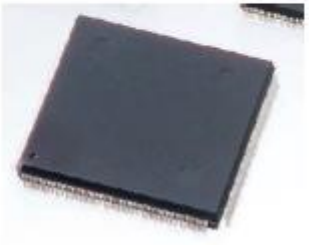
- **Package needed to protect chips physically and thermally.**
- **Packaging pin count did not increase as on-chip aggregate bandwidth.**
  - I/O constrained design
  - Higher data rate per pin
- **Attachment to board**
  - Through-hole

  - Surface-mount

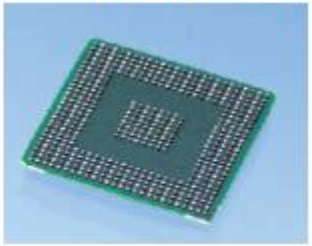
Package Type	Pin Count
Small Outline Package (SOP)	8 – 56
Quad Flat Package (QFP)	64 - 304
Plastic Ball Grid Array (PBGA)	256 - 420
Enhanced Ball Grid Array (EBGA)	352 - 896
Flip Chip Ball Grid Array (FC-BGA)	1089 - 2116

SOP

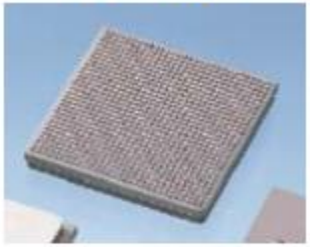
QFP



PBGA



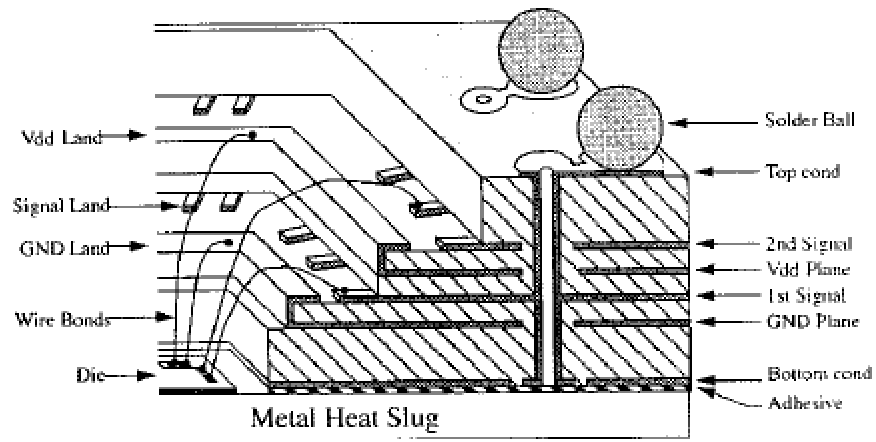
FC-BGA

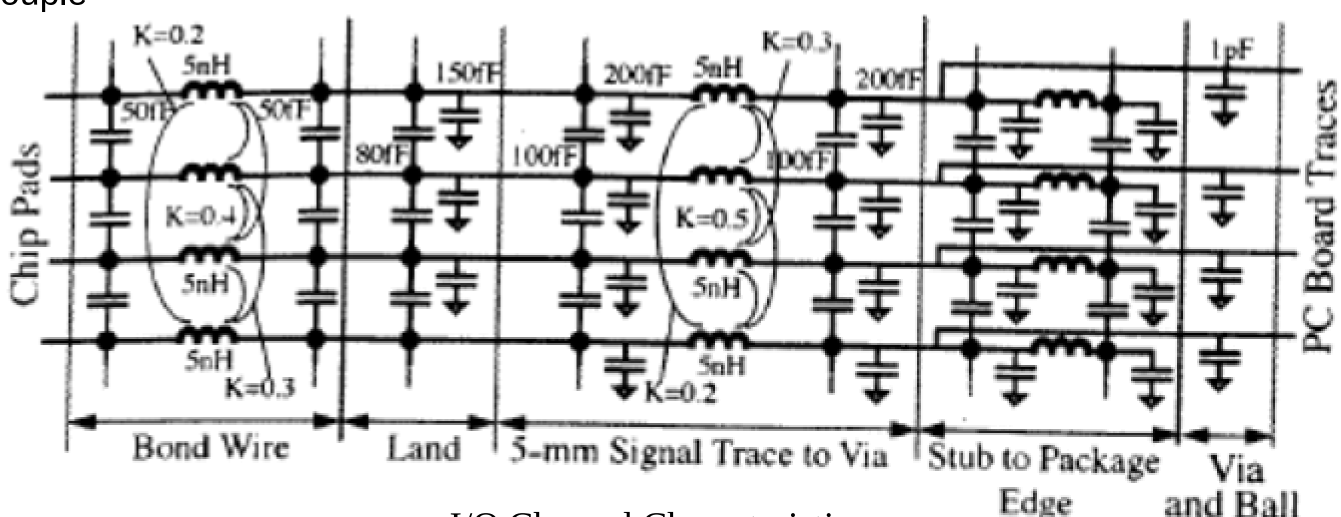


[Fujitsu]

IC Package Model

- **Bondwires**
  - L ~ 1 nH/mm
  - Mutual inductance
  - C_{couple} ~ 20 fF/mm
- **Package traces**
  - L ~ 0.7 – 1 nH/mm
  - Mutual inductance
  - C_{layer} ~ 80 – 90 fF/mm
  - C_{couple} ~ 40 fF/mm





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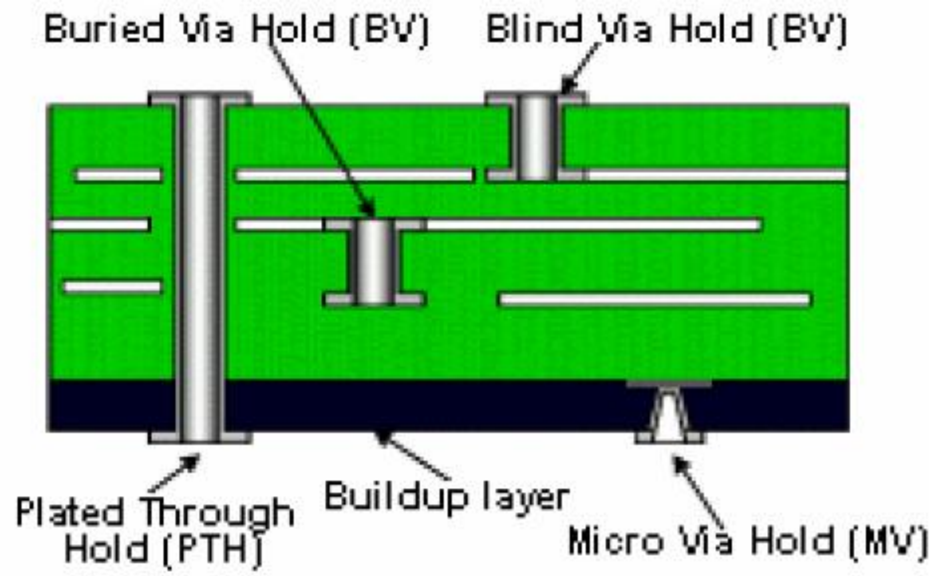
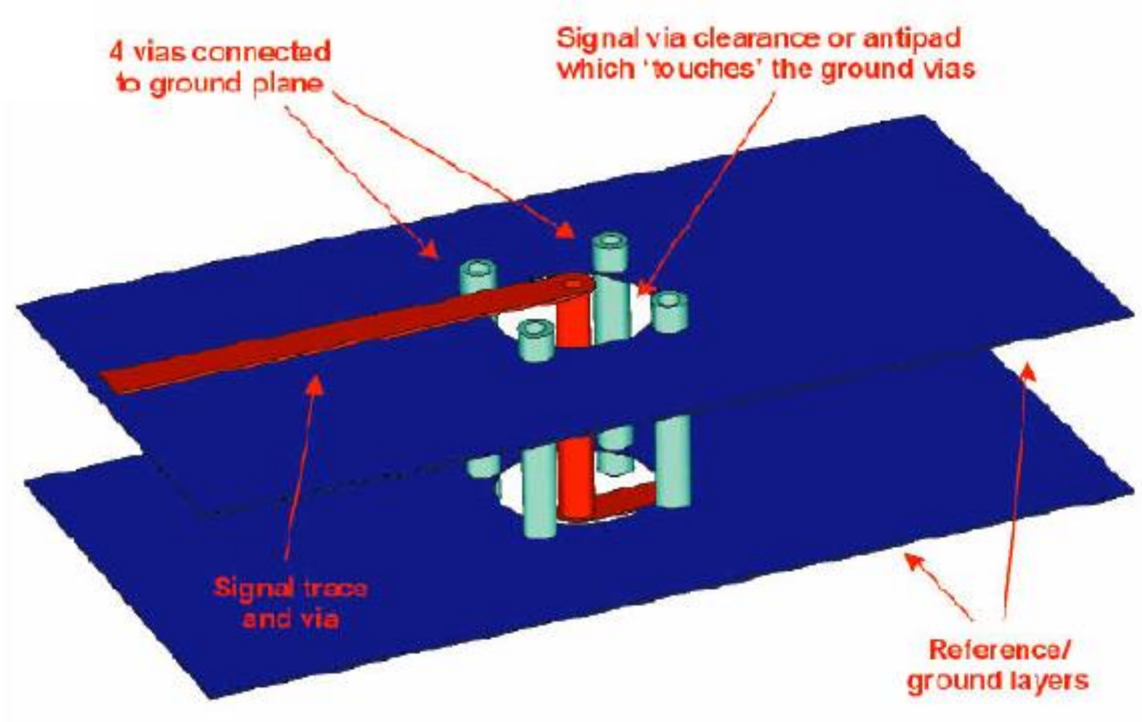
PCB Vias



- **Made by drilling a hole through the board which is plated with copper**
  - Pads connect to signal layers/traces.
  - Clearance holes avoid power planes.
- **Blind vias are better than through vias with respect to signal integrity as they are better impedance-controlled.**

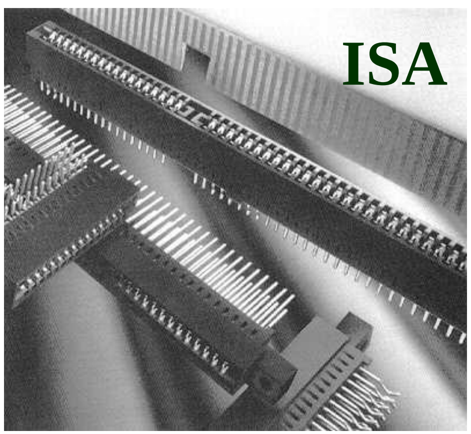
Coaxial-Type Vias

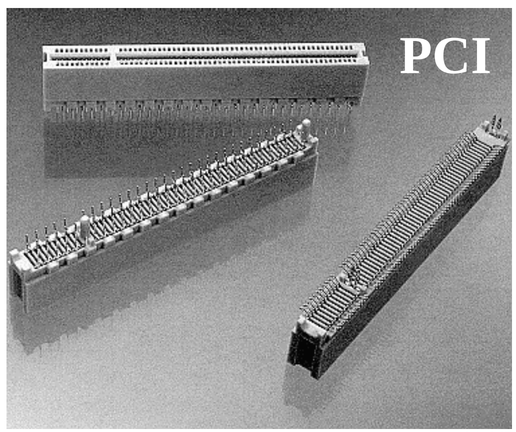


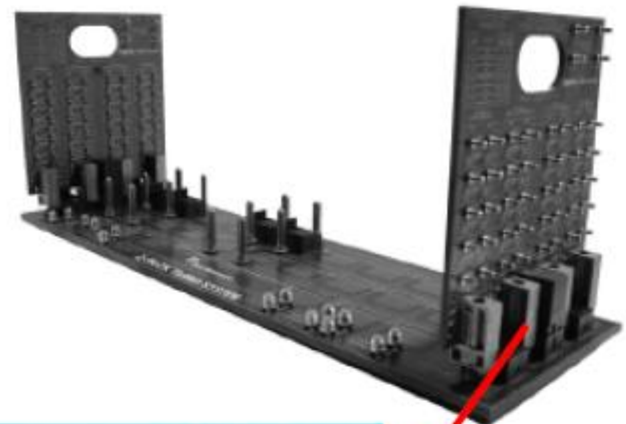
- **Extra vias for ground connections**
- **Spacing used for impedance control**

Connectors

- **Connectors are used to transfer signals from board to board.**
- **Typical differential pair density ranges between 16 – 32 pairs/10mm.**







[Tyco]

Common Connectors

- **Typical frequencies where attenuation gets to 1 dB.**

Connector type	Frequency Range
N-type (Neil)	11-18GHz
APC (sexless)	<18GHz
SMA (2.4mm air-gap)	<26GHz (26-50GHz)
SMB (snap on)	<3GHz
BNC (baby Neil)	<500MHz
D-Connector (RJ connectors)	<100MHz
Ribbon	<20MHz

Outline

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  - Impulse Response
  - S-Parameters
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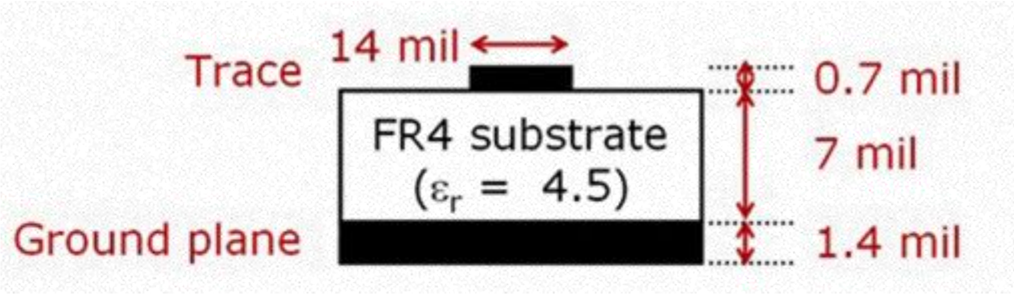
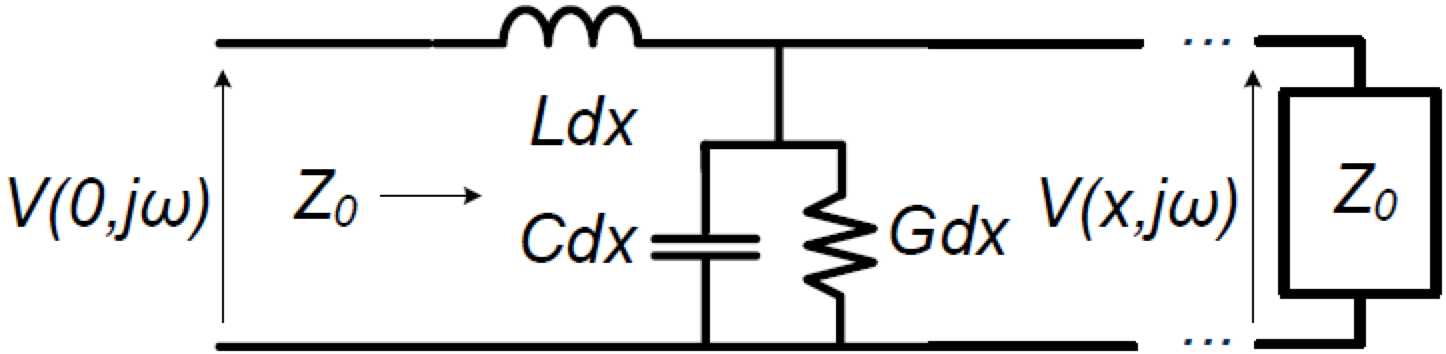
Channel Characteristics



- **Flight time typically exceeds bit period in Gb/s signaling**
- **Consider 5 Gb/s signaling over a 6´´ PCB trace**
  - Flight time is ~ 1ns. Bit period (1 UI) is 200 ps.
  - In any instant, five bits traveling on the channel.
- **Channel cannot be considered lumped.**
- **Trace is modeled as transmission line.**
- **Effects include signal attenuation, reflection and cross-talk.**

Loss Mechanisms: Dielectric Loss (1)



- **The parallel conductance causes signal attenuation.**

$$\gamma(j\omega) = j\omega\sqrt{LC}\sqrt{\left(1 - j\frac{G}{\omega C}\right)} \approx +\frac{1}{2}\underbrace{\left(\frac{G}{\omega C}\right)}_{\tan\delta}\omega\sqrt{LC} + j\omega\sqrt{LC}$$

Loss tangent

- **The loss increases with transmission wire length.**

$$\left|H_D(x, j\omega)\right| \triangleq \left|\frac{V(x, j\omega)}{V(0, j\omega)}\right| = \left|e^{-\gamma(j\omega)x}\right| = e^{-\alpha(\omega)x} = e^{-\frac{1}{2}x\omega\sqrt{LC}\tan\delta}$$

Loss Mechanisms: Dielectric Loss (2)

- **Loss tangent can be approximated as a constant**
  - Not true, but a reasonable approximation

$$\text{Dielectric loss} = -20\log_{10}\left|H_D(j2\pi f)\right|$$

$$= \left(20\pi f\sqrt{LC}\tan\delta\ \log_{10} e\right)x\ \ \text{dB}$$

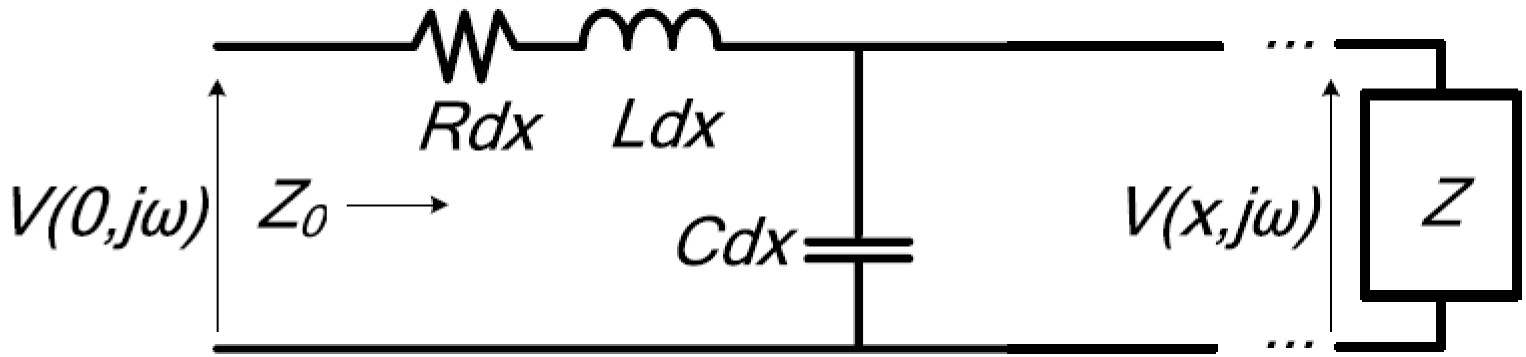
$$= \left(20\pi f\frac{\sqrt{\varepsilon_r}}{c}\tan\delta\log_{10} e\right)\ \ \text{dB/meter}$$

$$Note: \sqrt{LC} = \frac{\sqrt{\varepsilon_r\mu_r}}{c};\quad \mu_r = 1\ \text{usually}$$

Material	tan δ
FR4	0.035
Polyimide	0.025
GETEK	0.010
Teflon	0.001

- **Loss increases linearly with wire length.**
- **Loss rolls off as 20 dB/decade (like a 1st order filter past its bandwidth)**

Loss Mechanisms: Conductive Loss (1)



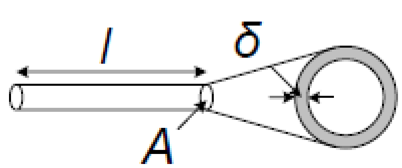
- **Finite conductivity of the conductors causes loss.**

$$\gamma(j\omega) = j\omega\sqrt{LC}\sqrt{\left(1 - j\frac{R}{\omega L}\right)} \approx +\frac{1}{2}\frac{R}{Z_0} + j\omega\sqrt{LC}$$

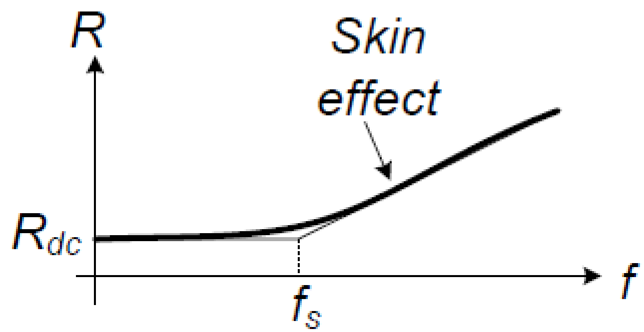
- **Again, loss increases with transmission wire length.**

$$\left|H_C(x, j\omega)\right| = e^{-\alpha(\omega)x} = e^{-\frac{1}{2}\frac{R}{Z_0}x}$$

Loss Mechanisms: Conductive Loss (2)



$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

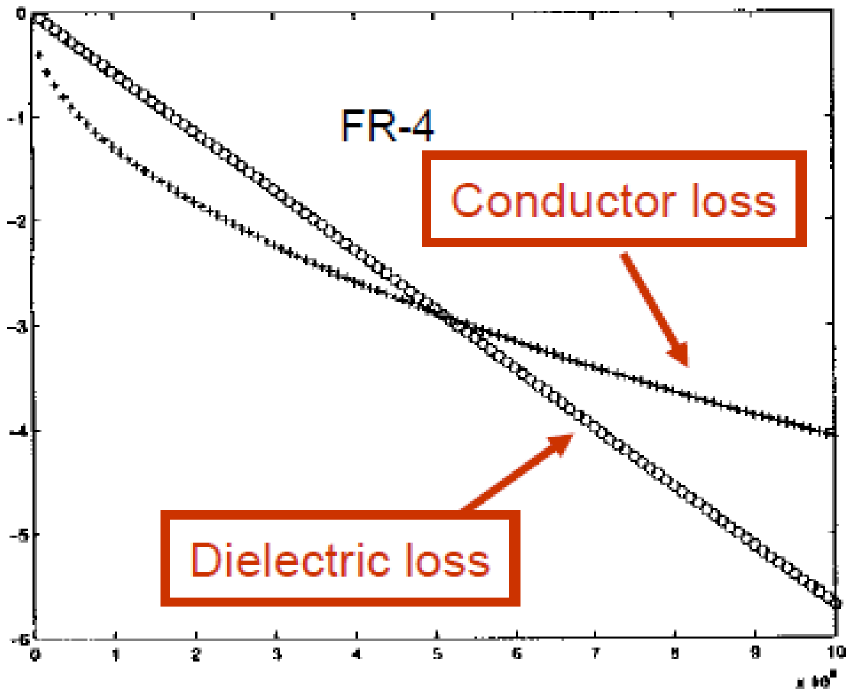


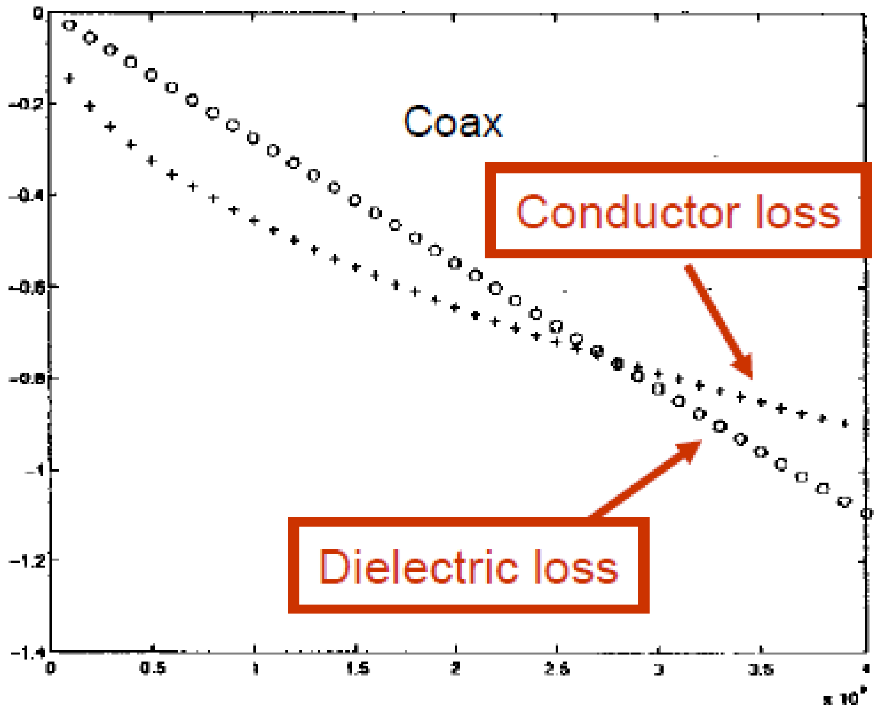
- **Conductivity decreases at high frequencies.**
  - Called skin effect.
  - Current flows close to the surface in a thin layer.
  - Skin depth, δ, is the depth where the current has fallen to e^{-1}.
  - f_s is the frequency where δ is equal to r or $h/2$.

$$\text{DC resistive loss} = 10\frac{R_{dc}}{Z_0}\log_{10} e \quad \text{dB/meter}$$

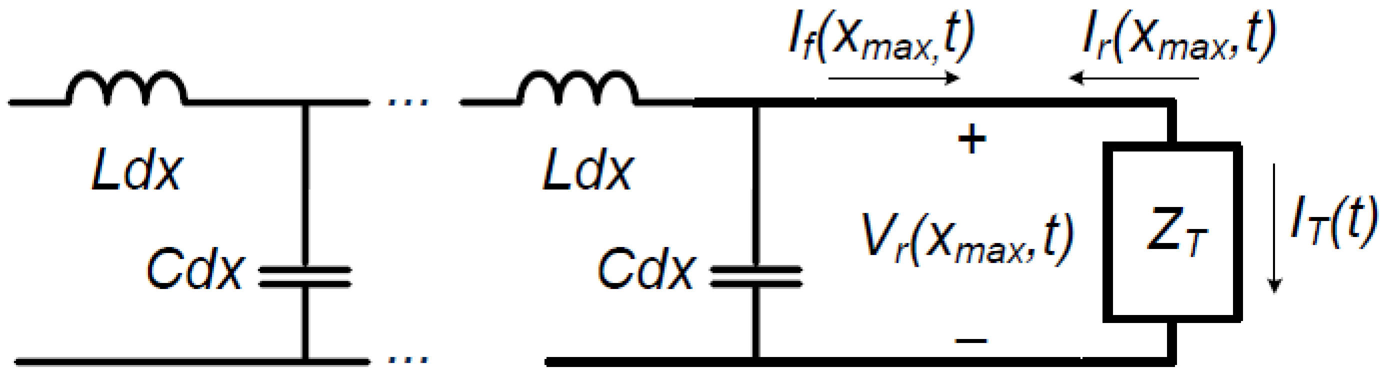
$$\text{Skin effect loss} = 10\frac{R_{dc}}{Z_0}\left(\frac{f}{f_S}\right)^{1/2}\log_{10} e \quad \text{dB/meter}$$

Losses: Cable vs. PCB Trace





Reflection

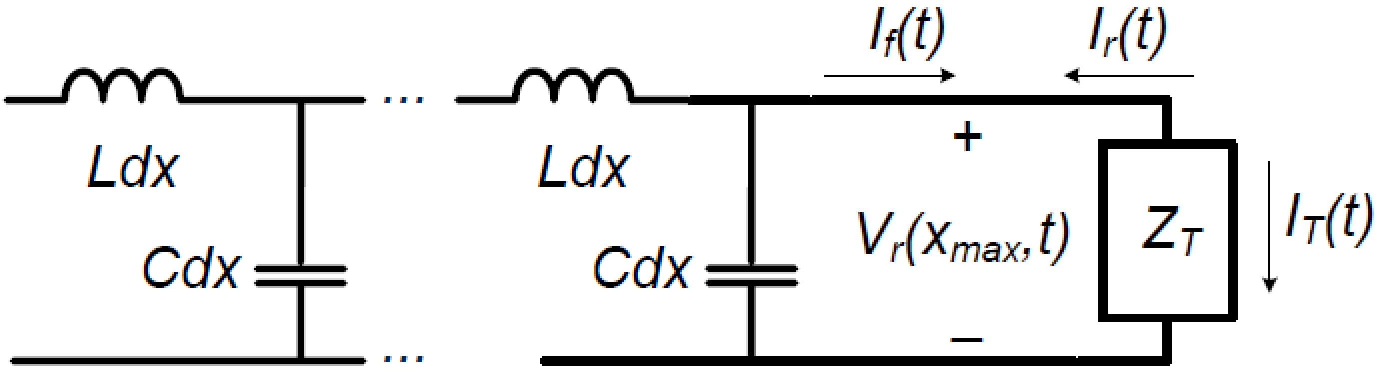


- **Suppose T-line is terminated by $Z_T \neq Z_0$.**
- **Forward wave will launch a backward traveling wave.**
  - Backward wave starts at Z_T with the following time waveform

$$V_r(x_{\max}, t) = \Gamma V_f(x_{\max}, t), \text{ where } \Gamma = \frac{Z_T - Z_0}{Z_T + Z_0}$$

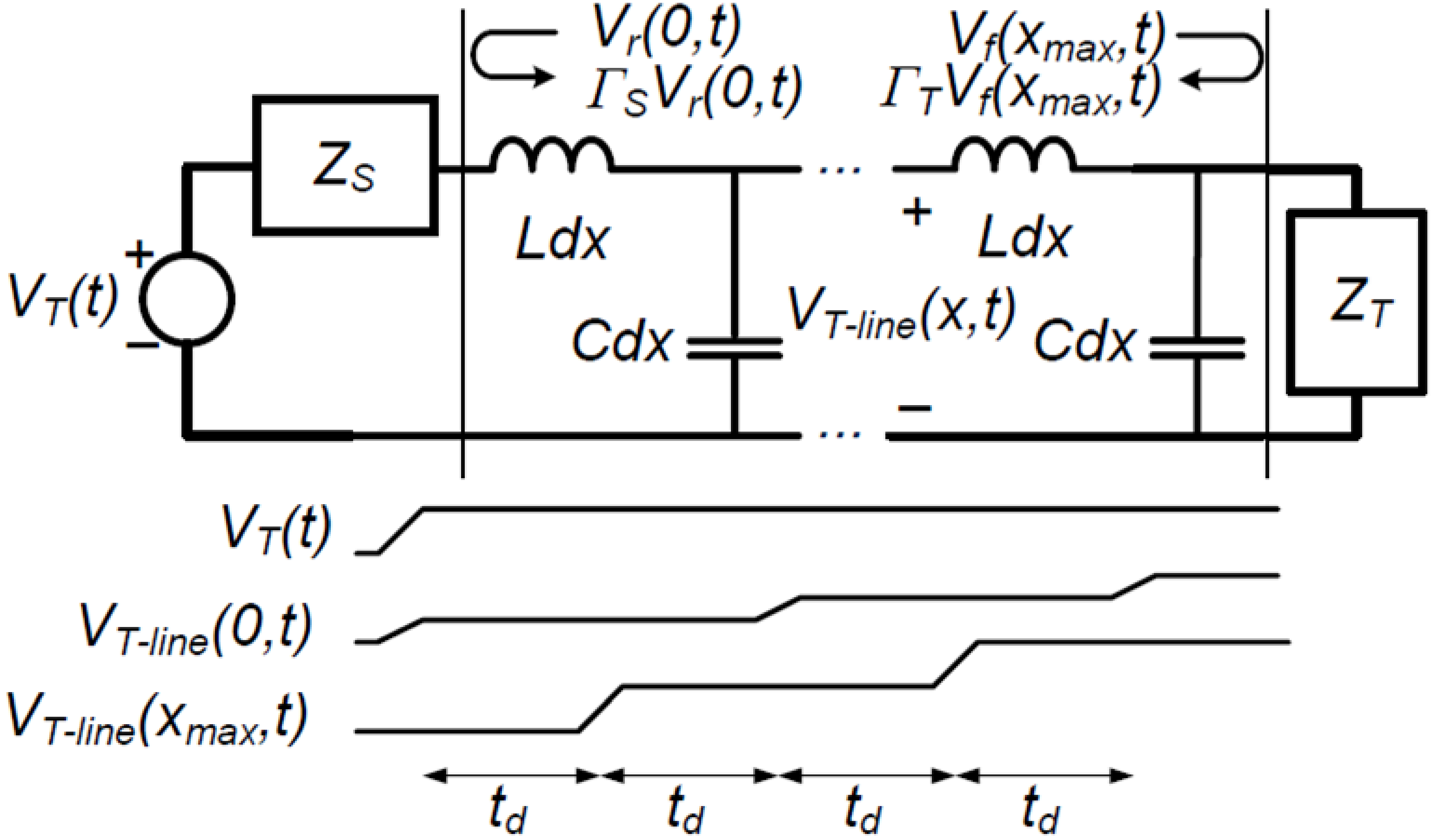
- **The reflected current is also given by the reflection coefficient, Γ** $I_r(x_{\max}, t) = \Gamma I_f(x_{\max}, t)$

Termination Examples



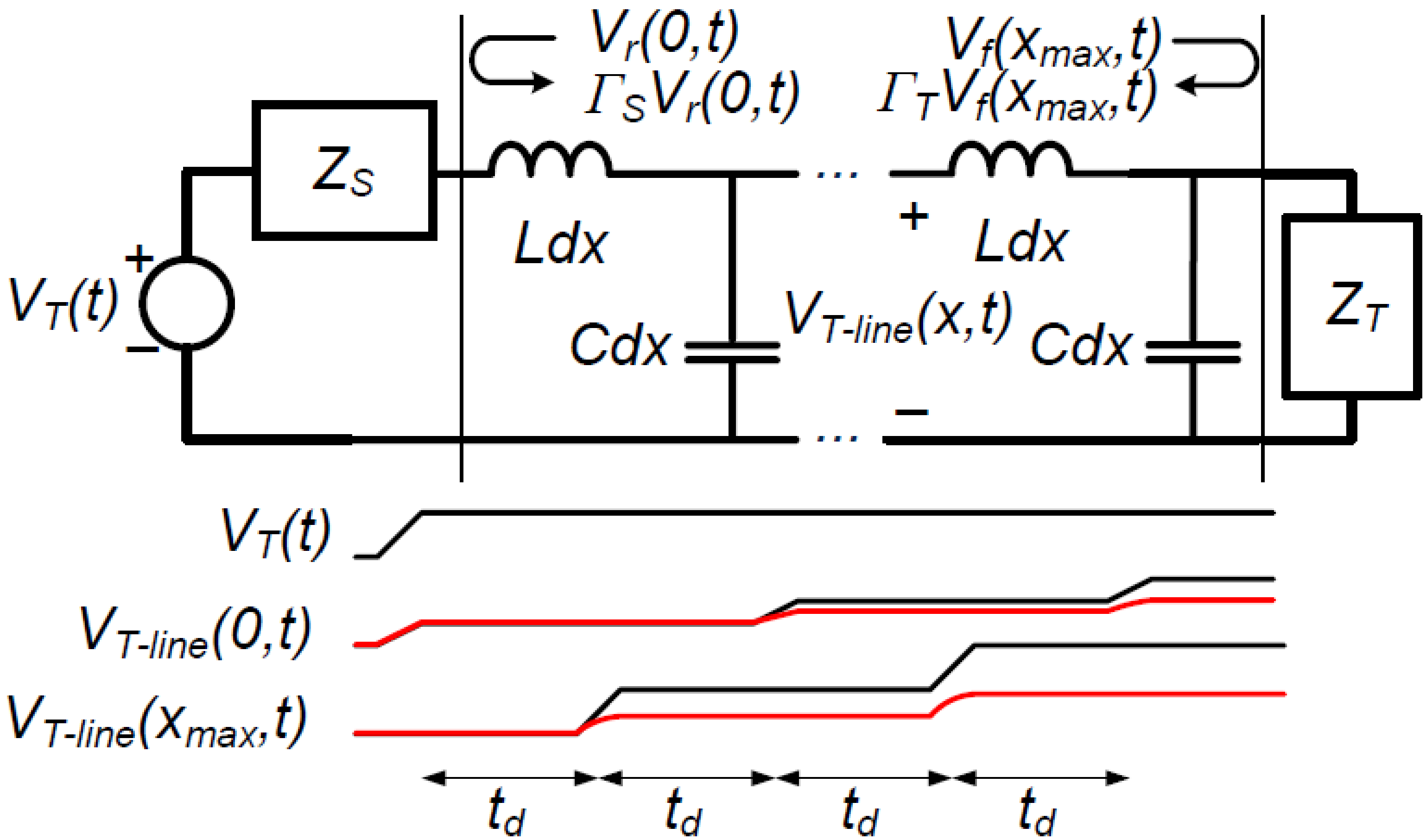
- **The voltage drop at Z_T is** $V_{T\text{-}line}(x_{max},t) = V_f(x_{max},t) + V_r(x_{max},t)$
- **If $Z_T = Z_0$,** $V_r(x_{max},t) = 0$
  - $V_{T\text{-}line}(x_{max},t) = V_f(x_{max},t) + V_r(x_{max},t) = V_f(x_{max},t)$
  - Like an infinitely-long TL
- **If $Z_T = 0$,** $V_r(x_{max},t) = -1 * V_f(x_{max},t)$
  - $V_{T\text{-}line}(x_{max},t) = V_f(x_{max},t) + V_r(x_{max},t) = 0$
- **If $Z_T = \infty$,** $V_r(x_{max},t) = V_f(x_{max},t)$
  - $V_{T\text{-}line}(x_{max},t) = V_f(x_{max},t) + V_r(x_{max},t) = 2 * V_f(x_{max},t)$

TL Wave Reflections



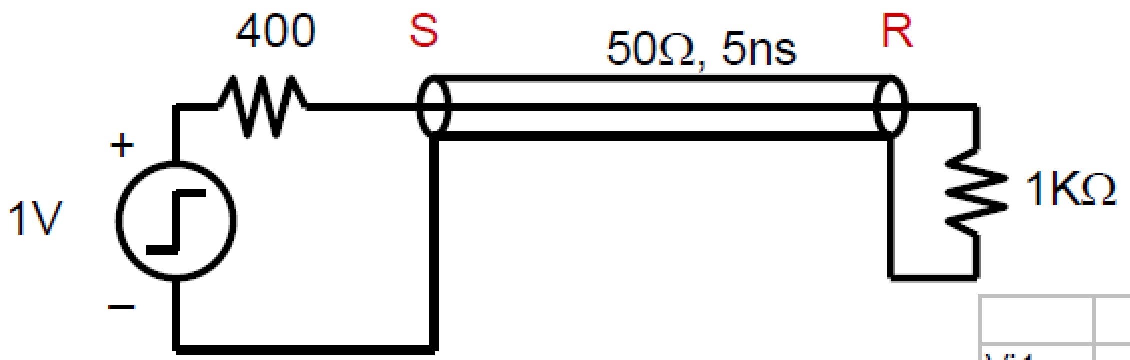
- **Multiple reflections are caused by the forward and backward waves reflecting at the source and load boundaries.**

Lossy TL Wave Reflections



- **Loss in TLs reduce the effects of reflections significantly**

Numerical Example of TL Reflections

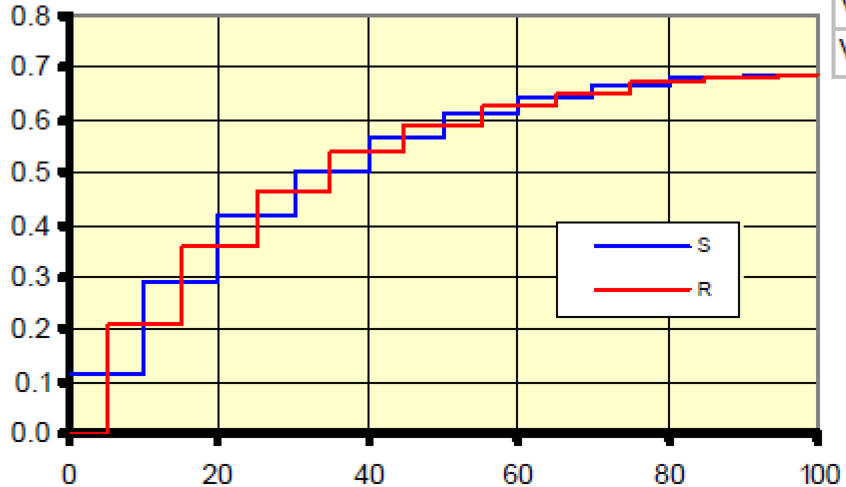


$$V_i = 1V\left(\frac{50}{400+50}\right) = 0.111V$$

$$k_{rS} = \frac{400-50}{400+50} = 0.778$$

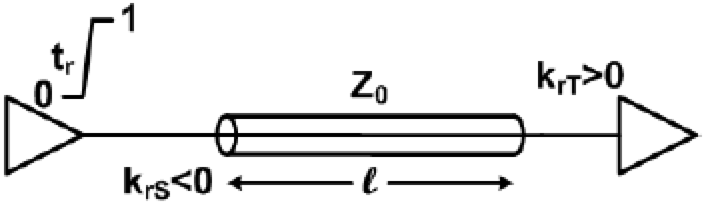
$$k_{rR} = \frac{1000-50}{1000+50} = 0.905$$

	Vwave	Vline	t
Vi1	0.111	0.111	0
Vr1	0.101	0.212	5
Vi2	0.078	0.290	10
Vr2	0.071	0.361	15
Vi3	0.055	0.416	20
Vr3	0.050	0.465	25
Vi4	0.039	0.504	30
Vr4	0.035	0.539	35
Vi5	0.027	0.566	40



Termination Schemes (1)

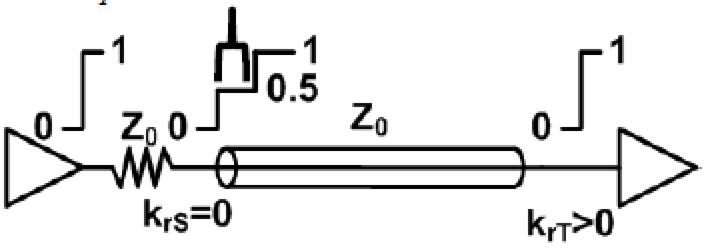
- **No Termination**
  - Little to absorb line energy
  - Can generate oscillating waveform
  - Line must be very short relative to signal transition time (n = 4 - 6)
  - Limited off-chip use



$$t_r > nT_{round-trip} = 2nl\sqrt{LC}$$

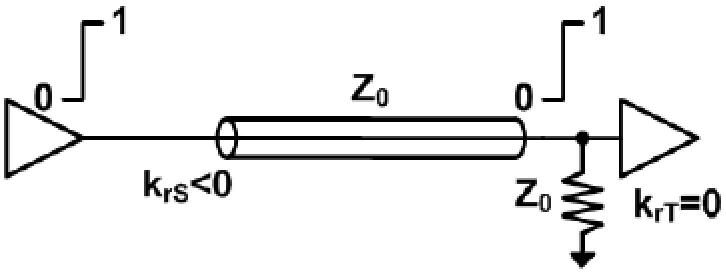
$$t_{porch} \cong 2l\sqrt{LC}$$

- **Source Termination**
  - Source output takes 2 steps up
  - Used in moderate speed point-to-point connections

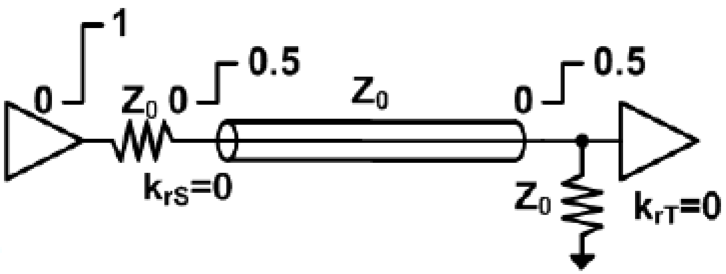


Termination Schemes (2)

- **Receiver Termination**
  - No reflection from receiver
  - Watch out for intermediate impedance discontinuities
  - Little to absorb reflections at driver

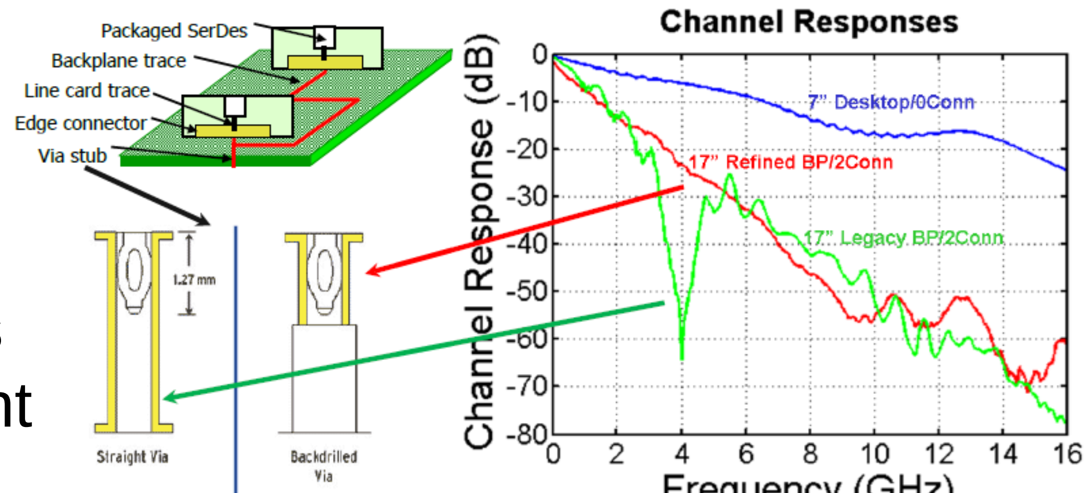


- **Double Termination**
  - Best configuration for minimum reflections
  - Get half the swing relative to single termination
  - Most common termination scheme for high performance serial links



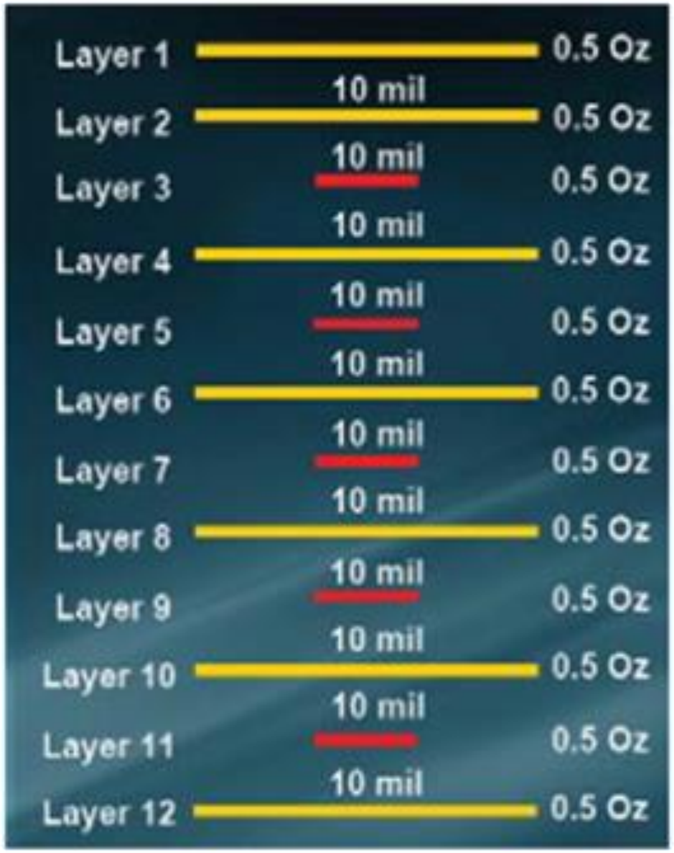
Sources of Reflections

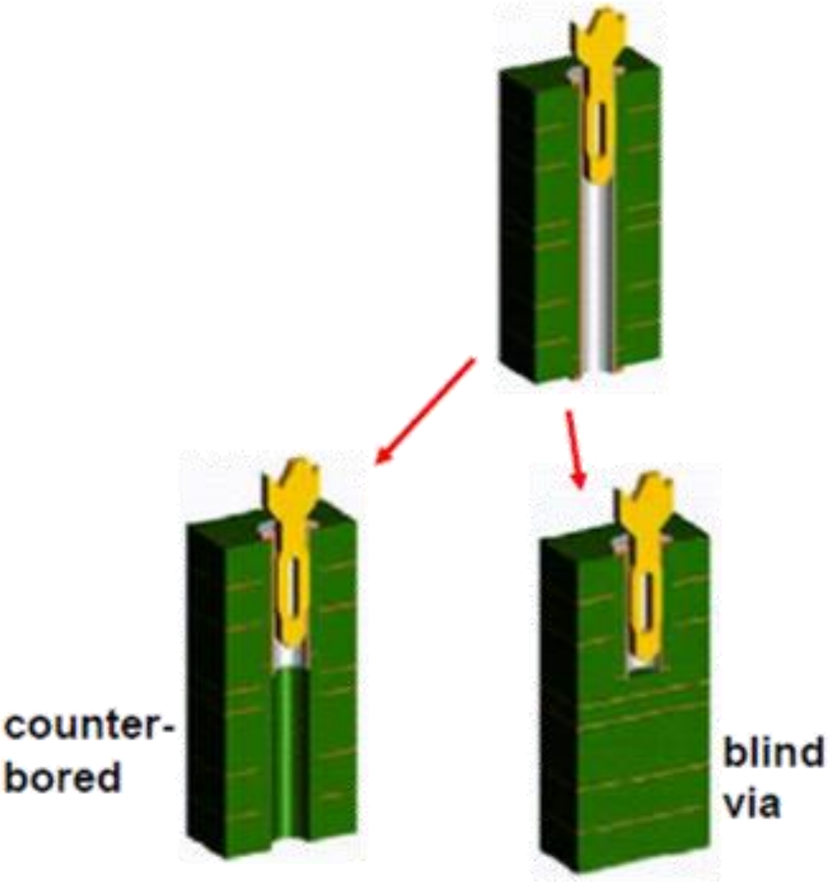
- **Z-Discontinuities**
  - PCB Z mismatch
  - Connector Z mismatch
  - Vias Z mismatch
  - Device parasitics
- **Example Via Stubs**
  - Legacy backplanes have default straight vias
  - Refined backplanes have expensive backdrilled vias



Minimizing Via Stubs

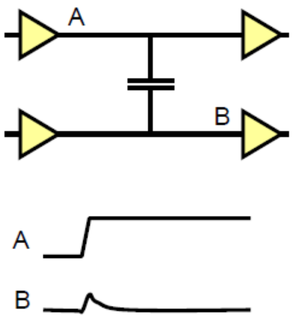
- Thinner PCBs
- Better vias
- But are expensive solutions

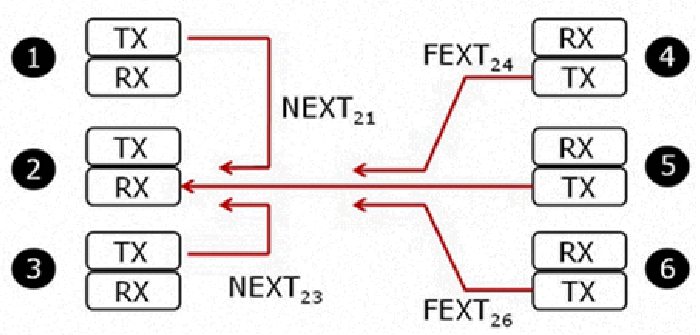


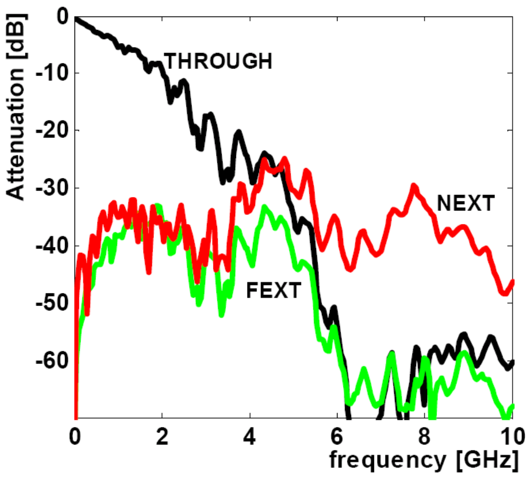


Cross-Talk

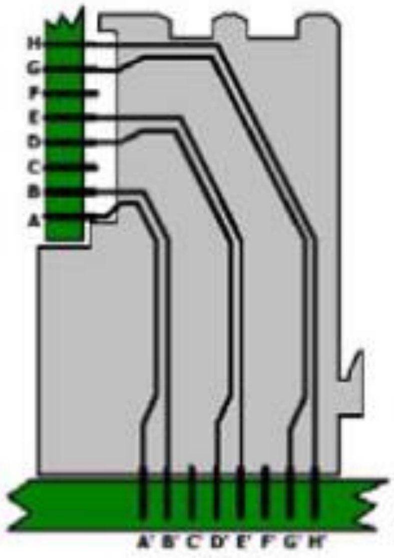
- Noise induced by one signal that interferes with another signal
- Capacitive coupling between on-chip lines
- Capacitive and inductive coupling between off-chip lines
- Coupling over shared signal returns
- Near end cross-talk (NEXT) and far end cross-talk (FEXT)
- Disturbances on both voltage and current
- Can exceed signal at high frequencies.







Connectors and Cross-Talk

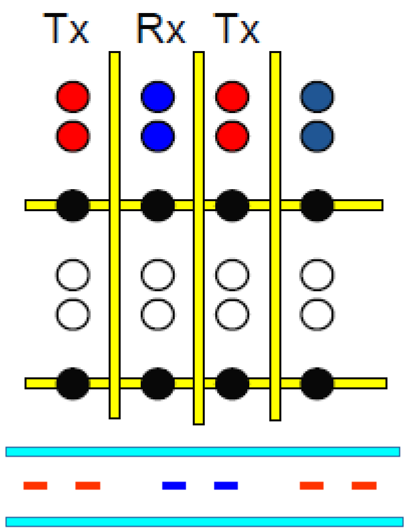


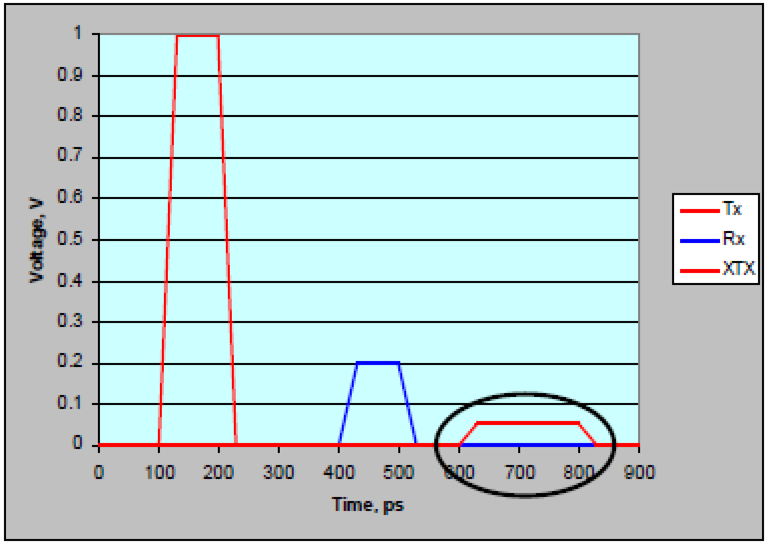
HSD 8 Propagation Delay Calculated from length	
H → H'	200ps
G → G'	194ps
E → E'	151ps
D → D'	145ps
B → B'	108ps
A → A'	99ps

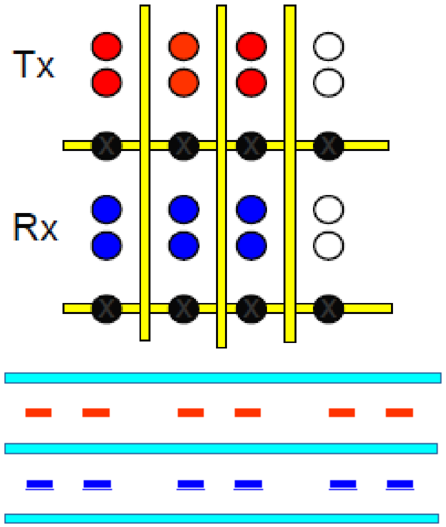
	NEXT	FEXT
	55 ps (20-80%)	55 ps (20-80%)
	80ps (10-90%)	80ps (10-90%)
AB	4.4%	3.7%
DF	3.3%	2.6%
GH	3.3%	2.6%
JK	4.3%	3.5%

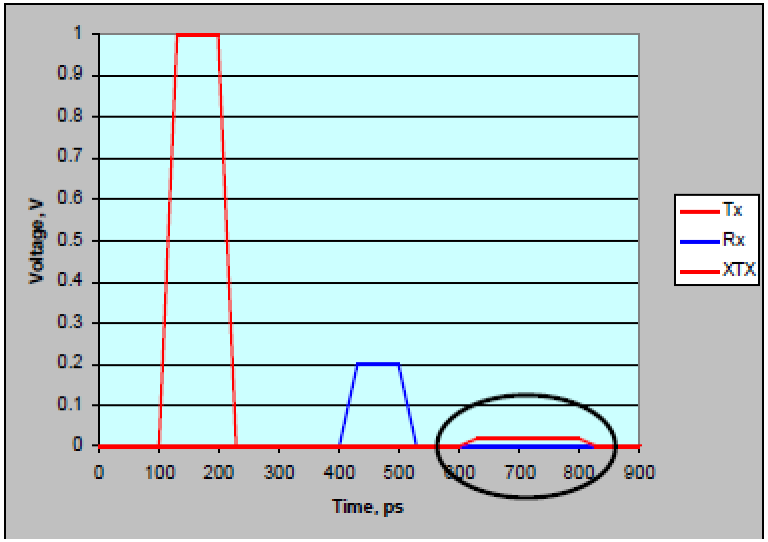
- **Connectors have tight footprint constraints.**
- **Hard to match pairs.**
- **Big source of impedance discontinuities.**
- **But above all, a major source of cross-talk.**

NEXT: To Do and Not To Do

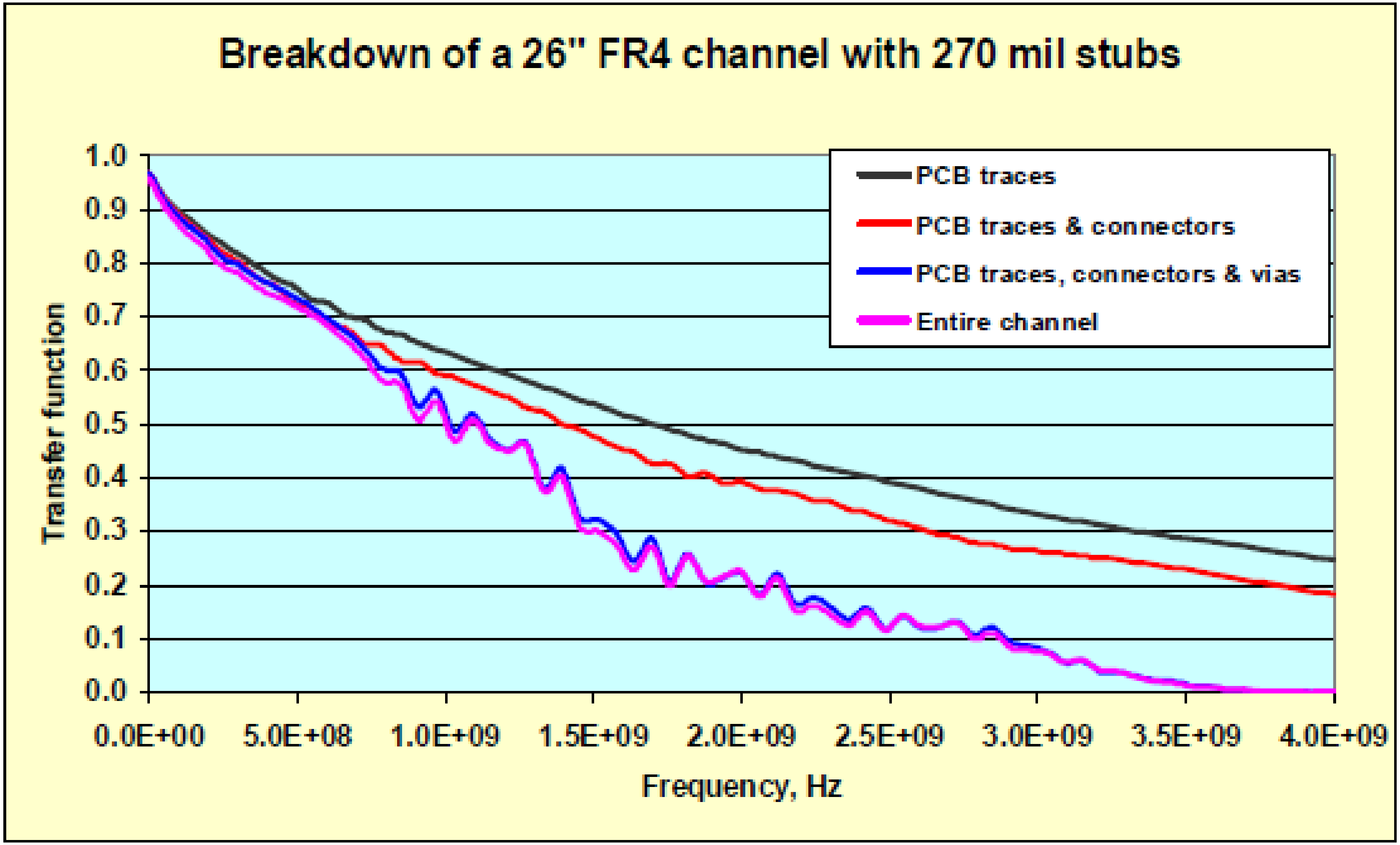








Everything together

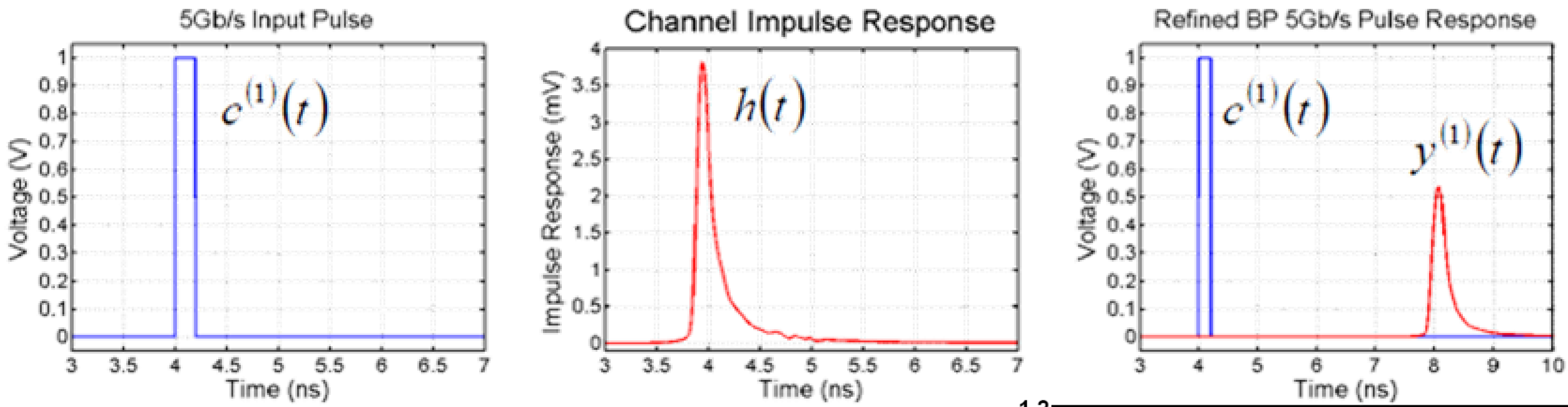


Outline

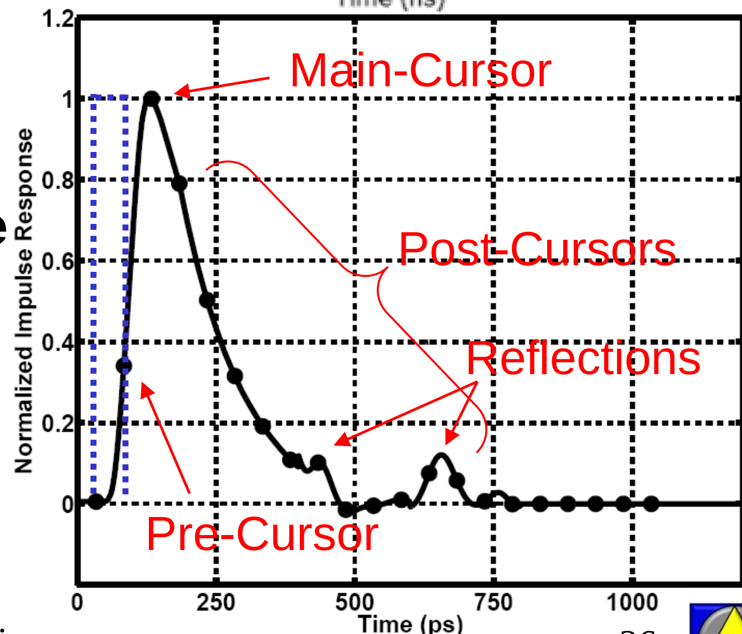
- **Channel Components**
  - Wires (PCB traces, Co-axial cables, twisted pairs, ..etc.)
  - IC Packages
  - Vias
  - Connectors
- **Channel Impairments**
  - Limited Bandwidth - Loss
  - Reflections
  - Cross-Talk
- **Channel Representations**
  - Impulse Response
  - S-Parameters
  - Eye Diagram
  - Time-Domain Reflectometry (TDR)

Channel Pulse Response

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

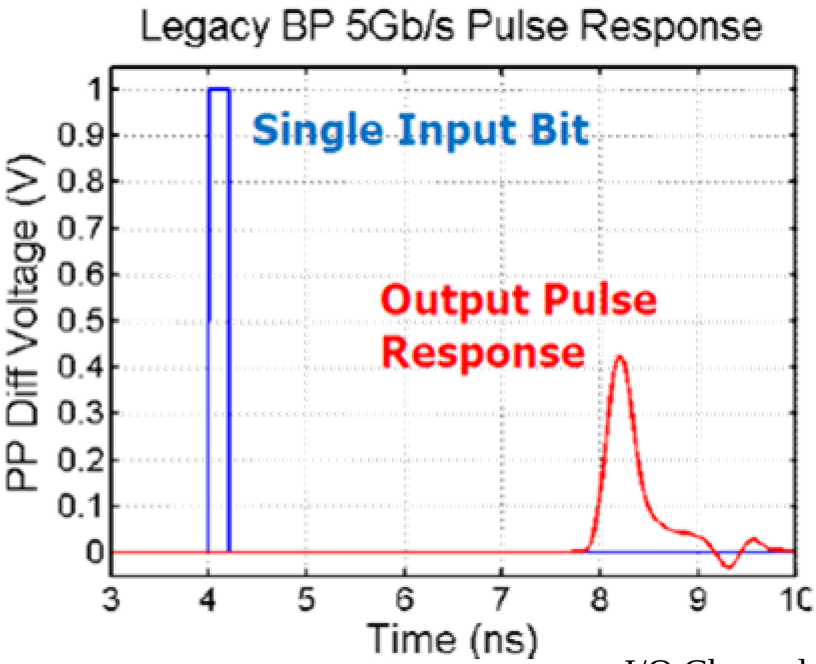


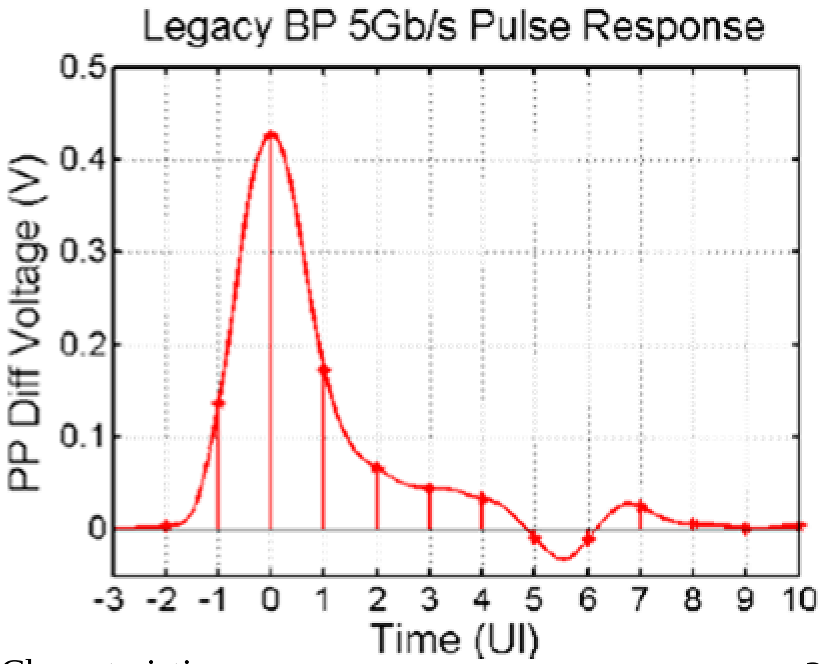
- **TX pulse spreads in time as it travels through the channel.**
- **Channel's pulse response is used in time domain simulations and link analysis.**
- **Many post-cursors and few pre-cursors exist due to spreading.**
- **Spreading causes interference with adjacent symbols (ISI).**



Inter-Symbol Interference (ISI)

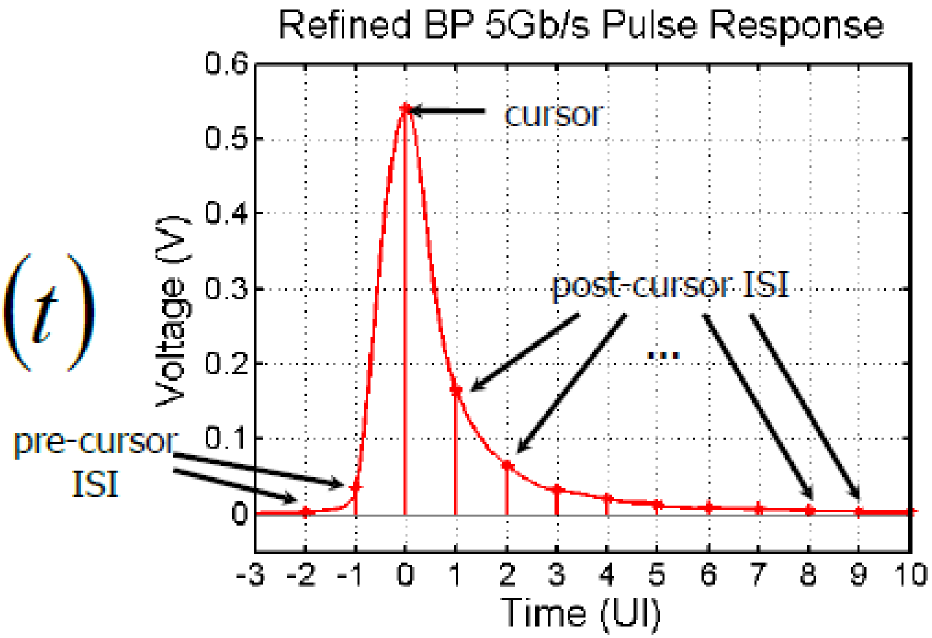
- **ISI is caused by channel loss (dispersion) and reflections.**
- **Previous bits residual state can distort the current bit.**
- **ISI creates a deterministic jitter in received signal's zero crossings.**
- **Left uncompensated, ISI leads to increased BER.**





Numerical Example

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



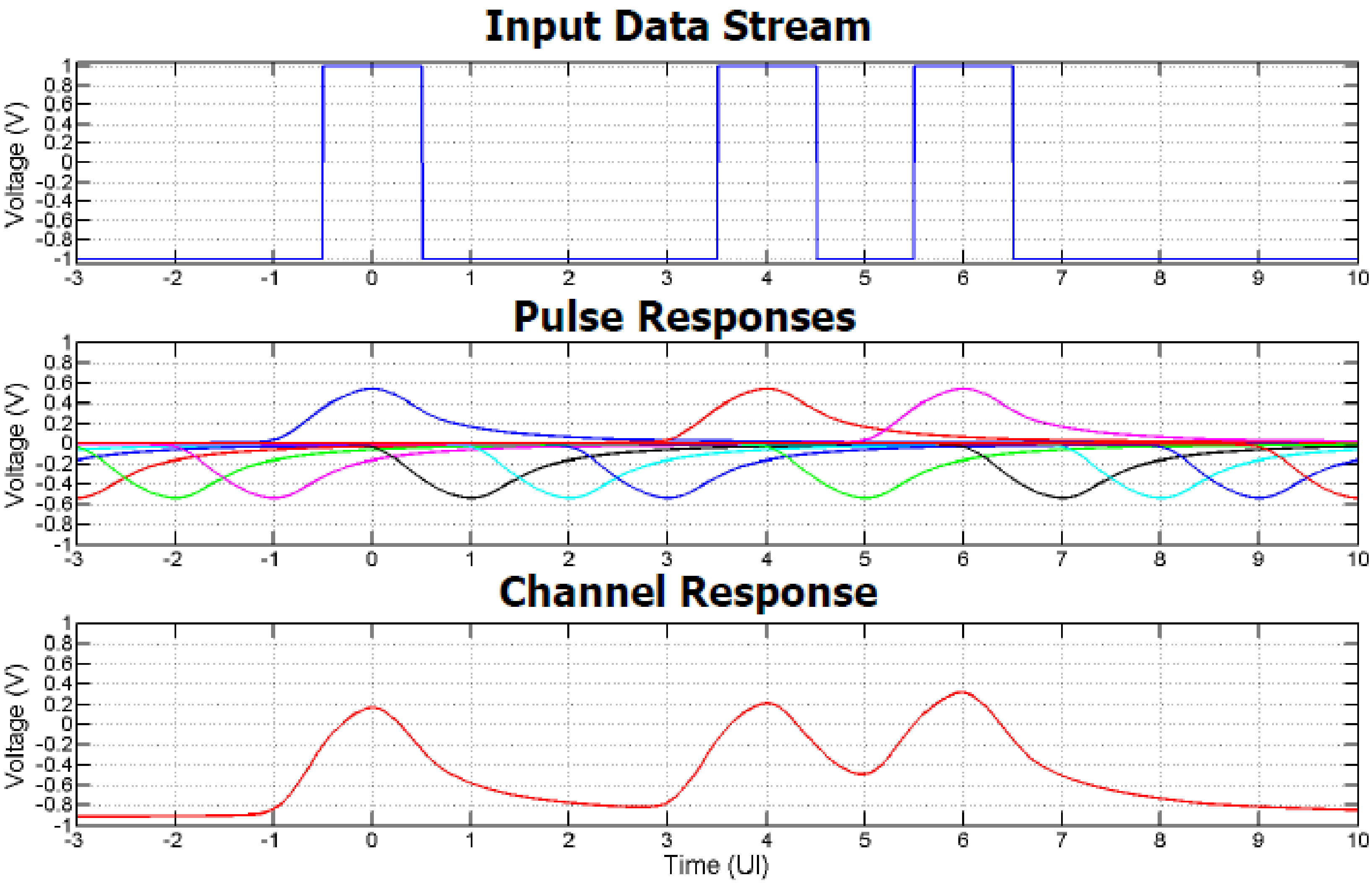
$y^{(1)}(t)$ sampled relative to pulse peak:

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

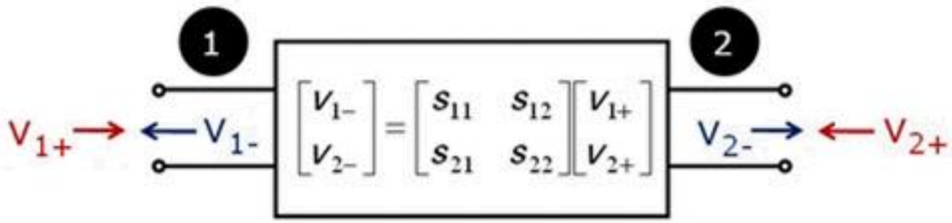
k =[... -2 1 0 1 2 3 4 5 6 ...]

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

Channel Data Stream Response



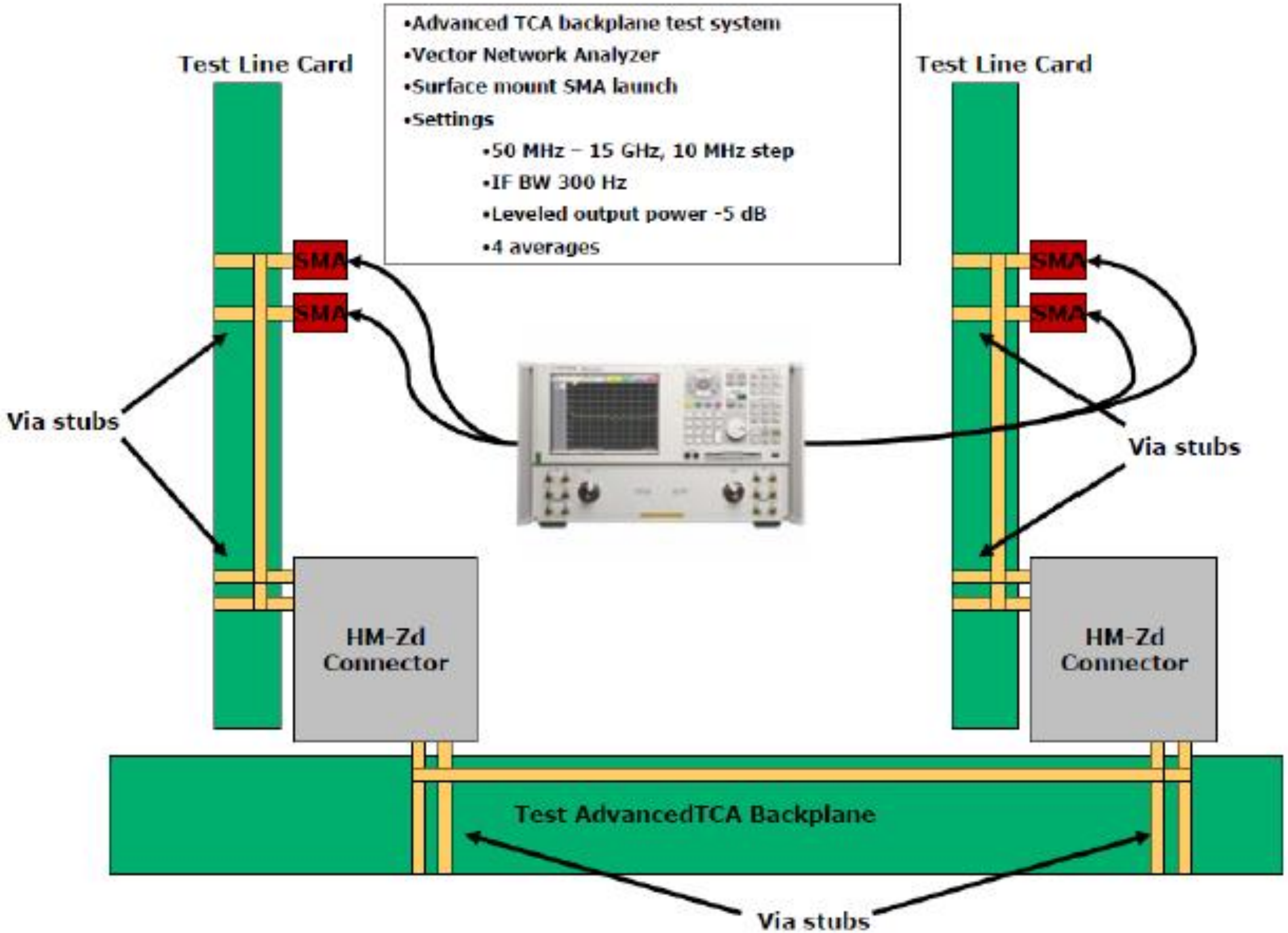
Channel S-Parameters



$$S_{11} = \left.\frac{V_{1-}}{V_{1+}}\right|_{V_{2+}=0} \qquad S_{21} = \left.\frac{V_{2-}}{V_{1+}}\right|_{V_{2+}=0} \qquad S_{12} = \left.\frac{V_{1-}}{V_{2+}}\right|_{V_{1+}=0} \qquad S_{22} = \left.\frac{V_{2-}}{V_{2+}}\right|_{V_{1+}=0}$$

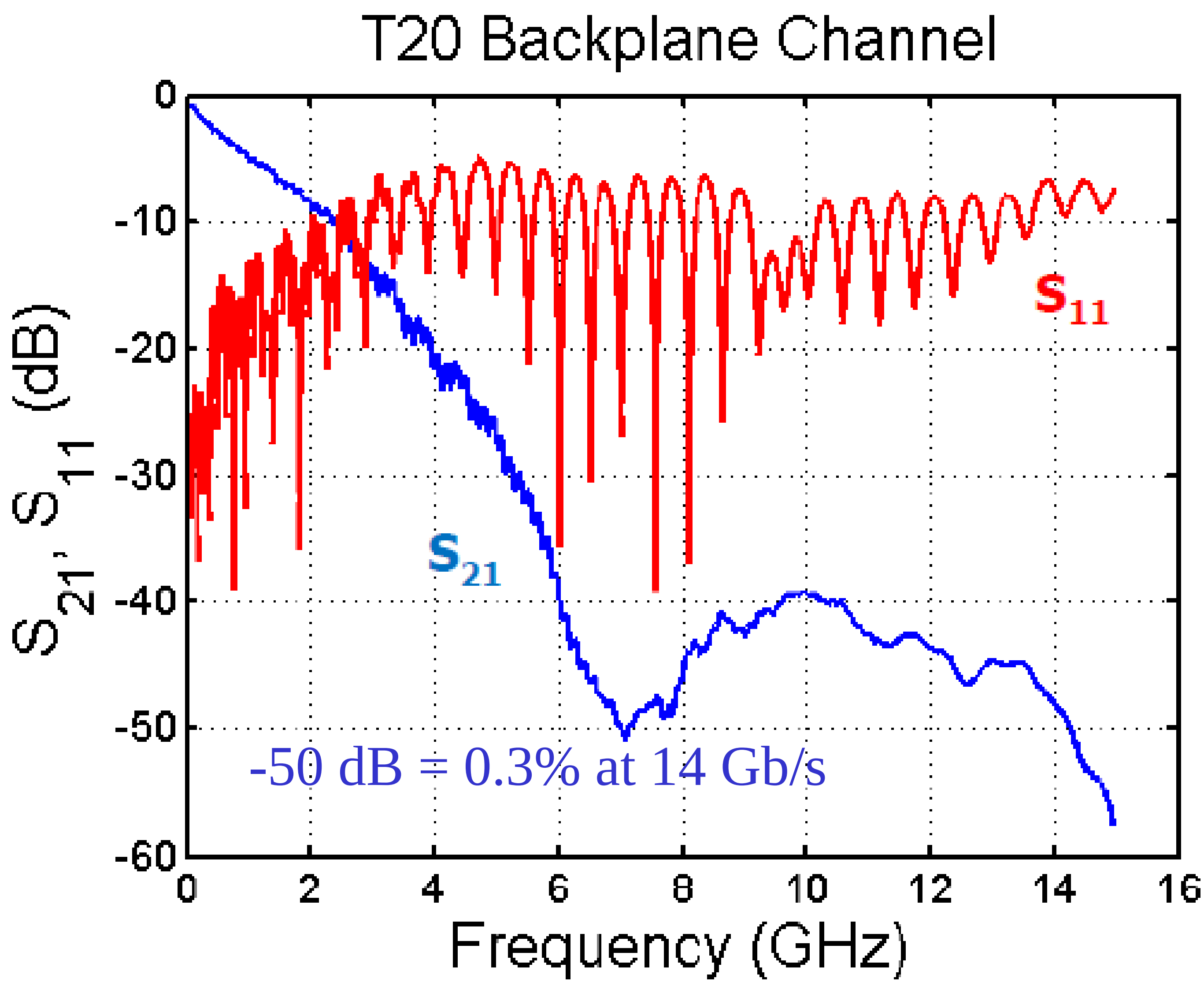
- **S-Parameters are easy to measure.**
  - Y, Z parameters need open and short conditions.
  - S-parameters are obtained with nominal termination.
- **S_{11} measures reflection from channel, port 2 matched.**
- **S_{11} is known as return loss.**
- **S_{21} measures fraction of signal delivered to matched load.**
- **S_{21} is known as insertion loss.**

S-Parameter Channel Example (1)



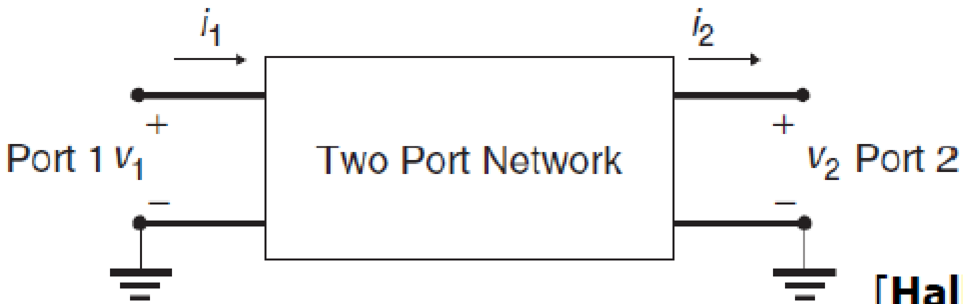
[Peters, IEEE Backplane Ethernet Task Force]

S-Parameter Channel Example (2)



Cascading S-Parameters

- **Convert to ABCD matrix and cascade.**



[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]

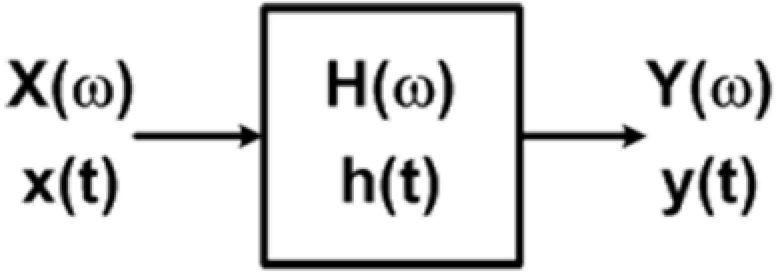
$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \qquad \begin{bmatrix} \dfrac{B - Z_n(D - A + CZ_n)}{B + Z_n(D + A + CZ_n)} & \dfrac{2Z_n(AD - BC)}{B + Z_n(D + A + CZ_n)} \\ \dfrac{2Z_n}{B + Z_n(D + A + CZ_n)} & \dfrac{B - Z_n(A - D + CZ_n)}{B + Z_n(D + A + CZ_n)} \end{bmatrix}$$

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

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

[Hall]

Impulse Response and S-Parameters (1)

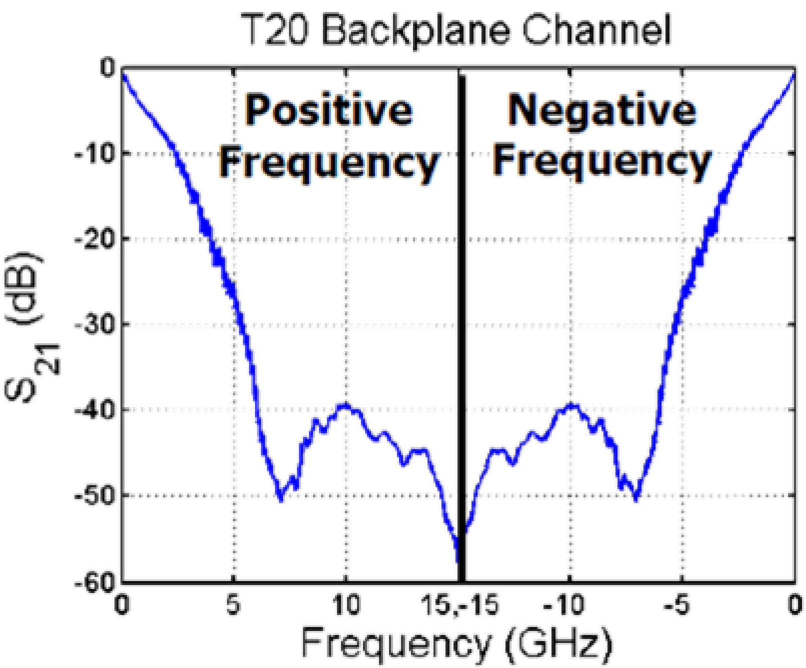


$$h(t) = F^{-1}\{S(\omega)\}$$

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

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

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



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

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

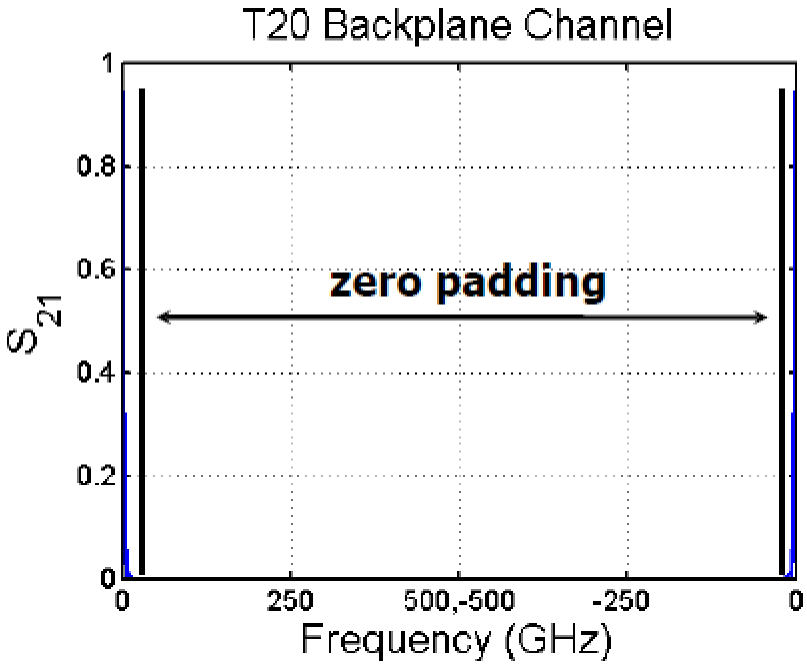
Impulse Response and S-Parameters (2)

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

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

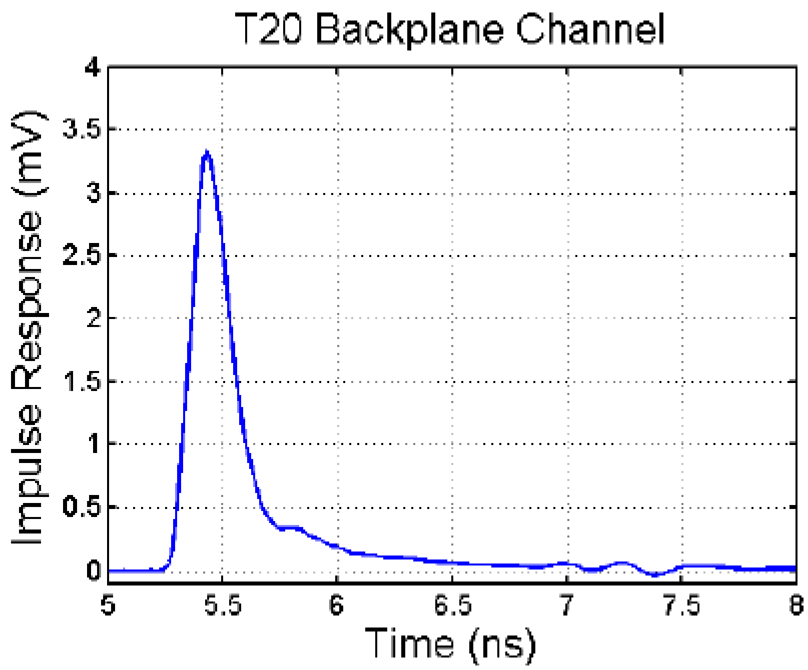
- **To improve response resolution, expand frequency axis and "zero pad".**

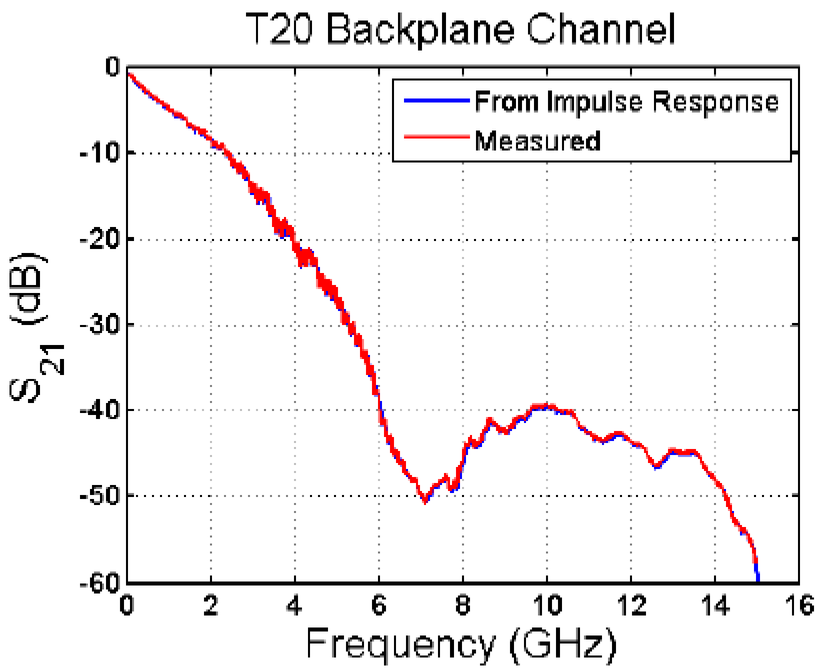
For 1ps resolution:
zero pad to +/-500GHz



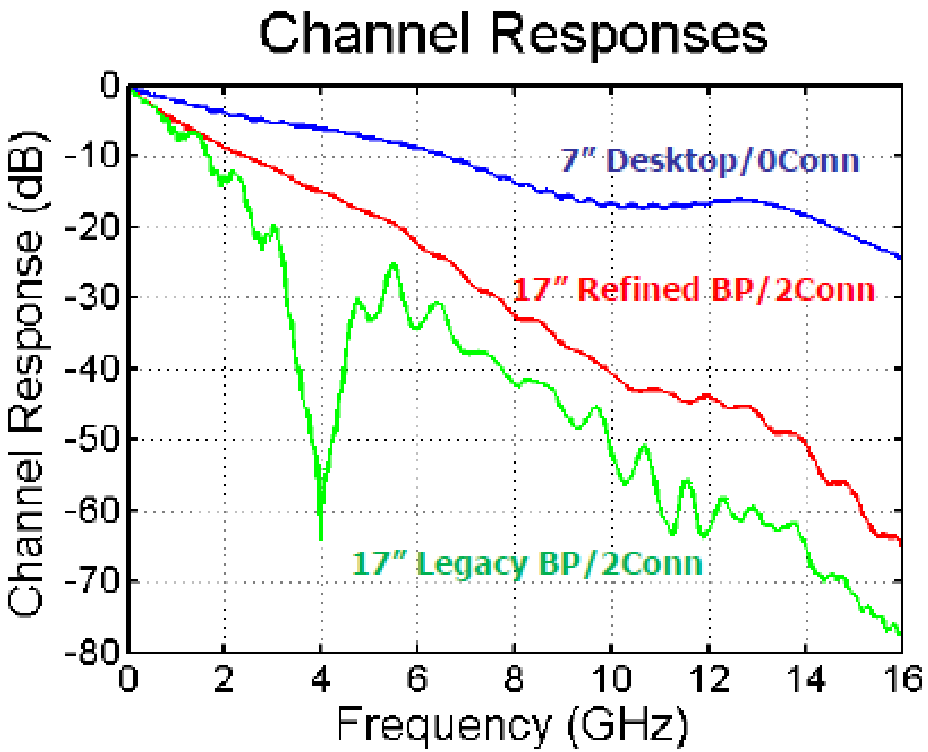
Impulse Response and S-Parameters (3)

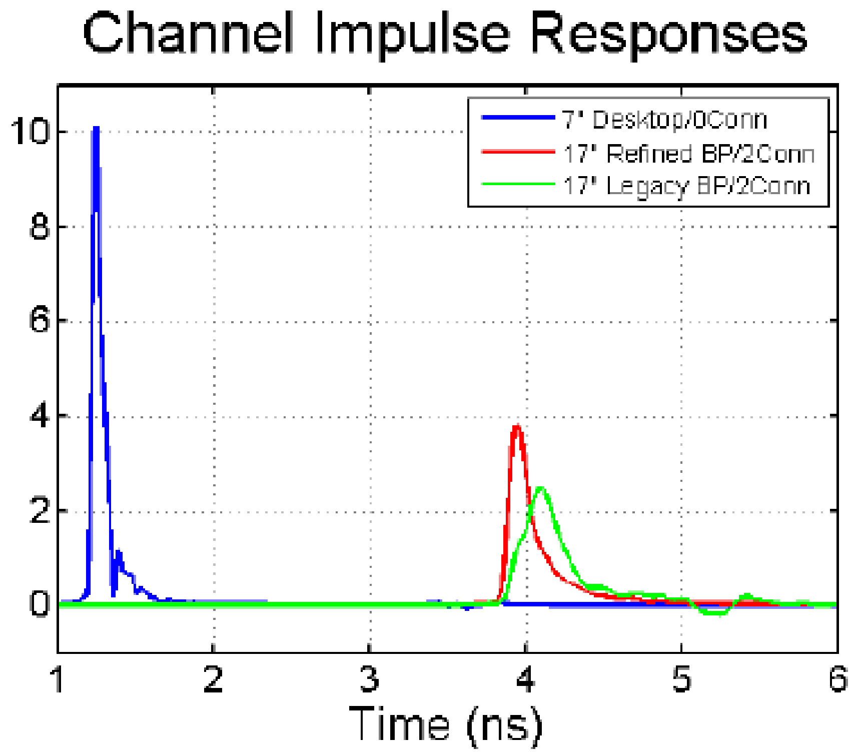
- Now perform ifft to produce impulse response
- Can sanity check by doing fft on impulse response and comparing to measured data



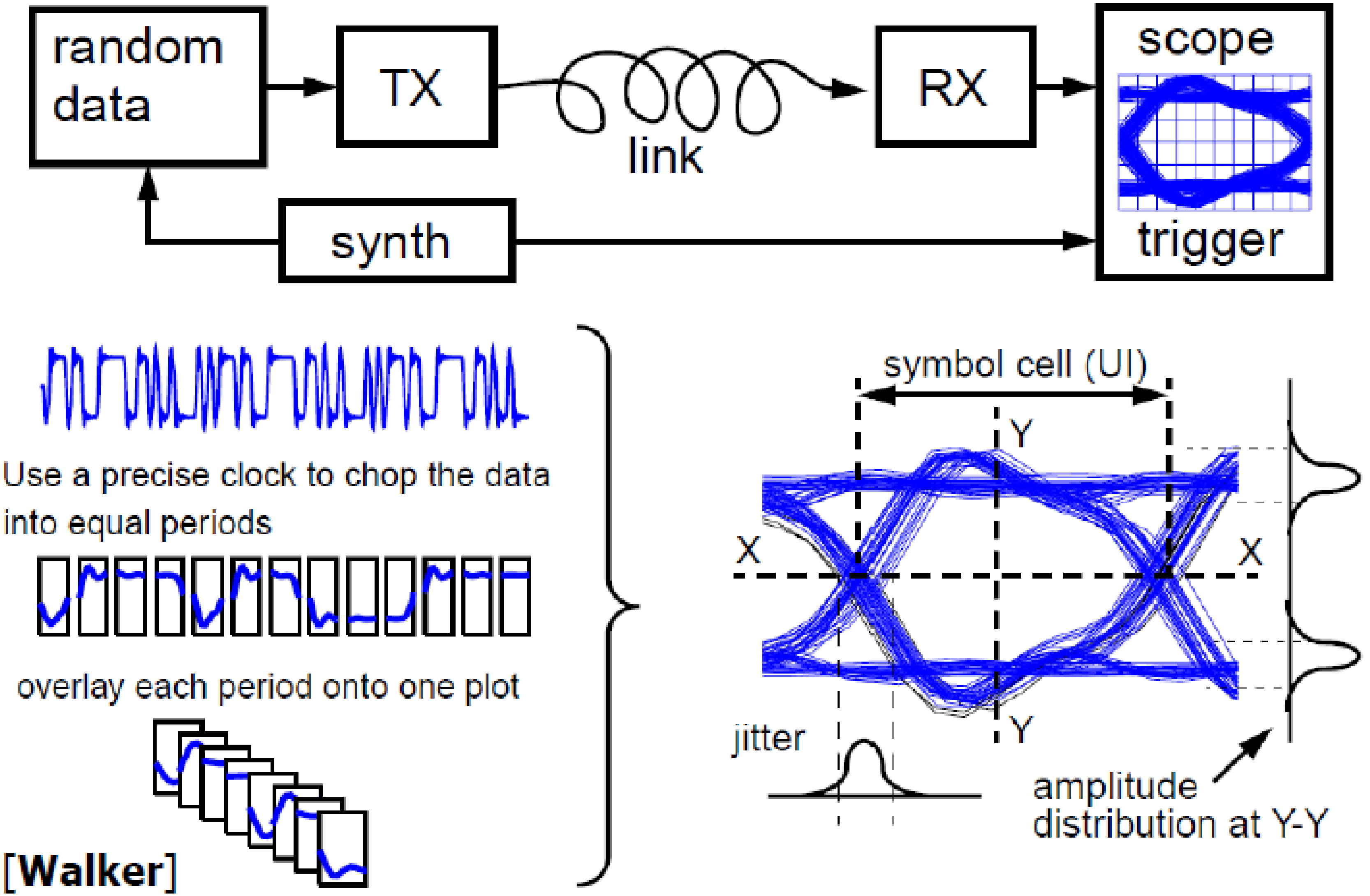


Different Channels Examples

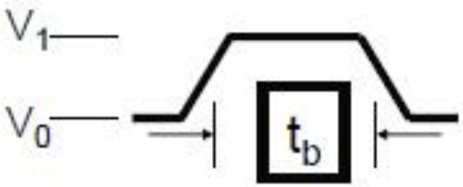




Eye Diagrams

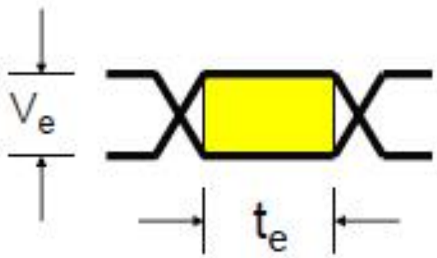


Eye Diagram Basics

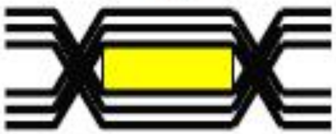


This is a "1"

This is a "0"



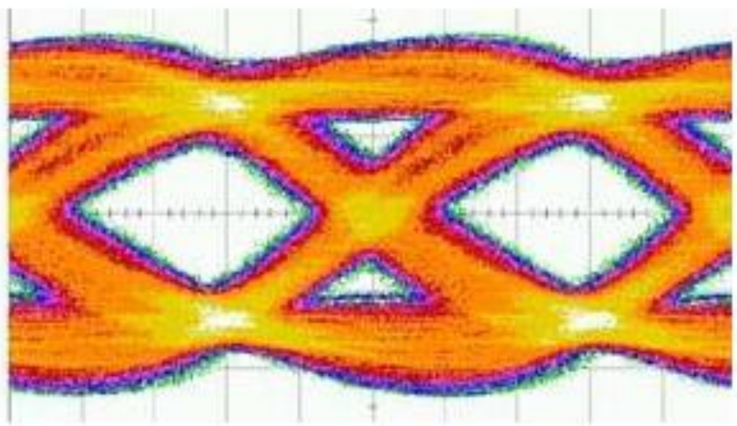
Eye Opening - space between 1 and 0



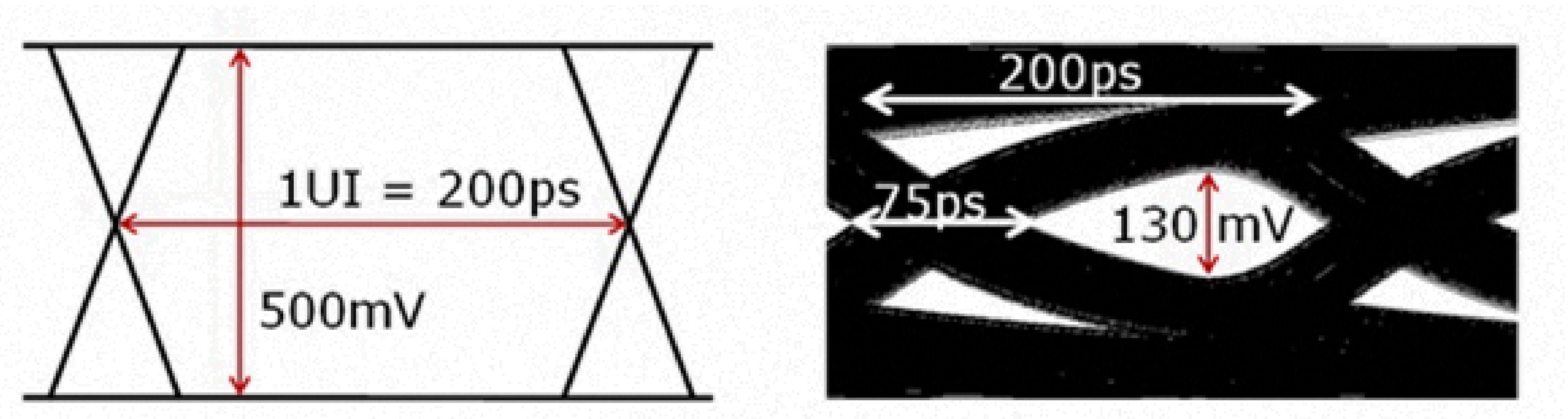
With voltage noise

With timing noise

With Both!



Loss-Less vs. Lossy Channel

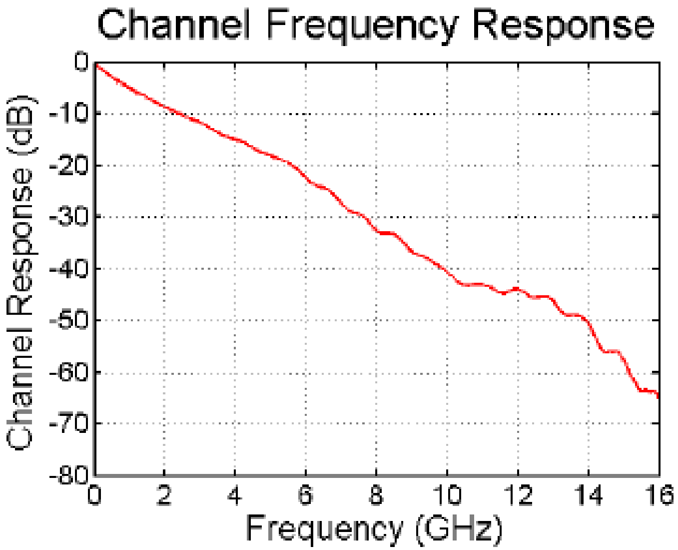


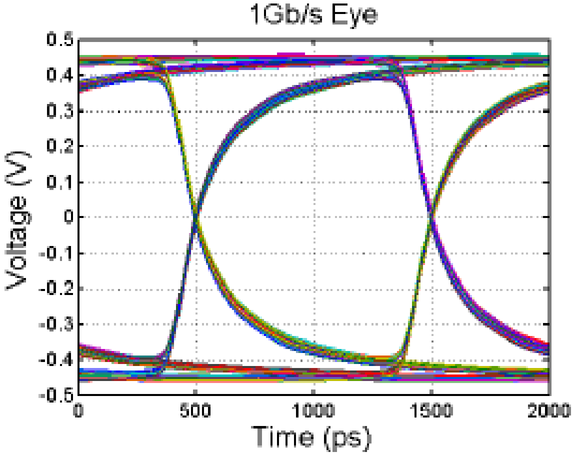
- Loss-less ideal channel
- RX eye = TX eye
- Eye opening = 500 mV
- Clear zero crossing
- No ISI, no jitter

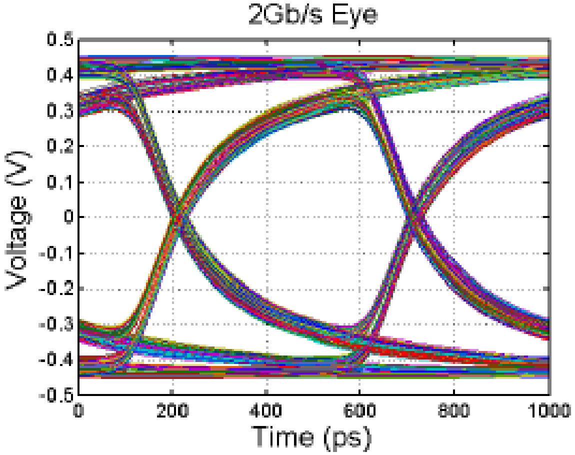
- 40´´ of FR4
- Data rate = 5 Gb/s
- Effect of attenuation only
- Eye opening = 130 mV
- Zero crossing jitter = 75 ps

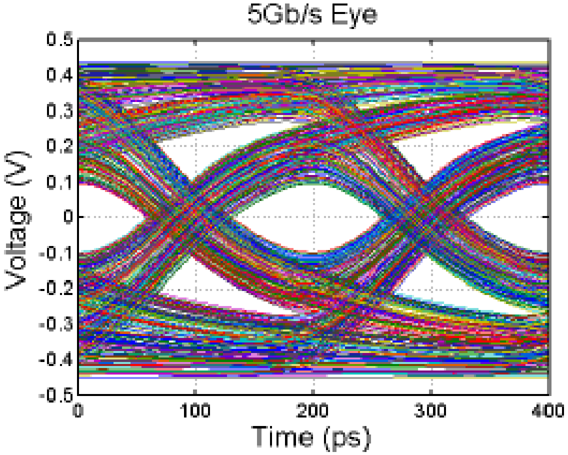
- Reflection and cross-talk further close the eye

Eye Diagrams vs. Data Rate

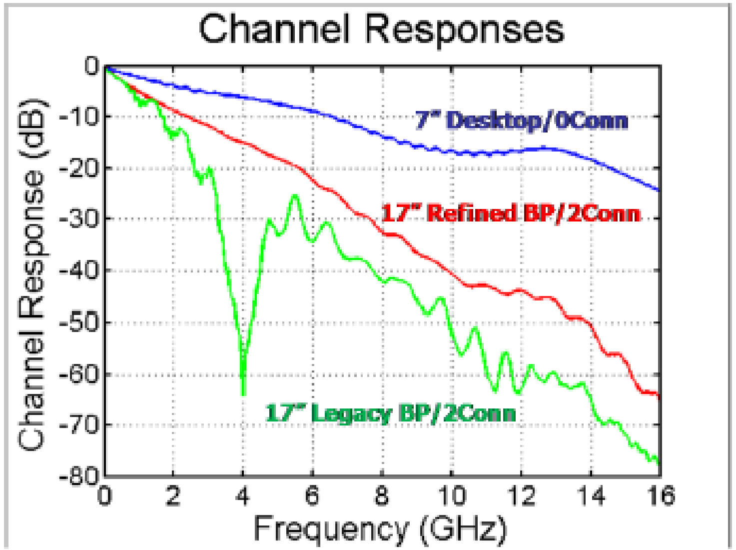


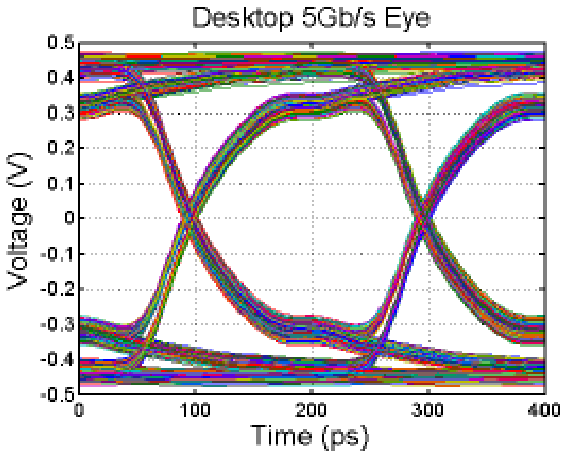


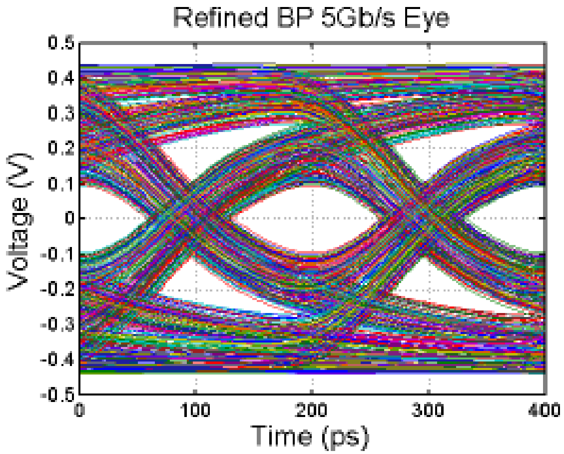


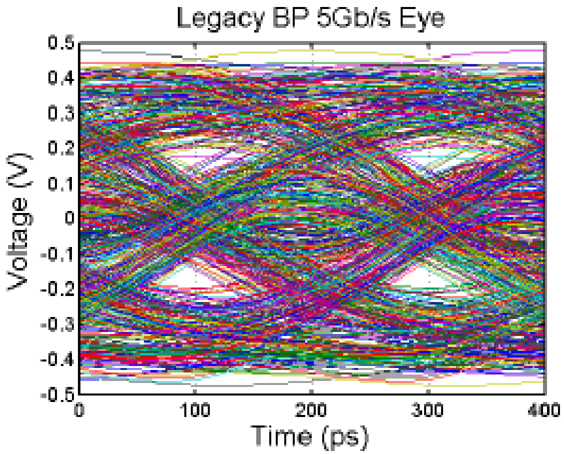


Eye Diagrams vs. Channel







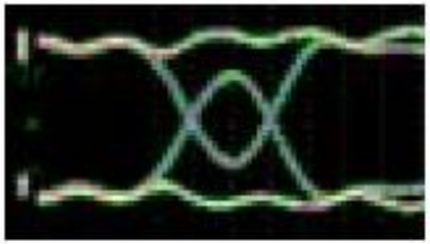


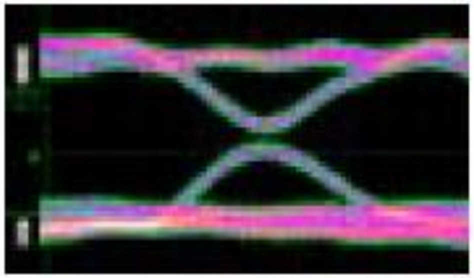
Attenuation and Eye Opening

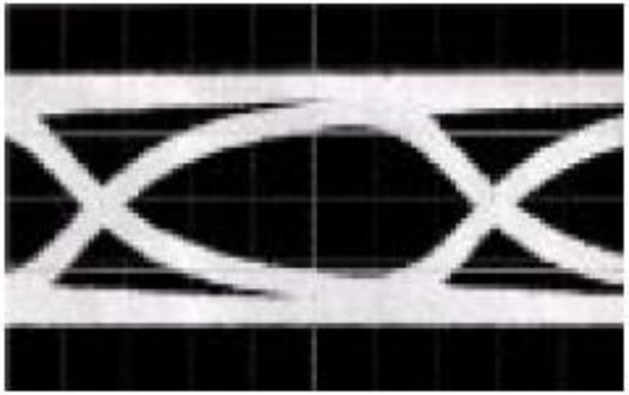
- **For an attenuation A, Eye opening is reduced to**

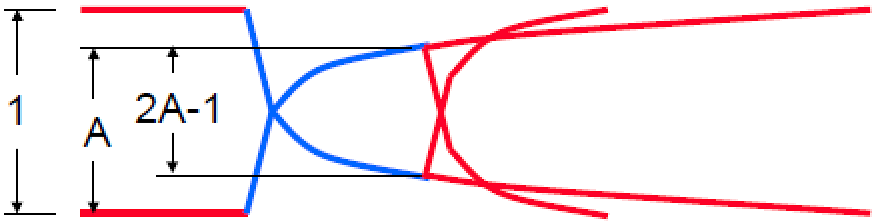
$$B = 2A - 1$$

- **No eye opening at 50% attenuation**
- **Significant degradation of margins at lower levels of attenuation**



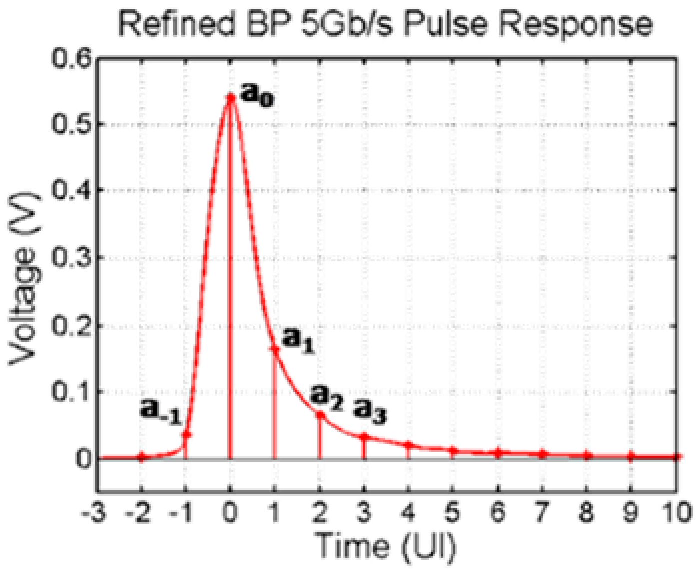






Estimating the Worst-Case Eye (1)

- **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.**

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

- **Worst-case "0" is summation of a "0" pulse with all positive non k=0 pulse responses.**

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

Estimating the Worst-Case Eye (2)

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

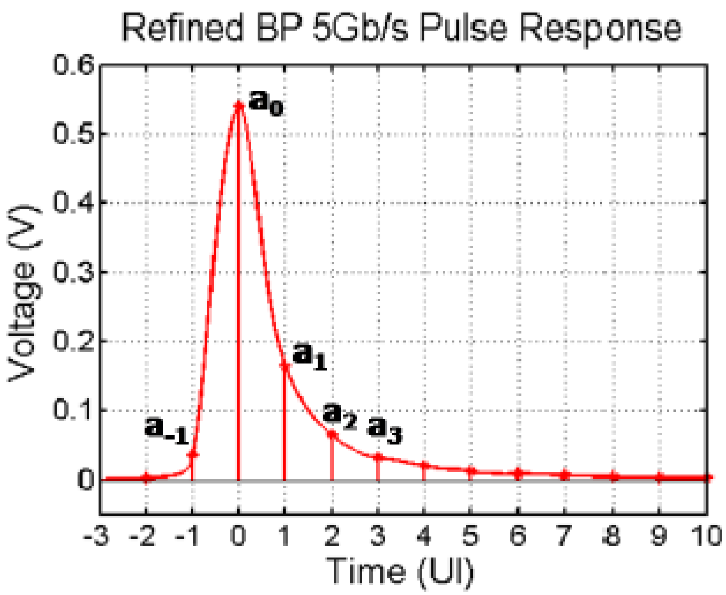
$$s(t) = s_1(t) - s_0(t) = \left(y_0^{(1)}(t) - y_0^{(0)}(t)\right) + \left(\sum_{\substack{k=-\infty \\ k\neq 0}}^{\infty} y^{(d_k)}(t-kT)\Big|_{y(t-kT)<0} - \sum_{\substack{k=-\infty \\ k\neq 0}}^{\infty} y^{(d_k)}(t-kT)\Big|_{y(t-kT)>0} \right)$$

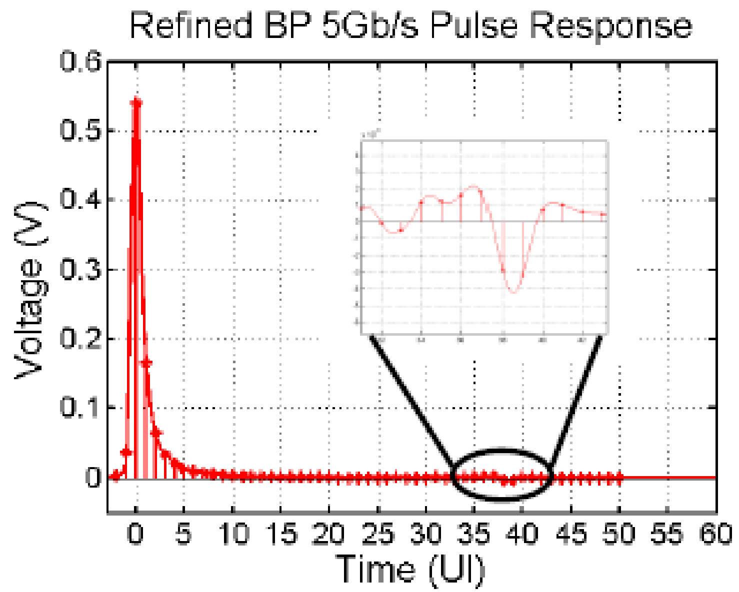
$$\text{Because } y_0^{(0)}(t) = -1\left(y_0^{(1)}(t)\right)$$

$$s(t) = 2\left(y_0^{(1)}(t) + \underbrace{\sum_{\substack{k=-\infty \\ k\neq 0}}^{\infty} y^{(1)}(t-kT)\Big|_{y(t-kT)<0}}_{\text{"1" pulse worst-case "1" edge}} - \underbrace{\sum_{\substack{k=-\infty \\ k\neq 0}}^{\infty} y^{(1)}(t-kT)\Big|_{y(t-kT)>0}}_{\text{"1" pulse worst-case "0" edge}} \right)$$

- **If symmetric "1" and "0" pulses, then only positive pulse response is needed.**

Worst-Case Eye Example 1



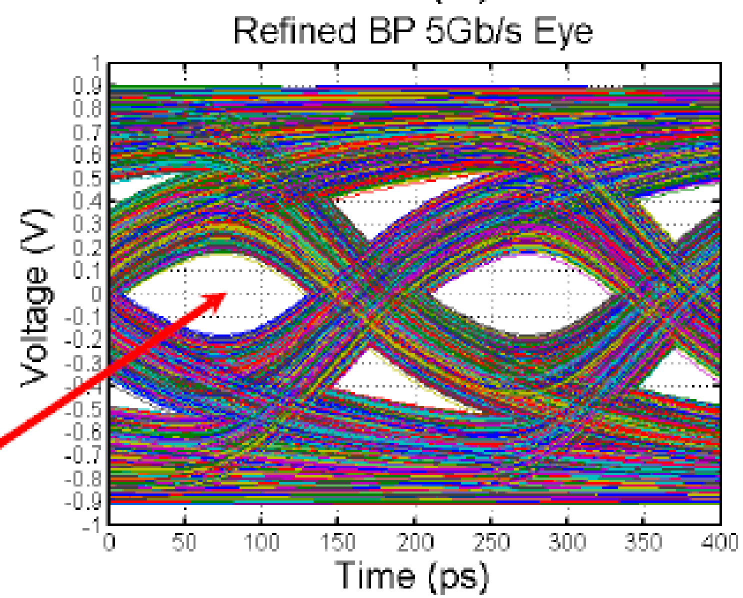


$$y_0^{(1)}(t) = 0.540$$

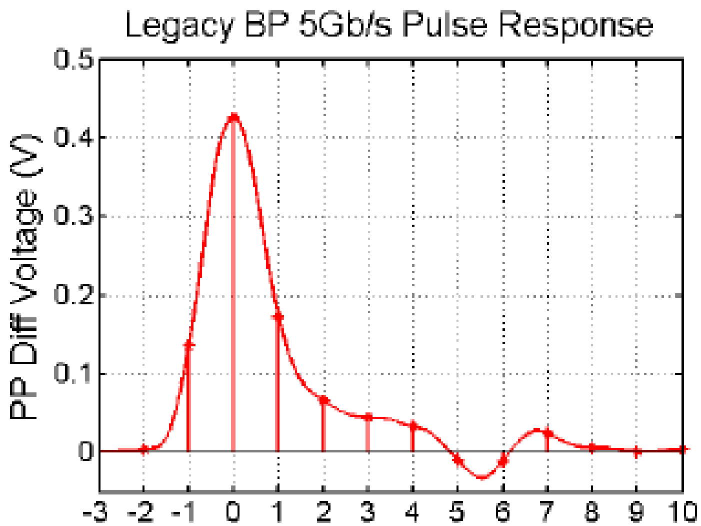
$$\sum_{\substack{k=-\infty \\ k\neq 0}}^{\infty} y^{(1)}(t-kT)\Big|_{y(t-kT)<0} = -0.007$$

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

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



Worst-Case Eye Example 2

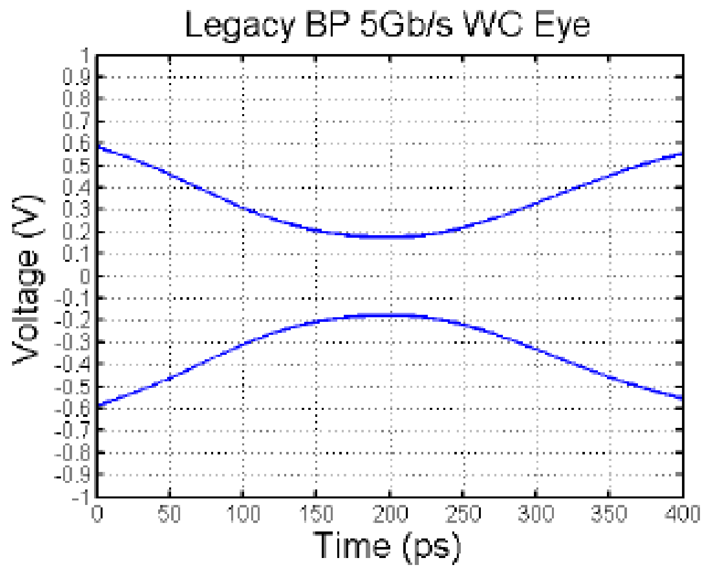


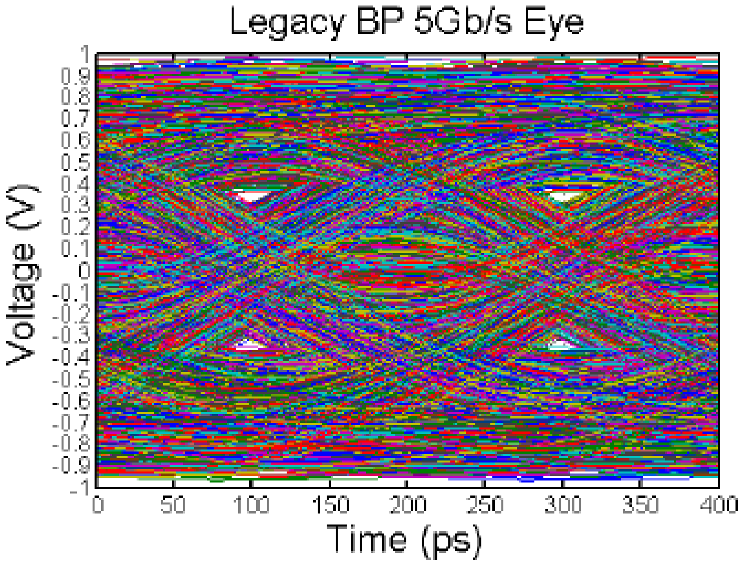
$$y_0^{(1)}(t) = 0.426$$

$$\sum_{\substack{k=-\infty \\ k\neq 0}}^{\infty} y^{(1)}(t-kT)\Big|_{y(t-kT)<0} = -0.053$$

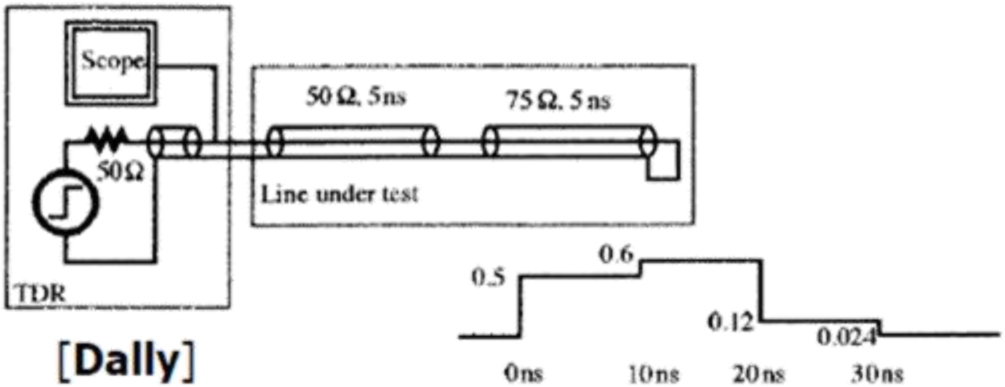
$$\sum_{\substack{k=-\infty \\ k\neq 0}}^{\infty} y^{(1)}(t-kT)\Big|_{y(t-kT)>0} = 0.542$$

$$s(t) = 2(0.426 - 0.053 - 0.542) = -0.338$$

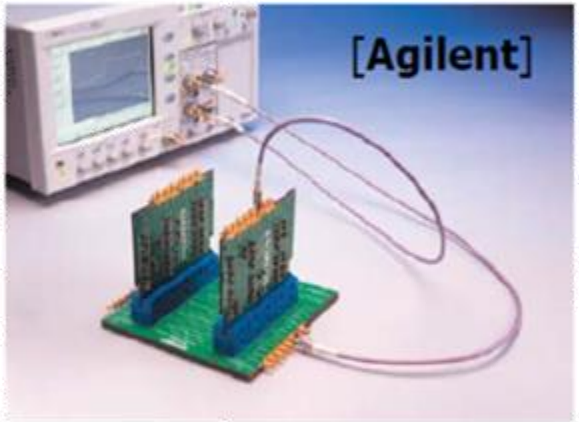




Time-Domain Reflectometer (TDR)



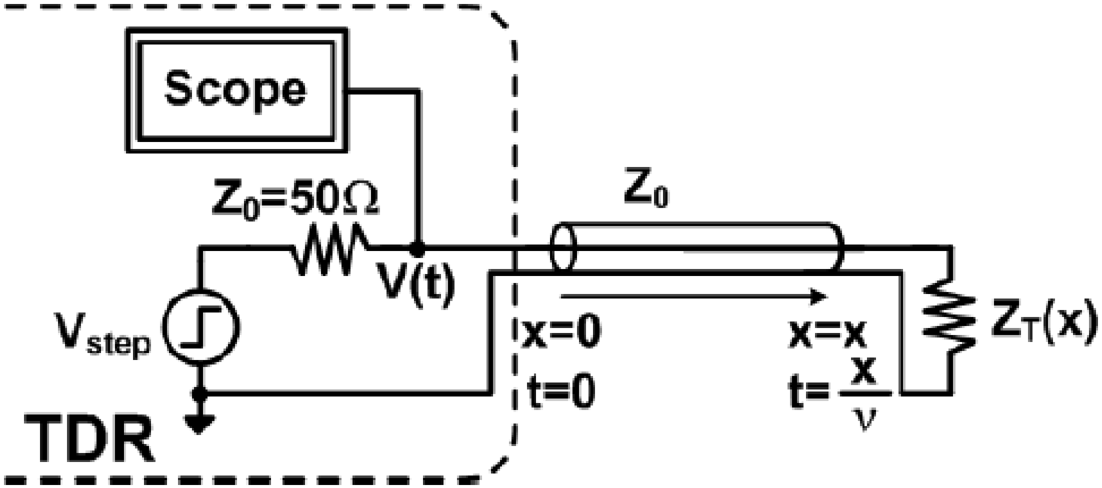
[Dally]



[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 include reflections
  - Voltage magnitude can be converted to impedance
  - Impedance discontinuity location can be determined by delay
- **Only input port access to characterize channel (vs. VNA)**

TDR Impedance Calculation



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

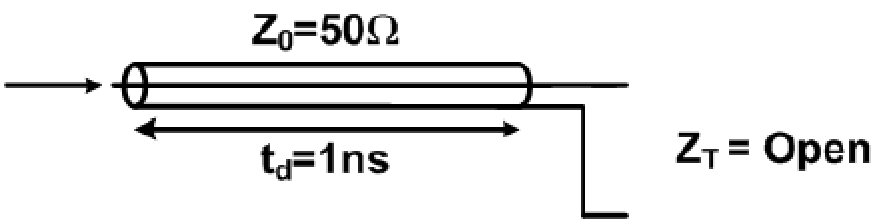
$$Z_T(t)=Z_0\left(\frac{1+k_r(t)}{1-k_r(t)}\right)=Z_0\left(\frac{V_i+V_r(t)}{V_i-V_r(t)}\right)=Z_0\left(\frac{V(t)}{2V_i-V(t)}\right)$$

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

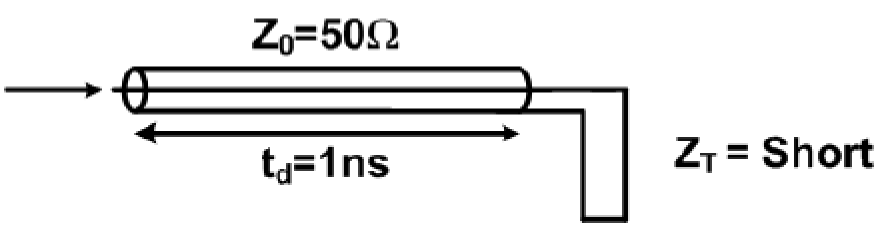
$$\boxed{Z_T(t)=Z_0\left(\frac{V(t)}{1V-V(t)}\right) \qquad Z_T(x)=Z_T\left(t=\frac{2x}{\upsilon}\right)}$$

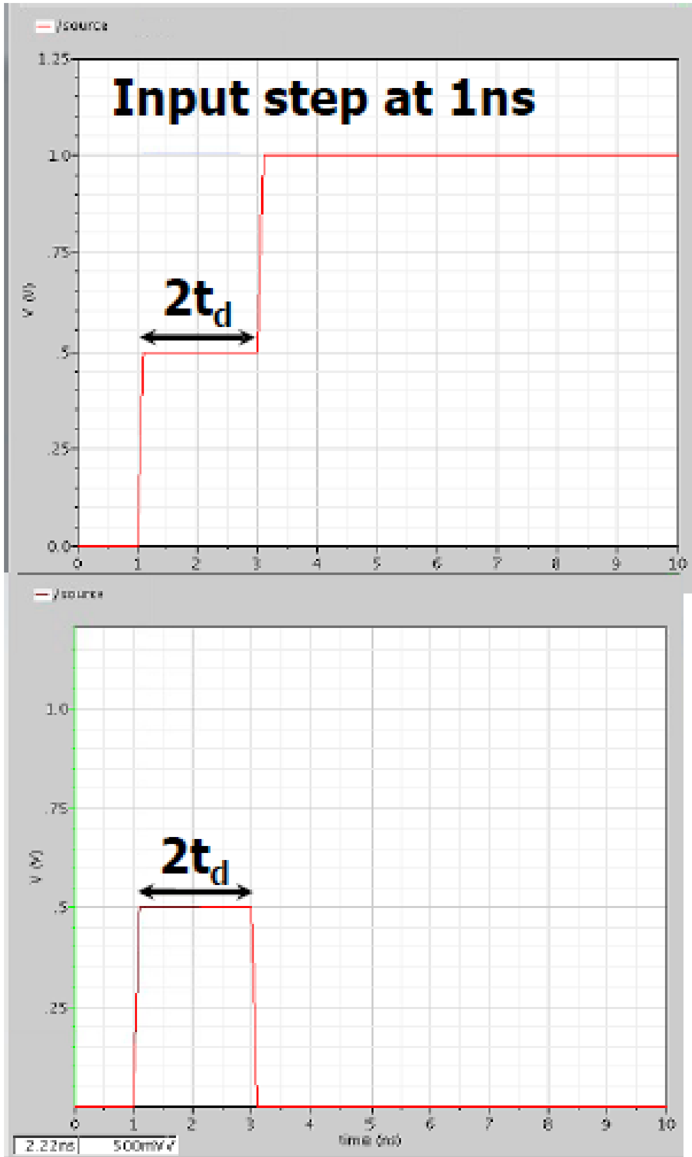
TDR Waveforms (Open & Short)

- **Open termination**



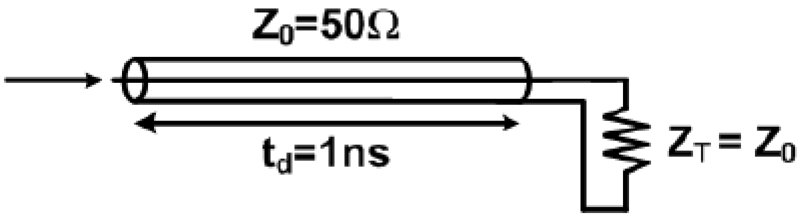
- **Short termination**



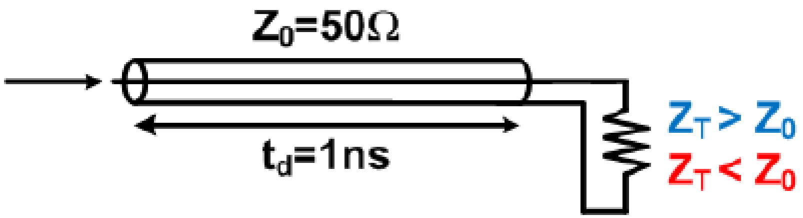


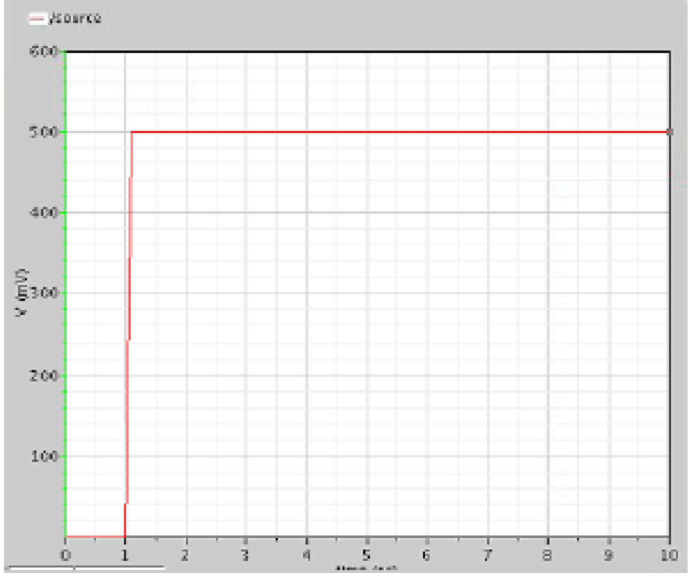
TDR Waveforms (Matched & Unmatched)

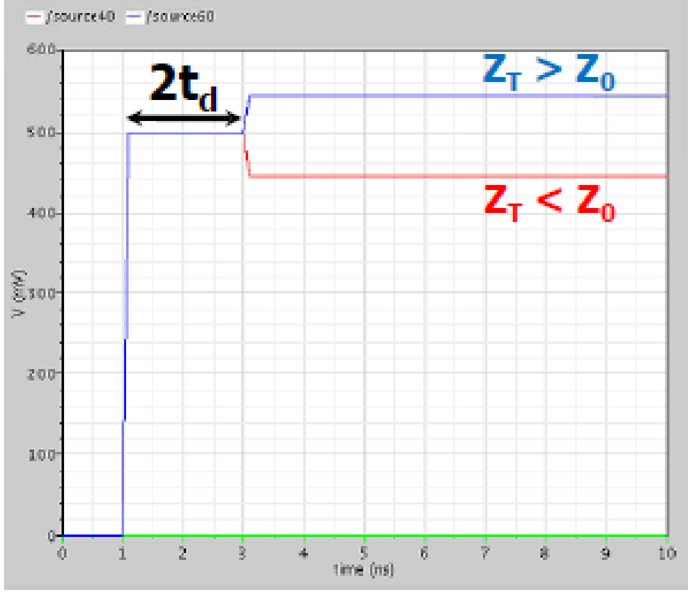
- **Matched termination**



- **Unmatched termination**

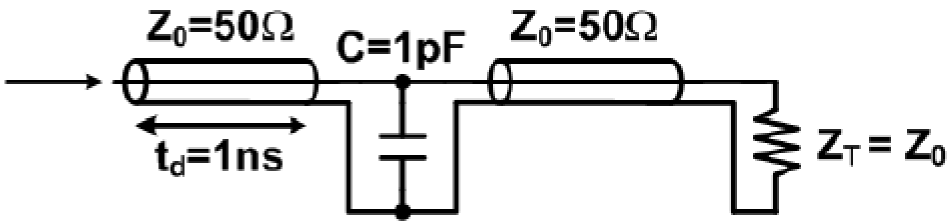




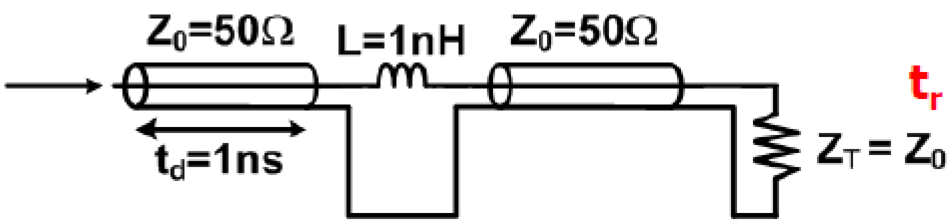


TDR Waveforms (C & L Discontinuity)

- **Shunt C discontinuity**

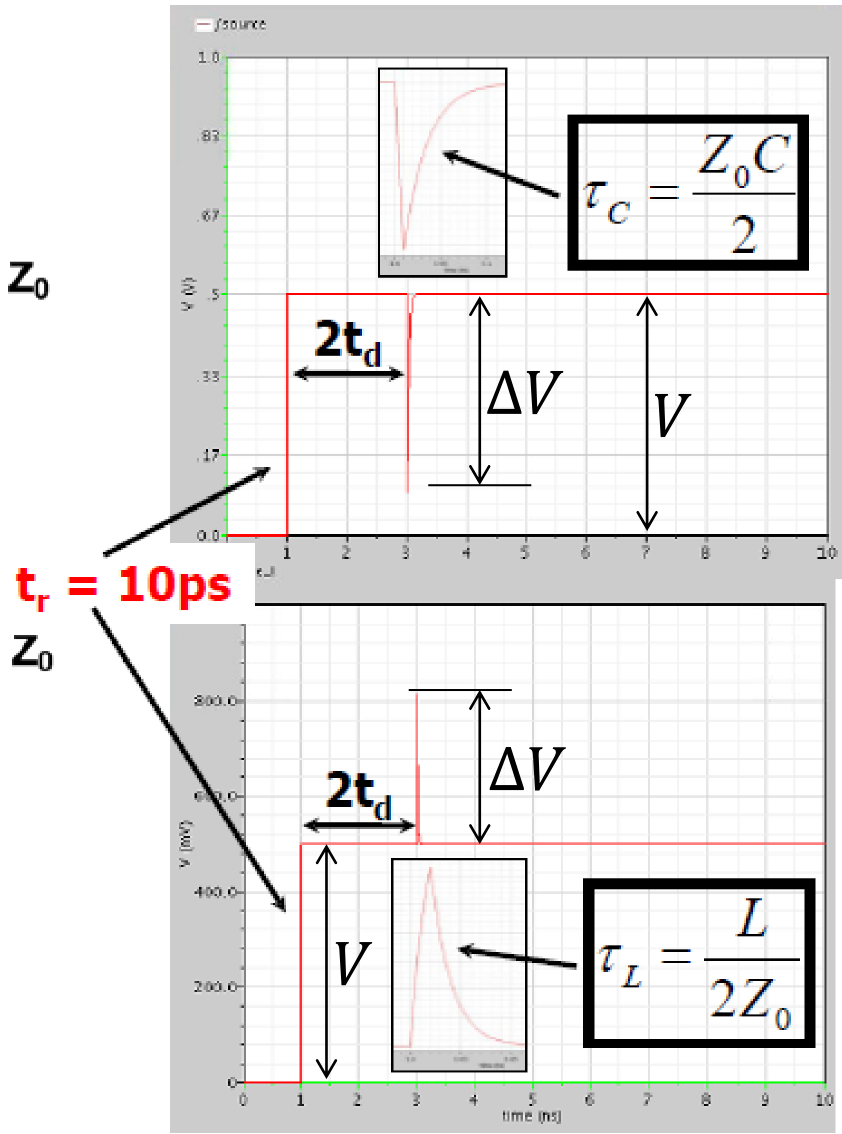


- **Series L discontinuity**



- **Spike depends on rise time**

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



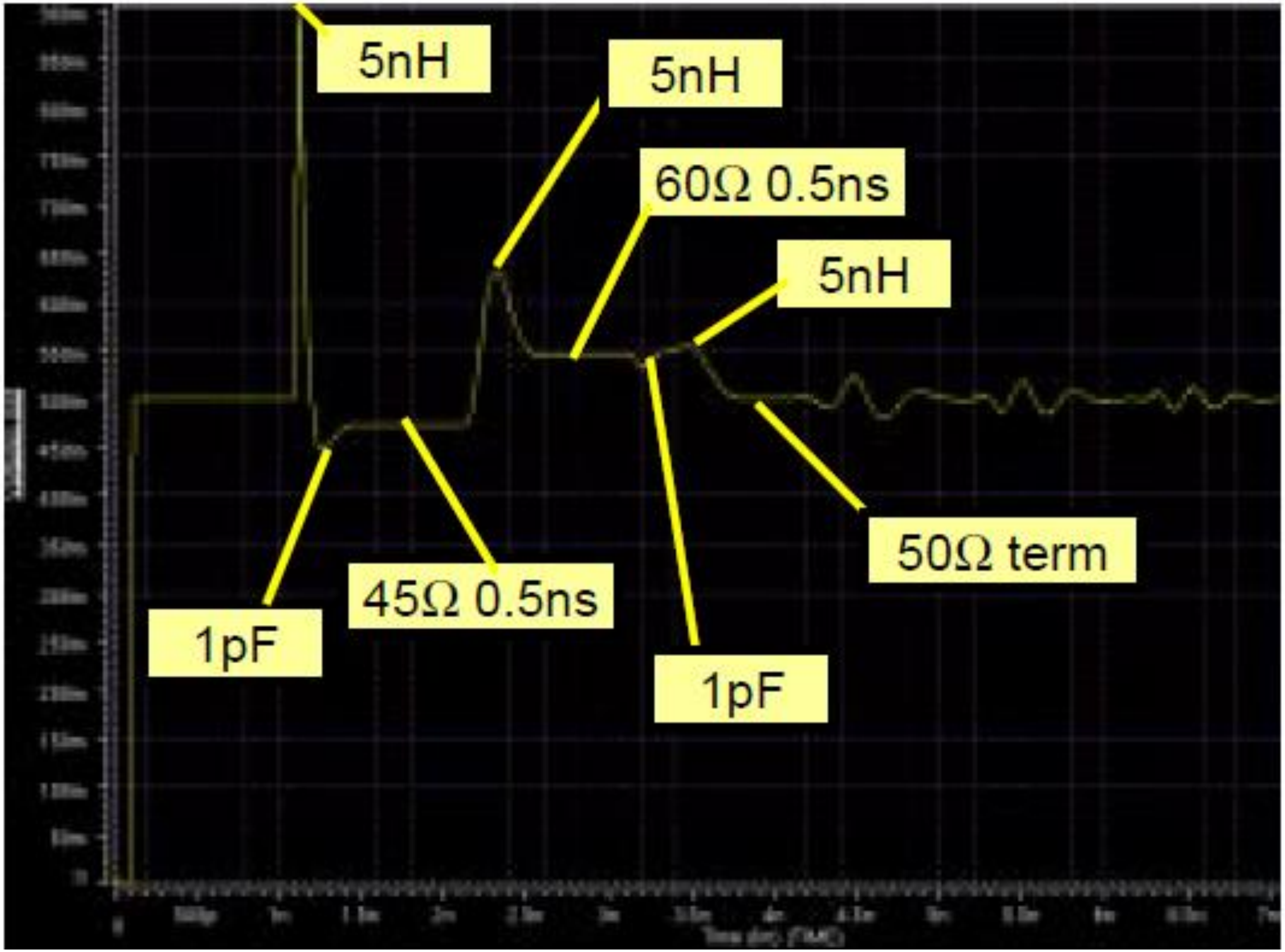
Rise-Time Degradation

- **Upstream elements (Ls & Cs) low-pass the signal resulting in a longer rise-time.**
- **This affects the reflections from down-stream elements.**
  - Slow rising edge
  - Spread out response
  - L & C responses do not go full swing.
- **This makes it**
  - Hard to extract L and C values.
  - Impossible to measure very small discontinuities.
    - But if the TDR cannot see them, neither can the signal.

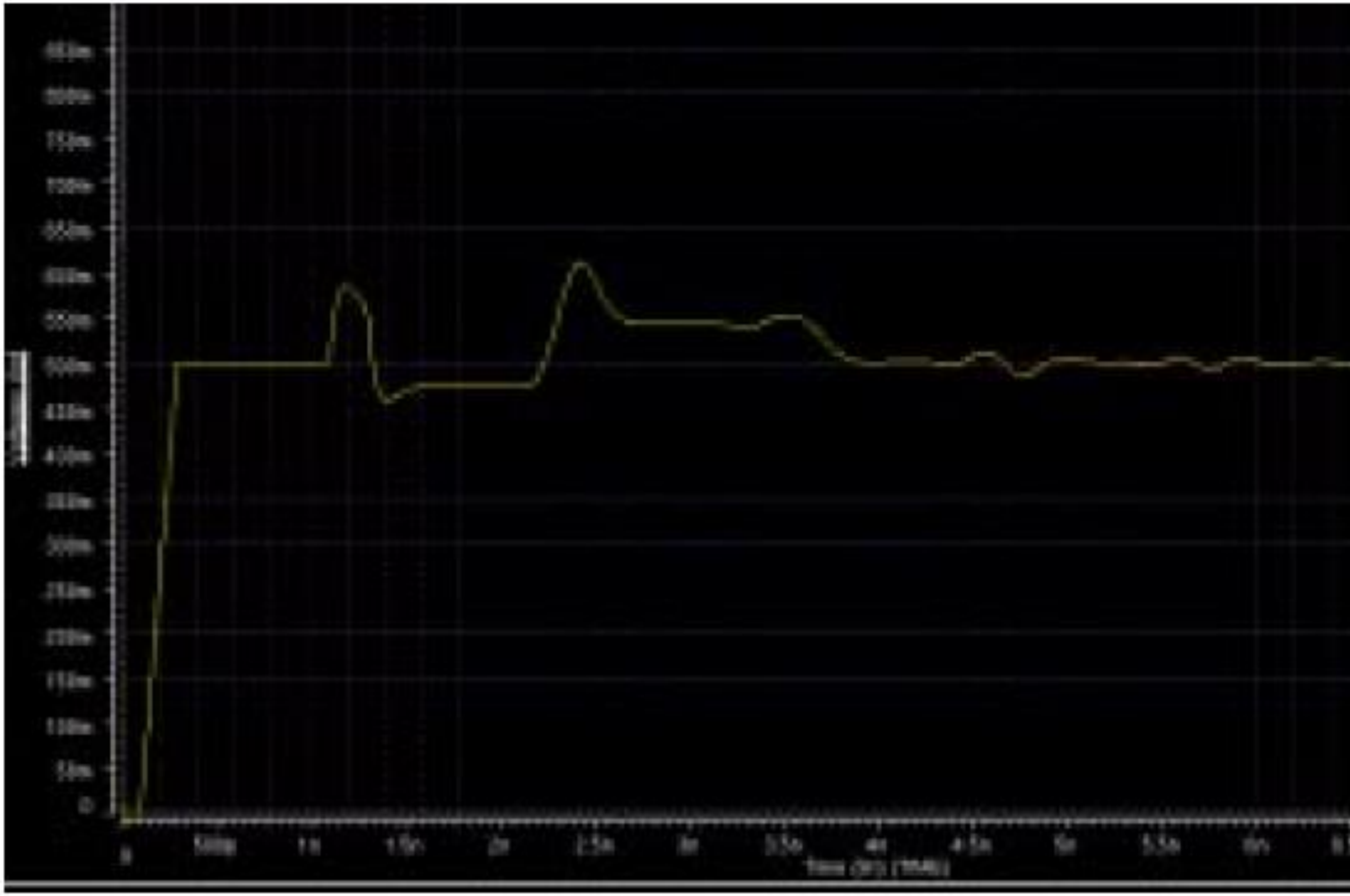
Extraction Procedure

- **Identify regions of the TDR plot as**
  - Flat region – transmission line
  - Bump up – inductor
  - Bump down – capacitor
- **Starting at source**
  - Determine value of Z & t_d, L, or C for nearest element.
  - Simulate to validate and determine new $t_{r.}$
  - Iterate as needed to get the value right.
  - Move on to the next element.
- **There is no need for models with more resolution than the fastest rise time.**

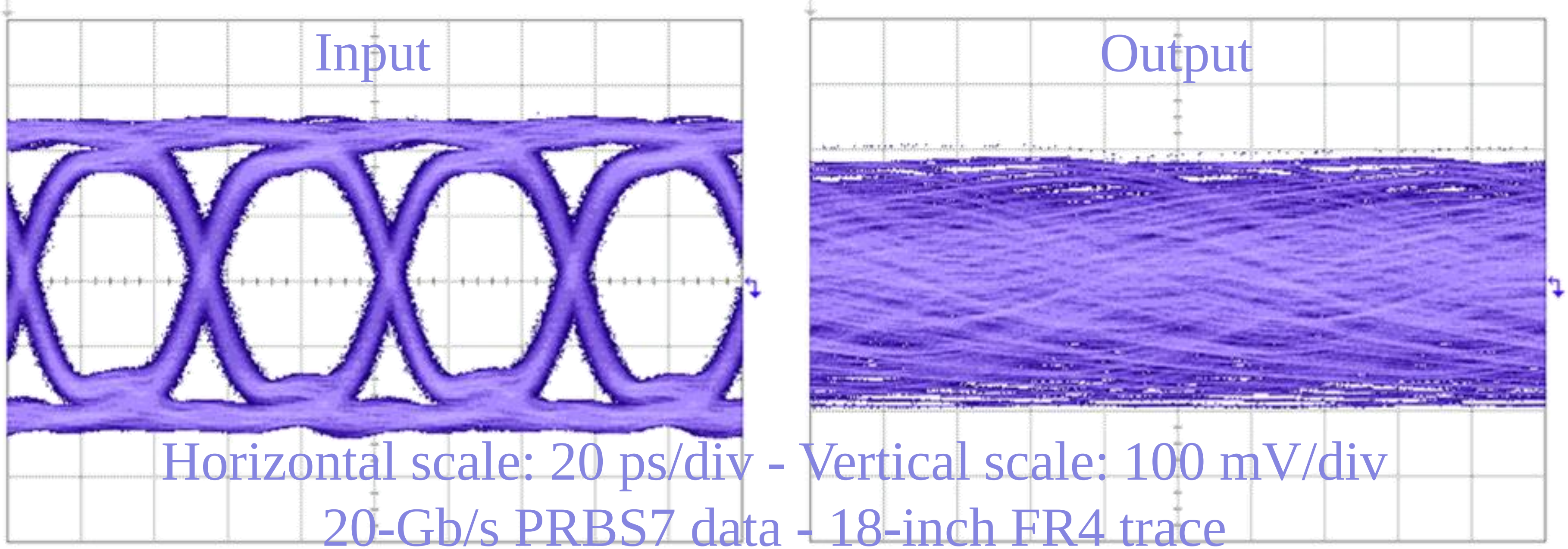
Example TDR Trace



Same Waveform with 200 ps Edge



Channel Summary



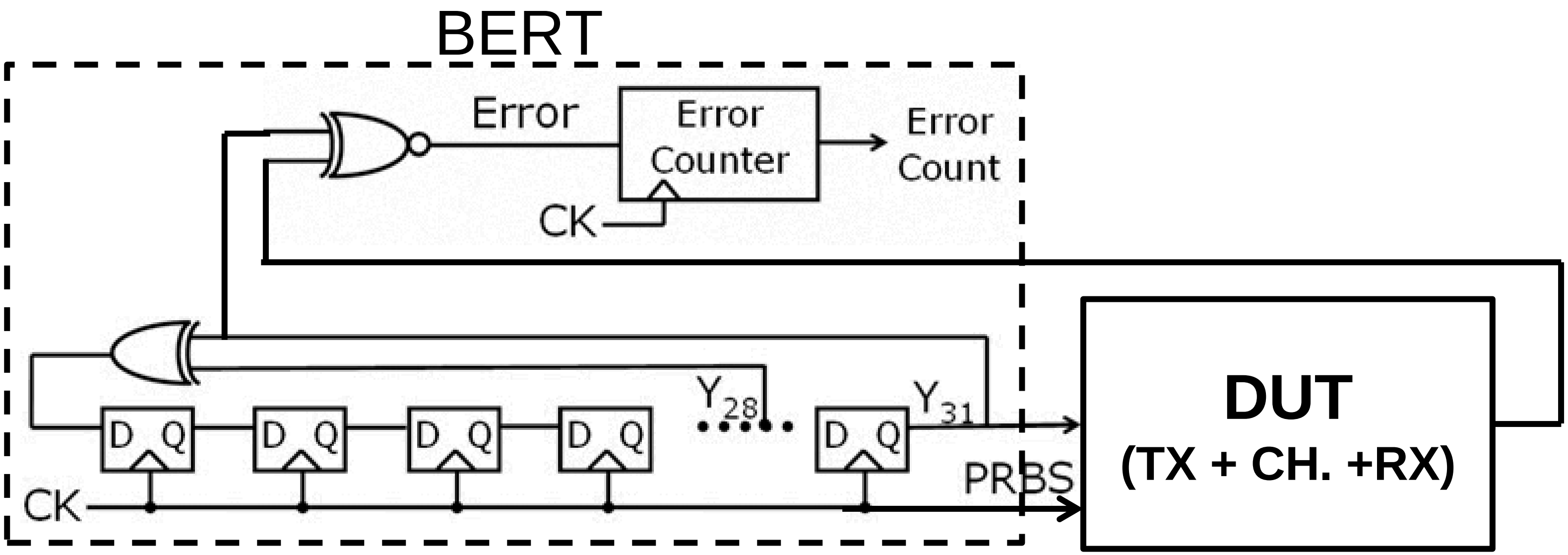
Horizontal scale: 20 ps/div - Vertical scale: 100 mV/div
20-Gb/s PRBS7 data - 18-inch FR4 trace

- **Untreated received eye is closed, or almost closed**
- **How can it be opened?**
  - Characterize channel & compensate for it at TX/RX.
  - Use signaling schemes that best match channel. (NRZ)
  - Use coding to relax constraints. (8b/10b)
- **How to quantize performance?**

Bit-Error Rate (BER)

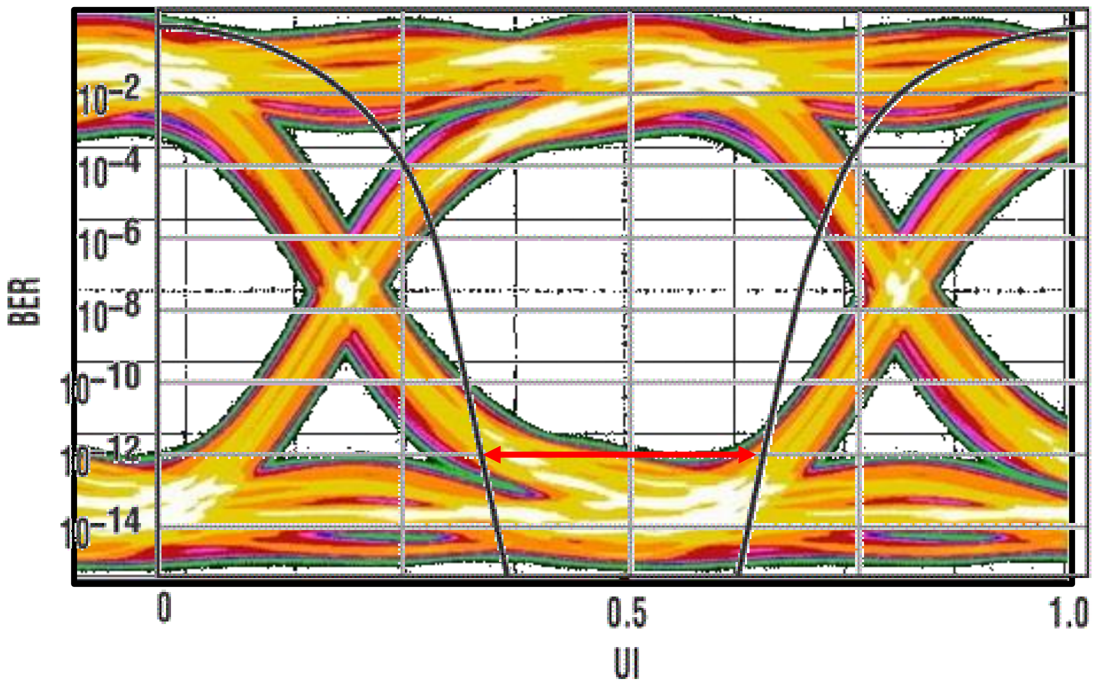
- **System overall performance is best described by BER.**
- **BER = # of erroneous bits / total number of bits.**
- **At multiple Gb/s rates, the BER requirement for most I/O communication standards is 10^{-12} or smaller.**
- **BER are measured using BERT.**
- **BERT consists of a pattern generator and error detector.**
- **Pseudo random binary sequence (PRBS) is the most common bit sequence used in BERTs to mimic a truly-random sequence.**
- **PRBS are generated by linear-feedback shift registers (LFSR).**

Link Performance Using BERT



N	Polynomial	Period	N	Polynomial	Period
31	$Y^{31}+Y^{28}+1$	$2^{31}-1$	7	$Y^{7}+Y^{6}+1$	$2^{7}-1$
23	$Y^{23}+Y^{18}+1$	$2^{23}-1$	3	$Y^{3}+Y^{1}+1$	$2^{3}-1$
15	$Y^{15}+Y^{14}+1$	$2^{15}-1$			

Bathtub Curve

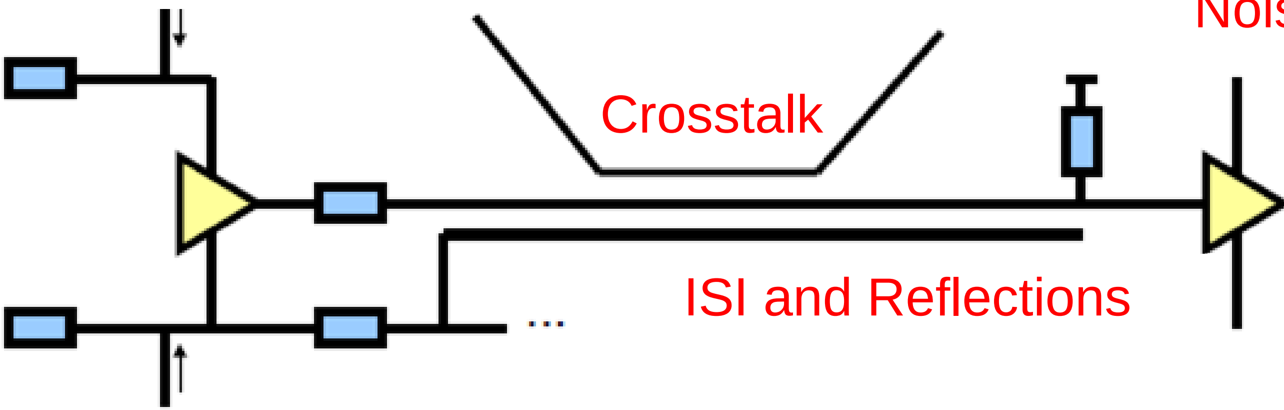


- **Shows the BER as a function of the sampling time.**
- **Determines the horizontal eye opening of the eye diagram.**
- **Heavily dependent on the system jitter.**
- **How can we predict this from the beginning?**

Traditional Approach

- **Borrowed from computer systems**
  - Built to be "error free" (10^{-20})
  - Worst-case analysis
- **Voltage/Time (VT) Budget**
  - Also called link Budget
  - Deterministic (Bounded) error sources [Cross-talk, residual-ISI, reflections, supply and reference noise, TX offsets, RX offsets and sensitivity] add in the same direction.
  - Random (Unbounded) error sources [Thermal and flicker noise] add in rms.
  - V & T completely separated.

Traditional Voltage Budget Example



- $BER = \frac{1}{2} erfc\left(\frac{h}{\sqrt{2}\sigma}\right)$
- $h = Swing - \sum DN$
- **Swing determined by residual ISI (worst case eye)**
- **DN = deterministic noise**
- **σ is obtained by rms addition.**

Signal Swing		400	mV
Vni	Rx offset + sensitivity	50	mV
	Uncancelled PS noise	20	mV
	Total Vni	70	mV
Kn	Crosstalk	10	%
	Reflections	10	%
	Total	20	%
	KnVs	80	mV
	Vn = Vni + KnVs	150	mV

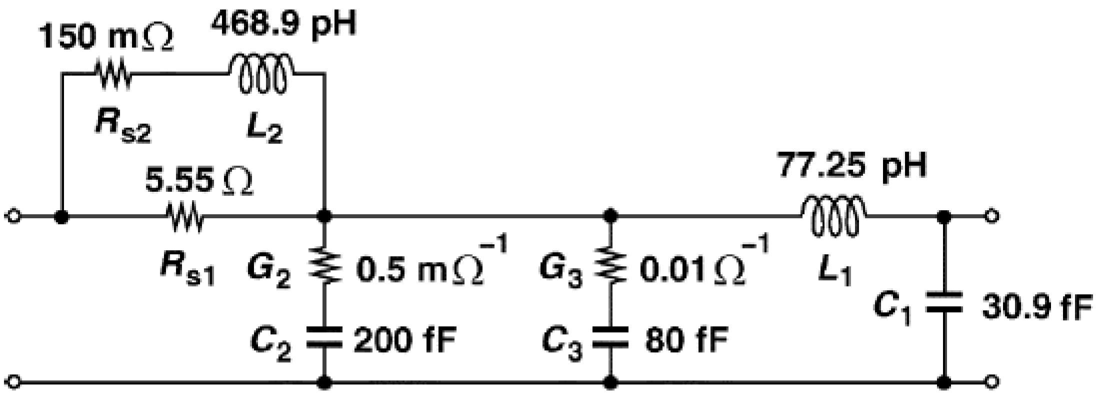
Issues with Traditional Approach

- **Worst-case analysis is not realistic, especially with large number of residual-ISI taps.**
- **Voltage and timing cannot be treated separately for modern links.**
- **Modern approach**
  - Uses noise and ISI statistics
  - Integrates timing noise with voltage noise
  - Needs mapping from time to voltage

Assignment 1

- **Assignment is due on 16/03/19 at 10 AM.**
- **Use the through channel s-parameters "channel.s4p" to provide the following plots:**
  - AC magnitude and phase (i.e., s21) from 0 Hz to 20 GHz.
  - Time-domain pulse response at 8 Gb/s indicating symbol-spaced sample values.

Assignment 1 (Contd.)



- **The figure shown is a model for a 1-inch FR4 trace that can be cascaded for longer traces.**
- **Provide the input and output eye diagram for a 6-inch FR4 trace using an 8-Gb/s PRBS source with 0.5 V_{pp} swing.**
- **Estimate the worst-case eye opening and compare it to the simulated eye.**