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

Lecture 5: Interconnect Measurement Techniques

Sam Palermo
Analog & Mixed-Signal Center
Texas A&M University

Announcements

- HW1 due NOW
- HW2 posted on website and due 2/5
- Current Reading
  - Chapter 3.4, 3.6 – 3.7
- For next time
  - TBD

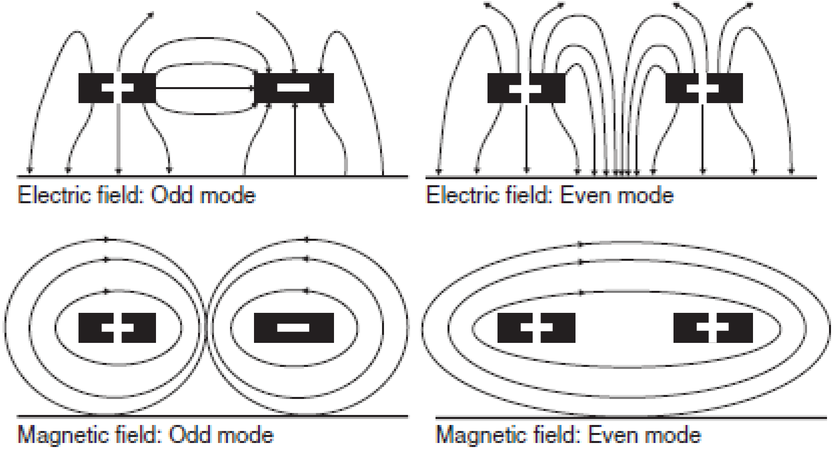
Agenda

- Differential transmission lines
- Interconnect measurement techniques
  - Time-domain reflectometry (TDR)
  - Network analyzer
    - S-parameters
- Majority of today's material from Dally Chapter 3.4, 3.6 - 3.7
- Some s-parameter material from Sackinger "Broadband Circuits" text

Differential Transmission Lines

- Differential signaling advantages
  - Self-referenced
  - Common-mode noise rejection
  - Increased signal swing
  - Reduced self-induced power-supply noise

- Requires 2x the number of signaling pins relative to single-ended signaling
  - But, smaller ratio of supply/signal (return) pins
  - Total pin overhead is typically 1.3-1.8x (vs 2x)



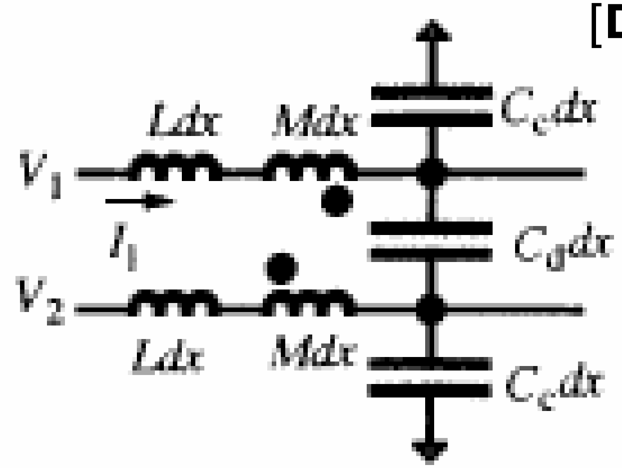
[**Hall**]

Balanced Transmission Lines

- Even (common) mode excitation
  - Effective C = C_C
  - Effective L = L + M
- Odd (differential) mode excitation
  - Effective C = $C_C + 2C_d$
  - Effective L = L – M

$$Z_{DIFF} = 2Z_{odd}, \quad Z_{CM} = \frac{Z_{even}}{2}$$

[Dally]

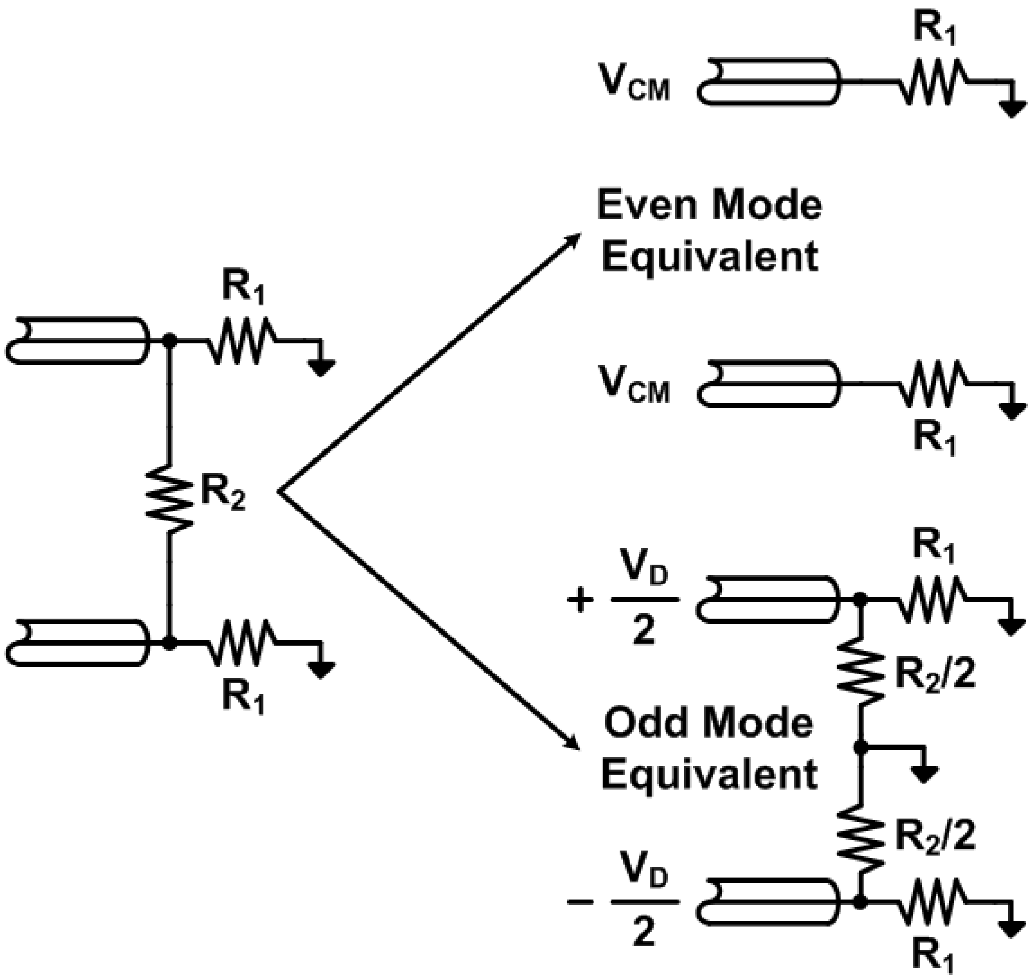


(a) Model of a Balanced Line

$$Z_{even} = \left(\frac{L+M}{C_c}\right)^{1/2}$$

$$Z_{odd} = \left(\frac{L-M}{C_c + 2C_d}\right)^{1/2}$$

PI-Termination

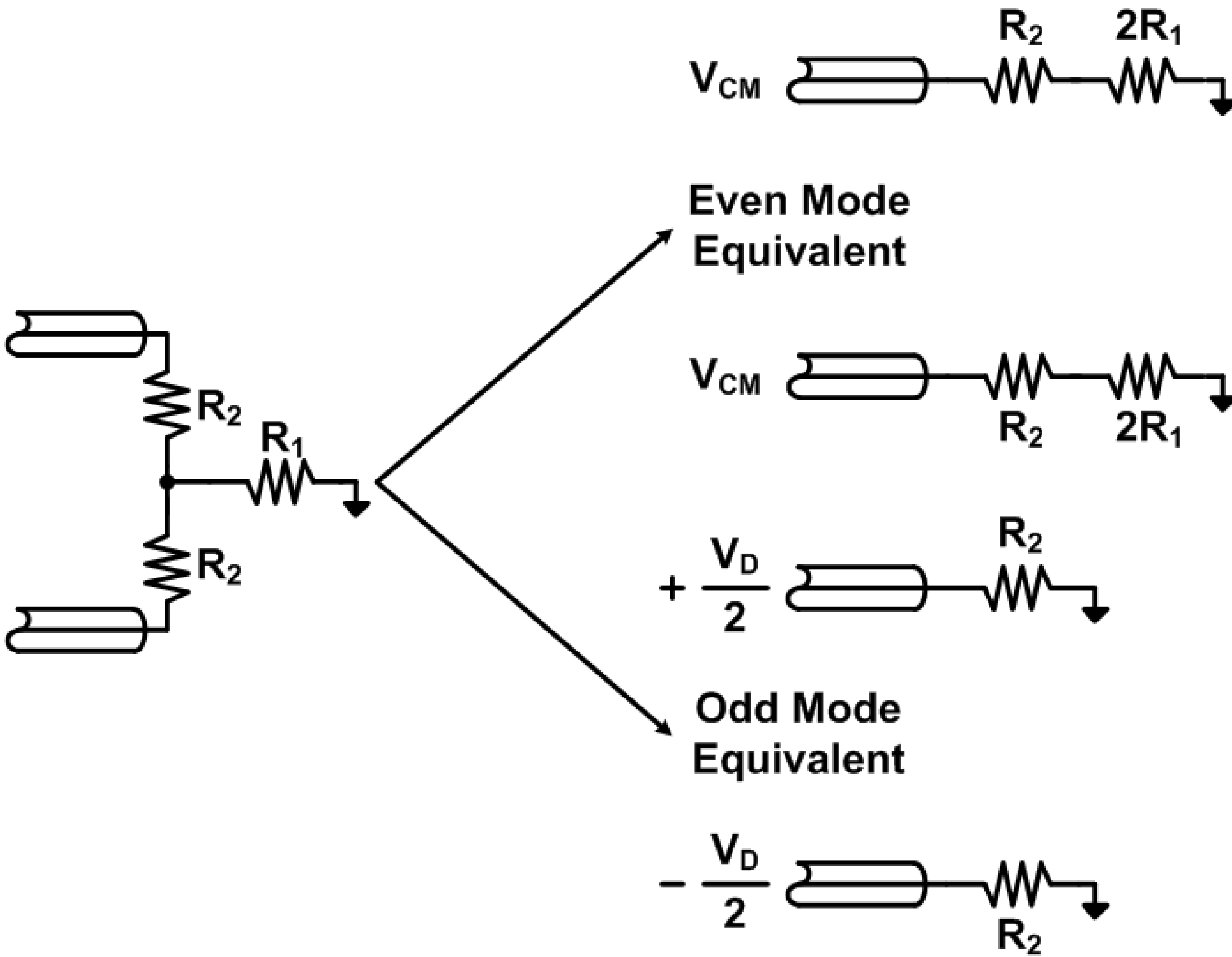


$$Z_{even} = R_1$$

$$Z_{odd} = R_1 \parallel R_2/2 = Z_{even} \parallel R_2/2$$

$$R_2 = 2\left(\frac{Z_{odd} Z_{even}}{Z_{even} - Z_{odd}}\right)$$

T-Termination

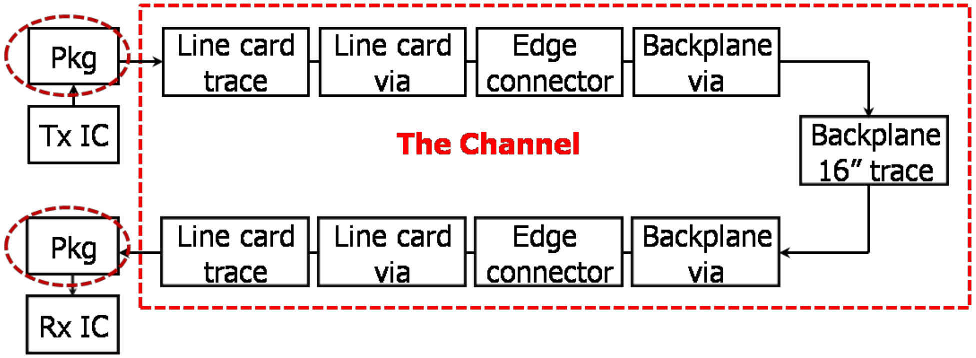


$$Z_{even} = R_2 + 2R_1$$

$$Z_{odd} = R_2$$

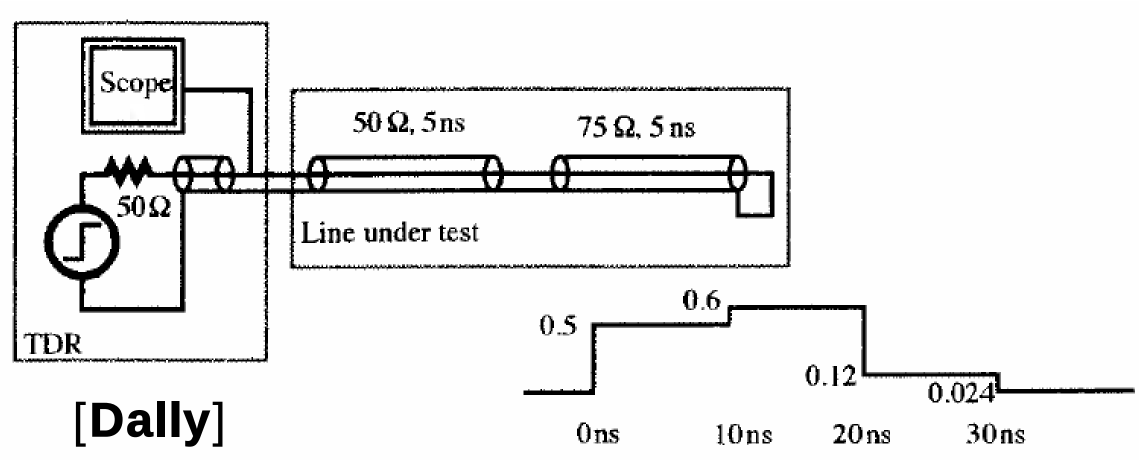
$$R_1 = \frac{1}{2}\left(Z_{even} - Z_{odd}\right)$$

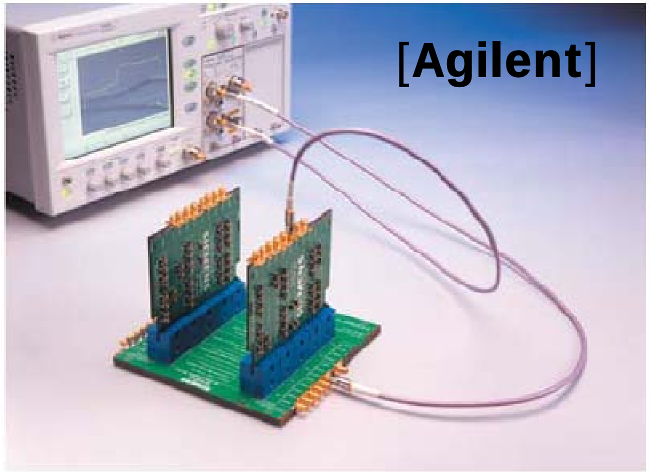
Interconnect Modeling



- 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)

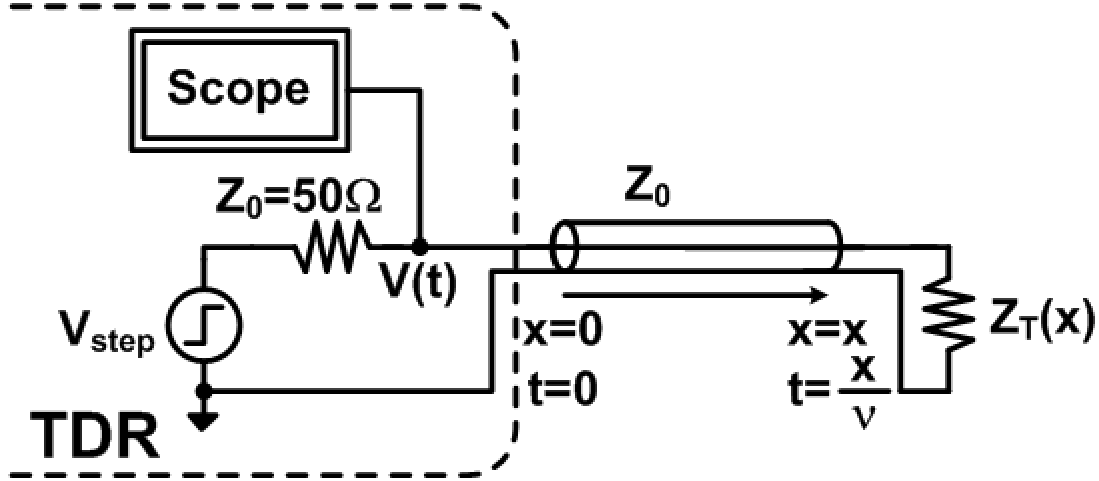
Time-Domain Reflectometer (TDR)





- 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



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

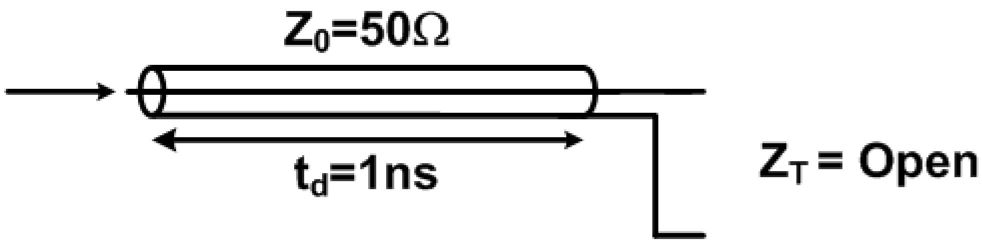
$$Z_T(t) = Z_0\left(\frac{1 + k_r(t)}{1 - k_r(t)}\right) = Z_0\left(\frac{V_i + V_r(t)}{V_i - V_r(t)}\right) = Z_0\left(\frac{V(t)}{2V_i - V(t)}\right)$$

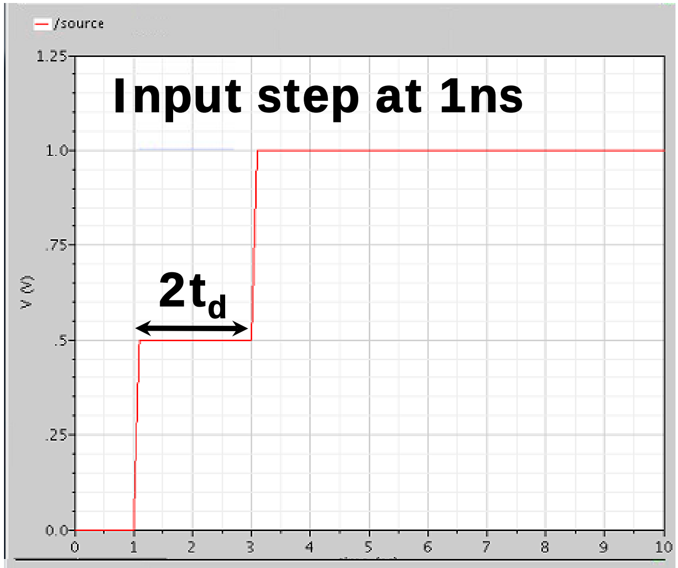
$$\text{If } V_{\text{STEP}} = 1V \Rightarrow V_i = 0.5\text{V}$$

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

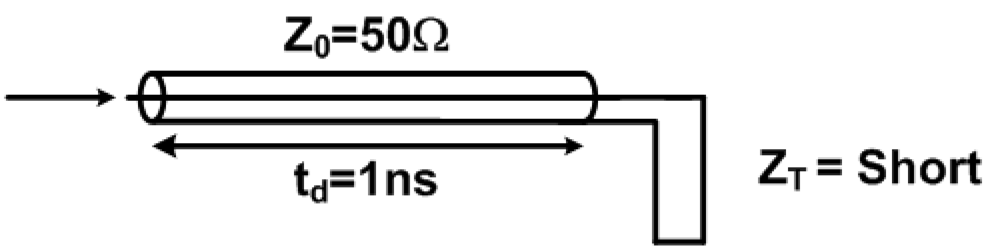
TDR Waveforms (Open & Short)

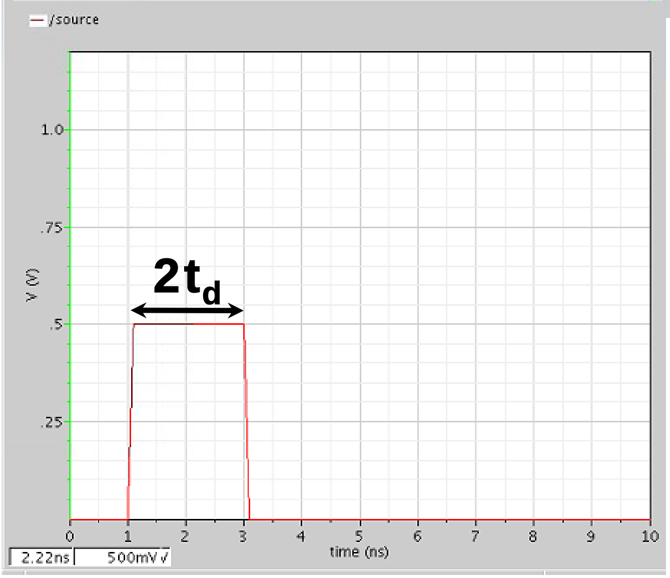
- Open termination





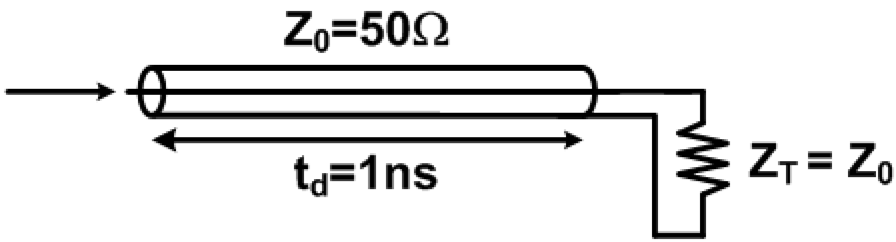
- Short termination

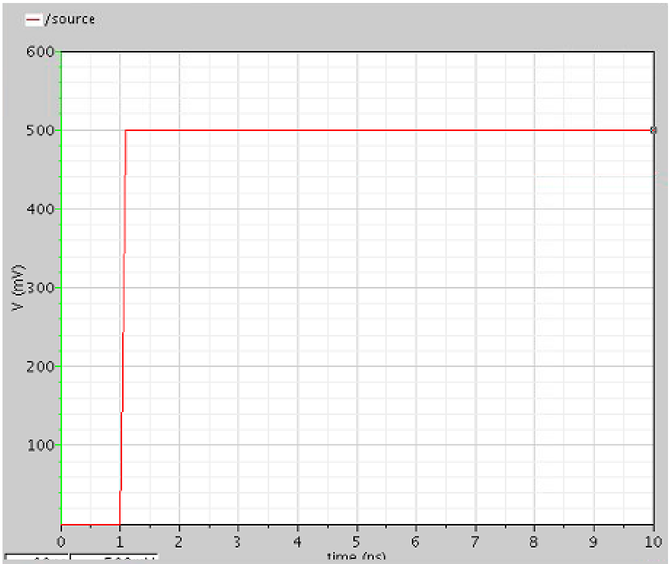




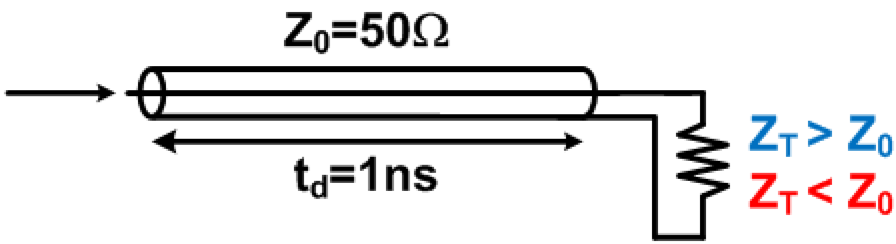
TDR Waveforms (Matched & Mismatched)

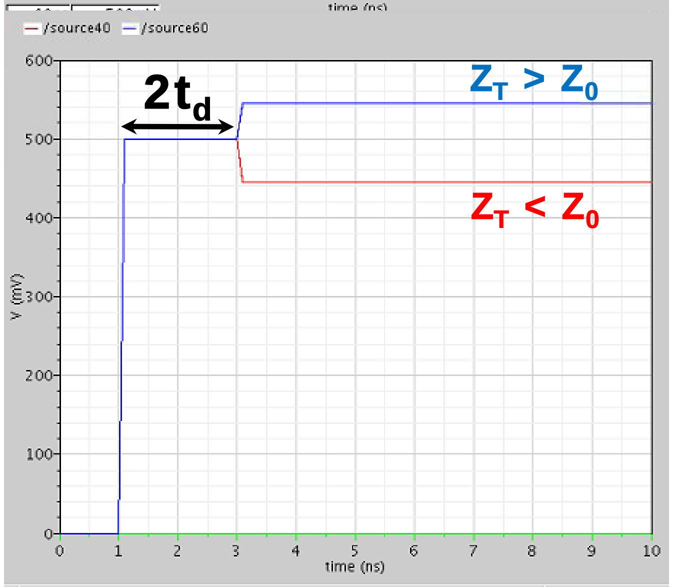
- Matched termination





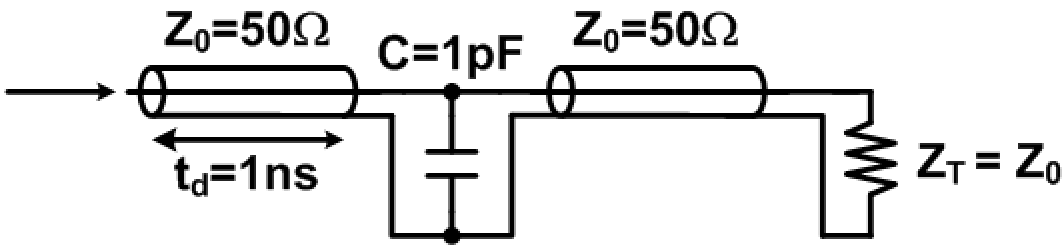
- Mismatched termination



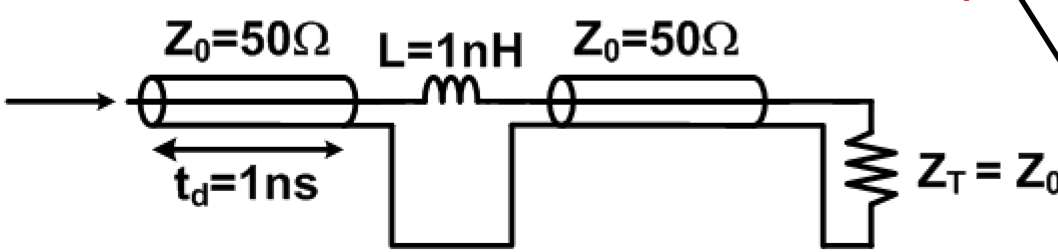


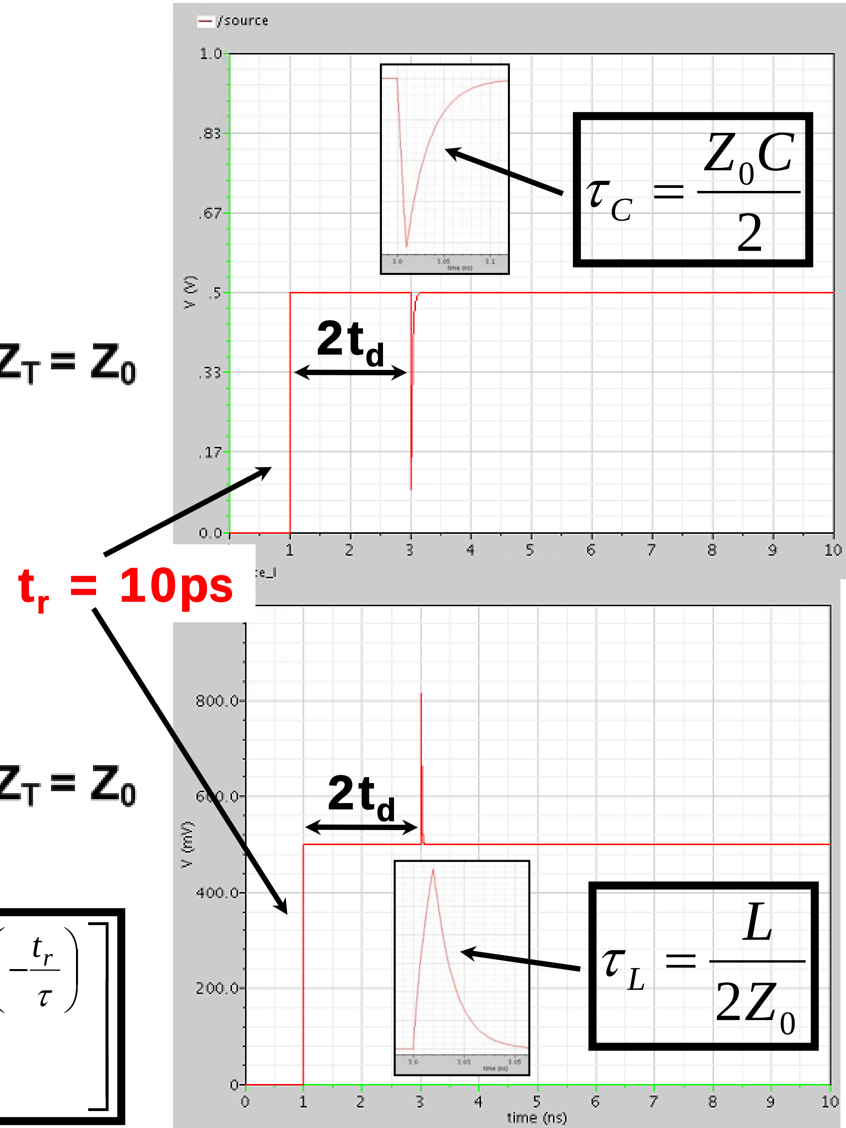
TDR Waveforms (C & L Discontinuity)

- Shunt C discontinuity



- Series L discontinuity





$$\tau_C = \frac{Z_0 C}{2}$$

$$\tau_L = \frac{L}{2Z_0}$$

Peak voltage spike magnitude:

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

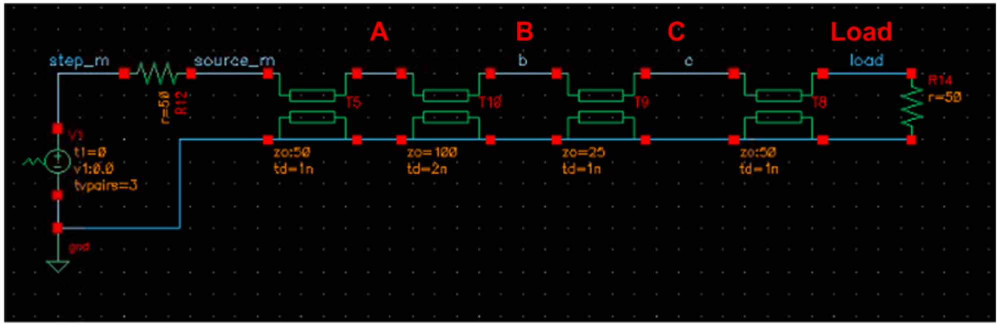
TDR Rise Time and Resolution

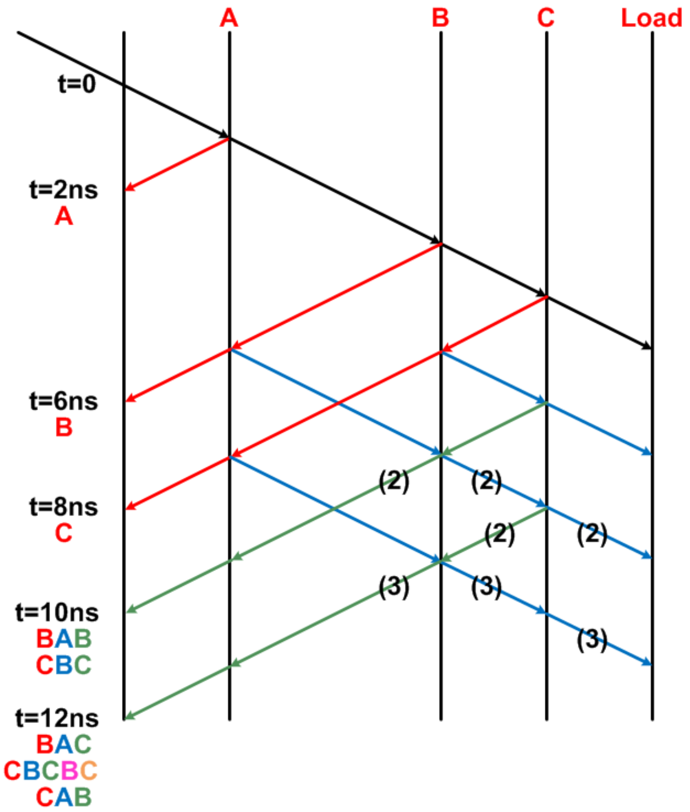
- TDR spatial resolution is set by step risetime

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

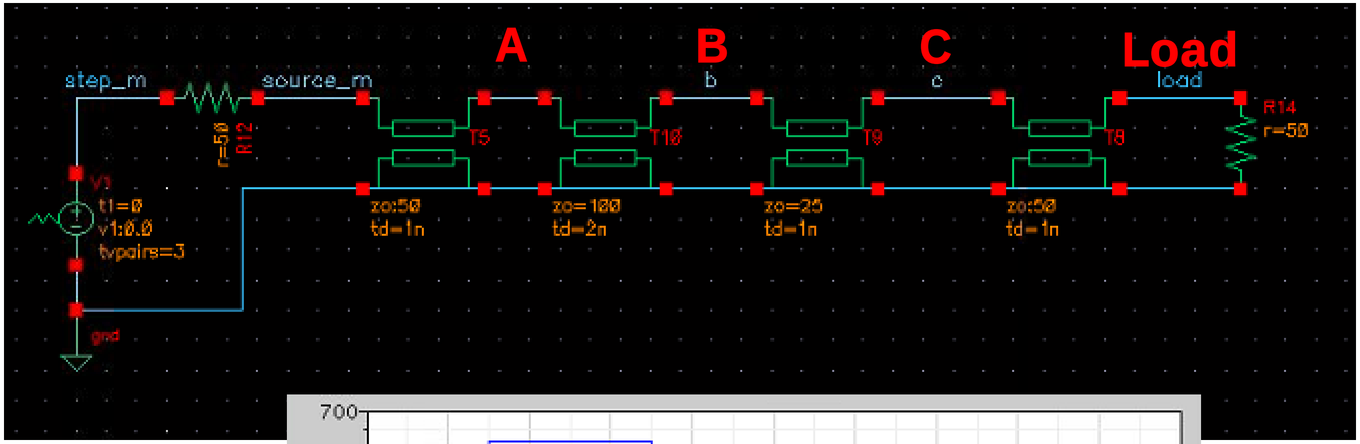
- Step risetime degrades with propagation through channel
  - Dispersion from skin-effect
  - Lump discontinuities low-pass filter the step
- Causes difficulty in estimating L & C values
- Channel filtering can actually compensate for lump discontinuity spikes ☺

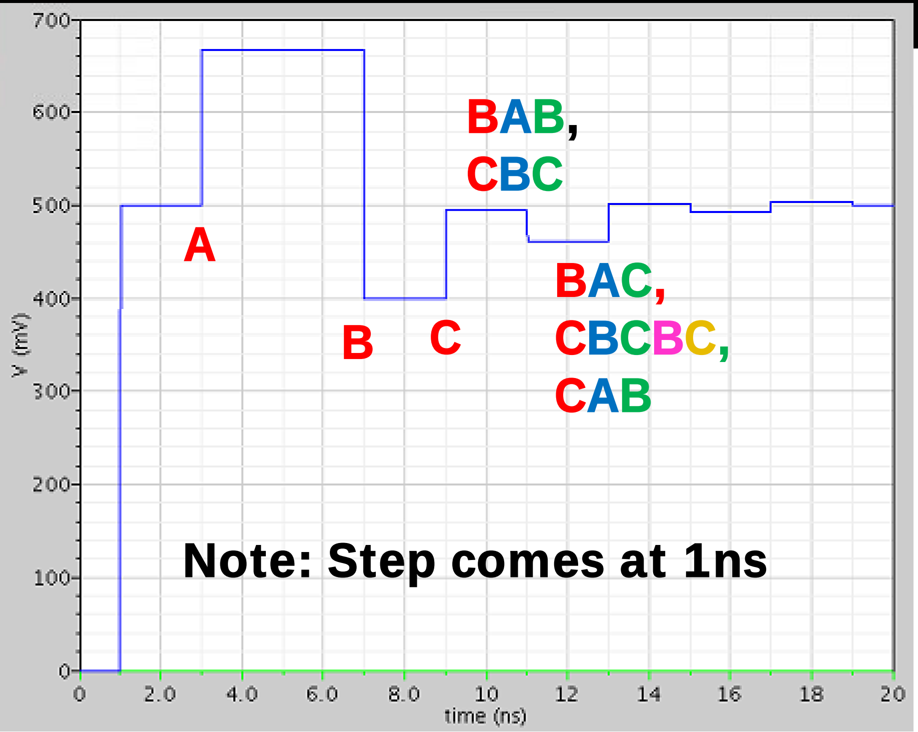
TDR Multiple Reflections



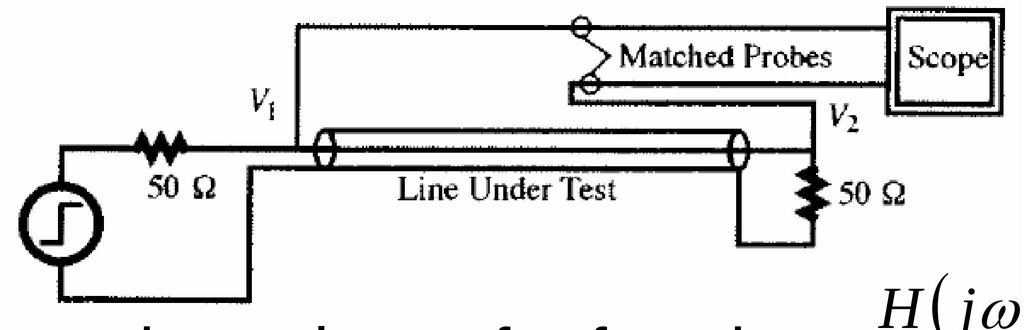


TDR Waveforms (Multiple Discontinuities)





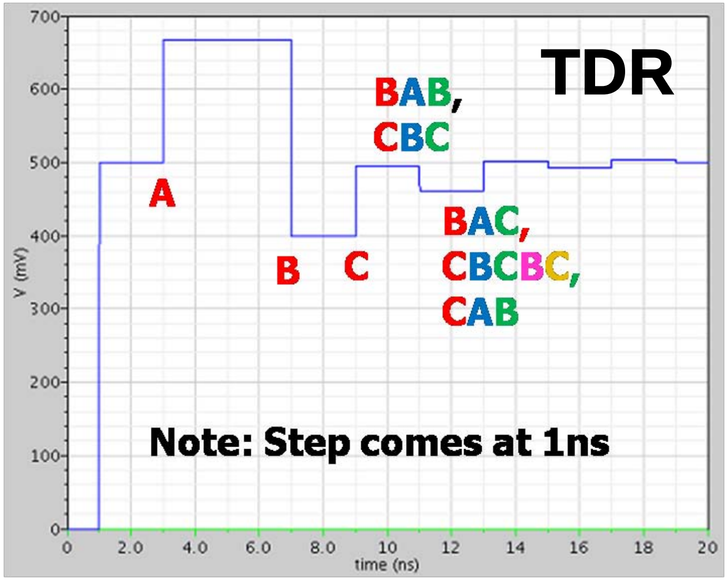
Time-Domain Transmission (TDT)

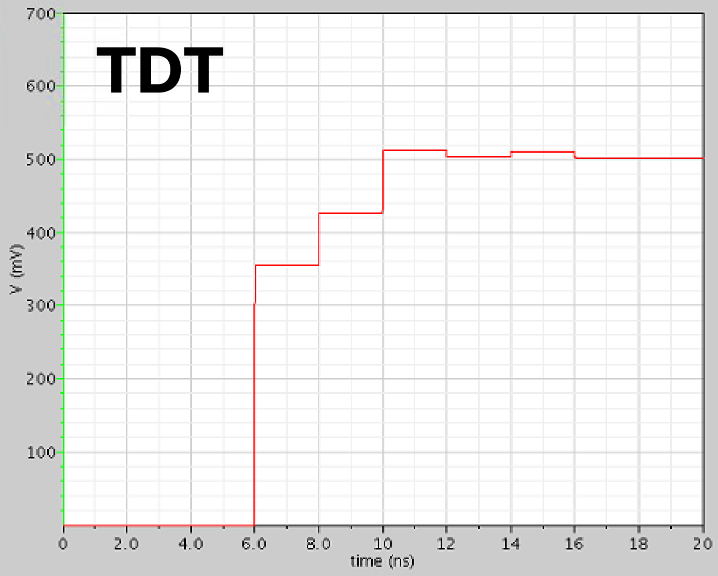


[Dally]

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

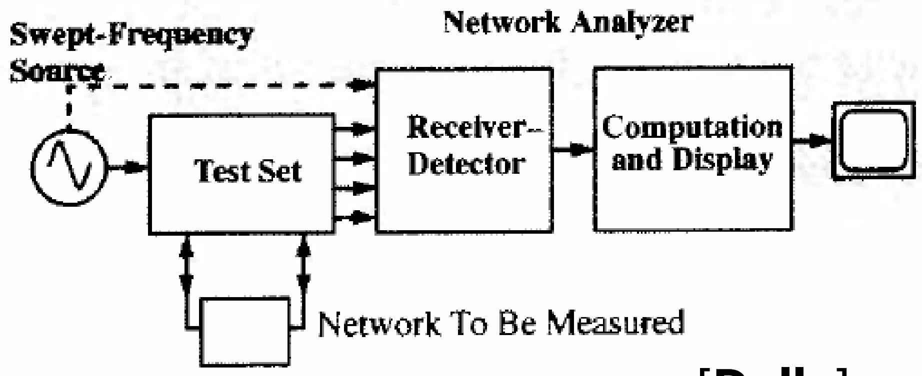
- Can measure channel transfer function
- Hard to isolate impedance discontinuities, as they are superimposed on a single rising edge





Network Analyzer

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



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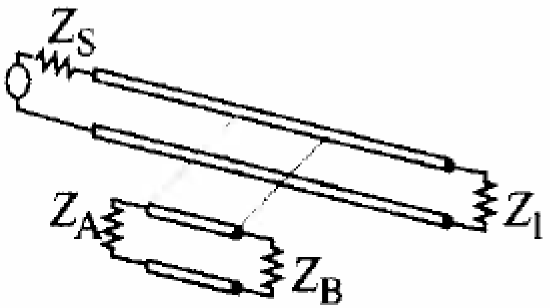
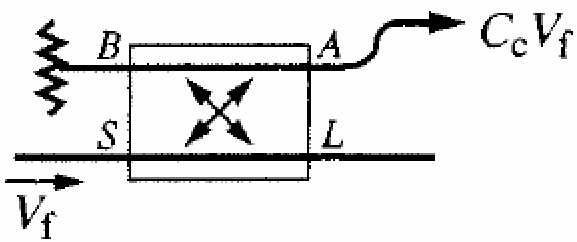
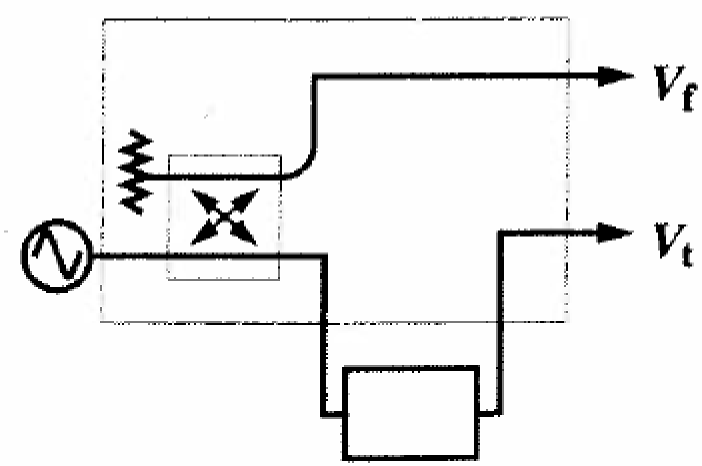


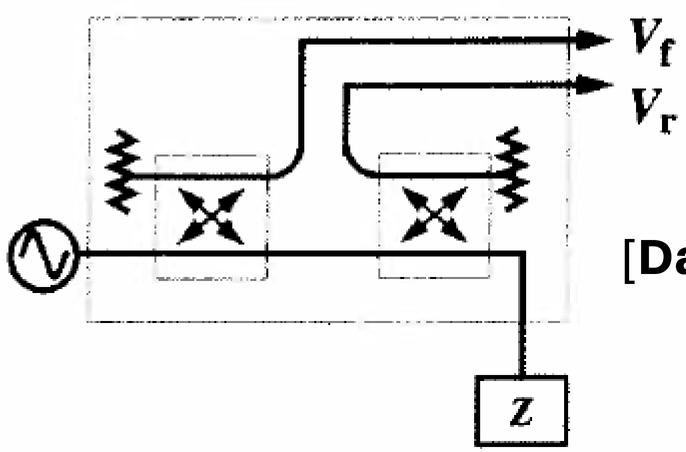
Direction Coupler



Transfer Function & Impedance Measurements



Test Set for Transfer Function

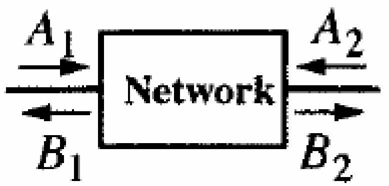


Test Set for Impedance Measurements

[**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

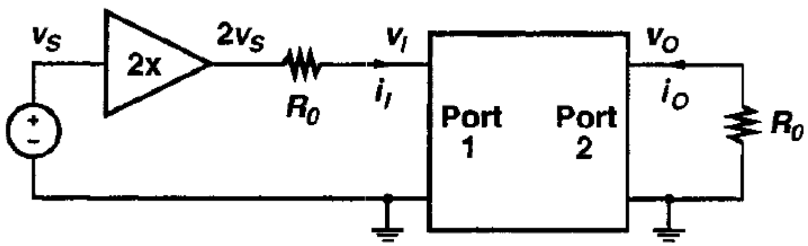


$$\begin{bmatrix} B_1 \\ B_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} A_1 \\ A_2 \end{bmatrix}$$

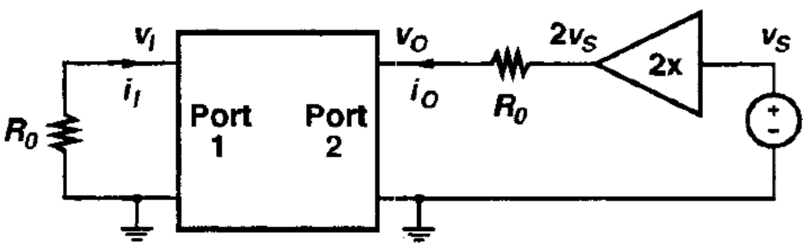
S-matrix

[**Dally**]

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
- 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 voltage gain

Next Time

- S-parameter examples
- Impulse response generation
- Communication techniques
  - Eye Diagram
  - Intersymbol interference
  - Modulation techniques