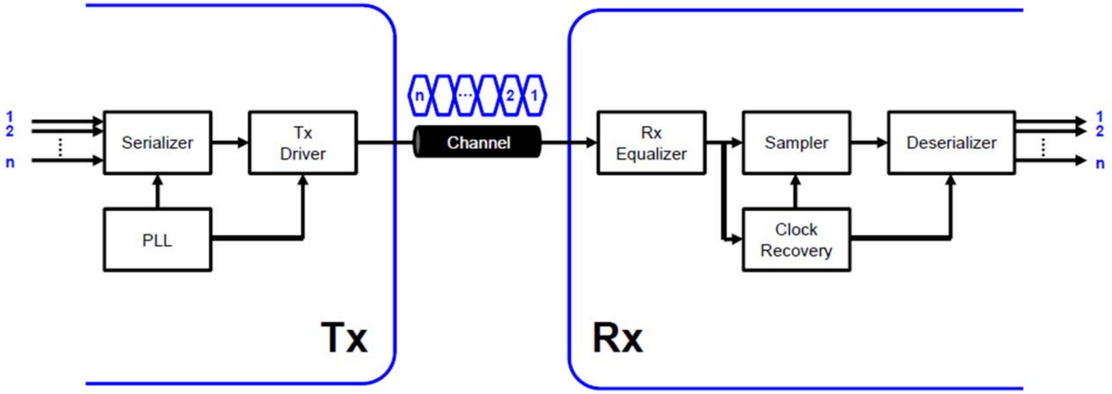
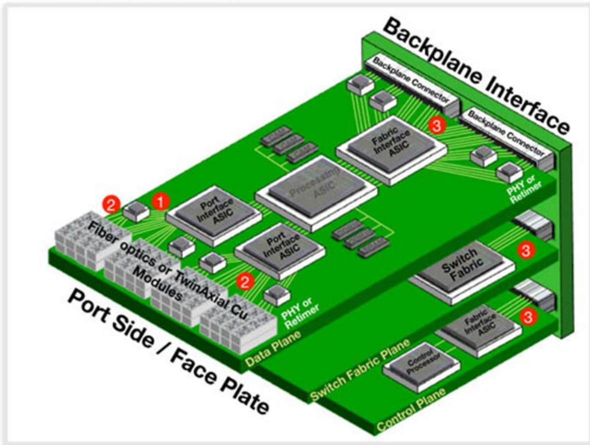
High-speed Serial Interface

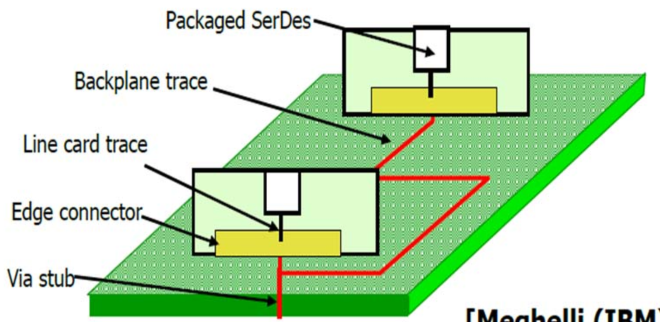
Lect. 6 – Channels

(Ref.: Prof. Palermo's Lecture Notes for "High-Speed Links Circuits and Systems", Texas A&M)

High-Speed Serial Interface



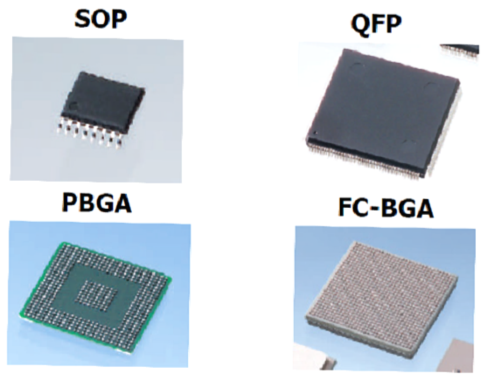


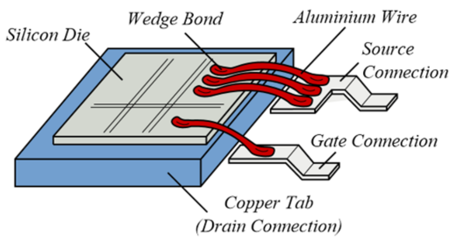


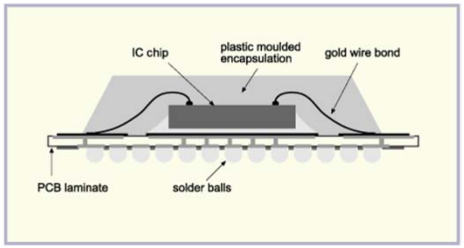
[Meghelli (IBM) ISSCC 2006]

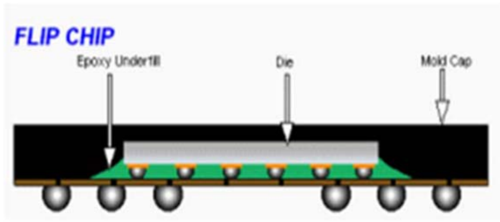
Chip Packages

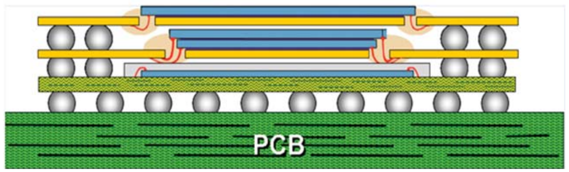
Package Type	Pin Count
Small Outline Package (SOP)	8 – 56
Quad Flat Package (QFP)	64 - 304
Plastic Ball Grid Array (PBGA)	256 - 420
Enhanced Ball Grid Array (EBGA)	352 - 896
Flip Chip Ball Grid Array (FC-BGA)	1089 - 2116

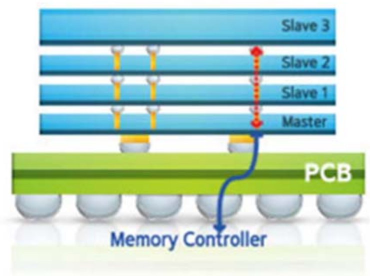








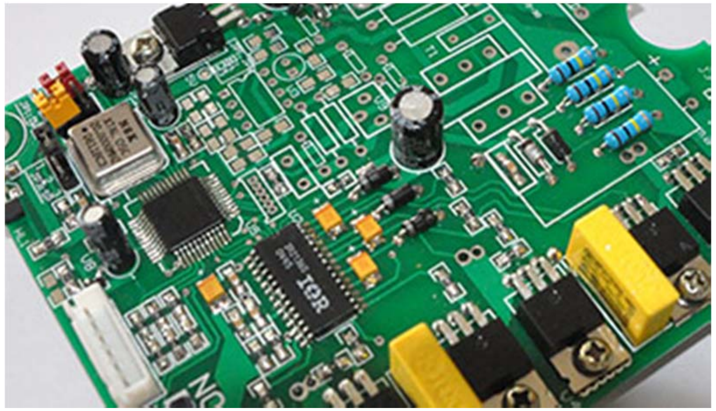


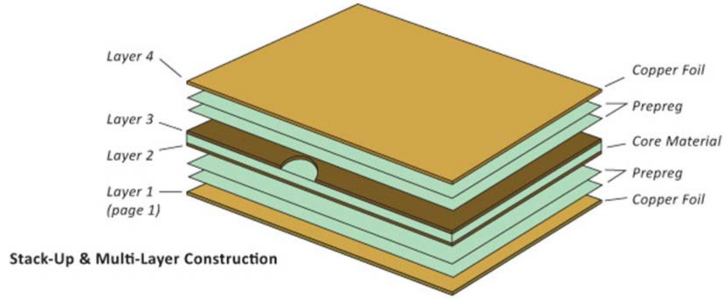


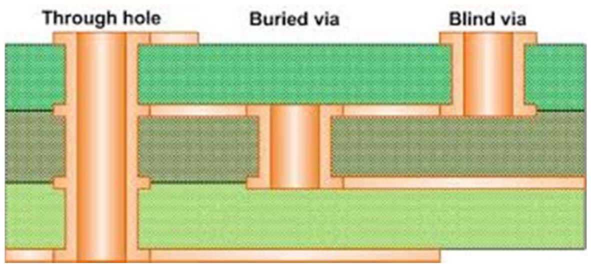
- Very important aspect of performance and cost

- Must be considered for high-speed design

PCB







- Pattern individual core layers
- Stack up core layers separated by prepreg (FR4, Flame Retardant)
- Place copper foils top and bottom
- 'Cook' in the oven with pressure
- Drill via holes and electro-plate
- Pattern top/bottom layers
- For buried via, stack after drilling and electro-plating

- FR4-based PCBs are mass-producible but lossy at high frequencies

- Since they are well established and cost-effective,

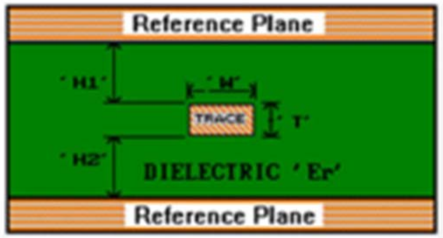
  industry does not want to replace it with better-performance materials

PCB Traces

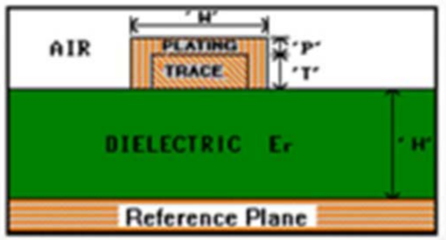
- Interconnects for high-speed signals require two metal electrodes separated by dielectric insulator

➔ Transmission Line

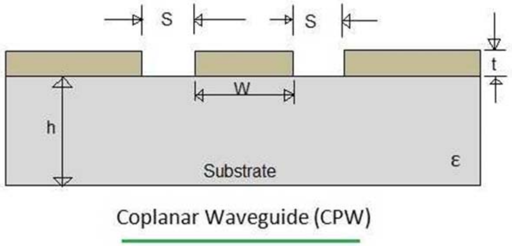
Strip line



Microstrip Line



Coplanar Waveguide

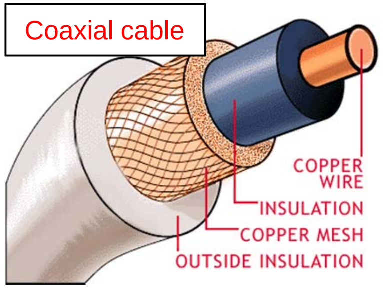


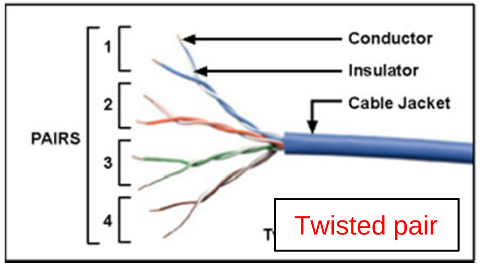
TL Parameters: L, C, R, G (per unit length)

Loss: conductor loss, dielectric loss

Cables

- Coaxial cable
- Mineral-insulated copper-clad cable
- Twinax cable
- Flexible cables
- Non-metallic sheathed cable
- Metallic sheathed cable
- Multicore cable
- Shielded cable
- Single cable
- Twisted pair
- Twisting cable





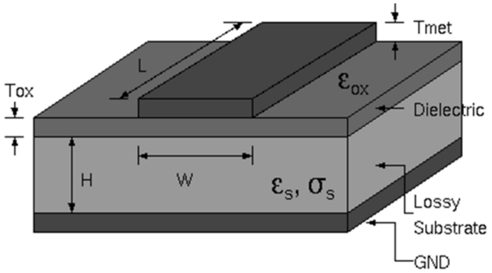
Name	Type	Bandwidth	Applications
Level 1		0.4 MHz	Telephone and modem lines
Level 2		4 MHz	Older terminal systems, e.g. IBM 3270
Cat3	UTP[7]	16 MHz[7]	10BASE-T and 100BASE-T4 Ethernet[7]
Cat4	UTP[7]	20 MHz[7]	16 Mbit/s[7] Token Ring
Cat5	UTP[7]	100 MHz[7]	100BASE-TX & 1000BASE-T Ethernet[7]
Cat5e	UTP[7]	100 MHz[7]	100BASE-TX & 1000BASE-T Ethernet[7]
Cat6	UTP[7]	250 MHz[7]	10GBASE-T Ethernet
Cat6a		500 MHz	10GBASE-T Ethernet
Class F	S/FTP[7]	600 MHz[7]	Telephone, CCTV, 1000BASE-TX in the same cable. 10GBASE-T Ethernet.
Class Fa		1000 MHz	Telephone, CATV, 1000BASE-TX in the same cable. 10GBASE-T Ethernet.

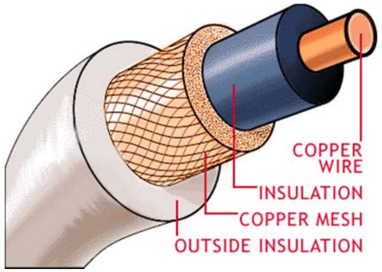
Cables are usually used for longer and flexible interconnects
High-quality cables provide good performance but expensive

Lossy at very high frequencies ➔ Optical fiber

Conductor Loss

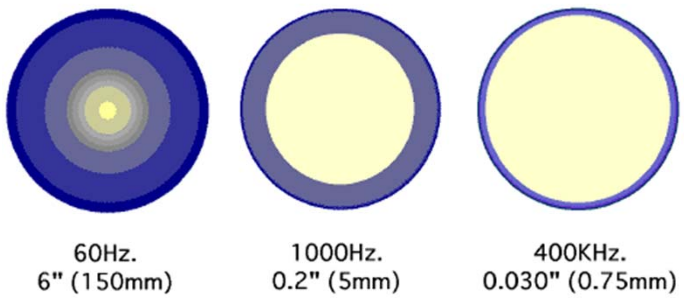
– Conductors used for traces and cables have high but finite conductivity (*R* among four trace circuit parameters)





– As frequency increases, skin depth decreases resulting in larger resistance

CURRENT PENETRATION DEPTH IN STEEL (CURRENT SHOWN IN BLUE)

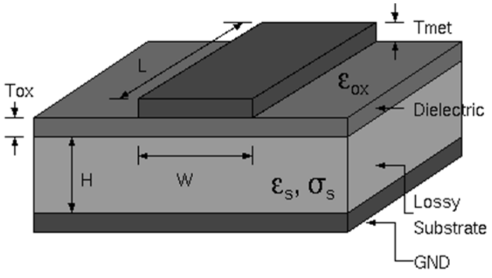


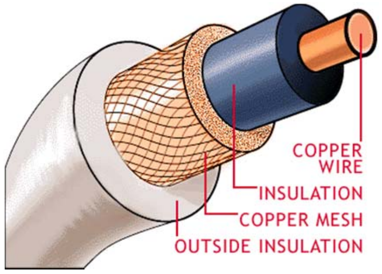
$$R(f) = R_{DC}\left(\frac{f}{f_s}\right)^{\frac{1}{2}}$$

- Conductor loss is proportional to $\sqrt{f}$

Dielectric loss

– Loss in the insulator between metal layers



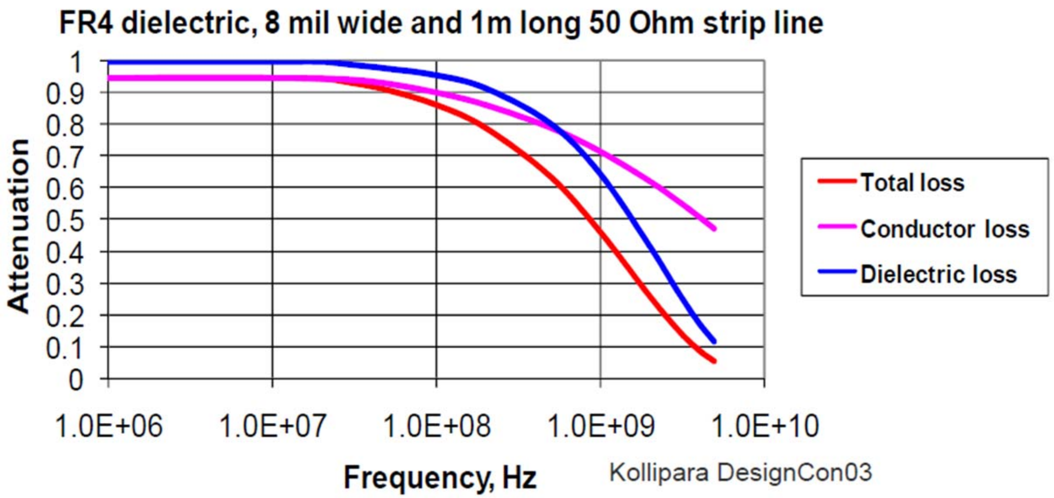


– Due to small but non-zero conductivity in the insulator (*G* among four trace circuit parameters)

– Dielectric loss is proportional to f

Channel loss

Total loss: Sum of conductor loss and dielectric loss

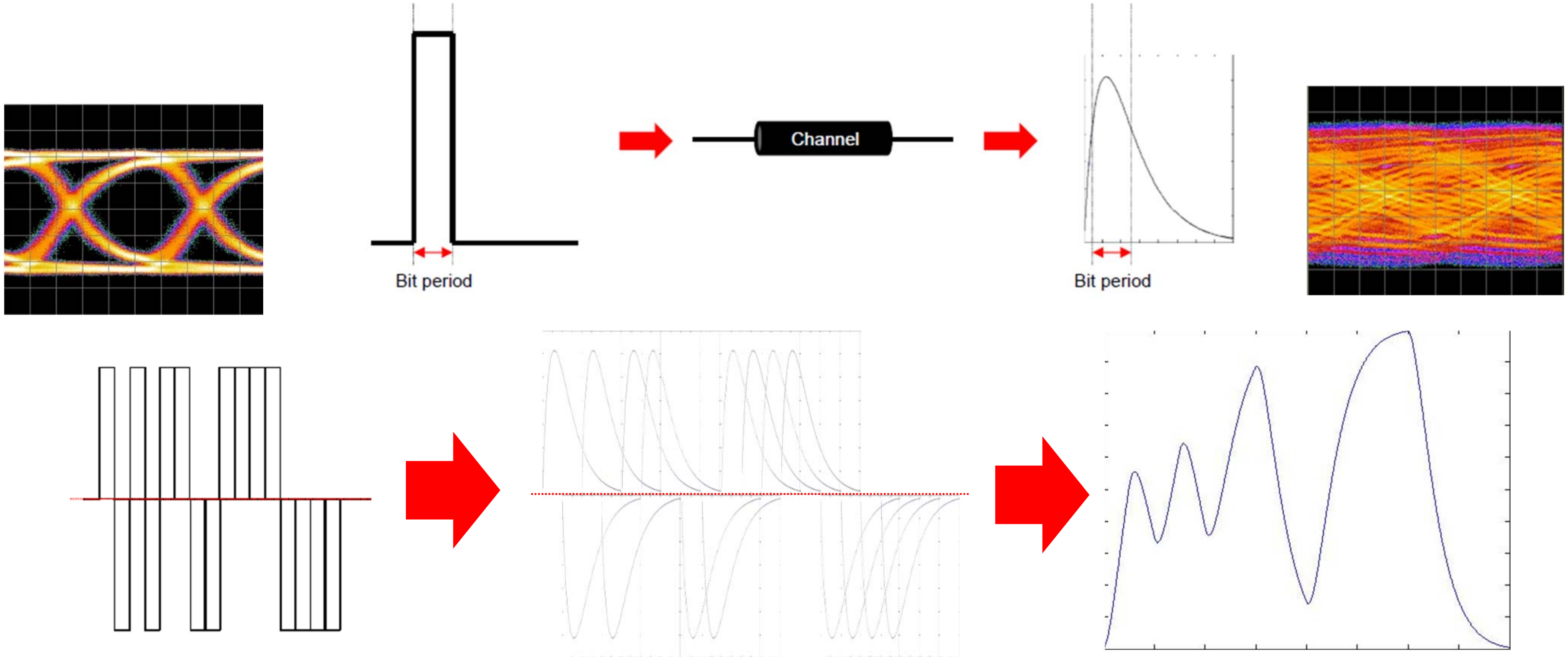


– In low frequency, conductor loss > dielectric loss
– In high frequency, conductor loss < dielectric loss

Bandwidth limitation due to f-dependent loss!

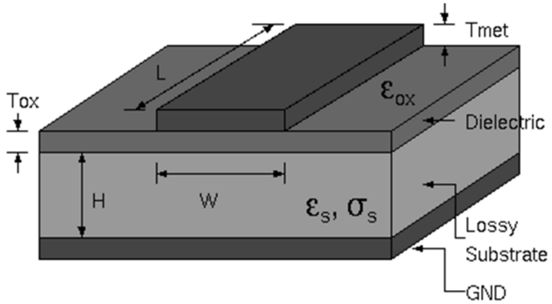
Inter-symbol interference due to f-dependent loss

– Broadened pulse response through the channel

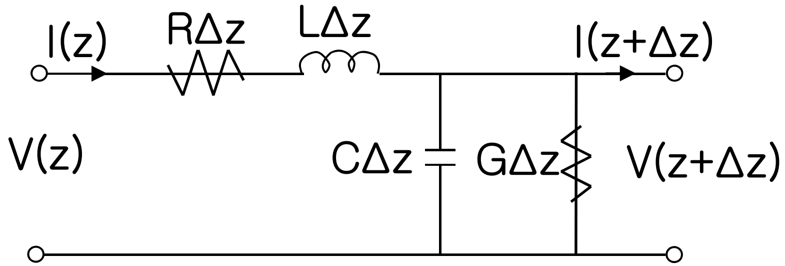


Challenges for high-speed serial links

Channel Modeling: Transmission Line



Circuit Model



Analyze the circuit in the frequency domain

$$V(z) - I(z)R\Delta z - I(z)\,j\omega L\Delta z = V(z+\Delta z)$$

$$\frac{V(z) - V(z+\Delta z)}{\Delta z} = RI(z) + j\omega LI(z)$$

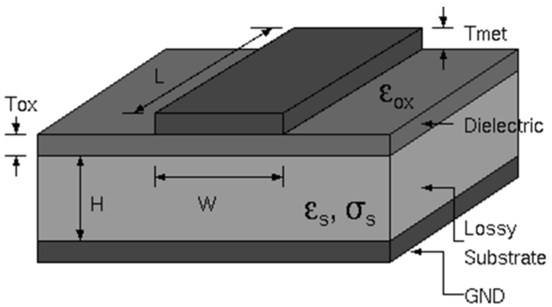
$$\Delta z \to 0 \qquad -\frac{dV(z)}{dz} = (R + j\omega L)I(z)$$

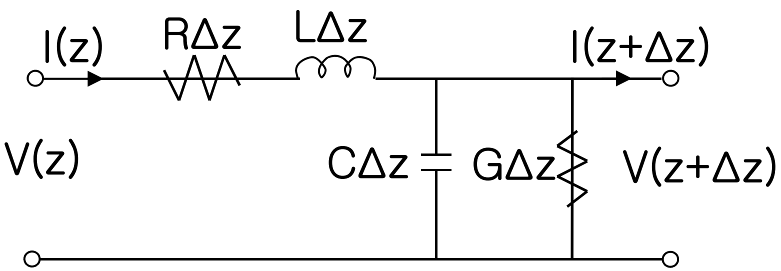
$$I(z) - V(z+\Delta z)G\Delta z - V(z+\Delta z)\,j\omega C = I(z+\Delta z)$$

$$\frac{I(z) - I(z+\Delta z)}{\Delta z} = GV(z+\Delta z) + j\omega CV(z+\Delta z)$$

$$\Delta z \to 0 \qquad -\frac{dI(z)}{dz} = (G + j\omega C)V(z)$$

Transmission Line





$$-\frac{dV}{dz} = (R + j\omega L)I \qquad -\frac{dI}{dz} = (G + j\omega C)V$$

$$\frac{d^2V}{dz^2} = (R + j\omega L)(G + j\omega C)V = \gamma^2 V$$

$$\frac{d^2I}{dz^2} = (R + j\omega L)(G + j\omega C)I = \gamma^2 I$$

➔ Transmission line equations

Transmission Line

Solutions for transmission line equation

$$\frac{d^2V}{dz^2} = (R + j\omega L)(G + j\omega C)V = \gamma^2 V$$

$$V(z) = V_0^+ e^{-\gamma z} + V_0^- e^{\gamma z}$$

$$\frac{dV}{dz} = -\gamma V_0^+ e^{-\gamma z} + \gamma V_0^- e^{\gamma z}$$

$$\frac{d^2V}{dz^2} = \gamma^2 V(z) \qquad \gamma = \sqrt{(R + j\omega L)(G + j\omega C)} = \alpha + j\beta$$

For $V_0^- = 0, \quad V(z) = V_0^+ e^{-\alpha z} e^{-j\beta z}$ Wave propagation with attenuation

α: attenuation constant

β: phase constant

$$\lambda = \frac{2\pi}{\beta}$$

Transmission Line

TL Characteristic Impedance:

For $V(z) = V_0^+ e^{-\gamma z}$

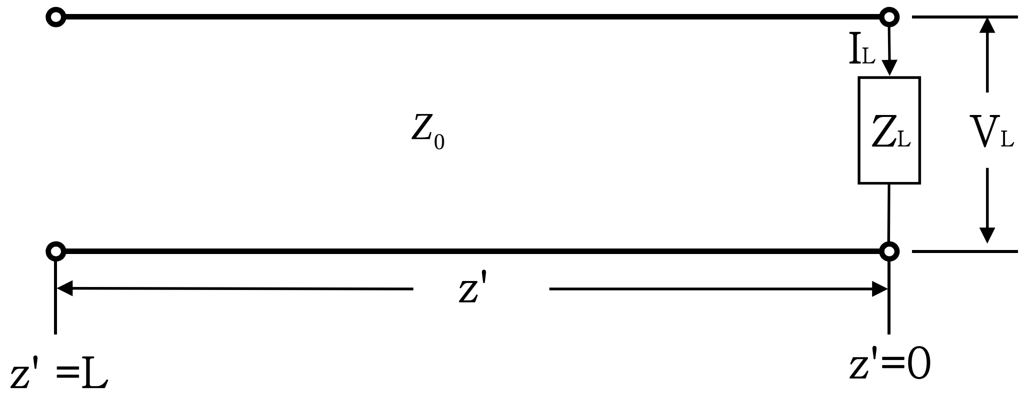
From $\dfrac{dV(z)}{dz} = -(R + j\omega L)I(z)$

$$-\gamma V(z) = -(R + j\omega L)I(z)$$

$$Z_0 = \frac{V(z)}{I(z)} = \frac{(R + j\omega L)}{\gamma} = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

- Z_0 is independent of TL location
- Z_0 is dependent on ω unless R=G=0
- If *R*=*G*=0, $Z_0 = \sqrt{\dfrac{L}{C}}$

Reflection in TL



$$\frac{d^2V}{dz^2} = \gamma^2 V, \quad \frac{d^2I}{dz^2} = \gamma^2 I$$

It can be shown

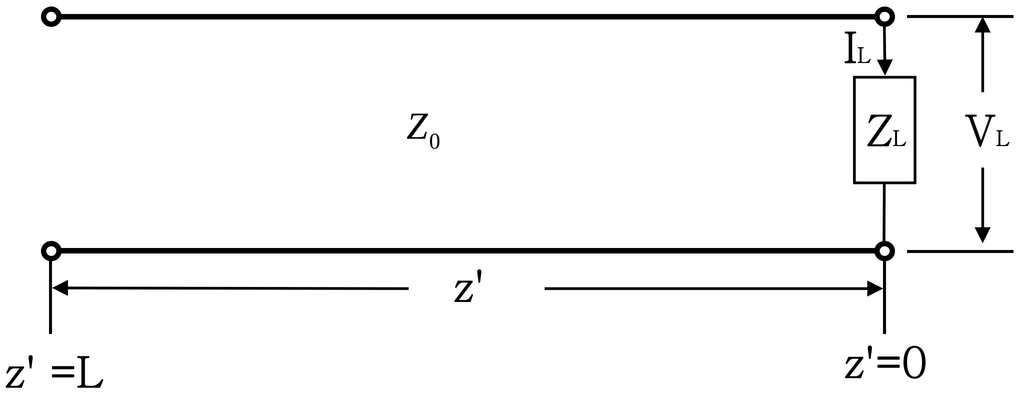
$$V(z') = \frac{I_L}{2}(Z_L + Z_0)e^{\gamma z'}\left[1 + \Gamma e^{-2\gamma z'}\right] \qquad I(z') = \frac{I_L}{2Z_0}(Z_L + Z_0)e^{\gamma z'}\left[1 - \Gamma e^{-2\gamma z'}\right]$$

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$ Reflection Coefficient

Γ = -1 for short Γ = 1 for open

$$Z(z') = Z_0 \frac{1 + \Gamma e^{-2\gamma z'}}{1 - \Gamma e^{-2\gamma z'}}$$

Reflection in TL



$$V(z') = \frac{I_L}{2}(Z_L + Z_0)e^{\gamma z'}\left[1 + \Gamma e^{-2\gamma z'}\right]$$

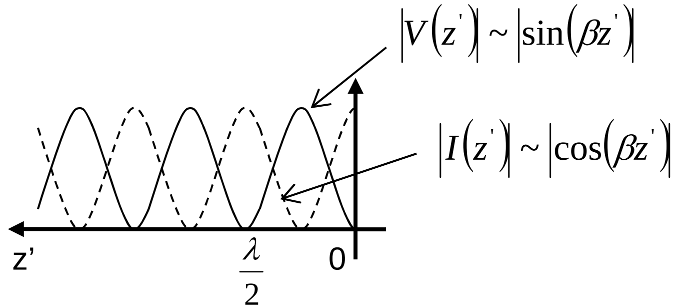
$$I(z') = \frac{I_L}{2Z_0}(Z_L + Z_0)e^{\gamma z'}\left[1 - \Gamma e^{-2\gamma z'}\right]$$

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$

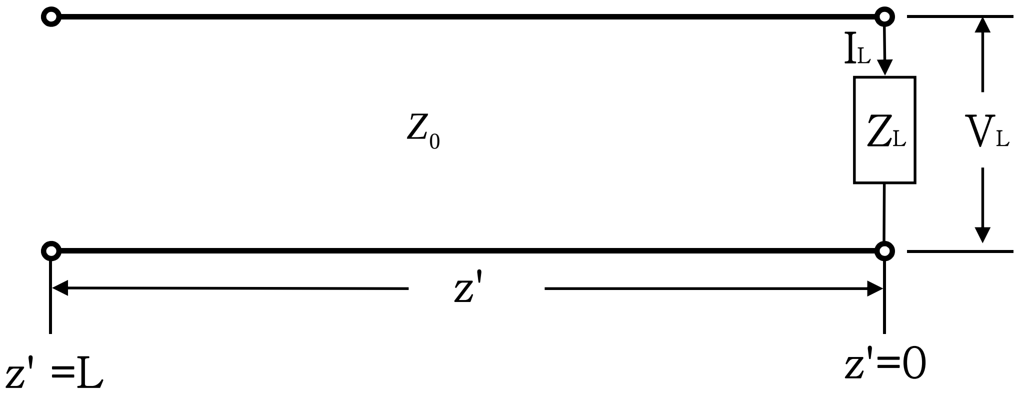
For γ=jβ and $Z_L = 0$

$$\left|V(z')\right| \sim \left|1 + \Gamma e^{-j2\beta z'}\right| = \left|1 - e^{-j2\beta z'}\right| = \left|e^{-j\beta z'} \cdot (e^{j\beta z'} - e^{-j\beta z'})\right| = 2\left|\sin(\beta z')\right|$$

$$\left|I(z')\right| = 2\left|\cos(\beta z')\right|$$



Reflection in TL

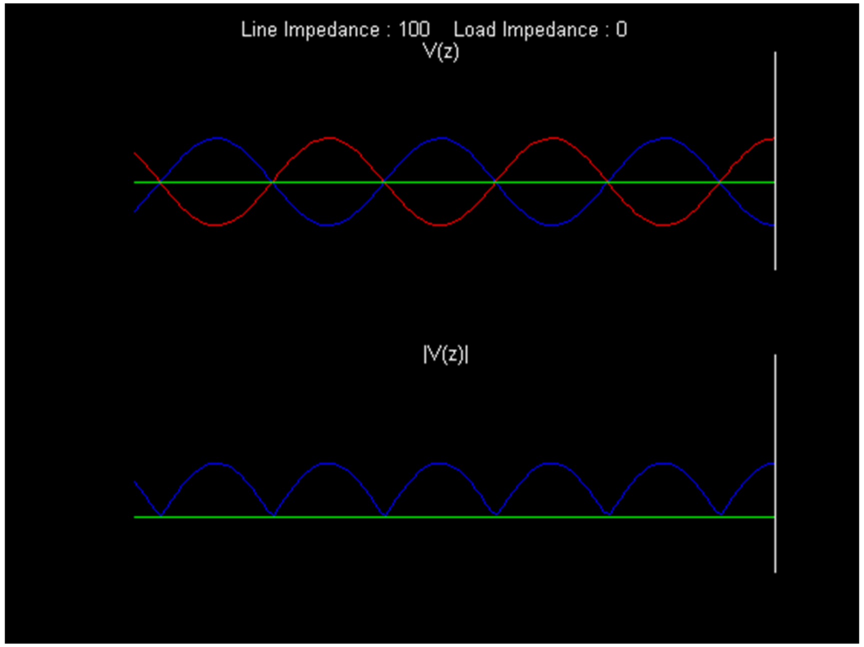


$$V(z') = \frac{I_L}{2}(Z_L + Z_0)e^{\gamma z'}\left[1 + \Gamma e^{-2\gamma z'}\right]$$

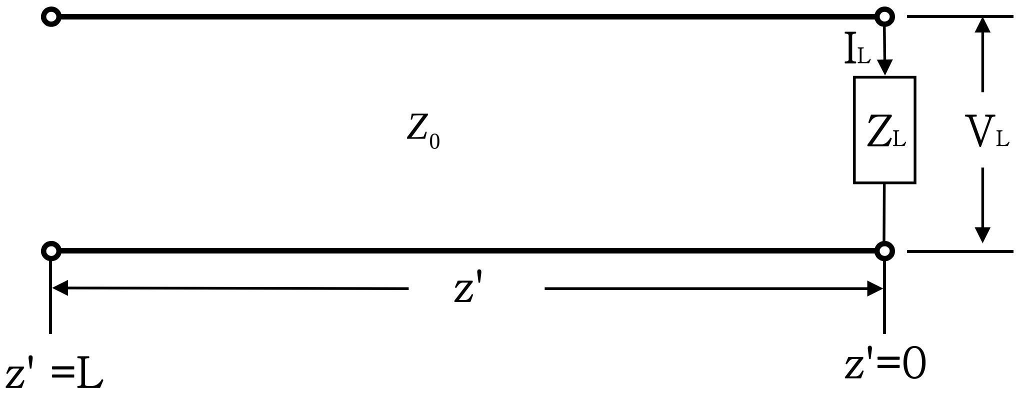
$$I(z') = \frac{I_L}{2Z_0}(Z_L + Z_0)e^{\gamma z'}\left[1 - \Gamma e^{-2\gamma z'}\right]$$

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$

For γ=jβ and $Z_L = 0$



Reflection in TL



$$V(z') = \frac{I_L}{2}(Z_L + Z_0)e^{\gamma z'}\left[1 + \Gamma e^{-2\gamma z'}\right]$$

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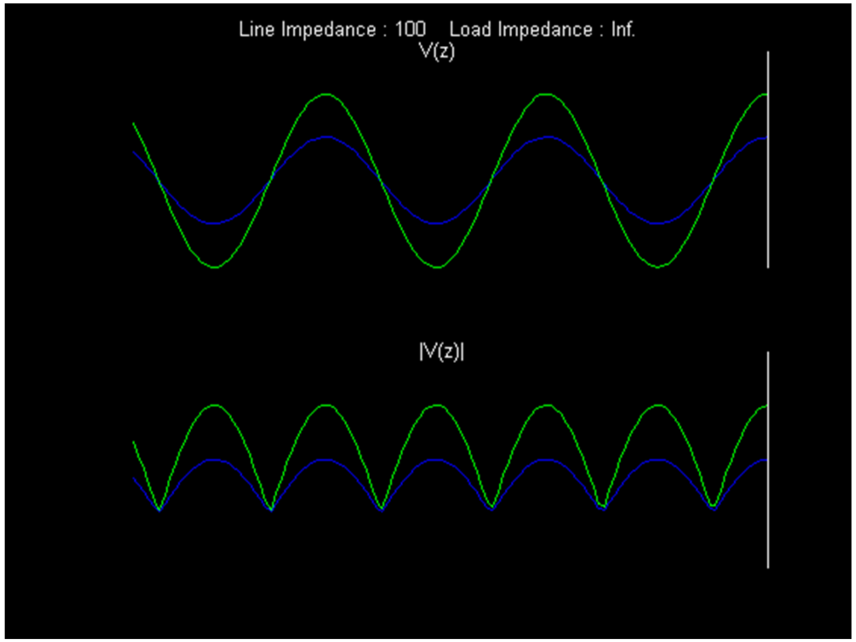
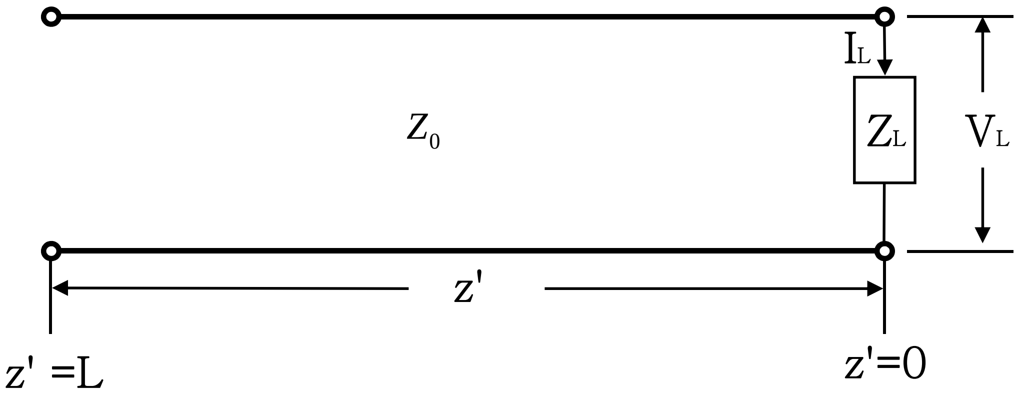
$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$

For γ=jβ and Z_L open



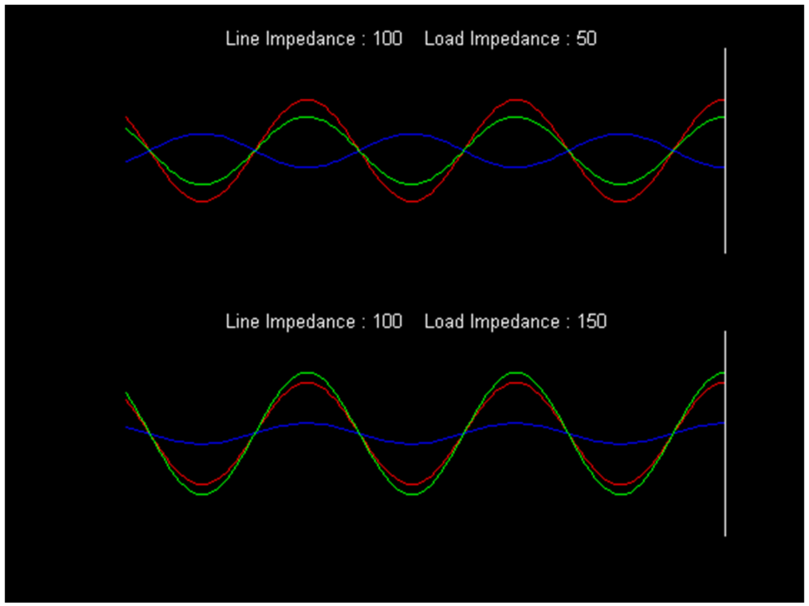
Reflection in TL



$$V(z') = \frac{I_L}{2}(Z_L + Z_0)e^{\gamma z'}\left[1 + \Gamma e^{-2\gamma z'}\right]$$

$$I(z') = \frac{I_L}{2Z_0}(Z_L + Z_0)e^{\gamma z'}\left[1 - \Gamma e^{-2\gamma z'}\right]$$

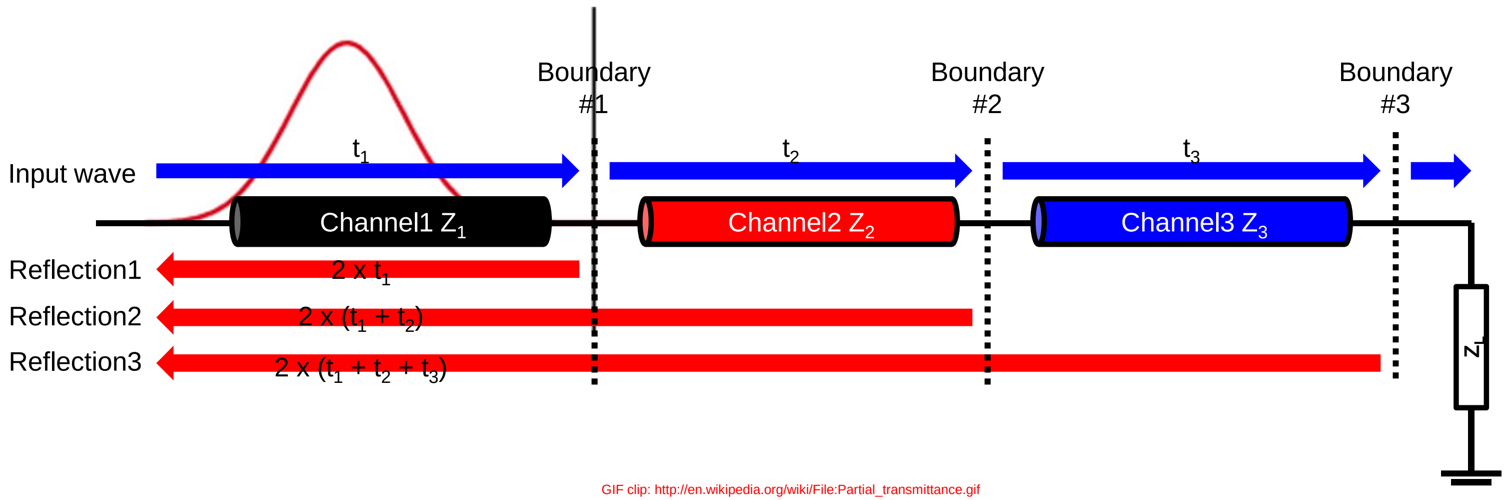
$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$



Impedance matching is very important for high-speed circuits

Time-Domain Reflectometer

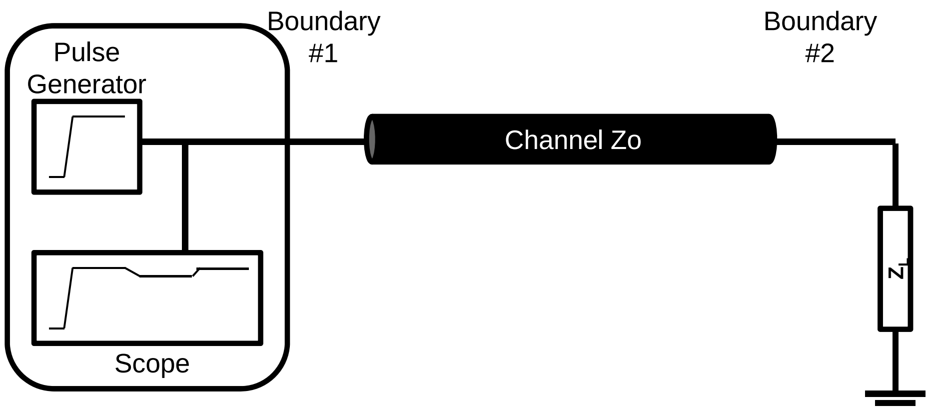
- Reflection is generated at boundaries if impedance is discontinuous
- Traveling time for each reflected wave can be different
- Channel characteristics can be determined by measuring reflected waves



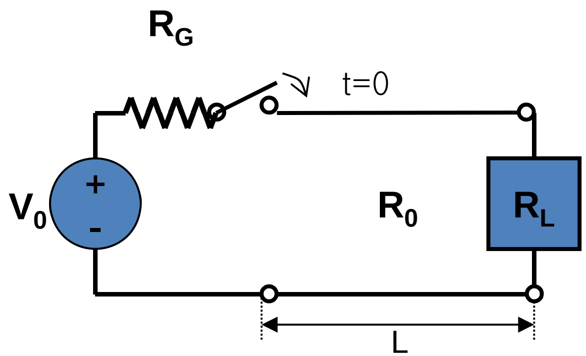
GIF clip: http://en.wikipedia.org/wiki/File:Partial_transmittance.gif

TDR

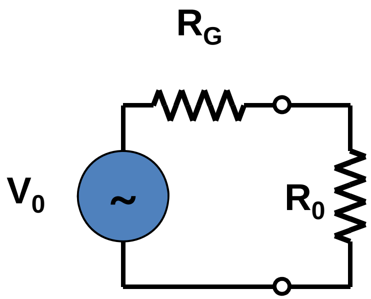
- Pulse generator produces step input with very large period.
- Scope measures the pulse shape

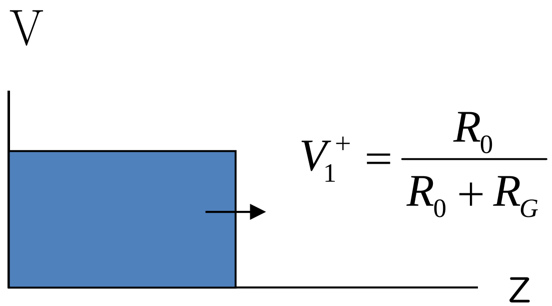


TDR



i) At $t = 0^{+}$

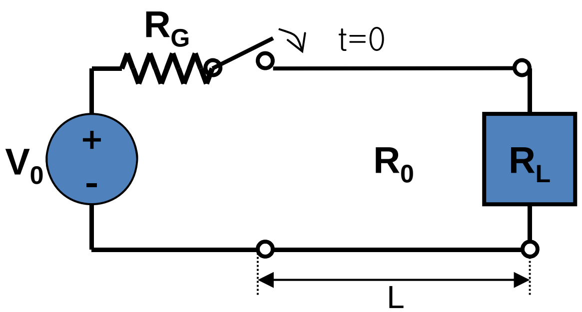




$$V_1^{+} = \frac{R_0}{R_0 + R_G} V_0$$

Initially, the voltage wave “sees” only R_0. => Voltage divider

TDR



ii) At $t = \frac{L}{u}$ $\quad V_1^- = \Gamma_L V_1^+, \quad \Gamma_L = \frac{R_L - R_0}{R_L + R_0}$

iii) At $t = \frac{2L}{u}$ $\quad V_2^+ = \Gamma_G V_1^-, \quad \Gamma_G = \frac{R_G - R_0}{R_G + R_0}$

iv) At $t = \frac{3L}{u}$ $\quad V_2^- = \Gamma_L V_2^+, \; .....$

$$V_{total(t=\infty)} = V_1^+ + V_1^- + V_2^+ + V_2^- + \dots$$

$$= V_1^+ \left(1 + \Gamma_L + \Gamma_L\Gamma_G + \Gamma_L^2\Gamma_G + \Gamma_L^2\Gamma_G^2 + \Gamma_L^3\Gamma_G^2 + \dots\right)$$

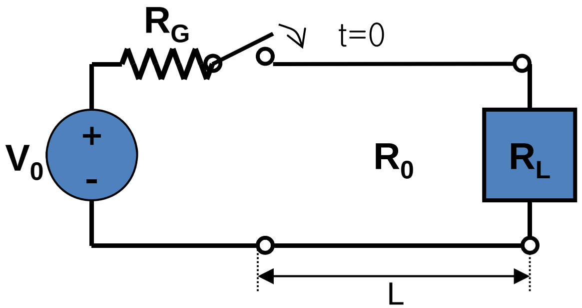
$$= V_1^+[(1 + \Gamma_L\Gamma_G + \Gamma_L^2\Gamma_G^2 + \dots) + \Gamma_L(1 + \Gamma_L\Gamma_G + \Gamma_L^2\Gamma_G^2 + \dots)]$$

$$= V_1^+\left(\frac{1+\Gamma_L}{1-\Gamma_L\Gamma_G}\right) = \left(\frac{R_0}{R_0 + R_G}\right)V_0\left(\frac{1+\Gamma_L}{1-\Gamma_L\Gamma_G}\right)$$

$$= \left(\frac{R_L}{R_L + R_G}\right)V_0$$

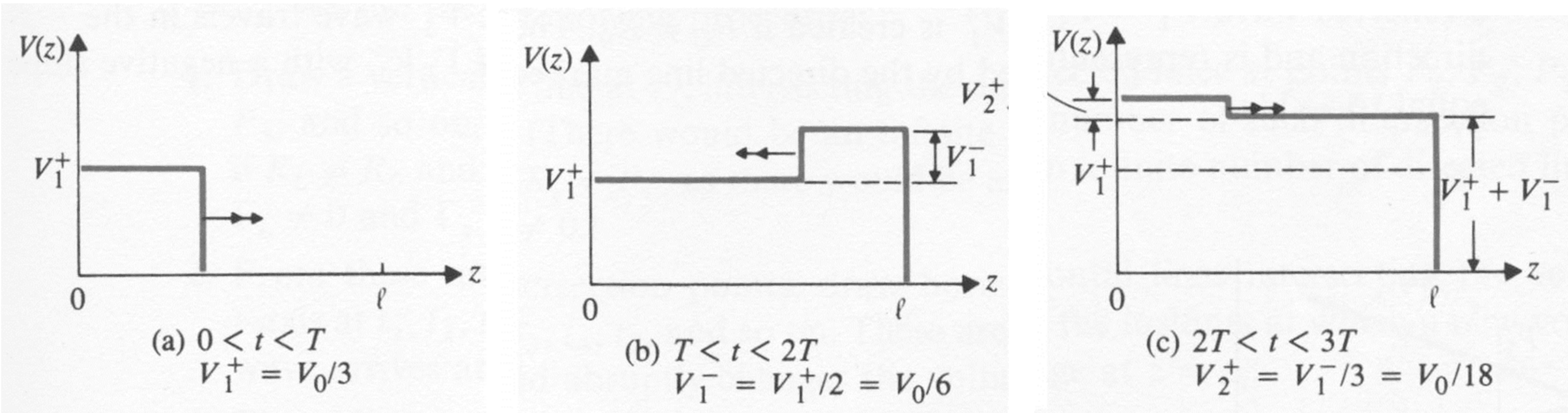
No TL effect:
All the wave characteristics have died out!

TDR



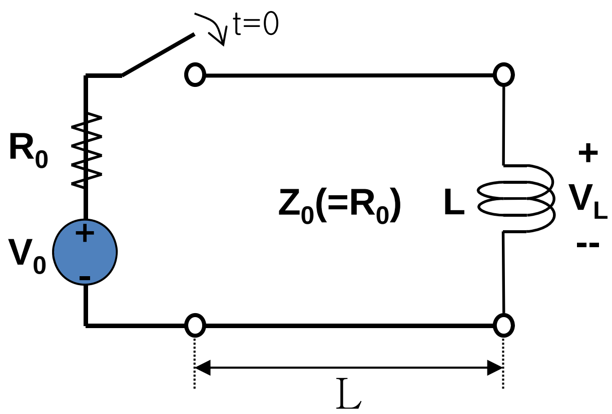
Example) $R_L = 3R_0,\ R_G = 2R_0$

$$\Gamma_L = \frac{R_L - R_0}{R_L + R_0} = \frac{2R_0}{4R_0} = \frac{1}{2},\ \Gamma_G = \frac{R_G - R_0}{R_G + R_0} = \frac{R_0}{3R_0} = \frac{1}{3}$$



$$V_{tot(t=\infty)} = \frac{3}{5}V_0$$

TDR

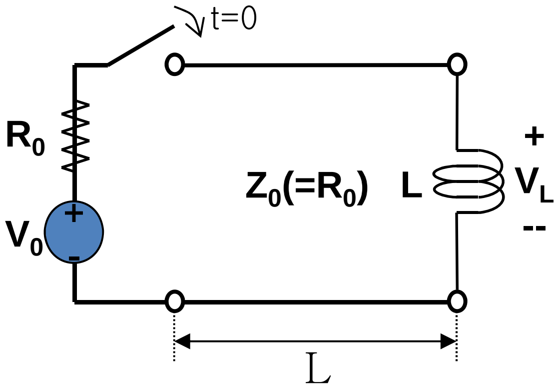


$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} \qquad Z_L = ?$$

$$Z_L = j\omega L$$ ➔ **only for sinusoidal signals**

- Requires somewhat complicated transient analysis
- But remember an inductor acts like open-circuit initially and short-circuit finally in its transient response

TDR



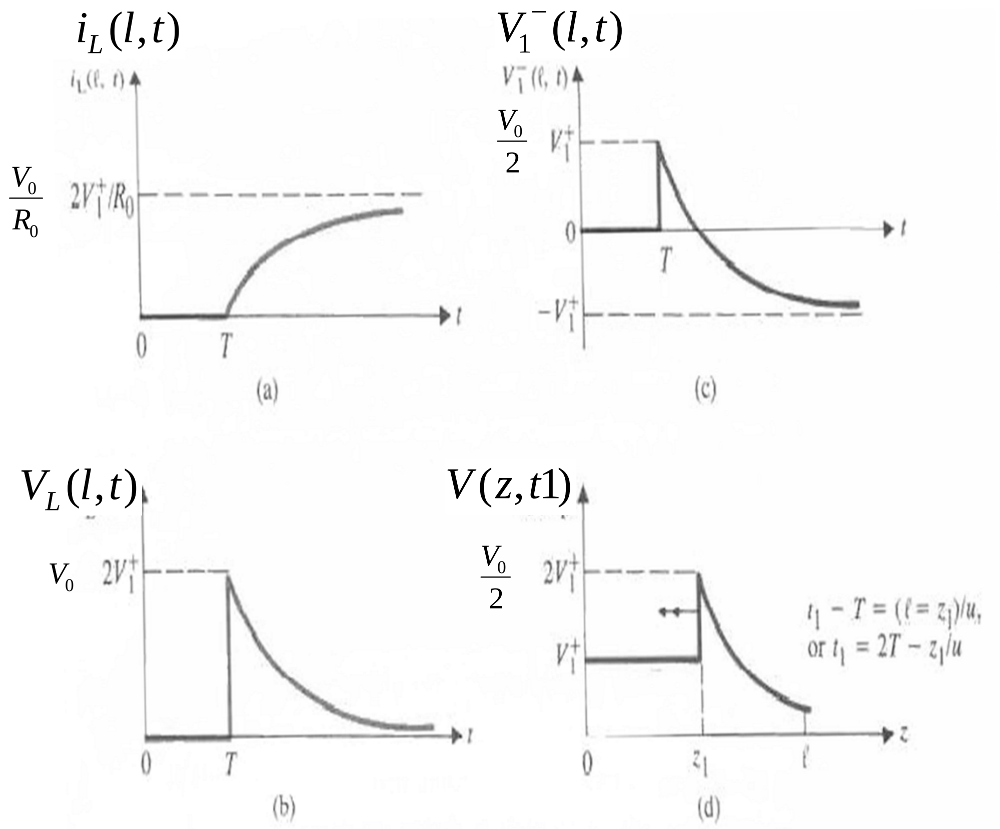
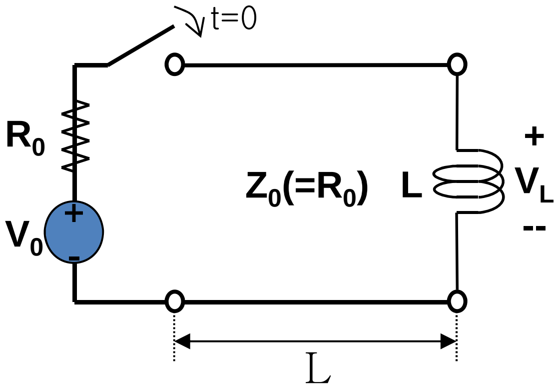
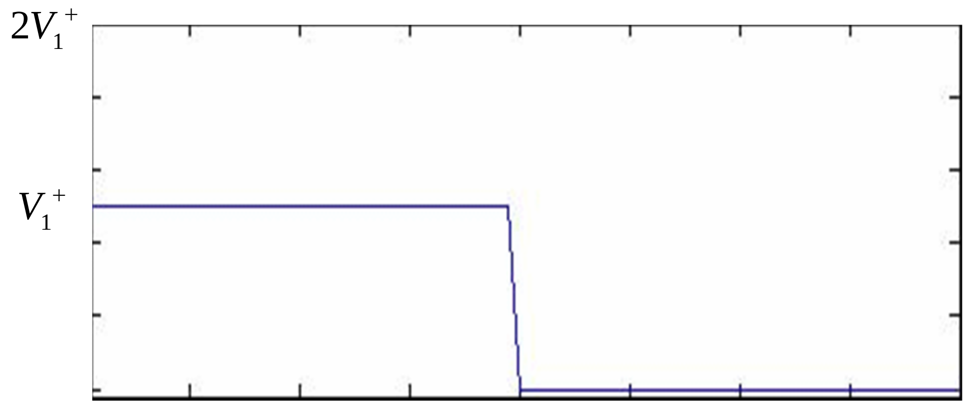


FIGURE 9–27
Transient responses of a lossless line with an inductive termination.

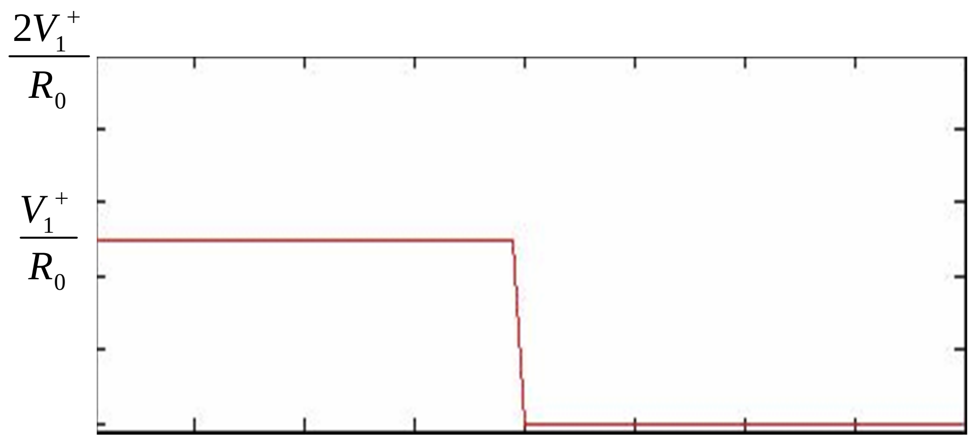
TDR



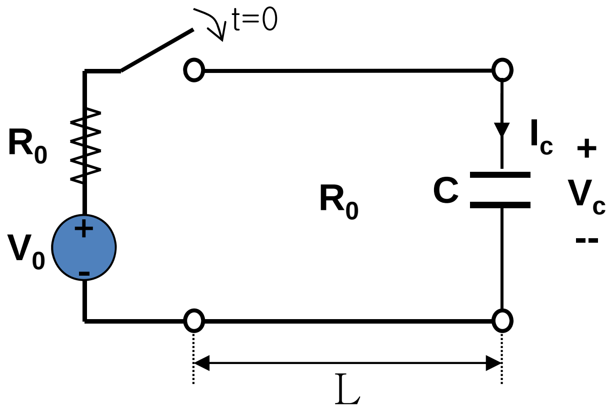
voltage



current



Time-domain reflectometer



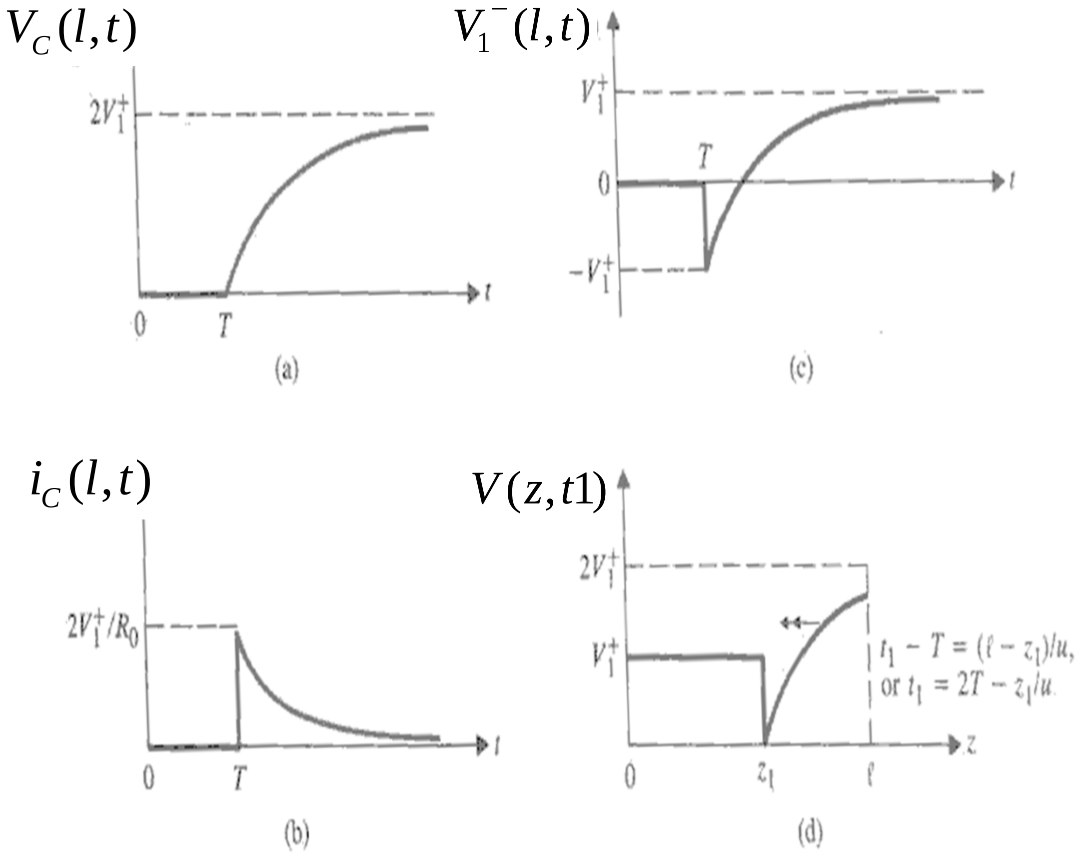
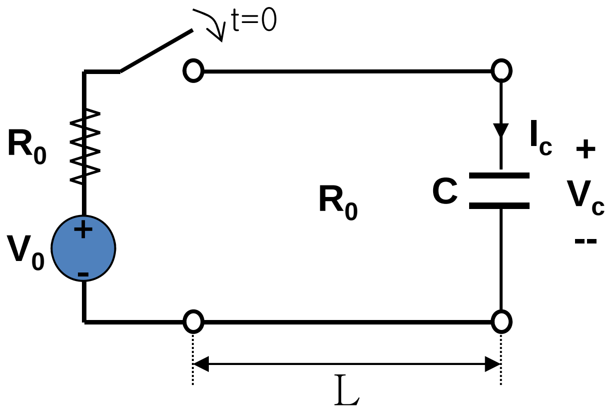
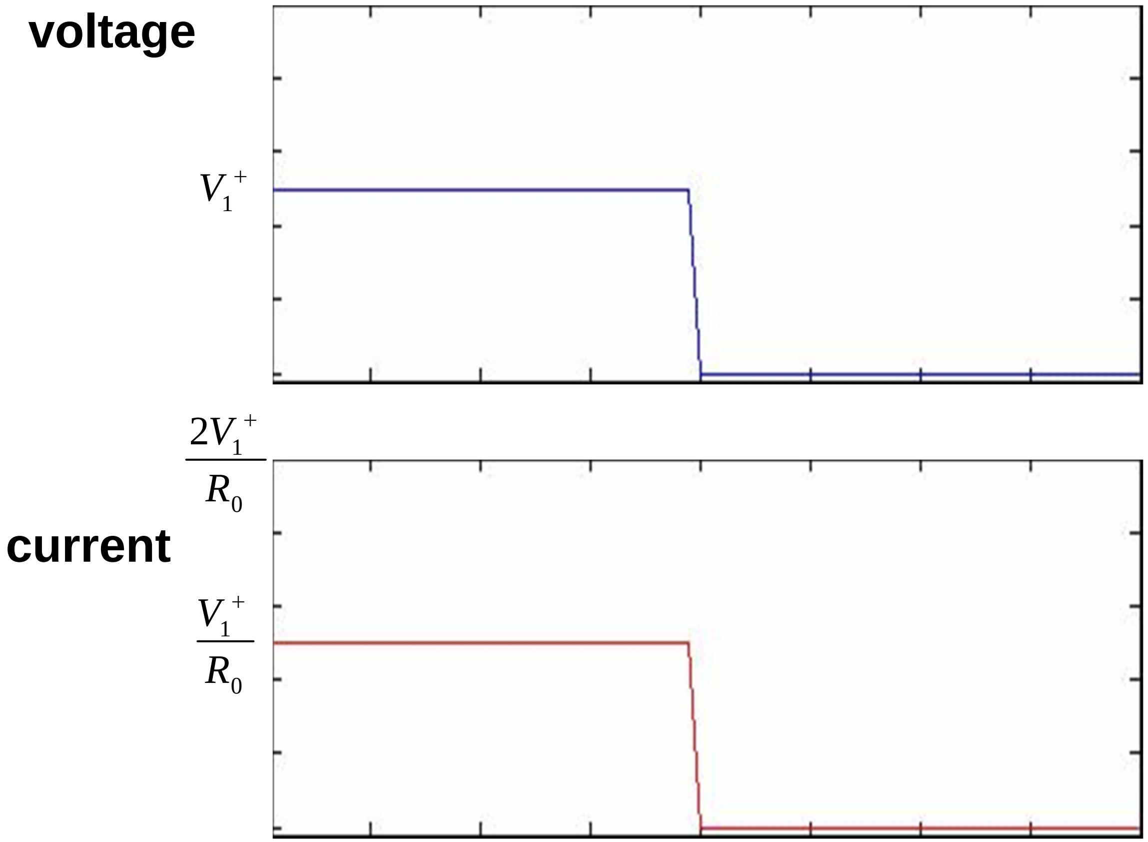


FIGURE 9–29
Transient responses of a lossless line with a capacitive termination.

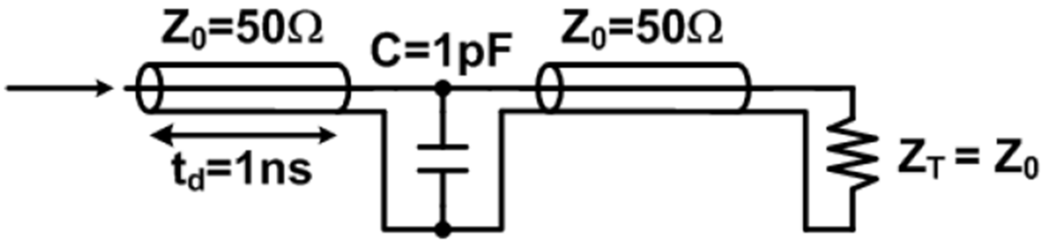
Time-domain reflectometer



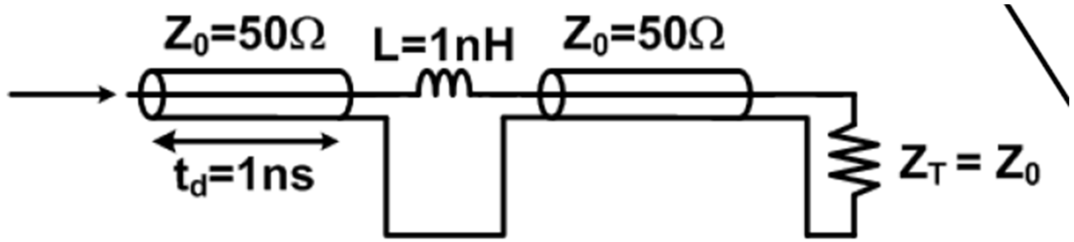


TDR

- TDR for shunt C discontinuity?

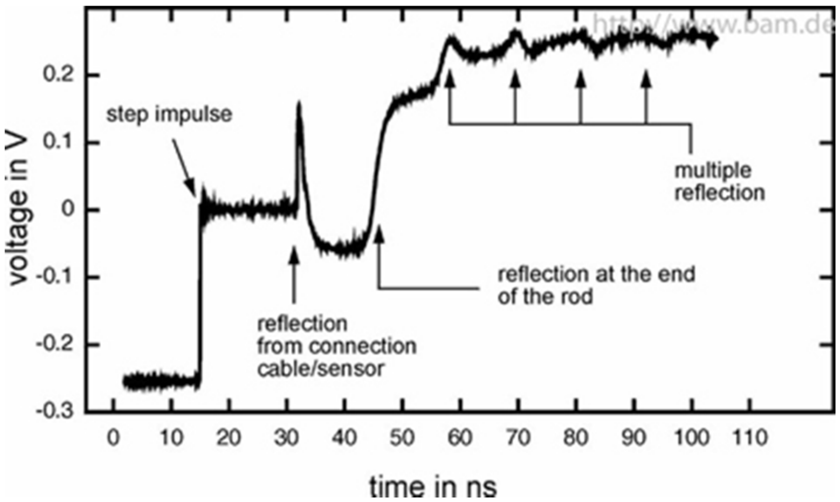


- TDR for series L discontinuity?



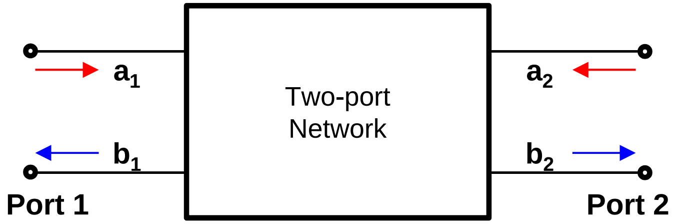
TDR

- What to be evaluated from TDR results?
  - Characteristic impedance of each segmented channel.
  - Recently-released oscilloscope software calculates characteristic impedance automatically.



http://www.bam.de/en/kompetenzen/fachabteilungen/abteilung_8/fg82/fachgruppe_82n.htm

S-parameters



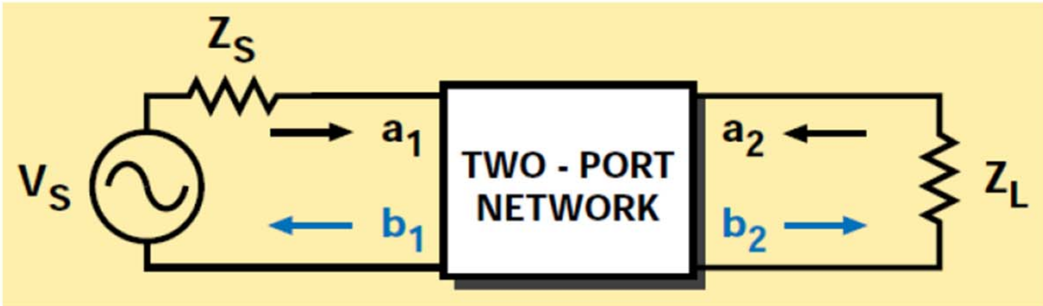
S-parameters

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

$$V_{1,2} = V_{1,2}^{\ +} + V_{1,2}^{\ -}, \; I_{1,2} = I_{1,2}^{\ +} - I_{1,2}^{\ -}$$

$$a_{1,2} = \frac{V_{1,2}^{\ +}}{\sqrt{Z_0}} \qquad b_{1,2} = \frac{V_{1,2}^{\ -}}{\sqrt{Z_0}} \qquad |a|^2, |b|^2$$ ➔ power

S-parameters



[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)

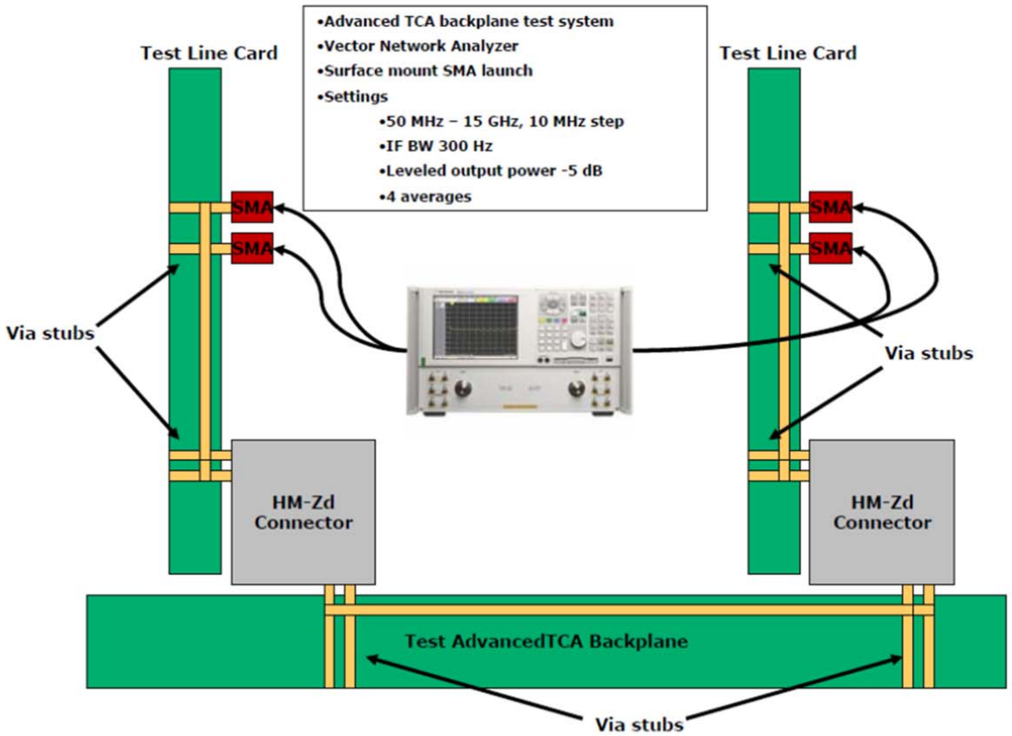
$$s_{22} = \left.\frac{b_2}{a_2}\right|_{a_1=0}$$ = Output reflection coefficient with the input terminated by a matched load (Z_S=Z_0 sets V_s=0)

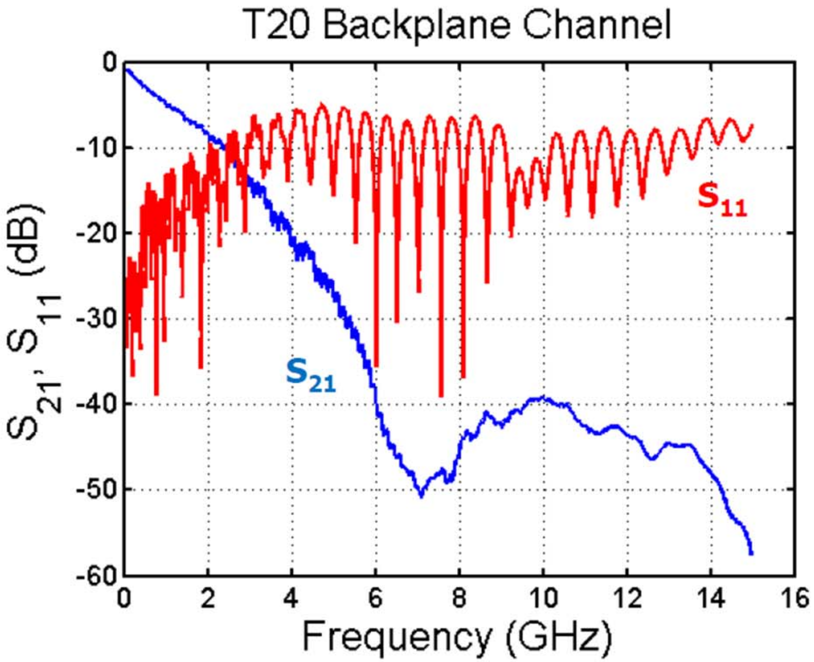
$$s_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0}$$ = Forward transmission (insertion) gain with the output port terminated in a matched load.

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

S- parameters are complex numbers (magnitude and phase)

S-parameter: Example





$$\Delta f = \frac{1}{T} = \frac{v}{2L}$$