

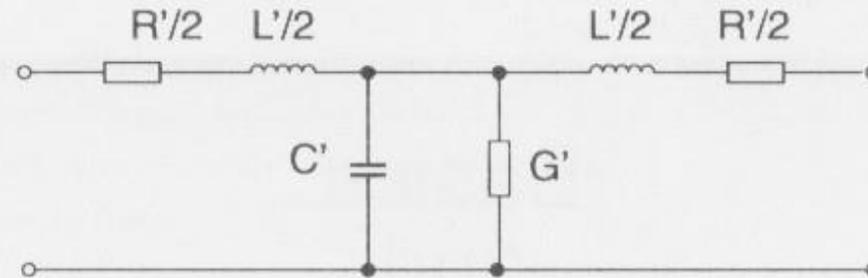


# High speed design

[Texas Instruments, Data Transmission Design Seminar, 1998, SLLDE01C; ti\_scaa082a]

# Basics and Practical Examples of Transmission

## Circuit Diagram of a Transmission Line



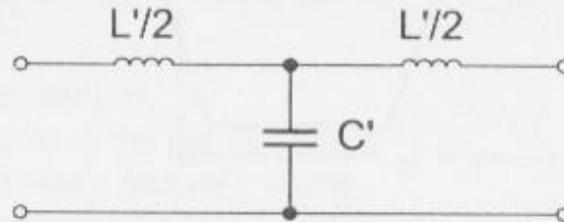
L'	Characteristic inductance per unit length	nH/cm
C'	Characteristic capacitance per unit length	pF/cm
R'	Characteristic resistance per unit length	$\Omega$ /cm
G'	Characteristic conductance per unit length	S/cm

Line Impedance  $\vec{Z}_0 = \sqrt{\frac{j\omega L' + R'}{j\omega C' + G'}}$

- Note: we are talking about a *distributed model* of a line; the upper one is the model of one segment only (there is an infinite number of them in series)

## Loss-free Transmission Lines

At high frequencies the transmission line losses ( $R'$ ,  $G'$ ) can be neglected compared with the impedance of the inductance and the conductance of the capacitance.

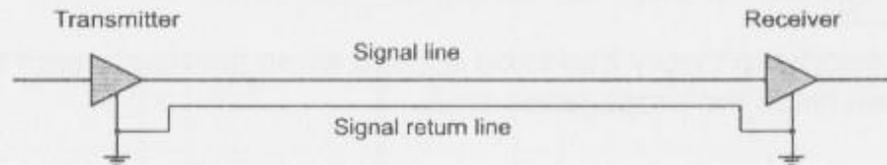


With  $R' \ll j\omega L'$  and  $G' \ll j\omega C'$ :

Line impedance  $Z_0 = \sqrt{\frac{L'}{C'}} \quad (\text{real number!})$

Propagation time  $t_p = \sqrt{L' \times C'}$

## Transmission Line

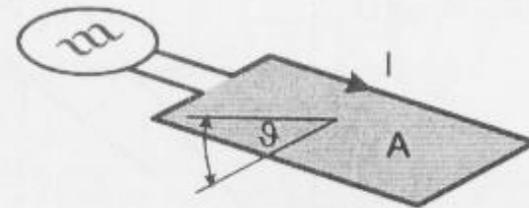


A transmission line consists of

- a signal line which carries the signal current
- a signal return line (mostly ground) which carries a return current of the same magnitude.

Any DC interconnect between the GND terminals of the two circuits (e.g. safety earth) will not provide a signal return path according to the laws of the transmission line theory.

The A area between the signal line and the return line determines the capability of the circuit to radiate RF and also its susceptibility to EMI.

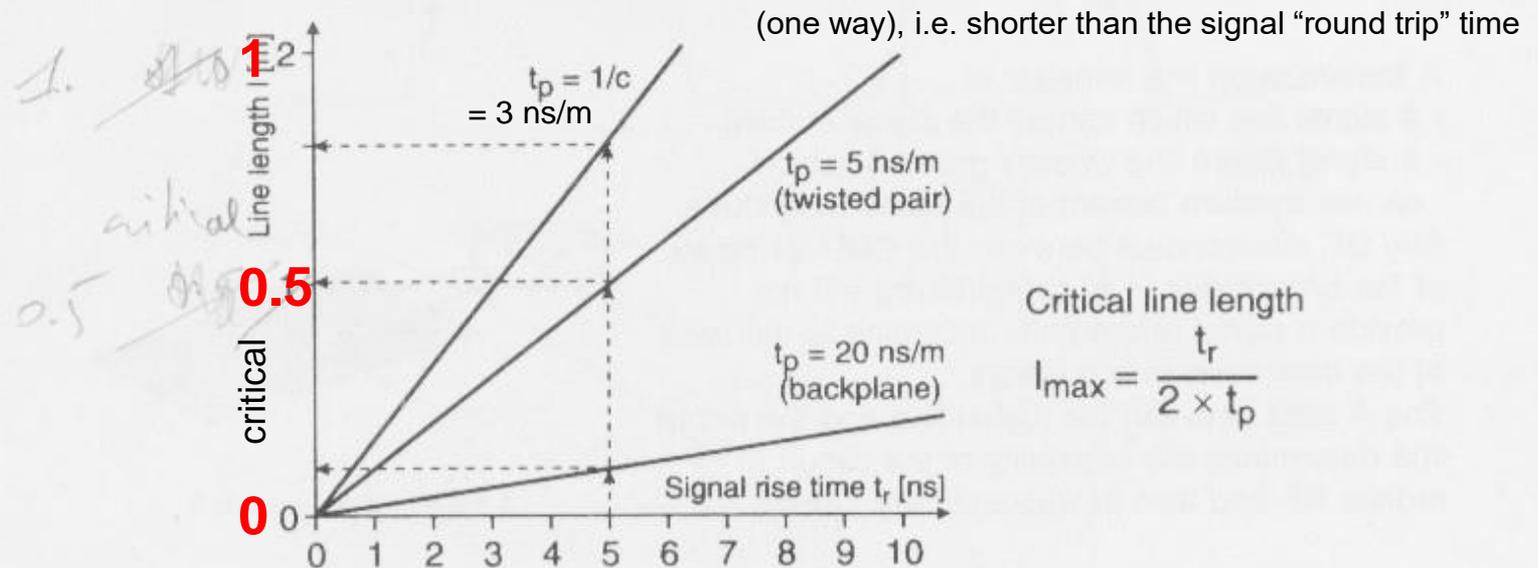


$$E = k \times I \times A \times \frac{1}{r} \times \sin \theta$$

# Transmission Line Theory

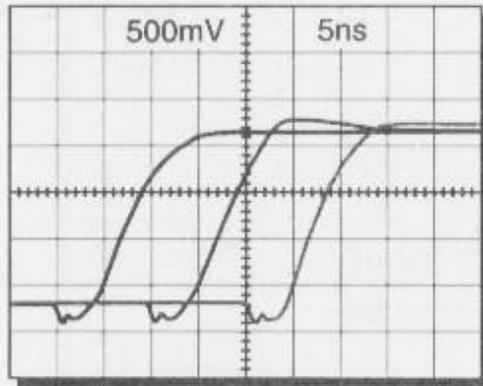
## Rule of Thumb:

The transmission line theory has to be applied when the rise time of the signal is shorter than twice the propagation time.

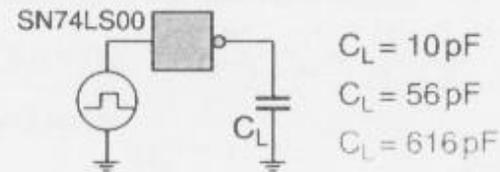
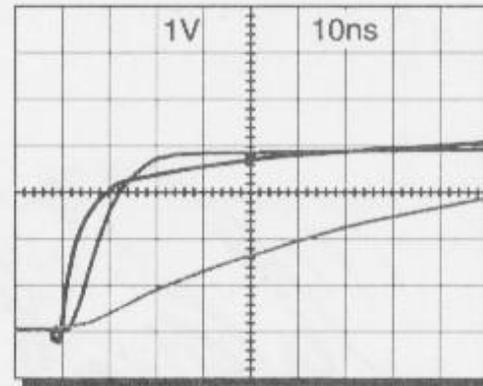
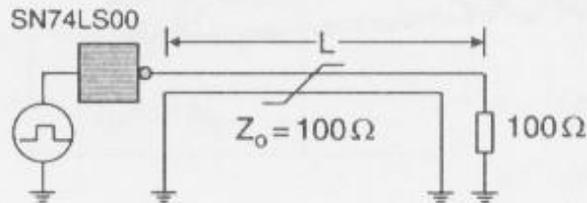


in these formulas  $t_p$  is the propagation time *per unit length*

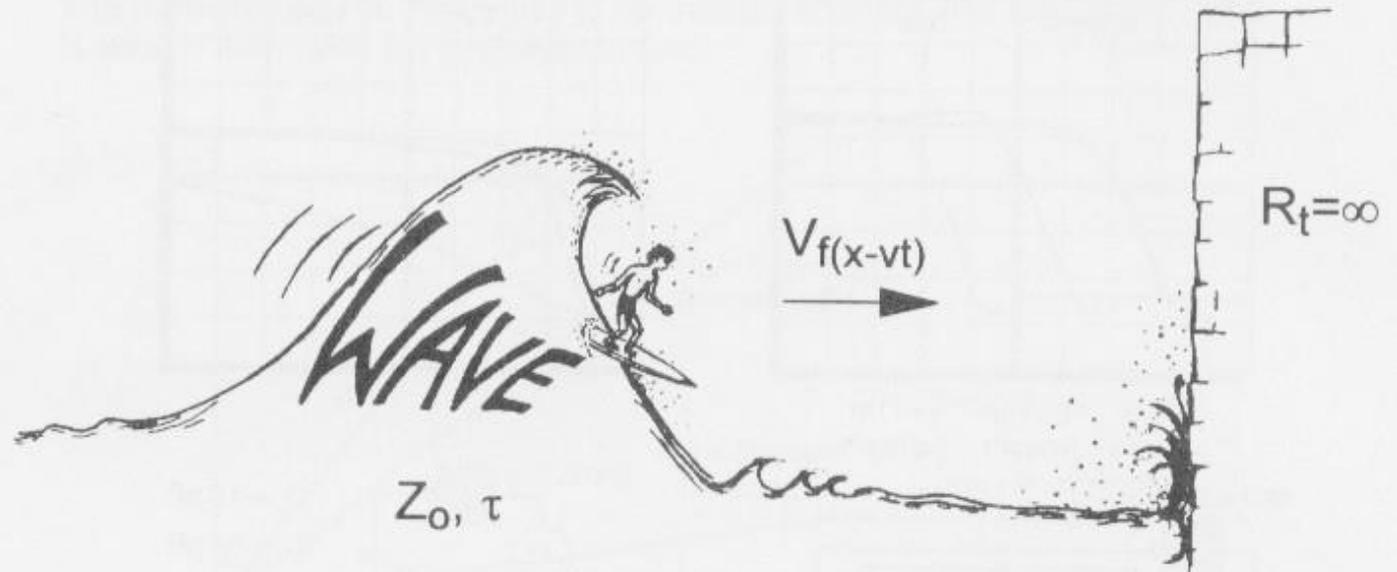
# Waveforms with Transmission Line and Capacitance Loads



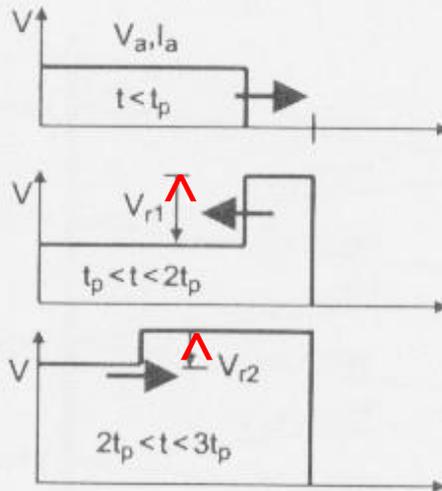
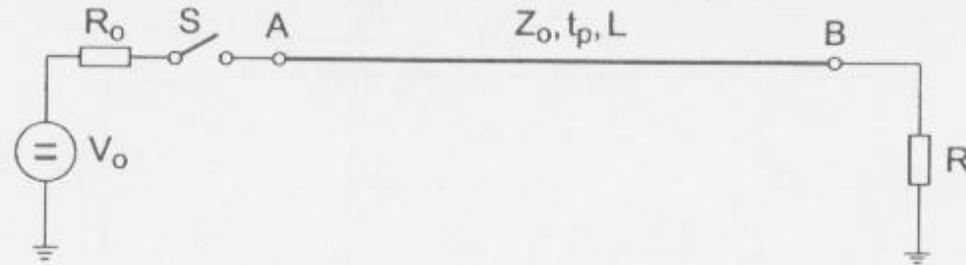
L=0m    L=1m    L=11m  
 (≈10pF)    (≈56pF)    (≈616pF)



## Analysis of Line Reflections



## Waveforms Caused by Line Reflections



Incident wave at the generator output:

$$V_a = V_o \times \frac{Z_o}{R_o + Z_o}$$

Wave reflected at the line end:

$$V_{r1} = V_a \times \rho_B \quad \rho_B = \frac{R_t - Z_o}{R_t + Z_o}$$

Wave reflected at the generator output:

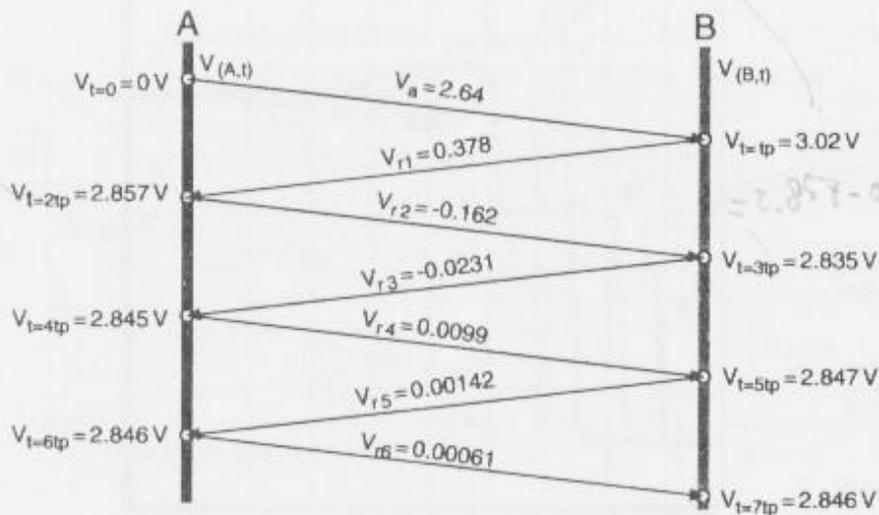
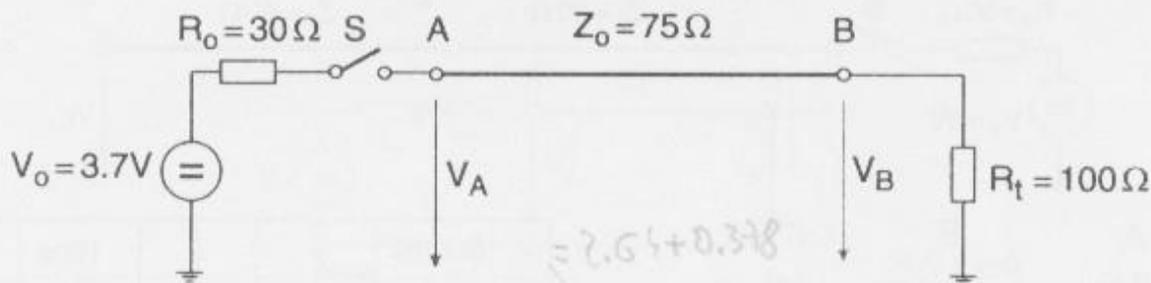
$$V_{r2} = V_{r1} \times \rho_A \quad \rho_A = \frac{R_o - Z_o}{R_o + Z_o}$$

Quiescent state:

$$V_{t=\infty} = V_o \times \frac{R_t}{R_o + R_t}$$

In this example,  $Z_o < R_o$  and  $Z_o < R_t$

# Lattice Diagram



$$\rho_A = \frac{30 - 75}{30 + 75} = -0.429$$

$$\rho_B = \frac{100 - 75}{100 + 75} = 0.143$$

$$V_o = 3.70 \text{ V}$$

$$V_a = V_o \times 75 \Omega / (75 \Omega + 30 \Omega) = 2.64 \text{ V}$$

$$V_{r1} = 2.64 \text{ V} \times 0.14 = 0.37 \text{ V}$$

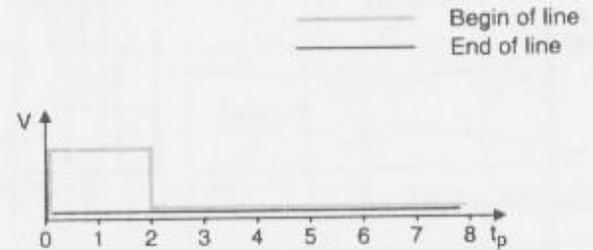
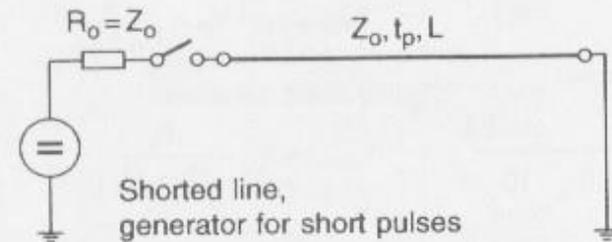
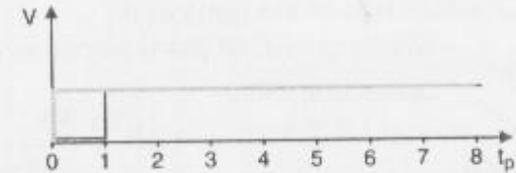
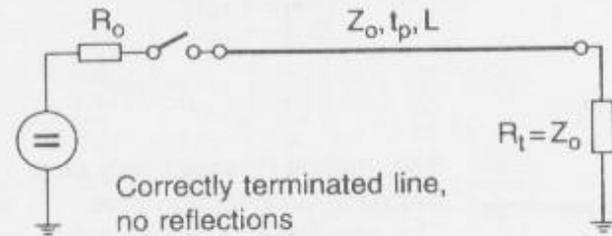
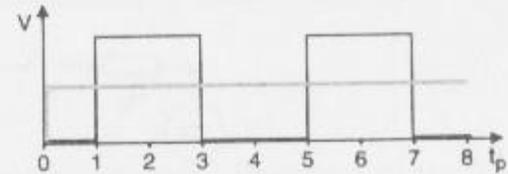
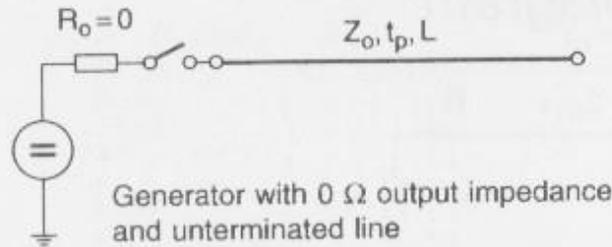
$$V_{r2} = 0.37 \text{ V} \times (-0.42) = -0.16 \text{ V}$$

$$V_{r3} = -0.16 \text{ V} \times 0.14 = -0.02 \text{ V}$$

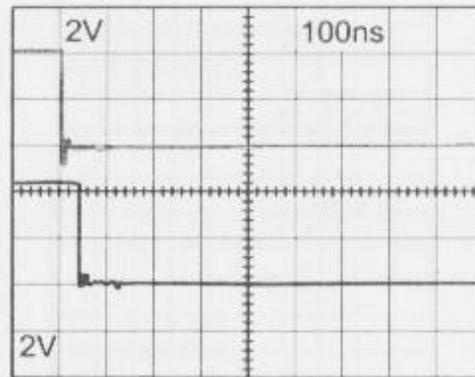
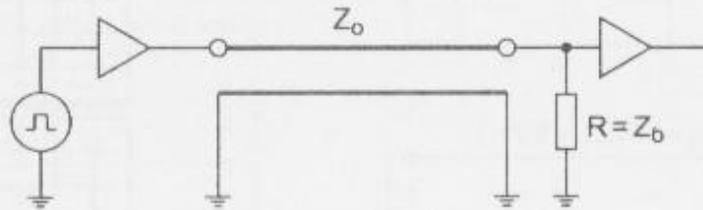
$$V_{r4} = -0.02 \text{ V} \times (-0.42) = 0.009 \text{ V}$$



# Line Reflections - Special Cases

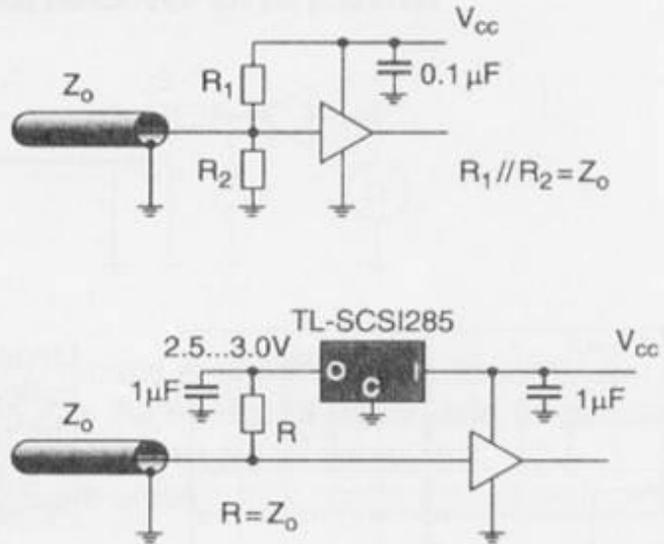
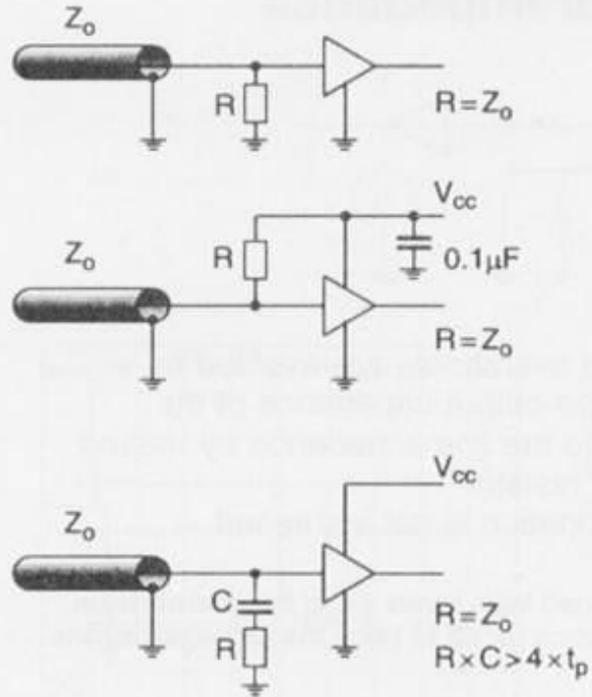


## Line Reflections Terminated Line

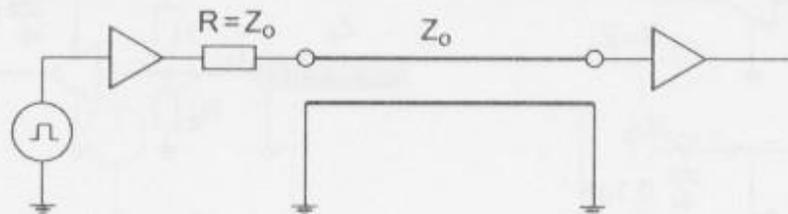


Line reflections are eliminated by correct line termination.

## Line Termination circuits



## Line reflections Matching of Generator Impedance



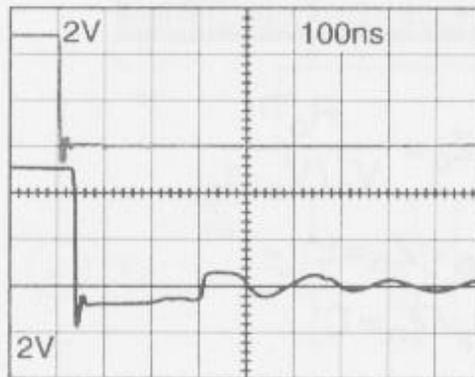
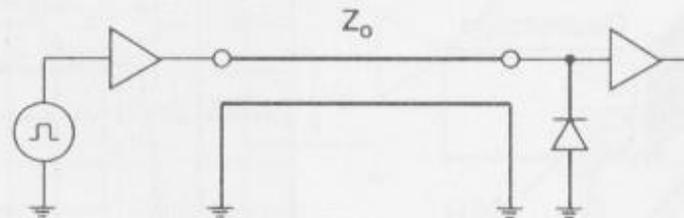
Under- and overshoots are avoided by matching the output impedance of the line driver to the line impedance by means of a series resistor  
Power dissipation is not increased.

Note: Undefined logic levels along the transmission line occurs for up to twice the propagation time.

## Series termination

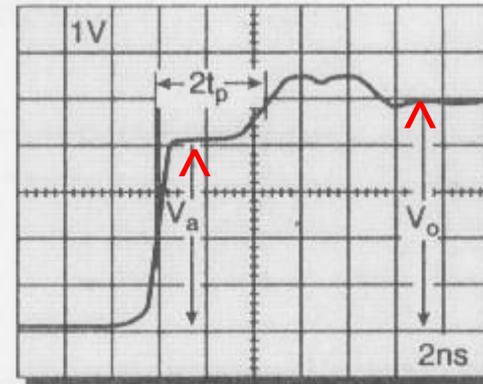
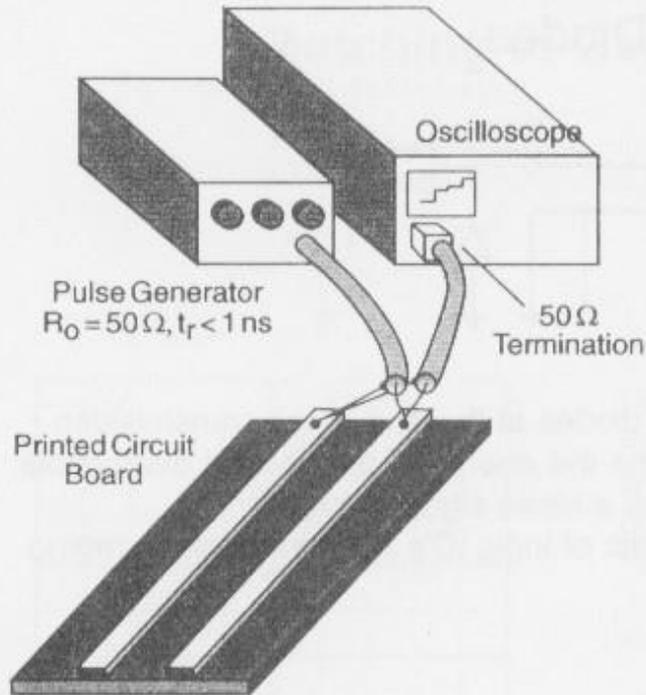
- Not recommended in multipoint applications (settling time  $\sim 2 * t_{prop}$ )
- If the driver has different values of  $Z_{out}$  at high and low level -> poor matching
  - but acceptable if  $(Z_{out}+R) \sim 60-100\%$  of  $Z_0$

## Line Reflections Clamping Diodes



Clamping diodes at the end of the transmission line absorb the energy of under- and overshoots and ensure a clean signal waveform. Input circuits of logic IC's contain these clamping diodes.

## Measurement of the Line Impedance



$$Z_0 = \frac{R_0^*)}{V_o/V_a - 1} \quad (1)$$

$$t_p \times Z_0 = L' \quad (2)$$

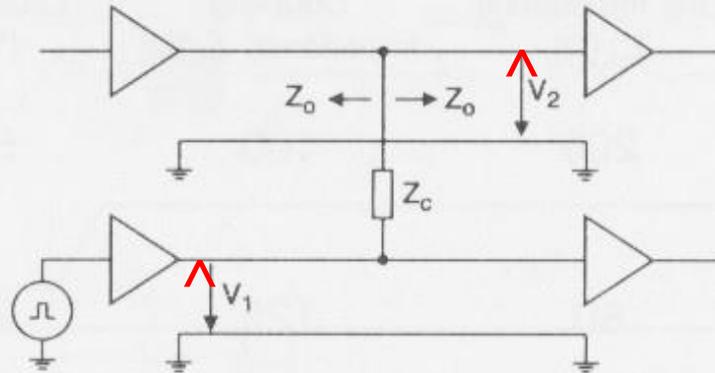
$$t_p / Z_0 = C'$$

\*) Note:  $R_0 = 50 \Omega // 50 \Omega = 25 \Omega$

(1) see slide /009/;  $R_{in, osc}$  and  $R_{out, gen}$  are in //  
 (2) see slide /003/

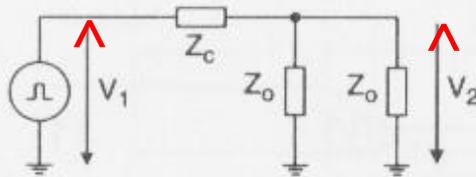
# Crosstalk

On long transmission lines ( $2 \times t_p > t_r$ ) the crosstalk can be calculated as follows:



$Z_o$  = line impedance

$Z_c$  = coupling impedance

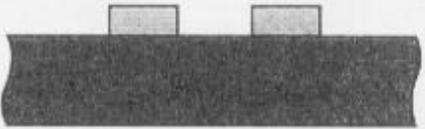
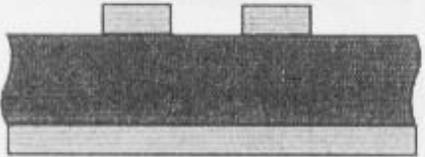
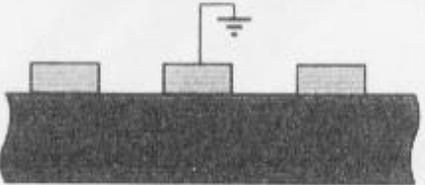


Crosstalk:

$$C = \frac{V_2}{V_1} \times 100\%$$

$$= \frac{0.5 \times Z_o}{0.5 \times Z_o + Z_c} \times 100\% = \frac{1}{1 + 2 \times Z_c / Z_o} \times 100\%$$

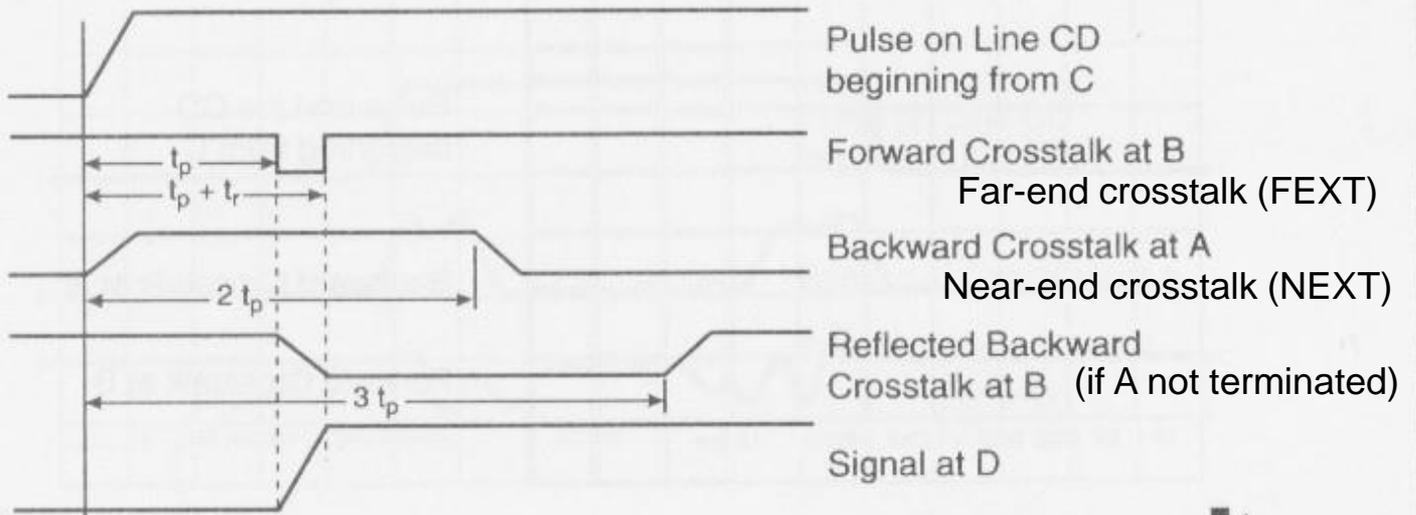
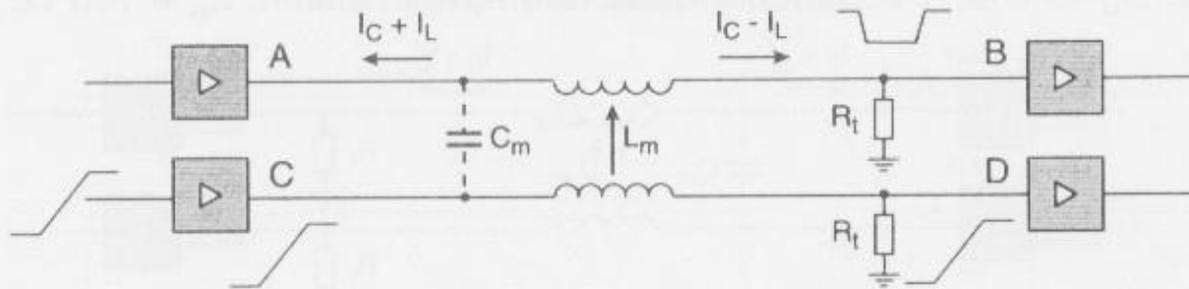
## Crosstalk on Printed circuit Boards (Typical Values)

	Line Impedance $Z_o$ [ $\Omega$ ]	Coupling Impedance $Z_c$ [ $\Omega$ ]	Crosstalk [%]
	200	100	50
	80	125	25
	100	400	11

Note: line width = line distance

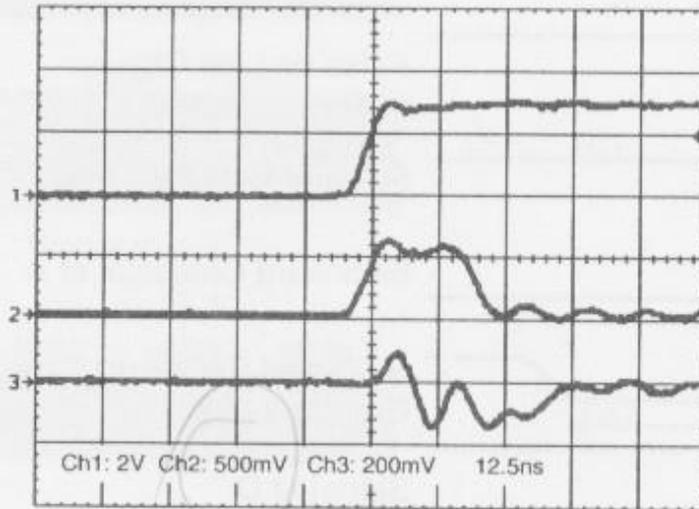
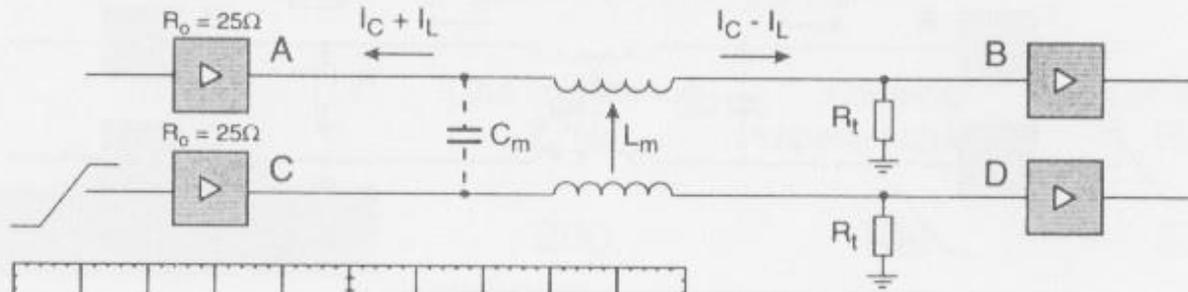
(case 3): shielding wire connected to ground at both ends

# Crosstalk on Transmission Lines



# Crosstalk on Transmission Lines

2 signal line, 1 common ground return, not twisted,  $Z_0 \approx 100 \Omega$ ,



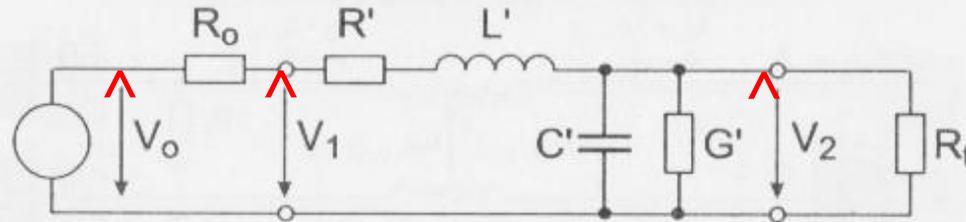
Pulse on Line CD  
beginning from C

Backward Crosstalk at A

Forward Crosstalk at B



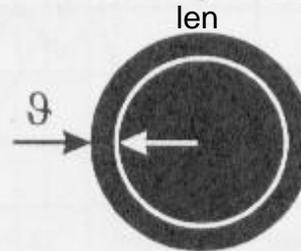
## Losses on Transmission Lines



$$V_2 = V_1 \times e^{\frac{-R'}{2 \times Z_0}}$$

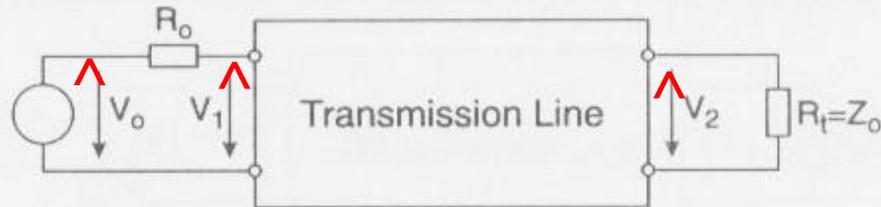
Due to the skin effect at frequencies above some hundred kHz only the outer layer of the wire conducts. Thus the losses increase by a factor  $\sqrt{f}$ .

f (MHz)	$\delta$ ( $\mu\text{m}$ )
1	68
100	6.8
10,000	0.68



$$\delta = \sqrt{2\rho / (\omega\mu)}$$

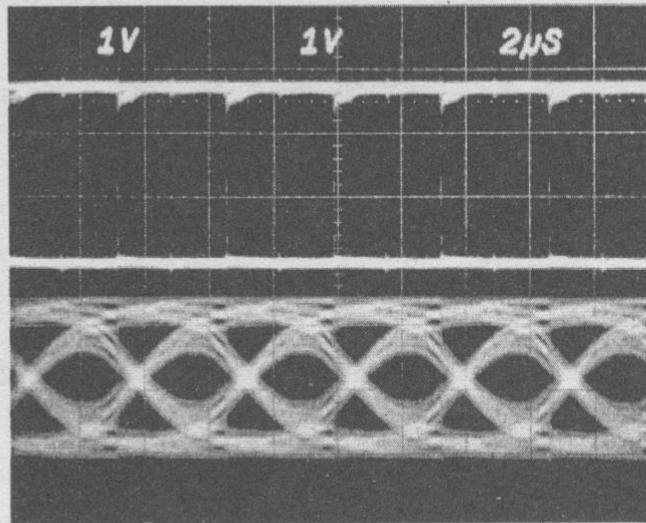
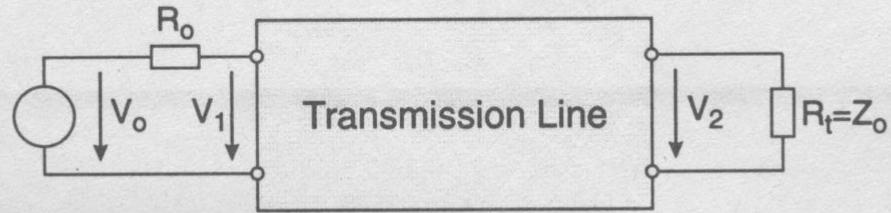
## Frequency Response of a Transmission Line



Twisted Pair Cable  
Diameter  $d = 2 \times 0.6 \text{ mm}$   
Length  $l = 20\text{m}$

As a consequence of the *skin effect*, a transmission line behaves as a low-pass filter

## Eye Pattern



Measurement conditions:  
Data rate: 250 kBit/s  
Coding: NRZ  
Cable: Twisted pair  
Cable length = 1000 m