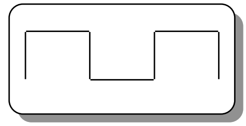
Chapter 4_1
Signal Integrity
in Digital Design

The Signals

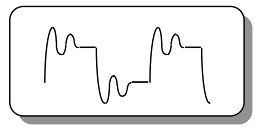
FORMAL : Digital

1 0 1



REAL : Analog

2.3, 0.5, 2.3



Signals use a physical magnitude (electrical: voltage, current, charge...) as a vehicle. Consequently, they belong to analog world.

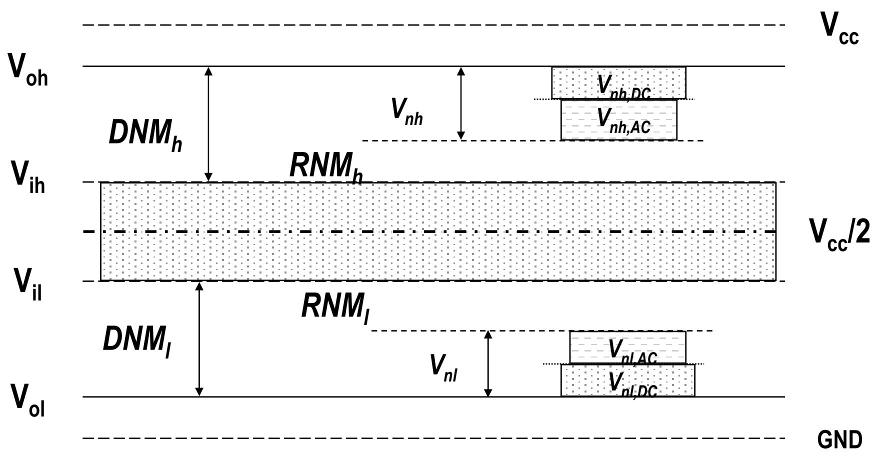
Noise

- DC
  - Supply Voltage
  - Temperature
- AC
  - Reflexion
  - Crosstalk
  - Switching

Of the energy consumed from power supply, the part that doesn't go to the signal goes to the noise. Consequently, in any conversion process with less than 100% efficiency, noise is generated.

Apart from that, any noise generated outside our system can be coupled to it, be through EM radiation or through conduction.

Noise Margins

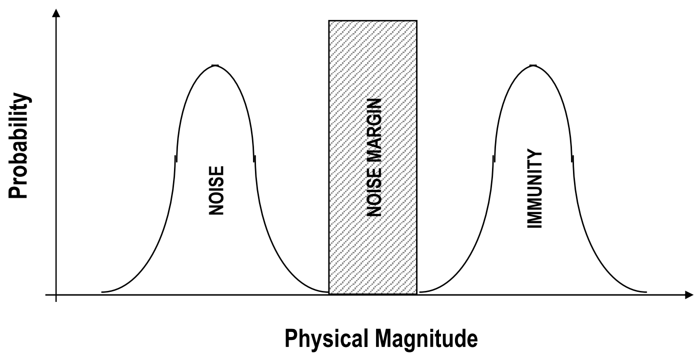


They define the tolerance of our system to noise.

Real Situation

NOISE and IMMUNITY have Gaussian Distributions

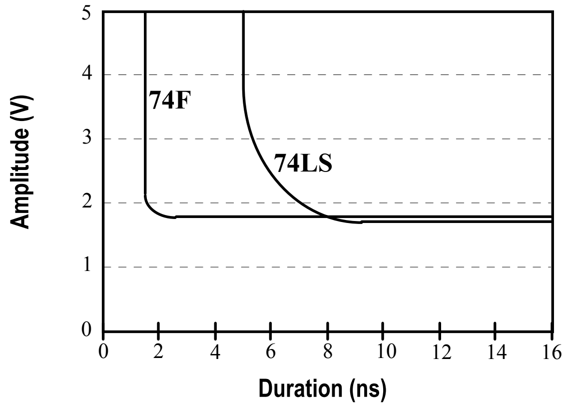
Failure Rate NEVER goes to zero



Because the physical magnitude has a statistical distribution (supposedly Gaussian) error probability **never goes to zero**. However, it wil decrease with increasing the difference between average values and also with decreasing standard deviation.

AC Noise Immunity

Logic circuits act as LOW PASS Filters



White noise has a constant and infinite spectrum. Bandwidth of our circuit then has to do with the effect of noise. Any noise falling outside the bandwidth will be attenuated in consequence

DC Noise: Supply Voltage

$$V_X(V) = V_X(V_0) + K_V(V - V_0)$$

K_V

		K_V
Bipolar	V_{oh}	1 V/V
	V_{ol}	0 V/V
MOS	V_{oh}	1 V/V
	V_{ol}	0 V/V

Estimated K_V values according to technology.

DC Noise: Temperature

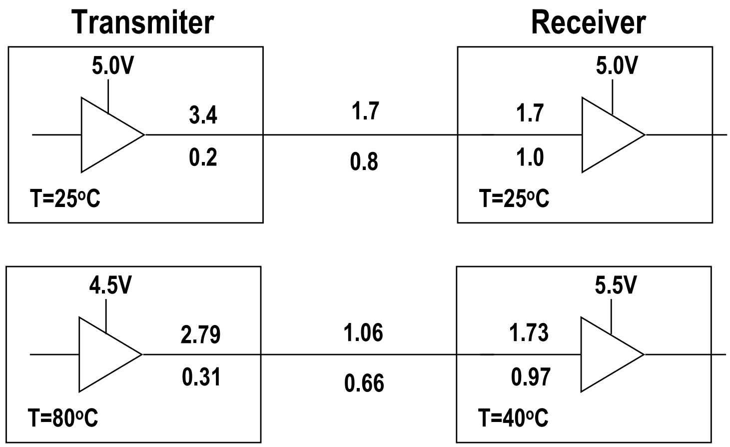
$$V_X(T) = V_X(T_0) + K_T(T - T_0)$$

K_T

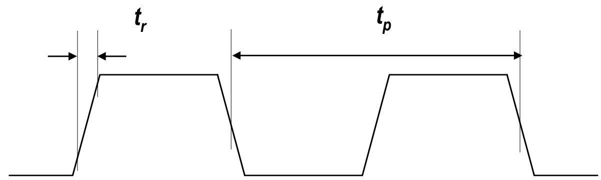
Bipolar	V_{oh} ➡	de 2 a 4 mv/°C
	V_{ol} ➡	1 mv/°C
MOS	V_{oh} ➡	0.5 mv/°C
	V_{ol} ➡	0.5 mv/°C

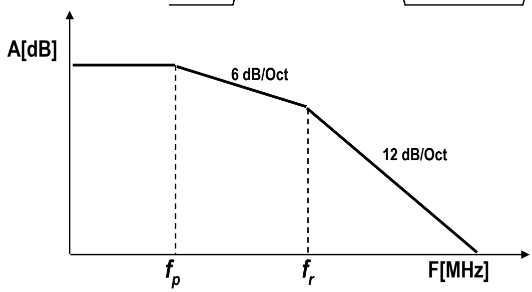
Estimated K_T values according to technology.

Example


Transmiter
Receiver
5.0V
3.4
0.2
T=25°C
1.7
0.8
5.0V
1.7
1.0
T=25°C
4.5V
2.79
0.31
T=80°C
1.06
0.66
5.5V
1.73
0.97
T=40°C

Spectrum of a Digital Signal



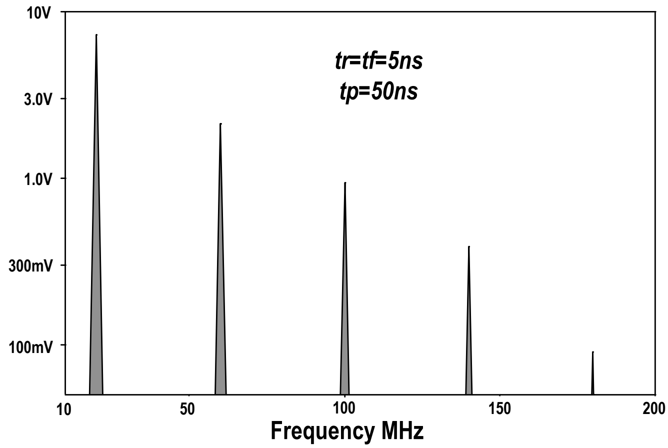


$$f_p = \frac{1}{t_p}$$

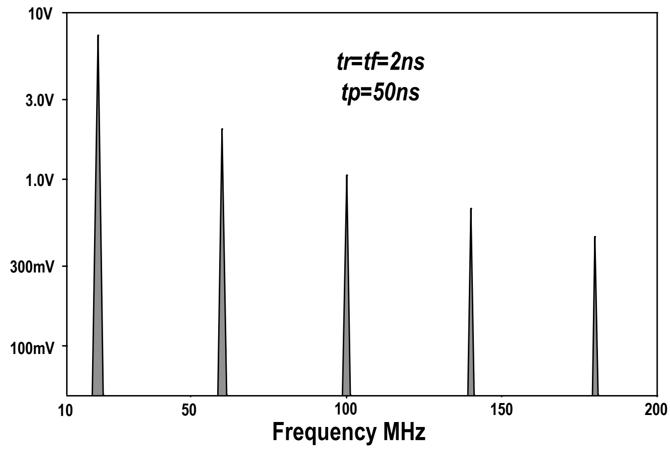
$$f_r = \frac{1}{\pi t_r}$$

In a digital signal (quasi-periodic and trapezoidal) the two parameters that define the spectrum are: Period and transition times (raise and fall)

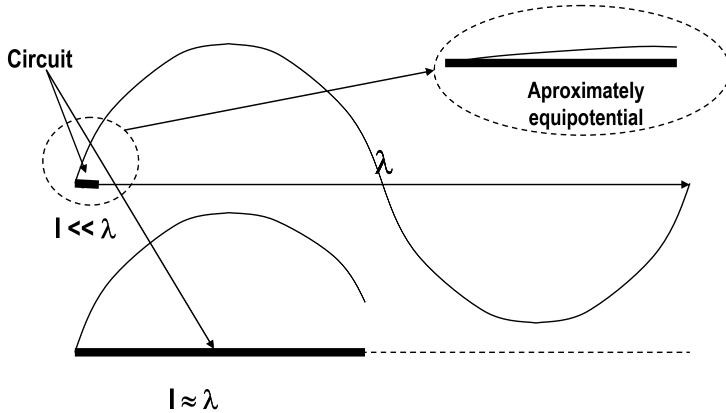
Spectrum (1)


10V
3.0V
1.0V
300mV
100mV
tr=tf=5ns
tp=50ns
10
50
100
150
200
Frequency MHz

Spectrum (2)

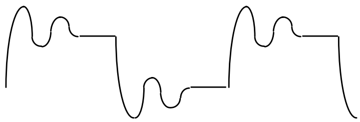

10V
3.0V
1.0V
300mV
100mV
tr=tf=2ns
tp=50ns
10
50
100
150
200
Frequency MHz

Wire or Transmission Line? (1)



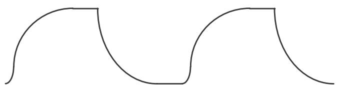
Wire or Transmission Line? (2)

Raise Time < 2 x Propagation Time



Reflexions outside the edges → Transmission Line

Raise Time << 2 x Propagation Time



Reflexions inside the edges → Capacitive Aproximation

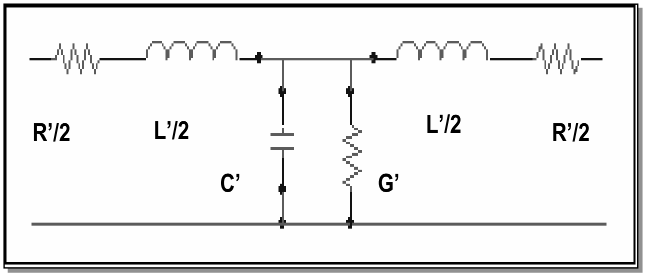
All the electrical magnitudes propagating through our system have a finite velocity (ideally that of light, if the medium is vacuum or air). Consequently, propagation delay depends on length of the conductor.

If that particular delay is much smaller than the wavelength of the maximum frequency propagating through our system, then it can be considered “equipotential” and propagation velocity can be considered infinite.

On the other side, if this condition is not met, we’ll have to consider our system as distributed and conductors as transmission lines

Therefore, this fact depends on frequency and system “size”.

Transmission Line Diagram



Line Impedance

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

Propagation Factor

$$\gamma = \sqrt{(j\omega L' + R')(j\omega C' + G')}$$

Associated values to a (distributed) transmission line are

L' Inductance per unit length. Associated to circulating current and its ability to induce magnetic field.

R' Resistance per unit length. Associated to circulating current and its associated voltage drop

C' Capacitance per unit length. Associated to voltage distribution and its ability to produce electric field.

G' Conductance per unit length. Is Associated to dielectric conduction current (losses)

Line Impedance (instantaneous voltage to current ratio) is Complex and Frequency dependent

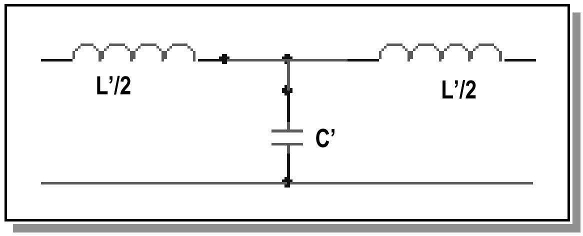
Propagation factor is Complex and Frequency dependent

Frequency ranges in a Transmission Line

- **Low frequency:** $j\omega L' \approx R'$ and/or $j\omega C' \approx G'$
  Z_0 and γ complex and function of ω : Dispersive regime
- **Medium frequency :** $j\omega L' >> R'$ and $j\omega C' >> G'$
  Z_0 and γ real and independent of ω : Ideal regime
- **High Frequency:** $j\omega L' > R'$ and/or $j\omega C' > G'$
  Z_0 and γ complex and function of ω : Cutoff regime

Lossless Transmission Line

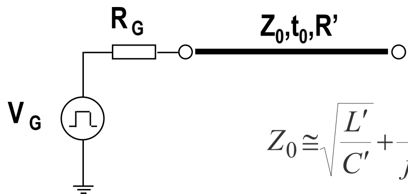
In printed circuits and in other connexion means used in digital systems, LOSSES CAN BE NEGLECTED



Impedance $$Z_0 = \sqrt{\frac{L'}{C'}}$$

Propagation time $$t_0 = \sqrt{L' \cdot C'}$$

Conductor Losses



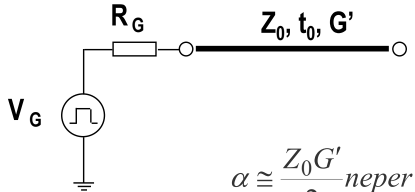
$$Z_0 \cong \sqrt{\frac{L'}{C'} + \frac{R'}{j2wt_0}}$$

$$t_0 \cong \sqrt{L'C'}$$

$$\alpha \cong \frac{R'}{2Z_0} neper/m$$

$$\alpha \cong 4.343 \frac{R'}{Z_0} dB/m$$

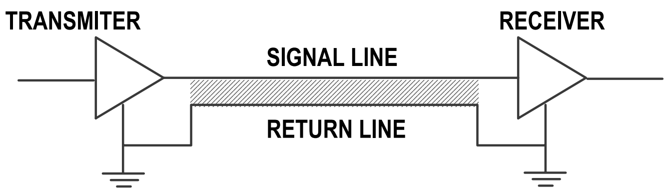
Dielectric Losses



$$\alpha \cong \frac{Z_0 G'}{2} neper/m$$

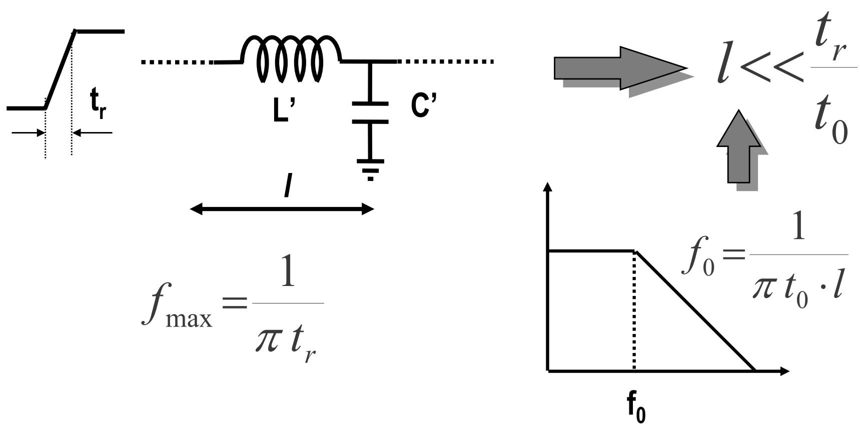
$$\alpha \cong 4.343 \cdot Z_0 G' \, dB/m$$

Transmission Line Elements



- Signal line conducts the signal current
- Return line conducts a return current equal to signal current
- Cross-hatched area determines the ability to radiate or sensitivity to radiation.

Transmission Line Simulation



$$l << \frac{t_r}{t_0}$$

$$f_{max} = \frac{1}{\pi t_r}$$

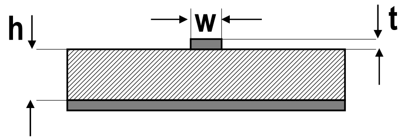
$$f_0 = \frac{1}{\pi t_0 \cdot l}$$

To simulate a transmission line (i.e., with PSPICE) we have to discretize it by substituting a given number of L-C sections. This sections are in fact low pass filters so we have to make sure that their bandwidth is enough to leave response substantially unaltered.

Examples of Transmission Lines

Line Type	L'(nH/cm)	C'(pF/cm)	Z_0(W)	t_0(ns/m)
Free space	μ_0	ε_0	370	3,3
Wire on ground	20	0,06	600	~4
Twisted pair	5-10	0,5-1	80-120	5
Flat cable	5-10	0,5-1	80-120	5
PC track	5-10	0,5-1,5	70-100	~5
Coaxial cable	2,5	1	50	5

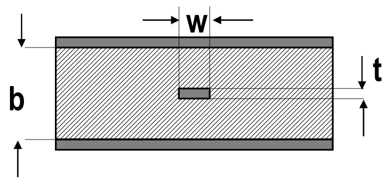
Transmission Lines in PCB



Microstrip

$$Z_0 = \frac{87}{\sqrt{\varepsilon_r + 1.41}} \ln\left(\frac{5.98h}{0.8w + t}\right) \Omega$$

$$t_0 = 3.34\sqrt{0.475\varepsilon_r + 0.67}\ ns/m$$



Strip Line

$$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \ln\left(\frac{4b}{0.67\pi(0.8w + t)}\right) \Omega$$

$$t_0 = 3.34\sqrt{\varepsilon_r}\ ns/m$$

Example

DATA

ε_r=4.7
w=0.010"(0.254mm)
t=0.002"(0.05mm)
h=0.012"(0.3mm)

Microstrip

Z_0=69.4 Ω
t_0=5.8 ns/m

DATA

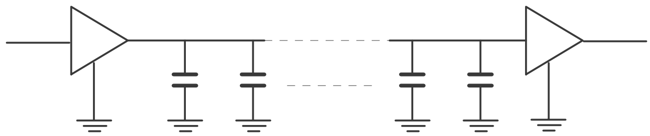
ε_r=4.6
w=0.010"(0.254mm)
t=0.0014"(0.036mm)
b=0.020"(0.5mm)

Strip Line

Z_0=50.7 Ω
t_0=7.3 ns/m

Real situation: The loaded line

Elements connected to the line act generally as a capacitive load. In a first approximation, we can treat them as distributed.



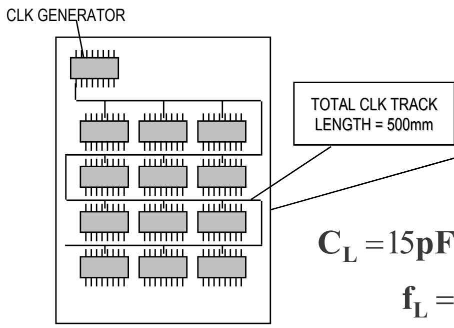
LOAD FACTOR ⇒ $f_L = \sqrt{1 + C'_L / C'}$

Impedance decreases ⇒ $Z_L = Z_0 / f_L$

Propagation time increases ⇒ $t_L = t_0 \cdot f_L$

Loaded line has: L' and (C' + C'_L)
where $C'_L = C_L / d$
where d is the distance between loads

Example 1: PCB track



DATA:

$Z_0 = 100\ \Omega$

$C' = 1$ pF/cm

$C_i = 15$ pF

$\tau_i = 5$ ns/m

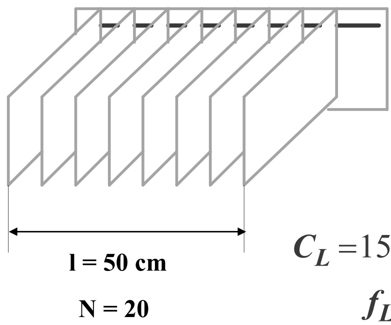
$$C_L = 15\,\mathbf{pF} \cdot 12 / 50\,\mathbf{cm} = 3.6\,\mathbf{pF / cm}$$

$$f_L = \sqrt{1 + 3.6 / 1} = 2.145$$

$$Z_L = 100 / 2.145 = 46.6\,\Omega$$

$$t_L = 5 \cdot 2.145 = 10.725\,\mathrm{ns / m}$$

Example 2: Bus line



DATA:
Z_0=100 Ω
C'= 0.6 pF/cm
C_i=15 pF
τ_i= 6 ns/m

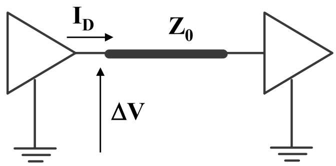
$$C_L = 15\,pF \cdot 20 / 50\,cm = 6\ pF / cm$$

$$f_L = \sqrt{1 + 6/0.6} = 3.317$$

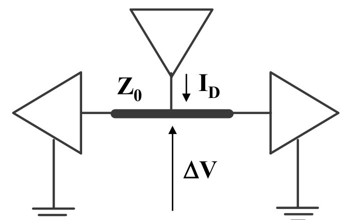
$$Z_L = 100 / 3.317 = 30\,\Omega$$

$$t_L = 6 \cdot 3.317 = 19.9\ ns/m$$

Driver's problem(1)



$$\Delta V = I_D \cdot Z_0$$

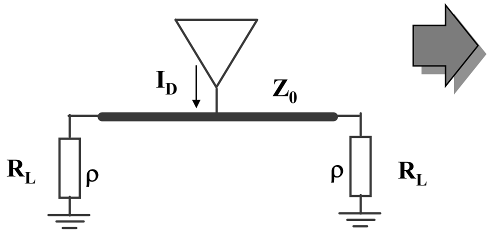


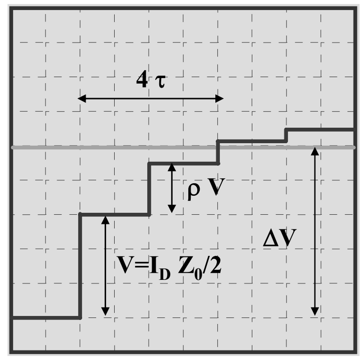
$$\Delta V = I_D \cdot \frac{Z_0}{2}$$

Driver's problem (2)

If we NEED ΔV and we HAVE I_D and Z_0 :

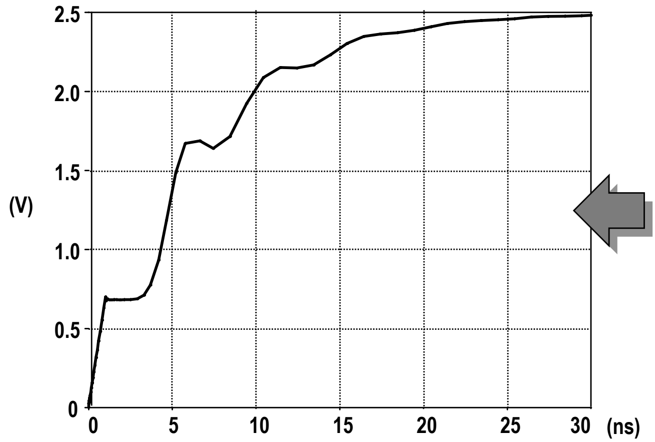
$$I_D < \Delta V / Z_0$$





If the voltage change is not large enough to produce a state change, then the change cannot occur at leading edge (Incident switching) and we have to rely in eventual positive reflexions.

Driver's problem simulation



DATA:
l = 10 cm
Z_0 = 100 Ω
t_0 = 6 ns/m
t_r = 1 ns
C_L = 6 pF/cm
I_D = 50 mA