ECE414/514
Electronics Packaging
Spring 2012 Lecture 6
Electrical D: Transmission lines (Crosstalk)

James E. Morris
Dept of Electrical & Computer Engineering
Portland State University

Lecture topics

- Inductive and capacitive coupling
- Forward and backward noise
- Far end and near end noise
- Incremental model and formulae
- Capacitive crosstalk systems
- No ground plane

Objectives

- Understand the origins of crosstalk
  - Inductive
  - Capacitive
- Calculate basic crosstalk noise levels
- Calculate signal crosstalk and delta-I noise in no ground systems

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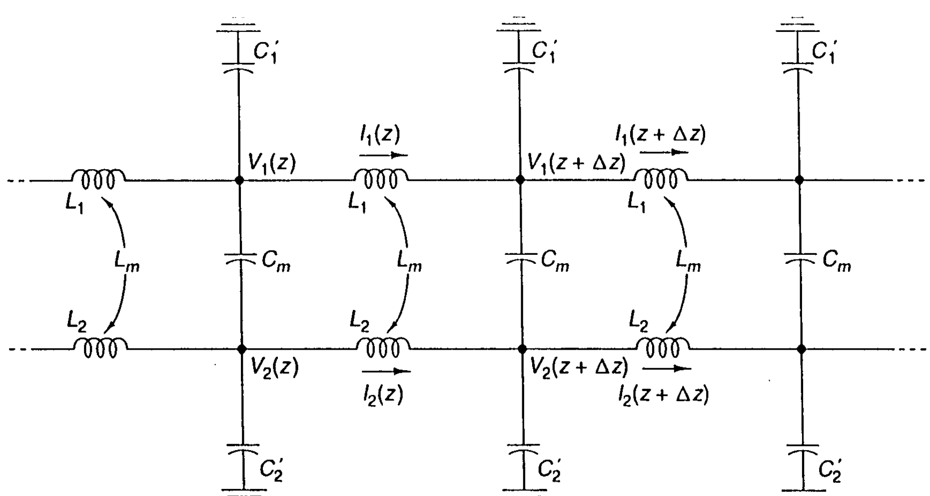
Incremental line model



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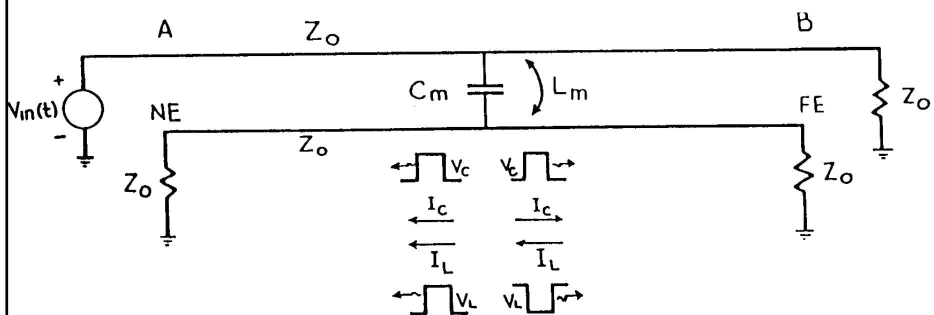
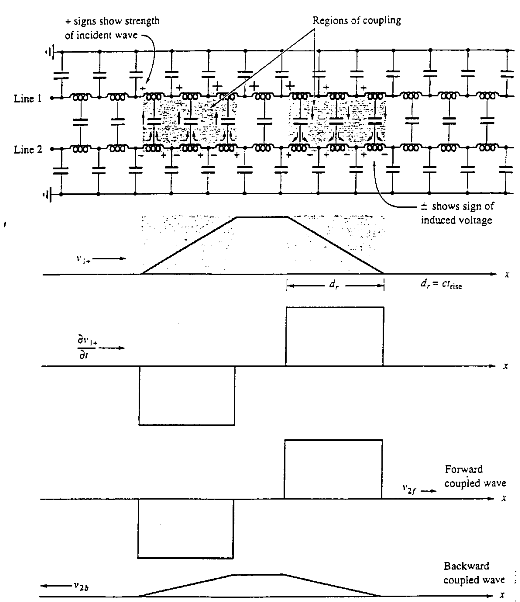
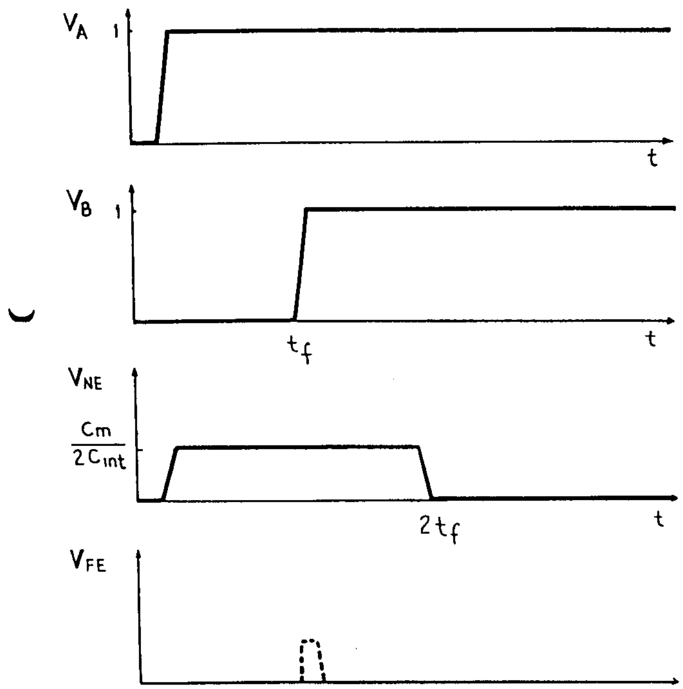
Crosstalk polarities



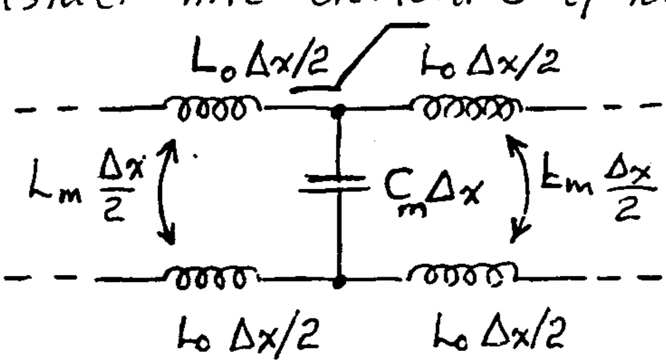
Forward and backward noise



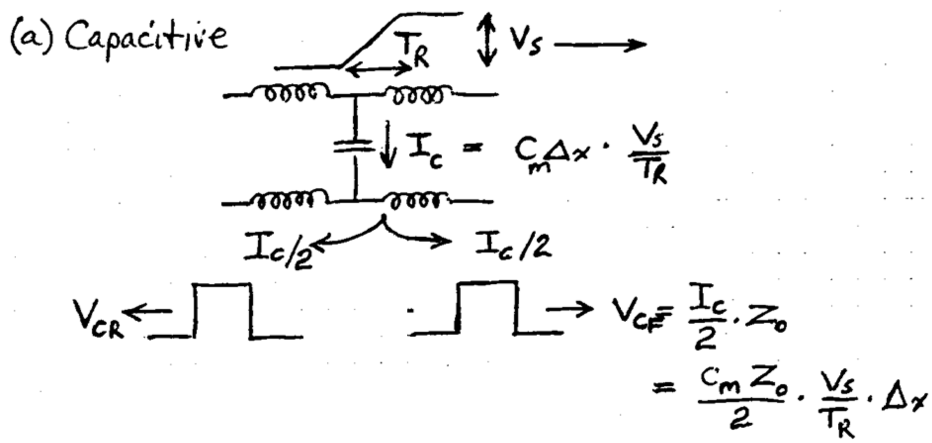


Theory: line segment

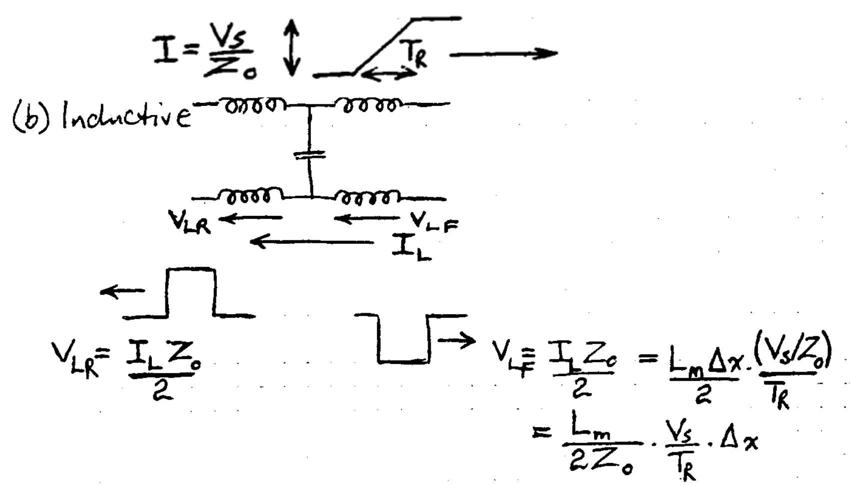
Consider line elements of length Δx



Capacitive noise

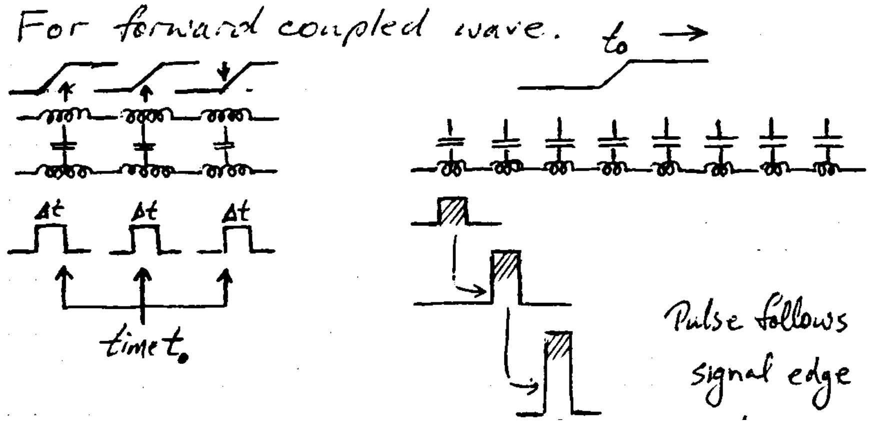


Inductive noise



Incremental model

For forward coupled wave.



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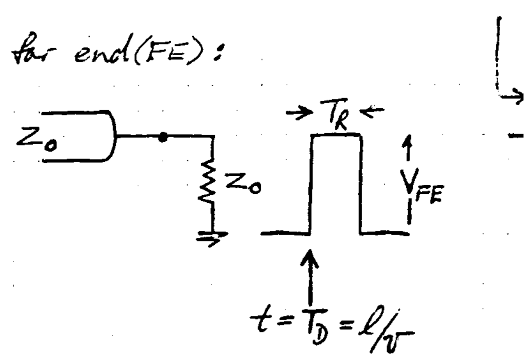
Far end formula

At far end (FE):



$$V_{FE} = \left(\frac{C_m Z_o}{2} - \frac{L_m}{2Z_o}\right)\frac{V_s}{T_R}\sum \Delta x$$

$$= \frac{1}{2}\left(C_m Z_o - \frac{L_m}{Z_o}\right)\frac{V_s}{T_R}\,\ell$$

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Zero far end noise

$$= \frac{1}{2}\left(C_m Z_0 - \frac{L_m}{Z_0}\right)\frac{V_S}{T_R}\,\ell$$

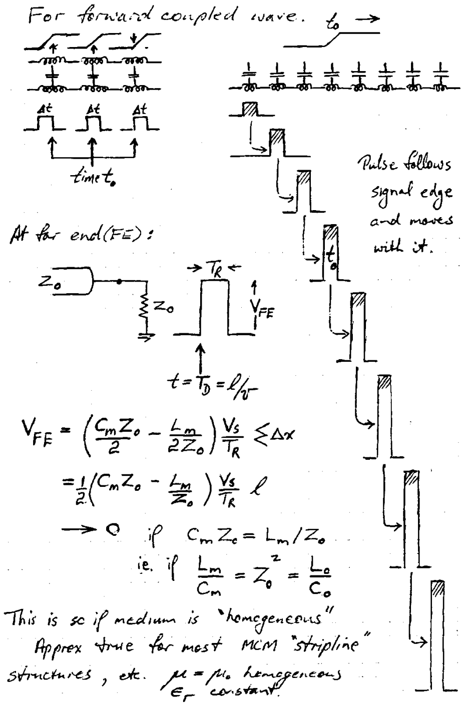
$$\rightarrow 0 \quad \text{if} \quad C_m Z_0 = L_m / Z_0$$

$$\text{i.e. if} \quad \frac{L_m}{C_m} = Z_0^2 = \frac{L_0}{C_0}$$

This is so if medium is "homogeneous"

Approx true for most MCM "stripline" structures, etc. $\mu = \mu_0$ homogeneous, ϵ_r constant.

For forward coupled wave.



$$V_{FE} = \left(\frac{C_m Z_0}{2} - \frac{L_m}{2 Z_0}\right)\frac{V_S}{T_R}\sum \Delta x$$

$$= \frac{1}{2}\left(C_m Z_0 - \frac{L_m}{Z_0}\right)\frac{V_S}{T_R}\,\ell$$

$$\rightarrow 0 \quad \text{if} \quad C_m Z_0 = L_m / Z_0$$

$$\text{i.e. if} \quad \frac{L_m}{C_m} = Z_0^2 = \frac{L_0}{C_0}$$

This is so if medium is "homogeneous"

Approx true for most MCM "stripline" structures, etc. $\mu = \mu_0$ homogeneous, ϵ_r constant.

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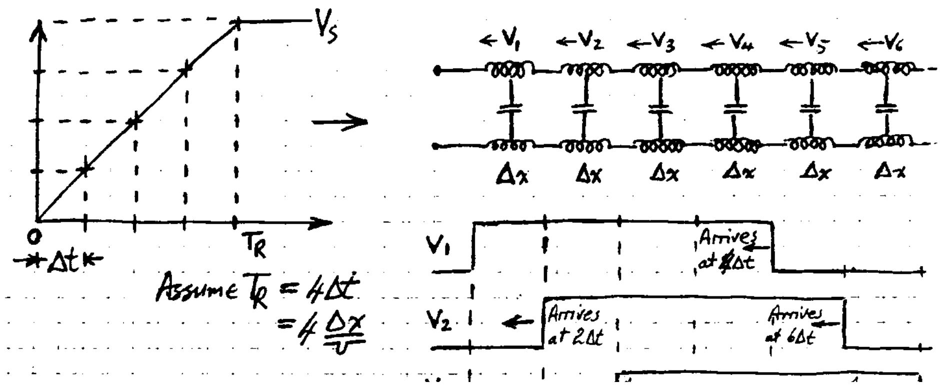
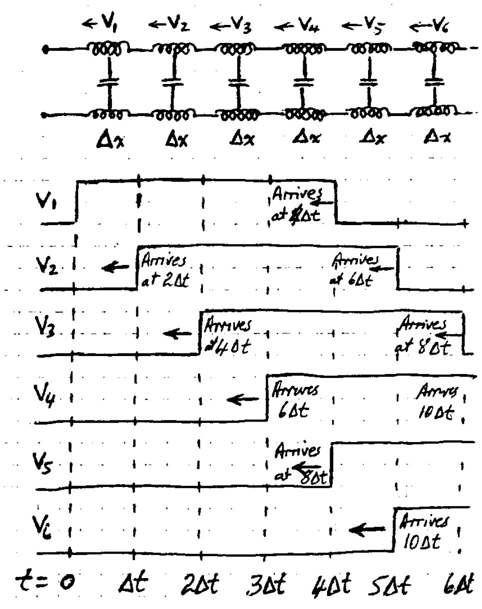
Backward wave model

For reverse coupled wave

Consider the near end (NE) as pulse starts:-



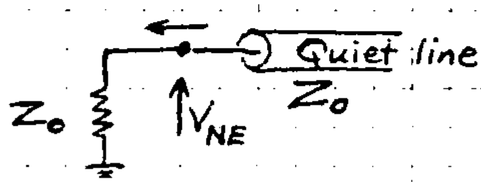
Backward wave construct



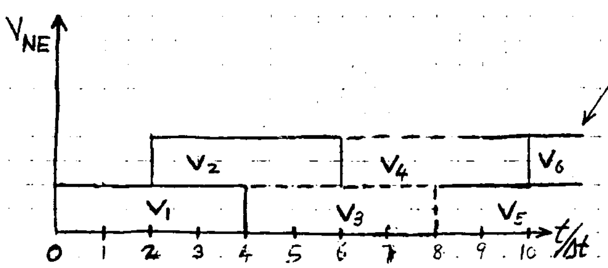
Near end formula

Each pulse

$$\Delta V = \left(\frac{C_m Z_0}{2} + \frac{L_m}{2Z_0}\right)\frac{V_s}{T_R}\Delta x$$



Near end noise waveform



Saturation at

$$V_{NE_{sat}} = 2\left(\frac{C_m Z_0}{2} + \frac{L_m}{2Z_0}\right)\frac{V_s}{T_R}\Delta x$$

$$= \frac{1}{2}\left(\frac{C_m Z_0}{2} + \frac{L_m}{2Z_0}\right)\frac{V_s}{T_R} \cdot T_R v$$

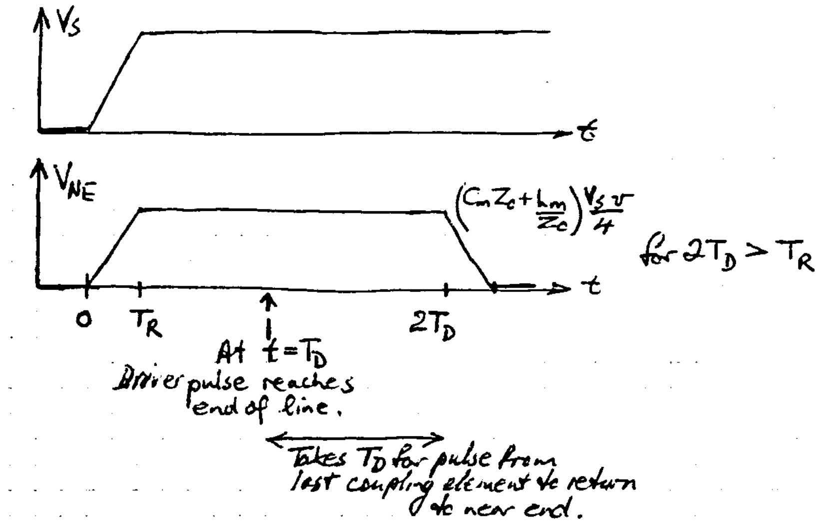
$$= \frac{1}{2}\left(\frac{C_m Z_0}{2} + \frac{L_m}{2Z_0}\right) V_s v$$

Note: Independent of T_R !!

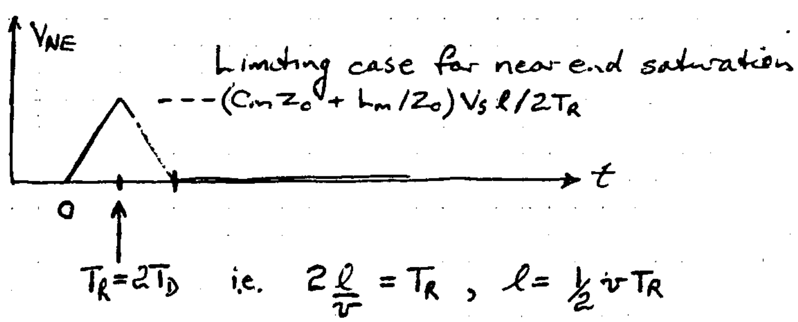
Also independent of ϵ_r $\quad C_m Z_0 v \propto \epsilon_r \epsilon_r^{-1/2} \epsilon_r^{-1/2}$

$$v/Z_0 \propto \epsilon_r^{-1/2}(\epsilon_r^{-1/2})^{-1}$$

Near end pulse shape



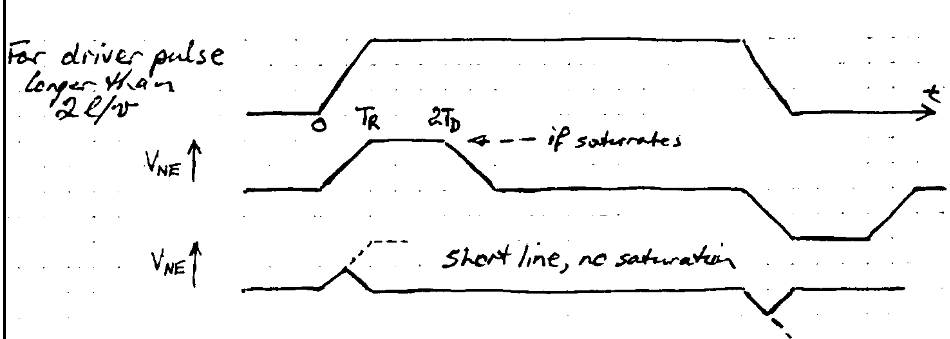
Near end saturation



If need to reduce $V_{NE})_{max}$, need to increase T_R &/or decrease ℓ

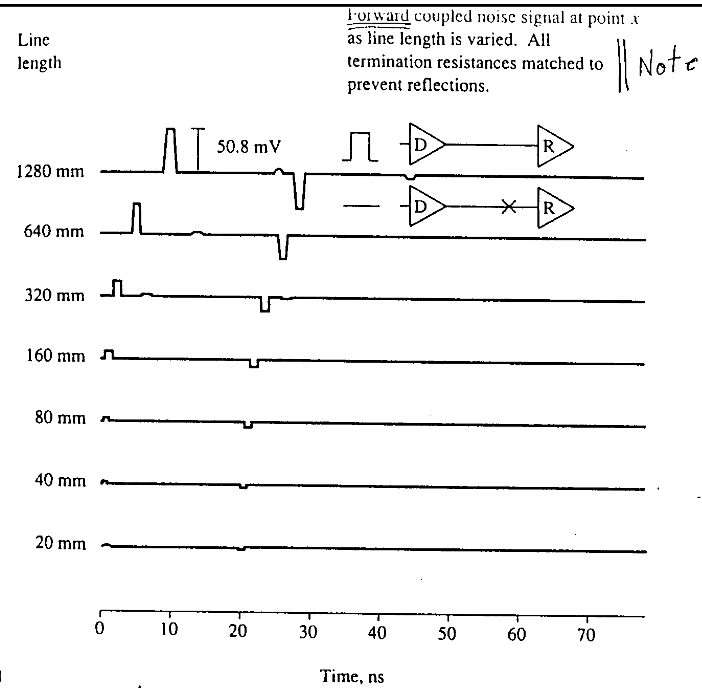
(i.e. decrease ℓ / T_R) so cannot saturate.

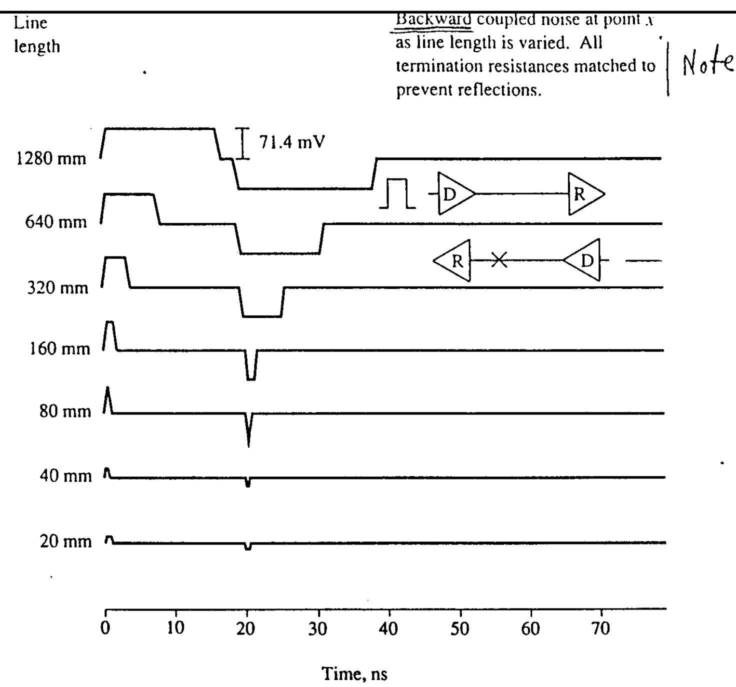
Near end saturation

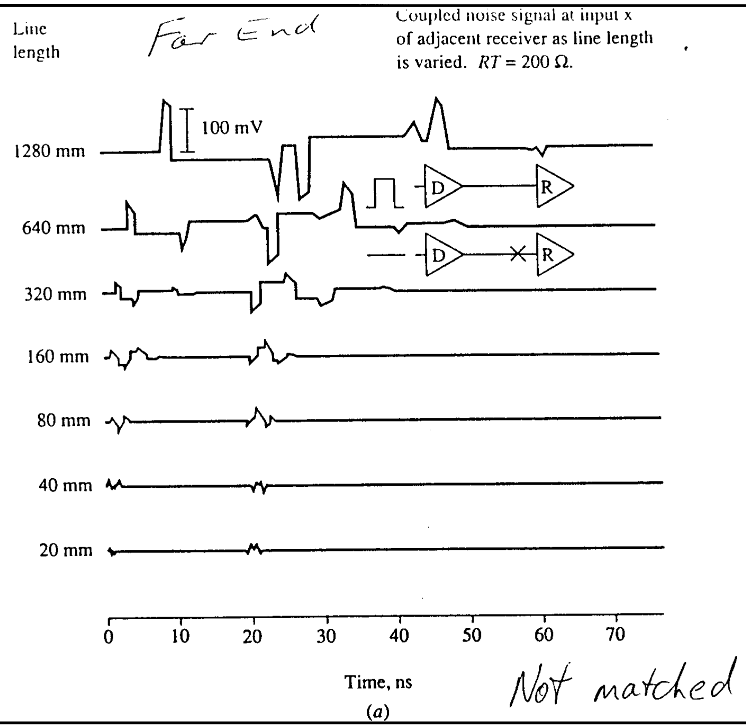


Pulse crosstalk noise examples

- Driver pulse
  - –0.5 volt amplitude
  - –20 ns pulse width
  - –1ns rise and fall times


Forward coupled noise signal at point x
as line length is varied. All
termination resistances matched to
prevent reflections.
Note
Line
length
50.8 mV
1280 mm
640 mm
320 mm
160 mm
80 mm
40 mm
20 mm
D
R
0
10
20
30
40
50
60
70
Time, ns
(a)


Backward coupled noise at point x
as line length is varied. All
termination resistances matched to
prevent reflections.
Note
Line
length
71.4 mV
1280 mm
640 mm
320 mm
160 mm
80 mm
40 mm
20 mm
D
R
0
10
20
30
40
50
60
70
Time, ns
(b)



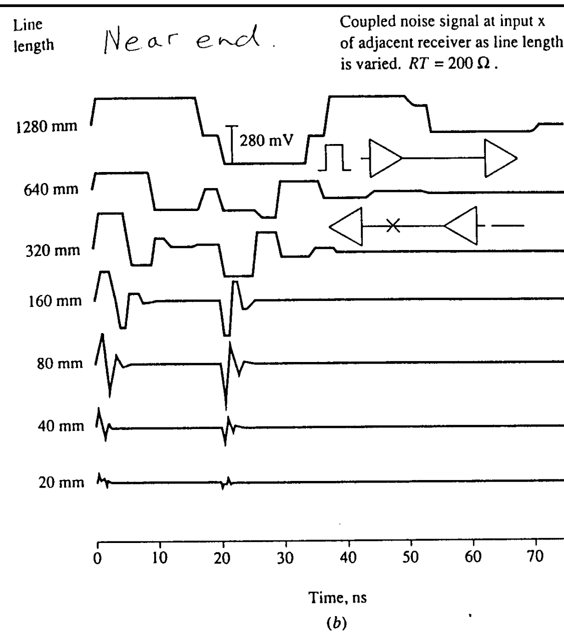
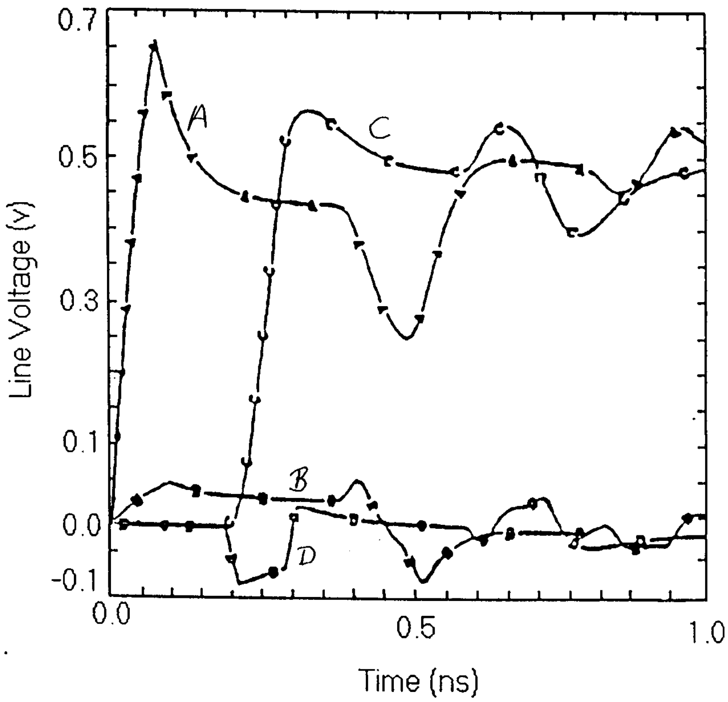


FIGURE 3-15
(*continued*) Not matched



Current distribution in ground

Current density at point D is proportional to

$$\frac{1}{1 + \left(\frac{D}{H}\right)^2}$$

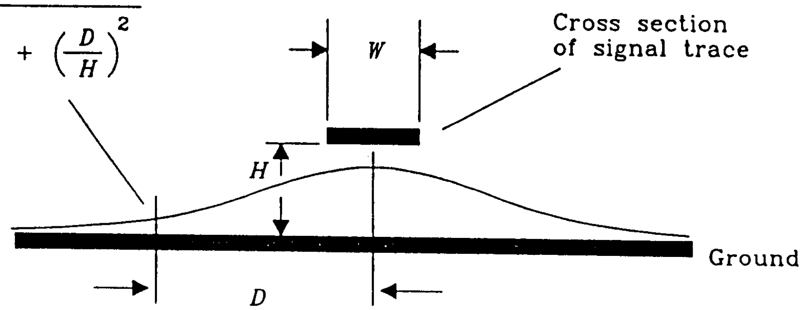


Figure 5.3 Distribution of high-frequency current density underneath a signal trace.

Ground coupled crosstalk

$$\text{Crosstalk} \approx \frac{K}{1+(D/H)^2}$$

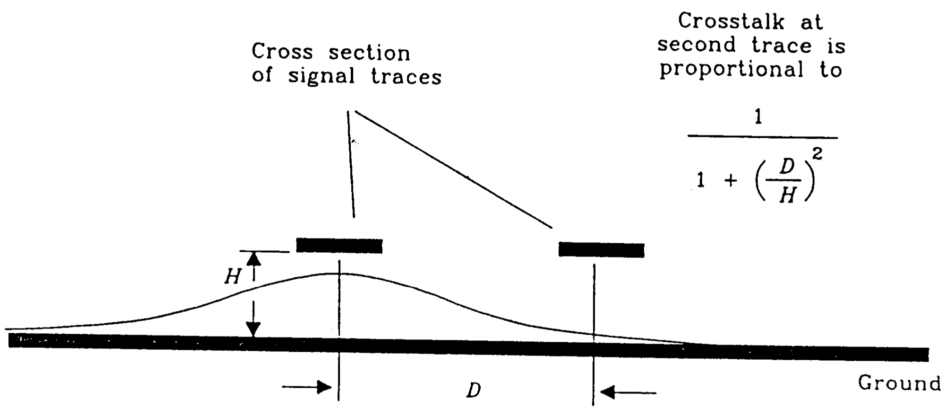


Figure 5.4 Cross section of two traces showing crosstalk.

Dielectric constant effect

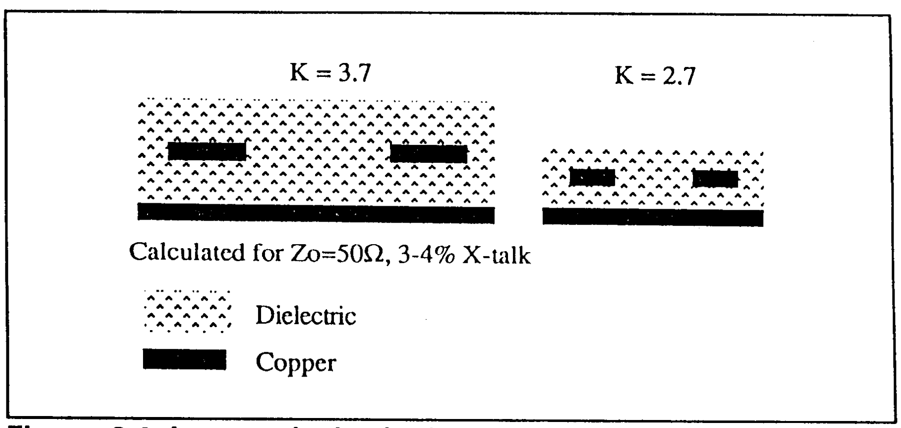


Figure 8.4 Increased circuit density through reduced dielectric constant.

Mutual capacitances

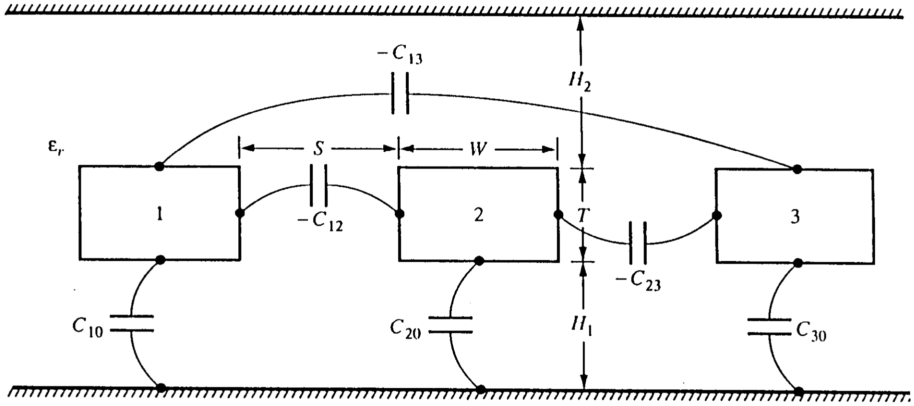
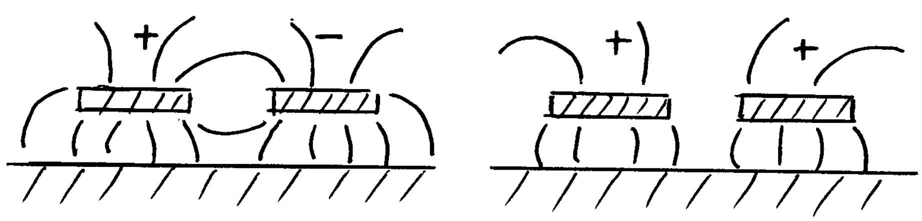


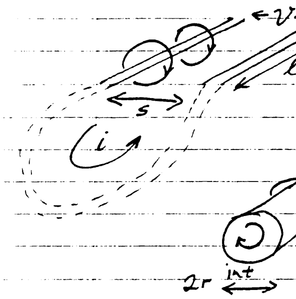
FIGURE 4-3
Cross section of three coupled lines in a homogeneous medium.

Even/odd modes



$C_{mo} > C_{me}$

Wire/lead inductance



$v = L\frac{di}{dt} = N\frac{d\phi}{dt}$

Split into 2 segments to get inductance of single wire. (Note: MUST have return wire.)

Internal & external fields → $L_{si} + L_{se}$

$L_{si} = \frac{\mu_0}{2\pi} \cdot \frac{\ell}{4} = \frac{\mu_0}{8\pi}$ /unit length

& $\mu_0 = 4\pi \times 10^{-7}$ H/m ∴ $L_{si} = 0.5$ nH/cm

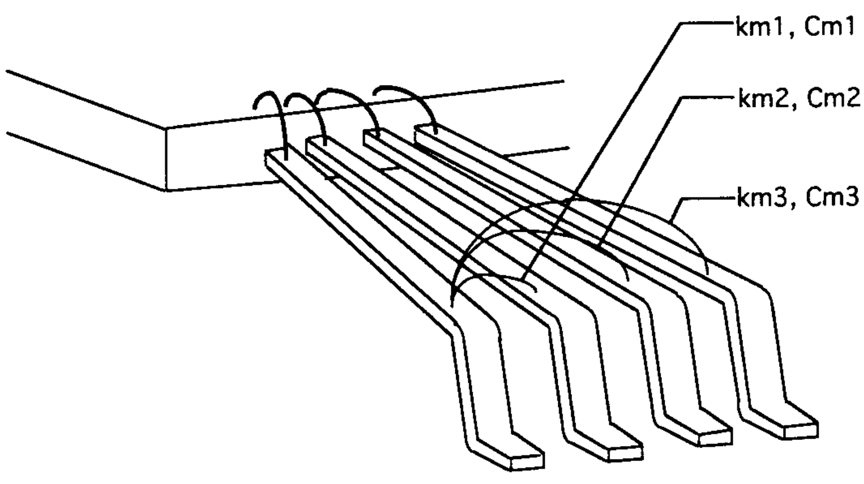
$L_s = L_{si} + L_{se}$ and typically $L_{se} \gg L_{si}$

$L_s \approx \frac{\mu_0}{2\pi}\left[\ln(2\ell/r) - 3/4\right]\ell$ for $r \ll \ell$. circular wire

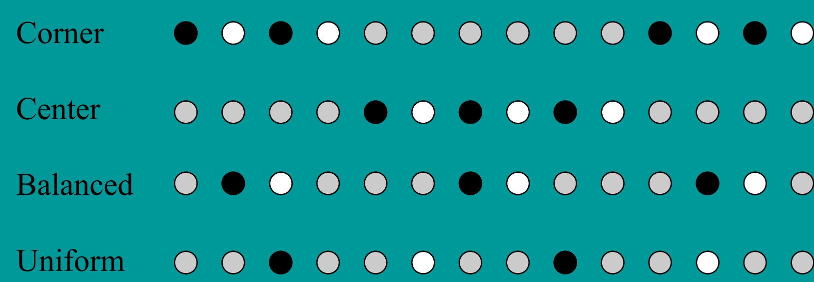
$\approx \frac{\mu_0}{2\pi}\left[\ln(4\ell/p) + 1/2\right]\ell$ for perimeter p rectangular lead

Mutual inductance $M = \frac{\mu_0}{2\pi}\left[\ln\left(\frac{\ell}{s} + \sqrt{1+(\ell/s)^2}\right) - \sqrt{1+(s/\ell)^2} + (s/\ell)\right]\ell$

Development of a SPICE model: Package leads



•User selectable configurations:



Power , ground, and signal line architectures

Analysis options

- 1. Delta-I noise model
- 2. Signal crosstalk model

V_P ⟶

Signal ⟶

G ⟶

Specify: ΔI noise i.e. set I_P (I_S=0)
& assume all power lines same current I_P /n

OR signal crosstalk i.e. set I_S (I_P=0)
& assume all signal lines same current (i.e. $n_S I_S$ total)

Matrix calculations

- Induced voltages v_i due to changing currents I_i:
- $V_i = L_{i1}dI_1/dt + L_{i2}dI_2/dt + \ldots\ldots L_{ii}dI_i/dt \ldots\ldots + L_{in}dI_n/dt$
- $= \Sigma L_{ij}\, d(I_j)/dt$ for line i = 1, 2,..., N
- where N = Number of leads/side
- V_i = voltage at line i for i = 1, 2,..., N
- I_i = current at line i for i = 1, 2,..., N
- L_{ij} = mutual inductance between line i and line j for i, j = 1, 2,..., N and $i \neq j$
- L_{ii} = self-inductance of line i for i = 1, 2,..., N

$$\begin{vmatrix} v_1 \\ v_2 \\ v_3 \\ \\ \\ v_N \end{vmatrix} = \begin{vmatrix} L_{11} & L_{12} & & L_{1N} \\ L_{21} & L_{22} & & L_{2N} \\ & & & \\ & & & \\ & & & \\ L_{n1} & & & L_{NN} \end{vmatrix} \begin{vmatrix} I_1 \\ I_2 \\ \\ \\ \\ I_N \end{vmatrix}$$

$|L|$ symmetrical, $L_{ij} = L_{ji} = M_{ij}$ $\qquad L_{ii} \rightarrow L_i$

[(N+1) by 1 matrix] = [(N+1) by N matrix] * [N by 1 matrix]

$$\left|\begin{array}{c} v_1 \\ v_2 \\ v_3 \\ \\ \\ v_N \\ 0 \end{array}\right| = \left|\begin{array}{cccccc} L_{11} & L_{12} & & & & L_{1N} \\ L_{21} & L_{22} & & & & L_{2N} \\ & & & & & \\ & & & & & \\ & & & & & \\ L_{N1} & & & & & L_{NN} \\ 1 & 1 & 1 & & & 1 \end{array}\right| \left|\begin{array}{c} I_1 \\ I_2 \\ \\ \\ \\ I_N \\ \\ \end{array}\right|$$

Model choice

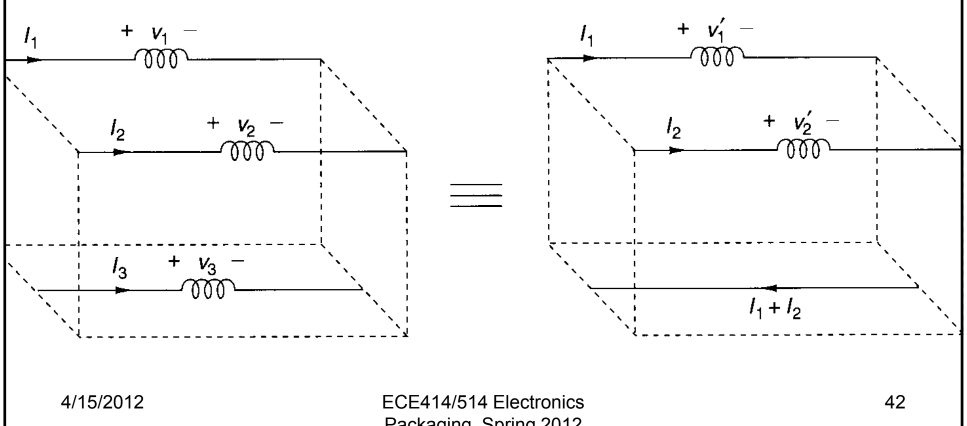
- According to the layout specified by the user,
- V_i's and I_i's are divided into three catagories: power (V_p, I_p), signal (V_s, I_s), and ground (V_g, I_g)
- For delta-I noise model,
- 1. set I_p (assuming all power lines have the same current)
- 2. set $I_s = 0$
- For signal crosstalk model,
- 1. set I_s (assuming all signal lines have the same current)
  - 2. set $I_p = 0$
- Assuming pin 1 is ground,
- set V_g's = V_1

$|A|\ |y| = |X|\ |x| \dashrightarrow |y| = |A|^{-1}\ |X|\ |x|$

- Rearranging the matrix equations by moving all $L_{ij}I_j$'s (where I_j is I_g) to the left side results in:
- [(N+1) by (N+1) matrix] * [(N+1) by 1 matrix] = [(N+1) by (N-n) matrix] * [(N-n) by 1 matrix]

1 0 0 0 0 $-L_{11}$	V_1		L_{12}	L_{1N}		
1 0 0	V_2					I_2
1 0 0	V_N					
0 1 0 0 0	I_1	=				
0 0 1 0						
0 0 1						
1 0						
0 0 0 1 $-L_{N1}$			L_{N2}	L_{NN}		I_N
0 0 0 0 0 -1 -1 -1			1 1	1 1		

Inductance/ground transform (in practice for Spice, etc) Need to reference a common ground



Effective inductance

$v_1 = L_{11}(dI_1/dt) + L_{12}(dI_2/dt) + L_{13}(dI_3/dt)$

$v_3 = L_{31}(dI_1/dt) + L_{32}(dI_2/dt) + L_{33}(dI_3/dt)$

and for ground return: $I_3 = -(I_1 + I_2)$

$v_1^{/} = v_1 - v_3$

$= (L_{11} - L_{13} - L_{31} + L_{33})\,(dI_1/dt) + (L_{12} - L_{13} - L_{32} + L_{33})\,(dI_2/dt)$

$= L^{/}_{11}(dI_1/dt) + L^{/}_{12}(dI_2/dt)$

So have $L^{/}_{ij} = L_{ij} - L_{ig} - L_{gj} + L_{gg} = 2(L_{ij} - L_{ig})$

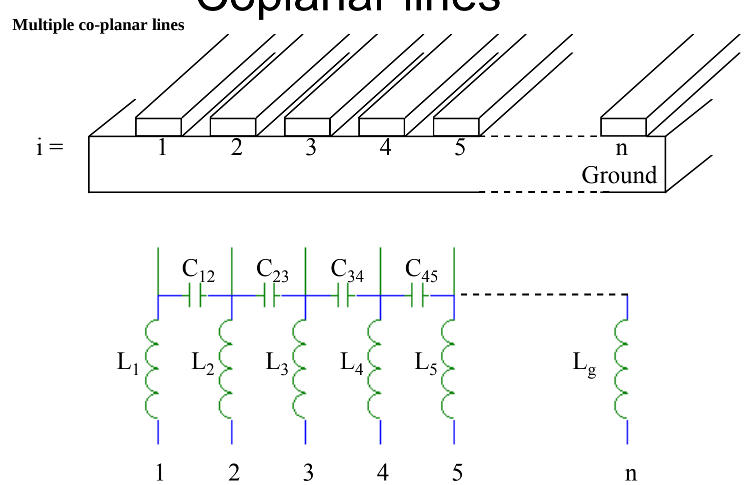
Use for inductive crosstalk $i \neq j$ $L_{ij}^{/} \rightarrow M_{ij}^{/}$

and delta-I noise $I = j = s(org)$ $L_{ij}^{/} \rightarrow L_s$, (L_g)

Also: Mutual capacitance crosstalk → crosstalk currents

(Develop voltages if impedances high)

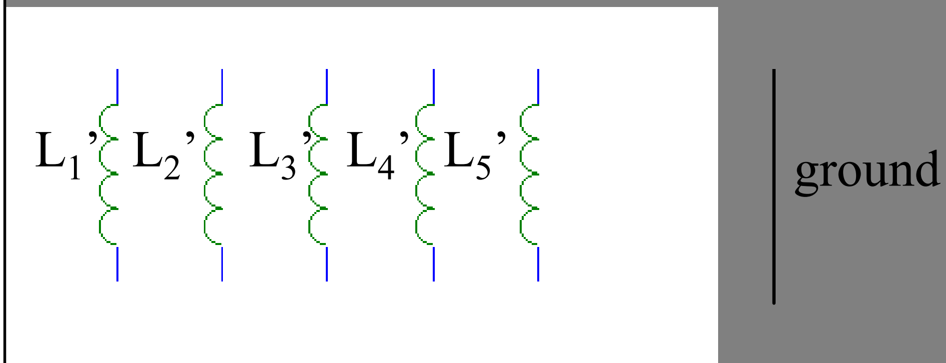
Coplanar lines



plus mutual inductance M_{ij}

where L_i is the self-inductance of an individual "isolated" wire.

Referencing all lines to v_n, taken as $v_n = 0$ to define ground

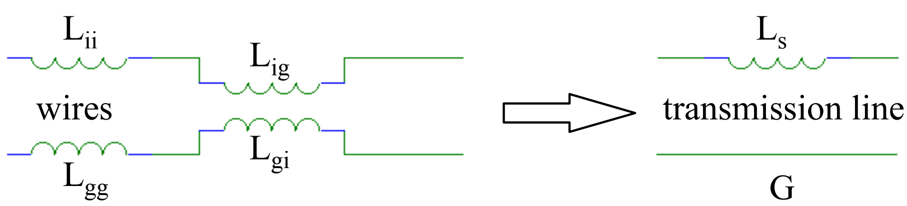


Effective L

- $L_s = L_i' = L_i + L_g - M_{ig} - M_{gi}$
- $M_{ig} = M_{gi}$ and if the lines are identical, $L_i = L_g$, so
  - $L_i' = 2(L_i - M_{ig})$
- To evaluate crosstalk in the transmission line system, the mutual inductances become
  - $M_{ij}' = M_{ij} + (L_g - M_{ig} - M_{jg})$
- The self-inductance L_s includes both internal and external inductances $L_s = L_{si} + L_{se}$
- L_{si} varies with frequency (skin effect)

Discrete wire to line model

Individual wires considered as a transmission line



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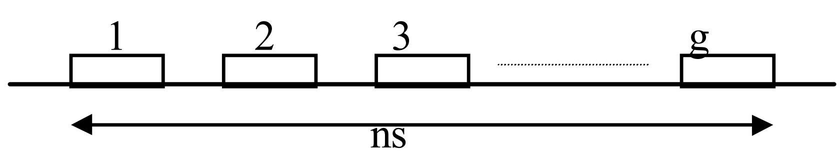
Coplanar lines with remote ground

4. Similarly, $M_{ij}' = L_{ij} - L_{ig} - L_{gj} + L_{gg}$, where



n = | i - j |

Co-planar lines with "remote" ground line

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Assignment #3

1. Dally et al, Problem 3.17 (see text for τ)
2. Dally et al, Problem 3.19
3. A lossless 10cm long microstrip transmission line as shown in Dally et al Fig. 3.17, is terminated in a load R_L equal to impedance Z_0 and driven by an ideal 1 volt voltage step source. Use SPICE (or any other similar program with which you are familiar) to plot the load waveforms over a period of 2.5 line delays, representing the line by:
   (a) a single lumped L-C section (b) 10 lumped L-C sections
   (c) 100 lumped L-C sections, and (d) a transmission line model.
   (e) Comment on your results.
4. For a transmission line of impedance 50Ω driven by a source of impedance 0Ω and terminated by load 100Ω , determine the source and load reflection coefficients. Draw the reflection diagram for a propagation time of 4T, and label all the quantities at each time interval.
5. Two identical signal lines of Z_0 = 50Ω are terminated by 50Ω loads. The signal lines are 2cm long, and the ramp-step source to line 1 changes at 10^9V/s. The mutual inductance between the two signal lines is 2nH, and the mutual capacitance is 2pF. Determine the crosstalk magnitudes on line 2, and sketch the crosstalk waveforms.