Crosstalk

吳瑞北
Rm. 340, Department of Electrical Engineering
E-mail: rbwu@ew.ee.ntu.edu.tw
url: cc.ee.ntu.edu.tw/~rbwu

S. H. Hall et al., *High-Speed Digital Design*, Chap.4
N. N. Rao, *Elements of Engineering Electromagnetics*, Sec. 6.7.

What will you learn

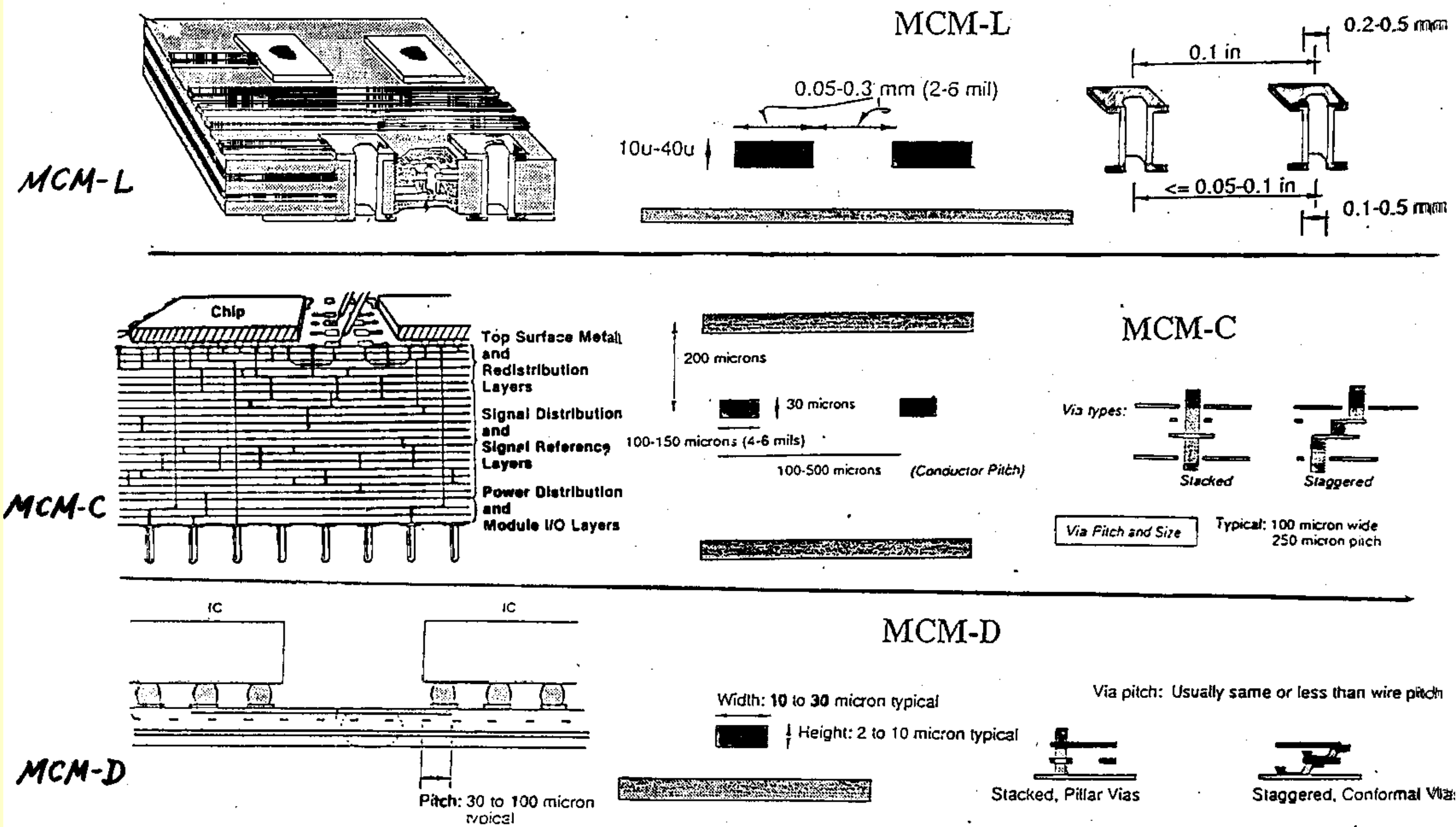
- **Physical** insight to inductive & capacitive coupling
- **Definition** of L and C matrices of multi-coupled tx-lines
- **Electrical parameter extraction** for coupled tx-lines
- Phenomenological description of crosstalk noise by **weakly coupling analysis**
- Analytic derivation for crosstalk noise by **model analysis**
- Construction of equivalent SPICE circuit for transient **simulation** of ideal coupled tx-lines
- Novel **designs** for minimization of crosstalk noise: matched termination, guard trace, spiral delay line.

Contents

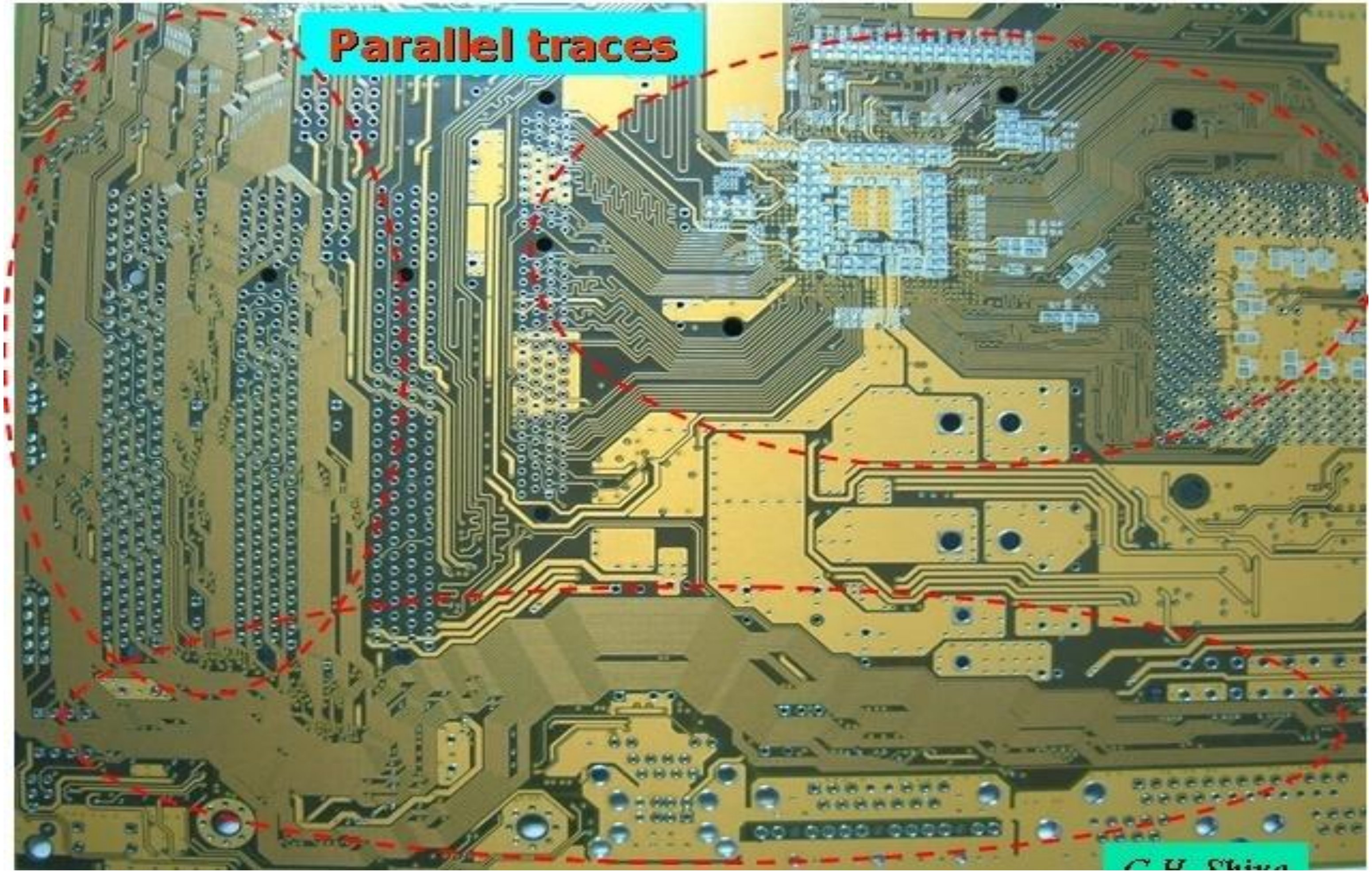
- Two mechanisms that Cause Crosstalk
- Crosstalk-induced Noise
- Even/Odd Mode Decomposition
- Modal Analysis
- Simulation in SPICE
- Design Issues

MCM Structures

Typical Conductor Cross-section   Typical via-size and pitch

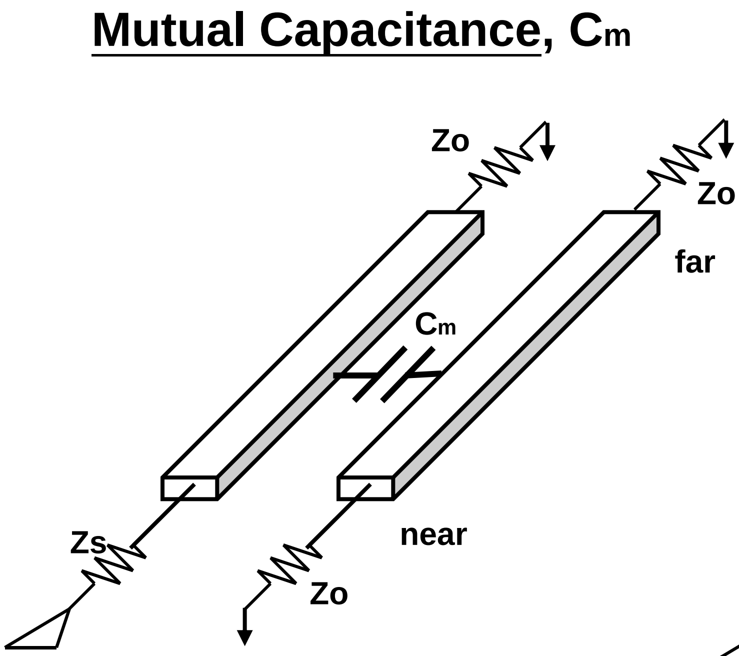


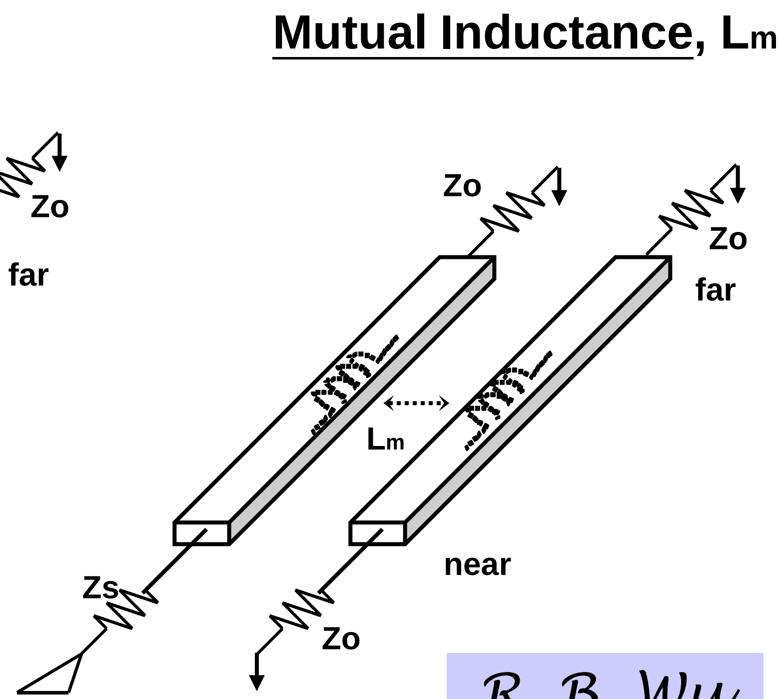
Example



Mutual Inductance and Capacitance

- Crosstalk is caused by energy coupling from one line to another via:
  - *Mutual capacitance (electric field)*
  - *Mutual inductance (magnetic field)*

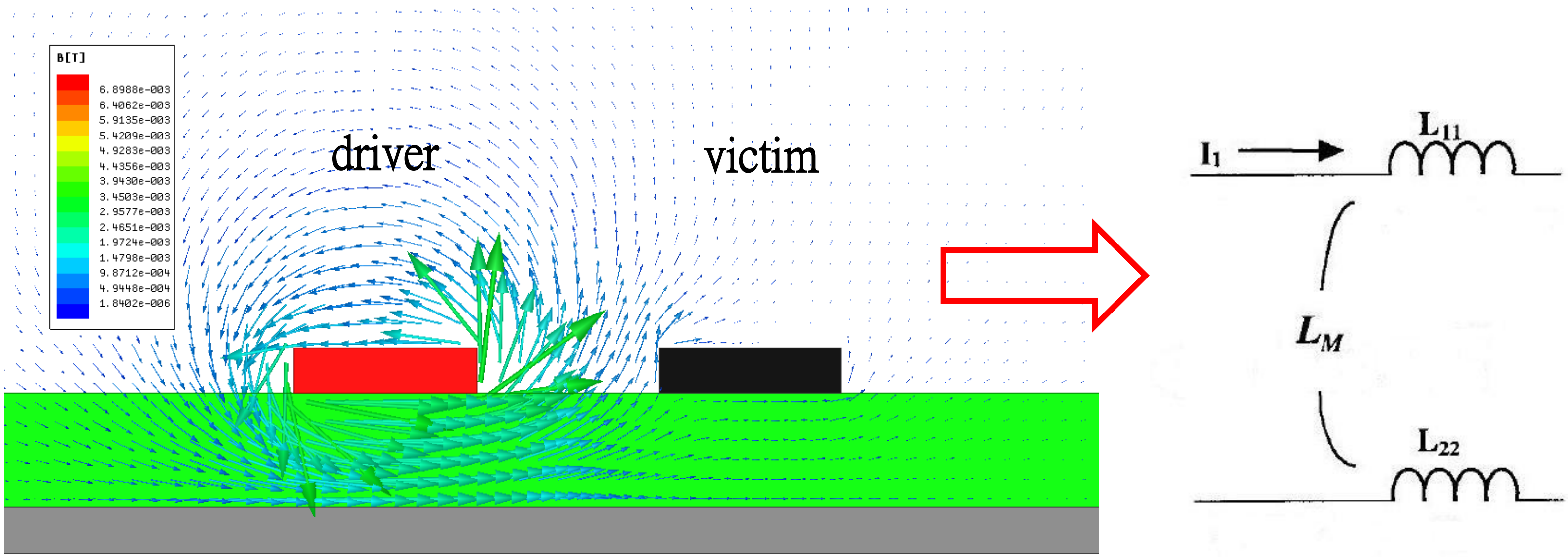




R. B. Wu

Mutual Inductance

Mutual L induces current from a driven line onto a quiet line by magnetic field。

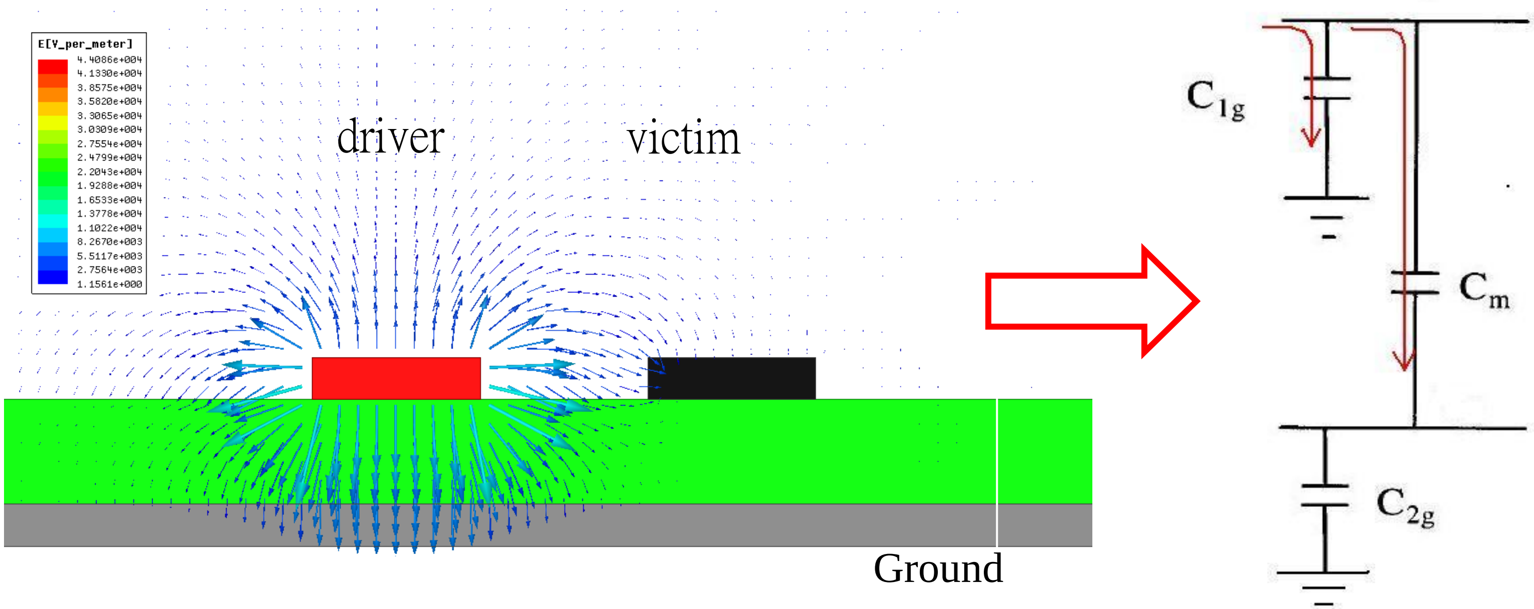


Ground

$$V_{noise} = L_m \frac{dI_{driver}}{dt}$$

Mutual Capacitance

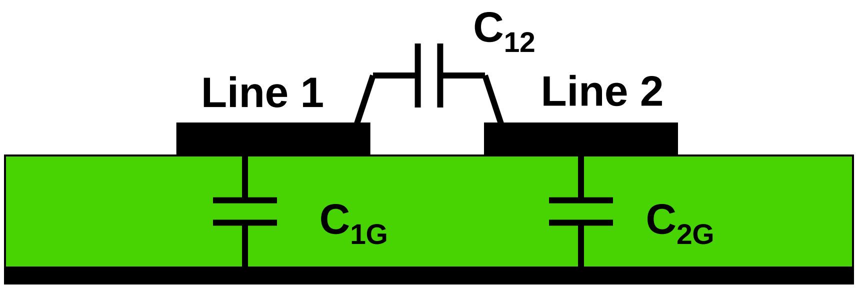
Mutual C is coupling of two conductors via electric field



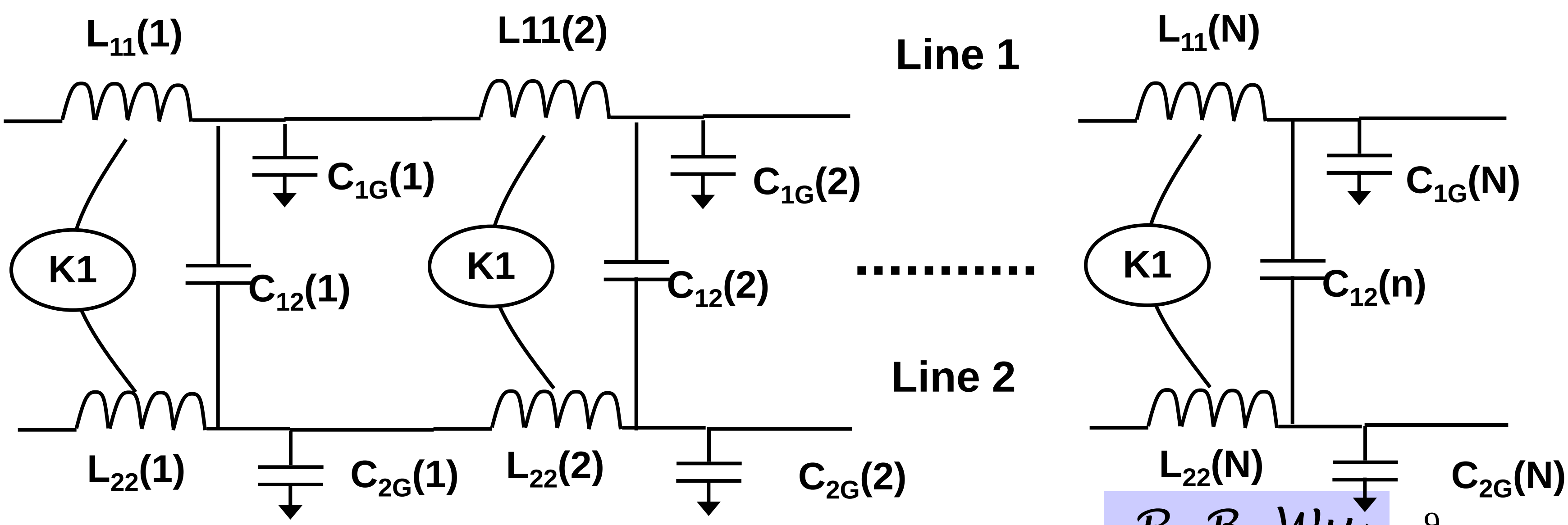
$$I_{noise} = C_m \frac{dV_{driver}}{dt}$$

Crosstalk Model by "*Equivalent Circuit*"

- Circuit is distributed into N segments



$$K = \frac{L_{12}}{\sqrt{L_{11} L_{22}}}$$



R. B. Wu

Inductance Matrix

- **Inductance matrix:**
  - L_{NN} = self inductance of line N per unit length
  - L_{MN} = mutual inductance between lines M and N

$$[L] = \begin{bmatrix} L_{11} & L_{12} & \cdots & L_{1N} \\ L_{21} & L_{22} & \ddots & \vdots \\ \vdots & & & \\ L_{N1} & \cdots & \cdots & L_{NN} \end{bmatrix}$$

Capacitance Matrix

- **Capacitance matrix:**
  - C_{NN} = self capacitance of line N per unit length where:

$$C_{NN} = C_{NG} + \sum |C|_{mutuals}$$

  - C_{NG} = Capacitance between line N and ground
  - C_{MN} = Mutual capacitance between lines M and N

$$[C] = \begin{bmatrix} C_{11} & -|C_{12}| & \cdots & -|C_{1N}| \\ -|C_{21}| & C_{22} & & \vdots \\ \vdots & & \ddots & \vdots \\ -|C_{N1}| & \cdots & \cdots & C_{NN} \end{bmatrix}$$

- **For example, for 2 line circuit:**

$$C_{11} = C_{1G} + |C_{12}|$$

Numerical Techniques

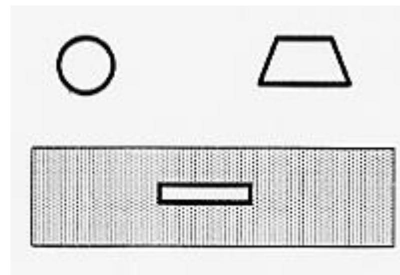
Geometry of lines:
width, separation, thickness, height, substrate, etc.

↓ C2D

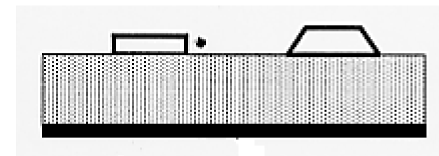
Electrical parameters:
capacitance matrix [C]
Inductance matrix [L]

- Based on IE formulation and MoM
- Exact integration formulae
- Four versions are available

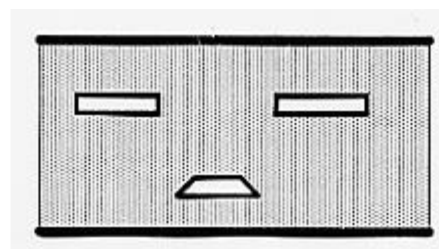
CAP1



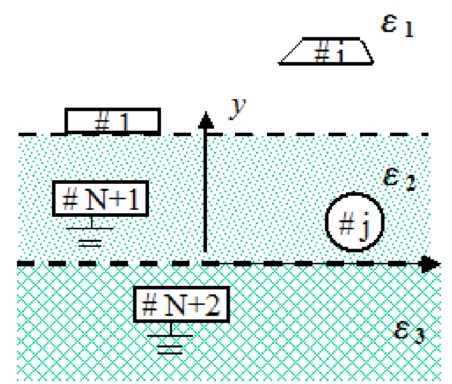
CAP2 - microstrip



CAP3 – triplate



CAP4 – e.g. CPW

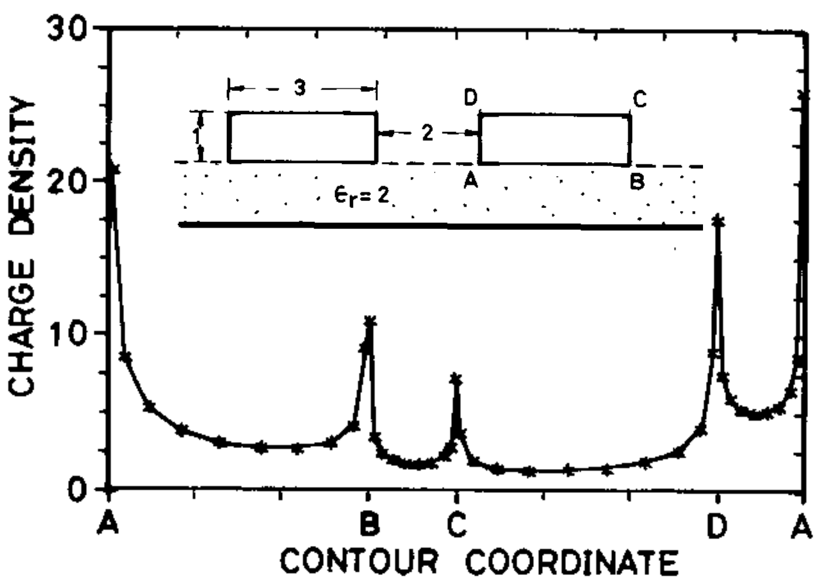


W. T. Weeks, “Calculation of coefficients of capacitance of multiconductor transmission lines in the presence of a dielectric interface,” *IEEE T-MTT*, Jan. 1970.

CAP2 Example

輸入檔案CAP2.DAT

```
1.   2.   1.                       # E1,  E2,  H
2    0                             # N,  Print/no
1                                  # Conductor 1 : rectangular
4    3    6                        # Polygen K,  Len_Div,  N_Min_Div
     -4.  1.   -1.  1.   -1.  2.   -4.  2.   -4.  1.
1                                  # Conductor 2 ....
4    3    6
     1.   1.   4.   1.   4.   2.   1.   2.   1.   1.
```



輸出檔案CAP2.OUT

```
Matrix of Capacitance Coefficients: (pF/m)
    93.4600      -8.5756
    -8.5756      93.4600

Matrix of Inductance Coefficients: (nH/m)
   198.1587      30.1863
    30.1863     198.1588

Approximate Characteristic Impedance: (ohm)
    46.0462      46.0462

Approximate Saturated Near End Noise
     1.0000       0.0610
     0.0610       1.0000
```

R. B. Wu

Crosstalk Induced Noise

Mechanism of coupling

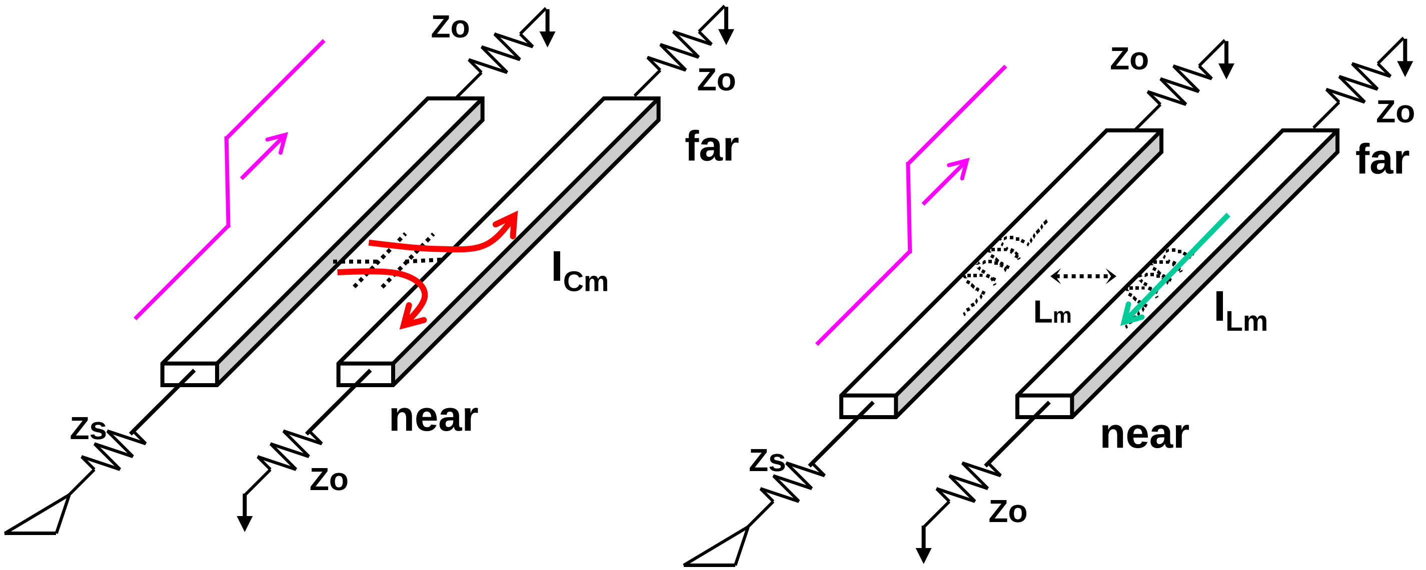
- Circuit element representing transfer of energy

$$V_{Lm} = L_m \frac{dI}{dt} \qquad I_{Cm} = C_m \frac{dV}{dt}$$

- Mutual inductance induces current on victim line opposite of driving current (Lenz's Law)
- Mutual capacitance passes current through mutual capacitance that flows in both directions on the victim line

Coupled Currents

- Coupled currents on victim line sum to produce near and far end crosstalk noise

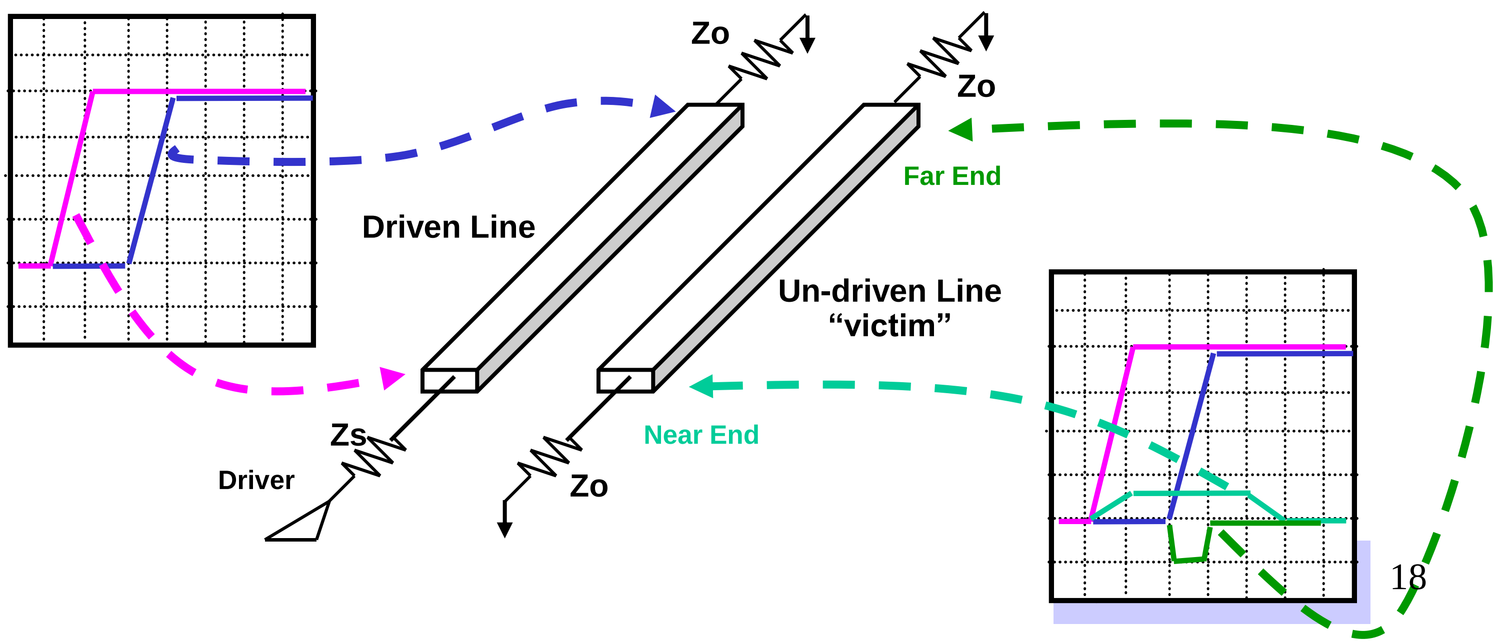


$$I_{near} = I_{Cm} + I_{Lm} \qquad I_{far} = I_{Cm} - I_{Lm}$$

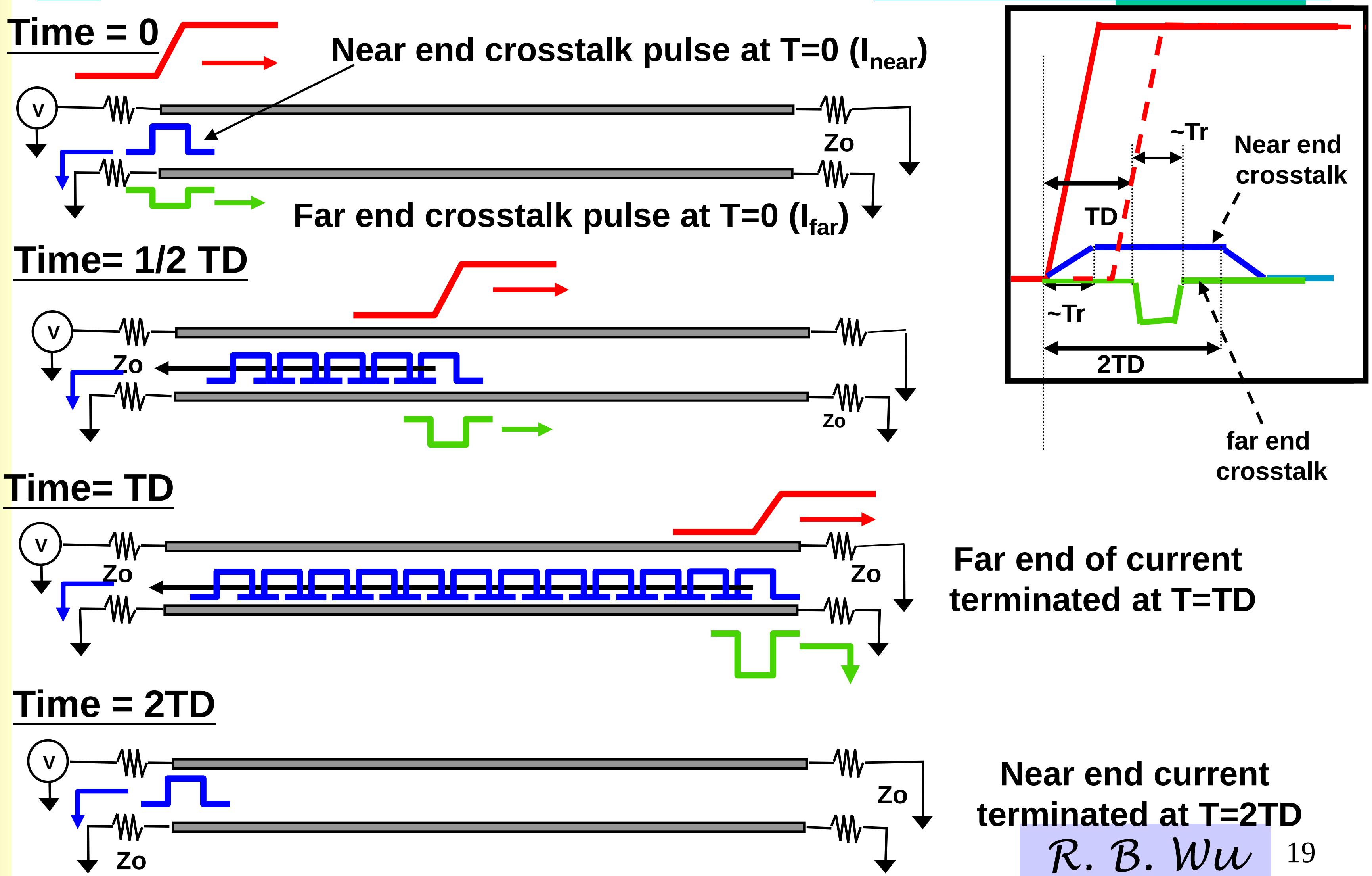
R. B. Wu

Voltage Profile of Coupled Noise

- **Near end crosstalk is always positive**
  - Currents from Lm and Cm always add & flow into the node.
- **For PCB's, far end crosstalk is "usually" negative**
  - Current due to Lm larger than current due to Cm
  - Note that far and crosstalk can be positive or **nullified**.

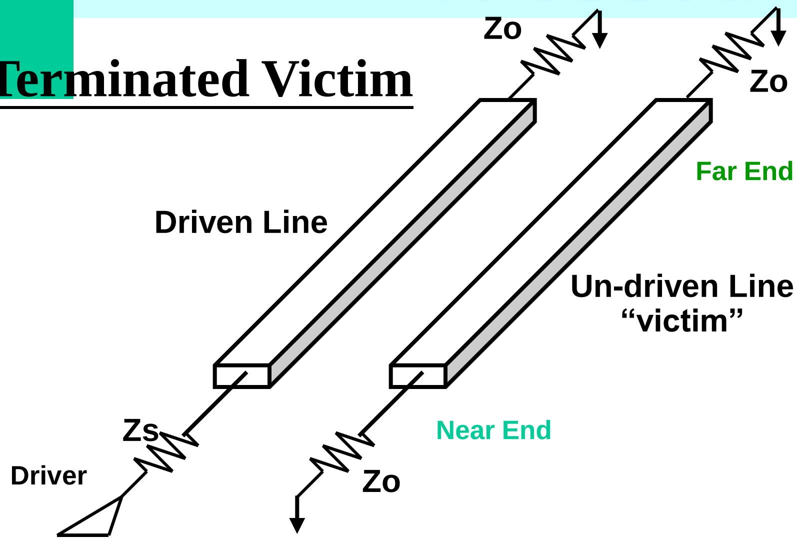


Graphical Explanation



Crosstalk Equations

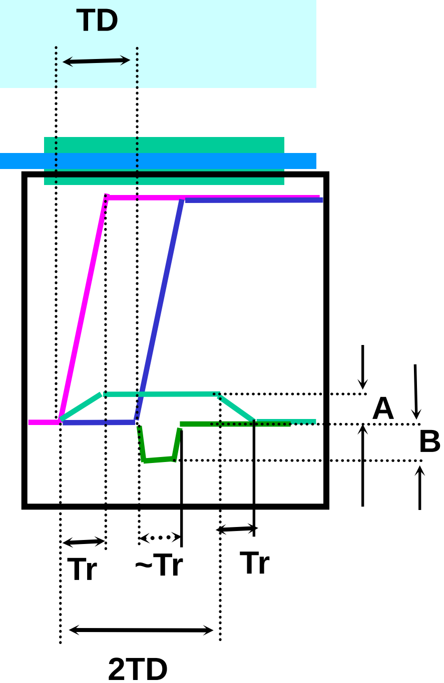
Terminated Victim



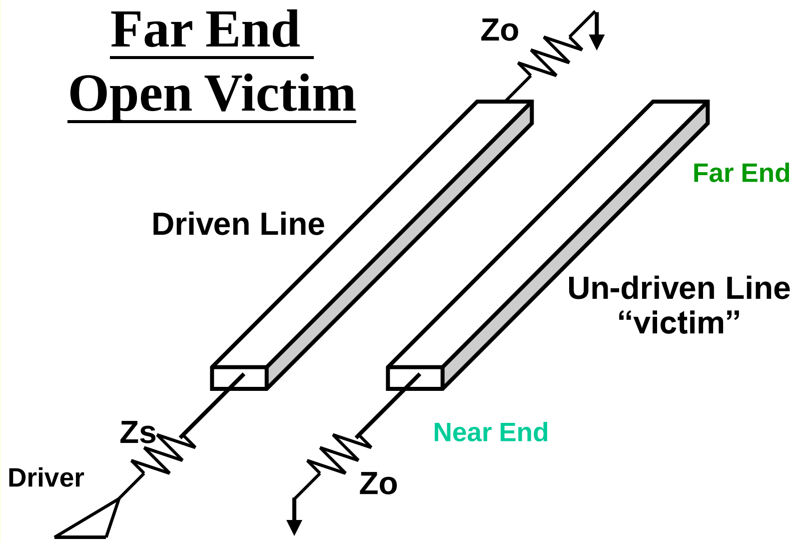
$$A = \frac{V_{input}}{4}\left[\frac{L_M}{L} + \frac{C_M}{C}\right]$$

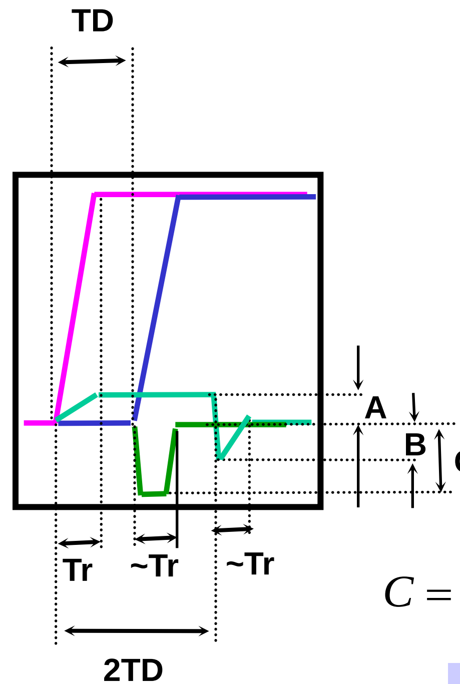
$$TD = X\sqrt{LC}$$

$$B = -\frac{V_{input} \cdot TD}{2T_r}\left[\frac{L_M}{L} - \frac{C_M}{C}\right]$$



Far End Open Victim





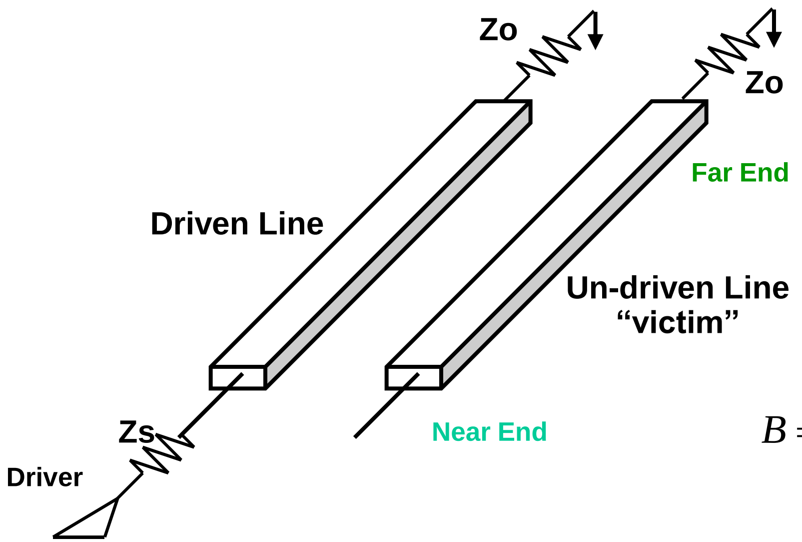
$$A = \frac{V_{input}}{4}\left[\frac{L_M}{L} + \frac{C_M}{C}\right]$$

$$B = \frac{1}{2}C$$

$$C = -\frac{V_{input} \cdot TD}{T_r}\left[\frac{L_M}{L} - \frac{C_M}{C}\right]$$

Crosstalk Equations -2

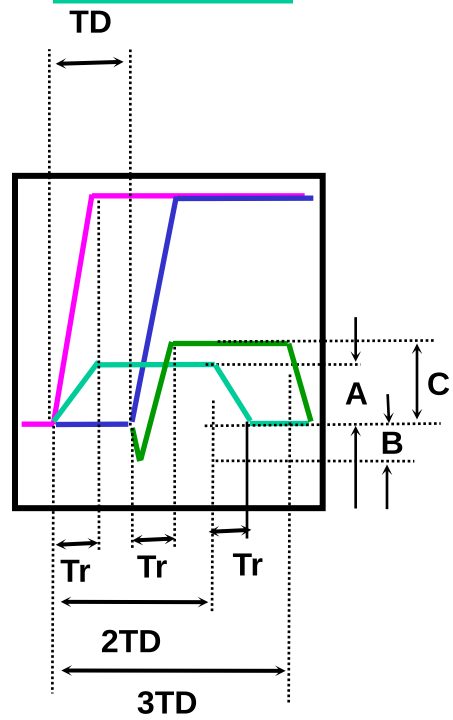
Near End Open Victim



$$A = \frac{V_{input}}{2}\left[\frac{L_M}{L} + \frac{C_M}{C}\right]$$

$$C = \frac{V_{input}}{4}\left[\frac{L_M}{L} - \frac{C_M}{C}\right]$$

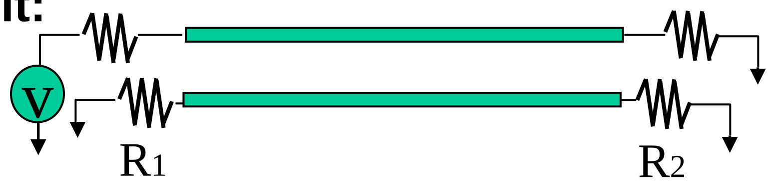
$$B = -\frac{V_{input} \cdot TD}{2T_r}\left[\frac{L_M}{L} - \frac{C_M}{C}\right]$$



- **The Crosstalk noise characteristics are dependent on the termination of the victim line**

Example

Calculate near and far end crosstalk-induced noise magnitudes and sketch the waveforms of circuit:



Vsource=2V, Trise = 100ps.
Length of line is 2 inches. Assume all terminations are 70 Ohms.
Assume the following capacitance and inductance matrix:

$$\mathbf{L} = \begin{bmatrix} 9.869 & 2.103 \\ 2.103 & 9.869 \end{bmatrix} \text{ nH / inch} \qquad \mathbf{C} = \begin{bmatrix} 2.051 & -0.239 \\ -0.239 & 2.051 \end{bmatrix} \text{ pF / inch}$$

Characteristic impedance is:

$$Z_O = \sqrt{\frac{L_{11}}{C_{11}}} = \sqrt{\frac{9.869nH}{2.051pF}} = 69.4\Omega$$

Therefore the system has matched termination. (Vinput = 1.0V), crosstalk noise magnitudes can be calculated as follows:

Example (cont.)

Near end crosstalk voltage amplitude:

$$V_{near} = \frac{V_{input}}{4}\left[\frac{L_{12}}{L_{11}} + \frac{|C_{12}|}{C_{11}}\right] = \frac{1V}{4}\left[\frac{2.103}{9.869} + \frac{0.239}{2.051}\right] = 0.082V$$

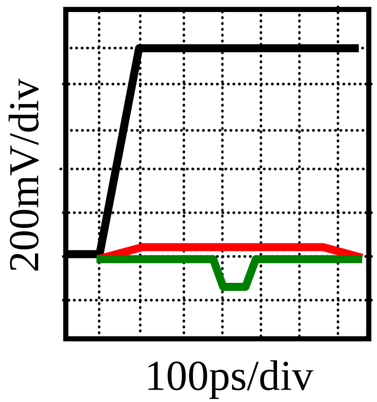
Propagation delay of the 2 inch line is:

$$TD = X\sqrt{LC} = 2\text{inch} * \sqrt{(9.869\text{nH} * 2.051\text{pF}} = 0.28\text{ns} = 280\text{ps}$$

Far end crosstalk voltage amplitude:

$$V_{far} = \frac{V_{input}}{2} \cdot \frac{\text{TD}}{T_{rise}}\left(\frac{L_{12}}{L_{11}} - \frac{|C_{12}|}{C_{11}}\right) = \frac{1V * 280\,\text{ps}}{2 * 100\text{ps}}\left(\frac{2.103}{9.869} - \frac{0.239}{2.051}\right) = -0.137V$$

Thus,



Even/Odd Mode Decomposition

Coupling Effects on Tx-line Parameters

Key Topics:

✓**Odd and Even Mode Characteristics**

✓**Microstrip vs. Stripline**

✓**Modal Termination Techniques**

✓**Modal Impedance's for more than 2 lines**

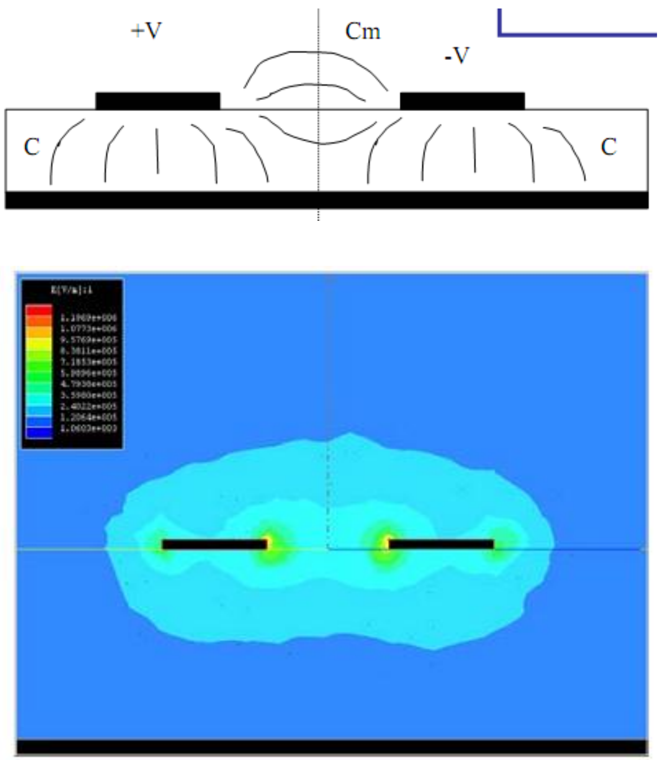
✓**Effect of Switching Patterns**

✓**Single Line Equivalent Model (SLEM)**

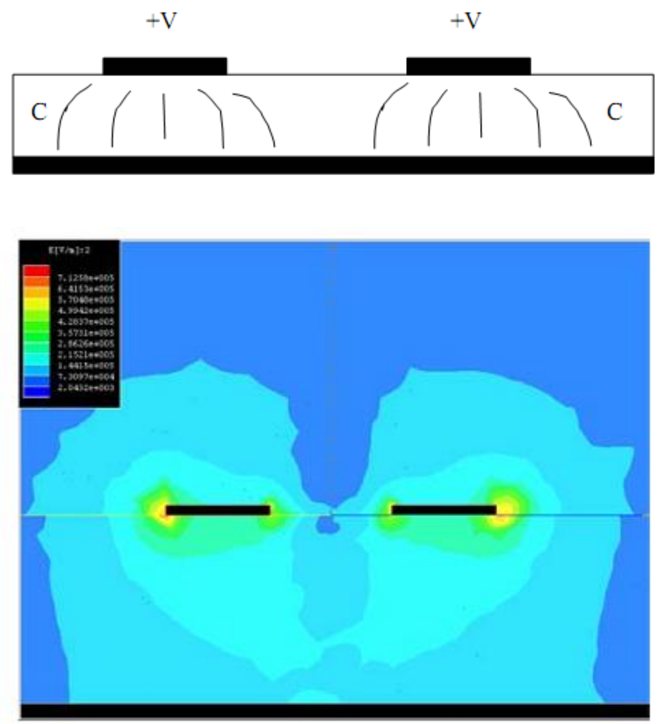
Field Distribution

- Differential and common mode signals have different field distribution, impedance and propagation velocity.

Differential mode

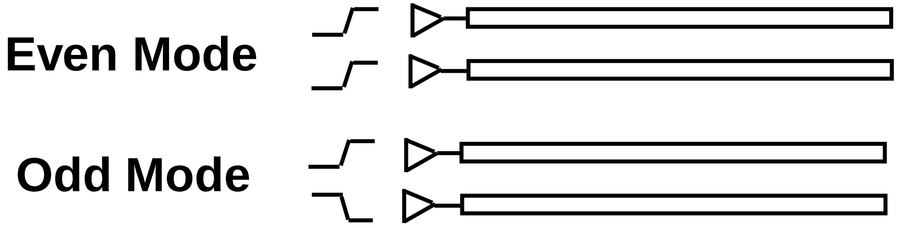


common mode



Odd/Even Transmission Modes

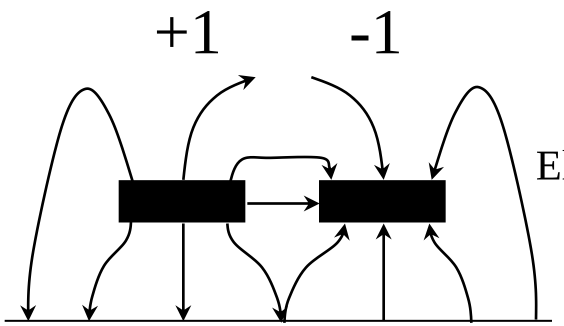
- EM Fields btw two coupled lines interacts with each other. These interactions affect the impedance and delay of tx-line
- A 2-conductor system has 2 propagation modes
  - Even Mode (Both lines driven in phase)
  - Odd Mode (Lines driven 180^o out of phase)



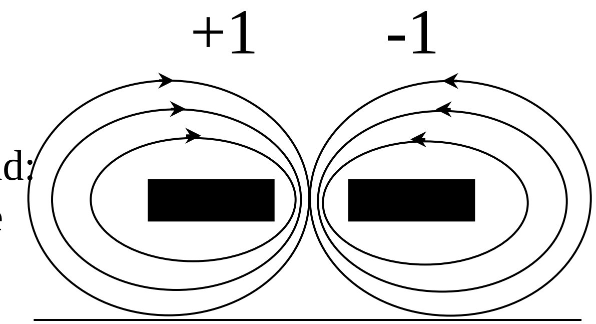
- Field interaction causes the system electrical characteristics to be dependent on the patterns.

Odd Mode Transmission

- **Potential difference btw conductors lead to *increase* of effective C equal to Cm**

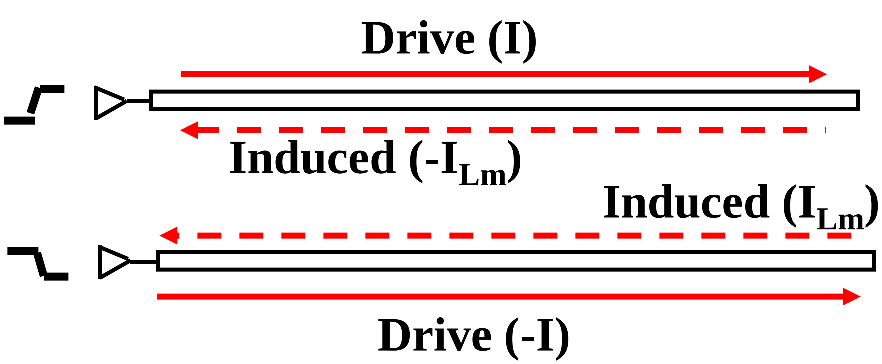


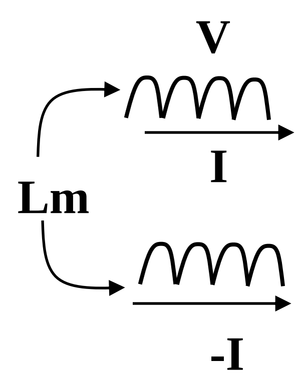
Electric Field:
Odd mode



Magnetic Field:
Odd mode

- **Because currents flow in opposite directions, total L is *reduced* by Lm**





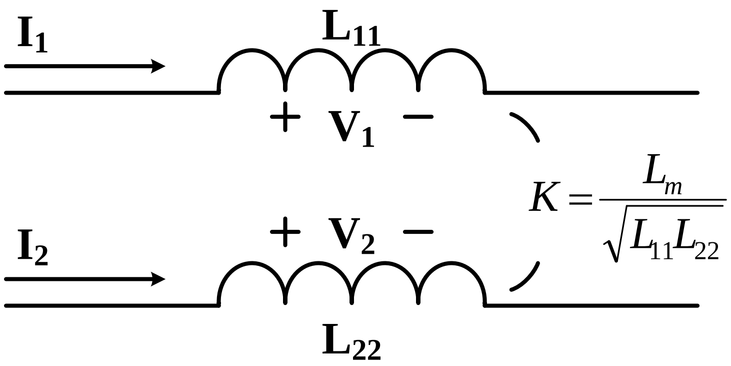
$$V = L\frac{dI}{dt} + Lm\frac{d(-I)}{dt}$$

$$= (L - Lm)\frac{dI}{dt}$$

Derivation of Odd Mode Inductance

Mutual Inductance:

Consider the circuit:



$$V_1 = L_O \frac{dI_1}{dt} + L_m \frac{dI_2}{dt}$$

$$V_2 = L_O \frac{dI_2}{dt} + L_m \frac{dI_1}{dt}$$

Since the signals for odd-mode switching are always opposite, $I_1 = -I_2$ and $V_1 = -V_2$, so that:

$$V_1 = L_O \frac{dI_1}{dt} + L_m \frac{d(-I_1)}{dt} = (L_O - L_m)\frac{dI_1}{dt}$$

$$V_2 = L_O \frac{dI_2}{dt} + L_m \frac{d(-I_2)}{dt} = (L_O - L_m)\frac{dI_2}{dt}$$

Thus, since $L_O = L_{11} = L_{22}$,

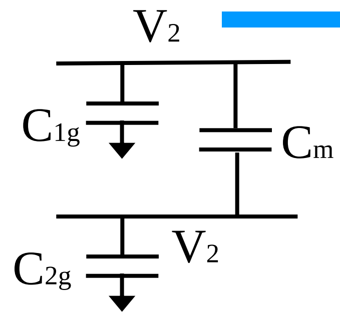
$$L_{odd} = L_{11} - L_m = L_{11} - L_{12}$$

equivalent inductance seen in an odd-mode environment is reduced by mutual inductance.

Derivation of Odd Mode Capacitance

Mutual Capacitance:

Consider the circuit:



$$C_{1g} = C_{2g} = C_O = C_{11} - |C_{12}|$$

So,

$$I_1 = C_O \frac{dV_1}{dt} + C_m \frac{d(V_1 - V_2)}{dt} = (C_O + C_m)\frac{dV_1}{dt} - C_m \frac{dV_2}{dt}$$

$$I_2 = C_O \frac{dV_2}{dt} + C_m \frac{d(V_2 - V_1)}{dt} = (C_O + C_m)\frac{dV_2}{dt} - C_m \frac{dV_1}{dt}$$

And again, $I_1 = -I_2$ and $V_1 = -V_2$, so that:

$$I_1 = C_O \frac{dV_1}{dt} + C_m \frac{d(V_1 - (-V_1))}{dt} = (C_{1g} + 2C_m)\frac{dV_1}{dt}$$

$$I_2 = C_O \frac{dV_2}{dt} + C_m \frac{d(V_2 - (-V_2))}{dt} = (C_O + 2C_m)\frac{dV_2}{dt}$$

Thus,

$$\boxed{C_{odd} = C_{1g} + 2C_m = C_{11} + C_m}$$

eq. capacitance for odd mode switching increases.

Odd Mode Transmission Characteristics

Impedance:

$$Z_{odd} = \sqrt{\frac{L_{odd}}{C_{odd}}} = \sqrt{\frac{L_{11} - L_{12}}{C_{11} + |C_{12}|}}$$

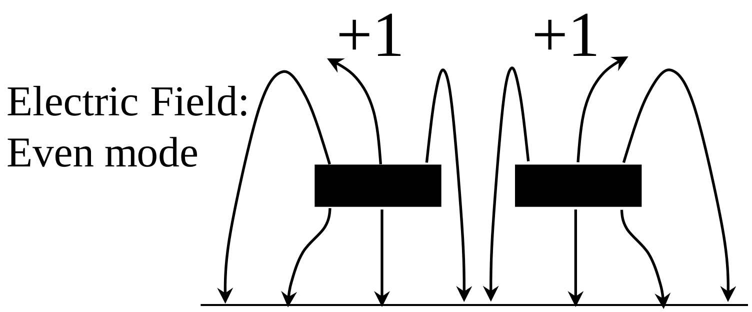
Note: $Z_{differential} = 2Z_{odd}$ Explain why.

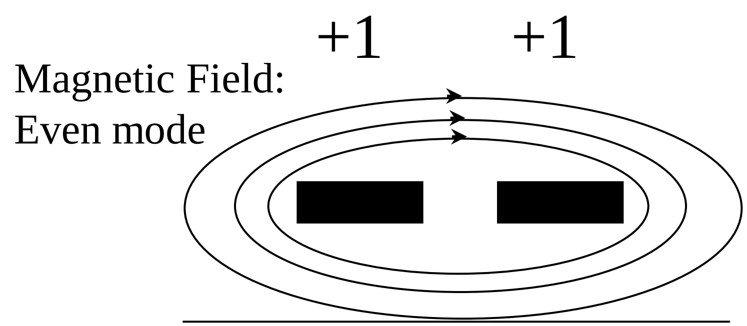
Propagation Delay:

$$TD_{odd} = \sqrt{L_{odd} C_{odd}} = \sqrt{(L_{11} - L_{12})(C_{11} + |C_{12}|)}$$

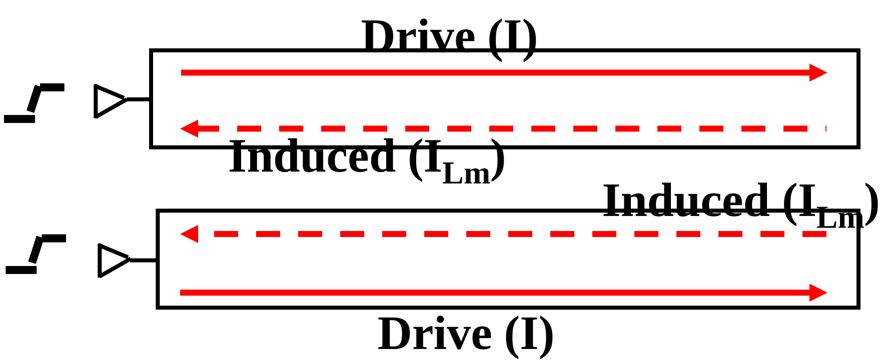
Even Mode Transmission

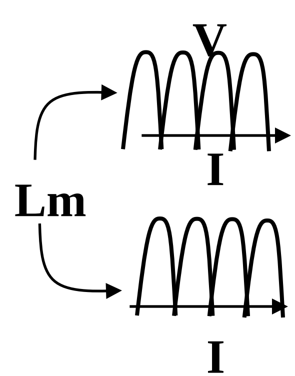
- **Since conductors are at equal potential, effective C is *reduced* by Cm**





- **Because currents flow in same direction, total L is *increased* by Lm**





$$V = L\frac{dI}{dt} + Lm\frac{d(I)}{dt}$$

$$= (L + Lm)\frac{dI}{dt}$$

R. B. Wu

Even Mode Transmission Characteristics

Impedance:

$$Z_{even} = \sqrt{\frac{L_{even}}{C_{even}}} = \sqrt{\frac{L_{11} + L_{12}}{C_{11} - |C_{12}|}}$$

Note: $Z_{even} > Z_{odd}$

Propagation Delay:

$$TD_{even} = \sqrt{L_{even} C_{even}} = \sqrt{(L_{11} + L_{12})(C_{11} - |C_{12}|)}$$

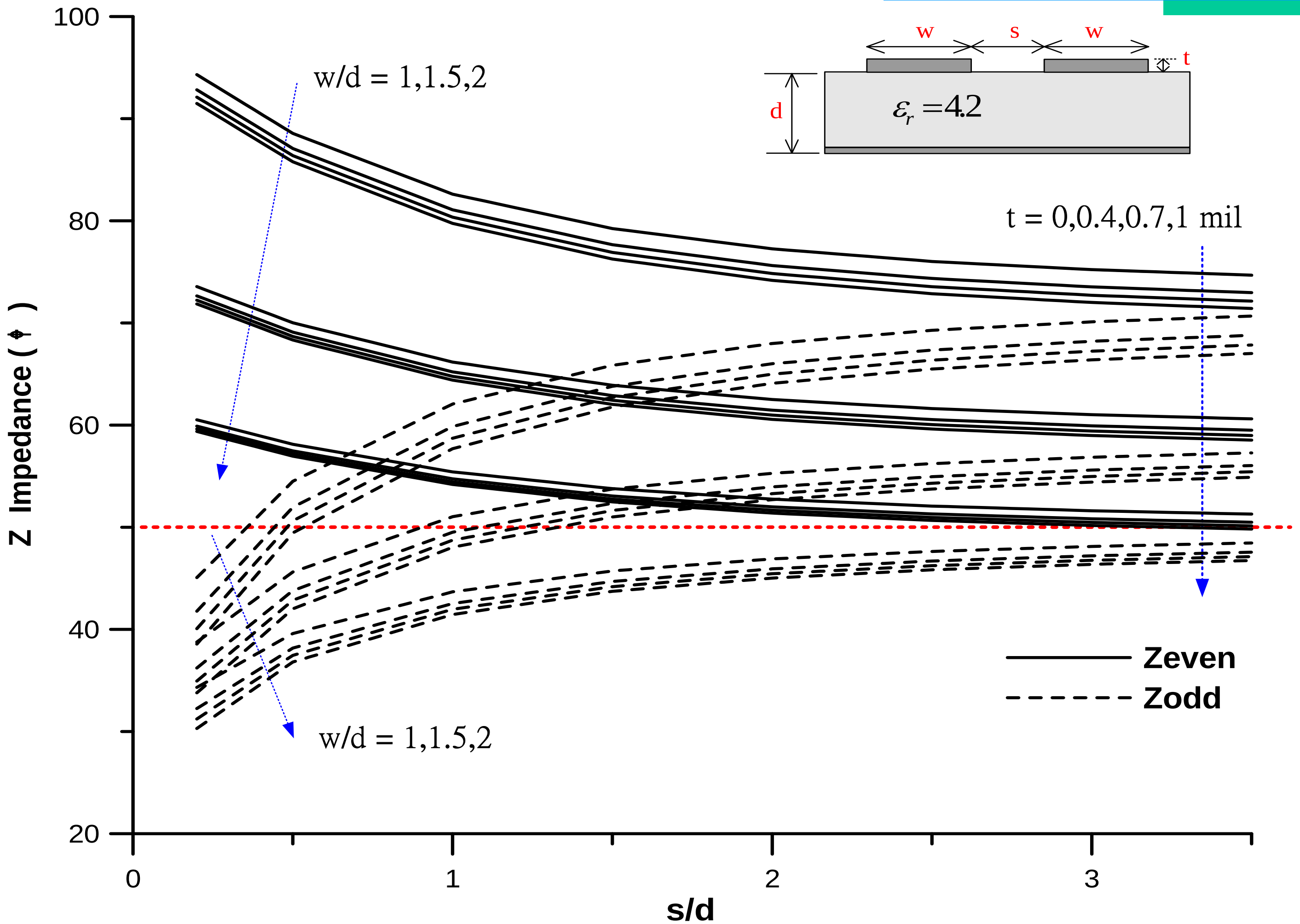
Note:

$TD_{even} > TD_{odd}$ for microstrip lines

$TD_{even} = TD_{odd}$ for strip lines

R. B. Wu

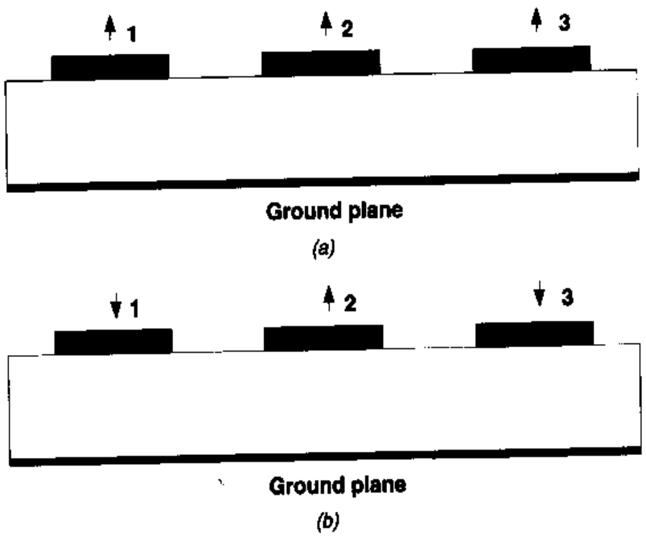
Variations in Impedance - microstip



Ref:吳瑞北、薛光華等，*磁碟容錯陣列控制電路板之訊號整合度分析*，普安案研究計畫報告，民92年2月，第2章。

Single-Line Eq. Model (SLEM)

- Goal:
  - Determine effective crosstalk-induced impedance & delay variation for a multi-conductor system.
  - Eestimate worst-case crosstalk effects during a bus design prior to actual layout
- SLEM



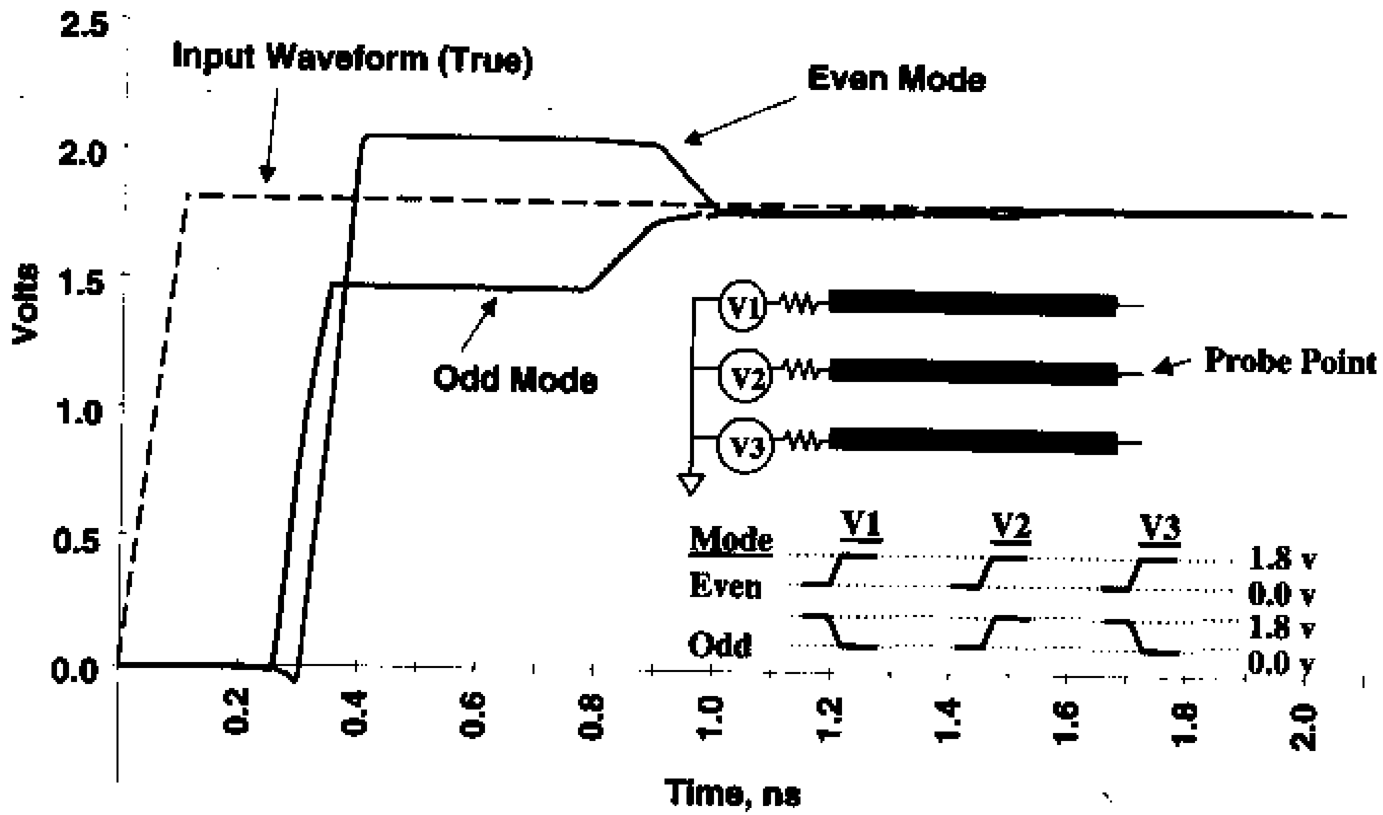
$$Z_{2,\text{eff.}} = \sqrt{\frac{L_{22}+L_{21}+L_{23}}{C_{22}-|C_{12}|-|C_{23}|}};$$

$$TD_{2,\text{eff.}} = \sqrt{(L_{22}+L_{21}+L_{23})\cdot(C_{22}-|C_{12}|-|C_{23}|)}\cdot \ell$$

$$Z_{2,\text{eff.}} = \sqrt{\frac{L_{22}-L_{21}-L_{23}}{C_{22}+|C_{12}|+|C_{23}|}};$$

$$TD_{2,\text{eff.}} = \sqrt{(L_{22}-L_{21}-L_{23})\cdot(C_{22}+|C_{12}|+|C_{23}|)}\cdot \ell$$

Effects on SI & Velocity *– on microstrip*



Rem: No velocity variations due to crosstalk in striplines.

Modal Analysis

Model Decomposition Theory

- For coupled lines, $$\frac{\partial}{\partial z}\mathbf{v} = -\mathbf{L}\frac{\partial}{\partial t}\mathbf{i}; \quad \frac{\partial}{\partial z}\mathbf{i} = -\mathbf{C}\frac{\partial}{\partial t}\mathbf{v}$$

Transformation: $\mathbf{v}=\mathbf{M_V v_m}$, $\mathbf{i}=\mathbf{M_I i_m}$;

$$\frac{\partial}{\partial z}\mathbf{M_V v_m} = -\mathbf{L}\frac{\partial}{\partial t}\mathbf{M_I i_m} \Rightarrow \frac{\partial}{\partial z}\mathbf{v_m} = -\mathbf{L_m}\frac{\partial}{\partial t}\mathbf{i_m}; \quad \mathbf{L_m} = \mathbf{M_V^{-1} L M_I}$$

$$\frac{\partial}{\partial z}\mathbf{M_I i_m} = -\mathbf{C}\frac{\partial}{\partial t}\mathbf{M_V v_m} \Rightarrow \frac{\partial}{\partial z}\mathbf{i_m} = -\mathbf{C_m}\frac{\partial}{\partial t}\mathbf{v_m}; \quad \mathbf{C_m} = \mathbf{M_I^{-1} C M_V}$$

$\mathbf{L_m}$, $\mathbf{C_m}$ both diagonal;

$$\because \mathbf{L_m C_m} = \mathbf{M_V^{-1}}\left(\mathbf{LC}\right)\mathbf{M_V} \Rightarrow \mathbf{M_V} \text{ is eigenmatrix of } \mathbf{LC}$$

modal impedance $Z_{m,i} = \sqrt{L_{m,ii} / C_{m,ii}}$;

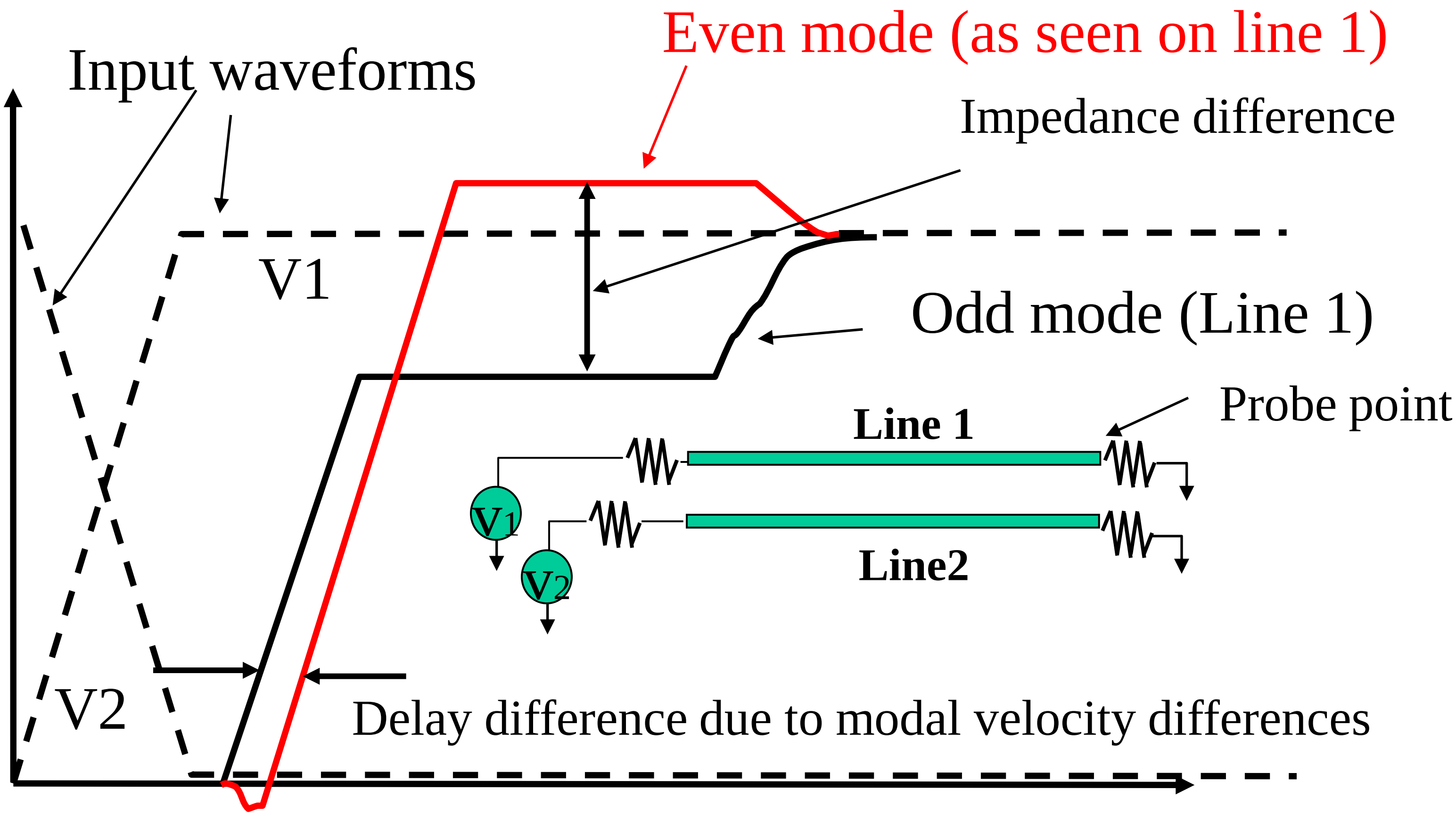
velocity $\upsilon_{pm,i} = 1 \big/ \sqrt{L_{m,ii} \cdot C_{m,ii}}$

R. B. Wu

Modal Analysis Procedure

- Find M_V, eigenvectors of LC (fairs if LC is diagonal)
- Find M_I, eigenvectors of CL,
  - usually take $\mathbf{M_I} = \left(\mathbf{M_V^{-1}}\right)^T$ s.t. $\mathbf{v}^T\mathbf{i}=\mathbf{v_m}^T\mathbf{M_V}^T\mathbf{M_I}\mathbf{i_m} = \mathbf{v_m}^T\mathbf{i_m}$
- Use M_V and M_I to calculate modal inductance, capacitance, voltages, and currents
- Calculate modal impedances and velocities
- Carry out traditional tx-line analysis for each mode
- Convert modal quantities back into line quantities.

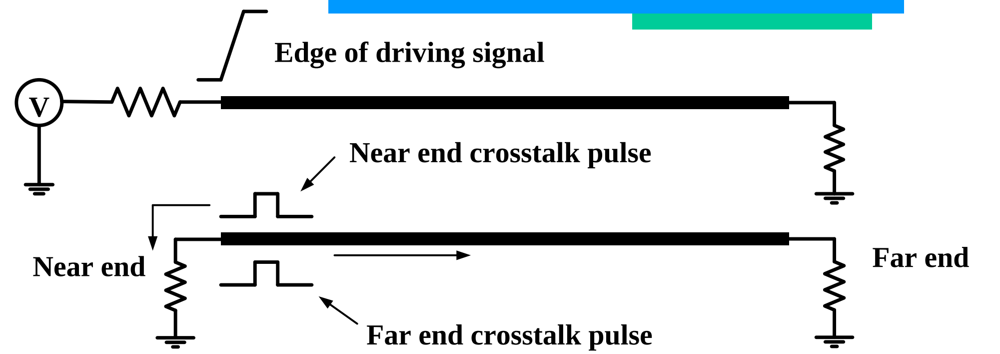
Odd/Even Mode Comparison for Coupled Microstrips



Symmetric Coupled Lines

$$[L] = L_{11}\begin{bmatrix} 1 & k_L \\ k_L & 1 \end{bmatrix}$$

$$[C] = C_{11}\begin{bmatrix} 1 & -k_C \\ -k_C & 1 \end{bmatrix}$$



$$\Downarrow \quad \mathbf{M_V} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix}; \quad \mathbf{M_I} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix}$$

$$\mathbf{L_m} = \mathbf{M_V^{-1} L M_I} = L_{11}\begin{bmatrix} 1-k_L & 0 \\ 0 & 1+k_L \end{bmatrix};$$

$$\mathbf{C_m} = \mathbf{M_I^{-1} C M_V} = C_{11}\begin{bmatrix} 1+k_C & 0 \\ 0 & 1-k_C \end{bmatrix}$$

modal characteristics: (1: odd; 2: even)

$$Z_{m,1} = Z_0\sqrt{\tfrac{1-k_L}{1+k_C}}; \quad \upsilon_{m,1} = \upsilon_0 \Big/ \sqrt{(1-k_L)(1+k_C)}$$

$$Z_{m,2} = Z_0\sqrt{\tfrac{1+k_L}{1-k_C}}; \quad \upsilon_{m,2} = \upsilon_0 \Big/ \sqrt{(1+k_L)(1-k_C)};$$

where $Z_0 = \sqrt{\tfrac{L_{11}}{C_{11}}}; \quad \upsilon_0 = 1\Big/\sqrt{L_{11}C_{11}}$

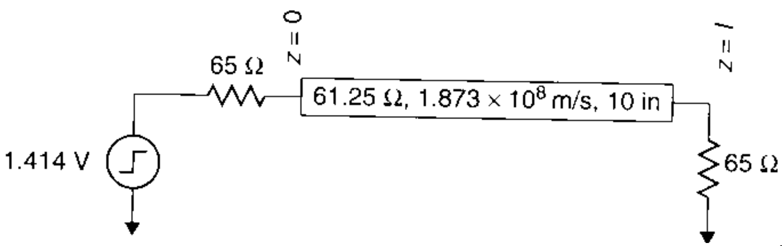
note: $Z_{m,1} < Z_0 < Z_{m,2}$

Equivalent Tx-Lines for Modes

- Modal decomposition

$$\mathbf{v}_s = \begin{bmatrix} 2 \\ 0 \end{bmatrix} u(t) = \left(\begin{bmatrix} 1 \\ -1 \end{bmatrix} + \begin{bmatrix} 1 \\ 1 \end{bmatrix} \right) u(t) \Leftrightarrow \mathbf{v}_{\mathbf{m},s} = \mathbf{M}_{\mathbf{V}}^{-1} \mathbf{v}_s = \left(\begin{bmatrix} \sqrt{2} \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ \sqrt{2} \end{bmatrix} \right) u(t)$$

- Equivalent tx-line



$$\Gamma_{L,i} \equiv \frac{Z_L - Z_{m,i}}{Z_L + Z_{m,i}}; \quad \Gamma_{s,i} \equiv \frac{Z_s - Z_{m,i}}{Z_s + Z_{m,i}}$$

- Modal voltages at both ends:

near end: $$v_{m,i}(0,t) = \frac{Z_{m,i}}{Z_{m,i} + Z_s} \cdot \left[v_{m,in}(t) + \Gamma_{L,i} \cdot \left(1 + \Gamma_{s,i}\right) v_{m,in}\left(t - \tfrac{2\ell}{\upsilon_{m,i}}\right) \right];$$

far end: $$v_{m,i}(\ell,t) = \frac{Z_{m,i}}{Z_{m,i} + Z_s} \cdot \left(1 + \Gamma_{L,i}\right) \cdot v_{m,in}\left(t - \tfrac{\ell}{\upsilon_{m,i}}\right);$$

Line Voltages at Both Ends

- Line voltages at both ends

$$\mathbf{v} = \mathbf{M_V v_m} \underset{\text{at } z=0 \text{ or } \ell}{\Rightarrow} \begin{bmatrix} v_1(t) \\ v_2(t) \end{bmatrix}(t) = \tfrac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} v_{m,1}(t) \\ v_{m,2}(t) \end{bmatrix}$$

- Near end crosstalk

$$v_2(0,t) = \left(\frac{Z_{m,2}}{Z_{m,2}+Z_s} - \frac{Z_{m,1}}{Z_{m,1}+Z_s} \right) u(t) \quad \text{for } 0 < t < 2T$$

$$+ \frac{Z_{m,2}\Gamma_{L,2}\left(1+\Gamma_{s,2}\right)}{Z_{m,2}+Z_s} \cdot u(t - \tfrac{2\ell}{\upsilon_{m,2}}) - \frac{Z_{m,1}\Gamma_{L,1}\left(1+\Gamma_{s,1}\right)}{Z_{m,1}+Z_s} \cdot u(t - \tfrac{2\ell}{\upsilon_{m,i}})$$

- Far end crosstalk

$$v_2(\ell,t) = \frac{2Z_L Z_{m,2} \cdot u(t - \tfrac{\ell}{\upsilon_{m,2}})}{\left(Z_{m,2}+Z_s\right)(Z_{m,2}+Z_L)} - \frac{2Z_L Z_{m,1} \cdot u(t - \tfrac{\ell}{\upsilon_{m,1}})}{\left(Z_{m,1}+Z_s\right)(Z_{m,1}+Z_L)} \quad \text{for } T < t < 3T$$

Exact Crosstalk at Matched Load

- Zero far end noise ==>

  (i) $\upsilon_{m,1} = \upsilon_{m,2} \Leftrightarrow k_C = k_L$

  (ii) $Z_{m,1}Z_{m,2} = Z_s Z_L \Rightarrow$ choose $Z_s = Z_L = Z_{eq}$

$$Z_{eq} = \sqrt{Z_{m,1}Z_{m,2}} \cong Z_0$$

- Crosstalk noise (with matched load)

$$v_2(\ell,t) = \frac{2Z_{eq}}{\left(\sqrt{Z_{m,2}} + \sqrt{Z_{m,1}}\right)^2} \cdot \left[u(t - \tfrac{\ell}{\upsilon_{m,2}}) - u(t - \tfrac{\ell}{\upsilon_{m,1}}) \right]$$

$$\approx \tfrac{1}{2}\left[u(t - \tfrac{\ell}{\upsilon_{m,2}}) - u(t - \tfrac{\ell}{\upsilon_{m,1}}) \right]$$

$$v_2(0,t) = \frac{\sqrt{Z_{m,2}} - \sqrt{Z_{m,1}}}{\sqrt{Z_{m,2}} + \sqrt{Z_{m,1}}} \cdot \left[u(t) - \frac{2Z_{eq}}{\left(\sqrt{Z_{m,2}} + \sqrt{Z_{m,1}}\right)^2} \cdot \left\{ u(t - \tfrac{2\ell}{\upsilon_{m,2}}) + u(t - \tfrac{2\ell}{\upsilon_{m,1}}) \right\} \right]$$

$$\cong \frac{k_L + k_C}{4} \cdot \left[u(t) - u(t - \tfrac{2\ell}{\upsilon_0}) \right]$$

Far End Crosstalk Noise – *Short Line*

$$v_2(\ell,t) \approx \tfrac{1}{2}\left[u(t-\tfrac{\ell}{\upsilon_{m,2}}) - u(t-\tfrac{\ell}{\upsilon_{m,1}})\right]$$

$$\Delta\tau \equiv \tau_{\text{even}} - \tau_{\text{odd}} = \frac{\ell}{\upsilon_{m,2}} - \frac{\ell}{\upsilon_{m,1}}$$

$$= \frac{\ell}{\upsilon_0}\left(\sqrt{(1+k_L)(1-k_C)} - \sqrt{(1-k_L)(1+k_C)}\right)$$

$$\cong \frac{\ell}{\upsilon_0}\cdot(k_L - k_C)$$

- Case 1: $|\Delta\tau| << t_r$;

$$v_2(\ell,t) \approx \tfrac{1}{2}u'(t-\tfrac{\ell}{\upsilon_0})\left[(t-\tfrac{\ell}{\upsilon_{m,2}}) - (t-\tfrac{\ell}{\upsilon_{m,1}})\right]$$

$$\cong -\frac{\Delta\tau}{2}u'(t-\tfrac{\ell}{\upsilon_0}) = -\frac{\ell(k_L-k_C)}{2\upsilon_0}u'(t-\tfrac{\ell}{\upsilon_0})$$

a pulse of value $-\frac{k_L-k_C}{2}\cdot\frac{T}{t_r}\cdot u_s$, width t_r

Far End Crosstalk Noise – Long Line

$$v_2(\ell,t) \approx \tfrac{1}{2}\left[u\left(t-\tfrac{\ell}{\upsilon_{m,2}}\right)-u\left(t-\tfrac{\ell}{\upsilon_{m,1}}\right)\right]$$

$$\Delta\tau \equiv \tau_{\text{even}} - \tau_{\text{odd}} = \frac{\ell}{\upsilon_{m,2}} - \frac{\ell}{\upsilon_{m,1}} \approx \frac{\ell}{\upsilon_0}\cdot(k_L - k_C)$$

- Case 2: $|\Delta\tau| > t_r$

  (long line or short risetime)

$v_2(\ell,t)$: a pulse of value $\pm\tfrac{1}{2}u_s$

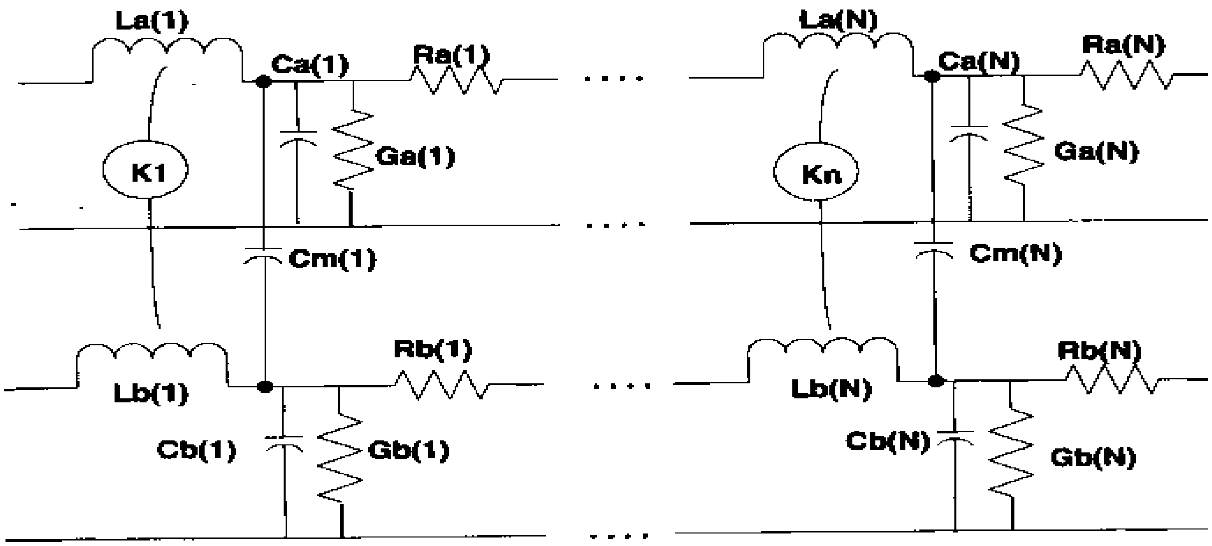
and width $|\Delta\tau|$

Remarks

- NEN occurs because odd (even) mode has smaller (larger) launched voltage and positive (negative) reflected wave.
- FEN occurs because even and odd modes arrives at a different time.
- Under matched load, modal analysis yields same results with weakly coupling analysis at near end.
- At far end, weakly coupling analysis fails for long line or shorter risetime, while modal analysis is still applicable and yield correct results.
- Modal analysis can apply to more complicated cases, i.e., asymmetric, multiple, lossy coupled lines, etc.

Simulation in SPICE

Eq-ckt Model in SPICE (1)



$$\text{Ex.: length} = 5\text{in},\ t_r = 100\text{ps}$$

$$C = \begin{bmatrix} 2.1 & -0.1 \\ -0.1 & 2.1 \end{bmatrix} (\text{pF/in});\ L = \begin{bmatrix} 9 & 0.7 \\ 0.7 & 9 \end{bmatrix} (\text{nH/in})$$

$$\text{TD} = \sqrt{\text{L}_{11} C_{11}} = 134\text{ps/in} \rightarrow 670\text{ps}$$

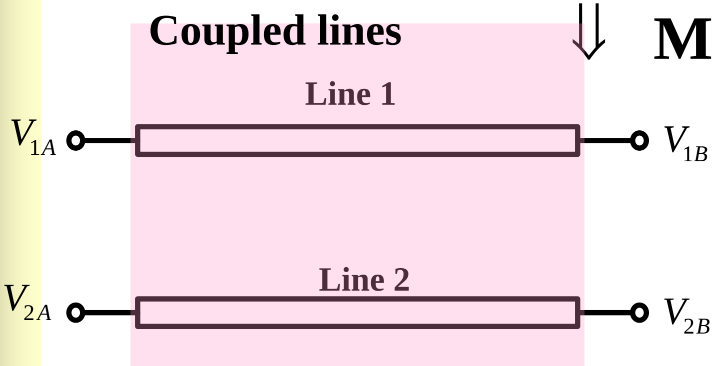
$$\#\,\text{segments} \geq 10\left(\frac{\text{TD}}{\text{t}_\text{r}}\right) = 67 \rightarrow \#\,\text{SPICE elements} \geq 67 * 2 * "3"$$

R. B. Wu

Eq. ckt by Even/Odd Decomposition

$\mathbf{v} = \mathbf{M_V v_m}, \quad \mathbf{i} = \mathbf{M_I i_m};$

$\Downarrow$

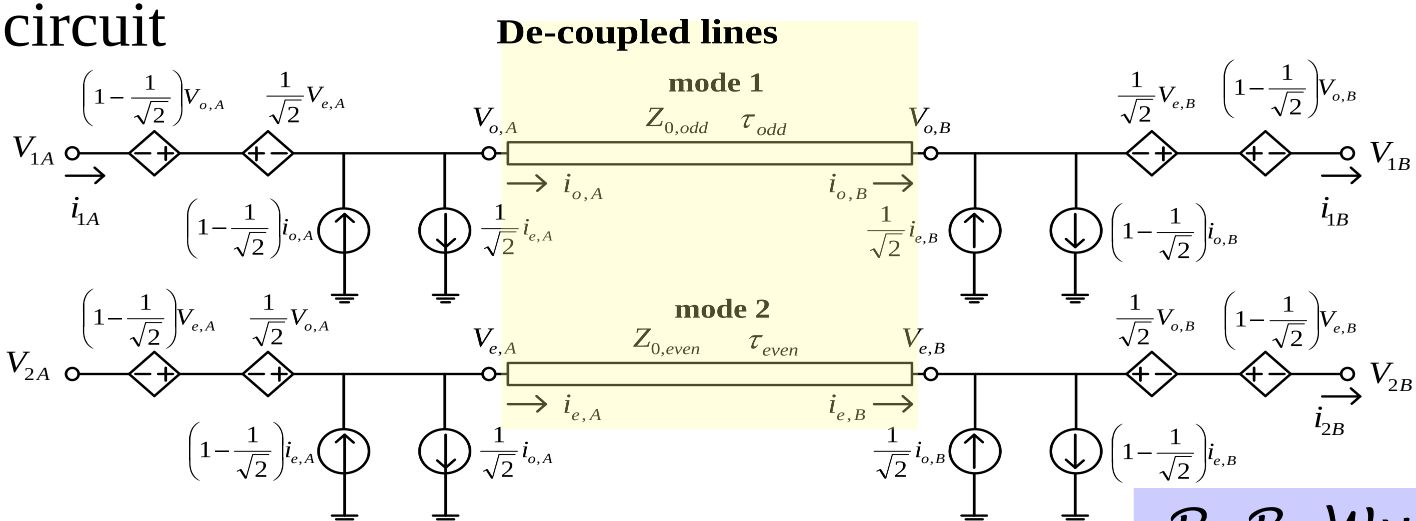


$$\mathbf{M_V} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix}; \quad \mathbf{M_I} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix}$$

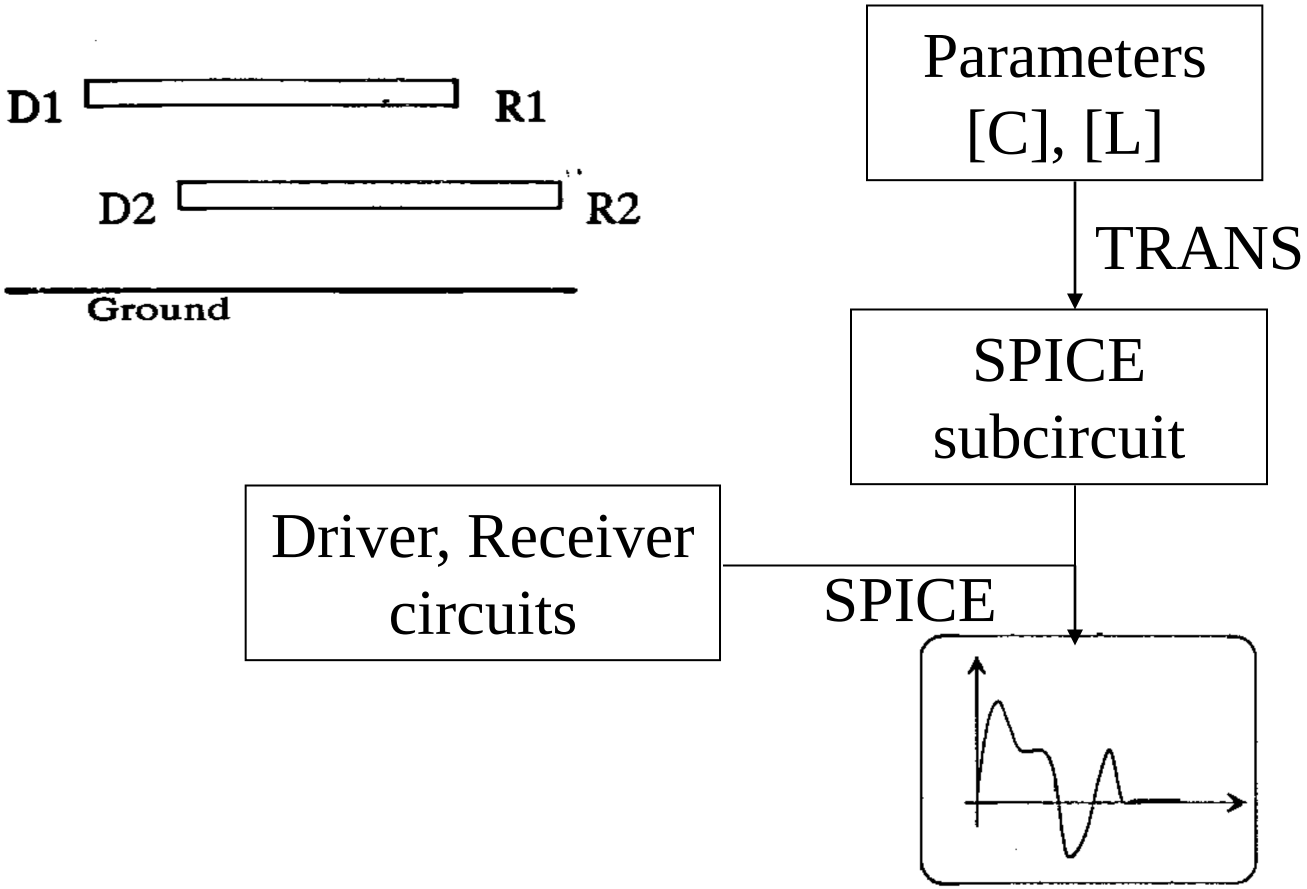
$$v_1 = \frac{1}{\sqrt{2}}(v_o + v_e) = -(1 - \frac{1}{\sqrt{2}})v_o + \frac{1}{\sqrt{2}}v_e + v_o$$

$$v_2 = \frac{1}{\sqrt{2}}(-v_o + v_e) = -(1 - \frac{1}{\sqrt{2}})v_e - \frac{1}{\sqrt{2}}v_o + v_e$$

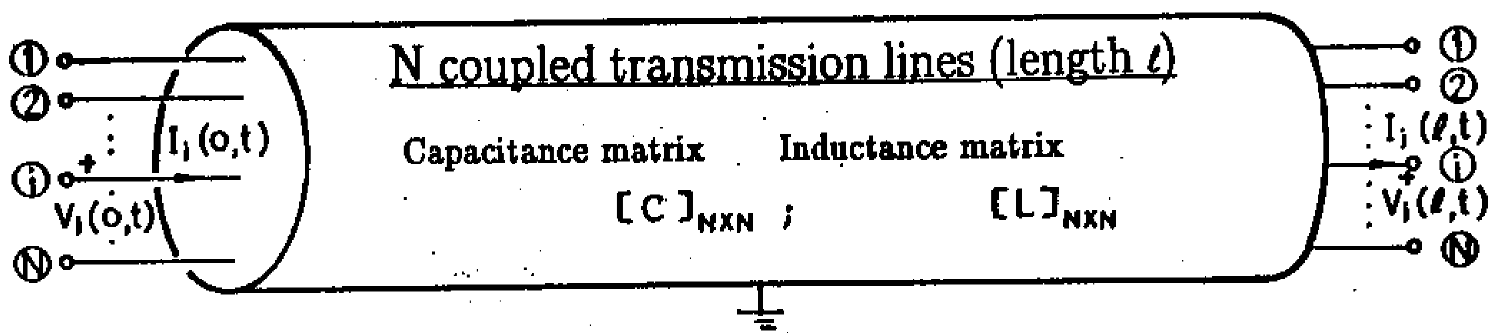
Eq. circuit

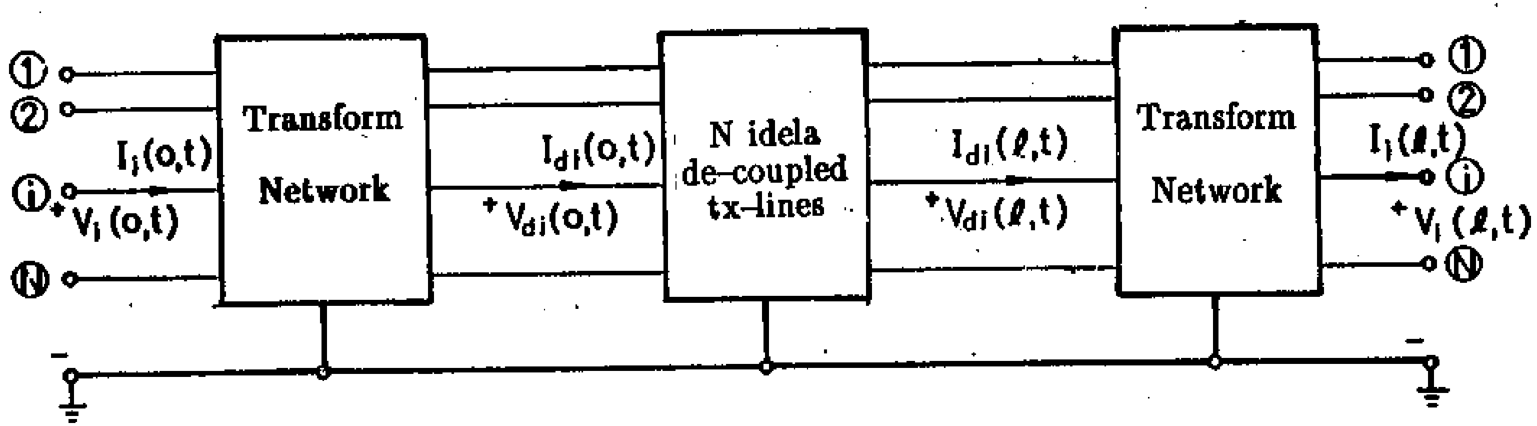


Crosstalk Simulation in SPICE



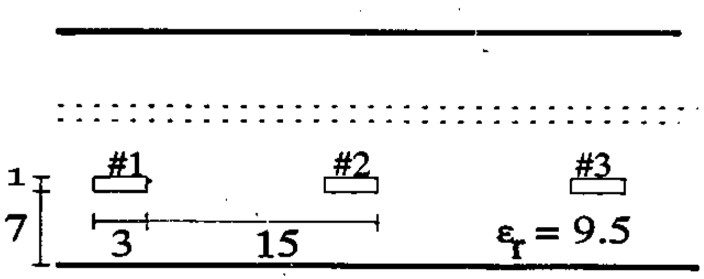
Equivalent SPICE Subcircuit (2)





F. Romeo and M. Santomauro, "Time-domain simulation of n coupled transmission lines," *IEEE Trans. Microwave Theory Tech.*, vol. 35, pp. 131-136, Feb. 1987.

TRANS Example



unit = mil

$$[C] = \begin{bmatrix} 219.02 & -12.19 & -0.365 \\ -12.19 & 219.76 & -12.19 \\ -0.365 & -12.19 & 219.02 \end{bmatrix} pF/m;$$

$$[L] = \begin{bmatrix} 479.03 & 26.70 & 2.28 \\ 26.70 & 478.88 & 26.70 \\ 2.28 & 26.70 & 479.03 \end{bmatrix} nH/m$$

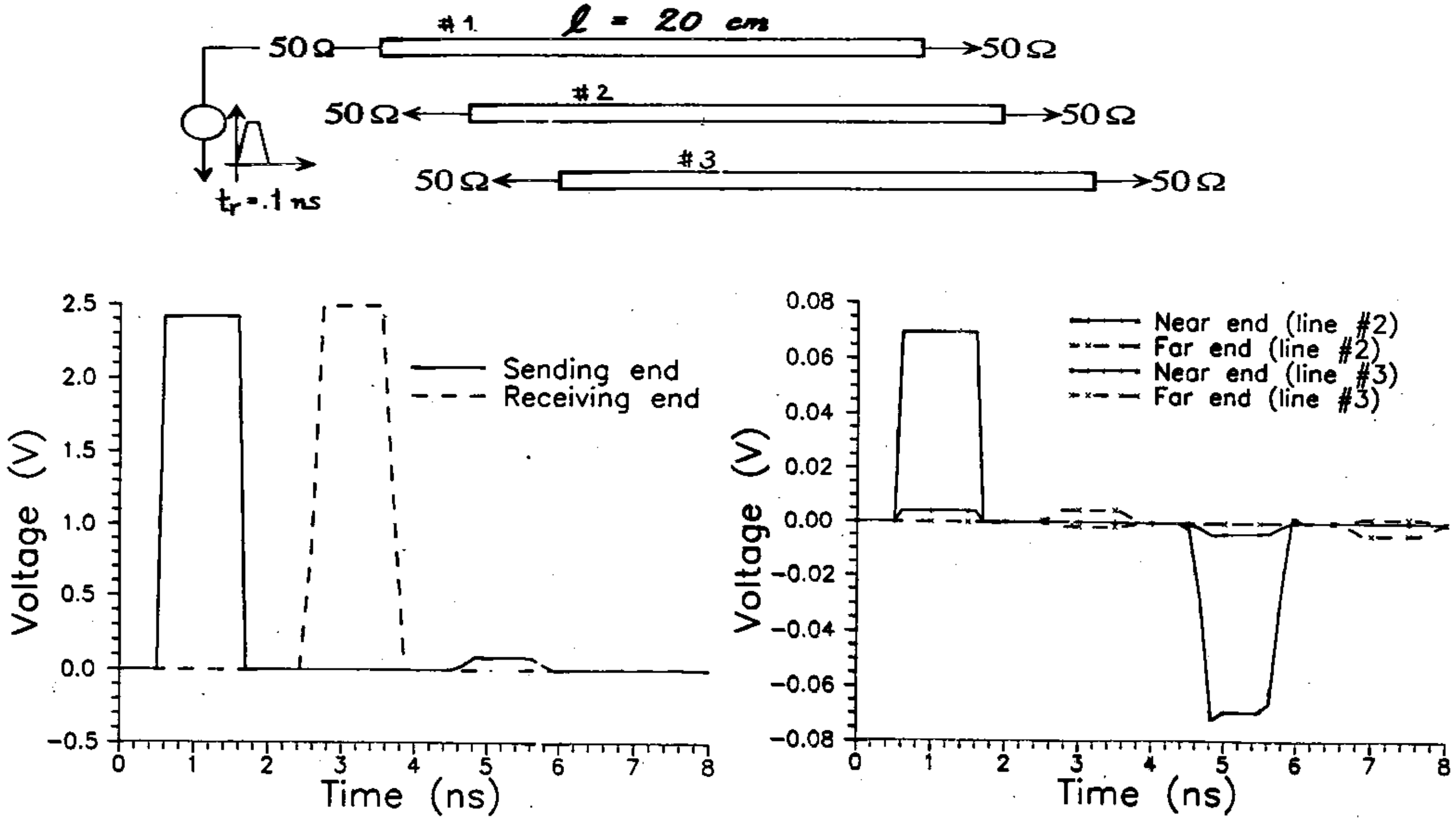
de-coupled tx-line

voltage-controled voltage source

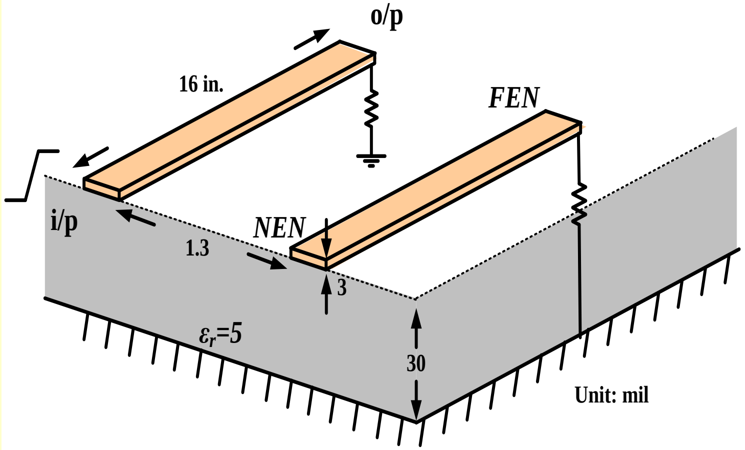
current-controled current source

```
.SUBCKT X33 SF1 SB1 SF2 SB2 SF3 SB3  PARAMS: LENGTH=100
* three ideal de-coupled transmission lines for normal modes
T1  TF1  0  TB1  0   Z0=46.62  TD={10.277NS*LENGTH}
T2  TF2  0  TB2  0   Z0=49.01  TD={10.277NS*LENGTH}
T3  TF3  0  TB3  0   Z0=44.88  TD={10.277NS*LENGTH}
* three voltage controlled voltage source at sending end
EF1 SF1 MF1 POLY(3) TF1 0 TF2 0 TF3 0 0.0 -0.2929 -0.6727 -0.1736
EF2 SF2 MF2 POLY(3) TF1 0 TF2 0 TF3 0 0.0  0.0000 -1.3082  0.9694
EF3 SF3 MF3 POLY(3) TF1 0 TF2 0 TF3 0 0.0 -0.7071 -0.6727 -1.1736
* three voltage controlled voltage source at receiving end
EB1 SB1 MB1 POLY(3) TB1 0 TB2 0 TB3 0 0.0 -0.2929 -0.6727 -0.1736
EB2 SB2 MB2 POLY(3) TB1 0 TB2 0 TB3 0 0.0  0.0000 -1.3082  0.9694
EB3 SB3 MB3 POLY(3) TB1 0 TB2 0 TB3 0 0.0 -0.7071 -0.6727 -1.1736
* three current controlled current source at sending end
FF1 MF1 0 POLY(3) VF1 VF2 VF3 0.0 -0.2929 -0.6869 -0.2184
FF2 MF2 0 POLY(3) VF1 VF2 VF3 0.0  0.0000 -1.2460  0.9534
FF3 MF3 0 POLY(3) VF1 VF2 VF3 0.0 -0.7071 -0.6869 -1.2184
VF1 MF1 TF1 0
VF2 MF2 TF2 0
VF3 MF3 TF3 0
* three current controlled current source at receiving end
FB1 MB1 0 POLY(3) VB1 VB2 VB3 0.0 -0.2929 -0.6869 -0.2184
FB2 MB2 0 POLY(3) VB1 VB2 VB3 0.0  0.0000 -1.2460  0.9534
FB3 MB3 0 POLY(3) VB1 VB2 VB3 0.0 -0.7071 -0.6869 -1.2184
VB1 MB1 TB1 0
VB2 MB2 TB2 0
VB3 MB3 TB3 0
.ENDS
```

Simulation Results

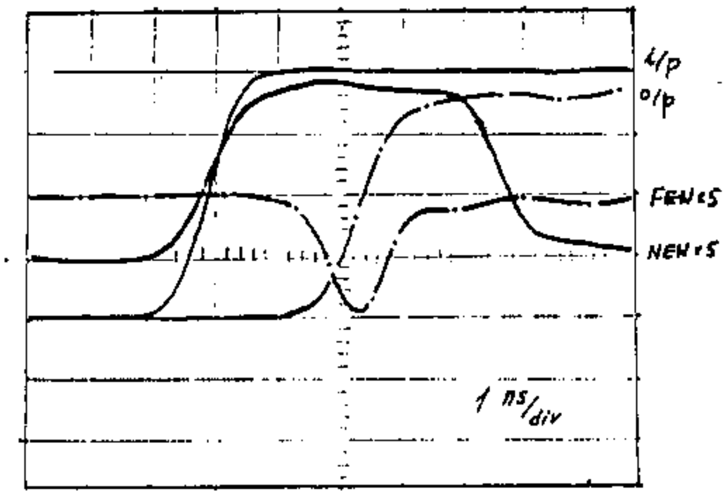


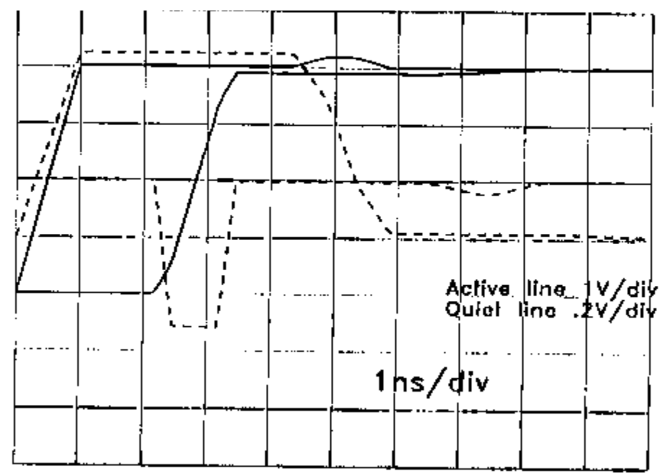
Measurement and Simulation



$$[C]=\begin{bmatrix}62.1 & -16.3\\ -16.3 & 62.1\end{bmatrix} pF/m$$

$$[L]=\begin{bmatrix}593 & 217\\ 217 & 593\end{bmatrix} nH/m$$





Further Reading -1

- A. Feller, et al., “Crosstalk and reflections in high-speed digital systems,” *1965 Fall Jt. AFIPS*, pp. 511-525.
- A. J. Gruodis and C. S. Chang, “Coupled lossy transmission line characterization and simulation,” *IBM J. R&D*, pp. 25-41, Jan. 1981.
- F. Romeo et al., “Time-domain simulation of n coupled transmission lines,” *IEEE T-MTT*, vol. 35, pp. 131-136, Feb. 1987.
- R. B. Wu & F. L. Chao, “Laddering wave in serpentine delay line,” *IEEE T-AdvP*, vol. 18, pp. 644-650, Nov. 1995.
- R. B. Wu & F. L. Chao, "Flat spiral delay line design with minimum crosstalk penalty," *IEEE T-AdvP*, vol. 19, pp. 397-402, May 1996.
- Y.-S. Cheng & R. B. Wu, “Enhanced microstrip guard trace for ringing noise suppression using a dielectric superstrate,” *IEEE T-AdvP*, vol. 33, pp. 961-968, Nov. 2010.
- G.-H. Shiue, et al., “Ground bounce noise induced by crosstalk noise for two parallel ground planes with a narrow open-stub line and adjacent signal traces in multilayer package structure,” *IEEE T-CPMT*, vol. 4, pp. 870-881, May 2014.

Further Reading -2

- J. Bernal, et al., "Crosstalk in coupled microstrip lines with a top cover," *IEEE T-EMC*, vol. 56, pp. 375-384, Apr. 2014.
- G.-H. Shiue, et al., "Ground bounce noise induced by crosstalk noise for two parallel ground planes with a narrow open-stub line and adjacent signal traces in multilayer package structure," *IEEE T-CPMT*, vol. 4, pp. 870-881, May 2014.
- M. S. Halligan and D. G. Beetner, "Maximum crosstalk estimation in weakly coupled transmission lines", *IEEE T-EMC*, vol. 56, pp. 736-744, Jun. 2014.
- M. S. Halligan and D. G. Beetner, "Maximum crosstalk estimation in lossless and homogeneous transmission lines," *IEEE T-MTT*, vol. 62, pp. 1953-1961, Sept. 2014.
- F. Grassi, et al., "On mode conversion in geometrically unbalanced differential lines and its analogy with crosstalk," *IEEE T-CPMT*, vol. 57, pp. 283-291, April 2015.

Further Reading -3

- G. Li, et al., “Measurement-based modeling and worst-case estimation of crosstalk inside an aircraft cable connector,” *IEEE T-EMC*, vol.57, pp.827-835, Aug. 2015.
- R. Araneo, et al., “Modal propagation and crosstalk analysis in coupled graphene nano-ribbons,” *IEEE T-EMC*, vol. 57, pp. 726-733, Aug. 2015.
- A. Chada, et al., “Crosstalk impact of periodic coupled routing on eye opening of high speed links in PCBs,“ *IEEE T-EMC*, vol. 57, pp. 1676-1689, Oct. 2015.
- V. Ramesh Kumar, et al., “An unconditionally stable FDTD model for crosstalk analysis of VLSI interconnects,” *IEEE T-CPMT*, vol. 5, pp. 1810-1817, Dec. 2015.
- B. R. Huang, et al., “Far-end crosstalk noise reduction using decoupling capacitor,” *IEEE T-EMC*, vol. 58, pp. 836-848, June 2016.
- F. Grassi, et al., "Crosstalk and mode conversion in adjacent differential lines," *IEEE T-EMC*, vol. 58, pp. 877-886, June 2016.