2003 ASPDAC Tutorial:

Power, Timing and Signal Integrity in SoC Designs

Speakers:
Dr. Eli Chiprout, Intel Labs
Dr. Howard H. Chen, IBM Research
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Outline

- **Section I: Interconnect circuit model generation**
  - **Dr. Lei He**
- **Section II: Detailed models for noise and timing**
  - **Dr. Eli Chiprout**
- **Section III: Current and power modeling**
  - **Dr. Lei He**
- **Section IV: Chip and package power supply noise analysis**
  - **Dr. Howard Chen**

Interconnect Circuit Model Generation

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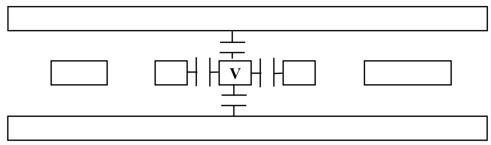
Outline

- Characteristics and extraction of capacitance
- Characteristics and extraction of inductance
- Complexity-reduced RLC circuit model

Capacitance Extraction

- Capacitance is a local effect

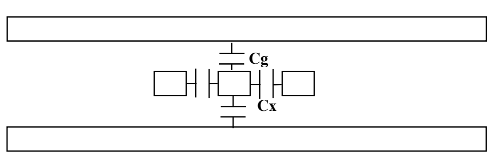


$$\begin{bmatrix} 2411 & -1340 & -87.27 & -24.9 & -16.94 & -833.2 \\ -1340 & 3048 & -1263 & -61.23 & -33.48 & -334.5 \\ -87.27 & Cx=-1263 & C=3047 & -1269 & -85.34 & -328.9 \\ -24.9 & -61.23 & -1269 & 3047 & -1346 & -330.7 \\ -16.94 & -33.48 & -85.34 & -1346 & 2605 & -1004 \\ -833.2 & -334.5 & Cg=-328.9 & -330.7 & -1004 & 4388 \end{bmatrix} \longrightarrow \begin{bmatrix} 2411 & -1340 & 0 & 0 & 0 & 0 \\ -1340 & 3048 & -1263 & 0 & 0 & 0 \\ 0 & Cx=-1263 & C=3047 & -1269 & 0 & 0 \\ 0 & 0 & -1269 & 3047 & -1346 & 0 \\ 0 & 0 & 0 & -1346 & 2605 & -1004 \\ 0 & 0 & 0 & 0 & -1004 & 4388 \end{bmatrix}$$

- Tables [He, et. al., 96] or formulae [Yu-Hu, 02] can be built for localized interconnect structures

Typical Structure for Cap

- Three layer model by formula



$$C_{f0} = \varepsilon\left[\frac{w}{h} + 2.217\left(\frac{s}{s+0.702h}\right)^{2.193} + 1.171\left(\frac{s}{s+1.510h}\right)^{0.7642} \cdot \left(\frac{t}{t+4.532h}\right)^{0.1204}\right]$$

$$C_c = \varepsilon\left[1.412\frac{t}{s}\exp\left(-\frac{4s}{s+8.014h}\right) + 2.3704\left(\frac{w}{w+0.3078s}\right)^{0.25724}\left(\frac{h}{h+8.961s}\right)^{0.7571}\exp\left(-\frac{2s}{s+6h}\right)\right]$$

h – dielectric height, s – separation of wires, w – wire width, t – wire thickness

Experimental Comparison

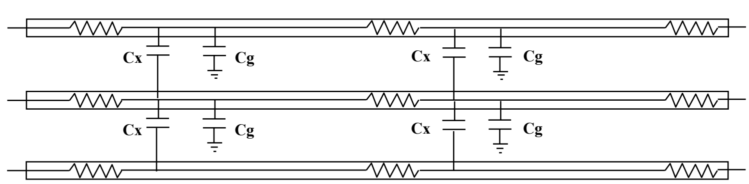
- **Experimental Setup**
  w = 0.25um, s = 0.25um, h = 0.5um, t = 0.5 um
- **Experimental Results:**

	FastCap	Formula
Cg	0.08923 fF	0.1276 fF
Cx	0.3305 fF	0.3050 fF

- **Table-based extraction is in general more accurate**
  - **Cg and Cx as functions of (w,s)**
  - **Can be extended to consider crossing wires rather than ground planes**

RC Circuit Model is Trivial

- **With consideration of coupling capacitance between adjacent nets**



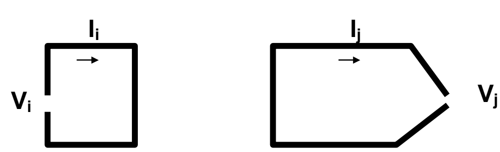
- **Accurate segmenting will be discussed in Section 2**

Inductance Extraction from Geometries

- **Numerical method based on Maxwell's equations**
  - **Accurate, but way too slow for <u>iterative</u> physical design and verification**

- **Efficient yet accurate models**
  - **Coplanar bus structure** [He-Chang-Shen-et al, CICC'99]
  - **Strip-lines and micro-strip bus lines** [Chang-Shen-He-et al, DATE'2K]
  - **Used in HP for state-of-the-art CPU design**

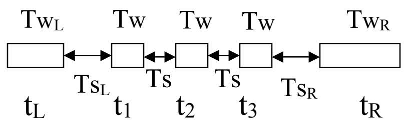
Definition of Loop Inductance



- **The loop inductance is**

$$L_{ij} = \frac{\mu}{4\pi} \bullet \frac{1}{a_i a_j} \bullet \frac{1}{I_i I_j} \oint_{loop_i} \int_{a_i} \oint_{loop_j} \int_{a_j} \frac{1}{r_{ij}} dI_i dI_j da_i da_j$$

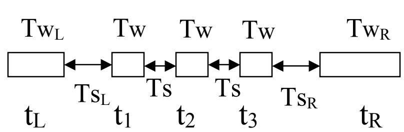
Loop Inductance for N Traces



1.73	1.15	0.53
1.15	1.94	1.24
0.53	1.24	1.92

- **Assume edge traces are AC-grounded**
  - **leads to 3x3 loop inductance matrix**
- **Inductance has a long range effect**
  - **non-negligible coupling between t_1 and t_3, even with t_2 between them**

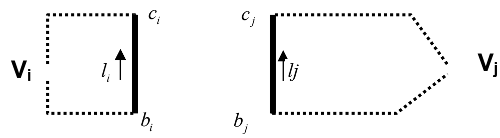
Table in Brute-Force Way is Expensive



1.73	**1.15**	**0.53**
1.15	**1.94**	**1.24**
0.53	**1.24**	**1.92**

- **Self inductance has nine dimensions:**
  - **(n, length, location,Tw_L,Ts_L,Tw,Ts,Tw_R,Ts_R)**
- **Mutual inductance has ten dimensions:**
  - **(n, length, location1, location2,Tw_L,Ts_L,Tw,Ts,Tw_R,Ts_R)**
- **Length is needed because inductance is not linearly scalable**

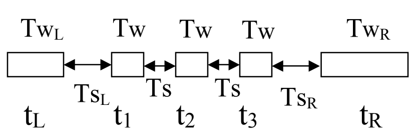
Definition of Partial Inductance



- **Partial inductance is the portion of loop inductance for a segment when its current returns via the infinity**
  - **called partial element equivalent circuit (PEEC) model**
- **If current is uniform (no skin effect), the partial inductance is**

$$L_{ij} = \frac{\mu}{4\pi} \bullet \frac{1}{a_i a_j} \bullet \int_{b_i}^{c_i} \int_{a_i} \int_{b_j}^{c_j} \int_{a_j} \frac{dl_i dl_j}{r_{ij}} da_i da_j$$

Partial Inductance for N Traces

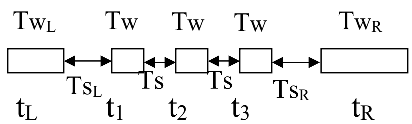


6.17	**5.43**	**5.12**	**4.89**	**4.66**
5.43	**6.79**	**6.10**	**5.48**	**5.04**
5.12	**6.10**	**6.79**	**6.10**	**5.33**
4.89	**5.48**	**6.10**	**6.79**	**5.77**
4.66	**5.04**	**5.33**	**5.77**	**6.50**

- **Treat edge traces same as inner traces**
  - **lead to 5x5 partial inductance table**
- **Partial inductance model is more accurate compared to loop inductance model**
  - **Without pre-setting current return loop**

Foundation I

The self inductance under the PEEC model for a trace depends only on the trace itself (w/ skin effect for a given frequency).



6.17	**5.43**	**5.12**	**4.89**	**4.66**
5.43	**6.79**	**6.10**	**5.48**	**5.04**
5.12	**6.10**	**6.79**	**6.10**	**5.33**
4.89	**5.48**	**6.10**	**6.79**	**5.77**
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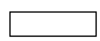
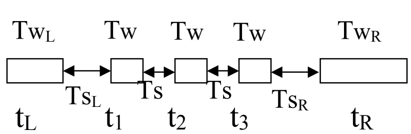


6.50

Foundation II

The mutual inductance under the PEEC model for two traces depends only on the traces themselves (w/ skin effect for given frequency).

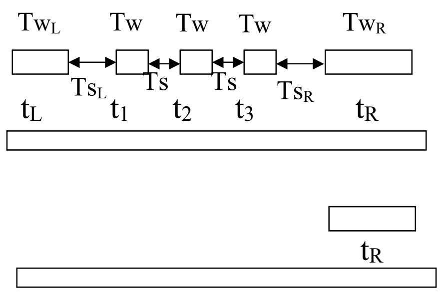


6.17	**5.43**	**5.12**	**4.89**	**4.66**
5.43	**6.79**	**6.10**	**5.48**	**5.04**
5.12	**6.10**	**6.79**	**6.10**	**5.33**
4.89	**5.48**	**6.10**	**6.79**	**5.77**
4.66	**5.04**	**5.33**	**5.77**	**6.50**

6.17	**4.66**
4.66	**6.50**

Foundation III

The self loop inductance for a trace on top of a ground plane depends only on the trace itself (its length, width, and thickness)

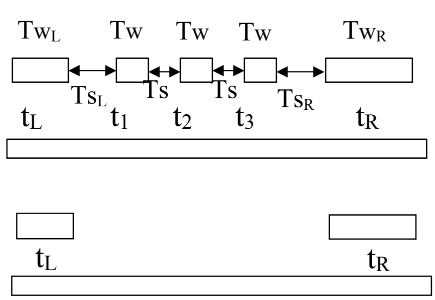


4.8	**2.5**	**1.3**	**0.7**	**0.14**
2.5	**5.5**	**2.9**	**1.5**	**0.7**
1.3	**2.9**	**5.7**	**2.9**	**1.3**
0.7	**1.5**	**2.9**	**2.5**	**2.5**
0.14	**0.7**	**1.3**	**2.5**	**4.8**

4.8

Foundation IV

The mutual loop inductance for two traces on top of a ground plane depends only on the two traces themselves (their lengths, widths, and thickness)



4.8	**2.5**	**1.3**	**0.7**	**0.14**
2.5	**5.5**	**2.9**	**1.5**	**0.7**
1.3	**2.9**	**5.7**	**2.9**	**1.3**
0.7	**1.5**	**2.9**	**2.5**	**2.5**
0.14	**0.7**	**1.3**	**2.5**	**4.8**

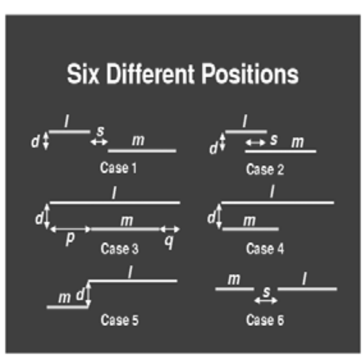
4.8	**0.14**
0.14	**4.8**

Validation and Implication of Foundations

- ❑ Foundations I and II can be validated theoretically
- ❑ Foundations III and IV were verified experimentally
- ❑ Problem size of inductance extraction can be greatly reduced w/o loss of accuracy
  - ◆ Solve 1-trace problem for self inductance
    - • Reduce 9-D table to 2-D table
  - ◆ Solve 2-trace problem for mutual inductance
    - • Reduce 10-D table to 3-D table

Inductance Model for Random Nets

[X.Qi, et al, 2000]



Case 2:

$$M = \frac{\mu_0}{4\pi}\left[(l-s)\ln\left(\frac{l+m-s}{l-s}\right) + m\ln\frac{(l+m-s)}{m-s} + s\ln\left(\frac{4s(m-s)}{d^2}\right) - 2s\right]$$

Case 3:

$$M = \frac{\mu_0}{4\pi}\left[m\ln\frac{4(m+p)(m+q)}{d^2} + p\ln\frac{(m+p)}{p} + q\ln\frac{(m+q)}{q} - 2m\right]$$

Case 4:

$$M = \frac{1}{2}\frac{\mu_0}{2\pi}\left[l\ln\left(\frac{l}{l-m}\right) + m\ln\left(\frac{4m(l-m)}{d^2}\right) - 2m + d\right]$$

Case 5:

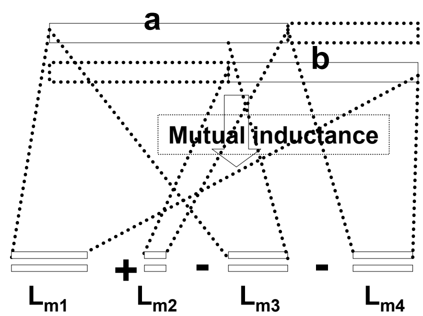
$$M = \frac{\mu_0}{4\pi}\left[l\ln\left(\frac{l+m}{l}\right) + m\ln\frac{(l+m)}{m} - d\right]$$

Case 1 & 6:

$$M = \frac{\mu_0}{4\pi}\left[(l+s)\ln\left(\frac{l+m+s}{l+s}\right) + m\ln\frac{(l+m+s)}{m+s} + s\ln\left(\frac{s}{m+s}\right)\right]$$

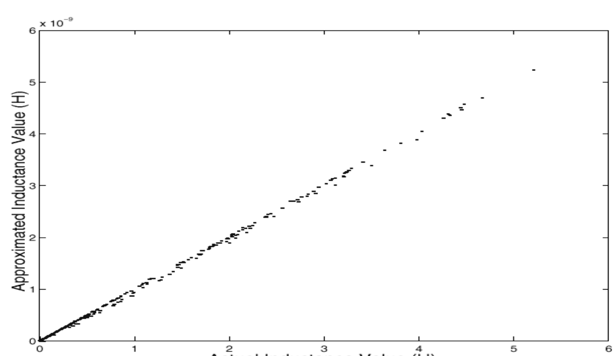
Inductance Model for Random Nets

[M. Xu-L. He, 2001]



- ◆ Arbitrary locations, lengths, thickness, and etc.
- ◆ Typically within 3% of numerical computation
- ◆ Available as a web-based tool WebHenry
  - •http://eda.ee.ucla.edu/tools.html

Experiment Result



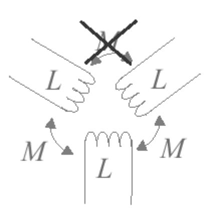
- ❑ WebHenry versus FastHenry
- ❑ 400 random displaced parallel wires cases

Outline

- Characteristics and extraction of capacitance
- Characteristics and extraction of inductance
- Complexity-reduced RLC circuit model
  - Inductance Sparsification
  - 2D Models

Sparsification of L Matrix

- Truncating off-diagonal entries cannot preserve passivity, and may lead to negative eigen-energy
  - L matrix is not diagonal dominant



$$\begin{bmatrix} L & M & 0 \\ M & L & M \\ 0 & M & L \end{bmatrix}$$

$$E = i^T \cdot L \cdot i \geq 0$$

$$i = \sum_{j=1}^{n} a_j \cdot v_j$$

$$E = \sum_{j=1}^{n} a_j^2 \cdot \lambda_j$$

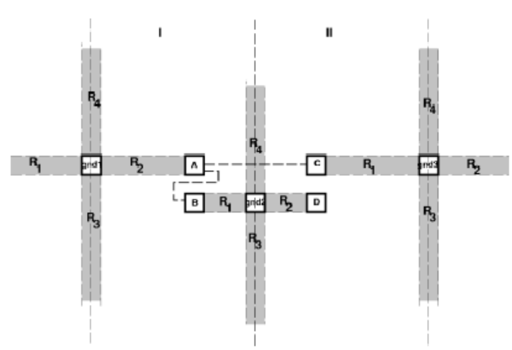
Non positive definite for $M > \frac{\sqrt{2}}{2} L$

Truncation Techniques

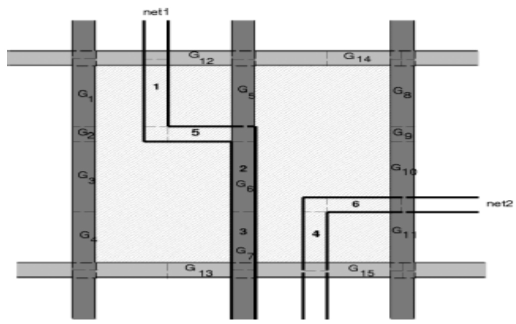
- ❑ **Loop-truncation**
  - ◆ [Shepard-Tian, 2000]
- ❑ **Shift-truncation**
  - ◆ Shift-truncate [Krauter-Pileggi, 1995] ->SPIE [He, et al, 1997]-> Shell [Beattie, et al, 2001]
- ❑ **Inverse-truncation**
  - ◆ K-element[Devgan, et al, 2000]->Susceptance[Krauter-Pileggi, 2001]

Loop-truncation

- ❑ **Assume return path at the nearest un-blocked power-ground lines (halos)**
- ❑ **Discard mutual inductances beyond such halos**



Example of Loop-truncation



M5,M4: power-ground
M3: signal net

Lef11: effective inductance of signal segment 1
L11: self inductance of signal segment 1 (PEEC)
L1'1': self inductance of ground segment 1' (PEEC)

$$Lef_{11} = \begin{pmatrix} L_{11} + L_{1'1'} - L_{1'1} - L_{11'} & L_{11} + L_{1'5'} - L_{15'} - L_{1'1} & L_{11} + L_{1'8'} - L_{18'} - L_{1'1} \\ L_{11} + L_{5'1'} - L_{11'} - L_{5'1} & L_{11} + L_{5'5'} - L_{15'} - L_{5'1} & L_{11} + L_{5'8'} - L_{18'} - L_{5'1} \\ L_{11} + L_{8'5'} - L_{11'} - L_{8'1} & L_{11} + L_{8'5'} - L_{15'} - L_{8'1} & L_{11} + L_{8'8'} - L_{18'} - L_{8'1} \end{pmatrix}$$

Intuition of Shift-truncation

- **Intuition**

$$\begin{bmatrix} L & M \\ M & L \end{bmatrix} \Rightarrow \begin{bmatrix} L-M & 0 \\ 0 & L-M \end{bmatrix}$$

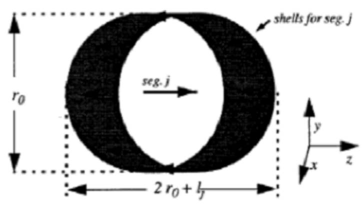
- Two eigen-values **(L+M, L-M)**
- Subtracting a constant from every matrix element results in an equivalent system
- Achieved by assuming that current returns from a shell

Inductance defined by vector potential

- Current returns from infinity

$$\mathbf{A}_{ij} = \frac{\mu_0}{4\pi a_j}\left[\int_{a_j}\int_{l_j} \frac{\mathbf{I}_j}{r_{ij}}\, dl_j\, da_j\right] \qquad M_{ij} = \frac{1}{I_j\, a_i}\left[\int_{a_i}\int_{l_i} \mathbf{A}_{ij}\cdot dl_i\, da_i\right]$$

- Current returns from the shell



$$\mathbf{A}_{ij} = \frac{\mu_o I_j}{4\pi}\int_{l_j} f\,(r_{ij}, r_o)\, dl_j$$

where

$$f(r_{ij}, r_o) = \left(\frac{1}{r_{ij}} - \frac{1}{r_o}\right), \qquad r_o \ge r_{ij}$$
$$= 0, \qquad r_o < r_{ij}$$

Implementation of Shifting

- New L matrix has additional entries, and is shifted to obtain a sparse matrix

$$\begin{bmatrix} L_c & L_{c,sh} \\ L_{c,sh}^T & L_{sh} \end{bmatrix} \rightarrow \begin{bmatrix} L_c - L_{c.sh} & 0 \\ 0 & L_{sh} - L_{c,sh} \end{bmatrix}$$

where

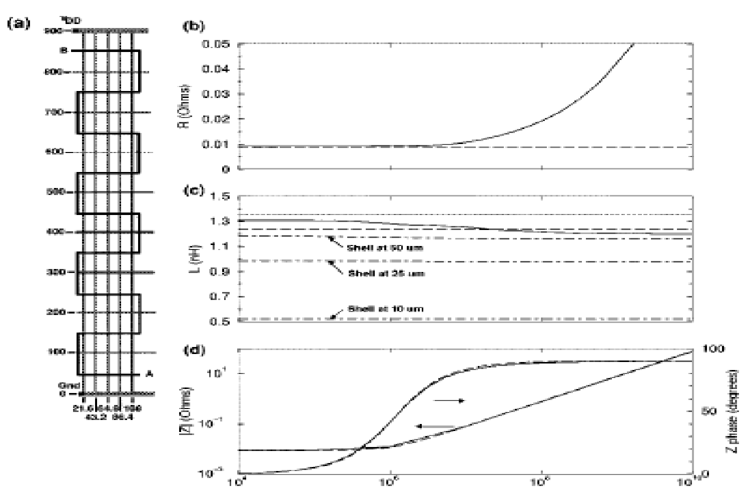
$$L_{c(i),sh(j)} = \frac{\mu_0}{4\pi r_0}\, dl_i \cdot dl_j$$

Limitation of Loop and Shift Truncation

- Loop-truncation: lose accuracy for signal nets located in different halos.

- Shift-truncation: how to define the r_0 ?

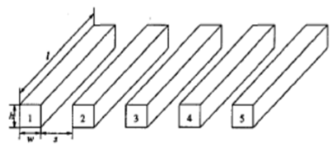
Experimental Comparison between Loop and Shift Truncation



Solid line: Fast Henry
Dashed line: Return loop
Dashed point: Shell method(r = 50,25,10 um)

Inverse-truncation

- Inversion of L matrix leads to a passive and strictly diagonal dominant K matrix



$$[L] = \begin{bmatrix} 11.4 & 4.26 & 2.54 & 1.79 & 1.38 \\ 4.26 & 11.4 & 4.26 & 2.54 & 1.79 \\ 2.54 & 4.26 & 11.4 & 4.26 & 2.54 \\ 1.79 & 2.54 & 4.26 & 11.4 & 4.26 \\ 1.38 & 1.79 & 2.54 & 4.26 & 11.4 \end{bmatrix} pH \quad [K] = \begin{bmatrix} 103 & -34.1 & -7.80 & -4.31 & -3.76 \\ -34.1 & 114 & -31.6 & -6.67 & -4.31 \\ -7.80 & -31.6 & 115 & -31.6 & -7.80 \\ -4.31 & -6.67 & -31.6 & 114 & -34.1 \\ -3.76 & -4.31 & -7.80 & -34.1 & 103 \end{bmatrix} \times 10^9 H$$

Simulation with Inverse-Truncation

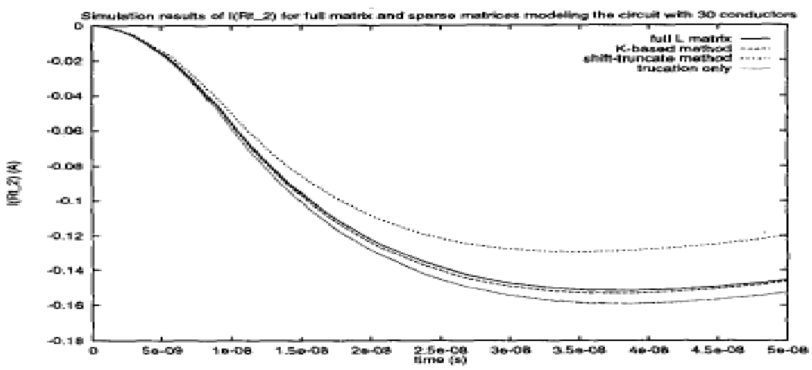
- Circuits equations changed from

$$V_i = L_{ii}\partial_t I_i + \sum_{j \neq i} L_{ij}\partial_t I_j \quad \text{to} \quad \partial_t I_i = K_{ii} + \sum_{j \neq i} K_{ij} V_j$$

- New simulation tool needed to handle the new circuit element K [Devgan-et al, 2000]

Experiments

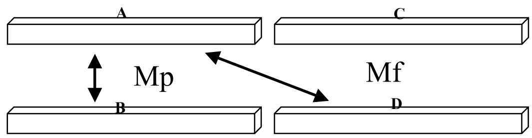
- Simulation of receiver current in 30-bit bus [Devgan-et al, 2001]



Further Work on Inverse-truncation

- Double inversion [M. Beattie-et al, 2001]
  - Avoid using K in simulation
- Wire duplication [G. Zhong-et al, 2002]
  - Reduce the complexity of K matrix

2D Inductance Model

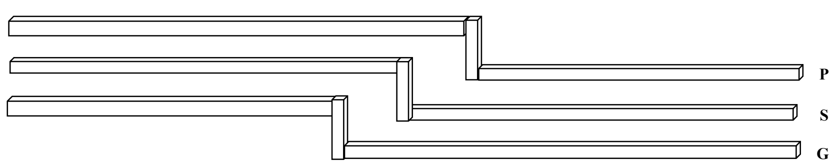


$$\begin{bmatrix} L_{AA} & L_{AB} & L_{AC} & L_{AD} \\ L_{BA} & L_{BB} & L_{BC} & L_{BD} \\ L_{CA} & L_{CB} & L_{CC} & L_{CD} \\ L_{DA} & L_{DB} & L_{DC} & L_{DD} \end{bmatrix} \quad \begin{bmatrix} L_{AA} & L_{AB} & 0 & 0 \\ L_{BA} & L_{BB} & 0 & 0 \\ 0 & 0 & L_{CC} & L_{CD} \\ 0 & 0 & L_{DC} & L_{DD} \end{bmatrix} \quad \begin{bmatrix} L_{AA}+L_{AC} & L_{AB}+L_{BC} & 0 & 0 \\ L_{AB}+L_{BC} & L_{BB}+L_{AC} & 0 & 0 \\ 0 & 0 & L_{CC}+L_{BD} & L_{CD}+L_{AD} \\ 0 & 0 & L_{CD}+L_{AD} & L_{DD}+L_{BD} \end{bmatrix}$$

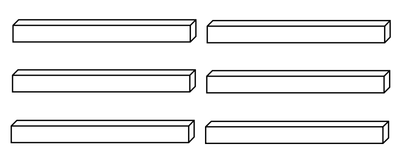
Full 2D Model | **Cascaded 2D Model** **[N. Chang, et al, 2000]** | **Normalized 2D Model** **[M. Xu-L. He, 2001]**

2D Inductance Model

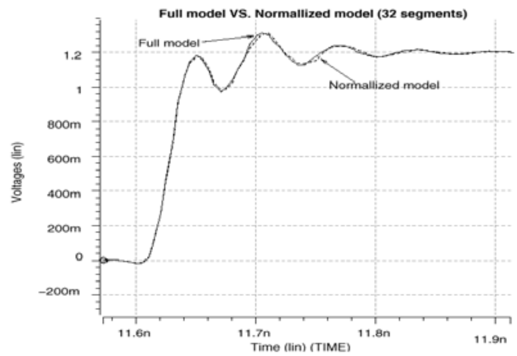
- **Cascaded 2D model has an acceptable accuracy for coplanar wave-guide**



- **Normalized 2D model has an acceptable accuracy for aligned bus structure**



Full Model Versus Normalized Model



- **Simulation of a bus with 32 segments per line**
- **Running time:**
  - **Full 99.0 seconds**
  - **Normalized 9.1 seconds**

References and Further Reading Assignments

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