Parallel-Distributed Time-Domain Circuit Simulation of Power Distribution Networks with Frequency-Dependent Parameters

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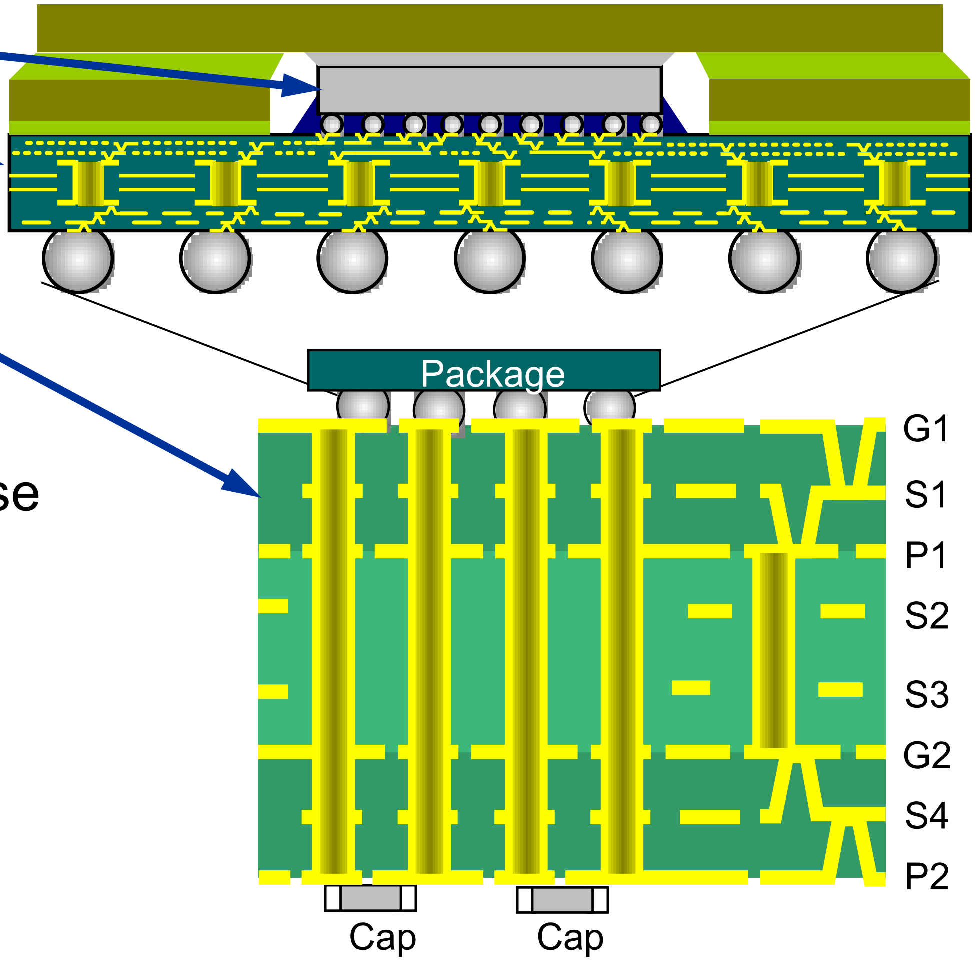
Outline

- Objective of Simulation for Power Integrity
- Latency Insertion Method (LIM)
  - Modeling of Power/Ground Planes
  - Modeling of Frequency-Dependent Effects
- Acceleration Techniques of LIM Simulation with Frequency-Dependent Parameters
  - Circuit Transformation
  - Parallel-Distributed Computation
- Numerical Results
  - Validity of Our Techniques

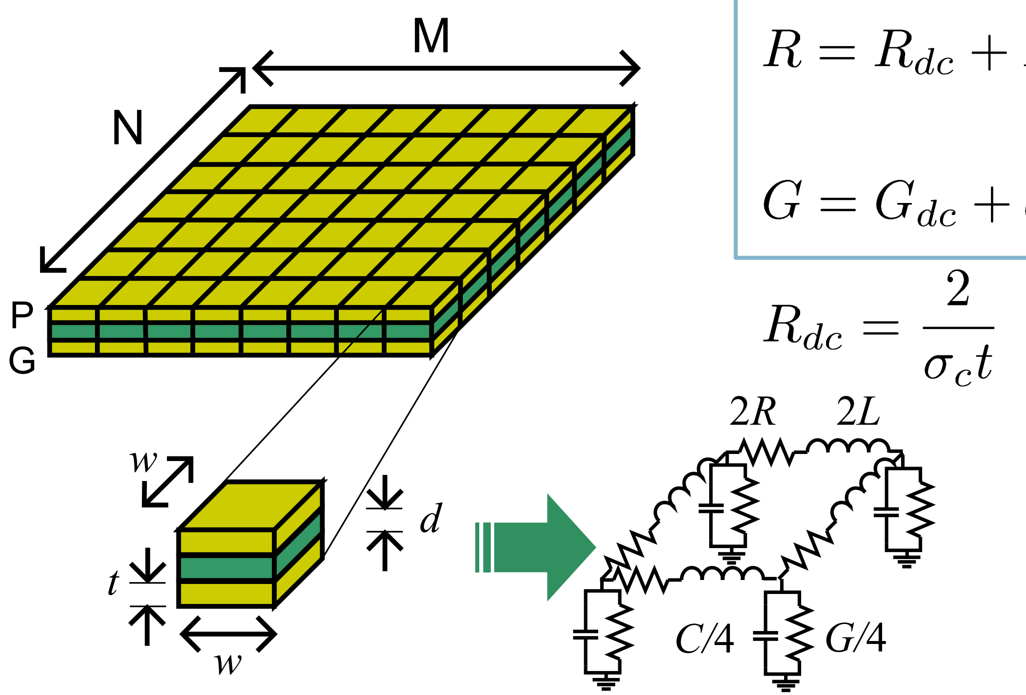
Objective of Simulation for Power Integrity

- Power Distribution Network
  - chip level
  - package/interposer level
  - board level
- Power Integrity
  - IR-drop
  - delta-I noise
  - simultaneous switching noise
  - ground bounce
  - plane resonance



Modeling of PDN

- On-Chip
  - power distribution grids
- PCB/Package
  - power and ground (P/G) plane pairs
  - P/G plane pair can be discretized spatially into unit cells



unit cell   lumped equivalent model

$$R = R_{dc} + R_{ac}\sqrt{\omega} \qquad L = L_{ext} + \frac{R_{ac}}{\sqrt{\omega}}$$

$$G = G_{dc} + \omega G_d \qquad C = \varepsilon_0 \varepsilon_r \frac{w^2}{d}$$

$$R_{dc} = \frac{2}{\sigma_c t} \qquad R_{ac} = \sqrt{\frac{2\mu_0}{\sigma_c}} \qquad L_{ext} = \mu_0 d$$

$$G_d = \varepsilon_0 \varepsilon_r \frac{w^2}{d} \tan(\delta)$$

Latency Insertion Method (LIM)

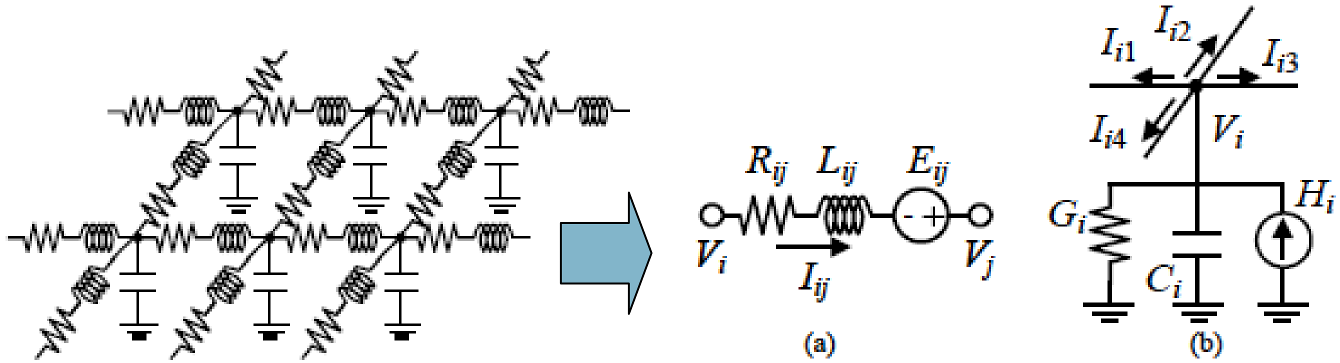
- Fast transient simulation algorithm for large RLC networks

J. E. Shutt-Ainé, "Latency Insertion Method (LIM) for the Fast Transient Simulation of Large Networks," *IEEE Trans. Circuits and Systems-I*, vol. 48, no.1 pp. 81-89, Jan. 2001.

  - derivative method in a class of the "leapfrog" finite-difference time-domain (FDTD) algorithms
  - no need to solve any matrix equations
  - 100x-1000x faster than SPICE-like simulator
- Limitation
  - Every branch must have an inductor
  - Every node must be connected with the grounded capacitor

Basic Algorithm of LIM

- Time-domain simulation is done by the alternate “leapfrog” updates of branch-currents and node-voltages



computation of branch current

computation of node voltage

- LIM Update Equation

branch-currents (from KVL)

$$I_{ij}^{n+1} = I_{ij}^{n} + \frac{\Delta t}{L_{ij}}\left(V_i^{n+1/2} - V_j^{n+1/2} - R_{ij}I_{ij}^{n} + E_{ij}^{n+1/2}\right)$$

node-voltages (from KCL)

$$V_i^{n+1/2} = \frac{\frac{C_i}{\Delta t}V_i^{n-1/2} + H_i^n - \sum_{k=1}^{M_i} I_{ik}^n}{\frac{C_i}{\Delta t} + G_i}$$

- Time Step Size

$$\Delta t \le \sqrt{LC}$$

Frequency-Dependent Effects of PDN

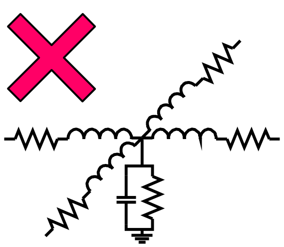
- Actual PDNs have some frequency-dependent properties:
  - skin effects
    - At high frequencies, the current redistribute to the surface of the plane, and resistance *R* is increased.
  - dielectric losses
    - At high frequencies, conductance *G* is increased due to the complex permittivity of the dielectrics.

$$R = R_{dc} + R_{ac}\sqrt{\omega} \qquad L = L_{ext} + \frac{R_{ac}}{\sqrt{\omega}}$$

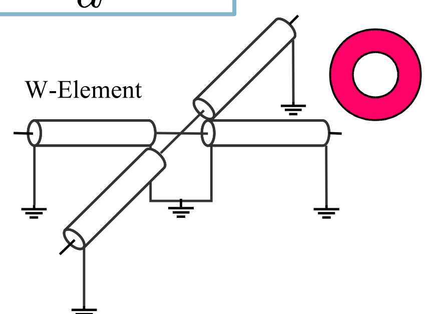
$$G = G_{dc} + \omega G_d \qquad C = \varepsilon_0 \varepsilon_r \frac{w^2}{d}$$

$$R_{dc} = \frac{2}{\sigma_c t} \qquad R_{ac} = \sqrt{\frac{2\mu_0}{\sigma_c}}$$

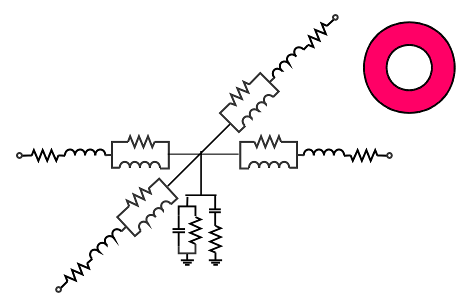
$$L_{ext} = \mu_0 d \qquad G_d = \varepsilon_0 \varepsilon_r \frac{w^2}{d} \tan(\delta)$$



frequency-independent model



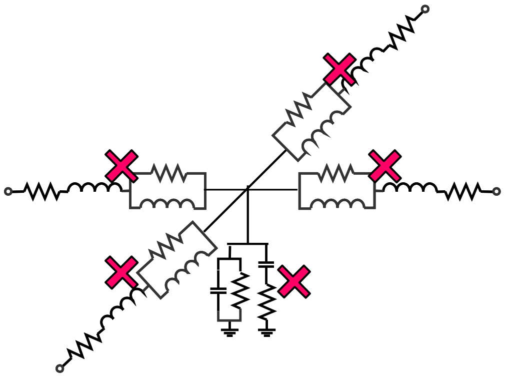
W-element model



first-order Debye model

LIM Simulation of Freq-dependent PDN

- Frequency-independent model is inadequate.
  - Frequency-dependent transmission line models (such as W-element) are available in only SPICE-like simulators (such as Star-Hspice)
- Is it possible to solve first-order Debye model using LIM?
  - Applicable conditions of LIM
    - Every branch must have an inductor
    - Every node must be connected with the grounded capacitor



- In this paper:
  - Circuit representation of the first-order Debye model is modified to a suitable form for LIM
  - LIM simulation is accelerated by a parallel-distributed computation

First-Order Debye Model

- Increasing the number of RL parallel networks and GC series networks, the accuracy of the model is increased
- For example:

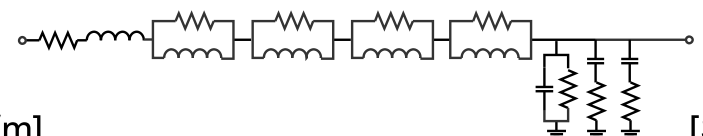
$$w = 2.5mm, d = 0.2mm, t = 0.03mm$$

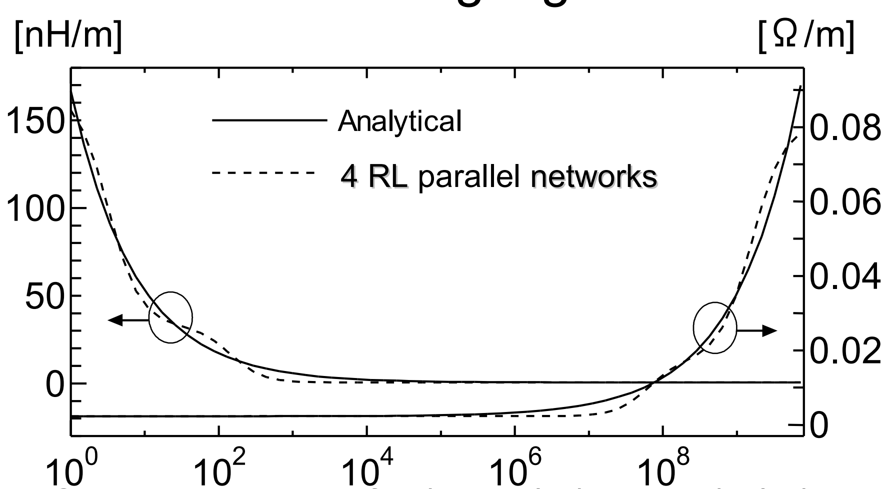
$$\sigma_c = 5.8 \times 10^7, \varepsilon_r = 4.5, tan(\delta) = 0.02$$

- Parameter Fitting:
  - MATLAB
  - Vector-fitting algorithm

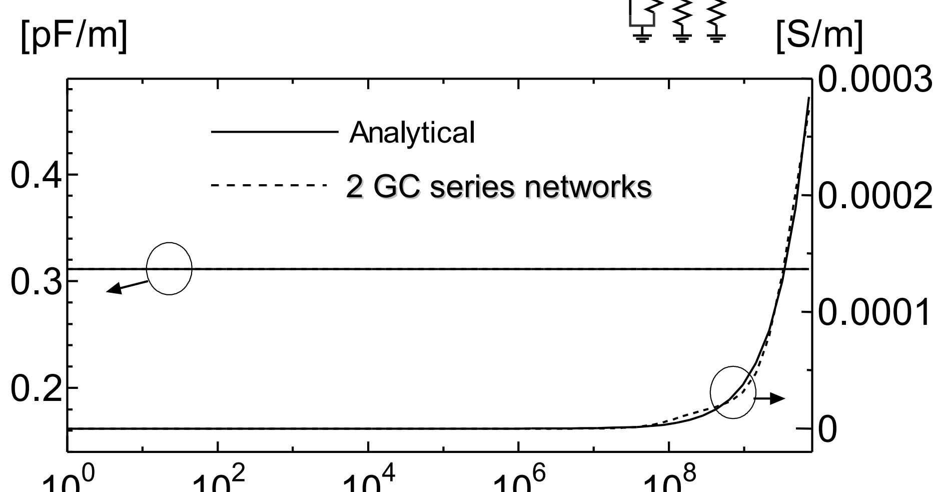
```
.SUBCKT RL2 p1 p2
R0  p1 2   1.149426e-003
L0  2  3   2.514000e-010
R1  3  4   1.350000e-006
L1  3  4   6.750000e-008
R2  4  5   1.450000e-005
L2  4  5   1.611111e-008
R3  5  6   7.616400e-003
L3  5  6   1.904100e-011
R4  6  p2  3.188935e-002
L4  6  p2  3.188935e-012
.ENDS
```

```
.SUBCKT GC4 p1 p2
C0   p1  p2  1.245094e-012
RG1  p1  2   1.453488e+004
C1   2   p2  8.600000e-014
RG2  p1  3   6.806425e+002
C2   3   p2  4.897333e-014
.ENDS
```





Characteristics of R(orms/m) and L(H/m)

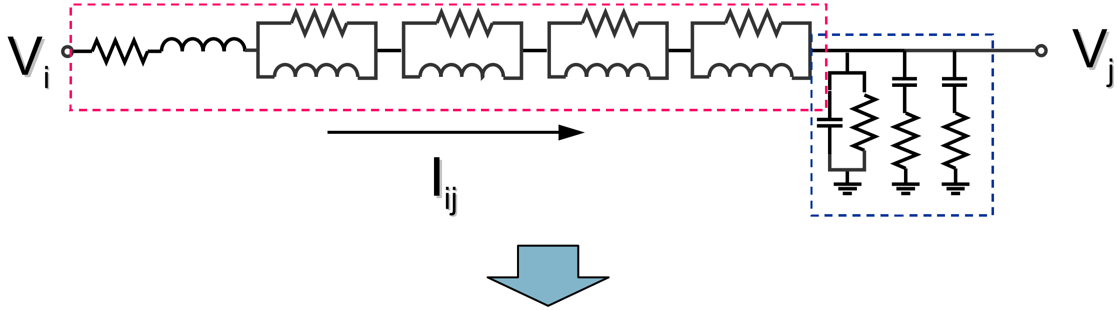


Characteristics of G(S/m) and C(F/m).

An Algorithm to Solve Debye Model with Leapfrog Scheme

Alberto Scarlatti and Christopher L. Holloway,"An Equivalent Transmission-Line Model Containing Dispersion for High-Speed Digital Lines—With an FDTD Implementation", *IEEE Trans. Electromagnetic Comp.*, vol. 43, no. 4, Nov. 2001.

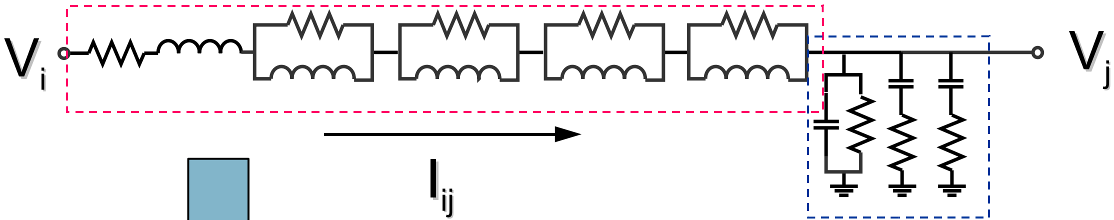
- In order to obtain branch-currents from node-voltages, every RL networks had to be solved via matrix inversion
- In order to obtain node-voltages from branch-currents, every GC networks had to be solved via matrix inversion



- This algorithm requires solving matrix equations, while LIM doesn't need to solve matrix equations

Our Method: Circuit Transformation

- First-order Debye model consists of distributed series impedance and shunt admittance



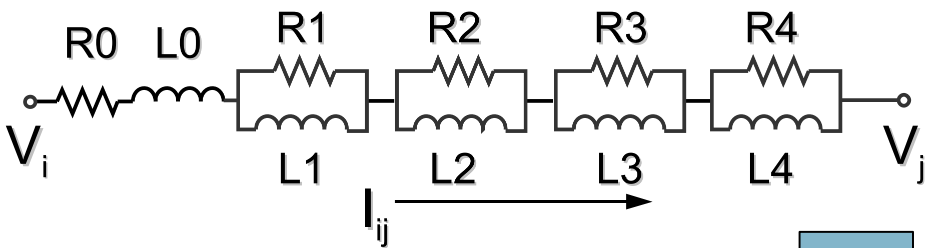
$$Z(s) = R_0 + sL_0 + \frac{R_1 L_1}{R_1 + sL_1} + \frac{R_2 L_2}{R_2 + sL_2} + \frac{R_3 L_3}{R_3 + sL_3} + \cdots$$

$$Y(s) = G_0 + sC_0 + \frac{G_1 C_1}{G_1 + sC_1} + \frac{G_2 C_2}{G_2 + sC_2} + \frac{G_3 C_3}{G_3 + sC_3} + \cdots$$

- Circuit representation of the first-order Debye model is modified to a suitable form for LIM
  - RL parallel network is transformed into RL series network
  - GC series network is also transformed into GC parallel network

Our Method: Circuit Transformation (cont.)

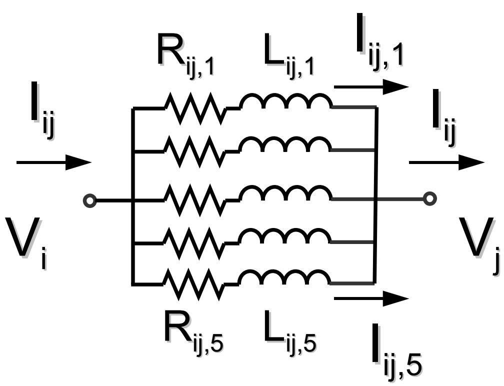
- Example: distributed series impedance



$$V_i - V_j = \left(R_0 + sL_0 + \sum_{m=1}^{4} \frac{R_m L_m}{R_m + sL_m} \right) I_{ij}$$

$$(V_i - V_j) \sum_{m=1}^{5} \frac{k_m}{s - p_m} = I_{ij}$$

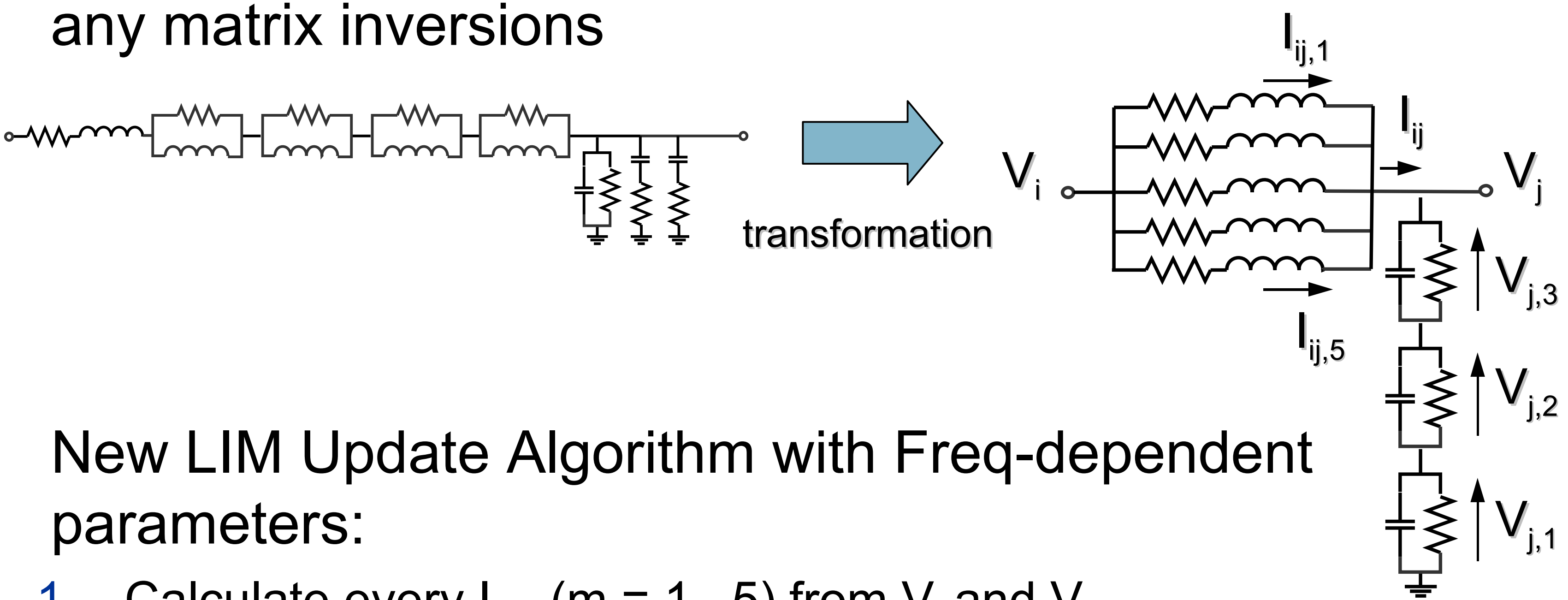
$$(V_i - V_j) \frac{k_m}{s - p_m} = I_{ij,m} \qquad (m = 1, \cdots, 5)$$



$$V_i - V_j = \frac{s - p_m}{k_m} I_{ij,m} = (sL_{ij,m} + R_{ij,m}) I_{ij,m}$$

Our Method: Circuit Transformation (cont.)

- Through this transformation, we do not have to perform any matrix inversions

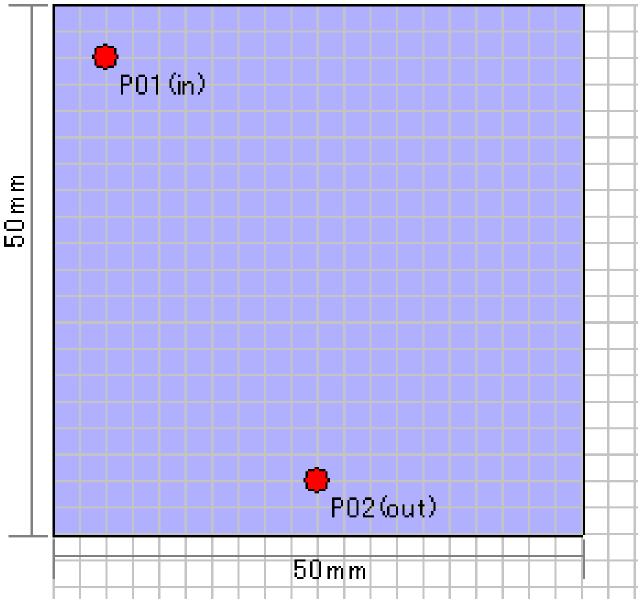


- New LIM Update Algorithm with Freq-dependent parameters:
  1. Calculate every $I_{ij,m}$ ($m = 1...5$) from V_i and V_j
  2. I_{ij} is sum of $I_{ij,m}$
  3. Calculate every $V_{j,m}$ ($m = 1...3$) from I_{ij}, $I_{i(j+1)}$, $I_{(i+1)j}$, $I_{(i+1)(j+1)}$
  4. V_j is sum of $V_{j,m}$

Verification of the Validity of Our Method

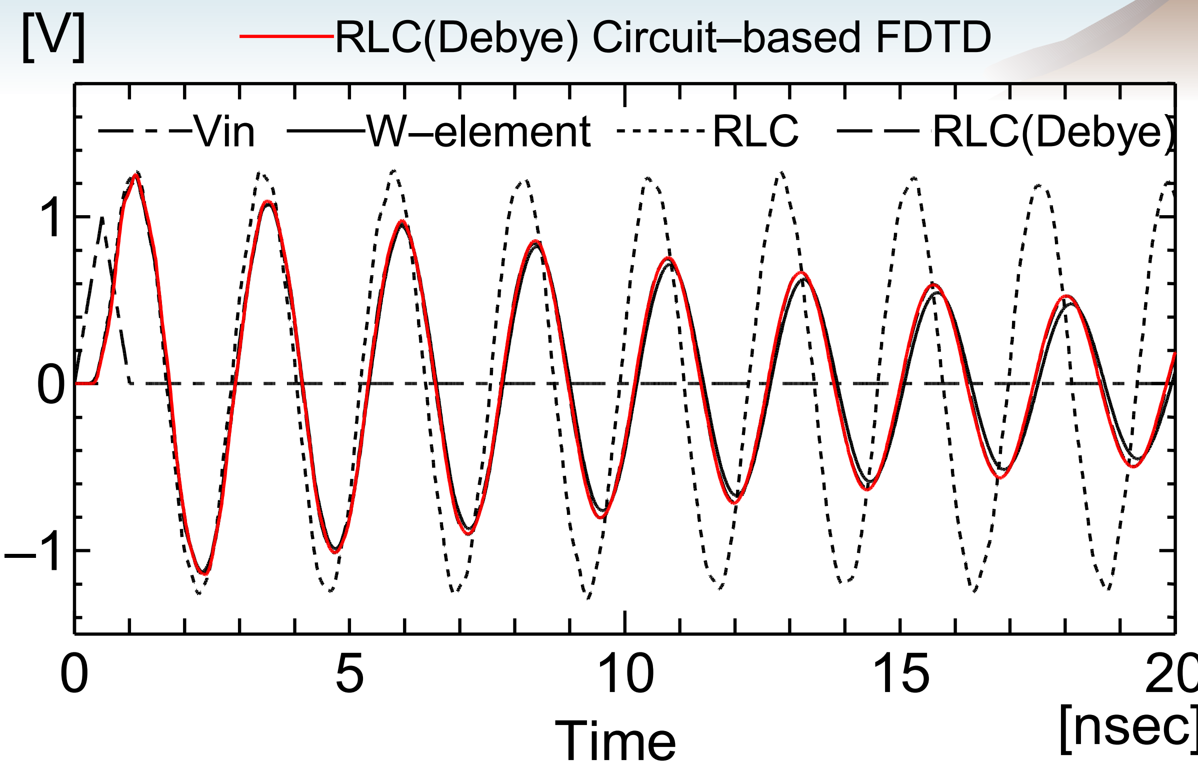
- We simulated a power/ground plane which has frequency-dependent properties
  - The source point P01 was excited with a triangular waveform

$$w = 2.5mm, d = 0.2mm, t = 0.03mm$$
$$\sigma_c = 5.8 \times 10^7, \varepsilon_r = 4.5, tan(\delta) = 0.02$$



  - Debye:
    - 5RL series networks
    - 3GC parallel networks
  - Simulation Environment:
    - SUN Blade Workstation
    - GNU compiler
    - We compared the transient responses simulated using the Star-Hspice and our LIM simulator

Numerical Results



Transient responses of the observation point P02

The CPU time comparisons

Simulator	Star-Hspice			LIM
Model	RLC	Debye	W-element	Debye
Problem Size	1282 nodes	5524 nodes	442 nodes	400 unit cells
CPU Time (sec)	3.3	19.7	365.6	0.47

Our Method: Parallel-Distributed Computation

- LIM is sufficiently faster than SPICE

↓

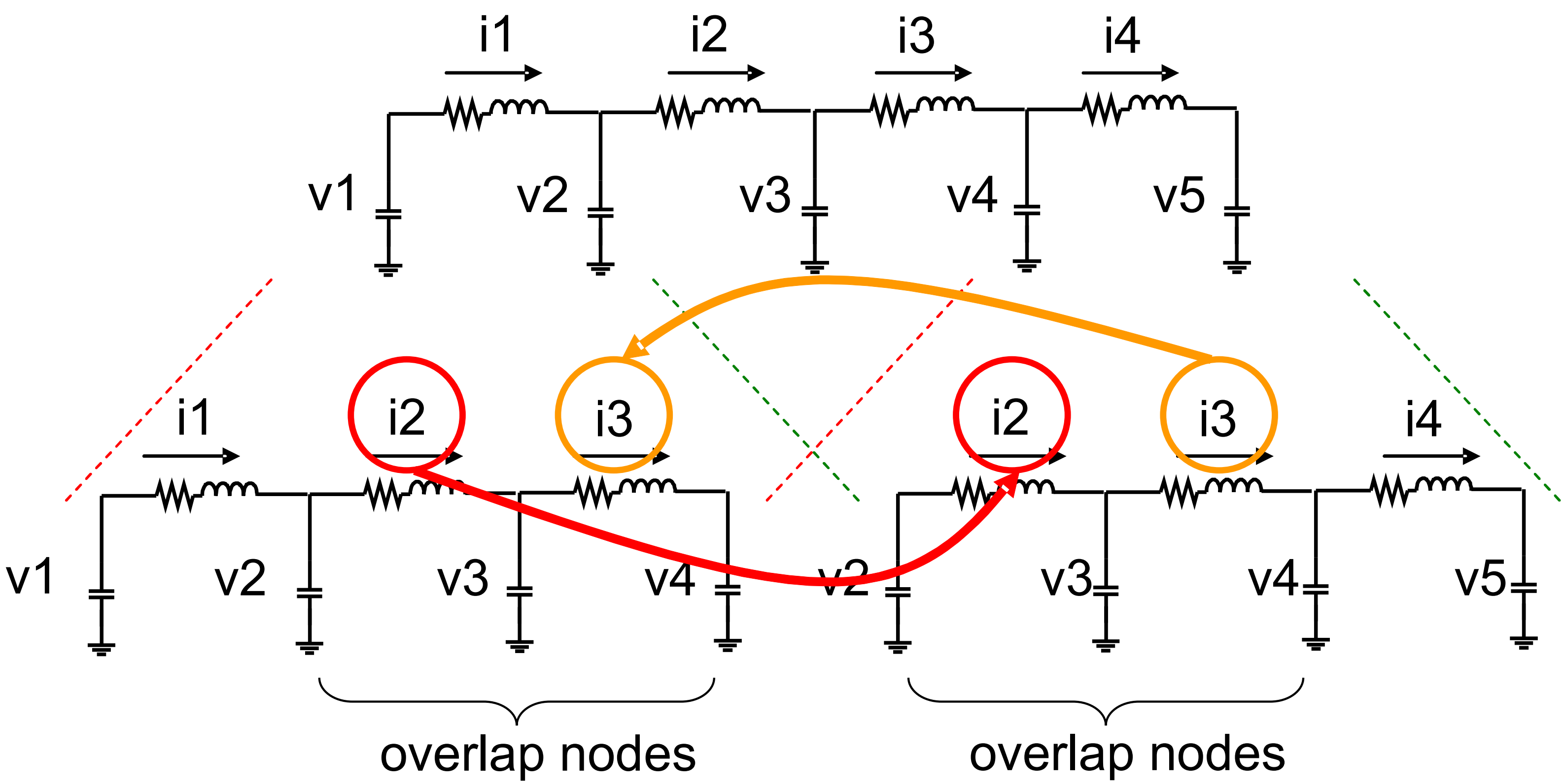
- However:
  - The size of the circuit is still increasing
    - Multilayered plane pairs
    - First-order Debye model
  - There is still a limit to the size of the circuit which can be solved by one PE (Processing Element) even in LIM.

↓

- To address this problem, the parallel-distributed LIM algorithm is proposed

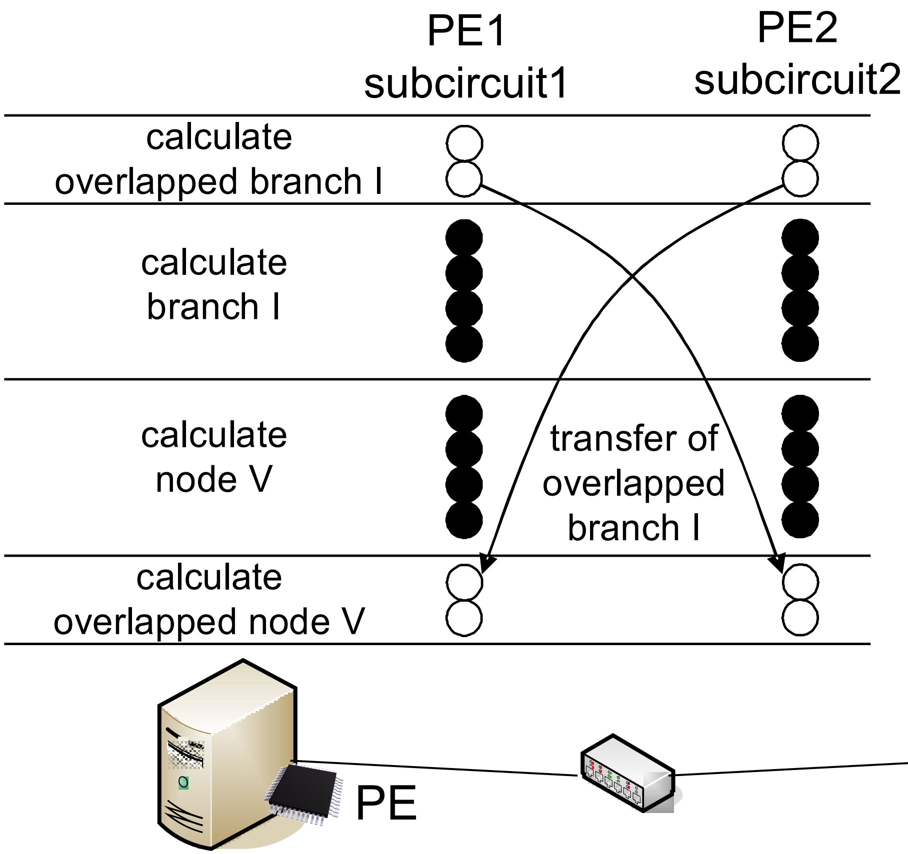
Our Method: Parallel-Distributed Computation (cont.)

- Divide the whole circuit into some subcircuits
  - Each subcircuit have to overlap neighboring subcircuits
  - Each subcircuit is assigned to different Processor Element (PE)



Our Method: Parallel-Distributed Computation (cont.)

- Parallel-Distributed LIM Algorithm:

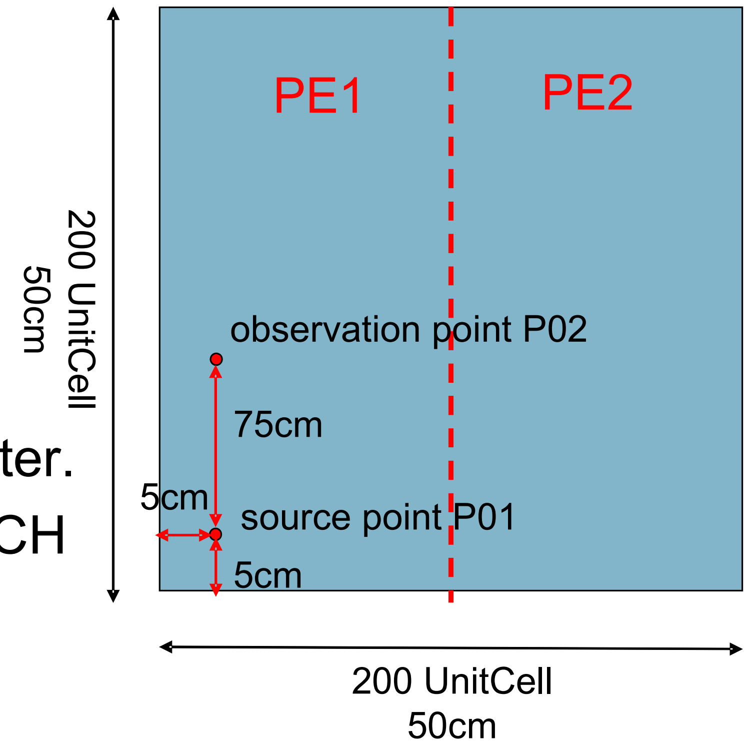


- Amount of transfer data is constant between frequency-independent case and frequency-dependent case

Verification of the Validity of Parallel-Distributed Computation

- We simulated a transient response of a power/ground plane using 1PE and 2PE with / without Freq-dependent parameters.
  - The source point was excited with a Gaussian pulse.

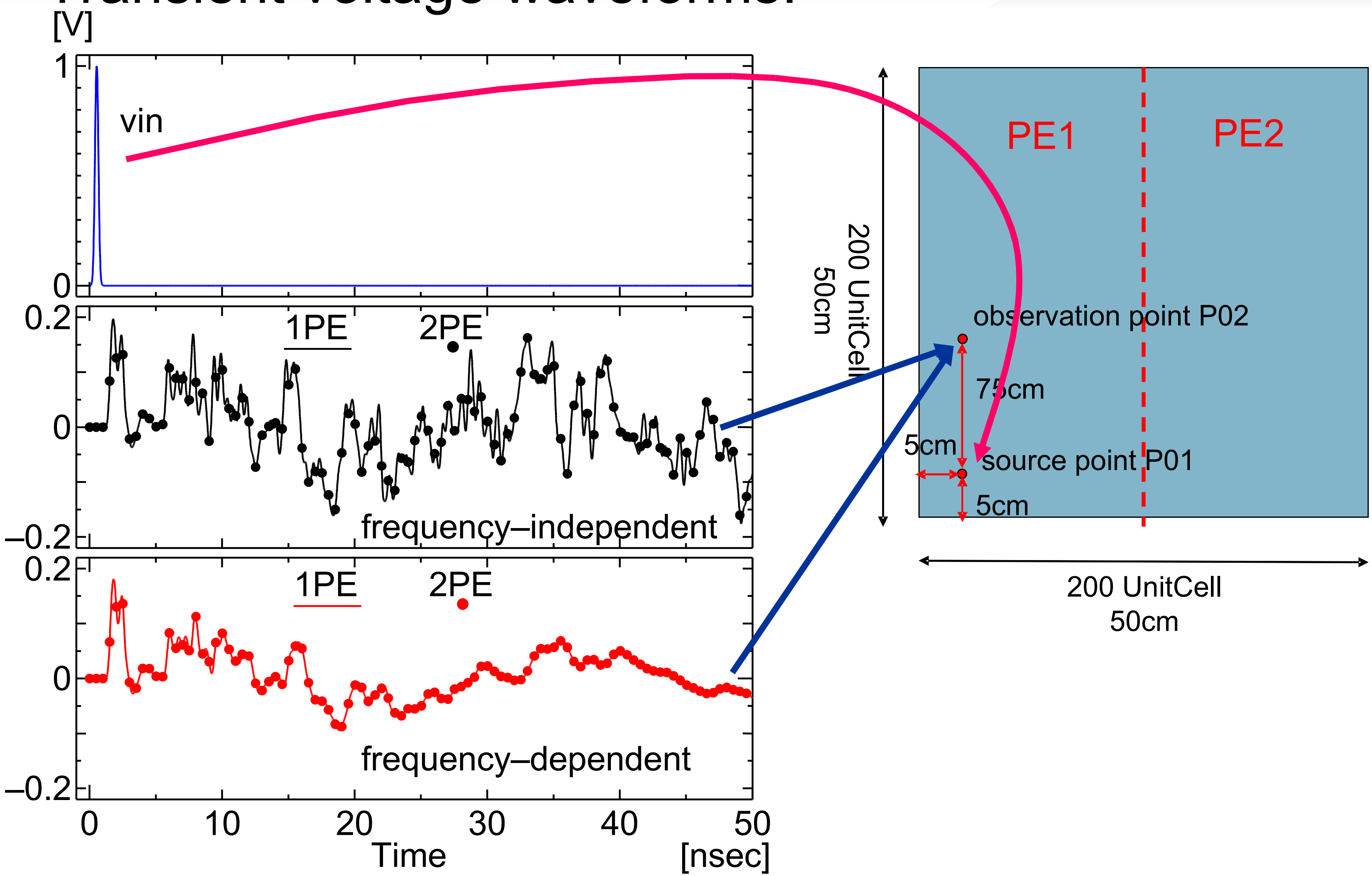
$$w = 2.5mm, d = 0.2mm, t = 0.03mm$$
$$\sigma_c = 5.8 \times 10^7, \varepsilon_r = 4.5, tan(\delta) = 0.02$$



- Simulation Environment;
  - All simulations were performed on Intel Xeon 2.2GHz personal computer.
  - Parallel programming library: MPICH
  - Network interface: 1000Base-T

Numerical Results

- Transient voltage waveforms:



Numerical Results (cont.)

- Complexity of the model
  - Frequency-independent unit cell model:
    - 1RL series network and 1GC parallel network
  - Frequency-dependent (Debye) unit cell model:
    - 5RL series networks and 3GC parallel networks
- CPU time of the 2PE simulation is almost half of the 1PE's CPU time

The CPU time comparisons

unit cell model	Freqency-independent		Frequency-dependent (Debye)	
Number of PE	1PE	2PE	1PE	2PE
CPU time (sec)	57.1	31.9	215.7	113.1

Conclusions

- In this paper:
  - An effective modeling of frequency-dependencies of the PDNs to solve by LIM
  - Parallel-distributed LIM algorithm

  - It is obvious that the parallel computation is very efficient for the LIM algorithm
  - Our transformed Debye model is quite effective to the LIM and parallel-distributed LIM simulation
- Future work:
  - Optimal partitioning of any irregular shaped power/ground plane for parallel computing

- Acknowledgments
  - This work was supported, in part, by Semiconductor Technology Academic Research Center (STARC), Japan.