Interconnect RL Extraction at a Single Representative Frequency

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Outline

- Background and motivation
- Frequency dependence of interconnect characteristics
- Representative frequency based on transfer characteristics
- Experimental results
- Conclusion
Background & Motivation

Interconnect design is a big problem in circuit design.

One difficulty is frequency-dependency.

On-chip wire

Frequency-dependent

RLC ladder circuit

Frequency-independent

Which frequency should we use for extraction?
Why frequency-independent model?

- Frequency-dependent models are already developed
  - Higher accuracy
  - Higher cost for creating the model
  - Which frequency is important?

RLC ladder is useful in the early stage of design
To clarify the important frequency helps wire design
Outline

- Background and motivation
- Frequency dependence of interconnect characteristics
  - Problem description
  - Conventional methods
- Representative frequency based on transfer characteristics
- Experimental results
- Conclusion
Frequency-dependence of RL

- Skin-effect, return-current distribution
  - In high freq., R increases and L decreases
  - Frequency dependence of C is negligible
Problem of frequency-dependence

In digital circuits, spectrum of pulse waveform widely spreads

Which frequency component is important?

Frequency dependent model can consider all freq. Components

We have to choose one frequency for freq.-independent model
Effects on waveform

Extraction at

too low freq. overestimates delay and amplitude

too high freq. underestimates delay and amplitude
Conventional methods

- Extraction at DC.
- Determine from the shape of input pulse significant frequency \((= 0.34/\text{tr})\)

Output waveform is more important

Our idea: determine extraction frequency from the transfer characteristic of interconnect
Outline

- Background and motivation
- Frequency dependence of interconnect characteristics
  - Transfer characteristic of interconnect
  - Proposed method
- Experimental results
- Conclusion
Transfer characteristic of transmission-line

Basic idea: the peak of transfer characteristics has strong effect on the waveform at the far-end

Transmission-lines have resonance frequencies

Ex. Open-ended line: the frequency where $\frac{\lambda}{4} = \text{wire length}$

(Preliminary work is presented in ASP-DAC2004)
Spectrum at the far-end

Resonance frequency is a peak regardless of the rise time
Relationship between the resonance freq. and the spectrum of input

Spectrum of input pulse also affect the waveform

Resonance freq. $\gg$ significant freq.

Input at the resonance freq. is small

The importance of the resonance freq. is small

In the proposed method, we use the significant freq. as the upper limit of extraction freq.
Resonance frequency of uniform transmission-lines

- Resonance frequency is easily derived from transmission-line theory

\[
\frac{V_{out}}{V_{in}} = \frac{1}{\cosh \gamma l + \frac{Z_0}{Z_t} \sinh \gamma l}
\]

\[Z_0: \text{characteristic impedance}\]
\[Z_t: \text{impedance of load}\]
\[\gamma: \text{propagation constant}\]
\[l: \text{wire length}\]

How to treat non-uniform or branching wire?
Non-uniform / branching wire

- Divide the wire into uniform segments
- Determine the extraction frequency for each segment

Load of A-B = parallel connection of the input impedance of B-C and B-D
Proposed method (1/3)

Step 1. Determine the freq. for terminal segment

Input of gates is assumed to be open-end

Extraction freq. for B-D, C-E, C-F are determined
Proposed method (2/3)

Step 2. Calculate the input impedance

The load of B-C is determined

The extraction freq. of B-C can be determined
Proposed method (3/3)

Iterates Step1. and Step2.

- Calculate the input impedance of B-C
- The load of A-B is determined
- The extraction frequency of A-B is determined
Outline

- Background and motivation
- Frequency dependence of interconnect characteristics
- Representative frequency based on transfer characteristics

**Experimental results**
- Case study
- Statistic of experimental results

- Conclusion
Case study: stub-bus

- 10µm wide interconnect (A-B-C-D-E) and 1µm wide stub
- Transition time of input is 10ps

Extraction frequencies by the proposed method
Transition waveform

- Waveform at the terminal of a stub

Result of our method meets that of FD
Summary of overall experiments

- 43,199 nodes in 9,545 configurations are evaluated

<table>
<thead>
<tr>
<th>Freq.</th>
<th>Delay</th>
<th>Transition time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max. err.</td>
<td>&gt;5%*</td>
</tr>
<tr>
<td>DC</td>
<td>-88.1%</td>
<td>11.5%</td>
</tr>
<tr>
<td>Proposed</td>
<td>-9.9%</td>
<td>5.4%</td>
</tr>
<tr>
<td>Sig. Freq.</td>
<td>+110.0%</td>
<td>12.2%</td>
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</tbody>
</table>

(*: ratio that the error is over 5%)

Proposed method achieve less than 10% error
Conclusion

- A representative frequency for RL extraction is proposed
- Determine the extraction frequency from the transfer characteristics
- The proposed method can handle non-uniform and branching wires
- The maximum error in delay and transition time is less than 10%