C-comp extraction methods for High-Speed I/O buffers

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Outlines

- Review C-comp extraction methods
  - Time domain
  - Frequency domain
- Look into C-comp for pullup, pulldown, powerclamp and groundclamp
  - Frequency domain with voltage variables
- Define frequency and voltages
- Conclusions
Time Domain

- Apply ramp voltage source ($\beta t$) & measure the current.
- Subtract DC current in pull up/down device.
- $C(t) = (I_1 - I_2)/2\beta = (I(t)_{\text{source}} - I(t)_{\text{device}})/\beta$.
- $C_{\text{comp}}$ varies with $\beta$ !!!!

Time Domain Methods

\[
C_{\text{comp}} = [(I_1-I_2)/2](dt/dv)
\]

- Time domain methods depends on $I_C = C*(dV/dt)$
Frequency domain

Voltage Dependence

\[ \omega_0 = \frac{1}{\sqrt{LC_{\text{comp}}}} \]

Vdc increases
C-comps for pullup, pulldown, powerclamp and groundclamp

- Pad DC levels
  - 3.3v, 2.2v, 1.1v, 0v
- Input DC levels
  - High, Low
- Enable DC levels
  - Enabled, Disabled

3 DC variables for C-comp frequency-domain extractions
Non-driving mode summary

- Almost identical C-comp values for clamps when frequency changes
- Pad DC levels impact C-comp values for clamps
- For I/O buffers, C-comps values for Pullup and Pulldown may not be zero. They could change with frequency changes
- For I/O buffers, non-driving mode C-comp values are different than driving mode’s. They could be big enough to affect your simulation analysis result
Non-driving mode @ 100MHz and 2500 MHz

C-Comps @ 100MHz @ Driving=Disabled

<table>
<thead>
<tr>
<th>Capacitance</th>
<th>C_comp</th>
<th>C_comp_pu</th>
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At 100MHz

C-Comps @ 2500MHz @ Driving=Disabled

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At 2500MHz
Pad DC = 3.3v
Driving mode = Disabled

C-Comp vs. Freq @ 3.3/H/H

<table>
<thead>
<tr>
<th>Capacitance</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2pF</td>
<td>1.00E+08</td>
</tr>
<tr>
<td>2.1pF</td>
<td>1.10E+08</td>
</tr>
<tr>
<td>1.5pF</td>
<td>1.50E+08</td>
</tr>
<tr>
<td>0.3pF</td>
<td>1.90E+08</td>
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<tr>
<td>0.25pF</td>
<td>2.10E+08</td>
</tr>
<tr>
<td>0.2pF</td>
<td>2.30E+08</td>
</tr>
</tbody>
</table>
Pad DC = 2.2v
Driving mode = Disabled

C-Comp vs. Freq @ 2.2/H/H

Frequency

Capacitance

- c_comp
- c_comp_pu
- c_comp_pd
- c_comp_pc
- c_comp_gc

1.75pF
1.6pF
1.0pF
0.3pF
0.25pF
0.2pF
Pad DC = 1.1v
Driving mode = Disabled

C-Comp vs. Freq @ 1.1/H/H

Capacitance

Frequency

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Pad DC = 0.0v
Driving mode = Disabled
Driving mode summary

- Identical C-comp values for clamps with frequency changes
- Pad DC levels impact C-comp values for clamps
- Pullup and Pulldown C-comp values vary with frequency changes. But it settles at a frequency point and up (being flat)
  - Input DC (level = High) impacts more on Pullup
  - Input DC (level = Low) impacts more on Pulldown
Driving mode with Vin=High @ 100MHz and 2500MHz

C-Comps @ 100MHz @ Vin=High @ Driving=Enabled

C-Comps @ 2500MHz @ Vin=High @ Driving=Enabled

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Pad DC = 3.3v, Input DC = High, Driving mode = Enabled

c_comp vs. Freq @ 3.3/H/L

- c_comp (black diamonds)
- c_comp_0u (pink squares)
- c_comp_pu (yellow triangles)
- c_comp_pd (cyan crosses)
- c_comp_pc (green stars)
- c_comp_gc (purple asterisks)

Capacitance vs. Frequency

- Capacitance values: 2.4pF, 2.1pF, 1.45pF, 0.7pF, 0.3pF, 0.2pF, 0.0pF
- Frequency values: 1.00E+08 to 2.30E+09
Pad DC = 2.2v, Input DC = High, Driving mode = Enabled

C-Comp vs. Freq @ 2.2/H/L

- **c_comp**: 3.65pF
- **c_comp_pu**: 1.8pF
- **c_comp_pd**: 1.7pF
- **c_comp_pc**: 1.0pF
- **c_comp_gc**: 0.6pF
- **c_comp_ga**: 0.3pF
- **c_comp_c**: 0.2pF

Frequency vs. Capacitance plot for different capacitance values at various frequencies.
Pad DC = 1.1v, Input DC = High, Driving mode = Enabled

C-Comp vs. Freq @ 1.1/H/L

- c_comp
- c_comp_pu
- c_comp_pd
- c_comp_pc
- c_comp_gc

Capacitance vs. Frequency

- 4.2pF
- 2.5pF
- 1.55pF
- 0.75pF
- 0.35pF
- 0.2pF
- 0.5pF
Pad DC = 0.0v, Input DC = High, Driving mode = Enabled
Driving mode with $V_{\text{in}}=\text{Low}$

@ 100MHz and 2500 MHz

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</table>
Pad DC = 3.3v, Input DC = Low, Driving mode = Enabled
Pad DC = 2.2v, Input DC = Low, Driving mode = Enabled
Pad DC = 1.1v, Input DC = Low, Driving mode = Enabled

C-Comp vs. Freq @ 1.1/L/L

- $c_{comp}$
- $c_{comp\_pu}$
- $c_{comp\_pd}$
- $c_{comp\_pc}$
- $c_{comp\_gc}$

Capacitance vs. Frequency

- $0.3pF$
- $0.4pF$
- $0.8pF$
- $2.5pF$
- $4.0pF$
- $1.55pF$
Pad DC = 0.0v, Input DC = Low, Driving mode = Enabled

C-Comp vs. Freq @ 0.0/L/L

Capacitance (pF)

Frequency (Hz)

0 2E-12 4E-12 6E-12 8E-12 1E-12 1.2E-12 1.4E-12 1.6E-12 1.8E-12

1.00E+08 3.00E+08 5.00E+08 7.00E+08 9.00E+08 1.10E+09 1.30E+09 1.50E+09 1.70E+09 1.90E+09 2.10E+09 2.30E+09
Define frequency and voltages

- Frequency
  - Use [Ramp] data as the reference
  - Buffer output frequency (Foutput)
    \[ F_{output} = \frac{1}{(\text{Rising}_\text{dt} + \text{Falling}_\text{dt})} \]
    (for the most of high-speed buffer, the calculated output frequency point is in the settled region)

- Input buffer c-comp is not impacted much by output frequency changes. But suggest to use slightly higher frequency
Define frequency and voltages

- **Voltages**
  - Typical application settings
  - Operation voltage ranges
  - Using High and Low level DC settings
  - Averaging extracted C-comp values is a practical way for IBIS model

- **Important to correctly define DC voltages**
Conclusions

- C-comp (die capacitance) is important in high-speed buffers
- Understand your high-speed buffer die-capacitance arrangement is the first step for extractions
- Frequency domain with defined frequency and DC voltage settings is practical for accurate C-comp extractions
- IBIS specification improvements are required:
  - Separate driving and non-driving mode C-comp values for accurate high-speed simulations
  - Separate different DC level C-comp values for different applications
Thank You

謝謝

ありがとうございました

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