Thermal-reliable 3D Clock-tree Synthesis Considering Nonlinear Electrical-thermal-coupled TSV Model

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http://www.ntucmosetgp.net
Outline

- Background and Motivation
- Electrical-thermal-coupled TSV Model
- Nonlinear Optimization of Skew Reduction
- Experimental Results
- Conclusion and Future Work
3D Server for Big-data Cloud Server

3D Processor

Supercomputer


http://www.techthefuture.com/energy/climate-change-supercomputer/

Thermal Challenges in 3D Integration

- **Thermal reliability is concerned**: large non-uniform thermal gradient as limited heat dissipation paths in 3D IC
- **3D clock-tree synthesis to balance electrical-thermal coupling induced skew**

Temperature adds up from longer heat dissipation path

3D CLK network with skew under temperature profile

- 80°C Skew: 100ps
- 60°C Skew: 10ps
- 40°C Skew: 1ps
- Skew: 100ps
- Skew: 10ps
- Skew: 1ps
Temperature Aware Clock-tree Synthesis

- Clock-skew reduction methods considering temperature
  - Buffer Insertion [1]
  - Merging point adjustment [2]
  - Wire length balancing[3]
- 3D clock-skew reduction by thermal TSV insertion, which requires
  - Accurate electrical-thermal TSV model
  - Skew balance method


TSV Fabrication Technology

- TSV material: Al/Cu, under-bump-metal
- TSV diameter: 1~20um
- TSV height: 20~50um
- Liner material: SiO$_2$ or Si$_3$N$_4$
- Liner thickness: 0.2~0.5um

Simplified TSV fabrication process

[Diagram showing the process: TSV Etch, Liner Deposition, TSV Fill, and Thinning and Stacking Tier N, Tier N+1]
Signal TSVs

- Signal TSVs provide electrical connection between adjacent tiers
- Non-linear MOS-capacitance (MOSCAP) is formed between signal TSV and substrate due to the existence of liner
  - Low-k liner is preferred ($\text{SiO}_2$)
  - Depletion region exists because of the work function difference between TSV metal and silicon substrate
  - The radius of depletion region is temperature and voltage dependent

C-V curve of MOSCAP
Signal TSV Modeling

- **RC equivalent circuit of signal TSVs**

\[
\frac{1}{C_T} = \frac{1}{C_{ox}} + \frac{1}{C_{dep}}; \quad R_T = \frac{\rho h}{\pi r_{metal}^2}
\]

\[
C_{ox} = \frac{2\pi \varepsilon_{ox} h}{\ln(\frac{r_{ox}}{r_{metal}})} \quad C_{dep} = \frac{2\pi \varepsilon_{si} h}{\ln(\frac{r_{dep}}{r_{ox}})}
\]

- *r_{ox} is the outer radius of liner,*
- *r_{metal} is the radius of TSV,*
- *r_{dep} is the outer radius of depletion region*

- **TSV model considering non-linear temperature effect**

\[
R_T = R_0 (1 + \alpha(T - T_0))
\]

\[
C_T = C_0 + \beta_1 T + \beta_2 T^2
\]

- *\(\alpha\) and \(\beta_1, \beta_2\) are the temperature coefficients*
Signal TSV Delay Modeling

- Signal TSVs introduce noticed delay
  - Process and capacitance dependent
- Non-linear function with temperature

### Buffer without TSV
- Diameter: 5um
- Height: 50um
- Liner: 200nm
- PTM Model

### Buffer with TSV
- Diameter: 5um
- Height: 50um
- Liner: 200nm
- PTM Model

### Graph
- Delay without TSV (pS) vs. Wn
- Delay with TSV (pS) vs. Wn
- Non-linear function with temperature

- 14ps
- 66ps (200C)

- Delay x5

- 65nm 60 1V
- 45nm 45 1V
- 32nm 30 1V
- 22nm 20 0.8V
- 16nm 15 0.8V
Nonlinear Electrical-thermal-coupled Signal TSV Delay Model

- **Scalable signal TSV delay model**

\[
\tau = R_{in}\alpha\beta_2 T^3 + R_{in}[(1 - \alpha T_0)\beta_2 + \alpha\beta_1]T^2 \\
+ [\alpha(\tau_0 + R_{in}C_0) + (1 - \alpha T_0)R_{in}\beta_1]T \\
+ (1 - \alpha T_0)(R_{in}C_0 + \tau_0)
\]

where \(R_{in}\) is the total resistance looking from \(C_T\) to the input and \(\tau_0\) is the delay of circuit without \(C_T\)

- **Non-linear function of in delay model with temperature**

\[
D_{TSV} = k_0 + k_1 T + k_2 T^2 + k_3 T^3
\]

where \(k_0, k_1, k_2, k_3\) are the temperature coefficient in different order
Dummy TSVs

- Dummy TSVs provide additional heat dissipation paths to heat-sink as TSV metal (Cu, 400W/m · K) has much larger thermal conductivity than liner (SiO₂, 1.2W/m · K)
  - Chip temperature can be reduced by adding thermal TSVs
  - High thermal conductivity liner material is preferred (Si₃N₄, 30W/m · K)
Dummy TSV Model

- Dummy TSV density ($\eta$) is the ratio equivalent area of thermal TSV over total chip area ($A$)

- Total thermal conductivity between chip and heat sink

$$\sigma_{Total} = \eta \cdot \sigma_{TSV} + (1 - \eta)\sigma_0$$

$\sigma_{TSV}$ and $\sigma_0$ are the chip thermal conductivity with and without TSV, respectively.
Thermal Gradient Reduction by Dummy TSV Insertion

- Temperature reduction saturation effect due to dummy TSV insertion

\[ \Delta T = T_0 - T_{TSV} = \frac{P \cdot l}{A \sigma_0} \cdot \frac{\eta}{\sigma_{TSV} - \sigma_0} + \eta \]

- \( P/A \) is the power density,
- \( l \) is the equivalent length of thermal dissipation,
- \( \Delta T \) increases linearly with \( \eta \) as \( \eta \) is smaller than \( \sigma_0 / (\sigma_{TSV} - \sigma_0) \),
- \( \Delta T \) is less sensitive to \( \eta \) when \( \eta \) is approaching or larger than \( \sigma_0 / (\sigma_{TSV} - \sigma_0) \),

- \( \eta \) is limited by the chip area overhead and saturation of temperature reduction effect
- Balanced thermal gradient will balance clock skew
Nonlinear OPT of 3D CLK Skew by Dummy TSV Insertion: Problem Formulation I

- **Objective function**: minimize the variance of skew in all clock branches

  \[
  \min : f(D) = \frac{1}{C - 1} \sum_{k=1}^{C} (D_k - \bar{D})^2
  \]

- **Parameters**: dummy TSV insertion density

  \[
  \min : f(x) = \frac{1}{C - 1} \sum_{k=1}^{C} (\hat{c}_k^2 + 2\hat{c}_k \hat{f}_k^T x \\
  + x^T (\hat{f}_k \hat{f}_k^T + \hat{c}_k \hat{H}_k) x \\
  + \hat{f}_k^T x^T \hat{H}_k x + \frac{1}{\lambda} x^T \hat{H}_k xx^T \hat{H}_k x)
  \]

- **Constraints**:

  \[
  lb \leq x \leq ub
  \]

  - \(lb\) is the min thermal TSV density determined by the foundry process limitation
  - \(ub\) is the max thermal TSV density determined by temperature reduction sensitivity function as well as the maximum allowed chip overhead
Nonlinear OPT of 3D CLK Skew by Dummy TSV Insertion: Problem Formulation II

Chip Gridding (M x N)

Benchmark Circuit
RC Extraction

Temperature Profile from Hotspot
Clock Tree Benchmarks

Each grid is available for the thermal TSV insertion with density of $x_i$, $i=1 \epsilon [1, M \times N]$

Nonlinear Delay ($D_k$)

$$D_k = \sum_{i \in C_k} \tau_i.$$

is the summation of delay of passing through all grids

Parent Node
Child Node
Dummy TSV Insertion Sensitivity

- Sensitivity of temperature reduction w.r.t. dummy TSV density

\[ \frac{\partial T}{\partial \eta} = \frac{\Delta T_0 \cdot \eta_0}{(\eta_0 + \eta)^2} \]

- \( \Delta T_0 = \frac{P \cdot l}{A \cdot \sigma_0} \) is relative chip temperature without dummy TSV insertion,

- \( \eta_0 = \frac{\sigma_0}{\sigma_{TSV} - \sigma_0} \) is threshold density of dummy TSV.

- Constant sensitivity is achieved when \( \eta < \eta_0 \).

- Sensitivity is approaching zero when \( \eta >> \eta_0 \).

Typical: 2~10 K for 100 dummy TSVs in 1mm\(^2\)
Original problem is relaxed with Lagrange penalty factor to remove the inequality constraint

\[\text{min} : f^*(x) = f(x) + \lambda \cdot h^2(x)\]

where

\[h(x) = \begin{cases} 0, & l_b \leq x \leq u_b \\ \rho \gg 0, & \text{otherwise} \end{cases}\]

Conjugate gradient method iteratively searches along the gradient drop reduction to find the \(x\) which minimizes \(f^*(x)\).

Problem is solved multiple times with properly selected \(x_0\) to avoid local minimum.
Nonlinear Electrical-thermal Coupling by Signal TSVs

- Measurement result [4] shows non-linear TSV capacitance
- Delay introduced by non-linear TSV model shows large difference from linear model at high temperature

Temperature Reduction by Dummy TSVs

- COMSOL multi-physics simulator for thermal analysis
- A 4-tier 3D-IC test case: Tier thickness: 40µm; Thermal TSV has a diameter of 15µm; Heat sink conductance: $1.24 \times 10^5 \text{ W/(K} \cdot \text{m}^2)$
- Chip temperature is linearly reduced by increasing thermal TSV density
Dummy TSV Insertion for 3D Clock Skew Reduction: Set-up I

- Two generalized 4-Tier 3D IC H-Trees designed
- 3D-IC chip divided into 64x64 grids for dummy TSV insertion

Dummy TSV Insertion for 3D Clock Skew Reduction: Set-up II

- HotSpot [7] is used to extract the temperature distribution at each location.
- Temperature distribution is calculated from the average input of all SPEC2000 benchmarks [8].
- Maximal thermal TSV density is limited to be lower than 7% of the local grid area.
- Different signal TSV-bundles T2, T4, T8 and T10 are deployed with number of 2, 4, 8 and 10 TSVs.

Dummy TSV Insertion for 3D Clock Skew Reduction: Result I

H-Tree 1 clock skew comparison before and after TSV insertion

Temperature profile before and after TSV insertion
Dummy TSV Insertion for 3D Clock Skew Reduction: Result II

Synthesized 3D Clock Tree of Benchmark r5
## Dummy TSV Insertion for 3D Clock Skew Reduction: Result III

### htree1 (14 Signal TSV locations)

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<thead>
<tr>
<th>Type</th>
<th>Orig</th>
<th>Lin</th>
<th>Impr%</th>
<th>Time(s)</th>
<th>Nonlin</th>
<th>Impr%</th>
<th>Time(s)</th>
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<tbody>
<tr>
<td>T2</td>
<td>15.34</td>
<td>10.02</td>
<td>34.70%</td>
<td>14.29</td>
<td>2.59</td>
<td>83.10%</td>
<td>57.95</td>
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<tr>
<td>T4</td>
<td>26.44</td>
<td>8.67</td>
<td>67.20%</td>
<td>14.19</td>
<td>4.48</td>
<td>83.10%</td>
<td>57.9</td>
</tr>
<tr>
<td>T8</td>
<td>47.42</td>
<td>12.1</td>
<td>74.50%</td>
<td>14.58</td>
<td>8.14</td>
<td>82.80%</td>
<td>58.81</td>
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<tr>
<td>T10</td>
<td>58.42</td>
<td>15.1</td>
<td>74.20%</td>
<td>15.35</td>
<td>10.19</td>
<td>82.60%</td>
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### htree2 (28 Signal TSV locations)

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<td>23.48</td>
<td>8.69</td>
<td>63.00%</td>
<td>13.98</td>
<td>3.57</td>
<td>84.80%</td>
<td>56.95</td>
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<tr>
<td>T4</td>
<td>43.97</td>
<td>12.4</td>
<td>71.80%</td>
<td>14.02</td>
<td>5.38</td>
<td>87.80%</td>
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<td>82.76</td>
<td>16.18</td>
<td>80.40%</td>
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<td>9.35</td>
<td>88.70%</td>
<td>58.87</td>
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<td>17.69</td>
<td>82.80%</td>
<td>13.93</td>
<td>11.44</td>
<td>88.90%</td>
<td>57.58</td>
</tr>
<tr>
<td>Mean</td>
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<td>13.96</td>
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### r1 (45 Signal TSV locations)

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<th>Nonlin</th>
<th>Impr%</th>
<th>Time(s)</th>
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<td>30.5</td>
<td>18.4</td>
<td>39.70%</td>
<td>41.5</td>
<td>15.34</td>
<td>49.70%</td>
<td>106.6</td>
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<tr>
<td>T4</td>
<td>61.87</td>
<td>36.29</td>
<td>41.30%</td>
<td>29.3</td>
<td>27.5</td>
<td>55.60%</td>
<td>158.4</td>
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<tr>
<td>T8</td>
<td>121.1</td>
<td>71.39</td>
<td>41.60%</td>
<td>31.9</td>
<td>57.1</td>
<td>52.80%</td>
<td>170.5</td>
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<tr>
<td>T10</td>
<td>152.7</td>
<td>91.1</td>
<td>40.30%</td>
<td>37.2</td>
<td>74.26</td>
<td>51.40%</td>
<td>108.1</td>
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<tr>
<td>Mean</td>
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<td>-</td>
<td>40.70%</td>
<td>35</td>
<td>-</td>
<td>52.40%</td>
<td>135.9</td>
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### r2 (60 Signal TSV locations)

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<th>Time(s)</th>
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<td>35.13</td>
<td>23.6</td>
<td>32.80%</td>
<td>134</td>
<td>20.2</td>
<td>42.50%</td>
<td>389</td>
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<tr>
<td>T4</td>
<td>69.75</td>
<td>48.31</td>
<td>30.70%</td>
<td>102.8</td>
<td>37.9</td>
<td>45.70%</td>
<td>393.8</td>
</tr>
<tr>
<td>T8</td>
<td>134.7</td>
<td>94.67</td>
<td>29.70%</td>
<td>106.5</td>
<td>74</td>
<td>45.10%</td>
<td>705.8</td>
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<tr>
<td>T10</td>
<td>169</td>
<td>119.3</td>
<td>29.40%</td>
<td>139.3</td>
<td>93.82</td>
<td>44.50%</td>
<td>325.6</td>
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<tr>
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<td>120.7</td>
<td>-</td>
<td>44.50%</td>
<td>453.6</td>
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### r3 (75 Signal TSV locations)

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<th>Impr%</th>
<th>Time(s)</th>
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<th>Impr%</th>
<th>Time(s)</th>
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<td>32.36</td>
<td>20.92</td>
<td>38.40%</td>
<td>220.7</td>
<td>19.5</td>
<td>39.70%</td>
<td>749.5</td>
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<tr>
<td>T4</td>
<td>64.8</td>
<td>41.02</td>
<td>36.70%</td>
<td>170.8</td>
<td>34.3</td>
<td>47.10%</td>
<td>451</td>
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<tr>
<td>T8</td>
<td>125.6</td>
<td>80.29</td>
<td>36.10%</td>
<td>177.8</td>
<td>66.9</td>
<td>46.70%</td>
<td>745.4</td>
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<tr>
<td>T10</td>
<td>157.7</td>
<td>100.7</td>
<td>36.20%</td>
<td>231</td>
<td>85.8</td>
<td>45.60%</td>
<td>436.7</td>
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<tr>
<td>Mean</td>
<td>-</td>
<td>-</td>
<td>36.90%</td>
<td>200.1</td>
<td>-</td>
<td>44.80%</td>
<td>595.7</td>
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### r4 (90 Signal TSV locations)

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<th>Impr%</th>
<th>Time(s)</th>
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<td>31.68</td>
<td>18.63</td>
<td>41.20%</td>
<td>211.8</td>
<td>17.63</td>
<td>44.00%</td>
<td>890.6</td>
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<tr>
<td>T4</td>
<td>64.57</td>
<td>38.3</td>
<td>40.70%</td>
<td>232.2</td>
<td>30.1</td>
<td>53.40%</td>
<td>557.8</td>
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<tr>
<td>T8</td>
<td>126.8</td>
<td>75.38</td>
<td>40.60%</td>
<td>233.4</td>
<td>69.8</td>
<td>45.00%</td>
<td>707.5</td>
</tr>
<tr>
<td>T10</td>
<td>159.8</td>
<td>93.1</td>
<td>41.70%</td>
<td>327.6</td>
<td>80</td>
<td>50.10%</td>
<td>564.7</td>
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<tr>
<td>Mean</td>
<td>-</td>
<td>-</td>
<td>41.10%</td>
<td>251.2</td>
<td>-</td>
<td>48.10%</td>
<td>680.2</td>
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### r5 (90 Signal TSV locations)

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<th>Impr%</th>
<th>Time(s)</th>
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<tbody>
<tr>
<td>T2</td>
<td>35</td>
<td>21.5</td>
<td>38.60%</td>
<td>665.6</td>
<td>19.9</td>
<td>42.60%</td>
<td>1963</td>
</tr>
<tr>
<td>T4</td>
<td>68.4</td>
<td>39</td>
<td>43.00%</td>
<td>695</td>
<td>33.62</td>
<td>50.90%</td>
<td>1716</td>
</tr>
<tr>
<td>T8</td>
<td>131</td>
<td>77.9</td>
<td>40.50%</td>
<td>725.2</td>
<td>65.2</td>
<td>50.20%</td>
<td>1694</td>
</tr>
<tr>
<td>T10</td>
<td>164.1</td>
<td>97</td>
<td>40.90%</td>
<td>938.5</td>
<td>80.13</td>
<td>51.20%</td>
<td>1750</td>
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<tr>
<td>Mean</td>
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<td>-</td>
<td>40.80%</td>
<td>756.1</td>
<td>-</td>
<td>48.70%</td>
<td>1781</td>
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</table>

**Overall**

- 58.4% clock-skew reduction
- 11.6% higher clock-skew from non-linear model than linear model
Conclusions

- Physics-based electrical-thermal models for both signal and (dummy) thermal TSVs are provided with the consideration of nonlinear temperature dependence: liner is important to form a nonlinear CAP for delay

- One nonlinear programming problem is formulated to reduce clock-skew by dummy TSVs insertion for the thermal-reliable 3D clock-tree synthesis

- Under realistic nonlinear TSV models, insertion of dummy TSV can effectively reduce the clock-skew by 58.4% on average, which is also 11.6% higher clock-skew reduction on average than using the linear model
Electrical-Thermal-Stress-Coupling to 3D Clock

- Stress needs to be considered in 3D clock distribution network of surrounding transistors.
- Insertion of dummy TSVs reduce the chip temperature and improve the transistor carrier mobility.
## Experiment Results with Electrical-Thermal-Stress-Coupling

### Type

#### Htree1 (14 Signal TSVs)

<table>
<thead>
<tr>
<th>Type</th>
<th>orig</th>
<th>Lin</th>
<th>Impr%</th>
<th>Time</th>
<th>Non Lin</th>
<th>Impr%</th>
<th>Time</th>
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<td>15.39</td>
<td>9.54</td>
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<td>2.45</td>
<td>84.08%</td>
<td>76.15</td>
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<td>26.62</td>
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<td>69.68%</td>
<td>16.85</td>
<td>3.92</td>
<td>85.27%</td>
<td>77.11</td>
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<td>T8</td>
<td>47.41</td>
<td>11.38</td>
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<td>7.03</td>
<td>85.17%</td>
<td>77.19</td>
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<td>58.64</td>
<td>14.8</td>
<td>74.76%</td>
<td>17.22</td>
<td>10.02</td>
<td>82.91%</td>
<td>77.36</td>
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<td></td>
<td></td>
<td></td>
<td>64.61%</td>
<td>71.025</td>
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</table>

#### Htree2 (28 Signal TSVs)

<table>
<thead>
<tr>
<th>Type</th>
<th>orig</th>
<th>Lin</th>
<th>Impr%</th>
<th>Time</th>
<th>Non Lin</th>
<th>Impr%</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2</td>
<td>23.55</td>
<td>8.15</td>
<td>65.39%</td>
<td>17.41</td>
<td>3.31</td>
<td>85.94%</td>
<td>79.02</td>
</tr>
<tr>
<td>T4</td>
<td>44.13</td>
<td>11.61</td>
<td>73.69%</td>
<td>17.51</td>
<td>4.81</td>
<td>89.10%</td>
<td>79.59</td>
</tr>
<tr>
<td>T8</td>
<td>82</td>
<td>14.6</td>
<td>82.20%</td>
<td>17.4</td>
<td>9.02</td>
<td>89.02%</td>
<td>79.98</td>
</tr>
<tr>
<td>T10</td>
<td>103.7</td>
<td>15.5</td>
<td>85.05%</td>
<td>17.49</td>
<td>9.51</td>
<td>90.83%</td>
<td>79.32</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>76.58%</td>
<td>17.4525</td>
</tr>
</tbody>
</table>

#### r1 (45 Signal TSVs)

<table>
<thead>
<tr>
<th>Type</th>
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<th>Lin</th>
<th>Impr%</th>
<th>Time</th>
<th>Non Lin</th>
<th>Impr%</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2</td>
<td>30.5</td>
<td>17.4796</td>
<td>42.69</td>
<td>41.5</td>
<td>14.4612</td>
<td>52.59</td>
<td>127.2951</td>
</tr>
<tr>
<td>T4</td>
<td>61.87</td>
<td>32.6635</td>
<td>47.21</td>
<td>29.3</td>
<td>25.5463</td>
<td>58.71</td>
<td>164.0101</td>
</tr>
<tr>
<td>T8</td>
<td>121.1</td>
<td>66.137</td>
<td>45.39</td>
<td>31.9</td>
<td>53.1844</td>
<td>56.08</td>
<td>182.709</td>
</tr>
<tr>
<td>T10</td>
<td>152.7</td>
<td>83.557</td>
<td>45.28</td>
<td>37.2</td>
<td>69.1715</td>
<td>54.70</td>
<td>197.4859</td>
</tr>
<tr>
<td>Mean</td>
<td>-</td>
<td>-</td>
<td>45.14</td>
<td>34.975</td>
<td>55.52</td>
<td>167.875</td>
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</table>

#### r2 (60 Signal TSVs)

<table>
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<tr>
<th>Type</th>
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<th>Impr%</th>
<th>Time</th>
<th>Non Lin</th>
<th>Impr%</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2</td>
<td>35.13</td>
<td>23.48</td>
<td>33.16</td>
<td>134</td>
<td>19.3329</td>
<td>44.97</td>
<td>475.3568</td>
</tr>
<tr>
<td>T4</td>
<td>69.75</td>
<td>46.2756</td>
<td>33.66</td>
<td>102.8</td>
<td>34.1747</td>
<td>51.00</td>
<td>485.1885</td>
</tr>
<tr>
<td>T8</td>
<td>134.7</td>
<td>86.8894</td>
<td>35.49</td>
<td>106.5</td>
<td>71.0108</td>
<td>47.28</td>
<td>490.5759</td>
</tr>
<tr>
<td>T10</td>
<td>169</td>
<td>118.8894</td>
<td>29.65</td>
<td>139.3</td>
<td>88.0831</td>
<td>47.88</td>
<td>513.4299</td>
</tr>
<tr>
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<td>-</td>
<td>-</td>
<td>32.99</td>
<td>120.65</td>
<td>47.78</td>
<td>491.1378</td>
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</table>

#### r3 (75 Signal TSVs)

<table>
<thead>
<tr>
<th>Type</th>
<th>orig</th>
<th>Lin</th>
<th>Impr%</th>
<th>Time</th>
<th>Non Lin</th>
<th>Impr%</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2</td>
<td>32.36</td>
<td>20.1915</td>
<td>37.60</td>
<td>220.7</td>
<td>19.2129</td>
<td>40.63</td>
<td>751.53</td>
</tr>
<tr>
<td>T4</td>
<td>64.8</td>
<td>39.969</td>
<td>38.32</td>
<td>170.8</td>
<td>31.1747</td>
<td>51.89</td>
<td>682.8994</td>
</tr>
<tr>
<td>T8</td>
<td>125.6</td>
<td>79.8619</td>
<td>36.42</td>
<td>177.8</td>
<td>60.707</td>
<td>51.67</td>
<td>658.8006</td>
</tr>
<tr>
<td>T10</td>
<td>157.7</td>
<td>95.4677</td>
<td>39.46</td>
<td>231</td>
<td>82.7985</td>
<td>47.50</td>
<td>708.3861</td>
</tr>
<tr>
<td>Mean</td>
<td>-</td>
<td>-</td>
<td>37.95</td>
<td>200.075</td>
<td>37.95</td>
<td>47.92</td>
<td>700.404</td>
</tr>
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</table>

#### r4 (90 Signal TSVs)

<table>
<thead>
<tr>
<th>Type</th>
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<th>Lin</th>
<th>Impr%</th>
<th>Time</th>
<th>Non Lin</th>
<th>Impr%</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2</td>
<td>31.68</td>
<td>17.9695</td>
<td>43.28</td>
<td>211.8</td>
<td>16.5271</td>
<td>47.83</td>
<td>912.3927</td>
</tr>
<tr>
<td>T4</td>
<td>64.57</td>
<td>36.2087</td>
<td>43.92</td>
<td>232.2</td>
<td>26.1332</td>
<td>59.53</td>
<td>844.4599</td>
</tr>
<tr>
<td>T8</td>
<td>126.8</td>
<td>70.6158</td>
<td>44.31</td>
<td>233.4</td>
<td>64.4995</td>
<td>49.13</td>
<td>898.2112</td>
</tr>
<tr>
<td>T10</td>
<td>159.8</td>
<td>88.811</td>
<td>44.42</td>
<td>327.6</td>
<td>76.8253</td>
<td>51.92</td>
<td>909.2504</td>
</tr>
<tr>
<td>Mean</td>
<td>-</td>
<td>-</td>
<td>43.98</td>
<td>251.25</td>
<td>52.10</td>
<td>891.0786</td>
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</table>

#### r5 (90 Signal TSVs)

<table>
<thead>
<tr>
<th>Type</th>
<th>orig</th>
<th>Lin</th>
<th>Impr%</th>
<th>Time</th>
<th>Non Lin</th>
<th>Impr%</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2</td>
<td>35</td>
<td>21</td>
<td>40.00</td>
<td>665.6</td>
<td>18.9</td>
<td>46.00</td>
<td>1992.597</td>
</tr>
<tr>
<td>T4</td>
<td>68.4</td>
<td>38.4</td>
<td>43.86</td>
<td>695</td>
<td>28.5</td>
<td>58.33</td>
<td>1843.766</td>
</tr>
<tr>
<td>T8</td>
<td>131</td>
<td>74.6</td>
<td>43.05</td>
<td>725.2</td>
<td>63.8</td>
<td>51.30</td>
<td>1705.817</td>
</tr>
<tr>
<td>T10</td>
<td>164.1</td>
<td>93.4</td>
<td>43.08</td>
<td>938.5</td>
<td>79.434</td>
<td>51.59</td>
<td>1934.662</td>
</tr>
<tr>
<td>Mean</td>
<td>-</td>
<td>-</td>
<td>42.50</td>
<td>756.075</td>
<td>-</td>
<td>51.81</td>
<td>1869.21</td>
</tr>
</tbody>
</table>

| Overall | -    | -   | 49.10% | -      | -      | 61.30% |

- 61.3% clock-skew reduction
- 12.2% higher clock-skew from non-linear model than linear model
Thank You!

Please send comments to haoyu@ntu.edu.sg
http://www.ntucmosetgp.net