# FuzzRoute: A Method For Thermally Efficient Congestion Free Global Routing in 3D ICs

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# Motivation

- Global routing phase of VLSI Physical Design is becoming more challenging with ever increasing design complexity
- Large problem space leads global routing problem to NP Complete one
- Heuristic based approaches are generally used
- One preliminary approach using fuzzy logic for global routing was stated in [1, 2]

# Objective

- Propose a novel multi-objective global routing technique to offer a thermal aware and congestion free solution for global routing of interconnects in 3D ICs using a powerful soft computing technique viz. fuzzy logic

# Contribution

- An existing placement heuristic is modified to get an overlap free 3D placement
- After placement and prior to routing, a set of guiding information is generated, helps routing in subsequent steps
- During global routing, decision is taken from a Fuzzy Expert System

# Contribution

- FuzzRoute is capable of generating congestion free solution for all the ISPD '98 benchmarks
- The improvements on routing time for Labyrinth, BoxRouter 2.0, and FGR are 91.81%, 86.87%, and 32.16%, respectively
- Success of proposed approach has opened up an avenue for research in global routing phase

# A Bird's Eye View...

- Problem Description
- Proposed Solution
- Proposed Fuzzified Approach for Global Routing
- Experimental Result
- Time Complexity
- Conclusion
- Future Work

# Problem Description

- Concept of Thermal Sensitivity [3] and Congestion Ratio
- Fuzzification of Thermal Sensitivity and Congestion Ratio
- Fuzzification of Ineligibility Factor
- Grade of Membership Function

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  - Routing eligibility is inversely proportional to these factors

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  - All variables vary within [0,1]
  - Belongs to premise part
  - Six fuzzy sets from two linguistic variables

# Problem Description

- Derived Fuzzy Sets from Linguistic Variables in Premise Part

| | |
|---|---|
| Thermal Sensitivity Ratio | Weakly Sensitive(WS)<br>Moderately Sensitive(MS)<br>Highly Sensitive(HS) |
| Congestion Ratio | Weakly Congested(WC)<br>Moderately Congested(MC)<br>Highly Congested(HC) |

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# Problem Description

- Fuzzification of Ineligibility Factor
  - One linguistic variable: Ineligibility Criteria ($\mu_r$)
  - Vary within [0,1]
  - Belongs to consequent part
  - Number of fuzzy sets: 9 fuzzy sets
  - Boundary values for all fuzzy sets are generated during guiding information generation
    - $\mu_r = \frac{(\alpha \times s_r + \beta \times o_r)}{(\alpha + \beta)}$ where, $\alpha + \beta = 1$.

# Problem Description

- Grade of Membership Function

$$\begin{aligned}
\mu_{ch} &= 0 && \text{for } x < l_3 \\
&= 1 && \text{for } x \geq l_4 \\
&= (x - l_3)/(l_4 - l_3) && \text{for } l_3 < x < l_4
\end{aligned}$$

$$\begin{aligned}
\mu_{cm} &= 0 && \text{for } x < l_1 \;\&\; x > l_4 \\
&= 1 && \text{for } l_2 \leq x \leq l_3 \\
&= (x - l_1)/(l_2 - l_1) && \text{for } l_1 < x < l_2 \\
&= (l_4 - x)/(l_4 - l_3) && \text{for } l_3 < x < l_4
\end{aligned}$$

$$\begin{aligned}
\mu_{cw} &= 0 && \text{for } x > l_2 \\
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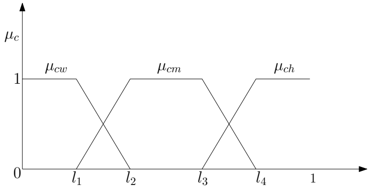
- Graph Corresponding to the Grade of Membership Functions



# Proposed Solution

- 3D Integration Structure
- Modified 3D Placement Procedure
- Pre-routing Information Generation
  - Proposed Rule Base
  - Proposed Fuzzy Expert System

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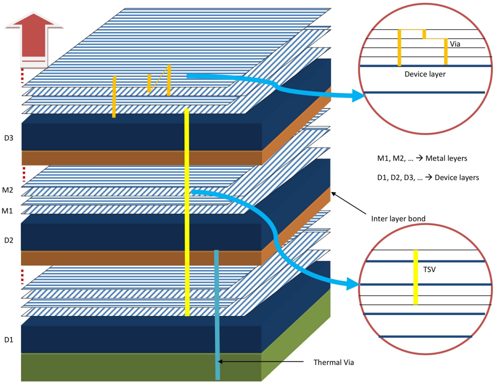
- 3D Integration Structure



# Proposed Solution

- Modified 3D Placement Procedure
  - Proper 3D placement benchmarks are unavailable till now
  - Heuristic proposed in [4, 5] is modified to get 100 % overlap eliminated placement
  - Non-overlapping placement structure in 3D is got

# Proposed Solution

- Pre-routing Information Generation
  - Proposed Rule Base

| | |
|---|---|
| 1. | If $s_r$ is WS and $o_r$ is WC then $\mu_r$ is $1^{st} I$ |
| 2. | If $s_r$ is WS and $o_r$ is MC then $\mu_r$ is $2^{nd} I$ |
| 3. | If $s_r$ is WS and $o_r$ is HC then $\mu_r$ is $3^{rd} I$ |
| 4. | If $s_r$ is MS and $o_r$ is WC then $\mu_r$ is $4^{th} I$ |
| 5. | If $s_r$ is MS and $o_r$ is MC then $\mu_r$ is $5^{th} I$ |
| 6. | If $s_r$ is MS and $o_r$ is HC then $\mu_r$ is $6^{th} I$ |
| 7. | If $s_r$ is HS and $o_r$ is WC then $\mu_r$ is $7^{th} I$ |
| 8. | If $s_r$ is HS and $o_r$ is MC then $\mu_r$ is $8^{th} I$ |
| 9. | If $s_r$ is HS and $o_r$ is HC then $\mu_r$ is $9^{th} I$ |

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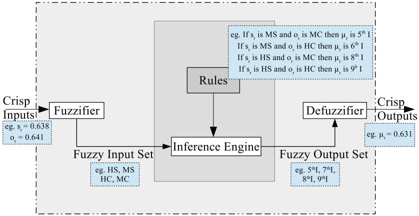
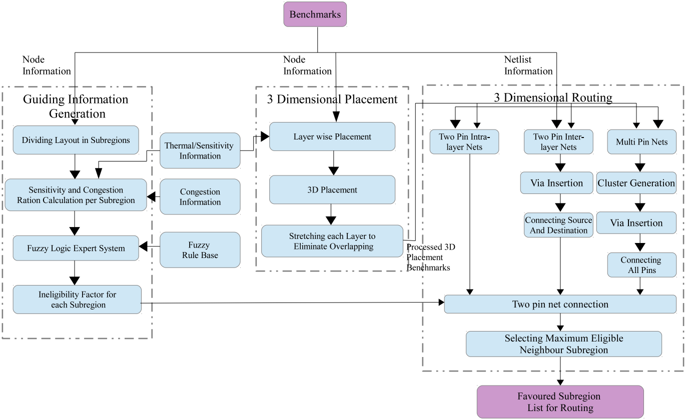
  - Proposed Fuzzy Expert System



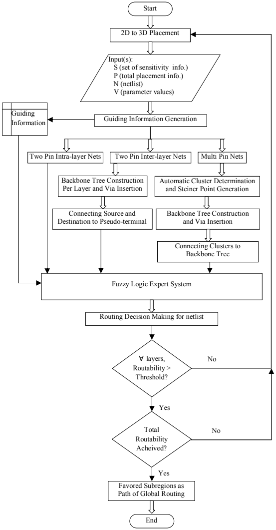
# Proposed Fuzzified Approach for Global Routing

- Overall Scheme



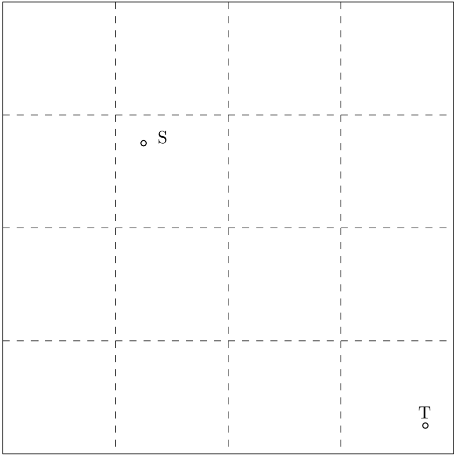
# Proposed Fuzzified Approach for Global Routing

- Overall Flow of Routing Procedure



# Proposed Fuzzified Approach for Global Routing

- A Scenario of Fuzzified Intra-layer Global Routing from Source to Destination



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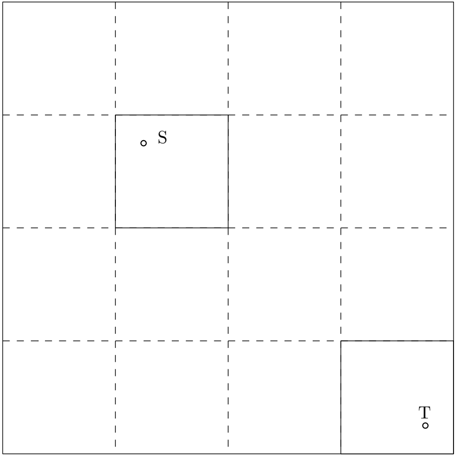

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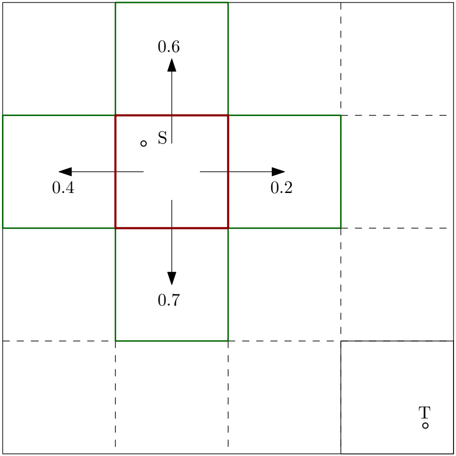

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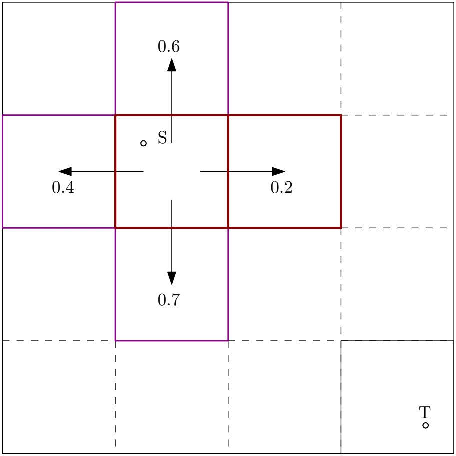

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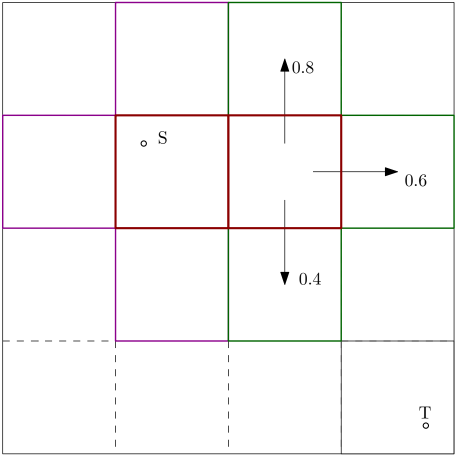

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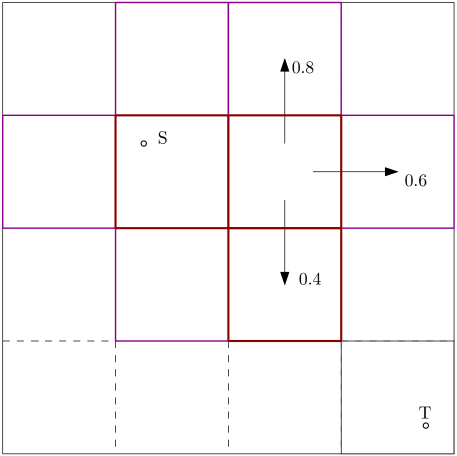

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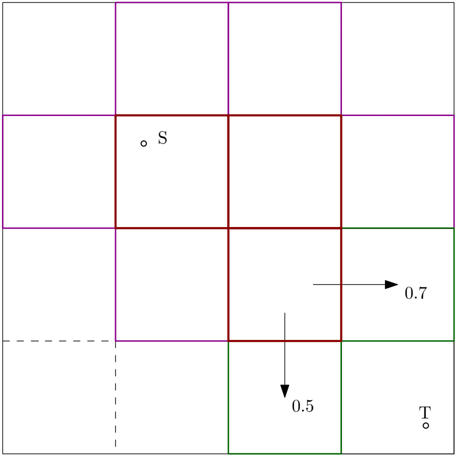

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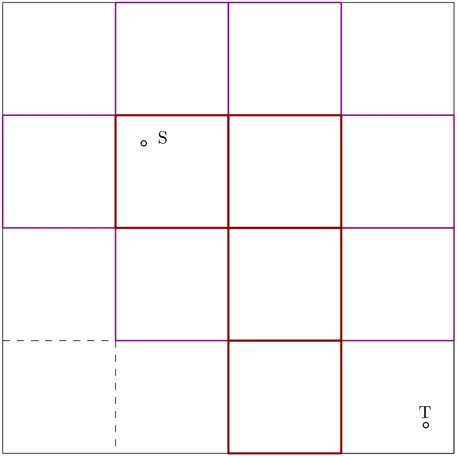

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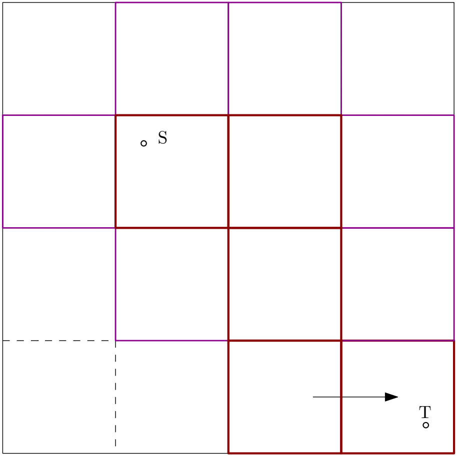

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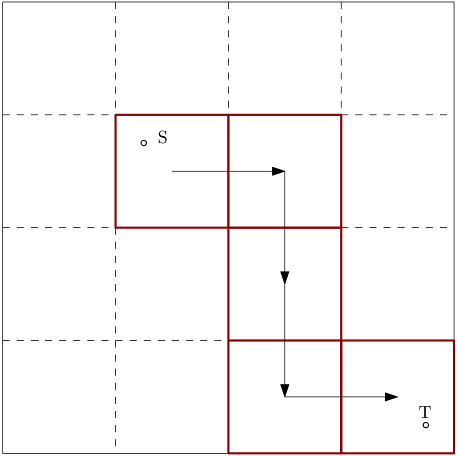
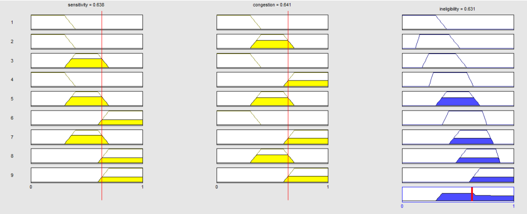


# Experimental Result

- Framework :
  - Software and Language: C, Java and MATLAB 7.14.0, MCR, and MATLAB Builder JA
  - Configuration: Intel chip @2.30 GHz
  - Benchmarks: ISPD'98[6] (IBM-PLACE 2.0)

# Experimental Result

- Fuzzification and Defuzzification with respect to Rule Base



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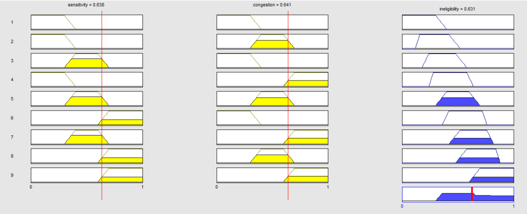
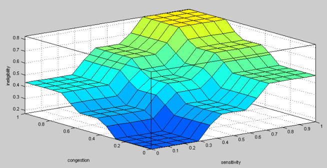
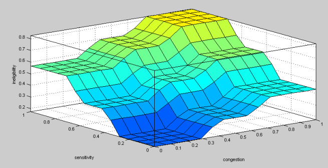



- Change of Ineligibility Factor with Sensitivity and Congestion Ratio



# Experimental Result

- Experimental Benchmark Statistics

| Benchmark | # Net | # Layer | Guiding Info Gen Time(s) | Routing Time(s) |
|---|---|---|---|---|
| ibm01 | 11507 | 4 | 85.0 | 3.0 |
| | | 6 | 36.0 | 3.0 |
| ibm02 | 18429 | 4 | 121.0 | 6.0 |
| | | 6 | 85.0 | 4.0 |
| ibm07 | 44394 | 6 | 247.0 | 22.0 |
| | | 8 | 220.0 | 20.0 |
| ibm08 | 47944 | 6 | 307.0 | 26.0 |
| | | 8 | 297.0 | 21.0 |
| ibm09 | 50393 | 6 | 294.0 | 28.0 |
| | | 8 | 278.0 | 22.0 |
| ibm10 | 64227 | 6 | 485.0 | 33.0 |
| | | 8 | 472.0 | 32.0 |
| ibm11 | 67016 | 6 | 372.0 | 74.0 |
| | | 8 | 367.0 | 57.0 |
| ibm12 | 67739 | 6 | 605.0 | 120.0 |
| | | 8 | 582.0 | 96.0 |

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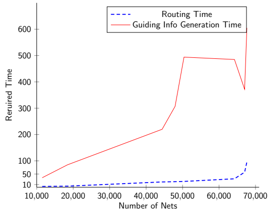
- Variation of Guiding Information Generation Time and Routing Time for Different ISPD '98 Benchmark Circuits with Layer Number = 6



# Experimental Result

- Layer wise Statistics for ibm10 Benchmark Circuit

| #Layers | Guiding Info Gen Time(s) | Routing Time(s) |
|---|---|---|
| 3 | 547.0 | 54.0 |
| 4 | 519.0 | 42.0 |
| 5 | 489.0 | 35.0 |
| 6 | 485.0 | 33.0 |
| 7 | 480.0 | 32.0 |
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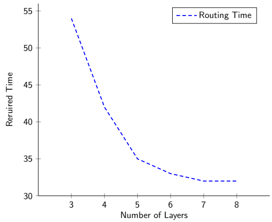
- Variation of Routing Time with Available Number of Layers for ibm10 Benchmark Circuit



# Experimental Result

- Comparison Between Published Global Routers and FuzzRoute on ISPD '98 Benchmark

| Benchmark | Labyrinth | | FastRoute3.0 | | NTHU-R | | BoxRoute 2.0 | | FGR | | FuzzRoute (**This Paper**) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | wlen | cpu(s) | wlen | cpu(s) | wlen | cpu(s) | wlen | cpu(s) | wlen | cpu(s) | wlen | cpu(s) |
| ibm01 | 77K | 21.2 | 64221 | 0.64 | 63321 | 4.17 | 62659 | 33 | 63332 | 10 | 46276 | 3.0 |
| ibm02 | 205K | 34.5 | 172223 | 0.85 | 170531 | 7.44 | 171110 | 36 | 168918 | 13 | 166922 | 4.0 |
| ibm07 | 449K | 228.1 | 369023 | 1.68 | 366288 | 15.89 | 365790 | 86 | 366180 | 18 | 357121 | 22.0 |
| ibm08 | 470K | 238.7 | 405935 | 1.82 | 405169 | 13.17 | 405634 | 90 | 404714 | 18 | 382855 | 26.0 |
| ibm09 | 481K | 505 | 414913 | 1.67 | 415464 | 11.59 | 413862 | 273 | 413053 | 20 | 403647 | 28.0 |
| ibm10 | 680K | 588 | 582838 | 3.61 | 580793 | 33.72 | 590141 | 352 | 578795 | 92 | 595465 | 33.0 |
| Total | 2362K | 1615.5 | 2010K | 10.27 | 2001K | 85.98 | 2009K | 870 | 1993K | 171 | 1952K | 116.0 |
| Norm | 1.21 | 13.92 | 1.03 | 0.088 | 1.03 | .74 | 1.03 | 7.5 | 1.02 | 1.474 | 1 | 1 |

# Time Complexity

- Time Complexity for Generating the Guiding Information is $O(l \times m \times n)$, where
  - $l$ = total number of layers
  - $m$ = number of subregions in $x$ direction
  - $n$ = number of subregions in $y$ direction of the layout

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  - $l =$ total number of layers
  - $m =$ number of subregions in $x$ direction
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- Time Complexity for Routing = Time Complexity for Generating the Guiding Information + Time Required to Process Fuzzy Expert System for Each Layer

# Conclusion

- Pioneering approach for global routing using fuzzy logic for standard cells
- Achieving a prominent degree of reliability and routability with a reasonable time complexity
- Successfully verified for all intra, and inter-layer nets for 3D ICs
- Tested on ISPD'98 benchmark suites and compared with some well known global routers
- Opened up an avenue for research in global routing phase

# Future Work

- Design of a Foolproof Global Router for 3D ICs Considering Other Metrics(like parasitic effect)
- Further Comparison with Recent ICCAD 2009, ISPD 2011 and ISPD 2014 Benchmarks
- Extension to Mixed Sized Cell Placements

# Reference I


[1] D. Roy and P. Ghosal. "A fuzzified approach towards global routing in VLSI layout design". In: *Fuzzy Systems (FUZZ), 2013 IEEE International Conference on*. 2013, pp. 1–8. DOI: 10.1109/FUZZ-IEEE.2013.6622477.

[2] D. Roy, P. Ghosal, and N. Das. "A thermal and congestion driven global router for 3D integrated circuits". In: *Students' Technology Symposium (TechSym), 2014 IEEE*. 2014, pp. 303–308. DOI: 10.1109/TechSym.2014.6808065.

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# Any Question???

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# Thank You!!!