FuzzRoute: A Thermally Efficient Congestion Free Global Routing Method for Three Dimensional Integrated Circuits

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The high density of interconnects, closer proximity of modules, and routing phase are pivotal during the layout of a performance centric three dimensional integrated circuit (3D IC). Heuristic based approaches are typically used to handle such NP complete problems of global routing in 3D ICs. To overcome the inherent limitations of deterministic approaches a novel methodology for multi-objective global routing based on fuzzy logic has been proposed in this paper. The guiding information generated after the placement phase is used during routing with the help of a Fuzzy Expert System to achieve thermally efficient and congestion free routing. A complete global routing solution is designed based on the proposed algorithms and the results are compared with selected fully-established global routers viz. Labyrinth, FastRoute3.0, NTHU-R, BoxRouter 2.0, FGR, NTHU-Route2.0, FastRoute4.0, NCTU-GR, MGR, and NCTU-GR2.0. Experiments are performed over ISPD 1998 and 2008 benchmarks. The proposed router called *FuzzRoute* achieves balanced superiority in terms of routability, runtime, and wirelength over others. The improvements on routing time for Labyrinth, BoxRouter 2.0, and FGR are 91.81%, 86.87%, and 32.16%, respectively for ISPD 1998 benchmarks. It may be noted that though FastRoute3.0 achieves fastest runtime, it fails to generate congestion free solutions for all benchmarks, which is overcome by the proposed FuzzRoute of the current paper. It also shows wirelength improvements of 17.35%, 2.88%, 2.44%, 2.83%, and 2.10% respectively over others for ISPD 1998 benchmarks. For ISPD 2008 benchmark circuits it also provides 2.5%, 2.6%, 1 %, 1.1%, and 0.3% lesser wirelength and averagely runs 1.68×, 6.42×, 2.21×, 0.76×, and 1.54× faster than NTHU-Route2.0, FastRoute4.0, NCTU-GR, MGR, and NCTU-GR2.0 respectively.

Categories and Subject Descriptors: B.7.2 [**Integrated Circuits**]: Design Aids—*Placement and Routing*

General Terms: Design, Algorithms, Performance, Experimentation

Additional Key Words and Phrases: VLSI Layout Design, Global Routing, Fuzzy Expert System, Fuzzified Global Routing

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1. INTRODUCTION

Nanoscale technology permits us to integrate systems with billions of transistors on a single chip. Layout design plays a pivotal role in the design cycle by transforming the circuit description into geometric description. Recent researches on global routing are aimed at optimization of different multi objective functions related to performance and congestion, thermal issues, proper insertion of thermal

One initial work of this approach has been reported in IEEE CS Annual Symposium on VLSI, 2014 in regular paper category [Roy et al. 2014b].

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vias [Goplen and Sapatnekar 2005], sensitivity, wire length, critical paths or crosstalk [Minz et al. 2005] etc. Consideration of net ordering problem in OTC (over the cell) routing is a big challenge to reach a polynomial time solution. Some other metaheuristics like Simulated Annealing, Genetic Algorithm etc based approaches are also influencing modern trends. But to the best of our knowledge no existing complete fuzzified method for global routing (proven to be an improved way out to the problems with deterministic approaches) is reported for large scale problem in global routing of three dimensional integrated circuits.

1.1. Global Routing: Trade-offs and Challenges

Global routing plays a very important role in VLSI physical design to achieve a faster response from any integrated circuits. Approximate connection paths among the nodes of any net are determined here that leads global routing problem to be an NP Complete one. An optimal connectivity for a circuit depends on several constrains imposed during global routing step and thereby specifying a special performance feature of that IC.

Addition of third dimension has allowed researchers to enrich performance of ICs in a better degree but have made the problem of global routing more complex. Consideration of third dimension during routing decision making is a witty and complex measure to perform in every global routing algorithm. One basic structure of 3 dimensional global routing has been demonstrated pictorially in Figure1.

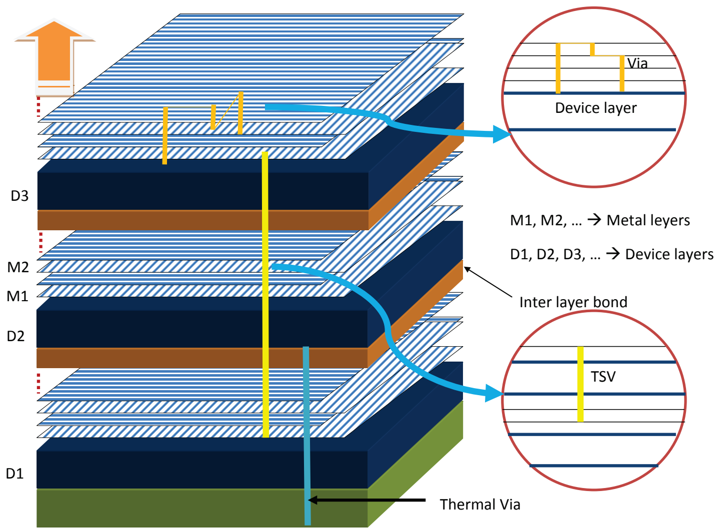


Fig. 1: 3D Integration structure.

1.2. Fuzzy Logic and FLC

Fuzzy logic is a form of multi-valued logic or probabilistic logic, that deals with approximate reasoning rather than fixed and exact. In contrast to traditional Crisp logic [True/False] they can have varying values, that ranges in degree between 0 and 1.

Linguistic variables are the input or output variables of the system whose values are words or sentences from a natural language instead of numerical values. A membership function is used to quantify a linguistic term and used in fuzzification and defuzzification procedure.

A fuzzy logic control(FLC) system may be defined as the nonlinear mapping of an input data set to a scalar output data. A FLC consists of four main parts: (a)fuzzifier, (b)rules, (c)inference engine, and (d)defuzzifier. These components and the general architecture of a FLC is shown in Figure 2.

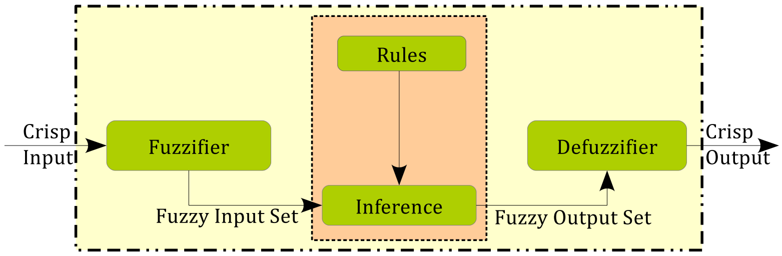


Fig. 2: A Fuzzy logic expert system.

The process of fuzzy logic is explained in Figure 3. Firstly, a crisp set of input data are gathered and converted to a fuzzy set using fuzzy linguistic variables, fuzzy linguistic terms, and membership functions. This step is known as fuzzification. Afterwards, an inference is made based on a set of rules. Lastly, the resulting fuzzy output is mapped to a crisp output using the membership functions, in defuzzification step.

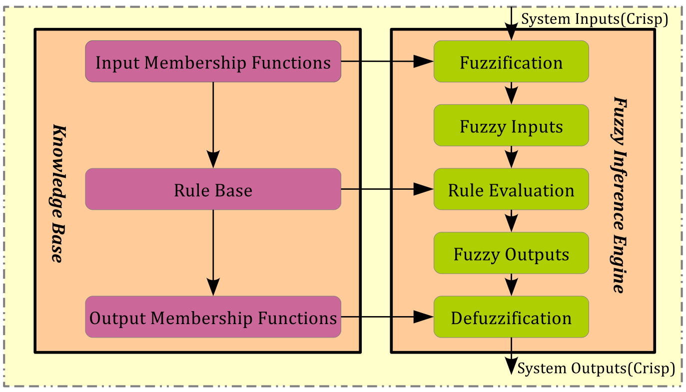


Fig. 3: A Fuzzy logic expert system.

During past decade, fuzzy logic control [Zadeh 1973] is being considered as one of the most promising research area in the application of industrial process control to medical diagnosis and securities trading [Pedryz and Gomide 2007],[Lughofer 2011]. The main idea behind FLC is to incorporate the *expert experience* of a human interface in designing a controller. Several possible ways of FLC implementation are demonstrated in [Abonyi 2003] and [Babuska 1998].

Rest of the paper is organized as follows. Section 2 summarizes the novelties of proposed work followed by section 3 providing current state-of-art and motivation behind this work. In section 4 formulation of overall problem is presented. Description of approaches for pre-routing guiding information generation and proposed fuzzy logic expert system is inscribed in section 5. The proposed heuristic for 3 dimensional routing has been explained in section 6. Next, overall proposed routing scheme has been presented in a glimpse in section 7. Proposed solution approach for fuzzified global routing for all the three categorized type of nets (may be considered as the backbone of this work) are covered in section 8. Experimental results like feasibility study for global routing model and various types of comparison study for complete fuzzified global router are given in section 9. Section 10 concludes the paper by giving important extensions and directions of our initiative.

2. NOVEL CONTRIBUTIONS OF THE CURRENT PAPER

A complete fuzzified global router is reported using the fuzzy logic concept for routing all the nets in a netlist in this article. Novelties of this approach lies in many folds including providing the solution within a feasible time, and with a better degree of reliability. Standard cell based design style is used for testing with benchmark circuits. However the proposed method can easily be extended to mixed cell design also.

An efficient fuzzified expert system has been designed for thermal, and congestion aware global routing in routing space for fully 3D IC structure. The concept of thermal sensitivity is adapted from [Ghosal et al. 2008]. This article corroborates the overall models and procedures of proposed fuzzified global routing in 3 dimensional space. To the best of our knowledge, proposed fuzzified approach for multi-pin global routing in 3D ICs is the first of its kind. The novelties are enlisted below to provide an overview of contributions.

— **Non-deterministic:** It provides a way out from the standard deterministic or heuristic based approaches to overcome their inherent limitations to handle complex design problems.
— **P solution to NP:** Proposed approach ensures in getting a polynomial time solution for this NP complete problem. Time complexity analysis of proposed algorithms has been reported in Section 9.7.
— **Exhibiting feasibility:** Depending upon the nature of complexity and size of problem, it is validated to provide a feasible fuzzified global routing model between a source and destination. The overall feasibility analysis with fuzzy expert system has been presented in Section 9.2.
— **Dynamic and Portable:** It ensures consideration of dynamic fuzzy expert system and making it portable for all circuits. The fuzzy expert system works dynamically by applying different boundary values for different fuzzy sets depending upon input benchmark circuit. Details has been depicted lucidly in Section 5.3 and 5.6.
— **Superiority:** Getting better result with respect to time and reliability than the other established global routers. Comparison with some of those has been provided in Table IV and V in Section 9.5.
— **Robust and Extensible:** It exhibits the robustness property by providing comparable results with varying parameter's values. Table II in Section 9.4 presents comparable results for different sets of parameter values. Due to the property of Fuzzy Logic based multiobjective optimization formulation used in this work the proposed tool is also open and extensible to handle more number of constraints with the primary constraints viz. thermal, and congestion, used in this work. It may be easily achieved by simply tweaking the formulation of the problem by incorporating other parameters.
— **Adaptability:** It exhibits good adaptive property by one proposed obstacle avoidance mechanism. The scheme has been described lucidly in Section 8.4.
— **Completeness:** The sequence of global routing path in terms of subregions is generated for all two-pin and multi-pin intra as well as inter layer nets in netlist. Extensive analysis on recent ISPD 1998 and 2008 benchmarks is presented in Section9.3 as validation of the proposed technique.

3. STATE-OF-THE-ART AND MOTIVATION

3.1. Some Existing Global Routing Techniques

In high-performance VLSI circuits, the on-chip power densities are playing dominant role due to increased scaling of technology, increasing number of components, frequency and bandwidth. Consumed power, usually converted into dissipated heat affects the performance and reliability of a chip. Generation of hot spots is a critical issue in the VLSI physical design phase. Several researches those have been reported in [Zhang et al. 2006], [Zhang et al. 2005], [Ghosal et al. 2009], [Ghosal et al. 2010c],[Ghosal et al. 2010b],[Ghosal et al. 2010a], [Ghosal et al. 2010d] have experimented on thermal aware placement, and routing for 2D as well as 3D integrated circuits. Pathak et. al. [Pathak and Lim 2009] have presented a novel algorithm on 3D Steiner routing by NLP based approach for thermal aware global routing in 3D stacked ICs. The complexity of Steiner tree based approach becomes very high with multi net.

In [Kastner et al. 2002], a concept of pattern routing was developed to guide subsequent maze routing. A global routing was proposed in [Zhang et al. 2008], where a fast maze routing was presented by introducing virtual capacity concept. A history based cost function driven multi-source and multi-sink maze routing was proposed in [Gao et al. 2008] and negotiated-congestion routing was proposed in[Roy and Markov 2008]. Bounded maze routing concept was used in [Dai et al. 2012] and [Liu et al. 2013] for 3D global routing to achieve significant wirelength and congestion on most recent benchmarks.

In case of inter-die routing, one ILP based technique has been introduced by Chang et al. [Chang et al. 2011]. Similarly, Integer Programming based approach was proposed by Wu et al. [Wu et al. 2009]. Their proposed approach optimizes wire length and via cost without going through a layer assignment phase. In [Cho et al. 2009] 2D to 3D mapping was done by the layer assignment which is powered by progressive via or blockage-aware integer linear programming. All these are global routing approaches in three dimensional space. In [Das et al. 2003] Das et al. has designed some routing and placement specific tools for 3D ICs.

Among different global routers reported so far [Chang et al. 2011], [Wu et al. 2009] optimize wire length and via cost without going through a layer assignment phase unlike [Cho et al. 2009]. Several other global routers were proposed in [Zhang et al. 2008],[Gao et al. 2008],[Roy and Markov 2008]. Recent global routing benchmarks like ICCAD 2009 [Moffitt 2009], and ISPD 2008[Nam et al. 2008], 2011 [Viswanathan et al. 2011] consider only 3D situation for metal layers. Multiple device layer i.e. fully 3D strategy is not been replicated in any benchmark till now.

3.2. Thermal Issues: Its Impact and Modeling

Localized region of high heat flux, called as hot spots, are becoming significant with increased scaling of process technology along with increase in total power dissipation. Problem is much severe in case of three dimensional integrated circuits due to the close proximity of neighboring modules. The temperature of hot spots are generally above average die temperature. Uniformity of power dissipation is quite desirable to achieve certain optimized chip performance. In some recent works like [Ghosal et al. 2008], [Ghosal et al. 2010c], [Ghosal et al. 2010d] authors have expressed their concern over this issue to achieve an optimized thermal aware placement in 3D ICs.

Thermal issues have always been an increasingly big concern throughout the layout design of 3D ICs. Recent researches like [Gupta et al. 2008], [Lu and Pan 2009] shows its present importance during routing. In [Gupta et al. 2008] authors have proposed one thermal aware global routing technique to reduce the probability of failure of chips due to interconnect failures, by routing more wires in the colder regions of chip and less wires in the hotter regions of chip. Next a reliability-aware global routing with thermal considerations has been reported in [Lu and Pan 2009] to reduce the probability of interconnect failures by thermal-driven Minimum Spanning Tree construction and thermal-driven maze routing. Some thermal aware placement techniques and models are also described later.

Voltage drop is another issue to affect the thermal profile of the chip though it has not been considered during the present formulation. As its impact is strongly correlated with thermal effects it may be taken into account into future works.

3.3. Application Specific Fuzzy Logic Implementation

Fuzzy systems has been an attract point of several researchers for the past decade due to its property as an universal approximator [Wang 1992], [Castro and Delgado 1996]. Application of fuzzy logic is being implemented extensively in diverse fields like medical [Kanthi et al. 2013], frequency control [Sabahi et al. 2014], vehicle path planning [Huang et al. 2014] etc. Sait et al had proposed a fuzzy simulated evaluation algorithm for placement in [Sait and Ali 1999]. One source-destination only fuzzified global routing model for VLSI layout designing has been reported in [Roy and Ghosal 2013]. A 2-pin only global router has also been presented in [Roy et al. 2014a]. But no such notable contribution has been found to apply fuzzy logic in designing a complete global router for 3D ICs, which is able to route an entire netlist consisting of two / multi-pin intra / inter-layer nets as well as critical nets.

3.4. Scope and Relevance of Present Work

In modern era the design complexity of different problems are increasing in exponential order. Due to very large problem size such problems are seemed to be unsolvable in feasible time even by some heuristics also. So taking decision only in a deterministic way leads the complexity of problem to NP Completeness. Global routing is also facing such problem recently. In proposed approach, we have tried to achieve a degree of reliability for each solution of global routing. Since fuzzy systems have already recognized as universal approximator, it is used to formulate our pioneering work. In fuzzified approach the search space is decreased for a particular solution, so the time and design complexity. This is possible only for global routing. Because detailed routing is not so far applicable as fine tuning is necessary there and can only be done in a deterministic way.

As the presently proposed technique was not motivated by any subtle shortcoming of a particular established global router so initial thrust was given on the feasibility study of the proposed method and to identify and establish its applicability thereby. The total algorithm has been first preferred to implement over a widely accepted benchmark suite (ISPD 1998 [Alpert 1998] and ISPD 2008[Nam et al. 2008]).

Here thermal optimization has been done during placement phase by an efficient thermal placer with certain necessary modifications introduced. Based upon the model and depending upon the thermal influence of each module over the overall thermal profile of the entire layout area the modules have been categorized in three different classes [Ghosal et al. 2008]. Thermal sensitivity of a module is defined as its effect towards the overall thermal scenario. When the circuit is in operation i.e. during dynamic scenario as the switching occurs then depending upon the nature of variation thermal sensitivity measures how much a module is responsible to change overall thermal profile of the chip. Depending on the amount of effect the modules are classified in three different classes of sensitivity. These three classes of modules viz. Strongly or Highly Sensitive, Moderately Sensitive, and Weakly Sensitive, obtained by this thermal sensitivity analysis have been used in the next phase of layout i.e. routing as a guiding factor. By this way an intelligent technique has been developed to route the nets avoiding hot spots and thermally sensitive areas. Here no "thermal via" or "thermal wire" insertion has been considered.

4. PROBLEM FORMULATION FOR FUZZIFIED GLOBAL ROUTER

4.1. Description of Problem

Let $P = \{p_1, p_2, p_3, ..., p_k\}$ be a set of pins of k pin net distributed across L layers
$L =$ Number of layers available
Let $M = \{m_1, m_2, m_3, ..., m_r\}$ be a set of modules spread over the routing layer where, (x_i, y_i) are the bottom left coordinates of module m_i.
Thermal Sensitivity (SI) of a module is in the range of 0 to 1.
Congestion ratio (CR) for each module is in the range of 0 to 1.
α, β are two cost factor coefficients, where $\alpha + \beta = 1$.
Weighted cost factor is generated from the thermal sensitivity and congestion ratio information incorporated with the α and β values.

4.2. Geometrical Description with Example

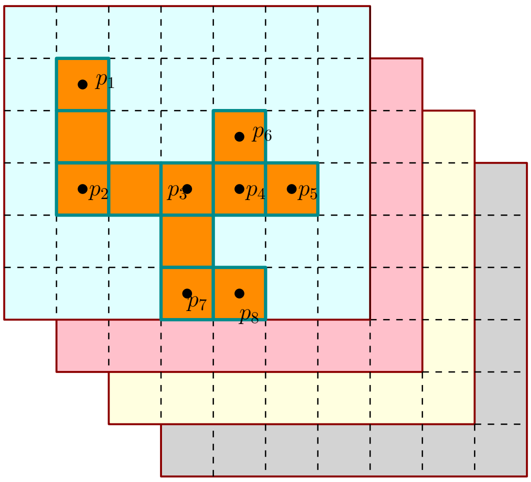


Fig. 4: Geometrical description of problem statement.

Standard cell based design style has been used for the implementation. So, the total routing layer is represented as a grid structure. The routing layout is devided in subregions, where each subregion is composed of certain grids. One subregion is the main routing unit here. In Figure 4, one net is shown on one device layer. Here, P=$\{p_1, p_2, p_3, p_4, p_5, p_6, p_7, p_8\}$. So, that multi-pin net is spread over eight modules those are darkened in that figure. Routing path needs to be determined for M depending on α, and β values and some constraints.

4.3. Definition and Formulation of Weighted Cost Factor

Thermal sensitivity and congestion are two considered constraints. Probability of getting selected as next followed subregion is determined by routing eligibility for each subregion. The relationship between routing eligibility and two constraints is represented by a weighted cost factor viz. Ineligibility Factor (IF).

Ineligibility Factor is inversely proportional to routing eligibility. Formulation of IF may be represented as a standard minimization problem as stated in 1.

$$\begin{aligned} \text{minimize} \quad & IF = SI \times \alpha + CR \times \beta \\ \text{subject to} \quad & \alpha + \beta = 1 \\ & 1 \geq \alpha, \beta \geq 0 \\ & 1 \geq SI \geq 0 \\ & 1 \geq CR \geq 0 \end{aligned} \tag{1}$$

4.4. Objective

To build a fuzzified global router able to route by determining the routing region with minimum wire-length for the total netlist depending upon the weighted cost function maintaining two constraints viz. thermal sensitivity, and congestion ratio for each net.

5. APPROACH FOR PRE-ROUTING INFORMATION GENERATION

Proposed routing procedure is a fuzzified approach to find one in between solution of deterministic and heuristic based approach. Prior to routing step, some pre-routing information are being generated that will help in subsequent routing steps. One main purpose of these globally routed paths will be to avoid the more heated and congested portion of layout. This constraint based approach takes decision during routing procedure from some pre-routing guiding information. Those guiding information are generated from a proposed fuzzy expert system and rule base. Every fuzzy expert system have two parts: (a) Premise i.e. the input part and (b) Consequent i.e. the output part. Different definition and assignment of fuzzy terms and guiding information generation procedure is been described below.

5.1. Linguistic Variables: Thermal Sensitivity and Congestion Ratio

Unlike numerical variables that take numerical values, linguistic variables take linguistic values. In any fuzzy based logic recognizing proper linguistic variables plays an important role. In this fuzzified global routing procedure thermal sensitivity and congestion ratio are two linguistic variables in premise part. Ineligibility factor (IF) is the only linguistic variable in consequent part. Here, the linguistic values to be taken are: (a) High (b) Moderate and (c) Weak for premise part.

5.2. Fuzzification of Thermal Sensitivity, Congestion Ratio and Ineligibility Factor

In fuzzy logic concept, linguistic variables vary within [0,1]. Here all derived fuzzy sets from three linguistic variables in both premise and consequent part are shown in Figure 5.

In consequent part, total 9 fuzzy sets are present. Only one rule base is sufficient for this purpose. For the rule base, there are total 9 i.e. all possible fuzzy sets($i^{th} I$, where, $i = 1 \ldots 9$) for this particular linguistic variable, is used.

5.3. Grade of Membership Function

The membership function is the characteristic function for fuzzy sets. In this proposed global routing procedure, overlapping trapezoidal nature is best suited because a moderately sensitive information with higher grade of membership value may also be considered as a highly sensitive information with a lesser grade of membership value. Gaussian function is not well fitted here because of its different response at each point and only one maximum response. But, our problem specification of having a particular response over a range.

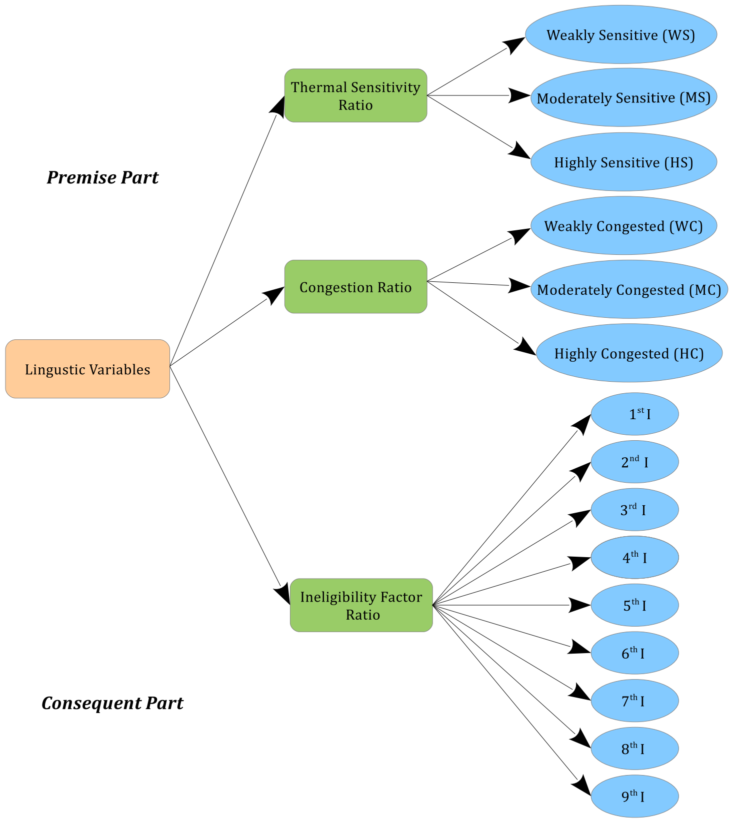


Fig. 5: Derived fuzzy sets from linguistic variables.

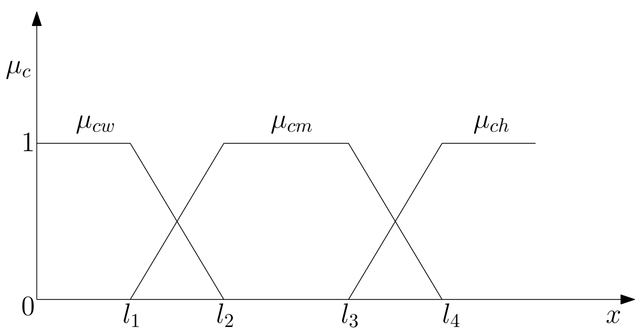


Fig. 6: The graph corresponding to the grade of membership values for sensitivity and congestion ratio.

The grade of membership values for three fuzzy sets corresponding to a linguistic variable of premise part will be according to equation 2, 3, and 4.

$$\begin{aligned}\mu_{ch} &= 0 && for\, x < l_3 \\ &= 1 && for\, l_4 \leq x \leq 1 \\ &= (x - l_3)/(l_4 - l_3) && for\, l_3 < x < l_4\end{aligned} \tag{2}$$

$$\begin{aligned}\mu_{cm} &= 0 && for\, x < l_1 \;\&\; x > l_4 \\ &= 1 && for\, l_2 \leq x \leq l_3 \\ &= (x - l_1)/(l_2 - l_1) && for\, l_1 < x < l_2 \\ &= (l_4 - x)/(l_4 - l_3) && for\, l_3 < x < l_4\end{aligned} \tag{3}$$

$$\begin{aligned}\mu_{cw} &= 0 && for\, x > l_2 \\ &= 1 && for\, 0 \leq x \leq l_1 \\ &= (l_2 - x)/(l_2 - l_1) && for\, l_1 < x < l_2\end{aligned} \tag{4}$$

The different boundary values l_1, l_2, l_3, l_4 in equation 2, 3, and 4 are dynamic for premise part and are generated in guiding information generation algorithm. The step by step procedure for determining l_1, l_2, l_3, l_4 for thermal sensitivity and congestion information are stated in Section 5.4.1. Similarly, for consequent part, total nine trapezoids are there in between [0,1] range and boundary values of each are also dynamically generated depending upon proposed rule base (described later).

5.4. Guiding Information Generation

The fuzzified global routing approach bifurcated in guiding information generation and main routing procedure. First part corresponds to generation of relevant information regarding to a specific unit of layout called subregion and generating a fuzzy expert system. The overall procedure of guiding information generation is been presented in Figure 7.

This part is executed immediately after placement phase for each layer separately. The procedure works here as guided routing which will be further fed to the fuzzy expert system to take decision during global routing between a source and destination. In Algorithm 1 the procedure *Generate_Guiding_Info()* is generating the guiding information as mentioned. This algorithm is called from *Generate_Routing_Path()* with a particular layer number. During execution of this algorithm, the total layout is divided into number of subregions for that particular layer. The grid size of the layout is scalable and can be controlled by the user. Then for each subregion normalized weighted average sensitivity ratio, normalized congestion ratio is generated. Mean and variance for all subregion is determined used to determine the boundary values of membership functions for corresponding fuzzy sets.

The boundary values of Highly Sensitive(HS), Moderately Sensitive(MS), Weakly Sensitive(WS), Highly Congested(HC), Moderately Congested(MC), and Weakly Congested(WC) are determined during guiding information generation as described below.

5.4.1. Description of the Algorithm. Due to the standard cell structure the implementation of this algorithm is quite simpler. The congestion estimation and the total area estimation for each subregion may be calculated easily from obstacle information (O) and placement information (P) for that specific layer. After the layer wise placement information is obtained, area covered by obstacles (AC) and weighted sensitivity(WSn) are calculated. Congestion and sensitivity ratio(CR and SR) information are also determined for each subregion.

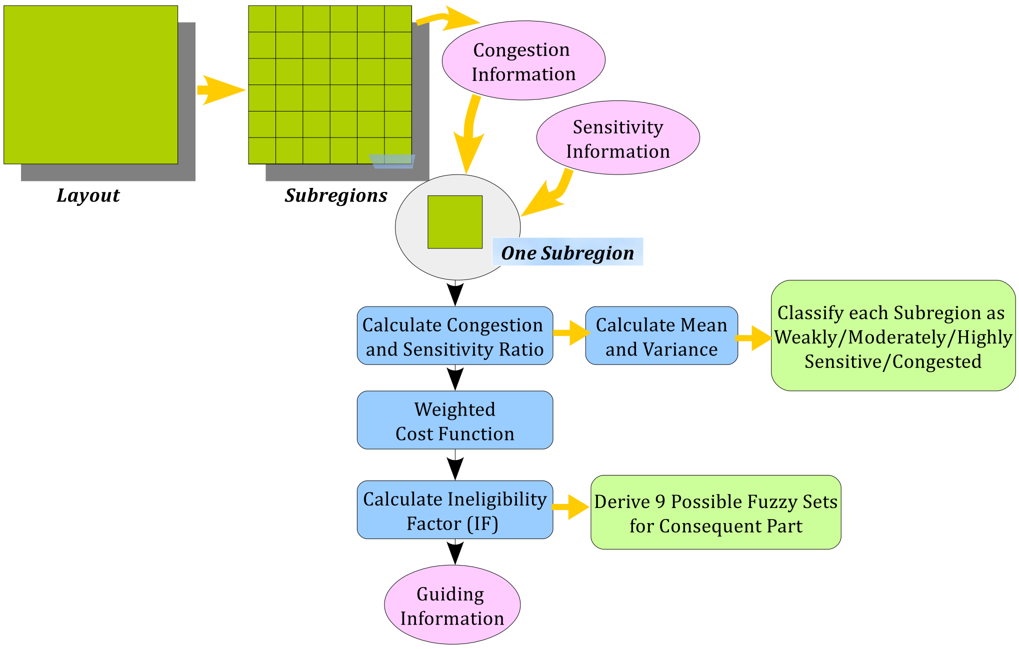


Fig. 7: Graphical representation of guiding information generation.

Classification of Sensitivity Information. The mean(s'), and variance (v_s) of thermal sensitivity for that particular layer is determined by equation 5, and 6, where N = total number of sub regions, and s_r = average sensitivity information of r^{th} subregion.

$$s' = \frac{1}{N}\sum_{r=1}^{N}(s_r) \tag{5}$$

$$v_s = \frac{1}{N}\sum_{r=1}^{N}(s_r - s')^2 \tag{6}$$

The standard deviation for thermal sensitivity of the total region is (d_s) = $\sqrt{v_s}$. Hence r^{th} sub region will be recognised as Highly Sensitive(HS), or Moderately Sensitive(MS), or Weakly Sensitive(WS). The boundary values according to equations 2, 3, and 4 are stated follows.

(1) $l_1 = s' - \frac{3d_s}{2}$

(2) $l_2 = s' - \frac{d_s}{2}$

(3) $l_3 = s' + \frac{d_s}{2}$

(4) $l_4 = s' + \frac{3d_s}{2}$

ALGORITHM 1: Guiding information generation for global router.

Generate_Guiding_Info( )

Input : S = Set of sensitivity information for each module,
P = Total placement information,
O = Obstacle information,
V = Parameter values,
L = Layer number
Output: GI = Generated guiding information

```
begin
    Layerwise_Place_Info();   /* Particular placement information for L layer from P */
    Num_Ter = Total_Terminals(P);   /* Calculating number of terminals for layer L */
    Get_Subregion_Information(P);
    SRN = Total_Subregion(L);   /* Number of subregions in layer L */
    for i ≤ SRN do
        AC = Area_Covered(O); /* Calculating total area covered by obstacles for i^th subregion of layer L */
        WSn = Weighted_Sensitivity(O, S); /* Calculating weighted sensitivity for each subrefor i^th subregion of layer L*/
        CR = AC / Total_Area();
        SR = WSn / Total_Area();
        IF = SR × V → α + CR × V → β;
        Add_to_GuidingInfo();   /* Add CR, SR and IF to GI */
    end
    Get_GuidingInfo();   /* Add mean and variance of CR and SR to GI for all subregions*/
end
```

Now the classifications for each subregion according to thermal sensitivity would be as follows.

(1) $s_r \geq s' + \frac{3d_s}{2}$, the sub region is HS

(2) $s' + d_s < s_r < s' + \frac{3d_s}{2}$, the sub region is HS with higher grade of membership and MS with lower grade of membership

(3) $s' + \frac{d_s}{2} < s_r < s' + d_s$, the sub region is MS with higher grade of membership and HS with lower grade of membership

(4) $s' - \frac{d_s}{2} < s_r \leq s' + \frac{d_s}{2}$, the sub region is MS

(5) $s' - d_s < s_r < s' - \frac{d_s}{2}$, the sub region is MS with higher grade of membership and WS with lower grade of membership

(6) $s' - \frac{3d_s}{2} < s_r < s' - d_s$, the sub region is WS with higher grade of membership and MS with lower grade of membership

(7) $0 < s_r \leq s' - \frac{3d_s}{2}$, the sub region is WS

So coarsely the classification can be presented as follows.

(1) $s_r \geq s' + d_s$, the sub region is HS
(2) $s' - d_s < s_r < s' + d_s$, the sub region is MS
(3) $0 < s_r \leq s' - d_s$, the sub region is WS

Classification of Congestion Ratio Information. Consequently the mean(o') and variance(v_o) of congestion ratio information are stated in equation 7 and 8, where N = total number of sub regions and o_r = average congestion information of r^{th} subregion.

$$o' = \frac{1}{N}\sum_{r=1}^{N}(o_r) \tag{7}$$

$$v_o = \frac{1}{N}\sum_{r=1}^{N}(o_r - o')^2 \tag{8}$$

Similarly the standard deviation for congestion information of the total region(d_o) = $\sqrt{v_o}$. Hence r^{th} sub region will be recognized as Highly Congested(HC) or Moderately Congested(MC) or Weakly Congested(WC). Here also the boundary values according to equations 2, 3, and 4 would be as follows.

(1) $l_1 = o' - \frac{3d_o}{2}$
(2) $l_2 = o' - \frac{d_o}{2}$
(3) $l_3 = o' + \frac{d_o}{2}$
(4) $l_4 = o' + \frac{3d_o}{2}$

Now the classifications for each subregion according to congestion ratio information are as follows.

(1) $o_r \geq o' + \frac{3d_o}{2}$, the sub region is HC
(2) $o' + d_o < o_r < o' + \frac{3d_o}{2}$, the sub region is HC with higher grade of membership and MC with lower grade of membership
(3) $o' + \frac{d_o}{2} < o_r < o' + d_o$, the sub region is MC with higher grade of membership and HC with lower grade of membership
(4) $o' - \frac{d_o}{2} < o_r \leq o' + \frac{d_o}{2}$, the sub region is MC
(5) $o' - d_o < o_r < o' - \frac{d_o}{2}$, the sub region is MC with higher grade of membership and WC with lower grade of membership
(6) $o' - \frac{3d_o}{2} < o_r < o' - d_o$, the sub region is WC with higher grade of membership and MC with lower grade of membership
(7) $0 < o_r \leq o' - \frac{3d_o}{2}$, the sub region is WC

Here coarse classification will be as follows.

(1) $o_r \geq o' + d_o$, the sub region is HC
(2) $o' - d_o < o_r < o' + d_o$, the sub region is MC

(3) $0 < o_r \leq o' - d_o$, the sub region is WC

So before routing is started, a prior information is generated related to each subregion that guides the global routing procedure further. And the total guiding information is dynamic in nature, i.e. the specified boundary values are determined during the execution of routing procedure. Different dynamic fuzzy sets with different boundary values may be produced per layer present in the 3 dimensional placement.

5.5. Proposed Rule Base

A rule base is an important factor during constructing a fuzzy expert system to define behavior of the system. There exists several rule models for this purpose. TS model is computationally efficient and it works well in optimization and adaptive techniques. The consequent part of the rules are not fuzzy so less intuitive. The Mamdani model is computationally less efficient but it is intuitive and well suited for human input. So it has widespread acceptance. In the expert system this model is used to generate rule base for total fuzzification of the process. The ineligibility weight factor is being determined by a mathematical function. So a conversation between the mathematical function to fuzzy sets is required.

Here TS model rule structure is, IF s_r is A_j and o_r is B_k THEN z = $f(.)$. The representation of mathematical function $f(.)$ is according to the equation 9, where $\alpha + \beta = 1$.

$$f(.) = \frac{(\alpha \times s_r + \beta \times o_r)}{(\alpha + \beta)} \tag{9}$$

The ineligibility weight factor (μ_r) of the consequent part depends upon sensitivity ratio (s_r), and congestion ratio (o_r). The formula for stating the corresponding weight factor is formulated in equation 10.

$$\mu_r = f(\alpha, s_r, \beta, o_r) = \frac{(\alpha \times s_r + \beta \times o_r)}{(\alpha + \beta)} \tag{10}$$

where, $\alpha + \beta = 1$. The preferable value for α, β are determined according to the requirement of objective function. Definition of the fuzzy sets for each rule in the consequent part is generated by putting the lower and upper limits for each fuzzy sets of the premise part in above function to determine the lower and upper limits respectively. In this way the proposed rule base can be represented according to Mamdani Model. The proposed rule base consists of 9 rules with 9 fuzzy sets corresponding to a linguistic variable of consequent part and 6 fuzzy sets corresponding to two linguistic variables of premise part. The rule base considers all possible rules with all fuzzy sets of premise part. The procedure of converting the TS model to Mamdani model is represented in Figure 8 and equation 11 for better understanding. The membership function's characteristics of trapezoidal fuzzy sets in the consequent part for the rule base is shown in Figure 9. The proposed rule base is stated in Table I.

$$\begin{aligned} a &= \frac{a_1 \times \alpha + a_2 \times \beta}{\alpha + \beta} \\ b &= \frac{b_1 \times \alpha + b_2 \times \beta}{\alpha + \beta} \\ c &= \frac{c_1 \times \alpha + c_2 \times \beta}{\alpha + \beta} \\ d &= \frac{d_1 \times \alpha + d_2 \times \beta}{\alpha + \beta} \end{aligned} \tag{11}$$

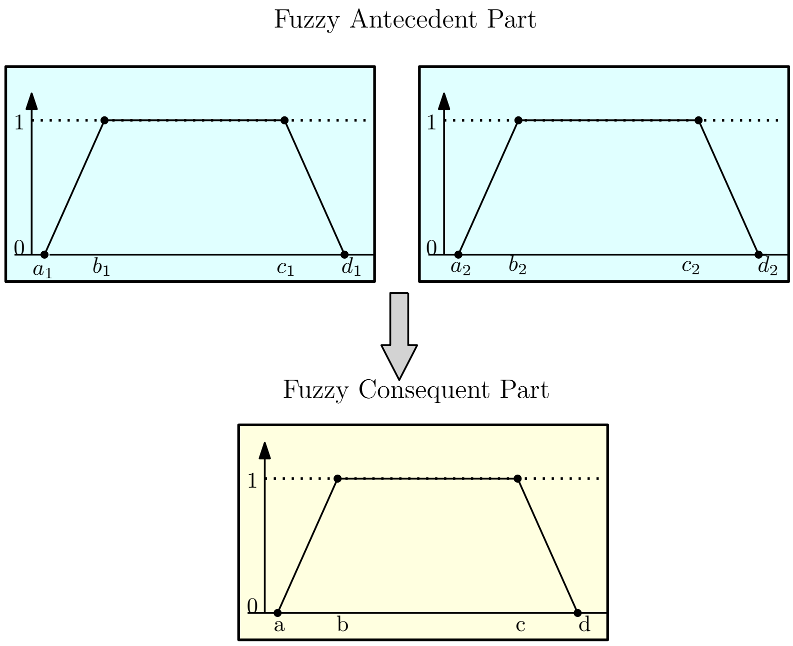


Fig. 8: Conversion procedure from TS model to Mamdani model.

Table I: The Proposed Original Rule Base for Inter-layer Net Routing.

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

5.6. Proposed Fuzzy Expert System

In Algorithm 2 the *Fuzzy_Expert_System()* procedure constructs different fuzzy expert systems for different layers with same proposed rule base but different membership functions. Here fuzzy sets for antecedent or premise part and consequent part are obtained from the generated guiding information. This fuzzy expert system produces a crisp output for the consequent part depending upon inserted values in the antecedent part and parameter values. Here proposed fuzzy expert system works dynamically by considering different boundary values for different fuzzy sets for different circuits. The total fuzzifcation and defuzzification is done inside the expert system according to the membership function and the proposed rule base. The block diagram of the proposed expert system is presented in Figure 10.

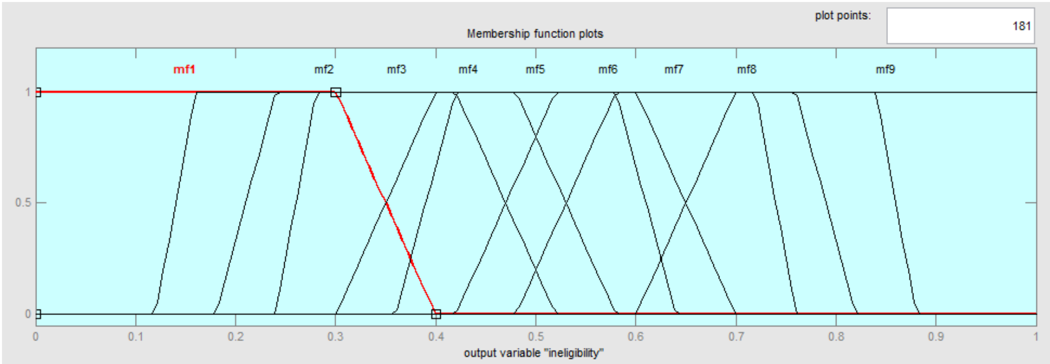


Fig. 9: Plotted membership functions of 9 fuzzy sets of consequent part in rule base.

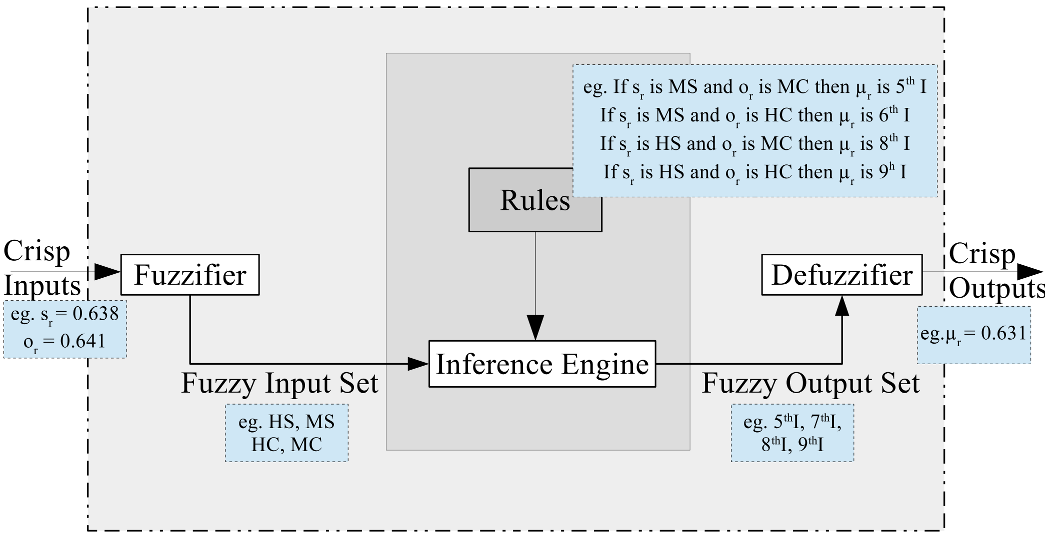


Fig. 10: Modeling of fuzzy expert system for 3 dimensional structure.

ALGORITHM 2: Modeling the fuzzy expert system.

Fuzzy_Expert_System( )

Input: *GI* = Information of premise and consequent part)

---

begin
  Mem_Fun_Premise(); /* Build membership functions for premise part from *GI* */
  Mem_Fun_Consequent(); /* Build membership functions for consequent part from *GI* */
  Gen_Rule_Base(); Build a rule base with 9 rules */
end

6. PROPOSED 3D PLACEMENT TECHNIQUE

6.1. Thermal Aware Modeling

Thermal effects have prominent impact on performance and reliability of a chip. Due to closer proximity of the modules in a 3D multi layered structure 3D ICs are significantly dependent on thermal parameters i.e. power dissipation issues. In their relevant work [Tsai and Kang 2000] authors have successfully addressed this issue in case of standard cell placement and have come up with an efficient placement technique to reduce hot spots [generated by high heat flux in localized regions] during placement without compromising traditional design metrics e.g. area and wire length. Moreover, in their paper they have first successfully pointed out that it is the power density [not the power dissipation] that may be treated as the most effective measurement parameter to account for thermal effects.

6.1.1. Analytical Die Temperature Model. As power density of the modules is much effective parameter [Tsai and Kang 2000] in thermal profiling of a placed layer compared to power dissipation by the modules itself it was really necessary to figure out a directly measurable parameter that can be taken as a measure of this effect and originates as a direct aftereffect of this issue. In another pioneering work [Im and Banerjee 2000] authors have successfully modeled this thermal effect and have shown that the die temperature is solely dependent upon the power density and the change in this temperature is linearly dependent on this. Therefore the change in die temperature may be considered as a directly measurable parameter to characterize the thermal profile of die.

A simple analytical model has been proposed to estimate the change in temperature in each active layer of 3D chips. The temperature rise (above the ambient temperature) of the j^{th} active layer in an n-layer 3D chip may be expressed as,

$$\triangle T_j = \sum_{i=1}^{j} \left[R_i \left(\sum_{k=i}^{n} \frac{P_k}{A} \right) \right] \tag{12}$$

where n is total number of active layers, R_i represents thermal resistance between the i^{th} and $(i-1)^{th}$ layers, and P_k is the power dissipation in the k^{th} layer. Assuming identical power dissipation (P) in each layer and identical thermal resistance (R) between layers, the temperature rise of the uppermost (n^{th}) layer in an n layer 3D chip can be expressed as,

$$\triangle T_n = \left(\frac{P}{A} \right) \left[\frac{R}{2} n^2 + \left(R_1 - \frac{R}{2} \right) n \right] \tag{13}$$

where R_1 is mostly due to the package thermal resistance between the first layer and the heat sink and R is the thermal resistance between the i^{th} and the $(i-1)^{th}$ layers respectively.

6.1.2. Dynamic Thermal Modeling. In the proposed thermal arrangement during placement, the non-uniformity of thermal conditions of modules was modeled in terms of intrinsic parameter of placement, called $ThermalBound$, reported in [Ghosal et al. 2009]. The probabilistic switching of modules is considered to satisfy a Poisson distribution [Press et al. 2001]. Hot spots are generally workload dependent and their duration may vary with switching activity of circuits. The Poisson distribution counts the number of discrete occurrences of an event during a specified time interval. In [Ghosal et al. 2009], switching of a module is considered as occurrence of an event, where, λ denotes the average number of switchings for a set of logic modules. Therefore, probability of a module switching exactly k times is given by

$$\xi(k,\lambda) = \frac{e^{-\lambda} \times \lambda^k}{k!} \tag{14}$$

where, k is a non-negative integer. It is clear that ξ counts for the number of switching of the corresponding module and lies between [0,1]. The actual number of times a module switches for average values λ is given by $\xi(k,\lambda) \times k$. In absence of any probability of switching, a module will switch exactly k times in a period of k cycles.

6.2. Proposed Algorithm

As of date design solutions for implementing a pure 3D integrated circuit is still not available readily. Available benchmarks in 3D also comes with multiple metal layers only in spite of multiple device layers. Due to this unavailability some 2D to 3D placer tool has been used to study the feasibility of the proposed approach. Output of one efficient thermal aware 3D placer reported in [Ghosal et al. 2010c],[Ghosal et al. 2010b] has been used in the present work with some necessary and suitable modification. An intelligent heuristic has been proposed for this placement migration. In this proposed approach an efficient overlap elimination technique has been introduced as a post placement procedure to optimize and improve the placement results. Pseudo-code of the proposed placement algorithm has been presented in Algorithm 3.

ALGORITHM 3: Generation of full 3D placed circuits from standard benchmark circuits.

Modified_3D_Placement( )

```
Input  : N= Number of cells to be placed,
         L= Number of layers available,
         A_r= Aspect ratio of the chip,
         S_t= sub-matrix order,
         I_t= Maximum iteration limit
Output: Thermally optimized 3D placement

begin
    Generate_3D(); /* Generate 3D matrix of minimum dimension satisfying constraints */
    Allocate_3D(); /* Allocate cells with corresponding power density values */
    while optimization_possible = yes do
        for layer_number = 1 to L do
            Layer_Therm_Opt(); /* Layer wise thermal optimization */
        end
        Inter_Layer_Therm_Opt(); /* Thermal optimization across all the layers */
        if optimized = no then
            Find_Layers(); /* Determine the layers where 2D optimization is necessary */
        else
            Stretch_Layers(); /* Stretching routing regions in each layers to eliminate
            overlapping in cells */
        end
    end
end
```

7. PROPOSED SCHEME FOR GLOBAL ROUTING

Overall flow of the proposed fuzzified global routing tool for 3D ICs may be represented as in the flowchart in Figure 11. This fuzzified routing technique proceeds by designing a fuzzy logic expert system for generating guiding information that helps in decision making during actual global routing phase. Placed region of individual layer is divided into sub-regions. Proposed heuristic is based on sensitivity information value for each node (signifies thermal response) and congestion information to specify congestion driven technique for routing.

For each subregion, the crisp values of sensitivity, and congestion information are transformed in two fuzzy sets. These are used to generate a crisp output by passing through a rule base based on Mamdani model and by defuzzification method. Thus the total fuzzy expert system works for generating the guiding ineligiility factor generation for each sub-region. During decision making of routing procedure, the sub-region with minimum ineligibility factor is favoured.

Proposed routing procedure does not allow detours and the global routing paths are generated in units of sub-regions. The un-routable nets will again start from guiding information generation step during rip-up and reroute procedure. Specific geometric paths are generated during detailed routing. Another aspect of the proposed global routing is, if one subregion is selected during routing of a particular net then that specific subregion will never be retraced again for the same net. After routing one net, the ineligibility factor gets increased by a factor for the subregions upon which the routed path has gone through and either vertical or horizontal capacity gets decreased for that subregion.

Different nets of a particular netlist is processed sequentially for the sake of easy implementation. One pre-routed net will contribute to increasing congestion ratio information in this sequential order of global routing.

(1) *Two pin intra-layer nets:* Here connections are made by normal fuzzified way according to Algorithm 4.

(2) *Two pin inter-layer nets:* Multi-layered two-pin connections by inserting pseudo-terminal points.
   - First, the backbone tree construction across multiple layers that specify the pseudo terminals for each layer and inject vias for inter-layer communication. The determination of pseudo terminals are based on sensitivity and congestion ratio of the sub-regions containing the source and destination terminal.
   - Second step consists of connecting the pseudo terminal points to source, and destination containing subregions in that particular layer by two pin intra-layer net connection in fuzzified way, according to Algorithm 4.

(3) *Multi pin nets:* Multi-layered or single layered Steiner tree construction by insertion of pseudo-terminal. The three steps are:
   - First, a numbers of clusters are generated by automatic cluster determination technique[Bandyopadhyay 2005] (required for larger nets) by simulated annealing method. The centers of clusters act as Steiner points during generation of intra-cluster Steiner trees for each layer. Connection between cluster center and each terminal is being done by Algorithm 4.
   - Second, the backbone tree construction across multiple layers that specify the pseudo terminals for each layer and inject vias for inter-layer communication. The determination of pseudo terminals are based on sensitivity and congestion ratio of the sub-regions. One obstacle avoidance heuristic is used here during insertion of inter-layer vias.

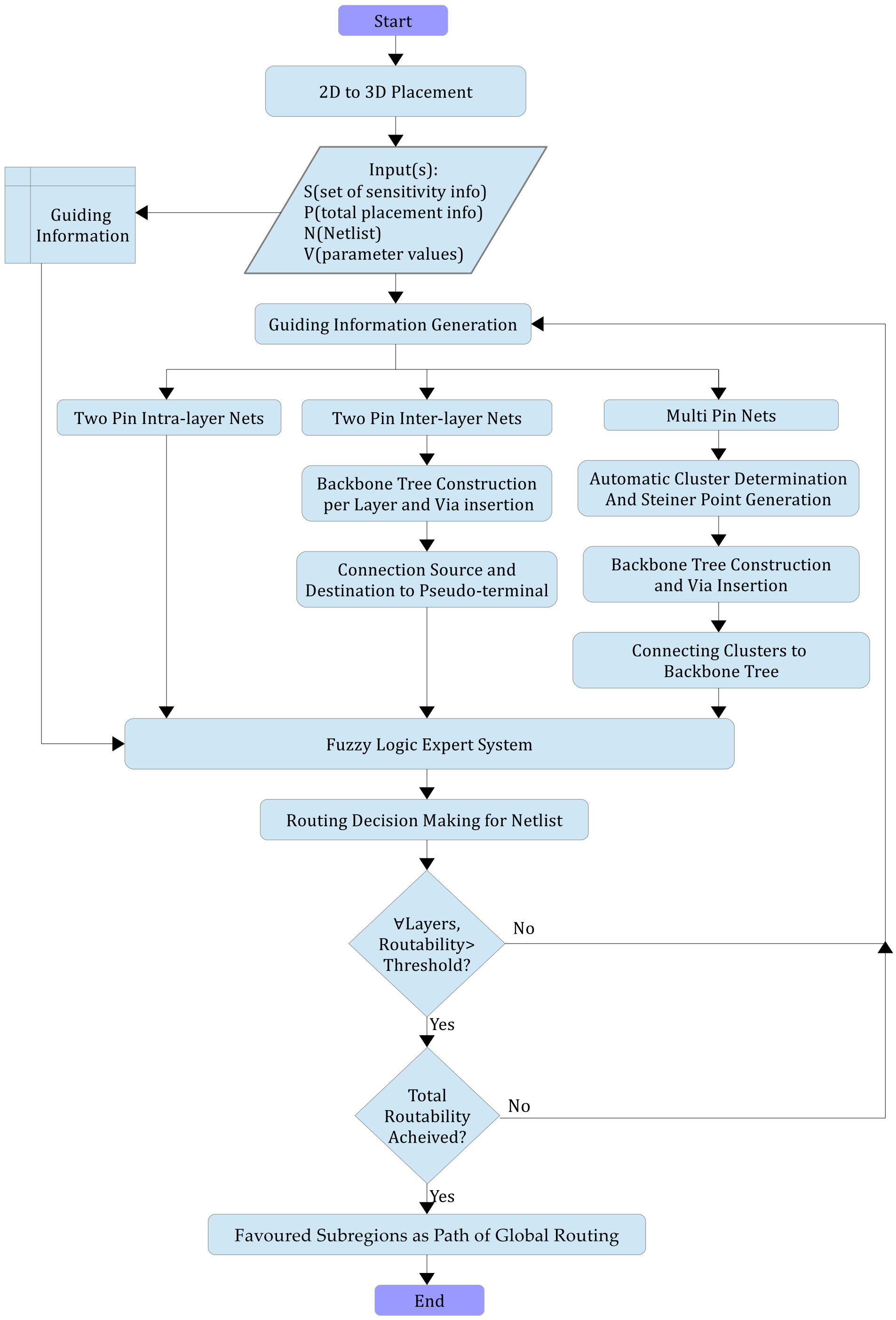


Fig. 11: Overall flow of the proposed fuzzified Global Router for 3D ICs.

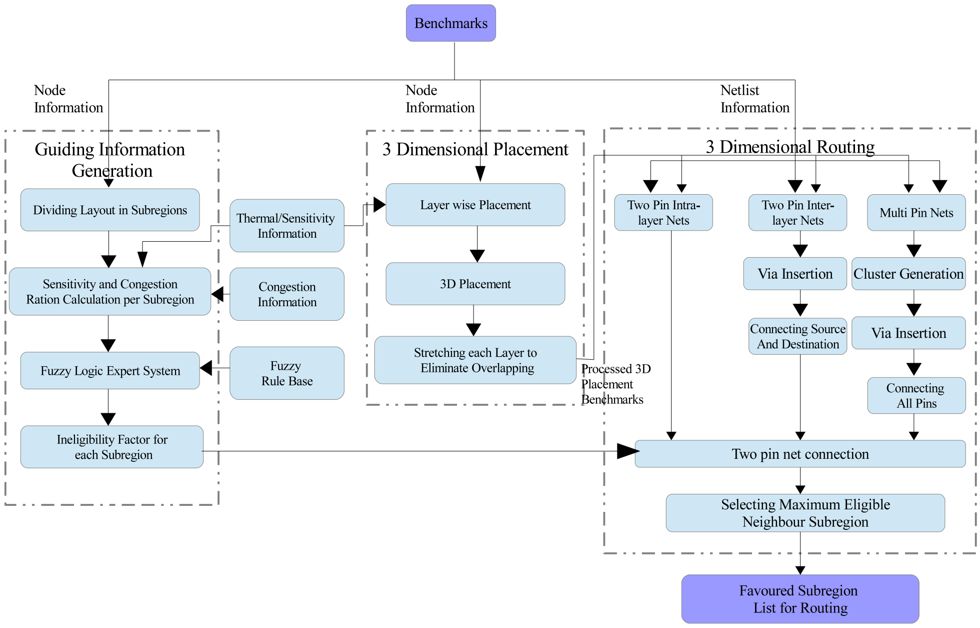


Fig. 12: The proposed thermally efficient congestion free Global Routing approach for 3D ICs.

— Third step connects each cluster centers or single terminals with the backbone tree i.e. the pseudo terminal points in that particular layer by two pin net connection in fuzzified way as stated in Algorithm 4.

The detailed working principle of the total procedure is described later. One obstacle avoidance heuristic is used here during insertion of inter-layer vias.

8. PROPOSED FUZZIFIED APPROACH FOR GLOBAL ROUTING

Proposed procedure *Generate_Routing_Path()* generates total routing path for all nets in terms of sub regions for a netlist of a circuit in Algorithm 5. It takes the output of Algorithm 3 for a circuit as its input and produce global routing path as output for the netlist of same circuit. At starting of Algorithm 5, the generation of subregion information, guiding information and building of fuzzy expert system is done through two procedures *Generate_Guiding_Info()* and *Fuzzy_Expert_System()* per layer. Then it heads towards the routing procedure. The proposed algorithm recognises several types of nets and perform the global routing accordingly. The functional level block diagram for the total router has been presented in Figure 12.

8.1. Two-pin Intra-layer Net Routing

In Algorithm 5, the procedure *Generate_Routing_Path()* first recognises all two-pin intra-layer nets and perform global routing in fuzzified way as stated in Algorithm 4. Here *Intra_Layer_Routing()* procedure generates the favoured subregions for connections between two pins. During the decision making of selection of next favoured subregion, one subregion is never re-selected for the same net routing.

When destination is a set of terminals, then this algorithm finds favoured path for each terminals belonged to the destination set from the specific source. Here decision making is done using the generated fuzzy expert systems depending upon different layers. One scenario of two-pin intra-layer net routing is shown pictorially in Figure 13.

ALGORITHM 4: Global routing path generation for fuzzified router.

Intra_Layer_Routing( )

Input : Src = Source Coordinate,
D = Destination Coordinate,
GI = Guiding Information,
V = Parameter value
Output: Favoured subregions($Subregion$)

```
begin
    MDSrc = MD(Src, D);  /* Manhattan distance between Src and D containing subregions */
    MD = MDSrc;
    PSrc = Src;  /* Setting a pivot subregion */ Fuzzy_Expert_System (GI);
    while MD > 0 do
        Explore_Neighbour();  /* Explore four neighbors around pivot subregion */
          NInfo = Get_Info();  /* Sensitivity, congestion information of each neighbors */
          IF = Defuzz();  /* Defuzzified value by centroid method using rule base */
        if Nbour_Not_Visited() then
            /* Check whether a neighbor is visited or not */
            PSrc = Select_Neighbour();  /* Select neighbor with min IF and set as new pivot */
        end
        MD = MD(PSrc, D);
    end
end
```

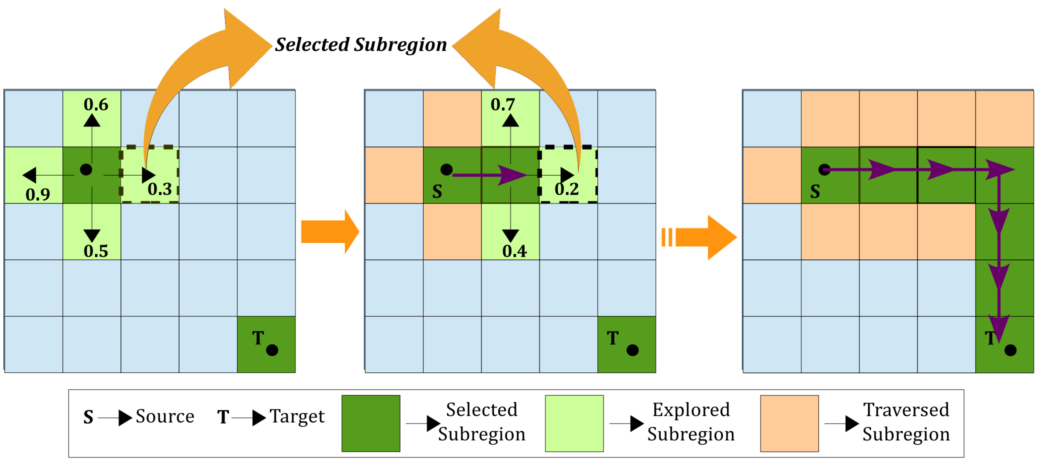


Fig. 13: A scenario of source to target intra-layer global routing.

8.2. Two-pin Inter-layer Net Routing

Next all two-pin inter-layer nets are sorted out in Algorithm 5. To route all those recognised nets, two steps are being followed.

8.2.1. Backbone Tree Construction and Determination of Pseudo-Terminal. Backbone tree is performing inter-layer connection during connection between two intra-layer pins. Backbone tree generation process is done by Backbone_Tree() function in Algorithm 5. Inter-layer vias are the technology to build a backbone tree here. Via insertion procedure can be done by two ways,as shown in Figure 14. The position of via insertion point should be inclined to direction of more sensitive or congested terminal.

In the figure the normal approach is showing general method of via insertion strategy during connection between a inter-layer source and destination. But the significance of our proposed approach lies in providing the more sensitive and congested terminal, a nearer way for heat dissipation path(through via), still giving less sensitive and congested one some favour.

One example case may be taken, as shown in Figure 14, main priority is given to the highly sensitive terminal by placing the via position near to it in both the approach. But in proposed approach the moderately sensitive terminal is also getting some extend of favour, which is not given in the normal approach. So here in the proposed technique, as a backbone tree determination strategy, the combined sensitivity-congestion information for two terminals are used, which is stated in equation 15, 16 and 17.

$$sc_{rl} = \frac{s_{rl} \times \alpha + c_{rl} \times \beta}{\alpha + \beta} \tag{15}$$

The average weight (sc_{rl}) for r^{th} subregion in l^{th} layer is determined in equation 15, where α, β are the two constraints provided by the user specification. s_{rl} and c_{rl} are the sensitivity and congestion information of r^{th} subregion residing on l^{th} layer. The x coordinate (x_b) of backbone for all layers for a particular two-pin net is determined in equation 16 and the y coordinate(y_b) of the same is determined in equation 17. Where, src_i is the subregion containing source terminal residing on i^{th} layer and $dest_j$ is same for destination terminal residing on j^{th} layer. The sc_{si} and sc_{dj} are the average weight for the source and destination containing subregions. Then the backbone may be drawn through (x_b, y_b) point intersecting all the layers in between.

$$x_b = \frac{src_i \rightarrow x \times sc_{si} + dest_j \rightarrow x \times sc_{dj}}{sc_{si} + sc_{dj}} \tag{16}$$

$$y_b = \frac{src_i \rightarrow y \times sc_{si} + dest_j \rightarrow y \times sc_{dj}}{sc_{si} + sc_{dj}} \tag{17}$$

Next final positions of pseudo-terminals are determined. In one layer, if there is no obstacle in (x_b, y_b) point, that point works as a pseudo terminal and participates in routing of that layer and one electrical via is inserted into that point according to the function Pseudo_Teminal_Insertion(). But if the point(x_b, y_b) falls on any obstacle in any layer, then one obstacle avoidance strategy have been introduced that considers weight factor information as impacting factor during its avoidance technique.

8.2.2. Connecting Source and Destination to Backbone Tree. Connection between source and destination with the pseudo terminals caused by the insertion of backbone tree is done by *Fuzzified_Intra_Layer_Routing()* procedure again. In *Connect_All_Pins()* procedure, all routed subregion information is generated and returned to the user.

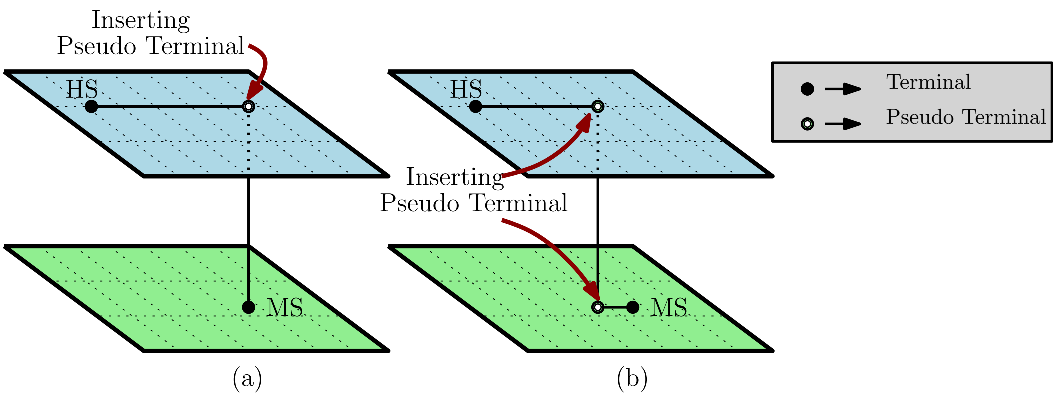


Fig. 14: Insertion of pseudo-terminal in during inter-layer two-pin net routing: (a) Normal approach (b) Proposed approach.

8.3. Multi-terminal Net Routing

Lastly, the multi-terminal nets are recognized in Algorithm 5. The intra and inter-layer multi-pin nets are handled quite in a similar approach during the execution of routing procedure. Multi-pin inter layer nets may be considered as a generalization of multi-pin intra-layer nets with a single layer. So the solution approach also takes this generalization concept. The three steps defined below are called repeatedly for each multi-pin net having inter or intra layer connection (for intra-layer nets the layer number will be one).

8.3.1. Automatic Cluster Determination and Connection within Clusters. This step is mainly required to process a large net to a smaller one, i.e. by making clusters of terminals with nearer proximity gives the larger net a smaller look.

As the total procedure is fuzzified and aimed at to escape the bound of deterministic approach, here one fuzzy clustering approach was used. For better degree of reliability the automatic number of fuzzy cluster determination technique using Simulated Annealing proposed in [Bandyopadhyay 2005] has been selected. The center of the generated cluster works as pseudo-terminal for that layout and can be used further for routing.

Now for each terminal(t) of l^{th} layer corresponding home subregion(r) and its combined sensitivity-congestion ratio(sc_{rl}) from generated guiding information are determined. The combined value is determined according to equation 15, where α and β are coming from parameter values(V). For a typical implementation, the selected values may be, α as 0.4 and β as 0.6 for congestion aware routing, and α as 0.6 and β as 0.4 for thermal aware routing.

The distance measure between two terminals is Manhattan Distance(MD) measurement in terms of subregions. Here automatically determined clusters may be of different sizes. Suppose for l^{th} layer the automatically determined number of clusters is N_l and the vertex of i^{th} cluster in l^{th} layer is v_{il}, where $i \in \{1...N_l\}$. Now for each cluster the *Intra_Layer_Routing()* procedure is called that connects all the terminals of the cluster with the center vertex of cluster.

For a large net also number of clusters are generally small. So number of inserted pseudo-terminals does not affect the cost significantly. Total automatic cluster determination and connection within clusters procedure is abstracted within Automatic_Cluster_Generation() function in Algorithm 5.

ALGORITHM 5: Algorithm for generation of routing path for a netlist.

Generate_Routing_Path( )

Input : S = Set of sensitivity information for each module,
P = The total placement information,
N = Netlist,
V = Parameter values
Output: Routing path in terms of favoured subregions

```
begin
    L = No_of_Layers(P);
    for layer_number = 1 to L do
        Generate_Guiding_Info(S, P, V); /* Guiding information generation for all layers */
        Fuzzy_Expert_System(); /* Build distinct fuzzy expert systems for all layers */
    end
    for net ∈ N do
        if intra_layer_two_pin_net then
            Intra_Layer_Routing(); /* Generate routing path from source to destination */
        else if inter_layer_two_pin_net then
            Backbone_Tree(); /* Determine pseudo terminal positions by constructing backbone
            tree */
            Pseudo_Terminal_Insertion(); /* Insertion of pseudo terminals and via */
            Connect_All_Pins(); /* Connecting source and destination pins to the pseudo
            terminal points */
        else
            /* For multi-pin intra and inter layer nets */

            Automatic_Cluster_Generation(); /*Generate Automatic number of clusters with
            multiple pins for all layers */
            Backbone_Tree(); /* Determine pseudo terminal positions by constructing backbone
            tree */
            Pseudo_Terminal_Insertion(); /* Insertion of pseudo terminals and via */
            Connect_All_Pins(); /* Connecting all pins of a net to the pseudo terminal points */
        end
    end
end
```

8.3.2. Backbone Tree Construction and Determination of Pseudo Terminals. Construction of backbone trees are mandatory for inter-layer via connections. In connecting points, vias are inserted in a particular layer and its position depends upon the behavious of generated cluster or terminals. The position of via insertion point should be inclined to direction of larger and more sensitive or congested clusters or terminals.

So backbone tree determination strategy combines both sensitivity-congestion information for each clusters or terminals and size of the clusters (stated in equation 18, 19 and 20).

In equation 18, the total summation of sc for each cluster is determined, where $c_{il} \rightarrow$ i^{th} cluster in l^{th} layer.

$$sc_{il} = \sum_{\forall r \in i} sc_{rl} \tag{18}$$

The x coordinate (x_b) of backbone for all layers for a particular net is determined in equation 19 and the y coordinate(y_b) of the same is determined in equation 20. Where

$vx_{il} \rightarrow x$ coordinate of the center of cluster i in l^{th} layer, $N \rightarrow$ total layer number and $N_l \rightarrow$ automatically determined cluster number in the l^{th} layer and $vy_{il} \rightarrow y$ coordinate of the center of cluster i in l^{th} layer. Then the backbone may be drawn through (x_b, y_b) point intersecting all the layers. Equation 19 and equation 20 are generalized from of equation 16 and equation 17.

$$x_b = \frac{\sum_{l=1}^{N} \sum_{i=1}^{N_l} (sc_{il} \times vx_{il})}{\sum_{l=1}^{N} \sum_{i=1}^{N_l} sc_{il}} \quad (19)$$

$$y_b = \frac{\sum_{l=1}^{N} \sum_{i=1}^{N_l} (sc_{il} \times vy_{il})}{\sum_{l=1}^{N} \sum_{i=1}^{N_l} sc_{il}} \quad (20)$$

The above described backbone tree construction procedure is done in Backbone_Tree() procedure. Here determination of final position of pseudo-terminals stage is done layer wise. In one layer, if there is no obstacle in (x_b, y_b) point, then that point works as a pseudo terminal. That pseudo terminal also participates in routing of that layer and one electrical via is inserted into that point according to function Pseudo_Teminal_Insertion().

But if the point(x_b, y_b) falls on any obstacle in any layer, then one obstacle avoidance strategy is used that also considers the cluster size and combined sensitivity-congestion ratio information as impacting factor during its avoidance technique. The avoidance scheme is described later. One example case is shown pictorially in Figure 15 for better understanding. In this figure it is clear that the insertion point of pseudo-terminal is inclined to more congested and more sensitive terminals to be connected to minimize heat dissipation as well as wire-length.

8.3.3. Connecting Clusters to Backbone Tree. Connection between each cluster center with pseudo terminal caused by insertion of backbone tree is done in Connect_All_Pin() procedure that calls *Intra_Layer_Routing()* procedure internally.

Ultimately, in Algorithm 5 the *Generate_Routing_Path()* procedure will return favoured subregions as global routing path.

8.4. Obstacle Avoidance Scheme during Determination of Pseudo-Terminal

The position of pseudo terminal, after avoiding obstacle, depends upon the total weight factor of clusters falling on four possible sides of obstacles. Here the position of pseudo terminal is skewed to more congested, sensitive, and large clusters, so that congestion does not increase more to that side.

By injecting the pseudo terminal vertical via position is actually inserted to help the electrical signal to pass quickly from the more sensitive, and congested regions to other layer that may be favourable for routing. One example of determination of pseudo terminal in obstacle avoidance scheme is shown in Figure 16. The scheme is stated below.

(1) The weight factor related to cluster size and combined sensitivity-congestion ratio for i^{th} cluster in l^{th} layer is w_{il}, stated in equation 21, where n_{il} = number of terminals in i^{th} cluster in l^{th} layer and sc_{ikl} = the average sensitivity-congestion ratio of corresponding subregion where k^{th} terminal belongs in i^{th} cluster in l^{th} layer.

$$w_{il} = n_{il} \times \sum_{k=1}^{n_{il}} sc_{ikl} \quad (21)$$

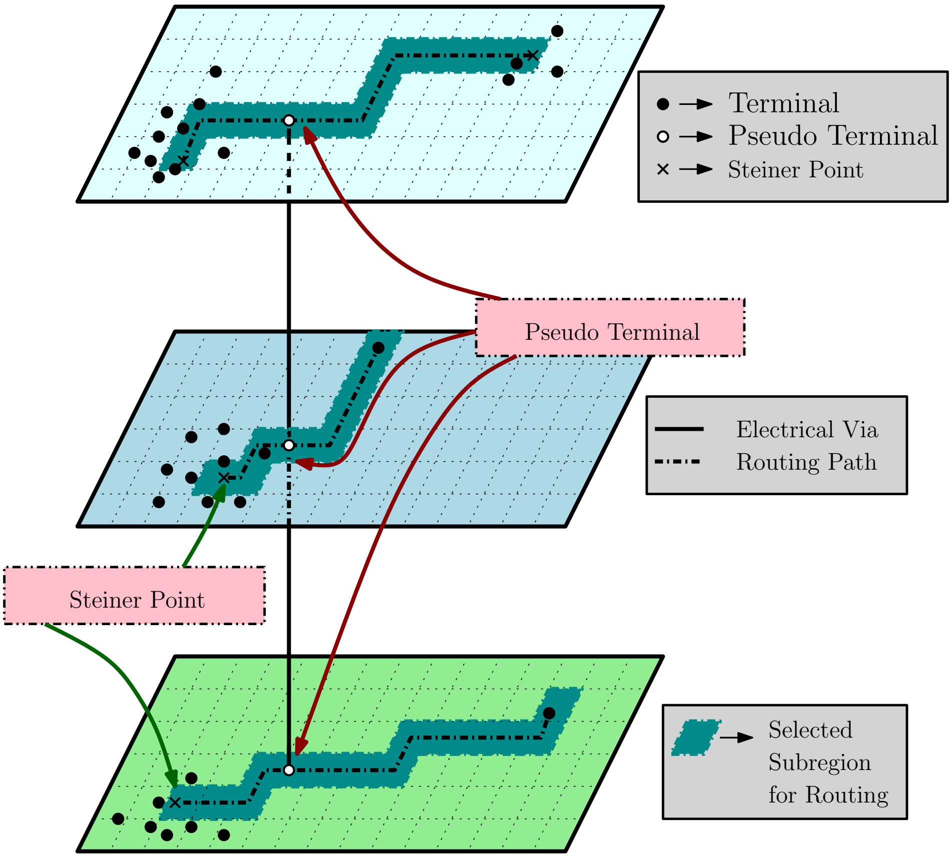


Fig. 15: Insertion of pseudo-terminal and backbone tree construction during multi-terminal inter-layer net routing.

(2) Next suppose the bottom left corner of obstacle is (x_o,y_o) and length and width of the obstacle is h_o and w_o respectively. The coordinate of four corner points of the obstacle anticlockwise are then (x_o,y_o),($x_o + w_o$,y_o), ($x_o + w_o$,$y_o + h_o$) and (x_o,$y_o + h_o$).
(3) Need to calculate the four components (m_1, m_2, m_3, m_4), where
 (a) $m_1 = (x_o + w_o - x_b) \times \sum_{vx_{il} > x_b} w_{il}$
 (b) $m_2 = (x_b - x_o) \times \sum_{vx_{il} \leq x_b} w_{il}$
 (c) $m_3 = (y_o + h_o - y_b) \times \sum_{vy_{il} > y_b} w_{il}$
 (d) $m_4 = (y_b - y_o) \times \sum_{vy_{il} \leq y_b} w_{il}$
(4) After determining the maximum value(m) among the four components according to equation 22, the final pseudo-terminal($x_{b'}$, $y_{b'}$) position will be determined.

$$m = max\{\, m_1,\, m_2,\, m_3,\, m_4 \,\} \tag{22}$$

So here four conditions may arise
 (a) if $m = m_1$ then $x_{b'} = x_o + w_o$ and $y_{b'} = y_b$
 (b) if $m = m_2$ then $x_{b'} = x_o$ and $y_{b'} = y_b$
 (c) if $m = m_3$ then $x_{b'} = x_b$ and $y_{b'} = y_o + h_o$
 (d) if $m = m_4$ then $x_{b'} = x_b$ and $y_{b'} = y_o$

(5) Ultimately, the determined point($x_{b'}$, $y_{b'}$) works as pseudo-terminal for that particular layer.

As a result of obstacle avoidance scheme, the upper and lower layer of the obstacle containing layer, need to add two pseudo terminals and some extra wire as shown in Figure 16. But this overhead does not affect much as present three dimensional technology supports maximum upto 6-8 layers.

This total step by step approach for avoiding obstacle is done in Pseudo_Terminal_Insertion() procedure, if required.

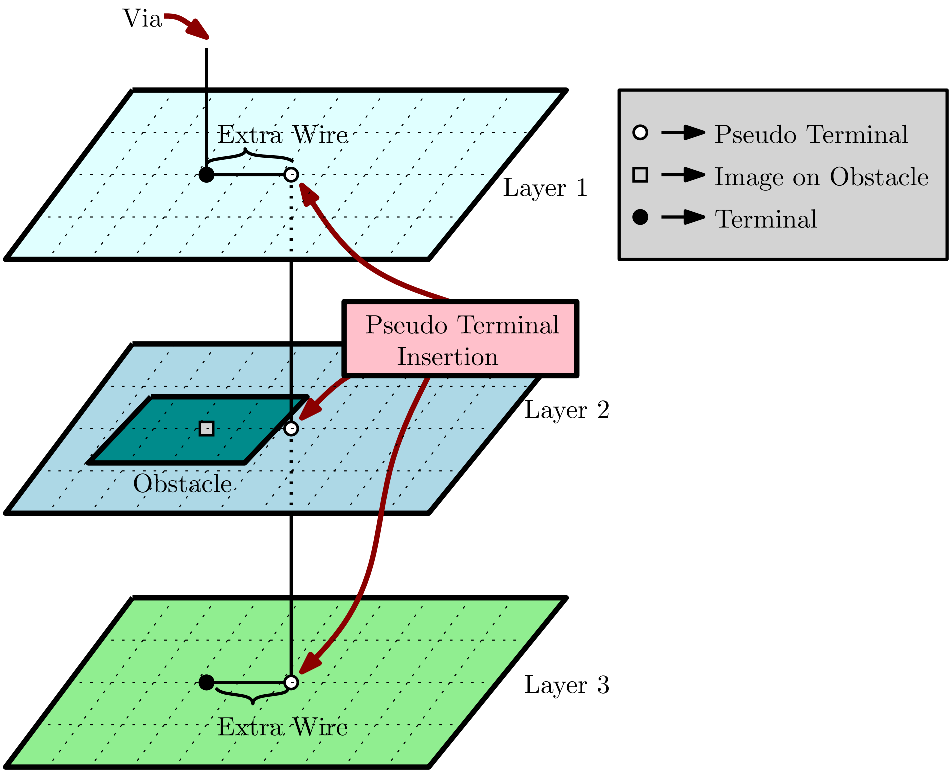


Fig. 16: Insertion of pseudo terminal in presence of obstacle during backbone tree construction.

9. RESULTS AND DISCUSSIONS

9.1. Experimental Framework

Proposed algorithms have been implemented in C, Java, MATLAB 7.14.0, MCR, Matlab Builder JA, and Swing. The GUI is designed in GUIDE and the fuzzy expert system is implemented using MATLAB fuzzy toolbox. The experiments were performed on a standard desktop environment of 4 GB memory with an Intel chip running at 2.30 GHz. ISPD 1998 (IBM-PLACE 2.0) benchmark suites [Alpert 1998] (for fixed-die placement) are used. Later the experiments were also implemented for ISPD 2007 [Nam et al. 2007] and ISPD 2008 [Nam et al. 2008] 3D benchmarks on a 8-core 2.0 GHz Intel Xeon-based server with 8GB memory. Two different frameworks have been taken for comparability issues with other standards routers for different benchmark suites.

9.2. Feasibility Study of the Proposed Model

The Figure 17 shows a snapshot of implemented fuzzy expert system of total implementation using fuzzy toolbox in MATLAB. For the crisp input set [0.638 0.641] the proposed rule base is producing a crisp output value of 0.631. The different activated fuzzy sets for premise part by two crisp inputs are the highlighted trapezoids that fall on the crisp line in first two grids. For consequent part those highlighted trapezoids are on the crisp output line in last grid. From the snap shots of Figure 18 it is clear that using rule base the expert system is producing quite accurate output as changing of ineligibility factor is quite smooth here. The α and β values can actually be user specified, though we have taken α = 0.5 and β = 0.5 in presented experimental result.

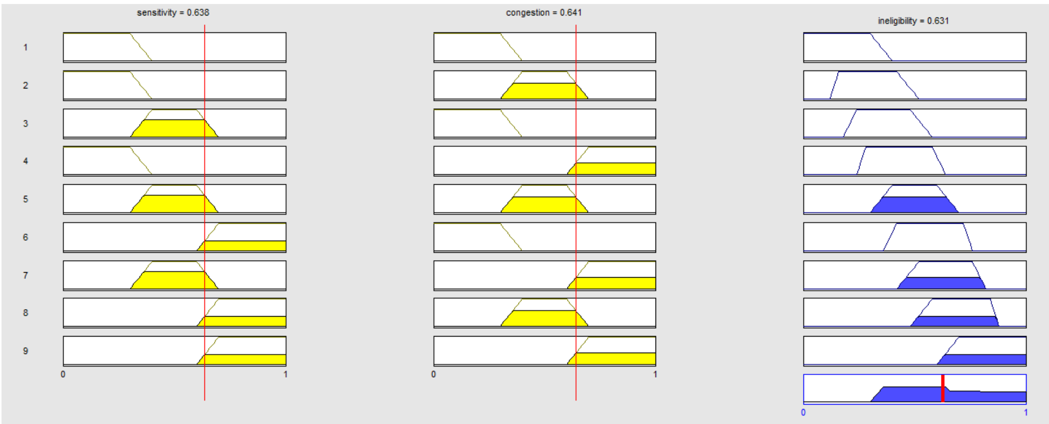


Fig. 17: The fuzzification and defuzzification with respect to rule base.

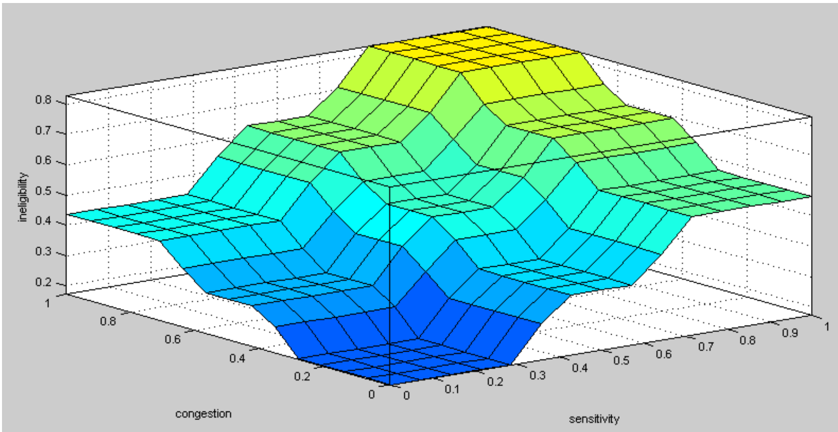
9.3. Implementation

After getting prior success in feasibility study of the proposed approach, the total global routing implementation over standard benchmarks are performed.

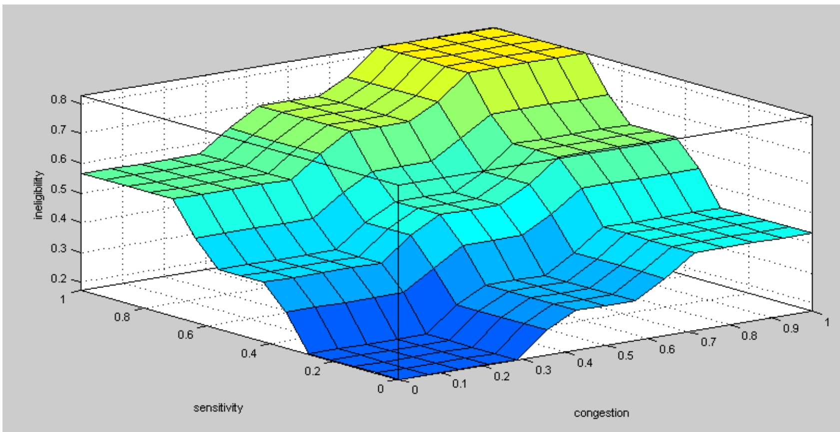
In Table III experimental results for IBM benchmarks for standard cells are reported. The implementation is heading to minimize the time complexity for 3D ICs in fuzzified way. 3D placement is generated by the proposed method for these 2D benchmarks. From the experimental results, it is clear that significant lesser time is required for routing. Main concern of the algorithm is the time required for guiding information generation phase. With more number of device layers in 3D placement the routing time is decreasing for larger circuits. This characteristic is in conformity with the concepts of 3D ICs. This work is aimed at to compare the fuzzified approach with other foolproof routers based on heuristics based approach. The implementation is being enriched consequently.

Experimental results for different IBM benchmarks with different device layers, are reported in Table III. For different number of device layers, variations of guiding information generation time as well as routing time are plotted in Figure 19.

Variation of routing time with increasing number of device layers for all benchmark circuits has been studied [see table III] and plotted in Figure 20. Results show routing time is significantly less than guiding information generation time. Moreover, it is even decreasing with increase in device layers for more availability of routing space in 3D ICs.



(a) Ineligibility factor with congestion and sensitivity



(b) Ineligibility factor with sensitivity and congestion

Fig. 18: Change of ineligibility factor with sensitivity, congestion for proposed rule base.

Some important observations may be put in the form of following Lemmas 9.1, 9.2, and Observation 9.1.

LEMMA 9.1. *Better routing time may be achieved with more number of layers in 3D ICs.*

PROOF. With more number of device layers, routing space increase vertically. So some distant terminals of each net will be nearer and can be connected through vias. This reason leads to decrease of routing time for total netlist. □

LEMMA 9.2. *Time to generate guiding information decreases with increasing number of device layers in 3D ICs.*

PROOF. Increasing number of device layers make layout area smaller and assign lesser number of terminals for each layer. So, lesser number of terminals will make

Table II: Variation in Resulting Metrics for IBM 02 (for 6 layers)with Different α and β Values.

α	β	Guiding Info. Gen Time(sec.)	Routing Time(sec.)	Wirelength
0.0	1.0	80.0	4.0	167561
0.1	0.9	88.0	4.0	167091
0.2	0.8	72.0	10.0	166934
0.3	0.7	83.0	10.0	162913
0.4	0.6	76.0	4.0	168014
0.5	0.5	85.0	4.0	166922
0.6	0.4	91.0	11.0	166242
0.7	0.3	76.0	4.0	185364
0.8	0.2	74.0	10.0	161371
.9	.1	76.0	4.0	166171
1.0	0.0	80.0	4.0	172575

each layer less complicated. Calculating sensitivity and congestion information will be easier for each layers during guiding information generation. Eventually, total guiding information generation time will decrease for a netlist with more number of device layers. □

OBSERVATION 9.1. *Rate of increase in routing time is much lesser than the rate of increase in guiding information generation time with increasing numbers of nets.*

9.4. Variation of Parameter Values

Here α and β are the two controlling parameter which determine objective function and therefore the outcome fuzzy expert system. An exhaustive analysis with variable α and β values for certain benchmark has been presented in Table II. Two extreme scenario can be named as follows.

(1) α = 0.0 and β = 1.0$\rightarrow$ Totally Congestion Aware Routing
(2) α = 1.0 and β = 0.0$\rightarrow$ Totally Thermal Aware Routing

It is clear from TableII that guiding information generation time varies within 72-91 seconds, routing time varies within 4-11 seconds and wire length varies within 161371-172575. Apparently, for a certain benchmark the variation in result is not drastic for variable set of parameter values. This quality signifies robustness of the proposed global router.

9.5. Comparison for ISPD 1998 Benchmarks

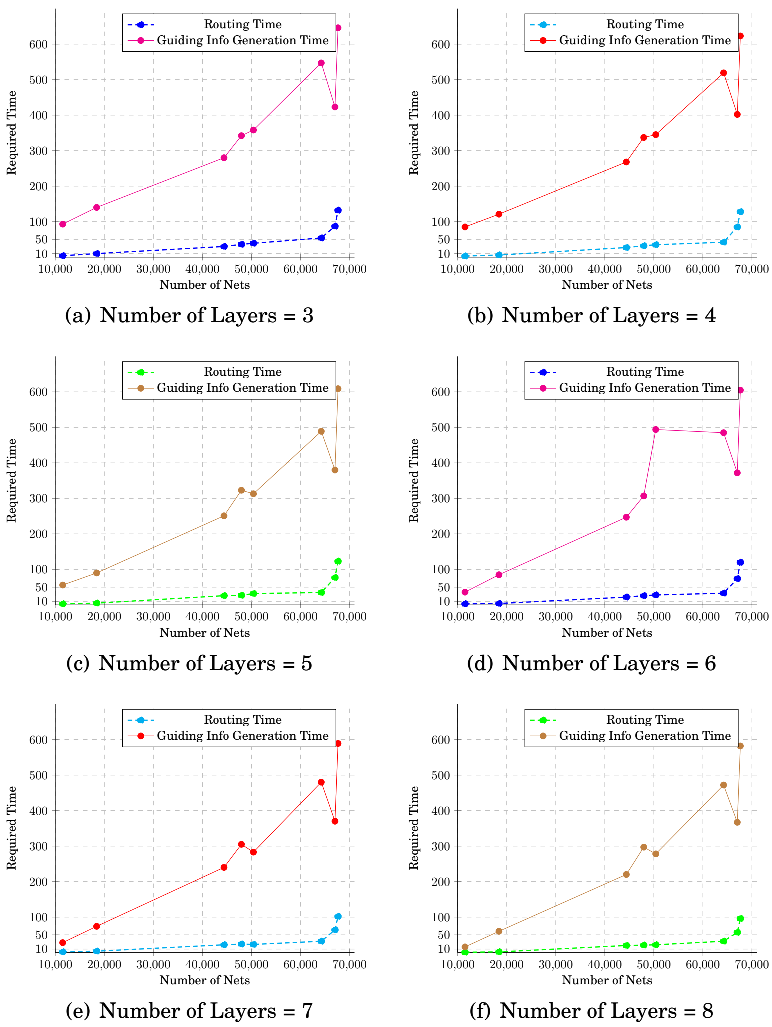
The authors have performed the simulation of FuzzRoute in mentioned(in Section 9.1) desktop environment to match the experimental framework descriptions with other established global routers to be compared. Table IV and V show performance of FuzzRoute for ISPD 1998 benchmarks. Comparisons are made with some foolproof published academic global routers viz. Labyrinth[Kastner et al. 2002], FastRoute3.0[Zhang et al. 2008], NTHU-R[Gao et al. 2008], BoxRouter 2.0[Cho et al. 2009], and FGR[Roy and Markov 2008]. We can not run our comparison with [Dai et al. 2012] and [Liu et al. 2013] because of unavailability of results with ISPD 1998 benchmarks there.

First, the result shows that FuzzRoute is able to route through all the benchmarks.

Second, it achieves good runtime. It can finish routing all benchmarks within reasonable time on our platform. The improvements on routing time over Labyrinth, FastRoute3.0, NTHU-R, BoxRouter 2.0, FGR are 91.81%, -10.29%, -34.91%, 86.87%, and

32.16% respectively. Among all quoted global routers, FastRoute3.0 achieves fastest runtime. But it fails to generate congestion free solutions for all benchmarks e.g. ibm01 and ibm09. Whereas, FuzzRoute can achieve 100% congestion free routability for all the circuits in much lesser time than other specified routers.

Third, in terms of total wirelength FuzzRoute is not only comparable to others but it is much better with improvements of 17.35%, 2.88%, 2.44%, 2.83%, and 2.10% over Labyrinth, FastRoute3.0, NTHU-R, BoxRouter 2.0, FGR respectively.

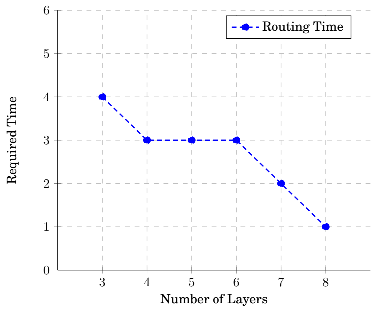


(a) Number of Layers = 3
(b) Number of Layers = 4
(c) Number of Layers = 5
(d) Number of Layers = 6
(e) Number of Layers = 7
(f) Number of Layers = 8

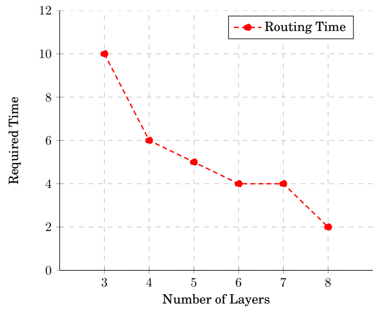
Fig. 19: Variation of Guiding information generation time and Routing time for different ISPD 1998 benchmark circuits [see table III] with different number of layers.

Table III: Experimental Benchmark Statistics for ISPD 1998 Benchmarks.

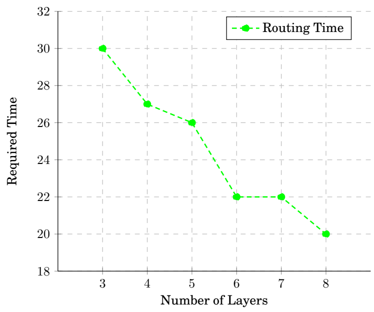
Benchmark	# Net	# Layer	Guiding Info. Gen. Time(sec.)	Routing Time(sec.)
ibm01	11507	3	93.0	4.0
ibm01	11507	4	85.0	3.0
ibm01	11507	5	56.0	3.0
ibm01	11507	6	36.0	3.0
ibm01	11507	7	28.0	2.0
ibm01	11507	8	16.0	1.0
ibm02	18429	3	140.0	10.0
ibm02	18429	4	121.0	6.0
ibm02	18429	5	90.0	5.0
ibm02	18429	6	85.0	4.0
ibm02	18429	7	74.0	4.0
ibm02	18429	8	60.0	2.0
ibm07	44394	3	280.0	30.0
ibm07	44394	4	268.0	27.0
ibm07	44394	5	251.0	26.0
ibm07	44394	6	247.0	22.0
ibm07	44394	7	240.0	22.0
ibm07	44394	8	220.0	20.0
ibm08	47944	3	342.0	36.0
ibm08	47944	4	337.0	32.0
ibm08	47944	5	323.0	27.0
ibm08	47944	6	307.0	26.0
ibm08	47944	7	305.0	24.0
ibm08	47944	8	297.0	21.0
ibm09	50393	3	358.0	39.0
ibm09	50393	4	345.0	35.0
ibm09	50393	5	313.0	32.0
ibm09	50393	6	294.0	28.0
ibm09	50393	7	283.0	23.0
ibm09	50393	8	278.0	22.0
ibm10	64227	3	547.0	54.0
ibm10	64227	4	519.0	42.0
ibm10	64227	5	489.0	35.0
ibm10	64227	6	485.0	33.0
ibm10	64227	7	480.0	32.0
ibm10	64227	8	472.0	32.0
ibm11	67016	3	423.0	87.0
ibm11	67016	4	402.0	85.0
ibm11	67016	5	380.0	77.0
ibm11	67016	6	372.0	74.0
ibm11	67016	7	370.0	67.0
ibm11	67016	8	367.0	57.0
ibm12	67739	3	646.0	132.0
ibm12	67739	4	623.0	128.0
ibm12	67739	5	609.0	123.0
ibm12	67739	6	605.0	120.0
ibm12	67739	7	589.0	102.0
ibm12	67739	8	582.0	96.0



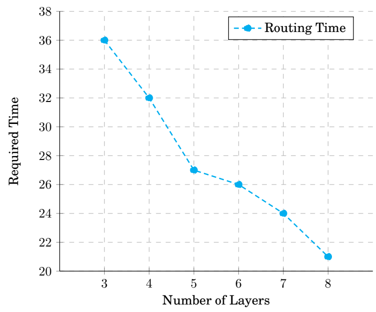
(a) IBM 01



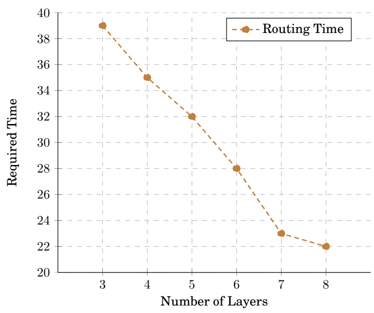
(b) IBM 02



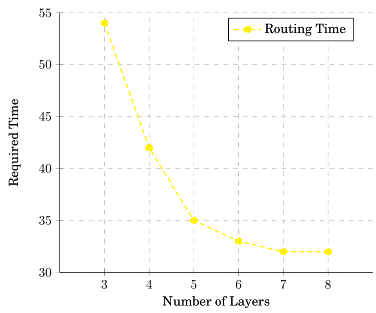
(c) IBM 07



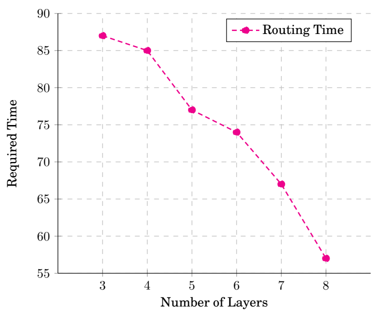
(d) IBM 08



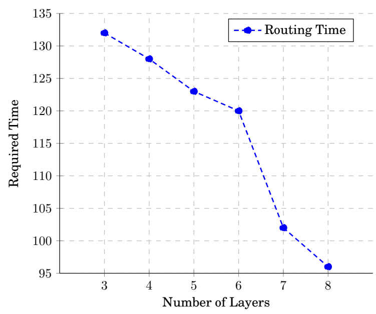
(e) IBM 09



(f) IBM 10



(g) IBM 11



(h) IBM 12

Fig. 20: Variation of Routing time with available number of layers for different ISPD 1998 benchmark circuits [see table III].

Table IV: Comparison of CPU Time in Seconds Between Published Global Routers and FuzzRoute on ISPD 1998 Benchmark Circuits.

Benchmark ISPD '98	Labyrinth [Kastner et al. 2002]	FastRoute3.0 [Zhang et al. 2008]	NTHU-R [Gao et al. 2008]	BoxRouter 2.0 [Cho et al. 2009]	FGR [Roy and Markov 2008]	FuzzRoute
ibm01	21.2	0.64	4.17	33	10	3.0
ibm02	34.5	0.85	7.44	36	13	4.0
ibm07	228.1	1.68	15.89	86	18	22.0
ibm08	238.7	1.82	13.17	90	18	26.0
ibm09	505	1.67	11.59	273	20	28.0
ibm10	588	3.61	33.72	352	92	33.0
Total	1615.5	10.27	85.98	870	171	116.0
Norm	13.92	0.088	.74	7.5	1.474	1

Table V: Comparison of Wirelength Between Published Global Routers and FuzzRoute on ISPD 1998 Benchmark Circuits.

Benchmark ISPD '98	Labyrinth [Kastner et al. 2002]	FastRoute3.0 [Zhang et al. 2008]	NTHU-R [Gao et al. 2008]	BoxRouter 2.0 [Cho et al. 2009]	FGR [Roy and Markov 2008]	FuzzRoute
ibm01	77K	64221	63321	62659	63332	46276
ibm02	205K	172223	170531	171110	168918	166922
ibm07	449K	369023	366288	365790	366180	357121
ibm08	470K	405935	405169	405634	404714	382855
ibm09	481K	414913	415464	413862	413053	403647
ibm10	680K	582838	580793	590141	578795	595465
Total	2362K	2010K	2001K	2009K	1993K	1952K
Norm	1.21	1.03	1.03	1.03	1.02	1

9.6. Comparison for ISPD 2007 and 2008 3D Benchmarks

Table VI, VII and VIII show performance of FuzzRoute for ISPD 2007 and 2008 3D benchmarks suites [Nam et al. 2007] and [Nam et al. 2008]. In table VI, VII FuzzRoute identifies 2.5 %, 2.6 %, 1 %, 1.1 %, and 0.3 % lesser wirelength and averagely runs 1.68×, 6.42×, 2.21×, 0.76×, and 1.54× faster than NTHU-Route 2.0 [Chang et al. 2010], FastRoute 4.0 [Xu et al. 2009], NCTU-GR [Dai et al. 2012], MGR [Xu and Chu 2011], and NCTU-GR 2.0 [Liu et al. 2013] respectively. It is clear from the result set that FuzzRoute can perform total routing operation in much faster than the existing state-of-art tools. It responses in a slower CPU time compared to MGR but providing 1% wirelength improvement in that. Similarly, 1.3% larger wirelength is resulted with a much faster execution compared to FastRoute 4.0.

FuzzRoute achieves overflow free solutions for maximum benchmarks of ISPD 2007 and 2008. Four of them viz. newblue3, newblue4, newblue7, and bigblue4 are generating overflows, represented in Table. VIII. FuzzRoute is showing comparable results with 0.2 %, -0.4 %, 2.1 %, 0.2 %, and 0.3 % improvement in case of total overflow with NTHU-Route 2.0, FastRoute 4.0, NCTU-GR, MGR, and NCTU-GR 2.0 respectively.

From overall analysis of different dominating matrices of performance characterization for different standard benchmarks it is clear that FuzzRoute is competent with state-of-art tools though it can provide an different kind of solution for NP Complete problems in possibilistic way (implementing fuzzy logic), unlike heuristics only.

9.7. Time Complexity Analysis

It is verified that the time complexity of generating guiding information is $O(l \times m \times n)$, where l is the total number of layers, m is the number of subregions in x direction and n is the number of subregions in y direction of the layout. To perform global routing for each net, the time complexity would be $O(l \times (m + n))$. Hence total global routing

Table VI: Comparison of CPU Time in Minute between Published Global Routers and FuzzRoute on ISPD 2007 / 2008 3D Benchmark Circuits.

Benchmark ISPD '07/'08	#Layer	NTHU-Route2.0 [Chang et al. 2010]	FastRoute4.0 [Xu et al. 2009]	NCTU-GR [Dai et al. 2012]	MGR [Xu and Chu 2011]	NCTU-GR2.0 [Liu et al. 2013]	FuzzRoute
adaptec1	6	4.86	3.31	3.90	4.93	2.30	1.73
adaptec2	6	1.42	0.95	1.45	1.04	0.64	0.32
adaptec3	6	6.16	3.69	4.88	4.83	2.96	2.12
adaptec4	6	2.08	1.25	2.28	1.41	1.18	3.72
adaptec5	6	11.95	6.70	9.07	7.95	4.97	4.73
bigblue1	6	6.93	4.22	6.35	5.04	3.44	2.97
bigblue2	6	6.47	12.12	11.18	6.00	3.45	1.95
bigblue3	8	3.91	2.06	4.38	2.89	1.78	3.31
bigblue4	8	52.63	93.25	65.37	21.31	63.55	56.29
newblue1	6	4.07	12.01	3.63	4.51	1.93	1.18
newblue2	6	1.17	0.85	0.90	0.80	0.63	0.74
newblue3	6	64.97	15.99	131.43	19.99	63.34	64.80
newblue4	6	52.01	65.23	40.92	15.64	17.48	3.02
newblue5	6	10.88	9.82	15.03	6.54	4.62	2.79
newblue6	6	10.34	8.78	9.67	7.04	4.02	3.82
newblue7	8	50.08	868.74	71.52	21.31	74.53	18.93
Total		289.93	1108.97	381.96	131.23	250.82	172.51
Norm		1.680	6.428	2.214	0.761	1.544	1

Table VII: Comparison of Wirelength between Published Global Routers and FuzzRoute on ISPD 2007 / 2008 3D Benchmark Circuits.

Benchmark ISPD '07/'08	NTHU-Route2.0 [Chang et al. 2010]	FastRoute4.0 [Xu et al. 2009]	NCTU-GR [Dai et al. 2012]	MGR [Xu and Chu 2011]	NCTU-GR2.0 [Liu et al. 2013]	FuzzRoute
adaptec1	53.49	53.73	53.50	52.28	52.35	52.31
adaptec2	52.31	52.17	51.69	51.69	51.30	50.23
adaptec3	131.11	130.82	130.35	128.92	128.34	128.65
adaptec4	121.73	121.24	120.67	119.96	120.17	120.96
adaptec5	155.55	155.81	154.70	153.23	151.85	152.03
bigblue1	56.35	56.64	56.56	55.82	55.33	54.89
bigblue2	90.59	91.18	89.40	88.92	86.71	86.21
bigblue3	130.76	130.04	129.66	128.75	127.67	126.34
bigblue4	231.04	230.24	223.99	225.73	227.10	226.65
newblue1	46.53	46.33	45.99	45.58	45.62	45.37
newblue2	75.85	75.12	74.88	74.46	74.51	74.44
newblue3	106.49	108.40	104.28	107.22	106.8	105.36
newblue4	130.46	130.46	126.79	128.54	129.27	128.97
newblue5	231.73	230.94	230.31	228.00	225.94	226.78
newblue6	177.01	177.87	176.87	174.86	171.10	170.56
newblue7	353.35	353.38	338.63	349.02	341.90	340.48
Total	2144.35	2144.37	2108.27	2112.98	2095.96	2090.23
Norm	1.025	1.026	1.009	1.011	1.003	1

Table VIII: Comparison of Overflow between Published Global Routers and FuzzRoute on ISPD 2007 / 2008 3D Benchmark Circuits.

Benchmark ISPD '07/'08	NTHU-Route2.0 [Chang et al. 2010]	FastRoute4.0 [Xu et al. 2009]	NCTU-GR [Dai et al. 2012]	MGR [Xu and Chu 2011]	NCTU-GR2.0 [Liu et al. 2013]	FuzzRoute
newblue3	31454	31276	31808	31026	31526	31426
newblue4	138	136	134	136	132	132
newblue7	62	54	114	56	54	56
bigblue4	162	130	164	134	132	134
Total	31816	31596	32220	31352	31844	31748
Norm	1.002	0.995	1.021	0.988	1.003	1

procedure for connecting two-pin, multi-pin, and critical nets requires that much of complexity multiplied by number of nets and, in addition with the time required to process fuzzy expert system for each layer.

With respect to two-pin intra-layer net, the proposed fuzzified approach will result in linear time complexity of $O(m + n)$. So, the proposed approach is presenting better time complexity than typical maze routing approaches, which is $O(m \times n)$ when l = 1. Hence proposed fuzzy logic based two-pin net routing will give linear time complexity instead of quadratic time complexity of maze routing. Here optimal solution is achieved satisfying certain constraints without any guarantee of finding optimum solution whereas maze routing concentrates the solution quality on optimum routing path finding.

10. CONCLUSION AND FUTURE DIRECTION

This article highlights the paramount aspect of global routing problem in 3D ICs by achieving a prominent degree of reliability and routability with a reasonable time complexity. The total methodology of the designed multi objective global router has been verified successfully for two-pin, multi-pin and critical intra, and inter-layer nets for 3D ICs. It may also be considered as a new type of guided global routing approach (using Fuzzy logic) for standard cells. The procedure is tested on ISPD 1998 and 2008 benchmark suites and compared with some well known global routers. Design of a foolproof global routing solution for 3D ICs considering other metrics as well, further comparison with other state-of-art tools in ISPD 2011 benchmark suite, extension to mixed sized cell placements, consideration of voltage drop impact as another working constraint may be considered as some possible future extensions of the present work.

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