Perimeter-Degree: A Priori Metric for Directly Measuring and Homogenizing Interconnection Complexity in Multilevel Placement

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ABSTRACT

In this paper, we describe an accurate metric (perimeter-degree) for measuring interconnection complexity and effective use of it for controlling congestion in a multilevel framework. Perimeter-degree is useful for uniformly spreading interconnection density. In modern designs interconnects consume significant area and power. By making interconnect spread homogeneous, it is possible to improve routability as well as power dissipation distribution.

Most of the existing congestion minimization heuristics are posteriori. In this work, we extend and complement our previous work [16] on priori congestion minimization techniques. In [16], we identified and used perimeter-degree for constructing congestion friendly clusters. This paper extends that work by unveiling perimeter-degree based whitespace allocation techniques.

We show why "number of external nets" is not a desirable candidate for identifying potential regions of high interconnect density and provide perimeter-degree as a possible alternative. We also provide empirical evidence for the effectiveness of perimeter-degree in effectively identifying congested regions even before they are formed. By implicitly allocating resources to these potential high interconnect density regions, 19% reduction in congestion was achieved.

Traditionally, bin capacity bounds are expressed in units of area. In a true interconnect centric approach we ignore area and instead use interconnect complexity as weights for clusters and capacity bounds for bins. This technique creates a placement with homogeneous interconnect density, but slightly unbalanced utilization. On average, this novel interconnect complexity driven scheme reduces congestion by 26%.

Categories and Subject Descriptors

B.7.2 [**Integrated Circuits**]: Design Aids – Placement and Routing.

General Terms: Algorithms, Experimentation

Keywords: Routability, perimeter-degree, multilevel global placement, Congestion, nonhomogeneity, interconnection complexity

1. INTRODUCTION

As predicted by Moore's law, the exponential scaling of process technology has increased the importance of interconnect centric approaches to physical design. A major problem of varying interconnection complexity in a chip is routing congestion. Alleviating interconnect congestion to ensure routability is a fundamental requirement of any VLSI placement system.

The sum of half perimeters of net bounding boxes metric (**half-perimeter wirelength**) is the most common metric used to evaluate the quality of placement. Minimum half-perimeter wirelength is consistent with substantially reduced congestion [19]. However, placement solutions produced using half-perimeter wirelength as the only objective tend to produce local regions of high congestion. In many existing approaches [7][15][21][23] congested regions are attended to after a wirelength reduction stage. Often such schemes involve injection of white space into congested regions either through cell inflation [2][7] or through capacity bound changes [15][23]. After white space allocation the placement solution for that local region is recomputed.

There are two components of congestion. Congestion caused by global wires connecting regions is referred to as **inter congestion** while nets that are completely hidden inside regions determine **intra congestion**. Simple metrics to measure inter congestion and intra congestion are number of external (exposed) nets and pin-density, respectively. A more accurate intra congestion estimate is average wirelength estimate based on regional Rent's exponent [3][4][17]. In [14], authors present a novel scheme for estimating "**local Rent's exponent**". A partitioner derived local Rent's exponent estimate is used for regional average wirelength estimation in [22]. Estimating inter congestion is relatively more difficult. Most physical design tools depend on global router to estimate inter congestion. In [15] authors use a regional router for congestion estimation. A fast incremental global router coupled with a physical hierarchy generation is used for congestion estimation in [27]. A stochastic model for interconnect routing is presented in [9]. A global net-length distribution prediction model for heterogeneous systems is provided in [24]. An area based probabilistic model that mimics supply and demand of routing resources among regions is described in [13].

Our Contributions

- A priori metric for directly measuring interconnection complexity and demonstration of it for pre-emptive whitespace allocation.
- Congestion minimization had been posteriori or on-line process. Most posteriori approaches undo many steps done earlier and result in significant degradation of wirelength. Our priori congestion minimization heuristics with a single-

constraint single-objective scheme enables finding a global solution with much lower congestion with negligible wirelength loss.

- Introduced a simple interconnect centric scheme that uses interconnection complexity for capacity constraint instead of traditional area.

Multilevel placement and related terminology is introduced in section 2. The motivations for using perimeter-degree are presented in 2.1. A static implicit whitespace allocation is given in section 3.1.1, while a dynamic variant is provided in 3.1.2. The section 3.2 presents a novel scheme of using interconnection complexity as bounds on bins to reduce congestion. We present the empirical results of applying these heuristics in section 4. Discussion and conclusion are provided in sections 5 and 6 respectively.

2. BACKGROUND

The problem of VLSI global placement is placing movable cells in approximate areas (**bins**) of the chip (**plane**) in such a way to ensure routable distribution of cells. **Pins** are locations on the cells that connect with nets. We define **region** as a general construct that may refer to a bin or a cluster (**clusters** are collection of cells) based on context. The number of nets exposed from a region is denoted as its **degree** (P). The **perimeter-degree** (P_{peri}) of the region is simply the region degree divided by the region perimeter. We use square root of area of the region as its estimate for region **perimeter**.

We report congestion in terms of **mild congested route edges** (routing demand is between 100% and 110%), **severe congested route edges** (routing demand exceeds 110%) and **routed wirelength** (measured in global routed tree length) as reported by our global router [26].

2.1 PROBLEM DEFINITION

Congestion is a local phenomenon, which occurs when routing demand exceeds available routing resources of a local region. There are two components of routing demand. Routing demand caused by wires that pass over a region (global demand) and routing demand originate from a region (local demand). To estimate the first component either routers or stochastic estimators are used. The second component is often measured in terms of the number of exposed nets (degree) of a region. These two components are inter-related too. For example, a region with high degree will require more "over pass" wires in the adjacent regions. In this paper we present heuristics to implicitly reduce spikes in local routing demand. We measure the effectiveness of our heuristics in terms of number of congested edges of routing grid.

2.2 MOTIVATION

The half-perimeter wirelength metric is capable of reducing global congestion substantially. However, natural solutions derived contain regional variations in interconnection density, as nonhomogeneity in interconnection complexity is not considered. When placed these "dense" portions of netlist create higher degree of the local regions and the resultant congestion. In the following sections we present our theoretical and experimental observations.

2.2.1 Relation of wirelength to degree

The wirelength is the prime indicator of congestion [19]. It is possible to measure wirelength associated with local regions to identify local regions of potential congestion. The degree of a region determines the wirelength associated with that region.

Observation 1 : A linear increase in degree of a bin will super linearly increase the wirelength associated with that bin.

The above observation is clear from the relationship between number of interconnects and their length of a local region. When number of interconnects and their length of a local region are plotted, the gradient of the fitted line corresponds to ($2r_L$-3). Where r_L is "local Rent's exponent" [14]. As r_L increases due to increase in bin degree (from regular Rent's formula), gradient of the fitted line becomes more horizontal. This implies that as the bin degree increases the composition of wires is dominated by wires of ever increasing length. Therefore, the sum of lengths of wires associated with that bin increases super linearly. Empirical evidence for the Observation 1 can be found in [8], where the authors used a multi-objective simulated annealing based refinement scheme with exponentially penalizing cost for higher bin degree. They noted decrease in overall wirelength when bin degree was balanced.

2.2.2 Metrics that correlate to congestion

The bin degree and pin density are two common metrics used for simple congestion control [25]. In this experiment we measured the values of degree, pin density and stochastic congestion [13] for bins containing about 10-30 cells. Then, we calculated the correlation of degree Vs congestion and pin density Vs congestion. This experiment was repeated for 20 industrial designs. The statistics of these 40 correlation numbers are plotted in Figure 1. A value of +1.0 indicates perfect correlation. Nevertheless, the average value of +0.7 as shown in Figure 1 indicates substantial influence of bin degree and pin density on congestion

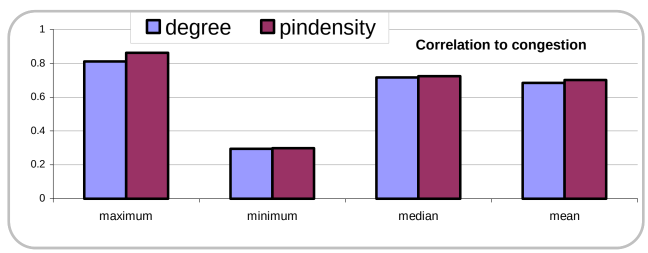

Figure 1 : Correlations to Stochastic Congestion

As one would expect, a bin with high pin density is likely to have high degree. We found the average correlation between bin pin density and bin degree for the bins (containing 10-30 cells) to be +0.82. According to our earlier internal empirical work, degree had turned out to be a better candidate for controlling congestion than pin density.

2.2.3 Comparing bin degree of less congested placements and more congested placements

In these experiments two different sets of placements of 20 industrial designs are created. The first set of placements was created with a single objective of half-perimeter wirelength (from here onward we refer this set as **wlOnly**). The second set of placements was created with both half-perimeter wirelength and congestion objective (we refer this set as **cong+wl**). The second set of placements is less congested[1] than the first set.

"Average bin degree" of a placement often indicates the quality of placement. "Standard deviation of bin degree" of a placement shows the variability of degree. "Maximum bin degree" of a placement indicates the worse local routing demand.

We measured these three metrics for both sets of placement and calculated ratios between cong+wl set and wlOnly set for all 20 designs. The statistics of these ratios are given in Table 1.

		Measured Metrics		
		"Average bin degree"	"Standard deviation of bin degree"	"Maximum bin degree"
statistics	Maximum	1.03	1.05	1.17
	Minimum	0.94	0.69	0.63
	Median	0.98	0.83	0.82
	Mean	0.98	0.85	0.86

Table 1 : ratio of metrics between (cong+wl) and (wlOnly)

When eliminating congestion, "average bin degree" reduces slightly (on average by 2%), but "maximum bin degree" and "standard deviation of bin degree" have on average reduced by 14% and 15% respectively. These results indicate the need to homogenize the distribution of degree for reducing congestion.

2.2.4 Why Perimeter Degree?

In the previous sections, when degree was measured, the area of the regions are same. However, it is misleading to compare degree of two regions with dissimilar area. Because degree is a composite metric of area (number of blocks) and local interconnection complexity. Therefore, we need to normalize the degree. One possible denominator is area. However, area indicates the amount of routing supply available for the entire region (for both intra and inter). But the degree represents the routing demand at the edges of a region. To resolve this discrepancy we define a new metric called perimeter-degree, in an effort to normalize the degree (routing demand at the periphery) by the perimeter (routing supply at the periphery) of a region.

Figure 2 further explains the utility of perimeter-degree as opposed to degree. Both regions A and B have same degree, but B has more supply of routing resources. Perimeter-degree of these two regions seamlessly captures routing supply demand variation at the periphery of these regions. Therefore, perimeter-degree is a suitable metric for estimating local routing demand.

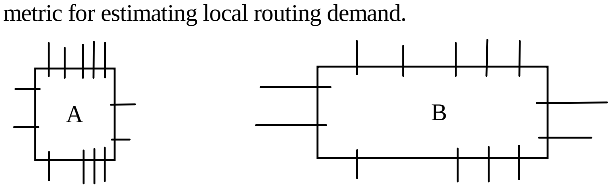

Figure 2 : Equal degree but different perimeter-degree[16]

The question arises as what to do with congestion in the middle of the regions (intra congestion). In a multilevel framework intra congestion at a higher level is captured as inter congestion at the subsequent levels. Therefore, perimeter-degree is a sufficient metric to identify and mitigate congestion in a multilevel placement.

[1] On average 50% reduction in severe congested edges, 18% reduction in mild congested edges and 2% reduction in routed wirelength.

Further, perimeter-degree is similar to Rent's formula for most of the circuits. We modify Rent's formula ($P=kB^r$) [12] to derive an equation for perimeter-degree [16]. (Assuming r >0.5)

$$\begin{aligned} P_{peri} &= P / perimeter \\ &= kB^r / sqrt(area) \\ &= const * B^{(r-0.5)} \end{aligned} \quad \textbf{(1)}$$

Where k – average number of I/O terminals per block
B – number of Blocks
r – Rent's exponent

Researchers have identified "local Rent's exponent" as a useful metric to measure regional interconnect distribution [6][14][22]. Most commonly used methods (curve fitting) to estimate local Rent's exponent are expensive. Instead of relying on such expensive operation we develop simple heuristics based on perimeter-degree to homogenize the interconnect complexity.

3. CONGESTION MINIMIZATION METHODS BASED ON PERIMETER-DEGREE

As discussed in section 2.2.4, the perimeter-degree metric correlates well with the regions of the design that are likely to become highly congested.

Motivated by this observation, we enhanced our placement algorithm to directly take into account extra information provided by this metric, toward the goal of lowering congestion, while still achieving low half-perimeter wirelength and reasonable utilization.

Our placement algorithm is based on the highly effective multilevel placement paradigm [1][10] that directly minimizes the half-perimeter wirelength [26]. Within the context of this multilevel placer, we developed new heuristics for whitespace allocation during the initial placement phase and perimeter-degree based balancing constraint during the refinement phase.

In the rest of this section, we first describe the overall structure of our multilevel placer followed by a description of the perimeter-degree aware heuristics.

3.1 MULTILEVEL PLACEMENT TOOL

The multilevel technique involves creating progressively smaller approximate versions of the netlist (coarsening). We use a clustering scheme similar to Edge Coarsening [10] with an additional denominator for balancing area of clusters (equation 2).

$$affinityWeight = \frac{weight_{net}}{area_{node} * area_{adjacent\_node} * (|net| - 1)} \quad \textbf{(2)}$$

Once the coarsened netlist is created, it is placed on coarsest level of *MxN* bins. We use a FM style [5] quadrisecting [18] refinement that directly minimizes half-perimeter wirelength. During refinement the plane is repeatedly traversed till convergence. Then these bins are quadrisected to create bins for subsequent levels, while refining the netlist, until the level in which a typical bin contains 10-30 cells.

Our tool is capable of simultaneous congestion elimination, timing convergence, logic optimization, clock tree synthesis etc. [26]. However, for most of our experimental purposes we turned off all these features and used the single objective of half-perimeter wirelength to generate placement solutions.

3.1.1 PERIMETER-DEGREE BASED CELL INFLATION

At the cell level perimeter-degree captures the inherent lack of homogeneity in interconnection complexity. In this method we inflate cells that have relatively larger perimeter-degree before the clustering phase to dilute the inherent higher density portions of the netlist. For lower utilization designs, it is possible to inflate cells more than higher utilization designs. Taking advantage of this, we used three different cell inflation levels (Pseudocode 1). We estimate mean and standard deviation of perimeter-degree, and then use these parameters to determine three threshold values. The amount to whitespace allocated is in relation to deviation of perimeter-degree from the maximum allowed threshold for that particular design.

```
Procedure Inflate_high_periDegree_cells()
Input: netlist
Output: netlist with some inflated cells
Variables: μ - mean perimeter-degree(cell)
           σ - standard deviation of perimeter-degree(cell)
           max_pd = maximum allowed perimeter_degree(cell)
Calculate perimeter_degree of each cell by dividing number of IO terminals by SQRT(area(cell)).
Calculate μ,σ of perimeter_degree.
if utilization_factor² < 0.60
  max_pd = μ -0.5*σ
elseif utilization_factor < 0.80
  max_pd = μ
else
  max_pd = μ +σ
foreach cell
  if perimeter_degree(cell) > max_pd
    set cell area as ( area(cell) * max_pd / perimeter_degree(cell) )
```

Pseudocode 1 : inflating high perimeter-degree cells

3.1.2 PERIMETER-DEGREE BASED CLUSTER INFLATION

The previous scheme captured inherently dense interconnect regions of the netlist. However, during clustering new dense interconnect regions may appear. Therefore it is necessary to dilute these dense regions. In this post-clustering method, we inflate higher perimeter-degree clusters after they are created.

Although inflating clusters after clusters are formed diverges from original clustering objective / constraint used, it captures and addresses nonhomogeneity introduced by the clustering formulation as well as nonhomogeneity inherently present in the netlist. Once the clusters for a particular quadrisection level are generated, all the clusters with perimeter-degree above mean + standard deviation are inflated. We empirically found this threshold to be appropriate for our tool. Pseudocode 2 describes the procedure used.

[2] utilization_factor = total cell area / total placeable area

```
Procedure Inflate_high_periDegree_clusters()
Input: clusters
Output: clusters with some of them inflated
Variables: μ - mean perimeter-degree(cluster)
           σ - standard deviation of perimeter-degree(cluster)
           max_pd = maximum allowed perimeter_degree(cluster)
Calculate perimeter_degree of each cluster by dividing its degree by SQRT(area(cluster)).
Calculate μ,σ of perimeter_degree(cluster).
max_pd = μ +σ
foreach cluster
  if perimeter_degree(cluster) > max_pd
    set cluster area as ( area(cluster) * max_pd / perimeter_degree(cluster) )
```

Pseudocode 2 : inflating high perimeter-degree clusters

3.2 USING SUM OF PERIMETER-DEGREE OF CLUSTERS AS A CAPACITY BOUND FOR BINS

Perimeter-degree of a cluster indicates the likelihood of it to cause congestion. If a bin contains clusters with relatively higher perimeter-degree, then that bin is likely to become more congested. The motivation of this approach is to place clusters in bins such that sum of perimeter-degrees of clusters in each bin is relatively balanced.

One straight forward implementation is to use both area and perimeter-degree of clusters as two capacity constrains on the bins and use a multi-constraint solver (similar to [11]). Another approach would be to use perimeter-degree of clusters directly. This will create somewhat area unbalanced solution. However, these overstuffed bins can be attended to in a quick bin area legalization phase.

For simplicity, we chose the latter option. To implement this approach we calculated a pseudo area for clusters that makes the perimeter-degree of the clusters uniform. In other words, cluster with a larger perimeter-degree gets larger pseudo area when compared with a cluster with a lower perimeter-degree.

After the clusters are generated, Pseudocode 3 applied to replace the actual areas of the clusters with pseudo areas. The bin capacities are left unchanged as the total actual cluster area is equal to total pseudo area.

Once these clusters are placed, a quick area legalization iteration is applied to reduce the utilization of over-stuffed bins. Relatively lower utilization factors of modern designs reduce the amount of legalization effort required.

```
Procedure make_periDegree_uniform_for_clusters()
Input: clusters
Output: clusters with pseudo area
Variables: μ - mean perimeter-degree(cluster)
Calculate perimeter_degree of each cluster by dividing its degree by SQRT(area(cluster)).
Calculate μ. of perimeter_degree(cluster).
foreach cluster
    set cluster area as ( degree(cluster) / μ )
```

Pseudocode 3 : Homogenizing perimeter-degree of clusters

4. EXPERIMENTAL RESULTS

To implement the above heuristics we used an industrial tool as described in section 3.1 [26].

The characteristics of benchmarks used in the following experiments are given in Table 2. All reported experiment results are average of 3 runs.

	Number of cells	Number of nets	Macro cells	Utili-zation (%)	Percentage of congested route edges[3]	
					mild	severe
m01	57638	60933	13	39.9	4.07	1.08
m02	100245	103404	33	42.3	0.60	0.01
m03	22336	27449	8	39.1	13.91	3.02
m04	22830	23041	13	50.3	4.45	0.21
m05	153263	201186	33	76.2	14.83	2.26
m06	78767	78522	0	69.8	25.81	6.31
m07	152178	195139	10	77.1	52.99	25.68
m08	117413	121239	54	79.7	4.15	0.41
m09	16056	18291	0	70.1	36.11	17.38
m10	99276	111610	0	65.8	82.89	68.74
m11	25409	29844	0	85.9	22.20	2.77
m12	56083	62745	4	81.5	34.92	13.75
m13	40730	45351	0	82.9	13.51	1.02
m14	45369	45309	0	88.1	1.33	0.05
m15	262079	327060	12	85.1	3.59	0.48
Avg	83311	96741		68.9	21.02	9.54

Table 2 : Details of benchmarks used

4.1 EMPIRICAL RESULTS OF CELL INFLATION

In this section we provide the empirical results of heuristic presented in 3.1.1. The ratios derived by dividing the results by wlOnly results are plotted in Figures 7,8 and 9. The numbers less than 1.0 implies better result and the ratio above 1.0 indicates a worse result. Figure 3 plots the statistics of these ratios. The average quality of placement as measured by half-perimeter has increased by half percent. But average routed wirelength has reduced by 0.2%. More importantly, mild congested edges and severe congested edges have on average decreased by 8% and 14% respectively.

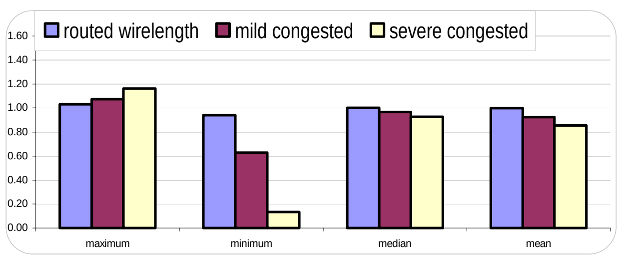

Figure 3 : Statistics of ratios of routed wirelength, congested edges of cell inflation

In this method, cells are inflated before the global placement begins. Therefore, whitespace added to the cells is taken into consideration when setting area capacity bounds on bins.

4.2 RESULTS OF CLUSTER INFLATION

This section presents the results of the heuristic given in 3.1.2. Figures 7, 8 and 9 present detailed results of applying Pseudocode 2 to clusters. In Figure 4, we depict the summary. Half-perimeter wirelength and routed wirelength have on average worsened by 1.3% and 0.75% respectively. In "m11", possibly due to over constraining we observed 43% worse congestion compared to wlOnly result. However, on average mild congested edges have decreased by 3%, while severe congested edges have decreased by 14%. Compared to previous scheme, median has reduced.

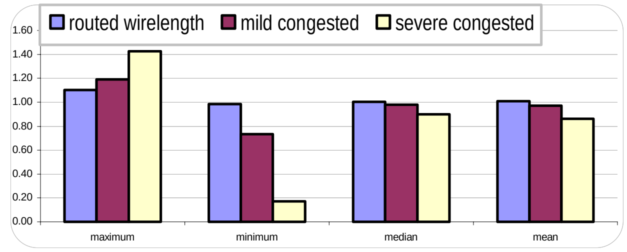

Figure 4 : Statistics of ratios of routed wirelength and congested edges of cluster inflation

A more aggressive whitespace allocation will in general reduce congested edges further. But capacity bounds on the bins in our current setup are set before the cluster inflation. Therefore, we avoided inflating more as it will over constrain the hill climbing ability of FM and result in inferior solutions.

4.3 A COMBINED METHOD

It is also possible to inflate both cells and clusters. In this method we combine the heuristics presented in 3.1.1 and 3.1.2 by inflating all the cells that have perimeter-degree above $\mu + 0.25\sigma$, and dynamically inflating all the clusters that have perimeter-degree above $\mu + 1.75\sigma$. We found these values to be most promising for the default configuration of our tool without any capacity bound relaxation.

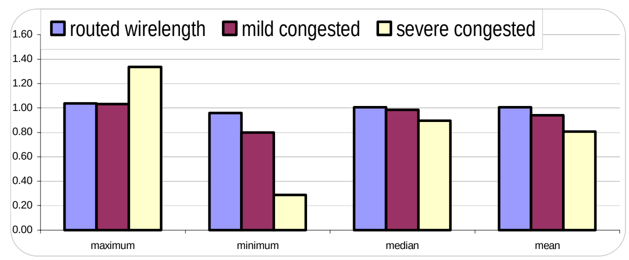

Figure 5 : Statistics of ratios of routed wirelength, congested edges of both cell and cluster inflation

In this method, half-perimeter and routed wirelength have increased by 1.1% and 0.5% respectively. On average mild congested edges have decreased by 6% while severe congested edges have decreased by 19% as shown in Figure 5. The detailed ratios are presented in Figures 7, 8 and 9. In 4.2, the design "m01" had 10% worse wirelength and resultant worse congestion. But in this combined method, wirelength is under control and congestion is reduced by 38%.

4.4 RESULTS OF USING SUM OF PERIMETER-DEGREE OF CLUSTERS AS A CAPACITY BOUNDS FOR BINS

Here we present empirical result of applying heuristic presented in section 3.2. Congestion is often a local phenomenon, hence it may not be necessary to balance degree early on. Therefore, we let our tool use actual areas of clusters for first few quadrisection levels. In this experimental setup, pseudo areas of clusters are used for last three quadrisection levels. The benchmarks used require 4 to 6 quadrisection levels to complete global placement. Although anticipated, we surprisingly did not encounter any legalization

[3] when original netlist is placed and routed with single objective of half-perimeter wirelength (average of 3 runs).

problems. Relatively lower utilization factors of the benchmarks may have helped. In Figure 6 we present the results.

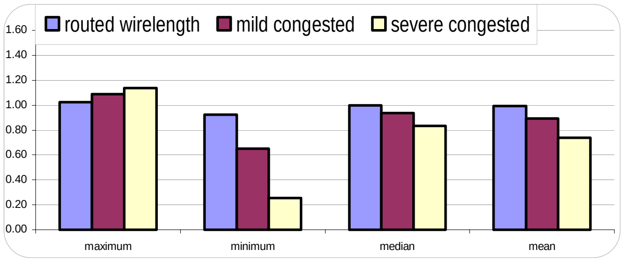

Figure 6 : Statistics of ratio of routed wirelength and congested edges of using sum of perimeter-degree of clusters as bin capacity bound

The results are presented in detail in Figures 7,8 and 9. The half-perimeter wirelength on average has increased by 0.1%, while routed wirelength has reduced by 0.7%. Mild congested edges have reduced by 11% and severe congested edges have reduced by 26%.

The methods 4.1 to 4.3 implicitly allocate whitespace to potential higher density regions. But this method proves that congestion can be reduced even without any whitespace allocation. An interesting point to note here is the negligible amount of half-perimeter wirelength loss.

5. DISCUSSION AND FUTURE WORK

Some of the factors that influence congestion are less optimal half-perimeter wirelength, nonhomogeneity in interconnection complexity and nonhomogeneity in routing supply. Routing supply varies due to the presence of macro cells as well as physical location of the region (since the amount of wires that pass over the region varies depending on physical location).

The main avenue to reduce congestion is to minimize half-perimeter wirelength. Most of the existing posteriori congestion minimization techniques result in significant wirelength loss. The results we have presented here shows no significant half-perimeter wirelength loss, which indicates that the congestion caused in our tool is mainly due to varying interconnection complexity and varying supply of routing resources. These results also indicate the limitation of half-perimeter metric.

We have presented effective techniques to tackle nonhomogeneity in interconnection complexity and currently focusing on handling nonhomogeneity in routing supply. It is possible to estimate perimeter-degree based bin bounds (similar to section 3.3) by accurately estimating routing supply. The motivation for such an approach is if a particular region has less supply, we can reduce the demand of that region by reducing the utilization factor for that region. We intend to use such estimated bounds on bins to further reduce congestion.

The implicit whitespace allocation schemes need more investigation to further understand optimal amount of allocation. One would need to consider the bin capacity bound relaxation parameters and other features of particular tool to determine the optimal amount inflation required. For these experiments, we used the default capacity bound configuration of our tool.

6. CONCLUSION

The metric perimeter-degree provides a simple and effective methodology for inherently homogenizing interconnection complexity without explicitly evaluating local Rent's exponent.

As far as we are aware, there is no other previous work on priori congestion minimization technique that is capable of reducing congestion substantially.

More significantly, ours is the first strategy to use interconnection complexity as a direct capacity constraint instead of the commonly used area. In the traditional flow, area of cells took the center stage. But for modern designs interconnect centric approaches are necessary. Perimeter-degree is easy to measure and we have shown the potential of it to replace area of cells in a true interconnect density driven approach.

Reducing nonhomogeneity in interconnection complexity also reduces other problems such as crosstalk, power dissipation etc. The framework presented here for improving routability can easily be extended to these aspects as well.

7. ACNOWLEDGEMENTS

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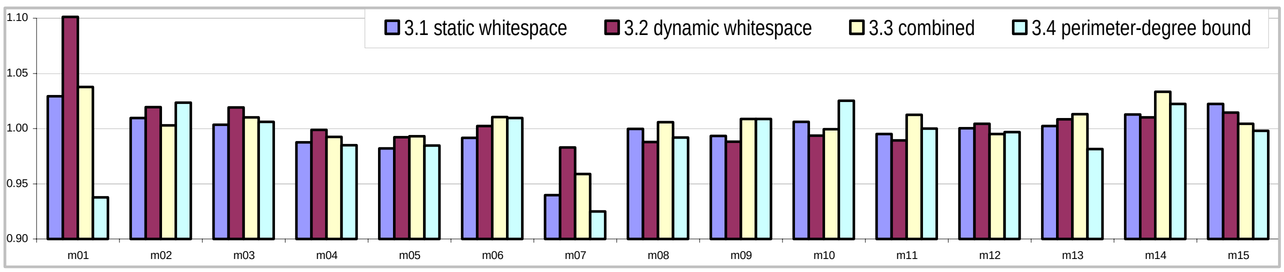

Figure 7: Ratios of Routed Wirelength (average of 3 runs)

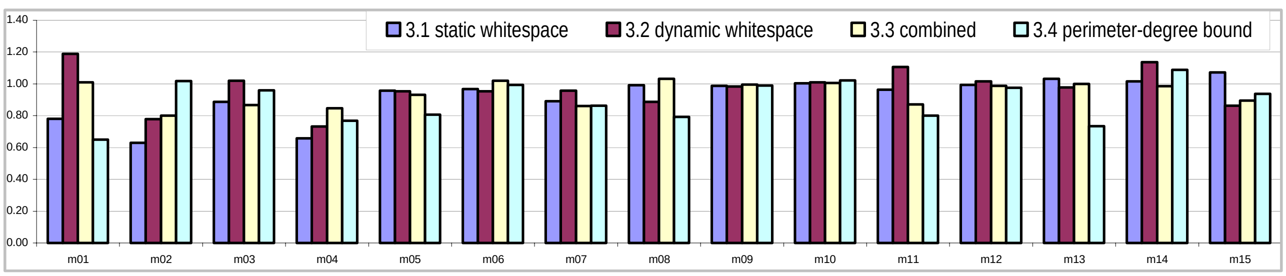

Figure 8: Ratios of Mild Congested Edges (average of 3 runs)

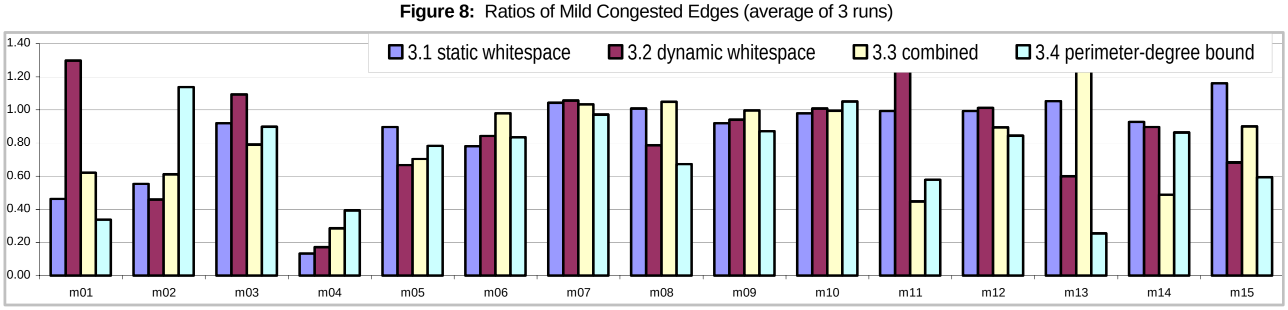

Figure 9 : Ratios of Severe Congested Edges (average of 3 runs)