Measuring Routing Congestion for Multi-Layer Global Routing

Tom Chen
Alkan Cengiz
Department of Electrical and Computer Engineering
Colorado State University
Fort Collins, CO 80523

Abstract

We propose an accurate measure of channel routing density and its application to global routing. Our congestion metric calculation method considers the wire scenarios in a channel.

1 Introduction

Interconnect routing consists of two major steps: global routing and detailed routing. The goal of global routing tries to balance the routing density of the channels involved with a given route. Detailed routing completes the routing process by assigning the nets to specific tracks in channels. The success of the detailed routing and the whole routing process relies on the quality of global routing.

Global routing employs a measure of routing capacity of a channel in order to balance the routing density. Routing density of a given channel can be measured using a variety of congestion metrics proposed to date [1, 3, 5, 6, 8].

We propose a new congestion metric to use with global routing. The proposed congestion metric incorporates many features seen in multi-layer routing, such as isolated vias on a routing layer due to layer promotions and demotions between the neighboring layers of the given layer. One congestion metric proposed in [4] can take a huge amount of CPU time and memory space for large channels with multi-layer metals. In the proposed scheme, a more pessimistic measure is used so that the congestion metric can be calculated without knowing the dominating set. Our results show that the proposed method for calculating congestion metric requires far less CPU time and memory space with little sacrifice in the accuracy of the congestion measurement.

2 Existing Work on Congestion Metric

Most congestion metrics use occupied tracks to find the routing density of a given channel, maximum number of occupied tracks on maximum density column is given as routing density in [1]. Ratio of terminals on a channel to nets to be routed in that channel provides a fixed metric for channel density [5, 9]. Some methods incorporates the number of nets on left-exit and right-exit in addition to the number of nets to be routed in the channel [6]. Ratio of pins to cells is also used for the routing density around cells [5]. Ratio of physical wire area to total area is among the proposed methods to calculate the routing density of a box [8]. Most of the methods lack from reflecting whether a particular net can be inserted into channel or not because they don't incorporate many features of interconnect routing such as isolated vias on multi-layer routing.

3 The New Congestion Metric

A channel, shown in Figure 1, is defined as a rectangular box T_h and T_v are the number of maximum horizontal and vertical tracks respectively. Layers are divided into two groups of layers, horizontal and vertical.

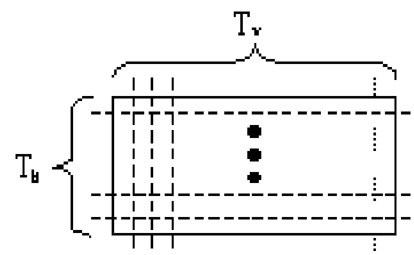

Figure 1: A channel

For a given routing channel, *routing requirement vector* ($\vec{rrv}$) is a 10-tuple vector representing existing routing and any additional routing we may want to add, the minimal dominating set is a set of maximally routable $\vec{rrv}$s ($\vec{dv}$s) that represents channel routing capacity, and finally, the blockage vector ($\vec{bv}$) is a 10-tuple vector representing channel routing limitation due to blockages.

3.1 Routing Requirement Vector

There are four scenarios that a net goes through a channel: a net enters and leaves from any one of the four sides of the channel; a net enters any one of the four sides of the channel and terminates in the channel; a net originates from inside the channel and leaves from any one of the four side of the channel; and a net starts and terminates within the channel. From congestion's point of the view, the last type of the wire can be viewed as blockage and is treated separately in Section 3.2.

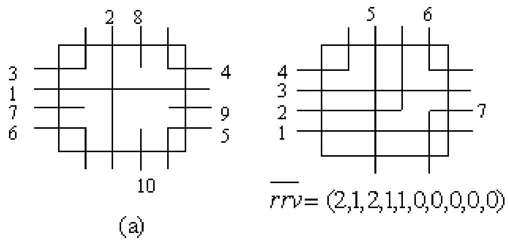

Figure 2: (a) Ten type of wires. (b) Routing vector

Figure 2 (a) illustrates ten type of wires related to a given channel. Type 1 to type 6 wires belong to the first scenario, and type 7 to type 10 belong to the second and third scenarios. The quantity of these ten types of wires in a given channel is expressed by a *routing requirement vector* as defined in Equation (1).

$$r\vec{r}v = (r_1, r_2, r_3, r_4, r_5, r_6, r_7, r_8, r_9, r_{10}) \quad (1)$$

Figure 2 (b) shows an example of a routing channel and its associated routing requirement vector. To calculate the routing requirement vector of a given channel, we need to enumerate the nets along the sides of the channel as shown in Figure 2 (b), and then use Equations (2) and (3) to determine the value of r_i.

$$\begin{aligned} b_n &= \begin{cases} 1 & \text{if any } n_{bi} = n,\ i = 1..T_v \\ 0 & \text{otherwise} \end{cases} \\ u_n &= \begin{cases} 1 & \text{if any } n_{ui} = n,\ i = 1..T_v \\ 0 & \text{otherwise} \end{cases} \\ l_n &= \begin{cases} 1 & \text{if any } n_{li} = n,\ i = 1..T_h \\ 0 & \text{otherwise} \end{cases} \\ r_n &= \begin{cases} 1 & \text{if any } n_{ri} = n,\ i = 1..T_h \\ 0 & \text{otherwise} \end{cases} \end{aligned} \quad (2)$$

$$\begin{aligned} T_n &= b_n + u_n + l_n + r_n \qquad ,n = 1..N \\ r_1 &= \textstyle\sum_{i=1}^{N} \frac{l_i * r_i}{T_i - 1} \qquad r_2 = \sum_{i=1}^{N} \frac{u_i * b_i}{T_i - 1} \\ r_3 &= \textstyle\sum_{i=1}^{N} \frac{l_i * u_i}{T_i - 1} \qquad r_4 = \sum_{i=1}^{N} \frac{u_i * r_i}{T_i - 1} \\ r_5 &= \textstyle\sum_{i=1}^{N} \frac{b_i * r_i}{T_i - 1} \qquad r_6 = \sum_{i=1}^{N} \frac{l_i * b_i}{T_i - 1} \\ r_7 &= \textstyle\sum_{i=1}^{N} l_i * \overline{(u_i + r_i + b_i)} \\ r_8 &= \textstyle\sum_{i=1}^{N} u_i * \overline{(l_i + r_i + b_i)} \\ r_9 &= \textstyle\sum_{i=1}^{N} r_i * \overline{(u_i + l_i + b_i)} \\ r_{10} &= \textstyle\sum_{i=1}^{N} b_i * \overline{(u_i + r_i + l_i)} \end{aligned} \quad (3)$$

A branching net is to be converted into multiple types of wires and weighted accordingly in the routing requirement vector so that number of occupied tracks by the net won't change.

3.2 Blockage Vector

In reality, there are blockages in the routing area such as some short wires inside the channel that doesn't fit definitions of any ten type wires or some isolated vias in layers due to a connection between two other layers. Blockages are presented in congestion metric as a 10-tuple *blockage vector* ($\vec{bv}$). Each element in the blockage vector is the upper limit of the number of paths available for one of the ten types of wires within a given routing channel.

Determining the blockage vector elements for types 1,2,7,8,9 and 10 wires are relatively straightforward. The blockage vector elements for types 1 and 2 wires are the number of horizontal and vertical tracks respectively in the routing space that don't have any blockages. The blockage vector elements for types 7,8,9, and 10 wires are the number of tracks at left, top, right, and bottom side of routing space respectively, that don't have any blockages on the left-most vertical track, the top-most horizontal track, the right-most vertical track, and the bottom-most horizontal track respectively.

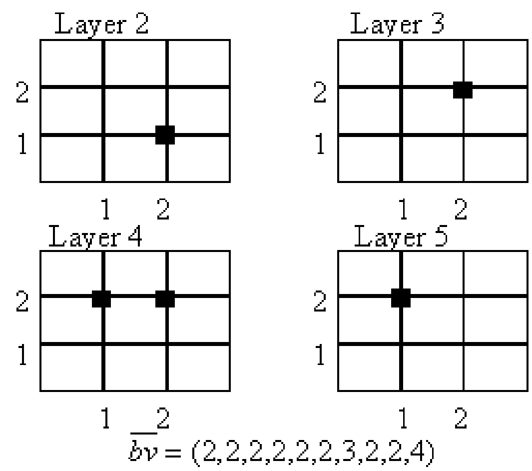

Figure 3: Blockages and blockage vector

Figure 3 shows a simple example when there are 2 vertical and horizontal tracks in a 4-layer routing space with some isolated vias. Layers 2 and 4 are horizontal layers. Layers 3 and 5 are vertical layers.

Determining the blockage elements for types 3,4,5, and 6 wire is a little more complicated. Here, we assume via stacking is allowed. Every horizontal track on a horizontal layer, h, is checked on two sides of the routing space, (i.e left and right). Every horizontal track is paired with every vertical track in the routing space to form V-H track pairs. Each track pair is traced from either the left or the right side of the routing space. The pairs traced from left and right sides before encountering any blockages are listed in S_{hl} and S_{hr}, respectively. Similarly, track pairs generated from vertical tracks are listed in S_{vt} and S_{vb}, where t and

b indicate the track direction from top and bottom side of the routing space, respectively.

Taking Figure 3 as an example with the isolated vias on layers 2,3,4, and 5, and assuming layers 2 and 4 are for horizontal routing and layers 3 and 5 are for vertical routing, then

$$\begin{array}{ll} S_{2l} = (1,1),(1,2),(2,2) & S_{2r} = (1,2),(2,2) \\ S_{3u} = (1,1),(1,2) & S_{3b} = (1,1),(2,1),(1,2) \\ S_{4l} = (1,1),(2,1) & S_{4r} = (1,1),(2,1) \\ S_{5u} = (2,1),(2,2) & S_{5b} = (1,1),(2,1),(2,2) \end{array} \quad (4)$$

where the first element in each of the V-H pairs is vertical track number and the second element is the horizontal track number. For each type of wire, k, where k=3,4,5 and 6, the list of the V-H pairs that type-k wire has a path on horizontal layer h and vertical layer v is

$$S_{hvk} = S_{hm} \bigcap S_i ... \bigcap S_{vn} \quad (5)$$

where S_i contains list of V-H track pairs that don't have blockages between layers h and v. For the example in Figure 3, $S_2 = (1,1),(1,2),(2,2)$, $S_3 = (1,1),(2,1),(1,2)$, $S_4 = (1,1),(2,1)$, and $S_5 = (1,1),(2,1),(2,2)$. m and n are one of the sides (l,r,t,b) of the routing space depending on wire type-k. S_{hvk} in Equation 5 is calculated for each possible combinations of horizontal layer h and vertical layer v for a given technology. Equation 6 shows the ones needed to calculate the type-3 wire for the given example in Figure 3. The pruned list of track pairs from the Equation 6 for wire type 3 is (1,1),(2,1) or (1,2),(2,1) and, therefore there are two paths for type-3 wire.

$$\begin{array}{rcl} S_{233} & = & S_{2l} \bigcap S_{3u} \\ & = & (1,1),(1,2),(2,2) \bigcap (1,2),(1,2) \\ & = & (1,1),(1,2) \\ S_{253} & = & S_{2l} \bigcap S_3 \bigcap S_4 \bigcap S_{5u} \\ & = & (1,1),(1,2),(2,2) \bigcap (1,1),(2,1),(1,2) \bigcap \\ & & (1,1),(2,1) \bigcap (2,1),(2,2) \\ & = & \phi \\ S_{343} & = & S_{3u} \bigcap S_{4l} \\ & = & (1,1),(1,2) \bigcap (1,1),(2,1) \\ & = & (1,1) \\ S_{453} & = & S_{4l} \bigcap S_{5u} \\ & = & (1,1),(2,1) \bigcap (2,1),(2,2) \\ & = & (2,1) \end{array} \quad (6)$$

3.3 The Congestion Metric

Congestion metric is a comparison of a given routing vector ($\vec{rrv}$) and blockage vector ($\vec{bv}$) with the dominating vectors ($\vec{dv}$) of a given routing channel. (refer to [4] for details about the dominating vectors) A pruning operation is done prior to calculation to eliminate the invalid maximally routable dominating vectors ($\vec{dv}$s) from dominating set. Equation 7 is a subset of dominating set that each $\vec{dv}$ in the subset dominates the routing vector and dominated by the blockage vector. Therefore, subset represents channel's possible routing configurations for given $\vec{rrv}$ and $\vec{bv}$.

$$\vec{dv_{sub}} = (\vec{dv} \supset \vec{rrv}) \subset \vec{bv} \quad (7)$$

$$R = \sum_{i=1}^{10} (e^{r_i - d_i} + e^{d_i - b_i}) \quad (8)$$

R, the new congestion metric, has two components: comparison of routing vector with dominating vector and comparison of the blockage vector with dominating vector as illustrated in Equation 8. In high density channels, the difference between dominating vector and routing vector, and between blockage vector and dominating vector are often small, resulting in a higher congestion. Congestion from each maximally routable $\vec{dv}$ in the subset will yield a different value. The average values of all congestions calculated from the subset are often used to determine the overall congestion. The problem with this approach is that it requires all dominating vectors in the dominating set be known. Our method uses the minimum congestion value among the congestions from the subset. Choosing the minimum congestion would be pessimistic, but it gives us an opportunity to calculate the congestion without knowing the whole dominating set.

The justification of using the minimum congestion can be explained as follows. Given the congestion metric defined in Equation 8, a minimum point at $d_i = (r_i + b_i)/2$ for a given $\vec{rrv}$ and $\vec{bv}$ as shown in Figure 4. The $\vec{dv}$ constructed from $d_i = (r_i + b_i)/2$ for a given $\vec{rrv}$ and $\vec{bv}$ is hardly a maximally routable $\vec{rrv}$. However, with this $\vec{dv}$, we can find a maximally routable $\vec{dv}$ with the following steps:

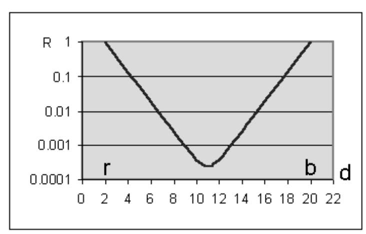

Figure 4: Min. Congestion value at $d = (r+b)/2$, $r = 2$, $b = 20$

1. An initial $\vec{dv}$ is constructed from the equation $d_i = (r_i + b_i)/2$ for a given $\vec{rrv}$ and $\vec{bv}$ of a routing channel. Since initial $\vec{dv}$ is a global minimum, any increase or decrease of d_i will result in an increase in the congestion.

2. Set the costs (C) for all ten type of wires to the amount of change in congestion when d_i is changed by one unit as shown in Equation 9.

$$C = \Delta R_i = (e^{\pm 1} - 1) * e^{r_i - d_i} + (e^{\mp 1} - 1) * e^{d_i - b_i} \quad (9)$$

3. Chose a wire type with minimum cost among other wire types. If wire type's value is bigger than the blockage value and smaller than the routing value of the same type wire, remove the wire type from list and repeat the Step 3.

4. Evaluate the new $\vec{dv}$ in the Inequalities (**??**). If the chosen wire type need to be increased to satisfy the inequalities, increase value of wire type by one unit and vice versa.

5. If the new $\vec{dv}$ satisfies the Inequalities (**??**), terminate the algorithm, otherwise set the new cost for the wire type using the cost in Equation (9) and then go to Step 3.

when the algorithm terminates, the last calculated $\vec{dv}$ is a dominating vector and it minimizes the congestion for a given $r\vec{r}v$ and $\vec{bv}$.

Figure 5 shows the error of congestion measure of our approach compared to the method using the average value of all congestions from the subset. The maximum congestion error happens when channel is least congested. With higher congestion, the minimum value is very close to the average value. It is clear that the proposed method is more efficient by not using the dominating set to determine congestion with little sacrifice on accuracy when it is needed the most, i.e. in the high congestion environment.

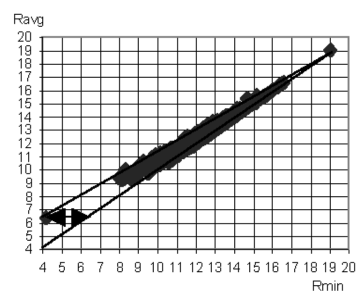

Figure 5: Min. values vs. ave. values of congestion

4 Experimental Results

We applied our congestion metric to several routing cases as shown in Figure 6. The congestion values shown in Figure 6 is for adding a type-1 wire into the existing channel. Figure 6 (a) is a empty channel and it's congestion is the lowest as expected. Figure 6 (b) is a channel with some routing inside with a slightly higher R value. Channel in Figure 6 (c) is full, therefore there is no dominating vector that dominates the routing vector. An empty dominating set shows that it is not possible to add a type-1 wire.

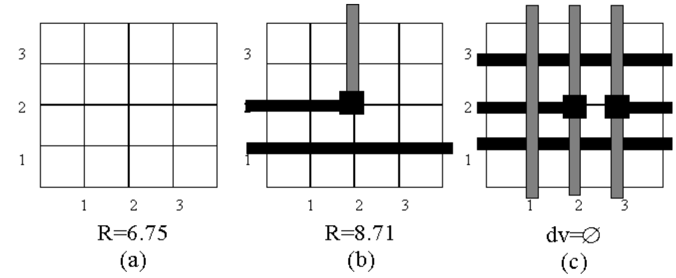

Figure 6: Congestion values under 3 diff. cases.

5 Concluding Remarks

This paper introduces a new congestion metric for measuring interconnect channel routing density. After the extraction of $r\vec{r}v$s and $\vec{bv}s$ from layout, it doesn't require to store the dominating set. This feature makes our algorithm be advantageous over the existing methods in terms of CPU time and memory requirements. Our experimental data show that the proposed congestion metric sacrifices very little accuracy for congestion measurement compared to that of using the entire dominating set.

References

[1] G.W.Zobrist, *Routing, Placement, and Partitioning*, Ablex Publishing Corp., Norwood, NJ, 1994.

[2] T.Xue, E.S.Kuh,D.Wang, *Post Global Routing Crosstalk Risk Estimation and Reduction*, ICCAD, 1996, pp 302-309.

[3] S.Nakatake, Y.Kajitani, *Channel-Driven Global Routing with Consistent Placement*, ICCAD, 1994, pp 350-355.

[4] S.Thakur, K.Zhu, D.F.Wong, *A New Global Routing Algorithm for FPGAs*, ICCAD, 1994, pp 356-361.

[5] M. Schlag, J.King,P.K.Chan, *Routability-Driven Technology Mapping for LookUp Table-Based FPGAs*, ICCD, 1992, pp 86-90.

[6] Y.Cai,D.F.Wong, *Channel Density Minimization by Pin Permutation*, ICCD, 1992, pp 378-382.

[7] J.Cong, Z.Pan, L.He, C.K.Koh, K.Y.Khoo, *Interconnect Design for Deep submicron ICs*, ICCAD, 1997, pp 478-485.

[8] C.E.Chen, *RISA: Accurate and Efficient Placement Routability Modeling*, ICCAD, 1994, pp 690-695.

[9] X.Liu, I.G.Tollis, *Improving Over-The-Cell Channel Routing In Standard Cell Design*, ICCAD, 1994, pp 606-609.