New Results on Channel Routing

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Abstract

In this paper, we present a new routing concept which guides the selection of wire segments in track-by-track fashion by inspecting the effects of the endpoints of each selected wire segment to column density and vertical constraint graph of the given channel routing problem. This new routing concept has been implemented in the two-layer and three-layer routers. The routing performance of the developed two-layer and three-layer routers has overwhelmingly outperformed all the currently existing two-layer and three-layer routers in most examples in the literatures as shown in experimental results.

Introduction

A channel router is designed to interconnect terminals on two opposite sides of a rectangular region called a *channel*. Traditionally, two layers are available for routing and the restricted-Manhattan model is adopted, i.e. all the horizontal wire segments are routed in one layer and all vertical wire segments in the other, and the connection between wires in different layers is through electrical contacts called *vias*. Since the interconnection area usually represents a significant portion of the total area in a typical polycell integrated circuit design, the primary goal of a channel router is to minimize the above interconnection area by minimizing the number of tracks used. The number of vias and the length of wires are also important in evaluating the quality of the routing.

Since the channel routing problem has been proven as NP-complete and theoretical achievements are limited, the development of the heuristic algorithms to approach better routing solutions has been considered mandatory and justified, which is discussed in this paper. The channel routing algorithm presented in this paper, which routes the wires in track-by-track fashion, is based on the concept of fully utilizing the current track to route the wires before going to the next track. Although many different strategies have been proposed to solve the channel routing problem, the unanimous consensus is that a routing problem with low channel density and simple vertical constraint graph, i.e. both longest path and cycle number of the vertical constraint graph is small, tends to have a routing solution of small channel width. Based on this consideration, a new concept which considers the effects of endpoints of selected wire segments to the column density and vertical constraint graph of the given channel routing problem is developed. According to different effects to both data structures, basically all possible endpoints are divided into safe and unsafe endpoints, and all possible wire segments are divided into safe wires and unsafe wires. The routing strategy is simply described as follows. In the first step, A set of safe endpoints is selected; in the second step, we select the safe wires by connecting the safe endpoints selected in the first step; in

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the third step, we defined the optimality criteria; in most cases, the density-related optimality criteria will be considered; then in the fourth step, we apply dynamic programming technique to exactly select the optimal set of safe wire segments according to the optimality criteria defined in third step. In this paper, we consider the algorithm for the two-layer routing problems and its extension for the three-layer routing problems.

The merits of the proposed algorithm are its simplicity, generality, flexibility, and effectiveness. The data structures used in this algorithm are column density, vertical constraint graph, and span of each net, which are all the information we need to select the wires. The systematic and general strategy adopted in the proposed algorithm makes it easy to extend the algorithm to switch-box, multi-layer, Manhattan, overlap, non-rectangular channel, and three-dimensional routing problems without extensive modification. Since the algorithm is flexible, any parameter other than column density and vertical constraint graph as mentioned above and proven better may be incorporated into the proposed routing algorithm. With time complexity O(wnc), where w is the channel width of the final routing solution, n is the number of nets, and c is the number of available columns, our algorithm found the best routing solutions in the two and three layer routing environments for most benchmark difficult examples given in the previous literatures [3,6,8].

Preliminary

Normally, a *channel routing problem* (CRP) is realized as a rectangular region with terminals, located on the top and bottom sides of this region, to be connected in as small an area as possible. The rectangular region is referred to as a *channel*. The vertical and horizontal spaces of unit width for routing in the channel are referred to as *columns* and *tracks* and are counted from left to right and top to bottom respectively. The terminals located on the top and bottom sides of the channel in column k are referred to as top-side and bottom-side terminals of column k, and are denoted as t_k and b_k respectively. Let net i, denoted as N_i, be the set of all terminals i; let W_i be the wire segments for connecting N_i; and let n be the number of nets. The necessary and sufficient condition for the routing solution $W = \cup W_i$, where $1 \le i \le n$ and $W_i \cap W_j = \emptyset$ if $i \neq j$, is referred to as the *routing requirement*, which should be satisfied for all the routing solutions in all models. If W_i contains multiple horizontal wire segments assigned to different tracks with a vertical wire segment in column k to connect these separated wire segments, we say the wire set for net i has a *dogleg* in column k (or the wire set for net i doglegs in column k).

For a given CRP, if all the vertical wire segments are restricted to run in specific layers and all the horizontal wire segments are restricted to run in the rest of the layers, this constraint is referred to as a *restricted Manhattan* routing model; otherwise, it is referred to as a *Manhattan* routing model. If no overlap of unit wire segments in different layers is allowed in the routing solution, the constraint is referred to as a *non-overlap* routing model; otherwise, it is referred to as an *overlap* routing model. For a given CRP with k layers for routing, considering the above two constraints simultaneously, it is not difficult to come up with the following four major routing models:

(1) *k-layer restricted-Manhattan overlap* (k-RM-O),
(2) *k-layer restricted-Manhattan non-overlap* (k-RM-NO),
(3) *k-layer Manhattan overlap (k-M-O), and*
(4) *k-layer Manhattan non-overlap* (k-M-NO) routing model.

A CRP in the k-RM-O routing model is also equivalently referred to as a k-RM-O-CRP, etc. Since no overlap is possible in the two-layer restricted-Manhattan routing model, the 2-RM-NO routing model and the 2-RM-NO-CRP are simply referred to as the

2-RM routing model and the 2-RM-CRP respectively in the following discussion.

For the 2-RM-CRP instance, it is not difficult to visualize that the endpoints of each horizontal wire segment for net i routed in the topmost track should be located in column k such that its related top-side terminal t_k=0 or t_k=i. Otherwise, the wiring requirement will be violated. The endpoint of a horizontal wire segment satisfying this condition is referred to as a *feasible endpoint*. The wire segment for net i routed in the topmost track with two feasible endpoints is called a *feasible wire* for net i, denoted as f_i. A set of non-overlapped feasible wires is denoted as an F. The F can be further divided into type 1 if after F is routed, the channel density of the new 2-RM-CRP $d_{max}' = d_{max}-1$, type 2 if $d_{max}'=d_{max}$, or type 3 if $d_{max}'= d_{max}+1$. If a feasible wire segment is included in F and the F is always type 2 or 3, then the feasible wire is referred to as an *unsafe wire*; otherwise, it is referred to as a *safe wire*. If a feasible endpoint is one of the endpoints of a wire segment and the wire segment is always an unsafe wire, then the feasible endpoint is referred to as an *unsafe endpoint*; otherwise, it is referred to as a *safe endpoint*.

Two-Layer Channel Routing

The developed two-layer router considers the routing solutions in the 2-RM model and routes nets from top to bottom in track-by-track fashion. For each 2-RM-CRP instance, after the topmost track has been routed and the related top-side and bottom-side terminals have been connected, the rest of the routing can be treated as a new 2-RM-CRP with new sets of nets and available columns.

For each 2-RM-CRP instance, to achieve the optimal routing solution, it is not difficult to see that type 1 F is most desirable if it exists. Obviously, the strategy to find an appropriate F for each 2-RM-CRP instance will critically affect the efficiency and the routing performance of the proposed routing algorithm. The routing strategy is simply divided into the following four steps.

Step 1: Select Candidate Endpoints:
To find the safe wires, in step 1 we select all safe endpoints as candidate endpoints.

Step 2: Select Candidate Wire Segments
Since safe endpoints are only a necessary condition of being the endpoints of a safe wire segment, in the second step we select all the safe wire segments with both candidate endpoints as candidate wire segments.

Step 3: Define Optimality Criteria
The wire segment is weighted according to the column density of the resulted channel after the wire segment is routed, which eventually defines the optimality criteria for selecting wire segments in each CRP instance. When type 1 F does not exist, the structure of resulted vertical constraint graph may also be considered.

Step 4: Select F
For the given candidate wire segments found in step 2, by scanning all the candidate endpoints in candidate wire segments from left to right and applying dynamic programming technique, all candidate endpoints are assigned a value and the pointers between candidate endpoints are constructed according to the optimality criteria defined in step 3. It is guaranteed that an optimal F for each 2-RM-CRP can always be found simply by following these pointers. For details of this section, see [7,8].

Three-Layer Channel Routing

The developed three-layer router simply incorporates some conditions for routing transformation into the selection of candidate endpoints in the developed two-layer router so that all two-layer routing solutions generated from the customized two-layer router are automatically the routing solutions in the 3-RM-O model, or in the 3-M-O model if we want to further improve routing performance, with simple reassignment of horizontal wire segments. The conditions for routing transformation are simply stated in the following two theorems:

Theorem 1: For a given CRP, if a routing solution W with channel width of w exists in the 2-RM model, and for each pair of tracks 2k-1 and 2k, where $1 \leq k \leq \lfloor w/2 \rfloor$, no vias exist for different nets in each column, then a routing solution W' with channel width of $\lceil w/2 \rceil$ always exists in the HVH model.
Proof: see [7,15].

For a given CRP, since the set of routing solutions in the 3-RM-O model is the subset of those in the 3-M-O model, to improve the routing performance, we may allow some vertical wire segments to run in alternative layers if it does not block any horizontal wire segment. With this consideration, the theorem 1 can be generalized in the following theorem.

Theorem 2: For a given CRP, if a routing solution W with channel width of w exists in the 2-RM model, and for each column k, no positive integers t, t', and t" exist such that

(1) t and t' are odd numbers, and t" is an even number,
(2) t' < t and t" > t+1,
(3) there exist vias for different nets in tracks t and t+1 ,and horizontal wire segments in W which pass tracks t' and t",

then a routing solution W" with channel width of $\lceil w/2 \rceil$ always exists in the 3-M-O model.
Proof: see [7,15]

The conditions for routing transformation shown in the above theorems can be simply implemented by considering these routing transformation conditions as extra constraints in selecting candidate endpoints in the two-layer router. In considering routing performance, the developed three-layer router considers the routing solutions in the 3-M-O model, but not in the HVH model. For details of this section, see [7,15].

Experimental Results

We implement the routing algorithm in two-layer and three-layer routers in C on Vax 11/780. The routing performance of the developed two-layer and three-layer routers is shown in table 1 and table 2 respectively. In tables 1 and 2, the examples 3a,3b, and 3c are from [9], diff. from [10], and r1 through r4 and cycle.tough from [11]; the number represents the number of tracks used; and blanks are for data not available.

Table 1: Performance Comparison for Two-Layer Routers

Example	Density	Our router	[16] 1986	[2] 1986	[11] 1985	[9] 1982
3a	15	15	15	15	15	15
3b	17	17	17	18	18	17
3c	18	18	18	19	19	18
cycle.tough	16	16	17	17	19	
diff.	19	19	19	19	19	20
r1	20	21	22	22	22	21
r2	20	20	20	20	21	20
r3	16	17	17	18	18	17
r4	15	16	17	17	17	20

Table 2: Performance Comparison for Three-Layer Routers

Example	Density	Our router	[12] 1988	[2] 1986	[1] 1986	[5] 1985	[4] 1984	[3] 1984
3a	15	8	8	8	8	15	8*	8
3b	17	9	9	10	10	16	10	10
3c	18	9	9	10	9	17	9	10
cycle.tough	16	9		9				
diff.	19	10	10	11	13	18	14	11
r1	20	11		12				
r2	20	10		11				
r3	16	9		9				
r4	15	8		9				

From table 1 and table 2, it is easy to see that our two-layer and three-layer routers hit the optimal solutions in most examples. For some of the theoretically non-optimal routing solutions, they also outperform other routers.

Extension

Logically, the multi-layer router can be developed by following the same line as shown in the above three-layer router. But extra factors may need to be considered, like blocking of horizontal wire segments by vias, control of via length, considering the invalid two-layer routing solutions, homogeneous mixture of horizontal and vertical wire segments if possible, etc. All these issues will be addressed in the future work.

Concluding Remarks

The success of the developed routing algorithm is mainly attributed to the new concept adopted and its generality. The new routing concept guides the routing according to the effects of endpoints of selected wire segments to column density and vertical constraint graph. Since it is general, it also allows the routing transformation conditions to be incorporated into the selection of candidate endpoints, which eventually eliminates a lot of effort in developing three-layer routers. Since the routing performance of the developed three-layer router has outperformed the currently existing multi-layer router [1,2] in the three-layer routing environment as shown in table 1, the potential of the proposed routing algorithm to be extended to multi-layer routers is optimistically expected.

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