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New Techniques for Four- and Five-Layer Channel Routing

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Abstract

In this paper, we propose two new models for the four- and five-layer routing problems based on the HHVH (or HVHH) and HHVHH models respectively instead of HVHV (or VHVH) and HVHVH models, which are traditionally used by most multi-layer channel routers. The key concept is that we consider the via-violations which may occur in routing transformation in advance in constructing two-layer routing solutions so that the resulting two-layer routing solutions are automatically four- or five- layer routing solutions with simple routing transformation. Since more horizontal layers are available in the new models and all possible via-violations in routing transformation can be avoided by applying extra constraints in selecting feasible endpoints in the two-layer routing solutions, the routing performance of the proposed four- and five-layer routers has outperformed all existing routers from our understanding. The experimental results are shown ,and the detailed five-layer routing solution of the Deutsch difficult example with channel width of six is demonstrated. The extension to a general multi-layer router is discussed.

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I. Introduction

The channel routing problem in layout is to realize a specified set of connections between two modules on opposite sides in as small an area as possible. Traditionally, two layers are assumed for routing, one for horizontal and the other for vertical routing, and the connections between the wire segments in these two layers are through some electrical throughs, which are referred to as *vias*. However, advances in manufacturing technology have made it possible to use three or more layers for interconnections. Many multi-layer routing algorithms with different restrictions have been proposed [1-8,11-13,14,16-17].

For most of the proposed multi-layer routers, the following convention is commonly adopted. First, all the layers are divided into two types: one is for horizontal routing and the other is for vertical routing, and are referred to as H and V layers respectively. Second, the layers are arranged in a way such that all the H and V layers are adjacent to V and H layers respectively. Under the above convention, to maximize the horizontal routing space, which is strictly related to the lower bound of channel width, obviously, the HVHV (or VHVH) and HVHVH models will be selected in the four- and five-layer routing environments respectively. Since no two H layers are arranged together in the traditional models, it is guaranteed that there is no intersection of a via and a wire segment for different nets, which is referred to as a *via-violation*. In the proposed HHVH and HHVHH models, since a via may cross more than two layers, possibly a via from an outer H layer may be blocked by an existing wire segment in an inner H layer or may block a wire segment to be routed in an inner H layer. Since the simplest two-layer routing problem, without considering the via-violation, has been proved as NP-complete, definitely the introduced via-violations in the new models will make the routing problem more complicated.

In this paper, we propose two routing models for the four- and five-layer routing environments based on the HHVH and HHVHH models respectively. Let R and R′ denote the two-layer routing solution and targeted four- or five- layer routing solution respectively. The basic concept to construct R′ is shown as follows. First, we determine the track mapping between R and R′. Each track t in

R maps to a certain track t' and a certain layer l' in R' and is denoted as $t \rightarrow (t', l')$. Let the layers be counted from one side to the other and m denote the number of available layers in R' in new models. Logically, $t' = \lceil t/(m-1) \rceil$, and l' depends on the routing strategy, which will be discussed in detail in section III. Second, after the track mapping is determined, construction of F, the set of non-overlapped feasible wire segments, in each track t of R will be considered differently. In constructing the F for an outer H layer, we need to consider the effect of generated vias on blocking an F to be routed in an inner H layer. In constructing the F for the inner H layer, we need to consider the effect of the F on blocking the vias of an F to be routed in the outer H layer. In both cases, via-violations should also be avoided. Third, since all the via-violations have been considered in advance, the resulting R can be transformed to a valid R' directly by simple routing transformation according to the track mapping defined in the first step.

The most important concept in the proposed four- and five-layer routers is that all the routing constraints are considered as a whole, if possible, to approach the optimal solution. Our preliminary experimental results [17], which constructed the two-layer routing solution without considering via-violations and then resolved the via-violations later, show that considering the routing constraints in separate steps generates worse results as well as much effort. We conjecture that the routing constraints formed in one step will restrict the domain of all possible solutions to be considered in the subsequent steps. If unfortunately the optimal solution is excluded from the domain to be considered, then there is no way to find the optimal solution in the subsequent steps. Dividing a channel routing problem (CRP) into some sub CRPs and solving the sub CRPs individually, or generating an approximate routing solution, then refining the routing solution later will be the good example for the later approach.

The implementation of the proposed four- and five-layer routing algorithm is straight-forward and simple. First, in constructing the feasible endpoints, we simply exclude the endpoints which will generate via-violations when the transformation of R to R' is concerned. Second, in constructing pointers in each track t, different optimality criteria are applied according to the defined track mapping $t \rightarrow (t', l')$.

The performance of our router is excellent and has outperformed all existing four- or five-layer routers. For most tested examples, our router approaches the optimal solutions, which are even better than the optimal solutions claimed by other routers in HVHV and HVHVH models. Although the optimal solutions of the Deutsch difficult example in HHVH and HHVHH models are not achieved by our routers, the respective channel width of 8 and 6 achieved also outperform the existing ones.

The remainder of this paper is organized as follows. In section II, we briefly introduce the basic terminologies and concepts of the developed two-layer router. In section III, we show the routing strategy and discuss the necessary changes in the selection of feasible endpoints and optimality criteria in different situations. In section IV, the experimental results are shown and the detailed routing solution of the Deutsch difficult example in the HHVHH model is demonstrated. The extension to a general m-layer router and concluding remarks are given in sections V and VI respectively.

II. Preliminaries

A *channel* is a layered rectangular routing area with terminals, coded as non-zero integers, placed at the top and bottom edges. Vertical and horizontal routing areas of unit width are referred to as *columns* and *tracks* respectively. A *net* i, denoted as N_i, is a set of terminals with assigned number i. Let c denote the number of columns for a given channel and t_k and b_k represent the top-side and bottom-side terminals in column k respectively. Different non-zero t_k and b_k in each column k is referred to as a *vertical constraint* and is denoted as $t_k \rightarrow b_k$. The set of all vertical constraints is characterized by a directed graph $G_{vc}=(V,E)$, where E denotes the set of edges e_{ij} representing vertical constraint $i \rightarrow j$, and V denotes the set of nets i which are connected by e_{ij} or e_{ji} in E. The G_{vc} is commonly referred to as the *vertical constraint graph*. The *level* of each vertex i in G_{vc} is defined as the longest path to its descendant vertices and is denoted as l_i. The longest path of G_{v_0} is denoted as l_{max}. The *left bound* and *right bound* of net i, denoted as $l(N_i)$ and $r(N_i)$, are defined as the minimum k (or 1 if net i will be connected to the left) and maximum k (or c if net i will be connected to the right) with $t_k=i$ or $b_k=i$ respectively. The *span* of a net i is defined as the set of columns k with $l(N_i) \le k \le r(N_i)$ if $l(N_i) < r(N_i)$; otherwise it is defined as an empty set. The *local density* of a column k, denoted as d_k, is defined as the number of nets whose span contains column k. The *channel density*, denoted as d_{max}, is simply defined as the maximum local density. The *channel routing problem* (CRP) is to connect terminals in each net by using a minimum number of tracks without any overlap of wire segments for different nets.

A CRP is in the *two-layer restricted-Manhattan* (2-RM) model if only two layers are available for routing, and one layer is restricted for vertical wire connections and the other is restricted for horizontal wire connections. A CRP in the 2-RM model is also referred to as a 2-RM-CRP. For a 2-RM-CRP, it is easy to see that the endpoints of the topmost horizontal wire segments for net i should be in column k such that $t_x=0$ or $t_x=i$. Such an endpoint is referred to as a *feasible endpoint* and a wire segment with two feasible endpoints for net i is referred to as a *feasible wire* for net i and is denoted as f_i. For an f_i, if there exists a column k which overlaps with the f_i with $t_k \ne 0$ and $t_k \ne i$ and $b_k=i$, then the b_k is referred to as an *unconnectable terminal* of f_i. A set of non-overlapped feasible wires is denoted as an F. Let d_{max}' denote the channel density of the new 2-RM-CRP instance which is defined after an F is routed. According to d_{max}', the Fs can be further divided into type 1, type 2, or type 3 if $d_{max}'=d_{max}-1$, $d_{max}'=d_{max}$, or $d_{max}'=d_{max}+1$ respectively.

A feasible wire is referred to as an *unsafe wire* if whenever the feasible wire is included in an F, either the F will never be a type 1 F or there exists no type 1 F in the new 2-RM-CRP instance after the F is routed; otherwise, it is referred to as a *safe wire*. A feasible endpoint is referred to as an *unsafe endpoint* if whenever a feasible wire has this kind of endpoint, the feasible wire will always be an unsafe wire; otherwise, it is referred to as a *safe endpoint*.

The developed two-layer router routed wires in a track-by-track fashion. For each CRP instance, we try to find an appropriate F; after the F is found and routed, a new CRP instance is defined and this process is repeated until all the nets are connected. The main goal of our two-layer router is to find a best F for each CRP instance, which is briefly described as follows. First, we identify all possible safe endpoints through all possible feasible endpoints for each net. Second, we identify all possible safe wire segments by connecting part of the safe endpoints for each net. Third, different optimality criteria(or weights) are defined for wire segments in different situations. Here, the major concerns are density structure, vertical constraint graph, and their relationship. Fourth, through the dynamic programming technique, which scans safe endpoints from left to right and assign the pointers and accumulative weight to each safe endpoint, the best type 1 F is guaranteed to be found if it exists. For details of this section, please refer to [16].

III. Routing Strategy

The proposed router routes the wires in track-by-track fashion as adopted by the developed two-layer router [16]. In the 2-RM model, it is clear that the wires are routed one track at a time from top to the bottom. But in the proposed models, since each track contains more than one H layer, the routing sequence of these H layers in one track, which defines the track mapping, will critically determine the structure and performance of the proposed routing algorithm.

(A) Defining Track Mapping

Imaginatively, three routing sequences can be considered. In the first sequence, wires are routed according to the layer number; the second sequence routes wires from inner H layers first to outer H layers; and the third sequence routes wires from outer H layers first to inner H layers. In all these possible routing sequences, the via-violation in fact can be formed in two ways

(1) The via is constructed first, and then the intersecting wire segment is constructed later, which is referred to as *type 1 via-violation*.

(2) The wire is constructed first, and then the intersecting via is constructed later, which is referred to as *type 2 via-violation*.

Considering the routing of each track t in the HHVHH model using the first routing sequence, in the first layer, we need to consider potential type 1 via-violations; in the second layer, we need to avoid type 1 via-violations; in the fourth layer, we need to consider potential type 2 via-violations; and in the fifth layer, we need to avoid type 2 via-violation. Using the second routing sequence, only the potential type 2 via-violations need to be considered or avoided; Using the third routing sequence, only the potential type 1 via-violations need to be considered or avoided. In the proposed router, we adopt the third routing sequence, the reason for which is explained as follows. First, with focusing on one type of via-violations, the developed algorithm can be more simplified and systematic. Second, the thought to avoid type 1 via-violations can be easily characterized by a similar weight function and be incorporated into the developed two-layer router. Third, the density structure and vertical constraint graph can be simplified systematically throughout the routing as shown below. According to the third routing sequence, the routing sequence of the layers in each track will be 1,4,2 and 1,5,2,4 for the HHVH and HHVHH models respectively, and the track mapping $t \rightarrow (t',l')$ for each track t in R is defined accordingly. For example, the track mapping in the HHVHH model is defined as $1\rightarrow(1,1)$, $2\rightarrow(1,5)$, $3\rightarrow(1,2)$, $4\rightarrow(1,4)$, $5\rightarrow(2,1)$, $6\rightarrow(2,5)$, and etc.

(B) Defining Optimality Criteria (or Weights)

After the track mapping has been determined, the remaining task is to choose optimality criteria to select Fs in different tracks and layers. In the proposed routing algorithm, three kinds of optimality criteria are used to select the F in different tracks and layers. Since l_{max} defines another lower bound other than d_{max} for the channel width as shown in [18] and only one V layer is available in the proposed models, effective use of the V layer (or possible H layers) to resolve the vertical constraints will critically determine the performance of the proposed routing algorithm.

Since vertical wires can be routed in H layers in the first and last tracks of R′ without causing any via-violation, the optimality criterion in selecting the F in the first and last tracks of R′ will focus on simplifying the vertical constraint graph. For the outer H layers in the middle tracks, since no type 1 via-violation is concerned, the optimality criterion in selecting the F solely focuses on simplifying the density structure. Of course, the effect of generated vias on blocking the routing in the inner H layer are also considered systematically in defining the optimality criterion . For the inner H layers in the middle tracks, since the vias generated from outer H layers have existed, fully devoting to simplifying the density structure will not be effective. So here we consider simplifying the density structure and vertical constraint graph at the same time. The routing strategy and heuristic we adopt to simplify both structures in this paper is a little bit different from the one adopted in the developed two-layer router as shown below.

Let a vector describing the density structure of a CRP be defined as

$$C(CRP)=(\ c(d_{max}+1),c(d_{max}),c(d_{max}-1),\ldots\ldots,c(1),c(0)\ )$$

where $c(x)$ represents the number of columns k with $d_k=x$ for the CRP. Let the effect of the vias of an F on blocking the routing of the inner H layer be reflected by a vector

$$VIA(F)=(\ v(d_{max}+1),v(d_{max}),v(d_{max}-1),\ldots\ldots,v(1),v(0)\ )$$

where $v(x)$ represents the number of columns k which are occupied by the vias of F with $d_k=x$. Let CRP′ represents the new CRP instance after F is routed. The weight of an F in the outer H layers and middle tracks is defined as

$$W'(F)=C(CRP)-C'(CRP')-VIA(F)$$

$$=(w'(F,d_{max}+1),w'(F,d_{max}),w'(F,d_{max}-1),\ldots\ldots\ldots,w'(F,1),w'(F,0)\ )$$

where $w'(F,x)$ can be interpreted as the overall effect of F to reduce the number of columns k with $d_k=x$.

In the first and last tracks of the channel as we have mentioned above, the main task is to reduce the l_{max}. The concept of l_{max} bounding has been extensively accepted as another important factor other than d_{max} to control the channel width and implemented by some heuristic routers [5,9,15-16]. The approach adopted in our two-layer router is to cut the longest path of G_{vc} through the middle, if possible, and pass this information from left to right through the dynamic programming technique. In this paper, we discard this heuristic. The main concern is that if a vertical constraint occurs in a low density column, even though it is in the longest path of G_{vc}, it may not be crucial. On the contrary, if a vertical constraint occurs in a high density column, even though it is not in the longest path of G_{vc}, it is crucial. So our conclusion is that the effect of a vertical constraint in G_{vc} on the channel width depends not only on where it is located in G_{vc} (or l_{max}) but also on the density of the column on which it is located. This assertion is supported by the simplicity of the algorithm developed at the end of this section and the performance shown in the next section. The above concept is characterized by the weight function defined below.

$$W''(F)=(w''(F,d_{max}+1),w''(F,d_{max}),w''(F,d_{max}-1),\ldots\ldots,w''(F,1),w''(F,0))$$

where $w''(F,x)$ represents the number of vertical constraint $v_i \rightarrow v_j$ in column k to be deleted from G_{vc} minus the number of vertical constraints $v_i \rightarrow v_j$ in column k to be added to G_{vc} after the F is routed such that $x=\max(0,\lceil (d_k+l_j+d_{max}-l_{max}+1)/2\rceil)$, where l_j represents the level of net j. In defining the x, the added one simply emphasizes the simplification of vertical constraint graph over density structure when it is tied in comparing the W, which will be defined below. From the above formula, it is easy to see that for a given vertical constraint $v_i \rightarrow v_j$ located in column k to be deleted after the routing of F, the one with larger l_j and d_k will get larger weight; the one with smaller l_j and d_k will get smaller weight; those with larger l_j and smaller d_k, or smaller l_j and larger d_k will be calculated in the same way as defined in the above formula. For given F_1 and F_2, $W''(F_1)$ and $W''(F_2)$ are calculated and compared only when F_1 and F_2 are of the same type, since selecting a type 1 F, if possible, in each track is still the main goal of the proposed routing algorithm.

As for the inner H layers in the middle tracks, the weight of an F is simply defined as

$$W(F)=W'(F)+W''(F)$$

Apparently, the VIA(F) of the above W' is a zero vector through its definition. Unlike the developed two-layer router, which defines the W differently according to the relationship between d_{max} and l_{max}, the W defined here is the only optimality criterion used by the proposed router throughout the two- and three-layer models. Same as before, $W''(F_1)$ and $W''(F_2)$ are calculated and compared only when they are of the same type. The sketch of using W', W'', and W in different tracks and layers of R' in HHVH and HHVHH models is shown in figure 3.1 by different regions.

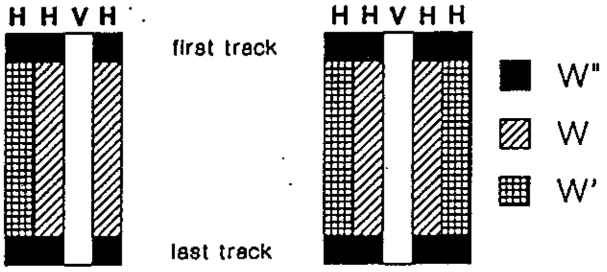

Figure 3.1 The optimality criteria in HHVH and HHVHH models

(C) Routing Rules

To enhance the routing performance, the proposed router allows some vertical wire segments to route in the H layers in certain situations if no routing violation occurs as shown below.

The vertical wire segment to be connected with terminals in the first and last tracks of R' are allowed to route in H layers as mentioned in (B). Also, the vertical connection of two doglegged horizontal wire segments can be routed in the H layers if these two wire segments are routed in adjacent tracks and the same layer of R', or more general, the path of the vertical connection does not cause any routing violation. Considering the routing of R, the above concept can be interpreted as follows. For any set of tracks t which map to same t' in each column k, if there exist two vias for different nets, then at least one of the vertical connection of these two vias should go through a H layer without causing any routing violation when R' is concerned.

The rule for avoiding type 1 via-violation is straight-forward under the defined track mapping. In the HHVHH model, if there exist a via for net i in column k and track 4t+1 (or 2) whose vertical connection should go through the V layer when R' is concerned, then no wire segment for the net other than net i can pass column k in track 4t+3 (or 4). Similar rules can be determined for the HHVH model.

Since we allow the vertical wire segments to route in H layers, it not necessary that a valid R′ can always find a corresponding valid R through the inverse track mapping. Possibly, some vertical wire segments in the corresponding R are overlapped. To further improve the routing performance of the proposed routing algorithm without major changes in the structure of the algorithm, the vertical wire segments are allowed to be overlapped in the last few tracks of R which map to the last track of R′. The extensive use of this concept is discussed in the next section.

(D) Algorithm

Let w and w′ denote the resulting channel width of R and R′ respectively. The proposed routing algorithm is briefly described as follows.

```
M_L_ROUTER
        for t= 1 to w do
                select a smallest type of F with maximum W', W", or W according to
                t' and l' as sketched in figure 3.1
        endfor
        trivial procedure to minimize the wire length and via number
END_M_L_ROUTER
```

Many things are worth mentioning for the above routing algorithm. First, no backtracking or major rerouting is applied. The last step to minimize the wire length and via number is optional without affecting the w or w′. Second, unlike our two-layer router, where W is defined differently according to the relationship between l_{max} and d_{max}, in this paper, the definition of W remains unchanged throughout the routing in the two- and three-layer models. Third, the *M_L_ROUTER* is able to route the tested data in two- through five-layer routing environments and generate the best routing solutions consistently. Fourth, least heuristic is applied. In the two- and three-layer models, W is the only optimality criterion used to select Fs. In four- and five-layer models, considering the potential type 1 via-violations, density structure, and vertical constraint graph, different optimality criterion, W′,W″, or W, is adopted according to t′ and l′. In summary, the proposed *M_L_ROUTER* is systematic, elegant, and efficient from our point of view.

IV. Experimental Results

We implemented the proposed four- and five-layer routing algorithm in C on Vax 3800. To improve the routing performance as mentioned in the previous section, we allow some overlaps of vertical wire segments in the last few tracks of R (i.e. the last track of R′), which will disappear when the defined track-mapping is applied to transform R to R′. The comparisons of routing performance in four and five-layer models are shown in figure 4.1, 4.2 respectively, where the examples 3a, 3b, and 3c are from [9], diff. represents the Deutsch difficult example, and the number with * represents the optimal solutions in the related models.

Example	Density	Our router	[5] 1988
3a	15	5^*	8
3b	17	6^*	9
3c	18	6^*	9
diff.	19	8	10

Table 4.1 Comparison of routing performance in the four-layer model

Example	Density	Our router	[2] 1986	[5] 1988
3a	15	4^*	5	5
3b	17	5^*	6	6
3c	18	5^*	6	6
diff.	19	6	7	7

Table 4.2 Comparison of routing performance in the five-layer model

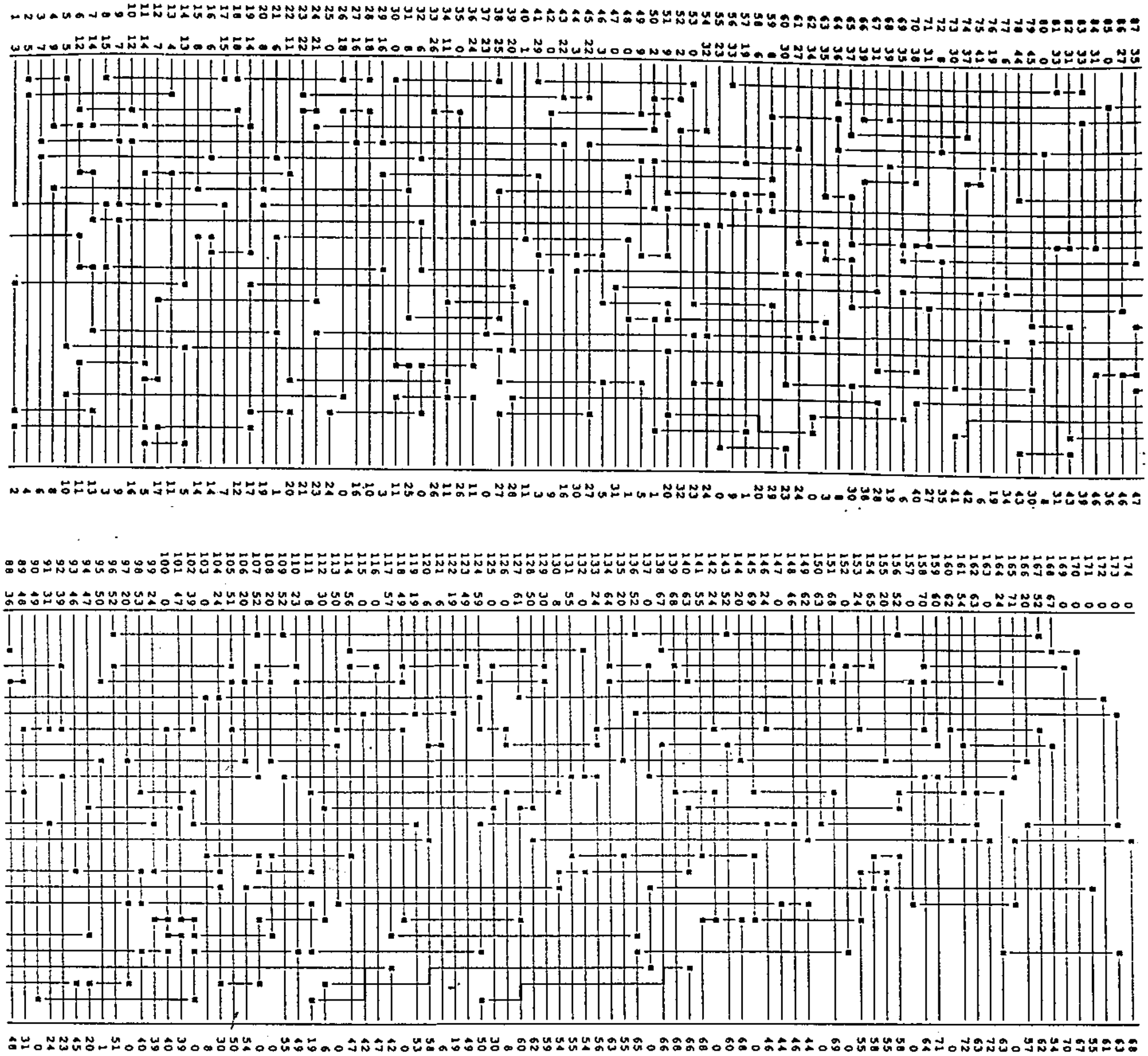

Figure 4.1 Deutsch difficult example in the HHVHH model

In tables 4.1 and 4.2, it is easy to see that our routers overwhelmingly outperform the existing routers and approach the optimal solutions in four- and five layer models for most tested examples. Although the optimal solutions of Deutsch difficult example in both models are not achieved, they are better than the existing ones generated from other routers. Currently, we are not certain that if the mathematic optimal solutions of the Deutsch difficult example in both models exist or not. The proposed router can also route the CRPs in the two- and three-layer models. Since the routing performance is as good as the best ones that have been published, the performance comparison in the two- and three-layer models are ignored for simplicity. To familiarize the readers with the routing solutions generated from our router, the detailed routing solution of Deutsch difficult example with channel width of six in the HHVHH model is demonstrated by a two-layer routing solution as shown in figure 4.1. If the readers consider the track mapping and routing rules defined in section III, a valid five-layer routing solution R' based on the HHVHH model can be found clearly.

V. Extension to A General m-Layer Router

It is obvious that we have more H layers for routing in the proposed models. For a routing environment of more than five layers, intuitively, one may consider to add more H layers to the proposed models. In fact, two obvious problems can be expected in this kind of extension. First, the inner the H layer is, the severer it will suffer from the blocking generated by the vias from the outer H layers. The extreme case is that when the number of H layers increases to some extent, the innermost H layer in fact is redundant for routing simply because of too much blocking generated by the vias from the outer H layers. Even though this problem can be overcome and all the vias can be appropriately connected, less routing space in the V layer, which is proportional to w', to resolve the vertical constraints will present another bottleneck problem.

But one advantage can be expected in the extension. Since use of H layers for vertical routing in the first and last track of R' is guaranteed to be free of routing violations, when the number of H layers increases, the capacity to resolve the vertical constraints through the first and last tracks of R' is also increased. This advantage will partially help to alleviate the mentioned problems in the extension.

To overcome the above mentioned problems systematically, the concept of routing the vertical wire segments in the H layers in the first and last tracks of R', which results in the overlap of vertical wire segments in the last few tracks of R as implemented, should be further expanded. The major concept is that we want to move the vertical wire segments to H layers if possible due to the fact that the ratio of the number of the V layer versus H layers will get smaller when more H layers are added. Obviously, we want to move the vertical wire segments in the V layer which are especially for connecting two doglegged wire segments to H layers. In other words, we want these two doglegged wire segments in adjacent tracks to be routed in the same layer. To extensively consider routing the vertical wire segment in the H layers, two vertical connections, through the V layer or H layers, should be considered for each dogleg. To consider the latter one effectively, the routing of the next (m-1)th track also need to be considered in advance, which is a big challenge for the proposed router which routes the wires in track-by-track fashion. Furthermore, if the routing vertical wire segments in H layers is considered in all tracks of R′, there may exist feasible endpoints for more than one net in a column k for each track, which violates the basic assumptions and structure of the proposed routing algorithm. For the successful implementation of the extended m-layer router, we expect major changes in the structure of the proposed routing algorithm with increased complexity and calculations for above mentioned considerations.

VI. Concluding Remarks

In this paper we proposed two new models for the four- and five-layer CRPs based on the HHVH and HHVHH models. The experimental results show that the proposed models using the presented routing strategy are not only feasible but also better than other models in terms of the number of tracks used. Beside the excellent routing performance achieved, it still leave a lots of room to improve. First, we can apply the backtracking technique when the type 1 F does not exist. Second, overlap of vertical wire segments discussed in the previous section can be applied in all tracks. Third, simultaneous selection of type 1 Fs in a track can be considered, which we leave as an open problem as shown below.

We show that the complexity of G_{vc} should not be measured just by l_{max}, which is extensively accepted by most other heuristic routers and our developed two-layer router. Instead, considering each vertical constraint and the density of column where it is located at a whole represents better heuristic in capturing the complexity of G_{vc}, which is supported by our experimental results in section

IV and explained by the simplicity of the developed *M_L_ROUTER* in section III.

Through the discussion in section V, we know that the extension to a general m-layer router is not impossible. But to overcome the mentioned difficulties to achieve a reasonable routing performance will be much tougher than the methodology presented in this paper, which is closely related to our developed two-layer router. In the extension, we expect major changes in the assumptions and structure of the proposed routing algorithm and the complexity of the routing algorithm will be increased tremendously.

The comparison of the preliminary results [17] and the results of this paper suggests that the more routing constraints are considered as a whole, the better routing performance can be achieved with high probability and less effort. The above observation motivates us to answer the following question. Given a set of feasible wire segments for a m-layer CRP in the proposed or extended model, is it always possible to find a set of m-1 type 1 Fs if they exist? If the answer to the above question is positive, then the power and performance of the proposed routing algorithm will be upgraded further. We leave this as an open problem and hope it will be answered by interested researchers in the future.

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