Two-Layer Via-Free Routing in Channels and Switchboxes*

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Abstract

We introduce the *two-layer via-free routing problem* (2LVFRP) and propose an optimal algorithm to solve it. Given a set of nets (with terminals on the boundary) and two layers for routing them, the algorithm determines the layer assignment and detailed routing for each net such that no via is needed, if such solution exists.

1 Introduction

As the VLSI fabrication technology progressed, more layers became available. (Traditionally, there were two layers available for routing.) In a multi-layer environment, reserving a layer for critical nets is afforded. Other multi-layer environments (e.g., multi-chip modules) systematically employ single-layer routing [1, 4]. These facts motivate the study of ***single-layer*** (or ***planar***) routing.

Previous research work on single-layer detailed routing problem includes: *river routing* and its extension [2, 5, 10], single-layer routing involving only two nets (e.g., power and ground) [12]. Other research work related to single-layer routing problems can be found, for example, in [3, 4, 6, 8, 9, 11].

In single-layer routing problem, two concepts are to be considered: the *topological realization* and the *detailed realization*. In the topological realization, the configurations of nets are examined to see whether a single-layer routing exists assuming "enough" capacity is available. The detailed realization concerns whether there is enough space (i.e., capacity) to route the nets in one layer such that no two nets cross each other. In this paper, we assume the given instance is topologically realizable in one layer, and the routing is performed in grid environment. (Note that the topological realization can be efficiently checked by *STACK-Algorithm*[6].)

In this paper, we study the *two-layer via-free routing problem (2LVFRP)*. An instance of the two-layer via-free routing problem in switchbox environments (*S-2LVFRP*) is an instance of 2LVFRP with rectangle routing plane. Figure 1 shows an instance of S-2LVFRP and one possible solution. Details of S-2LVFRP will be investigated in Section 3.

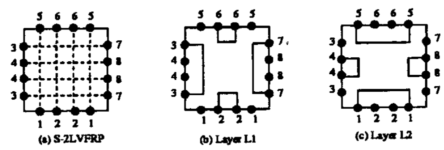

Figure 1: An instance of S-2LVFRP and one possible solution.

2 Channel Environment

In this section, we shall discuss a restrictive case of 2LVFRP – the two-layer via-free routing problem in channel environments (*C-2LVFRP*).

An instance of C-2LVFRP is specified by the set of two-terminal nets $N^* = \{N_1, \ldots, N_n\}$, where each net N_i is specified by terminals $t_{i,1}$ and $t_{i,2}$ on the two horizontal boundaries: *TOP* and *BOTTOM*. Without loss of generality, we assume the horizontal position of $t_{i,1}$ is always at the left of $t_{i,2}$, and is formally denoted by $t_{i,1} < t_{i,2}$. Also, we can assume that there is no trivial nets (i.e., nets with both terminals on the same horizontal position); otherwise, we remove those trivial nets and route them after all nets are processed. We call the horizontal interval from $t_{i,1}$ to $t_{i,2}$ the *interval* of net N_i and denote it by I_i. In an instance of C-2LVFRP, let N^T denote the set of nets with both terminals on TOP. N^B is similarly defined. N^{TB} is the set of nets with one terminal on each boundary. For a net $N_i \in N^{TB}$, if $t_{i,1}$ is on TOP, then N_i is called a *falling net* (note that we assume $t_{i,1} < t_{i,2}$); if $t_{i,1}$

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is on BOTTOM, then N_i is called a *rising net*. The *density* at a column j is the number of intervals that pass through column j, and is denoted by d_j. The set of nets in N^B that contributed to d_j is denoted by $NC^B(j)$. $NC^T(j)$ and $NC^{TB}(j)$ are similarly defined. Let $NC(j) = NC^B(j) \cup NC^T(j) \cup NC^{TB}(j)$, then $d_j = |NC^B(j)| + |NC^T(j)| + |NC^{TB}(j)|$. The value of $max(d_j)$, for all j, is called the maximum density of this instance and is denoted by d_{max}. Figure 2a shows an instance of C-2LVFRP with $N^T = \{N_2, N_3\}, N^B = \{N_4, N_5\}, N^{TB} = \{N_1\}$, and $d_{max} = 5$.

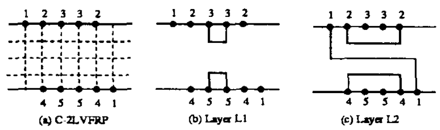

Figure 2: An instance of C-2LVFRP and one optimal solution.

A solution of C-2LVFRP is the assignments of N_i, for all i, to L1 or L2 such that all nets in the same layer can be routed without crossing. Since any subset of a set of topologically realizable nets is also topologically realizable. Thus, when the instance of C-2LVFRP is topologically realizable, any assignment of N^* is a solution of C-2LVFRP. Let T_{L1} and T_{L2} be the number of tracks used in L1 and L2, respectively. A solution of C-2LVFRP is *optimal* if $max(T_{L1}, T_{L2})$ is minimized, and we denote this number as T_{opt}. We call the corresponding assignment the *optimal assignment*. (Note that the optimal solution of an instance of C-2LVFRP might not be unique.) Figure 2b and Figure 2c show one optimal solution of Figure 2a.

For any two nets N_i and N_j, $\{N_i, N_j\} \subseteq N^T$ or $\{N_i, N_j\} \subseteq N^B$, we say N_i *covers* N_j if $t_{i,1} < t_{j,1} < t_{j,2} < t_{i,2}$ (and we say that N_j is *covered* by N_i). A *component* in N^T is the maximal subset N' of N^T that for any two nets in N', one covers the other. Components in N^B is similarly defined. A component with the largest cardinality among all components in N^T (N^B) is called the *maximal component* in N^T (N^B). For a component N', we associate a value $level(i) = k + 1$ to each net N_i in N', where k is the number of nets that are covered by N_i. Two nets in a component are *adjacent* if their level values are differed by one.

For each column j, the *topological order* of net N_i (denoted as N_i^{to}), $N_i \in NC(j)$, is defined as follows: (1) if $N_i \in NC^B(j)$, then $N_i^{to} = level(i)$; (2) if $N_i \in NC^T(j)$, then $N_i^{to} = |NC(j)| - level(i) + 1$. Define column i as a *local-peak column* if $d_{i-1} < d_i$ and $d_i \geq d_{i+1}$. The collection of local-peak columns is denoted by C_{peak}. Let C_{max} be the set of column in C_{peak} with density being d_{max}. (Note that C_{max} and C_{peak} are readily available after scanning the channel from left to right.)

In a solution of C-2LVFRP, the net N_i with the largest level value (for component N') in layer Lx ($x = 1, 2$) is called the top-net of N' and is denoted by $N'(top, x) = N_i$. The closed region formed by the boundary and the routing of $N'(top, x)$ is called the *contour* of component N' in Lx. Note that due to the planarity, no other net that is not in N' can use the routing space inside the contour of N'.

According to the cardinality of N^T, N^B and N^{TB}, we can classify C-2LVFRP into three types:

- **(TYPE-1)** $N^{TB} = \emptyset$ and one of N^T, N^B is empty;
- **(TYPE-2)** $N^{TB} = \emptyset$ and neither of N^T, N^B is empty;
- **(TYPE-3)** $N^{TB} \neq \emptyset$.

Without loss of generality, we assume $N^T = \emptyset$ in TYPE-1, that is, all nets are on the boundary BOTTOM. The following technique, called *Alternative-Assignment-and-Boundary-Dense-Routing (AABDR)*, is proposed to solve the instances of TYPE-1. For each component N' in N^B, net N_i with level(i) being an odd number is assigned to L1, and net N_j with level(j) being an even number is assigned to L2. We call this assignment strategy *alternative-assignment*. Then, for each layer, we route each net using the lowest available track (track that is not used by previously routed nets) and change to lower track whenever one is available, net with smaller level value is routed earlier. We call this routing method *boundary-dense-routing*.

Lemma 1 *TYPE-1 of an instance of C-2LVFRP can be solved optimally by AABDR using* $\lceil d_{max}/2 \rceil$ *tracks, where* d_{max} *is the channel density.*

Now we consider TYPE-2 in C-2LVFRP, where $N^{TB} = \emptyset$ and neither N^T nor N^B is empty. Intuitively, in order to avoid the interference between components on opposite boundaries, we shall keep each component's contour in each layer as small as possible (so that there is no space wasted). This can be achieved by the proposed method - *channel-alternative-assignment-and-boundary-dense-routing (CAABDR)*, which includes two steps: layer-assignment and boundary-dense-routing.

We shall first perform the layer-assignment. For each column x in C_{max} (starting from the column with smaller index value), we do as follows: (Case 1) if any net in $NC(x)$ is assigned to a layer, then assign others alternatively (that is, no two adjacent nets are assigned to the same layer); (Case 2) if no net in $NC(x)$ is assigned to any layer, then for each net $N_i \in NC(x)$: if N_i^{to} is odd, then N_i is assigned to L1; otherwise, assign N_i to L2. If there are nets with undetermined layer assignment after all columns in C_{max} are processed, , we apply above procedure to columns in $C_{peak} - C_{max}$. Note that the layer-assignment for all nets in a component are determined once any net of it is assigned to a layer (since we always assign adjacent nets to different layers).

After the layer-assignment is done, we apply boundary-dense-routing to nets in each layer to determine the detailed routing. The correctness of CAABDR is proved by following lemma.

Lemma 2 *TYPE-2 of an instance of C-2LVFRP can be solved by CAABDR using at most* $\lceil d_{max}/2 \rceil + 1$ *tracks, where* d_{max} *is the channel density.*

The discussion and analysis for TYPE-3 of C-2LVFRP is similar to the ones of TYPE-2, please see [7] for details.

3 Switchbox Environment

In this section, we study the two-layer via-free routing problem in switchbox environments (S-2LVFRP).

An instance of S-2LVFRP is specified by the set of two-terminal nets $N^* = \{N_1, \ldots, N_n\}$, where each net N_i is specified by terminals $t_{i,1}$ and $t_{i,2}$ on the boundaries of a switchbox. An instance of S-2LVFRP is solvable if we can find the layer assignments for each net such that nets assigned to the same layer are detailed realizable in that layer. Figure 1 shows a solvable instance of S-2LVFRP, and Figure 3 shows an unsolvable instance of S-2LVFRP.

Denote the four boundaries of a switchbox as *North, West, South, East*. Let the coordinate of the south-west corner be (0,0), and the coordinate of the north-east corner be (x_{max}, y_{max}). For each net N_i, let $(x_{i,1}, y_{i,1})$ and $(x_{i,2}, y_{i,2})$ be the coordinates of its two terminals. The horizontal interval from $x_{i,1}$ to $x_{i,2}$ is denoted by I_i^H; the vertical interval I_i^V is similarly defined. We call the number of vertical intervals pass through a track k as the vertical density at track k, and

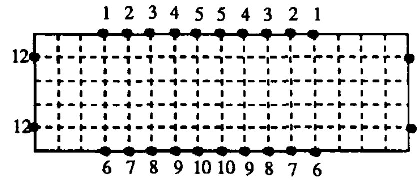

Figure 3: An instance of unsolvable S-2LVFRP.

denote it by d_k^V. The horizontal density d_j^H at column j is defined symmetrically. (Note that track k is the line segment from $(0, k)$ to (x_{max}, k), and column j is the line segment from $(j, 0)$ to (j, y_{max}).) The value of $max(d_j^H)$, for all j, is called the maximum horizontal density of this instance and is denoted by d_{max}^H. The maximum vertical density, d_{max}^V, is similarly defined.

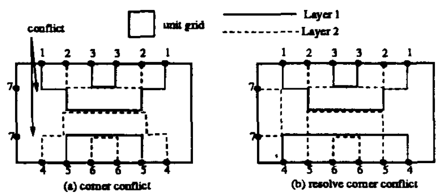

Figure 4: An example of corner conflict.

We introduce an algorithm, *switchbox-alternative-assignment-and-boundary-dense-routing (SAABDR)*, to determine if an instance of S-2LVFRP is solvable (and generate the layout if it is solvable). In SAABDR, first we check the larger of d_{max}^H and d_{max}^V. (Without loss of generality, we assume d_{max}^H is larger.) Then we apply CAABDR to nets on boundaries *North* and *South*, and check for *corner conflict* (see Figure 4.a). If there is no corner conflict, we proceed to apply CAABDR to nets on boundaries *West* and *East*. If corner conflict occurred, we need to modify the layer assignment for nets belonging to the component that conflicted with other nets (see Figure 4.b). (Note that the number of modification is limited, thus the algorithm is still efficient.)

Lemma 3 *Algorithm SAABDR determines if an instance of S-2LVFRP is solvable, and generate the layout if it is solvable.*

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