Equidistance Routing in High-Speed VLSI Layout Design

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ABSTRACT
In VLSI system, a certain set of nets is required to propagate their signals within a tolerable skew of delays. Though the delay of the signal on a wire is determined by a complex environment, it is hard to satisfy this requirement unless all the concerned nets are routed within a certain skew of length. This paper approaches this problem by the concept of l-equidistance routing which aims to route the concerned nets by prescribed length l. After a basic technique to route a 1-sink net with prescribed length l, an algorithm is presented for the channel routing where sink terminals are on the upper line and source terminals on the bottom lines. The key idea is in the symmetric slant grid interconnect scheme by which the problem is reduced to the ordinary grid routing problem. An algorithm that attains minimum total wire length is presented. Then a solution is given for the case when terminals are on the perimeters on a rectangle. These algorithms are explained on the Euclidean space. But it is shown that a straightforward transformation of the routes to those on the orthogonal grid is possible keeping the property of equidistance. Proposed algorithms were implemented and applied to random data to demonstrate their ability.

Categories and Subject Descriptors
J.6 [Computer Applications]: Computer-Aided Design

General Terms
Algorithms, Design

Keywords
VLSI system, Equidistance routing, Slant symmetric grid, Channel routing, Box routing, Dynamic programming, Rectilinear route

1. INTRODUCTION
In a clock driven VLSI layout design, some nets are often required to propagate their signals within a tolerable skew of delays. For example, all the n-bit bus signals on PCB are required to be propagated to respective destinations approximately at same time. Though these nets are usually routed along together in parallel, still a skew of arrival times is incurred between nth bit signal and (n – 1)th bit signal which degrades timing integrity in high frequency ICs. The delay of a signal on a wire is determined by a complex electrical environment. But the length of the signal path from the source to the sink is the major factor. Routing of plural nets within a negligible skew of length, equidistance routing, is our target.

Concerning delay aware routing, timing-driven routing has been studied by many researchers, e.g. [2, 4, 3]. But their objective is in minimization of the maximum delay, not in bounding the minimum delay. While clock routing considers the difference (skew) of the maximum and minimum delays as the index to be minimized (zero-skew routing). It has been studied extensively (see examples [1, 6]) but their algorithms have been developed to construct a unique routing tree. They are based commonly on one idea of “merging pair of sinks”. Though this is a merit since a clock-tree has been studied extensively (see examples [1, 6]) but their algorithms have been developed to construct a unique routing tree. They are based commonly on one idea of “merging pair of sinks”. Though this is a merit since a clock-tree is constructed by repetition of local operations, it is also a drawback for global optimization with respect to routability, distance, length, area, etc. Actually, recent study in [5] needed Lagrangian Relaxation formulation to calculate enough spaces for snake insertion. The solution specifies each net with a routing resource (area) but little instruction for routes and as predicted, this algorithm is slow and generates many uncontrolled long series of snakes which would be a cause of inductances.

In this paper, equidistance routing algorithms for plural nets are proposed for two special classes of problems. The content of the paper is sketched along sections as follows. In Section 2, a basic technique to route 1-sink net with the prescribed length is presented. In Section 3, equidistance routing of plural nets is proposed for the channel routing where sources and sinks are on two parallel lines. A novel idea of slant grid by a single slant angle is introduced and it is shown that each net is routed in a freedom of choice of routes on the grid. As a consequence, the problem to minimize the total wire length comes out. A dynamic programming approach is proposed to solve the problem. This approach is enhanced in Section 4 to the case that sinks are on the perimeter of a rectangle. Several comments are cited. 1) For clarity, all these results are discussed on the Euclidean space. But there is a straightforward transformation to the conventional Manhattan routes keeping the property of equidistance. 2) Any conventional Manhattan router is applicable to the routes on the slant grid so that their difficulties (e.g. routability, minimizing the channel width, number of bends and/or vias, obstacle avoidance, etc.) and merits (e.g. routing by Maze, application for λ rule, etc.) are all inherited in equidistance routing. In Section 5, the proposed
channel routing algorithm is implemented and demonstrated on three instances of sizes.

2. PRELIMINARIES

The on-chip interconnect scheme (which is called the rout ing space or simply space) is mostly the Manhattan or grid space. However, our ways of routing are better explained in the Euclidean space where a route consists of line-segments with arbitrary slant angles. (Later, transformation of routes to those in a conventional Manhattan space keeping the property of equidistance is discussed.) A set of terminals that are required to be mutually connected is called a net. We assume naturally that a net has exactly one source. (All the results here are extended if each net is a multi-source multi-sink net.) A net is called the n-sink net if the number of sinks is n. Also a net is realized by a tree so that any sink is connected by a unique path to the source. Its length is the distance and a tree, where the distance from the source to any sink, is a prescribed length l is called l-equidistance routing.

The simplest case is routing of a 1-sink net. A line segment connecting two points p1 and p2 is denoted by p1p2 and its length by |p1p2|. A path which is a series of line segments is denoted by the sequence of points on the way such as {p1, p2, ..., pk}. Each step is illustrated in Figure 1.

<table>
<thead>
<tr>
<th>l-equidistance routing for 1-sink net</th>
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<tbody>
<tr>
<td><strong>Input:</strong> Source s, sink t and length l such that l ≥</td>
</tr>
<tr>
<td><strong>Step 1:</strong> If</td>
</tr>
<tr>
<td><strong>Step 2:</strong> Generate a point p1′ at arbitrary place such that segment p1p1′ is of length l.</td>
</tr>
<tr>
<td><strong>Step 3:</strong> Draw line l′ which is orthogonal to p1p1′ and intersects at the center (bisecting line with respect to p1p2). The intersection point is denoted by p2.</td>
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<tr>
<td><strong>Step 4:</strong> Output route r = {p1, p2, p2}.</td>
</tr>
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</table>

Figure 1: l-equidistance routing for 1-sink net

**Theorem 1.** The algorithm outputs a correct tree.

**Proof.** The proof is rather trivial except the property that line l′ intersects segment p1p2 (in Step 3). However, if l′ does not intersect with p1p2, it does with p1p2. Then, it trivially holds that |p1p2| > l that is a contradiction to |p1p2| ≤ l.

3. EQUIDISTANCE CHANNEL ROUTING

3.1 Slant Symmetric Space

The concept of “skew zero routing” is particular to two or more nets because it is based on the comparison (equality or difference) of lengths of nets. While l-equidistance routing in this paper is based on a different concept: a reference length l is specified and each net is required to be equal to this length. Therefore, the algorithm is applied even to a single 1-sink net. A more consideration is necessary but currently our proposing concept shows advantages only to some restricted classes of problems. The channel routing problem is such an example.

A channel consists of two parallel lines U and B with separation h. The sinks are all on B and sources on U.

First, as an interconnect scheme, slant symmetric grid by slant angle θ is introduced. The grid consists of positive or negative slant lines, the former by slant angle +θ, the latter by −θ with respect to the reference line B. Then the route of each net is searched from the source along the slant grid in downward direction.

**Theorem 2.** If l ≥ lmax where lmax is the maximum of source-sink distances of all nets in Euclidean metric, an l-equidistance channel routing is possible on the slant grid by slant angle θ such that sinθ = h/l.

**Proof.** Let a path on the slant grid connecting a source and a sink consist of slant segments s1, s2, ..., sn and the difference of y-coordinates between endpoints of si be dyi. The distance is calculated as follows.

\[ \sum_{i=1}^{n} |s_i| = h \sum_{i=1}^{n} \frac{dy_i}{\sin \theta} = h \frac{\sin \theta}{\sin \theta} = l \]

If the minimum separation rule λ is applied, additional constraint δsinθ ≥ λ must be satisfied where δ is the distance of two adjacent terminals on U and B. The situation is understood by an illustrative example shown in Figure 2.

Since routing on the slant grid is executed the same way as on the ordinary grid architecture, existing routers are available with those hard problems such as the routability, minimization of length, number of vias, obstacle avoiding, etc.

![Figure 2: 1-sink nets routed in a slant symmetric grid](image)

3.2 Minimum Total-Length Routing

Equidistance channel routing has a freedom in choosing segments in the slant grid as long as the direction is downward. As a consequence, the total length of a tree differs and then the minimization problem occurs. An algorithm to solve this problem is proposed.

On the slant symmetric grid, the route is realized as a binary tree and any solution tree is drawn in a recursive form as shown in Figure 3.

The sink terminals t0, t1, ..., tn−1 are on B at x = x0, x1, ..., xn−1, respectively, from the left. The cross point of two lines, one with angle +θ intersecting with B at x0 and the other with angle −θ intersecting with B at xn−1 is called the root. Since l ≥ lmax, the root is inside the channel and its distance from the source s to the root is constant. Therefore, the minimization shall be considered for the binary tree with the root. If the minimum length of the tree connecting
This is a typical dynamic programming formulation which follows.

For each net, the time complexity is $O(n^3)$ where $n$ is the number of its sinks. It is because, to explain very roughly, the number of possible $L(i, j)$ is $O(n^2)$ and each can be calculated in $O(n)$.

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An application of the algorithm is shown in Figure 7.

Figure 7: Equidistance box-routing algorithm

The following property of equidistance holds.

**Theorem 3.** For \( l = \sqrt{x_{\text{max}}^2 + y_{\text{max}}^2} \), an \( l \)-equidistance box-routing is attained by its algorithm.

**Proof.** It is trivial that there is a route connecting any pair of a sink and a source of each net on the slant grid. In the algorithm, \( l \)-equidistance channel routing is executed in Step 3.2 and the distance of a source and a temporary sink of each net is \( l \). After flipping the path in Step 3.3.2, its \( l \)-equidistance channel routing is executed in a same way as a conventional orthogonal routing. The feature of the idea is that routing on such a slant grid is enhanced to the equidistance box-routing. The important feature of the idea is that routing on such a slant grid is executed in a same way as a conventional orthogonal routing. The equidistance channel routing algorithm was implemented and demonstrated to show its speed.

A naive application of the equidistance box-routing algorithm, some unfavorable defects may happen after flipping of segments as illustrated in Figure 8. They are *crossing* and *overlapping*. By imposing additional rules these occurrences are avoided. To avoid crossing in Figure 8, if \( t_1 \) is on the right(left) side of the rectangle, the segment over \( t_1 \) should be in up-right(left) direction. To avoid overlapping, the route should not be turned on \( t_1 \).

Figure 8: Equidistance box-routing errors

### 5. Experiments

We implemented the equidistance channel routing algorithm and applied to the random data which are generated as follows: The number of nets is 20, 50 or 100. Terminals and their positions are generated randomly according to the instances. The \( x \) coordinates ranges from 0 to 40, 0 to 100, or 0 to 200, respectively. The distance between two parallel lines is set to either 20, 50, or 100 correspondingly to the numbers of nets being 20, 50 and 100, respectively. Routing scheme is the 2-layer similar to HV rule grid routing, the algorithm generates the route of each net by dynamic programming and delete overlaps by repetition of routing modification algorithm. Source codes are programmed by C language and we execute the program on a personal computer with CPU 2GHz and 512 MB RAM. The experimental results are shown in Table 1. For all the results, equidistance routing is achieved very quickly within one second even for the largest problems.

### 6. Conclusion

An equidistance algorithm for plural nets is proposed. It is shown that this works so well for equidistance channel-routing that a simple dynamic programming technique makes it possible to minimize the total wire length. This approach is enhanced to the equidistance box-routing. The important feature of the idea is that routing on such a slant grid is executed in a same way as a conventional orthogonal routing. The equidistance channel routing algorithm was implemented and demonstrated to show its speed.

### 7. References