MULTI-PADS, SINGLE LAYER POWER NET ROUTING IN VLSI CIRCUITS

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ABSTRACT

An algorithm is presented for obtaining a planar routing of two power nets in building-block layout. In contrast to other works, more than one pad for each of the power nets is allowed. First, conditions are established to guarantee a planar routing. The algorithm consists of three parts, a top-down terminal clustering, a bottom-up topological path routing and a wire width calculation procedure. Because of the hierarchical nature of the algorithm, it is inherently fast.

1. Introduction

Integrated circuits must be fed by at least two power nets, a ground (GND) net and a power supply (VDD) net. The power nets must be routed in metal, since neither poly nor diffusion are suitable for the heavy currents on these nets. Even in double metal process it is preferable to route the power nets in a single metal layer, leaving the other metal layer free for other nets. As a consequence the power nets may not cross each other. This constraint restricts the topology of the paths of these nets. We call it the *planar routability constraint* of the power nets.

Another observation about power nets is that the more current they have to carry, the wider they must be. Metal wires that are required to carry too much current suffer metal migration. If this happens, the atoms move within the wire leaving a break in the conductor. Typical process rules specify the minimum wire width as a function of the maximum current density. A secondary criterion in power net routing is to minimize the layout area occupied by the power wires.

Algorithms to route the power nets given one pad for each of the two power nets are reported in [Syed82, Roth81, Lie82, Moul83, Xion86]. Some of them impose restrictions on the pad or terminal positions [Roth81, Lie82]. Two interdigitated connection trees, one for each net, with the root at the pad and leafs at the terminals are usually constructed. To guarantee the planar routability of the power nets, it has been proven [Syed82] that given one power supply pad and one ground pad the planar routability can always be guaranteed if for every block there exists a cut (a line that intersects a block boundary at exactly two points) separating the power supply terminals and ground terminals. In this paper we propose a more general algorithm for the planar power net routing where the number of pads for each net is not restricted to one.

More than one pad per power net is needed in the cases, (1) where the number of pads per power net on an integrated circuit is not restricted to one, so that the restriction on the power terminal ordering on the blocks mentioned above can be relaxed allowing for more flexible power net routing; (2) to ease the current load of each pad; (3) to shorten the wiring length, especially in the case of hierarchical layout construction. For example, in Fig. 1.a three pads are placed on the boundary of the hierarchical module (bounded by the dashed line) to avoid parallel running power wires which is the case if only one pad may be used, see Fig. 1.b.

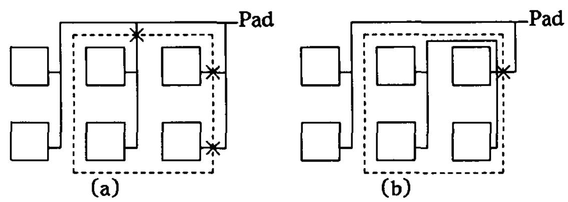


Figure 1. Hierarchical layout structure

In the following section some basic definitions are given. In section 3 conditions to guarantee a planar power net routing are established by deriving a formula to calculate the minimum number of pads needed for a given placement. In section 4 an algorithm is presented to construct a planar routing given a number of pads not less than the minimum. In section 5 an illustration of the algorithm is presented.

2. Definitions and problem formulation

In building-block layouts, a circuit (or a hierarchical module) contains a number of rectangular blocks of arbitrary size. The blocks may have any number of power terminals on the block boundaries. Let us call the power terminals on the periphery of the circuit, *pads* and the power terminals on the blocks, *terminals*. Obviously, terminals will become pads when we go down in the hierarchy. Some terminals on a block are internally connected. We call the internal connections of the terminals *feedthroughs*. It is assumed that only one terminal of a group internally connected terminals needs to be connected externally.

Definition 1: *Equivalent block (EB):* the equivalent block of a block is obtained by (1) removing all but one terminal of each group of consecutive power terminals belonging to the same net, and (2) removing all but one terminal of each group of internally connected terminals, in an order such that the number of remaining terminals on the block is minimal.

Definition 2: *Equivalent terminal (ET):* the equivalent terminals on a block are the remaining terminals on the equivalent block of the block.

An example of an equivalent block is shown in Fig. 2. The dashed line is a feedthrough.

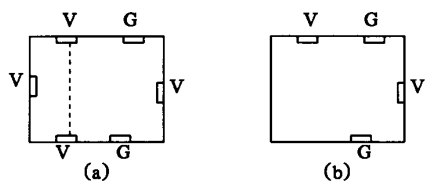


Figure 2. (a) a block (b) its equivalent block

Definition 3: *Minimum number of pads (MNP) of a net:* The minimum number of pads (MNP) of a power net is the minimum number of pads required to guarantee a planar power net routing.

The planar power net routing problem can be seen as follows: the pads and the terminals on the blocks must be divided into a number of clusters each of which contains a single pad and some terminals of the same net. A tour of a cluster is a closed path of the terminals and the pad. It is known that an optimal tour of points in the plane never crosses itself. If we can ensure that the tours of the clusters do not cross each other, a planar routing can be achieved. In this case, for each cluster, a metal wire can then be used inside the tour to connect all terminals to the pad enclosed by the tour without crossing other power wires. An example of such a clustering is shown in Fig. 3. In the example two VDD and one GND pads are specified. All terminals are connected. The tours are indicated by the dotted lines. VDD terminals are indicated by a 'V' and GND terminals are indicated by a 'G'.

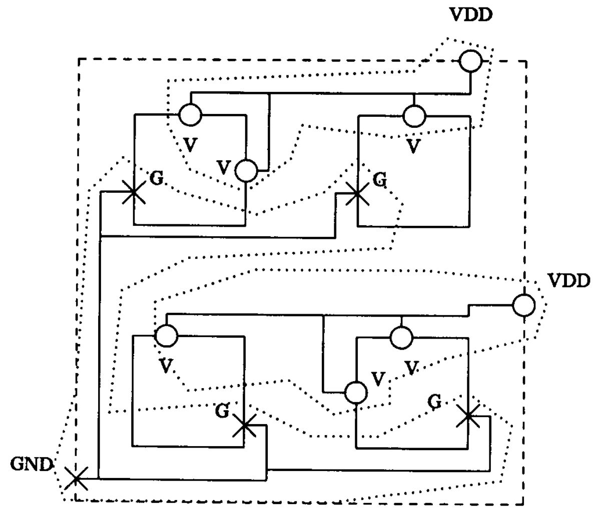


Figure 3. Planar routing of power nets

3. Conditions to guarantee a planar routing

Given a placement, in this section we consider the problem of finding the minimum number of pads, MNP, required for each net to guarantee the planar routing for two power nets. It is assumed that the relative order of the pads in different nets is not fixed. We begin by presenting two lemmas, needed in the proof of the main theorem in this section.

Lemma 1: For a single block, a planar routing exists if and only if the minimum number of pads (MNP) for each net is equal to the number of ETs of the net.

Proof: Sufficiency: since there is one pad for each ET and the order of the pads is not fixed, it is obvious that a planar routing exists. Note that if an ET can be connected to a pad the real terminals merged into the ET can also be connected to the pad.

To prove the necessity part of the lemma let us assume that a planar routing exists while two ETs share a common pad. From the definition we know that no two ETs of the same net can be adjacent to each other. The two possible ways to obtain a connection for these two ETs are shown in Fig. 4.a and Fig. 4.b. In both cases there are other ETs isolated from their pads, hence no planar routing exists for either case. This contradicts our assumption and the lemma has been proved.

Lemma 2: For two blocks a planar routing exists for two power nets if and only if the minimum number of pads (MNP) for each net is equal to the total number of ETs of the same net on the two blocks minus one.

Proof: Since the VDD ETs and the GND ETs of a block

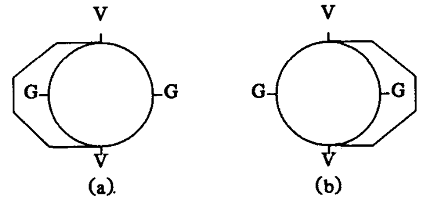


Figure 4. No planar routing exists for a block that has two ETs connecting to the same pad

always interleave each other in the two power net routing, we can always construct a composite block from the two blocks such that one pair of VDD ETs shares a common VDD pad and one pair of GND ETs shares a common GND pad. Figure 5 shows such a composite block. Then, using lemma 1, it is clear that if the number of pads for a net is equal to the total number of ETs of the net minus one, a planar routing can be achieved.

To prove the necessity part of the lemma let us assume that a planar routing exists while the number of pads of a net is less than the total number of ETs of the net minus one. From lemma 1 we know that no two ETs on the same block can share a common pad. Suppose that two pairs of ETs of the same net but on different blocks share two different pads, it is not hard to see that the closed circle formed by the two connections will always isolate some ETs of the other net from the outside due to the fact that the ETs of the two nets interleave each other. Hence no planar routing exists. This contradicts our assumption and the lemma has been proved.

Note that the MNPs for the two power nets are equal, because the number of VDD ETs is equal to the number of GND ETs on each block. Therefore we can speak of the MNP of the circuit. For example, the MNP of the circuit in Fig. 5 is (5 - 1) = 4.

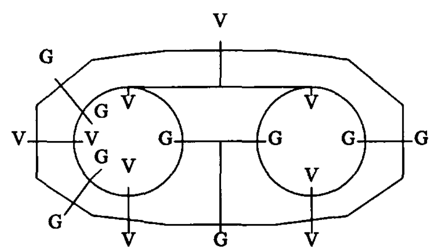


Figure 5. Planar routing for two blocks

The following theorem presents the MNP condition to ensure a planar routing of n blocks in two power net routing.

Theorem 1: A planar routing for two power nets with each net connecting to each of the n blocks exists ($n \geqslant 1$), if and only if the minimum number of pads (MNP) of each net is equal to the total number of ETs of the net minus ($n-1$).

Proof: We prove the theorem by induction. For one block and two blocks the proof is given by Lemma 1 and Lemma 2 respectively. Suppose the theorem is correct for n blocks. Hence the following expression is true:

$$MNP_n = T_n - (n-1)$$

where MNP_n is the minimum number of pads for n blocks and T_n is the total number of ETs on n blocks.

The case of n+1 blocks can be considered as a composite block of a basic block, j, and a composite block of n blocks. Suppose the number of ETs on block j is T_j. The total number of ETs on n+1 blocks, T_{n+1}, is then $T_{n+1} = T_n + T_j$. Because the the minimum number of pads on the composite block of n blocks MNP_n is actually the number of ETs on the composite block, according to Lemma 2 the minimum number of pads for n+1 blocks is:

$$\begin{aligned} MNP_{n+1} &= MNP_n + T_j - 1 \\ &= T_n - (n-1) + T_j - 1 \\ &= T_n + T_j - n \\ &= T_{n+1} - ((n+1)-1) \end{aligned}$$

Hence the theorem is also correct for n+1 blocks, and the theorem has been proved.

Notice that if each block has only one VDD ET and one GND ET, according to theorem 1, the minimum number of pads per net is one. This special case has already been proved [Syed82].

4. The planar power net routing algorithm

We propose an algorithm for the planar topological routing of two power nets. Within this algorithm the number of pads is not restricted to one per net. The algorithm consists of three parts. In the first phase, a terminal clustering algorithm is performed which divides the set of terminals and pads into clusters each of which contains exactly one pad and some terminals. In the second phase a topological routing path is found for each net. Finally, in the third phase wire widths are calculated. Instead of using a "flat" approach by connecting one terminal at a time or one tree at a time [Russ85, Haru87], we follow a hierarchical approach by a top-down terminal clustering and then a bottom-up path routing. This approach considers all terminals at the same time at each hierarchical level and guarantees a solution if one exists.

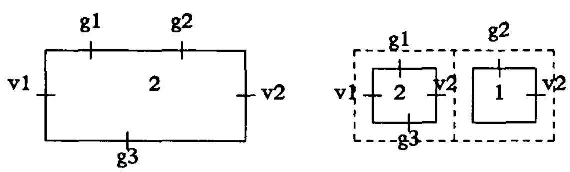
4.1 Top-down terminal clustering

By terminal clustering we mean that a cluster of terminals of the same net is determined for each pad (a terminal in the cluster is said to be assigned to the pad). The task of the terminal clustering algorithm is to assign each terminal to a pad while the planar routability is guaranteed. Notice that this clustering is not required if there is only one pad for each of the nets. After the clustering the clusters belonging to the same power net can be considered as different nets and their trees will not be connected to each other.

To guarantee a planar routing not only the number of pads is crucial but also the order of the pads on the circuit boundary. A planar routing can be achieved if the pads are ordered in such a way that if we replace the circuit by its EB, the number of resulting ETs of each net is not less than the MNP of the circuit. Let us call this the *MNP constraint*. Assume a number of pads not less than the MNP is given for each power net and a position or a desired side is provided for each pad. First, we do a virtual placement of the floating pads on their desired side in an order such that the MNP constraint is satisfied. The blocks are replaced by their EBs, however, without removing the consecutive terminals.

We assume that a slicing placement is given with a feasible channel routing order. The underlying idea of the clustering algorithm is now the following. The clustering algorithm partitions the placement recursively according to the given channel routing order. This means that, starting at the root level, a module is partitioned into two submodules by a horizontal or a vertical channel recursively. For the two submodules, first the MNP is calculated for each of them, then pads on the module are assigned to the submodules. They are placed on the boundary of each of the submodules so that two conditions are satisfied: (1) in the submodules a planar routing is guaranteed; (2) a planar routing is guaranteed between the module and the two submodules.

Basically, depending on the MNPs and the relative sizes of the two submodules the pads on the module are divided into two groups and assigned to each of the submodules. To guarantee the planar routing in the submodules the number and order of the pads assigned to the submodules must satisfy the MNP constraint in the submodules. Due to this constraint some pads of the farther module may need to be assigned to both submodules. On the other hand, referring to the proof of Lemma 2, to guarantee a planar routing between the farther module and the submodules, the number of pads assigned to both submodules may not be more than two, one for each net, and in such an order that the "reverse cyclic order" [Syed82] is satisfied. This order implies that if there are two pads assigned to both submodules, then starting from the pads on the two submodules assigned from the same high level pad, and moving along the corresponding boundaries in opposite directions, it should be possible to reach the pads assigned from the other high level pad without encountering any other pads (e.g. Fig. 5). The theorem ensures that this pad assignment can always be achieved. Further, the wiring length is taken into consideration by placing the pads on the submodules as close as possible to the corresponding high level pads. In Fig. 6 an example of such a pad assignment is given. The numbers inside the (sub)modules are the MNPs of the (sub)modules. The VDD pad v2 (Fig. 6(a)) on the module is assigned to both submodules (Fig. 6(b)) to guarantee the planar routing in the submodules.



(a) (b)

Figure 6. (a) a module (b) partitioning in submodules

If there is only one pad left for each net on the module, no further partitioning is needed. All terminals of the net inside the module are assigned to it. If the number of blocks inside the module becomes one, the terminals on the block are assigned to the nearest pads while maintaining the planar routability to the pads.

The pseudo code form of the terminal clustering algorithm is given below:

The terminal clustering algorithm:

INPUT: A placement of blocks and a number of pads

OUTPUT: An assignment of each terminal to a pad.

```
METHOD:
 {
 Calculate the MNP of the circuit.

 If the circuit is planar routable (checking MNP)
   {
   Give the pads on the circuit boundary a virtual place.

   Assign_pad (circuit)
   }
 }
Procedure Assign_pad(module)
 {
 If (the number of pads per net ≡ 1
 or the number of blocks inside the module ≡ 1)
   {
   Assign the terminals inside the module to the pads
   }
 else
   {
   Partition the module into two submodules.

   Calculate the MNPs for the two submodules.
```

Assign pads on the boundaries of the submodules (keeping the planar routability).

Assign_pad(submodule1), Assign_pad(submodule2).
}
}

4.2 Bottom-up path routing

After the terminals are assigned to the pads the routing becomes rather simple. The clusters of the same power net are considered as different nets. The topological path routing of the power nets is also performed hierarchically, however, bottom-up, in the opposite direction as the terminal clustering. Channels with lower routing orders are considered first. The two neighboring modules of a channel will form a composite module after the channel is processed. The path is optimized locally in wiring distance while keeping the planar routability constraint satisfied.

Basically, terminals facing the boundary of the composite module are connected directly to the boundary; a terminal inside the channel is routed to the end of the channel which results in the shortest Manhattan distance to the pad it is assigned to. The pad order on each hierarchical level determined in the terminal clustering phase is maintained. Thus, the terminals assigned to the same pad must be routed to the consecutive positions on the boundary of the composite module and the order of the terminals assigned to different pads must obey the order of the pads. To satisfy these conditions terminals outside the channel must sometimes be routed through the channel. For instance, in Fig. 7 if one VDD pad is placed on the bottom and one GND pad is placed at the top, one solution is to route the VDD terminal on the left module through the channel to the bottom side of the composite module.

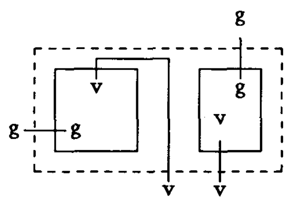


Figure 7. Local power net routing

4.3 Wire width calculation

After the topological routing is done a tree is formed for each pad of which the root at the pad and the leaves are at the terminals connected to the pad. Given the current demand of each power terminal, the width of the power wire segments corresponding to each branch of the tree can be calculated. Although any accurate methods, for example [Chow87], can be adopted here to calculate the wire width we used a simple scheme by accumulating the current demand from the leaf terminals to the root and converting the current demand on each tree branch into wire width. The relationship between the metal wire width and the current density is usually provided in the design rules.

5. An example

To illustrate the algorithm the following example is worked out stepwise. In Fig. 8 a placement of three blocks is shown. VDD terminals are indicated by a 'v' and GND terminals by a 'g'. Two VDD pads, v1 and v2, and two GND pads, g1 and g2, are placed on the circuit boundary, one on each side. The two routing channels are also shown in the figure.

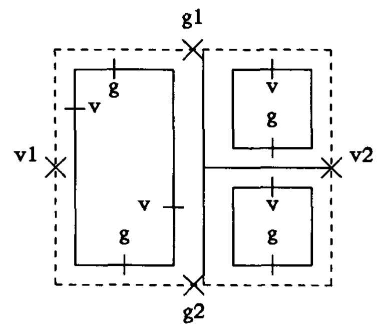


Figure 8. A power net routing example

5.1 Terminal clustering

Since the MNP of the circuit is 2 and these are two VDD and two GND pads this example is planar routable. At the first step pads are assigned to the first level of the hierarchy, see Fig. 9. V2 and g2 are assigned to both submodules, because the MNP of module m1 is 2.

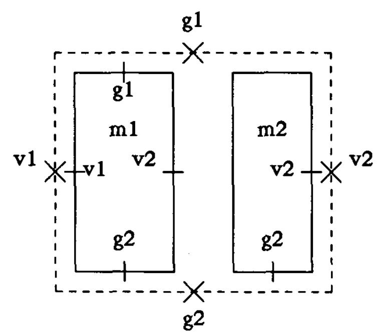


Figure 9. Terminal clustering at the first hierarchical level

Since the number of blocks in m1 is one and the number of pads per net on m2 is one, at the second step, all terminals are assigned to the pads and the terminal clustering is finished, see Fig. 10.

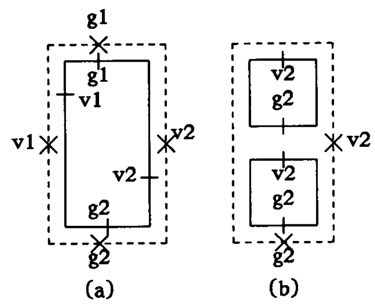


Figure 10. Terminals are assigned to the pads

5.2 Path routing

The path routing is carried out starting from the lowest level. At the first step the second level of the hierarchy is routed, see Fig. 11.

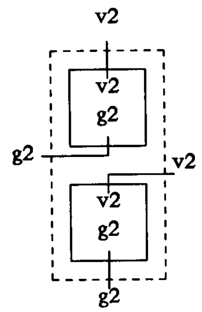


Figure 11. Path routing at the second hierarchical level

At the second step the first level of the hierarchy is routed using the result of the first step, see Fig. 12.

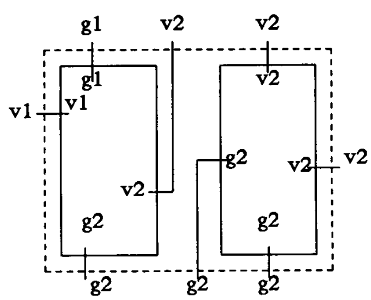


Figure 12. Path routing at the first hierarchical level

After these steps the routing from the boundary to the pads is simple. The final result is shown in fig. 13.

6. Conclusions

A novel algorithm is presented to solve the problem of planar routing for two power nets. More than one pad per power net is allowed which results in a forest of multiple trees. The conditions to guarantee a planar routing are outlined by deriving the minimum number of pads (MNP) requirement. The algorithm guarantees a solution if these conditions are satisfied. The algorithm is efficient because of its hierarchical nature. The nets are processed all at the same time which prevents net or terminal ordering. Further, it provides a good starting point to tackle the planar routing problem for more than two power nets or critical nets.

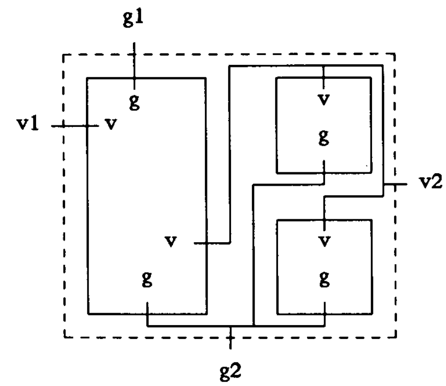


Figure 13. The result of the power net routing

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