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Three Layer Routing for Reliability Enhancement

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Abstract

In this paper we study two important reliability issues in deep submicron VLSI design, namely antenna effect and crosstalk noise, in the context of three-layer channel routing. Cost functions for both of the failure mechanisms are introduced and based on these cost models, reliability enhancement techniques are presented. For antenna effect minimization, a layer reassignment algorithm is adopted while for crosstalk minimization, an algorithm that combines layer reassignment and track reassignment is presented. Experimental results show that these algorithms can reduce the antenna effect and the crosstalk noise considerably without increasing the routing area. The relationship between these two objectives has also been studied and a technique for optimizing them simultaneously is proposed.

KEY WORDS: antenna effect, crosstalk, channel routing, design for reliability.

1. Introduction

Due to the scaling down of device geometry in deep-submicron technologies, antenna effect and crosstalk noise have become major concerns in high performance VLSI circuit design. The antenna problem is a side effect of various plasma-based manufacturing processes such as etching, etc [9, 14, 15, 16]. These plasma-based processes are widely used to get the fine feature size of modern IC. Plasma etchers or ion implanters can induce a voltage into isolated leads, overstressing thin gate oxides. The leads (polysilicon or metal) act like antennas collecting charges and the accumulated charges may result in oxide breakdown. These charges may also have a negative effect on the hot-carrier device aging lifetime [4]. As devices are further scaled, the oxides are getting thinner and, as a result, the problem of antenna effect is expected to worsen.

Unlike antenna effect, where damage is done during the manufacturing process, crosstalk noise is caused by coupling capacitance between long adjacent nets when the circuit operates at a high frequency. Increased coupling noise can cause signal delays, logic hazards and even malfunctioning of circuits [1, 13], and thus controlling the level of crosstalk noise in a chip has become an important task for IC designers.

In this paper we study the problem of antenna effect minimization and crosstalk minimization in 3-layer HVH channel routing. This routing style allows using two horizontal layers (layer 1 and layer 3) and one vertical layer (layer 2) for routing. Another popular 3-layer routing style is VHV where two vertical layers and one horizontal layer are available. Both routing styles can be found in various designs, but HVH routing can usually achieve a smaller routing area than VHV routing [17].

The only published research in the area of routing for antenna effect minimization is by Wang et al [20]. They proposed several techniques to minimize the antenna effect in 3-layer channel routing. One drawback of their approach is the penalty of channel height increase. For example, their router requires four more tracks in the Deutsch difficult example to minimize the antenna effect. This drawback makes their solution unacceptable in many cases. We adopt a different approach. Instead of creating a new router to target the antenna effect, we developed a layer reassignment algorithm that can be used as a layout post-processor to modify any already routed layout to minimize the antenna effect with no increase in routing area. Experimental results show that this approach is promising and substantial reductions in antenna length can be achieved.

For crosstalk minimization, though there are several reports on crosstalk minimization in 2-layer channel routing [10, 11], only a very limited number of papers have been published on crosstalk minimization in 3-layer routing. In [18], Thakur et. al formulated the layer reassignment problem in 3-layer VHV routing as a longest path problem. This formulation however, is invalid for HVH routing. To tackle the crosstalk problem in 3-layer routing, we present an algorithm that combines layer reassignment and track reassignment techniques. This algorithm can iteratively modify the layout so that the crosstalk in the channel can be minimized.

2. Routing for Antenna Effect Minimization

2.1. Antenna Effect in 3-Layer Channel Routing

Antenna effect is caused by plasma-based manufacturing processes. Though the plasma-induced charging mechanism is not fully understood, it has been found that the charging appears to be a problem when some poly and/or metal wires, which are neither covered by a shielding layer of oxide nor connected to the substrate by previously formed p-n junctions, are exposed to plasma [9, 14, 15, 16]. It has also been found that stressing due to plasma etching can be modeled as a constant current stress with the stressing current being proportional to the peripheral length of the metal or polysilicon pattern [14]. In channel routing, the peripheral length can be simply represented by the length of the metal or poly wire segment and therefore, minimization of the antenna effect in channel routing can be achieved by minimizing the length of potential antennas.

During the manufacturing process, all terminals belonging to the same net will finally be connected. However, before the net becomes fully connected there are situations when some interconnects are fabricated while they are connected to receivers (where the gate oxides are) only, and this can cause an antenna effect. More specifically, after the Layer_2 etching and Layer_1/Layer_2 via fabrication in HVH routing, some receiver type terminals may be connected to long incomplete interconnects which comprise of Layer_1 and Layer_2 segments, and they are not connected to their drivers (where the p-n junctions are) due to the lack of the Layer_3 interconnects. Those long incomplete interconnects act like antennas and the charges collected by them during the previous manufacturing processes can have a negative effect on the gate oxide of the receivers. An example of an antenna in 3-layer channel routing is shown in Figure 1, where Figure 1(a) is a given layout and the antenna in this layout is shown in Figure 1(b).

Since the risk of the gate oxide damage is proportional to the charge collected by the antenna, which is in turn proportional to the antenna length, we can reduce the probability of a gate oxide damage by minimizing the antenna length for each net. Based on this argument we formulate our objective function as minimizing the longest antenna in the channel:

$$\begin{array}{c} Minimize\ \{Max\ (\text{antenna length of net } i)\} \\ \text{for every net } i \end{array} \qquad (1)$$

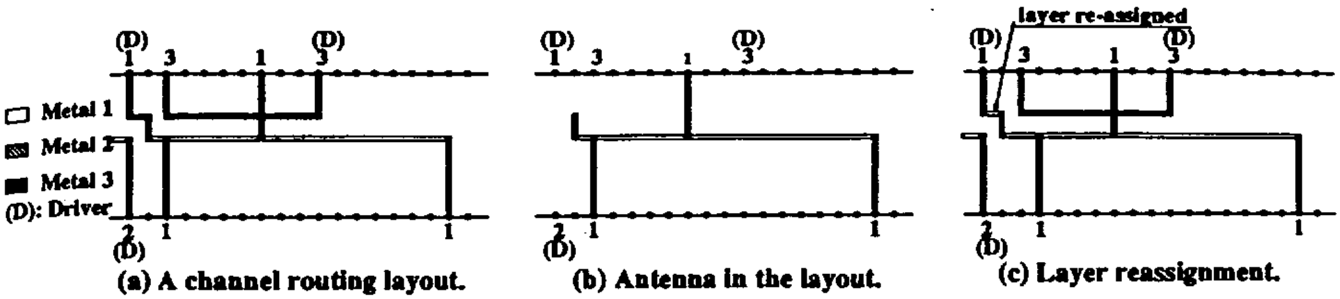
If two or more solutions tie in the cost function defined in (1), we can use the following secondary cost function to break the tie:

$$Minimize \left\{ \sum_{\text{all nets}} (\text{antenna length of net } i) \right\} \qquad (2)$$

2.2. Layer Reassignment to Minimize Antenna Effect

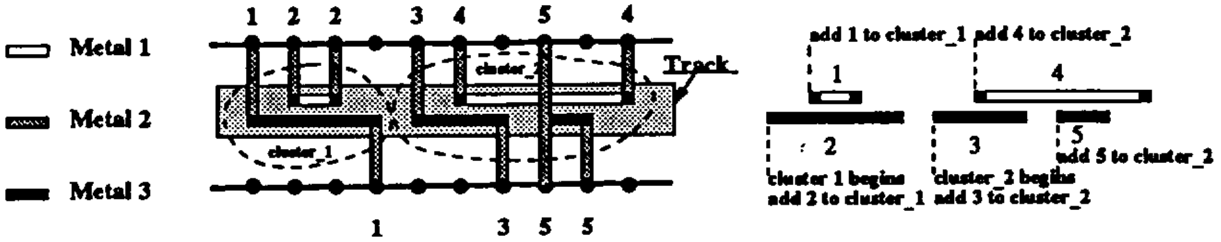
We assume that we are given a layout which may have been generated by any HVH router. Several such routers are available [2, 3, 7]. We keep the vertical wire segments unchanged and for each horizontal wire segment there are two possible choices for layer assignment, one is Layer_1, and the other is Layer_3. To illustrate the basic idea of layer reassignment for antenna effect minimization, we use the example in Figure 1(a). We can reassign one of the wire segments of net 1 from Layer_3 to Layer_1, as shown in Figure 1(c), and all the antennas in net 1 can be eliminated by this layer reassignment.

Basically, a horizontal wire segment will not become part of an antenna iff



(a) A channel routing layout. (b) Antenna in the layout. (c) Layer reassignment.

Figure 1: Antenna effect in 3-layer channel routing.



(a) A channel routing layout. (b) Building a cluster.

Figure 2: A set of wire segments can be grouped into a cluster.

Table 1: 3-layer channel routing benchmark examples.

Examples	#nets	#tracks	#columns
ex1[21]	21	6	35
ex3a[21]	33	8	45
ex3b[21]	46	9	61
ex3c[21]	54	9	79
ex4b[21]	55	9	119
ex5[21]	64	10	121
D1[7]	60	9	155
Diff[8]	72	10	174

- it is in Layer_3, or
- it is in Layer_1 but it can be connected to its driver without using any Layer_3 wire segment

We can use these two criteria to determine the contribution of a horizontal wire segment to the antenna effect during layer reassignment.

By representing each horizontal wire segment as a vertex in a graph, we can formulate the layer reassignment problem as a network bipartitioning problem. There are two possible choices for each node, Layer_1 or Layer_3, and our problem is to find an optimal bipartitioning of the nodes such that the objective function defined in (1) and (2) can be minimized. This is similar to the classical network bipartitioning problem; however, in our problem the assignments of vertices, which represent the horizontal wire segments, are not independent, which means that sometimes two wire segments must be placed in the same layer, while sometimes they must be put in different layers. This is illustrated in the example shown in Figure 2(a). In Figure 2(a), there is a single track channel, and there are five wire segments belonging to five different nets in this track. To get a valid channel routing solution, the horizontal wire in *net_1* and the horizontal wire in *net_2* must be placed in two different layers to prevent *net_1* from being connected to *net_2*.

To solve this inter-dependence problem, we introduce the notion of *cluster*. A *cluster* is a set of wire segments whose layer assignments are dependent on each other. Clusters in a track can be easily found by scanning the track from one end to the other. When the scan line encounters a new wire segment, we check whether this segment overlaps with other wire segments in the current cluster. If it overlaps, we add this segment to the current cluster, otherwise, we start a new cluster. An example of building a cluster is shown in Figure 2(b), where five wire segments form two clusters. We select one wire in each cluster as a reference point to represent the layer the cluster belongs to, and there are only two possible layer assignments for any cluster, one is assigning the reference wire segment to Layer_1 and the other assigning it to Layer_3. The layer assignments of different clusters are independent of each other. By using clusters to represent the horizontal wire segments, we can get a formulation similar to the classical network bipartitioning problem, but they are not identical since we are minimizing here the objective function defined in (1) and (2) instead of the total weighted cuts between the bipartite subgraphs.

2.3. Experimental Results

To test the effectiveness of the proposed technique, three-layer layouts have been generated for a set of channel routing examples by using the three-layer channel router described in [7]. The information about each benchmark, such as number of nets, number of tracks and number of columns in the channel is shown in Table 1.

Since no driver/receiver information is provided in these benchmarks, we randomly select one terminal from each net as a driver while assigning all other terminals in the net as receivers. We use the Kernighan-Lin based network bipartitioning algorithm [12] to perform layer reassignment to minimize the antenna effect. The cost function for the antenna effect is the maximum antenna length. Benchmark examples with different randomly assigned drivers and receivers have been run. The results of these experiments are shown in Table 2.

The second and the third columns in Table 2 are the maximum antenna length and the total antenna length for the original layouts while their corresponding values for the modified layouts are shown in column 4 and column 5, respectively. From this table, we can see the impact of our layer assignment technique on antenna effect minimization. For all the benchmark examples we have tested, an average of 42.1% reduction in maximum antenna length has been achieved and the total antenna length has also been reduced by 32.2%. Considering the average improvement only may be misleading, since the amount of improvement varies significantly from one example to the other. The decrease of the antenna length can be as high as 87.7% in example D1, or as low as 0% in ex5. The reason behind this is that ex5, as well as ex1, ex3b, and ex3c, has a very short antenna in its original layout due to the lack of doglegs, and therefore, the room for improvement is much smaller compared with ex3a, ex4b, D1 and Diff.

Since the 3-layer channel router used in [20] is unavailable, we could not use their router to generate antenna effect optimized routing solutions for the benchmark examples and compare them with those obtained by our layer reassignment technique. The only comparison we can do is to compare our result for the Deutsch difficult example with theirs. Both results for the Deutsch difficult example are shown in Table 3.

From Table 3 we can see that the two approaches achieve similar quality solutions for the Deutsch difficult example in terms of maximum antenna length and average antenna length. However, in [20] 14 tracks were used, while we use only 10 tracks.

3. Routing for Crosstalk Minimization

3.1. Crosstalk in a Channel

Crosstalk noise between two adjacent nets is determined by a number of factors including the coupling capacitance between them, the driving capacity of the two nets, timing of the signals, etc [19]. Among all these factors the coupling capacitance provides a first order estimation and it has been used to represent the crosstalk value in [10] and [11]. Since the coupling capacitance is determined by the overlap and the distance between these two wires, we use the overlapping length between two adjacent wires to represent the coupling capacitance between them. Associated with each net in the channel, there is a value representing the margin between its current noise level and the predefined noise upper bound. This value is called noise slack and it can be represented by the number of coupling capacitance units, or the number of overlap length units. Since a larger noise slack corresponds to a more reliable design, the objective of the crosstalk minimization problem can be formulated as maximizing the minimum slack for all the nets in the channel

$$\begin{array}{c} Maximize\ \{Min\ (\text{noise\_slack of net } i)\} \\ \text{for every net } i \end{array} \tag{3}$$

3.2. Crosstalk Minimization Algorithm

The routing in a channel can be represented by a graph as follows. Let each node represent a horizontal wire segment. The relationship among these

Table 2: Experimental results for antenna effect minimization.

Examples	Antenna Length (original)		Antenna Length (modified)	
	max	total	max (%reduc.)	total (%reduc.)
ex1	4.4	21.1	4.1 (5.5)	21.9 (-0.0)
ex3a	23.0	149.9	8.5 (63.1)	101.8 (32.1)
ex3b	7.9	129.7	7.8 (0.1)	68.2 (47.4)
ex3c	9.9	160.9	7.8 (20.5)	119.8 (25.7)
ex4b	52.8	308.0	8.2 (84.5)	148.2 (51.9)
ex5	10.0	210.9	10.0 (0.0)	123.0 (41.7)
D1	72.9	358.5	9.0 (87.7)	232.8 (35.1)
Diff	56.9	712.1	14.0 (75.2)	542.7 (23.8)
Average			42.1	32.2

Table 3: Comparison with previous work.

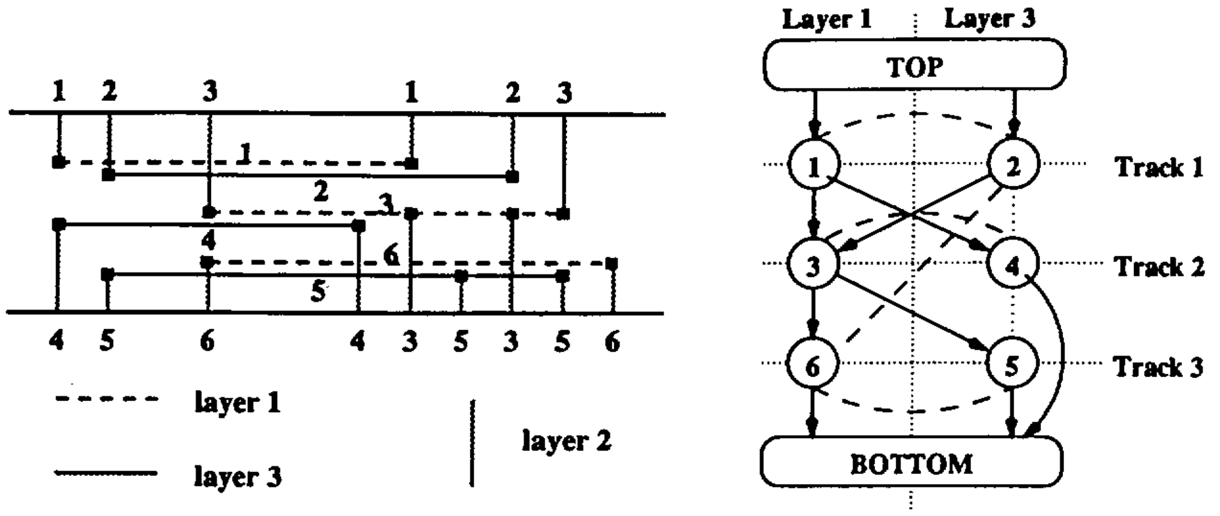
	max antenna length	average antenna length	#tracks used
Result in [20]	15.0	7.2	14
Our Result	14.0	7.5	10

horizontal wire segments can be represented by horizontal and vertical constraints. A vertical constraint from wire segment i to wire segment j means that segment i must be placed on top of segment j. A horizontal constraint between two wire segments means that these two segments can not be placed in the same track. In the graph representation of the 3-layer channel, there is a directed arc from node V_i to node V_j if there is a vertical constraint from V_i to V_j. There is an undirected arc between two nodes if there is a horizontal constraint between these two nodes. Nodes representing wire segments can be divided into two groups, one is for those nodes whose corresponding wire segments are in layer 1 and the other one is for those whose corresponding wire segments are in layer 3. An example shown in Figure 3 illustrates the graph representation of a channel, where Figure 3(a) is the layout of the channel and Figure 3(b) is its corresponding constraint graph representation. In this figure, solid lines with arrows represent vertical constraints, dashed lines represent horizontal constraint, horizontal dotted lines represent tracks, and the vertical dotted line shows the division between the layer_1 group and the layer_3 group.

The 3-layer HVH routing crosstalk minimization problem can be stated as follows: given a graph representation of a channel, find an appropriate position for each node so that the crosstalk cost defined in (3) is minimized. The final layout should also satisfy all the vertical and horizontal constraints and should not increase the channel height.

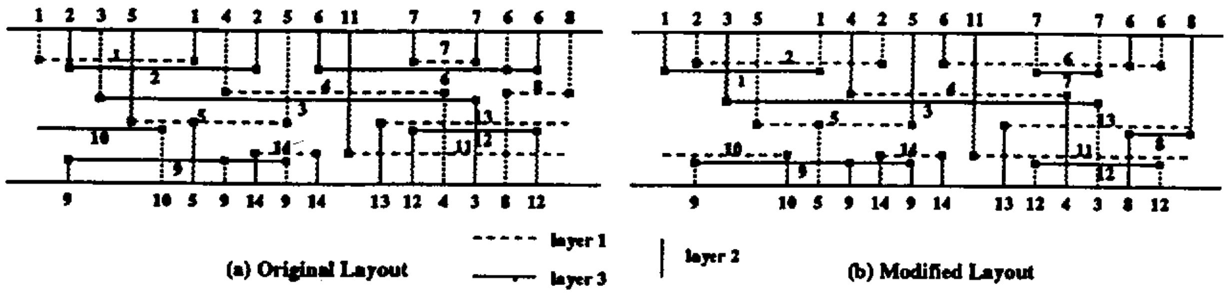
Track permutation for crosstalk minimization in 2-layer routing has been proved to be NP-hard [10] and therefore, we need to resort to heuristics to solve our problem, which is a generalized version of the track permutation problem. We found that several techniques can be adopted to reassign the layer and position of wire segments (or nodes in the constraint graph) to reduce the crosstalk noise in a channel. To illustrate these techniques we use the channel routing example shown in Figure 4, where Figure 4(a) is the original layout, and Figure 4(b) is the modified layout by applying some of the layer reassignment and track reassignment techniques. In the original layout, net 3 has the worst crosstalk noise and the following techniques can be applied to reduce its crosstalk cost.

- layer reassignment: since wire segment 3 has a long overlap with segment 2, we can reassign wire segment 2 to the other layer to eliminate the overlap between these two wires. In the constraint graph, this layer reassignment operation is equal to moving node 2 from the group of layer_3 to that of layer_1. Notice that this will



(a) (b)

Figure 3: Routing in a channel can be represented by a graph: (a) layout of the channel; (b) the constraint graph representation of the layout.



(a) Original Layout

(b) Modified Layout

Figure 4: Various techniques for crosstalk minimization

force node 1 to move in the opposite direction to satisfy the horizontal constraint. Though this will introduce new crosstalk noise between net 1 and net 3, the crosstalk of net 3 will be reduced since segment 2 has a longer overlap with segment 3 than segment 1 does. Similar operations can be applied to nodes 6 and 7.

- track reassignment: the overlap between segment 3 and segment 12 can be eliminated if we reassign wire segment 12 from track 3 to track 4. This is equivalent to moving node 12 from track 3 to track 4 in the constraint graph.
- a combination of track reassignment and layer reassignment: we can move segment 10 to track 4 and reassign it to layer 1 eliminating the overlap between segments 10 and 3.
- reducing crosstalk between vertical wires: node 8 can be moved to track 2 (after node 12 has been moved to track 4) to reduce the crosstalk of net 3. Though this track reassignment has no effect on the overlap between the horizontal wire segments of net 3 and net 8, the overlap between the vertical wire segments of these two nets, however, is reduced, which leads to a reduction of the crosstalk for net 3.

The above are the basic operations we adopted to minimize crosstalk. A more complicated layer/track reassignment such as swapping among two (and even more) nodes is also allowed in our algorithm. Another technique we adopted is dogleg insertion. By introducing additional doglegs, we can overcome the situation when the up or down movement of a horizontal wire segment is blocked by vertical/horizontal constraints, and this is illustrated in the example shown in Figure 6. In our algorithm dogleg candidates are introduced and they are added to the wire segments whose vertical/horizontal constraints block the movement of wire segments in and

```
function crosstalk_minimization()
{

 1:repeat {
     select Net_cr which is the net with the lowest noise slack;
     introduce potential additional doglegs to Net_cr;
     for each wire segment Wire_i in Net_cr {
         if (it can decrease cost ) do layer_reassign (Wire_i);
         if (Net_cr is not critical any more) break;
         if (it can decrease cost) do track_reassign (Wire_i);
         if (Net_cr is not critical any more) break;
         if (it can decrease cost) do layer_track_reassign (Wire_i);
         if (Net_cr is not critical any more) break;
         if (it can decrease cost)
             do complex_layer_track_reassign(Wire_i)
         if (Net_cr is not critical any more) break;
     }
  } until (cost function can not be improved any more);

  if (lowest noise slack < 0) {
     add one more track to the channel;
     got to 1;
  }
}
```

Figure 5: Algorithm psuedo code.

Table 4: Experimental results for crosstalk minimization.

Examples	Original Design		Modified Design			
	Max	Total	Max	% Reduce.	Total	% Reduc
ex1	68	602	53	19.1	560	7.0
ex3a	103	1040	84	18.4	958	7.9
ex3b	123	1642	96	22.0	1648	- 0.0
ex3c	156	2162	128	17.9	2124	1.8
ex4b	223	2530	189	15.2	2336	7.7
ex5	98	2328	84	14.2	2194	5.8
Diff	328	5886	302	7.9	5720	2.8
average				16.4		4.7

around critical nets.

Our algorithm works as follows. It first selects the net with the worst crosstalk noise, which is called the "critical" net. Then it tries to reduce its crosstalk by applying the above mentioned techniques. If the net is not "critical" any more after applying these techniques, we select a new critical net and apply the same techniques. This process continues until no further reduction of crosstalk cost is possible. If the lowest noise slack is negative after applying the algorithm, we add one more track to the channel and repeat the track/layer reassignment process. The pseudo code for the algorithm is listed in Figure 5.

Let T, C and S represent the numbers of tracks, columns and wire segments in the channel, respectively. The time complexity of this algorithm can be analyzed as follows. For each wire segment, we need to check $O(T)$ tracks to find the best position in terms of crosstalk and for each possible position, $O(S^2)$ time is needed to find its new crosstalk cost. A net can have at most $O(S)$ wire segments and so for each iteration, the time complexity is $O(TS^3)$. The maximum possible crosstalk reduction is O(T+C) and the worst case is that all nets have the same slack value and for each iteration the cost function is reduced by 1. Since there are at most S nets, the loop will stop after $O((T+C)S)$ iterations, resulting in a time complexity of $O(T(T+C)S^4)$ for the whole crosstalk minimization process.

3.3. Experimental Results

The proposed algorithm has been applied to the same set of channel routing benchmark examples used in Section 2.3. Since there is no noise slack information available for these examples, we make the following assumption. The minimum noise slack is 0 in the original layout and it happens in the net with the largest coupling capacitance value, which is denoted by $C_{coupling\_max}$. The noise slack for any other net i in the original layout is assumed to be $C_{coupling\_max} - C_{coupling\_i}$, where $C_{coupling\_i}$ is the total coupling capacitance of net i. Under this assumption, the optimization of cost function (3) is equal to the minimization of the maximum coupling capacitance in the channel, and maximizing the total noise slack is equal to minimizing the total coupling capacitance. The results under this noise slack assumption are shown in Table 4. In this table columns two and three include the values of the worst coupling capacitance and the total coupling capacitance in the channel, respectively, in the original layouts, while their corresponding values for the modified layouts are shown in column 4 and column 6, respectively. The percentage improvements for the maximum and total crosstalk are shown in column 5 and column 7, respectively. In our examples, all the original HVH 3-layer routing layouts were obtained by using the router reported in [7]. As mentioned before we use the overlap length between adjacent wires to represent the crosstalk between them. From Table 4 we can see that an average of 16.4% reduction in maximum crosstalk can be achieved by our algorithm. The total crosstalk in the channel has also been reduced by 4.7% though it is not one of our objectives. The algorithm is fast and for all the benchmark examples reported here it takes less than a minute to get the results on a IBM RS6000 workstation.

The original and modified routing solutions for ex1 are shown in Figure 7. In the original layout, shown in Figure 7(a), net 6 has the largest crosstalk value which is 68 units. The modified layout, obtained by applying our algorithm, is shown in Figure 7(b) and it has a maximum crosstalk of 53 units occurring in net 12.

4. Optimizing for Both Objectives

The crosstalk of a net depends not only on the location of the net itself but on the location of its neighboring nets as well. This fact makes it difficult to minimize the crosstalk especially when the channel is compacted. Compared with crosstalk minimization, antenna effect optimization faces a much better situation, since antenna length can be fully controlled by assigning different layers to the wires in the net. The high improvement rate in the benchmark examples also suggests that there is much more freedom to explore in antenna minimization than in crosstalk minimization. Based on this observation, we conjecture that antenna effect minimization can be performed after the solution for crosstalk minimization has been obtained while using the optimal crosstalk value as a constraint, if we want to minimize the two objectives at the same time. This conjecture is supported by the results shown in Table 5. In this table, column 2 shows the maximum antenna length for the layouts after crosstalk minimization. These layouts are then optimized for antenna effect in two different ways, with and without crosstalk constraint. The solutions with the crosstalk constraint, shown in the last column, are not far away from the solutions without the constraint, shown in the third column, with the maximum difference in antenna length being less than 5 units.

5. Conclusion

We have presented algorithms for reducing antenna effect and crosstalk noise during the routing stage of VLSI design. For antenna effect, the layer reassignment is a simple yet very effective approach to minimize the antenna length in 3-layer routing. For the benchmark examples with long antennas we manage to reduce the maximum antenna length by over 60%. Compared with previous work, an important feature

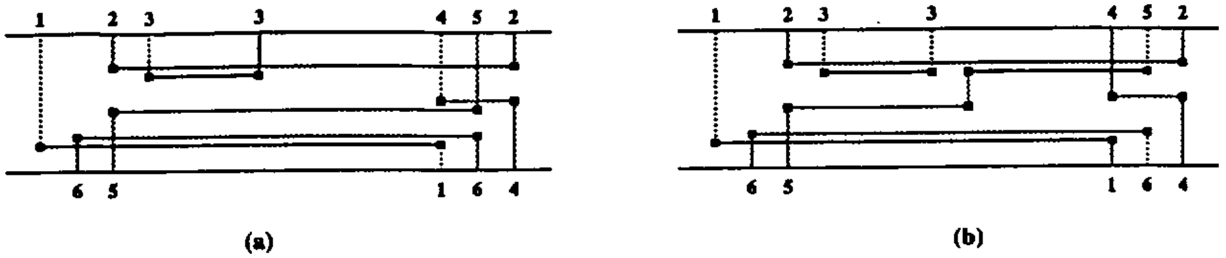


Figure 6: Additional doglegs can allow further reduction in crosstalk: (a) In the original layout, net 5 has a maximum coupling capacitance of 16 units; (b) After introducing a dogleg into net 5, its maximum coupling capacitance is reduced to 11.

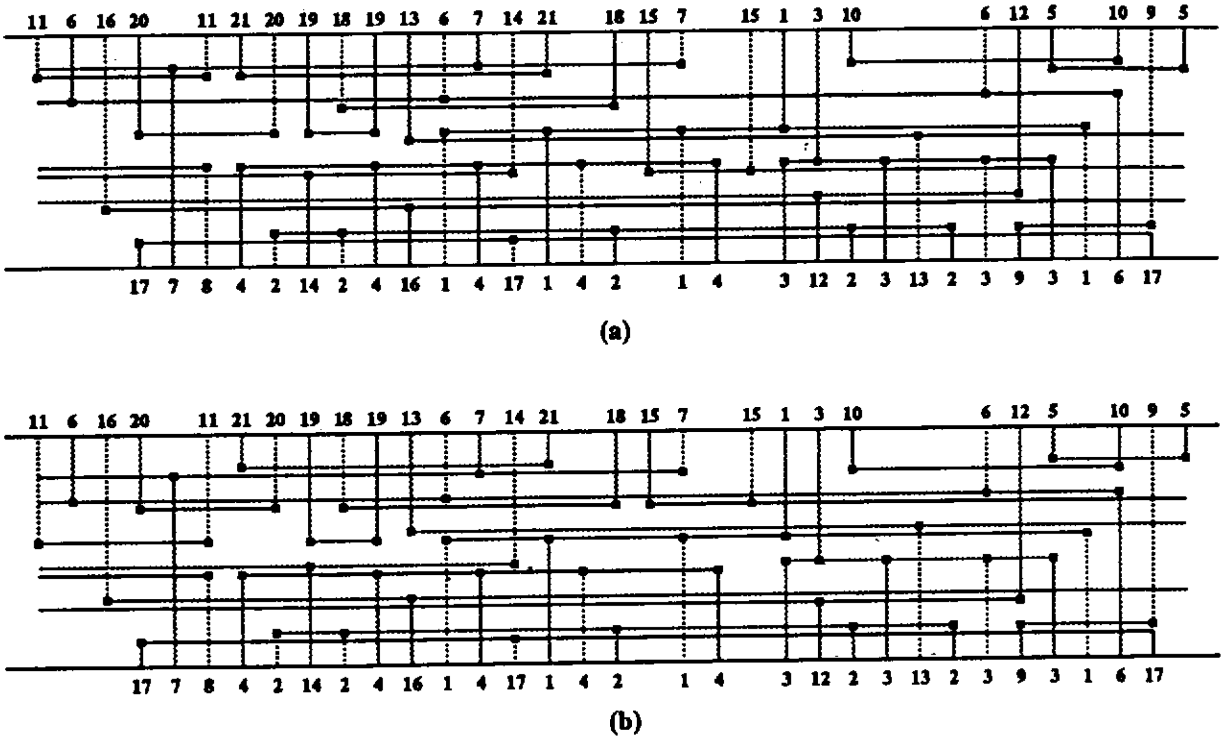


Figure 7: (a) Original layout and (b) modified layout for crosstalk minimization.

of our approach is that it requires no additional routing area. For crosstalk minimization, an algorithm that combines layer reassignment and track reassignment was proposed. This algorithm can also introduce additional doglegs as needed to further reduce the crosstalk noise in a channel. This polynomial time algorithm is fast and it has been shown to reduce the maximum crosstalk by an average of 16.4% on a set of benchmark examples. Though a simplified crosstalk cost model has been adopted in the research, we believe that our approach is valid when more accurate crosstalk models are applied.

The relationship between these two objectives has also been studied and we found that the solution space for crosstalk minimization is much more constrained than that for antenna effect minimization. So if optimization for both of the objectives is required, the crosstalk should be minimized first, followed by optimizing the antenna effect cost function with the optimal crosstalk value as a constraint. Our experimental results show that solutions for antenna effect minimization with and without crosstalk constraints differ only marginally.

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Table 5: Minimization of antenna effect and crosstalk at the same time.

Examples	Max Ant1	Max Ant2	Max Ant3
ex1	5.5	3.8	3.8
ex3a	8.4	6.5	6.8
ex3b	7.9	7.8	7.9
ex3c	19.3	7.4	8.0
ex4b	9.8	8.3	9.0
ex5	37.4	10.0	12.0
D1	93.3	9.3	10.3
Diff	71.3	14.1	18.8

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