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# Cross Point Assignment Algorithm with Crosstalk Constraint*

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**Abstract**: An algorithm to resolve the coupling effect problem is proposed during the cross point assignment (CPA) stage. In the algorithm, the priority queue concept and the rip-up and reroute strategy are combined to control crosstalk noise caused by interconnect coupling capacitance. First, the nets are arranged into different priority queues according to their weighted sum of their length and criticality. Then, the CPA problem for one queue of nets is translated into a linear assignment problem. After the assignment of one queue of nets, a post-CPA checking routine is performed to check and rip up the net pairs which violate the crosstalk noise constraint and then push them into the next queue to be reassigned. The algorithm is tested by a set of bench mark examples, and the experimental results are promising.

**Key words**: routing; cross point assignment; crosstalk; interconnect

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## 1 Introduction

As VLSI technology reaches very deep submicron feature size and gigahertz clock frequencies, interconnect has become the dominating factor in determining the performance, power, reliability, and the cost of the overall chip. One of the most critical issues is the increasing effect of the coupling capacitance between interconnect on the same layers. Thus, the routing turns out to be a more and more challenging problem. The objective of routing is to accomplish high completion rate under satisfying crosstalk and timing constraints.

Because of the complexity of the routing problem, it is often solved by divide-and-conquer approaches, which is a global routing followed by the detailed routing. On one hand, although the coupling effect control during the global routing stage may have more flexibility, the routing resource estimation can not be very accurate without detailed routing information. On the other hand, the coupling effect control during the detailed routing stage is in a local scope and short of flexibility, though the estimations can be of high accuracy. So, neither of the two routing stages can offer perfect opportunities to address the crosstalk noise problem caused by interconnect coupling capacitance. With enough flexibility and fairly accurate net routing information, the CPA stage proves to be an ideal place to solve the problem[1].

In Ref. [2], a general architecture CPA algo-

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rithm is proposed, which considers accurate local congestion information and optimizes the alignment of cross points, but does not consider the crosstalk issue. References[5~ 7] present different CPA algorithms based on analysis of net type. They all simultaneously assign the cross points on each GRC boundary and thus settle the net ordering problem, but none of them take the coupling effects between adjacent nets into consideration. However, References [3, 4] put forward different algorithms to control the crosstalk noise during the CPA stage.

## 2 Overview of our CPA algorithm

After the global routing, the whole routing area is dissected into an $a \times b$ two-dimensional array of GRC's. From Ref. [9], the cross point assignment is independent of each other column by column or row by row. Without loss of generality, we assume that the CPA is performed column by column in this paper. First, we construct all the subnets in the column and assign the subnets different priorities according to their weighted sum of their criticality and length. Then we push them into different priority queues. The cross point assignment for the subnets is in four steps as follows:

(1) Assign the cross point positions for one priority queue of subnets at a time and higher priority queue is processed earlier. Details about the priority queue strategy are described in section 4.1.

(2) For one queue of subnets, we first construct the cost matrix and then find a minimum cost matching using the linear assignment algorithm. For details about the CPA problem formulation, please refer to Refs. [5~ 8].

(3) Break the assigned subnets into line segments and calculate the total coupling capacitance between the victim critical subnets and the aggressive subnets to check for crosstalk noise violation. Section 3 explains the issues about the coupling effect control.

(4) If there are crosstalk violations between the subnets, some of the subnets need to be ripped up and pushed into the next priority queue to be processed again. This strategy is expressed in section 4.2.

The four steps form an iteration are repeated until all queues of subnets are processed without crosstalk violation or reaching the predefined maximum iterative number.

## 3 Coupling effect control

For the CPA algorithm, the input consists of the global routing solution, a set of design rules, a set of critical nets, and the corresponding noise constraint. The objective of the CPA algorithm is to determine the exact cross point position for all the crossing nets aiming at minimizing the total wire length and the total number of vias under the noise constraint of the critical nets.

### 3.1 Coupling capacitance estimation

Here we use the simple coupling model in Ref. [10] because it is not necessary to take efforts to adopt a very complicated coupling model during the CPA stage. But we should emphasize that our algorithm is not restricted to any specific model.

In Fig. 1, the coupling capacitance between the two wires $i$ and $j$ can be calculated as Eq. (1) where $w_i$ and $w_j$ are the widths of wires $i$ and $j$ ($w_i$, $w_j > 0$), $f_{ij}$ is the unit length fringing capacitance between wires $i$ and $j$, $l_{ij}$ is the overlap length of wires $i$ and $j$, and $d_{ij}$ is the distance from the center line of wire $i$ to the center line of wire $j$.

$$C_c(i,j) = \frac{f_{ij} \times l_{ij}}{d_{ij}} \times \frac{1}{1 - \frac{w_i + w_j}{2d_{ij}}} \quad (1)$$

### 3.2 Crosstalk noise estimation

To calculate the crosstalk noise between wire segments, we use the conservative formula for two terminal nets presented in Ref. [14]. According to Ref. [14], the peak crosstalk noise $V_{noise}$ for the circuit in Fig. 2 can be estimated with the Eq. (2)

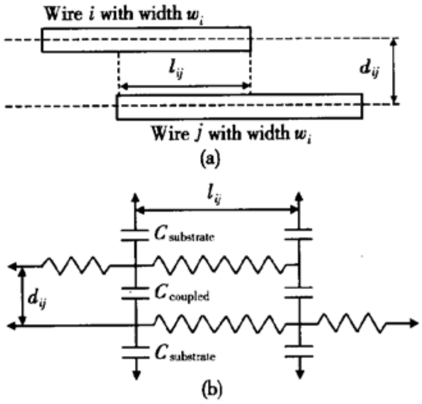


Fig. 1 Coupling capacitance between two nets

where $C_a$ and $C_v$ are the intrinsic capacitances of the aggressor and the victim respectively, $R_v$ is the line resistances. The aggressor is driven by a step voltage source of $V_{DD}$ whose intrinsic resistance is $R_{out,A}$ and the victim is connected to ground via its intrinsic resistance $R_{out,V}$, the coupling capacitance between the two lines is $C_x$. We use the simple noise calculation model for the same reason presented in section 3.1 due to our special routing stage.

$$V_{noise} = \frac{V_{DD}C_x}{\frac{R_{out,A}}{R_{out,V} + R_v/2}C_a + C_v} \tag{2}$$

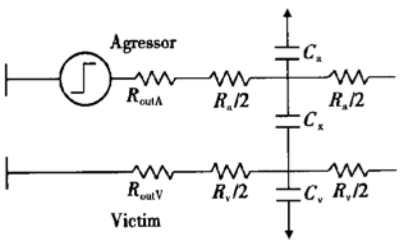


Fig. 2 Crosstalk noise between two nets

### 3.3 Crosstalk noise constraint

In our implementation, we assume that there is crosstalk noise constraint on each critical net. We divide the global net in the whole routing area into a set of subnets inside the bounding box of each column and evenly distribute the constraint on the global net onto the subnets in proportion to the length of the subnets. For simplicity, we define a coupling set for every critical net that can be specified by the user. We assume that each net in the set has coupling effect on the critical net and should not be assigned nearby to observe the crosstalk noise constraint. We can also utilize the coupling set to avoid some nets from being assigned close to each other for specific layout optimizations.

$$\mathrm{NC} = \sum_{i=1}^{n} \mathrm{NC}_i \tag{3}$$

where $\mathrm{NC}_i = L_i/L \times \mathrm{NC}$

Based on the assumption given above, we can deduce the Eq.(3), where $NC$ and $NC_i$ are the noise constraint on the global net and the $i$th corresponding subnet respectively. And the length of the $i$th subnet and the global net is $L_i$ and $L$. Here the global net has $n$ subnets. Any subnet $i$ with the crosstalk noise calculated by Eq.(2) exceeding $\mathrm{NC}_i$ is considered a violation to the noise constraint and should be ripped up and reassigned.

## 4 Crosstalk-free CPA

In our algorithm, we try to find a CPA solution with the minimum total wire length and vias under the crosstalk noise constraint on each subnet. It is assumed that if there is no noise violation on any critical subnet in each column and row, then there is no noise violation on any critical net and thus no violation in the whole routing solution.

### 4.1 Priority queue

In Ref.[6], nets are assigned different priorities to achieve a better routing solution for long nets. It sorts the global nets according to their length and longer nets are assigned higher priorities. Then the corresponding subnets with higher priorities will be processed earlier to get their favorite cross point positions. But our CPA algorithm processes all subnets in one column at a time, so it is obvious that a long global net is uncertainly long in each crossing GRC column and the routing solution may not be optimal. So in our algorithm, the length of the subnets is used for one of comparison criteria to decide their priorities. Besides the net's length, we also consider the criticality of a net and assign critical nets to higher priorities. Therefore, our priority queue is based on the weighted sum of subnet length and criticality.

### 4.2 Rip-up and reroute strategy

Based on the priority queue, we combine the rip-up and the reroute strategy to realize the noise control on the subnets. When a queue of subnets has been processed with the CPA algorithm in one column, a post-CPA checking routine will be performed to estimate the final routing result, compute the crosstalk noise between the critical nets with the nets in their coupling sets and check if there is any violation. If there is no noise violation, the next queue will be processed with an updated cost matrix by the exclusive cost of the assigned subnets; otherwise, some subnets should be ripped up and pushed into the next queue. This process will be repeated until all the subnets in the queue have been processed with no coupling violation or the predefined maximum iterative number is reached.

When some noise violations are checked out, we should decide which subnets to be ripped up. One way is to rip up the minimum number of subnets, which can be formulated as a max-clique problem. We can use some max-clique algorithm (See Refs. [11, 12]) to find the solution. However, the max-clique problem is a NP-hard problem (See Ref. [13]) and no polynomial time algorithms are expected to be found. When the solution space is very large, the running time is not endurable.

Therefore, we adopt a heuristic algorithm that considers the criticality, length, and number of violation pairs of each subnet. Then we assign each subnet a weighted sum of the above-mentioned three items, leaving the factors to be defined by users. To facilitate the computation of the number of the violation pairs of each subnet, we employ a coupling array CA[subNetNum + 1][subNetNum + 1], where subNetNum represents the number of subnets in the current priority queue, $CA_{i,i} = 0$. We set $CA_{i,j} = CA_{j,i} = 0$ if no violation occurs between subnets $i$ and $j$ and $CA_{i,j} = ca_{j,i} = 1$ otherwise.

By summation of the rows, we can get the number of the violation pairs for each subnet, which is shown as Eq. (4).

$$ca_{i,0} = \sum_{j=1}^{\text{subNetNum}} ca_{i,j},\ 1 \leqslant i \leqslant \text{subNetNum} \quad (4)$$

During the rip-up routine, we rip up one subnet each time with the maximum weight and at the same time update the coupling array for the next rip-up process until the no subnet pair couples. With the coupling array, our heuristic algorithm can find the subnet with the maximum weight in $O(n^2)$ time for addition and $O(n)$ time for comparison with a queue of $n$ subnets.

When the post-CPA checking routine has been processed for one queue of subnets, some of the subnets are ripped up and pushed into the next queue. In order to protect the already assigned critical subnets from being coupled by the ones in the coupling set at lower priority queue, we add the exclusive cost to the feasible cross positions around the critical net. The exclusive cost can hold other nets in the coupling set from being assigned adjacent to the critical nets and thus forms a protective region along them. Therefore, the noise of critical nets can be controlled under a constraint.

## 5 Experimental results

We have implemented our algorithm in GNU C on SUN Enterprise E450. The experimental results are shown as follows. Table 1 shows the characteristics of the test cases. We use two layers for the routing and compare our CPA results with that of Ref. [7]. Table 2 presents the comparison of detailed routing results using our gridless detailed router[15]. In Table 2, we can see although we have added the noise constraint in our algorithm, we still do not lose much in the total wirelength and the number of vias. This is because that we have added some heuristics such as the subnet priority queue which contributes a lot to reducing the total wire length and at the same time keeping the completion rate. The first column shows the name of the test cases and the second column shows the number of the critical nets. The columns under "ND" show the number of critical nets that fall in each noise range. The pointed numbers indicate the value of noise in the form of the times of $V_{DD}$. For instance, the column under "0~0.1" gives the number of critical nets whose noise is between 0 and $0.1V_{DD}$. The average and the maximum noise of all the critical nets are shown under the "AVG" and "MAX" respectively. Since the completion rate of our algorithm is 99%~100%, which is the same with Ref. [7], we do not show the data here. From the results we can see that our CPA algorithm has controlled the noise of the critical nets under $0.3V_{DD}$ without much loss of other objectives such as the wire length and the number of vias. Without coupling control in the CPA stage, the average noise of the critical nets in Ref. [7] after detailed routing is 0.0057~$0.060V_{DD}$. However, in our algorithm, when we set the noise constraint on the critical nets to be $0.3V_{DD}$, the average noise can be reduced to 0.0043~$0.037V_{DD}$ (25%~38% reduction). At the same time, the maximum noise of the critical nets, which is 0.403~$0.447V_{DD}$ in their results, is reduced to 0.149~$0.290V_{DD}$ (34%~63% reduction). Except for the noise control of the critical nets, our CPA algorithm can also be used to gain a better noise distribution for the whole routing layout.

Table 1 Test cases

| Bench mark | Number of nets | Number of GRC's |
|---|---|---|
| C2 | 745 | 9×11 |
| C5 | 1764 | 16×18 |
| C7 | 2356 | 16×18 |
| Avq | 21851 | 65×68 |

Table 2 Detailed routing results

| BM | CN | Noise distribution | | | | | | | | | | | | AVG | | MAX | | Vias | | Wire length /mm | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0~0.1 | | 0.1~0.2 | | 0.2~0.3 | | 0.3~0.4 | | 0.4~0.5 | | 0.5~0.6 | | | | | | | | | |
| | | A1 | A2 | A1 | A2 | A1 | A2 | A1 | A2 | A1 | A2 | A1 | A2 | A1 | A2 | A1 | A2 | A1 | A2 | A1 | A2 |
| C2 | 149 | 122 | 132 | 12 | 14 | 9 | 3 | 1 | 0 | 5 | 0 | 0 | 0 | 0.060 | 0.037 | 0.439 | 0.279 | 7846 | 7882 | 457.0 | 454.4 |
| C5 | 252 | 211 | 229 | 20 | 17 | 16 | 6 | 4 | 0 | 1 | 0 | 0 | 0 | 0.047 | 0.031 | 0.423 | 0.275 | 20290 | 20690 | 1247.7 | 1257.0 |
| C7 | 942 | 848 | 884 | 52 | 48 | 19 | 10 | 17 | 0 | 6 | 0 | 0 | 0 | 0.037 | 0.025 | 0.447 | 0.290 | 25819 | 26277 | 1953.6 | 1951.7 |
| Avq | 1457 | 1436 | 1446 | 15 | 11 | 3 | 0 | 1 | 0 | 2 | 0 | 0 | 0 | 0.0057 | 0.0043 | 0.403 | 0.149 | 224783 | 231346 | 9254.7 | 9031.3 |

A1: CPA algorithm in Ref. [7]; A2: Our CPA algorithm; BM: Bench marks; CN: Critical nets; AVG: Average noise of single critical nets; MAX: Maximum noise of single critical net

# 6 Conclusion

In this paper, we propose a CPA algorithm to deal with the crosstalk problem during routing stage, which makes a combination of the priority queue with rip-up and reroute strategy. The detailed routing results show that our CPA algorithm can effectively bring the crosstalk noise of the critical nets under control and at the same time achieve high completion rate and satisfactory number of vias.

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# 串扰噪声约束下的过点分配算法*

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**摘要**: 提出了一种在过点分配阶段解决噪声耦合效应问题的算法. 该算法采用优先队列同拆线重布策略相结合的方法, 控制由互连线耦合电容引起的串扰噪声. 算法中, 首先按照线长和约束限制, 将线网划分到若干个优先队列中. 然后, 将每个优先队列的过点分配问题转换为线性分配问题. 在完成一个线网队列的分配后, 通过过点分配后处理过程检查串扰约束满足情况, 对违反约束的线网对进行拆除, 放入后续线网队列进行重新分配. 实验数据表明, 该算法能够取得好的效果.

**关键词**: 布线; 过点分配; 串扰; 互连线

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