

SHIELDING AREA OPTIMIZATION UNDER THE SOLUTION OF INTERCONNECT CROSSTALK¹

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ABSTRACT

As the technology advances into deep sub-micron era, crosstalk reduction is of paramount importance for signal integrity. Simultaneous shield insertion and net ordering (SINO) has been shown to be effective to reduce both capacitive and inductive coupling. Although shield insertion could reduce crosstalk efficiently, a large scale of unnecessary shields will bring the shielding area problem which is also critical for an efficient SINO algorithm. In this paper, we propose three novel algorithms using fewer shields to solve SINO problem: namely, net coloring (NC), efficient middle shield insertion (EMSI) and NC+EMSI. Compared to the corresponding algorithms in previous work [1], our algorithms can reduce shielding area largely with short runtime.

1. INTRODUCTION

It has been shown for years that interconnect crosstalk and delay have become bottle necks in determining circuit performance. Even though most current research on interconnect synthesis uses the RC model [2, 3, 4, 5, 6], it is evident that the RLC model becomes more appropriate as the on-chip inductive effect gains increasing prominence in gigahertz designs [7]. As the inductive has long-range effect in the sense that the mutual inductance between non-adjacent nets cannot be ignored when compared to the self inductance [1]. Therefore, shield insertion is needed to reduce inductive noise. However, as shielding area is directly decided by the number of shields, extra shields will waste the shielding area. It is of paramount important to find an efficient way to solve crosstalk problem. The more efficiently shields minimize the crosstalk, the fewer shields need to insert, and the shielding area could be much more optimized. Furthermore, as the increase of IC scale and the number of wires, the short routing resource and the routing congestion become more serious. It is crucial to develop algorithms to reduce the shielding area considering crosstalk at the same time.

Several previous studies have considered interconnect optimization under the RLC model. Assuming that current will return from the nearest shield, the loop inductance model is used in [1, 8, 9]. A table-based partial inductance model is adopted

without pre-assuming any current return path [10, 11, 12]; additionally, a coupling inductance screening rule [9] is employed to decide the scope of the current return path. Also, a formula-based K_{eff} model is proposed in [8] as the figures of merit for inductive coupling. Although, the assumption of K_{eff} model is less intuitive to the designer [7], it is easy to compute and keeps a high fidelity versus the SPICE-computed RLC noise voltage for SINO solutions [8].

Based on K_{eff} model [8], Prof He provided greedy shield insertion, graph coloring and simulated annealing SINO algorithms to solve SINO/NB problem [1]. As overabundance shields are inserted in these algorithms, there is still much space for reducing the number of shields to economize the routing resources. In order to optimize the shielding area, in this paper, we develop three algorithms which are extremely efficient to reduce the shielding area while satisfying the crosstalk constraints. First, NC algorithms is proposed to color nets so that no sensitive wires adjacent to each other. Then, considering inserting shield in the key position, the EMSI algorithm is provided to reduce the inductive coupling. Finally, combining NC and EMSI algorithms into NC+EMSI algorithm, noise-bounded problems could be solved using fewer shields.

The remainder of this paper is organized as follows: Section 2 briefly introduces the SINO problem and mostly analyzes algorithms provided in this paper. Section 3 presents three SINO algorithms as Net Coloring algorithm, Efficient Middle Shield Insertion algorithm and NC+EMSI algorithm separately. Section 4 compares experimental results obtained by different algorithms to the existing algorithms [1]. Section 5 concludes the paper.

2. PROBLEM FORMULATIONS

2.1 Preliminaries

In this paper we consider coplanar interconnect structures [8] with inductive K_{eff} model [8]. Shielding area is directly decided by the number of shields with the same width as signal wires (denoted as s-wires). And the group of wires sandwiched between adjacent shields is called a block. Two net s_1 and s_2 are defined to be sensitive to each other if a switching signal on s_1 will cause s_2 to malfunction or vice-versa [1]. A sensitivity matrix S is used to represent the sensitivity of wires. In the rest of paper, formula-based K_{eff} model [8] is used to compute the inductive coupling coefficient K_{ij} between two wires.

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2.2 Optimal SINO Problems

Considering capacitive and inductive coupling, SINO/NF and SINO/NB problems are defined in [1] to solve crosstalk minimization. For a given placement P , find a new placement P' by simultaneous shield insertion and net re-ordering such that the total area of P' is minimal and P' is noise free. This defines SION/NF problem. In the requirement that P' is capacitive noise free and the inductive coupling K_i satisfied $K_i \leq K_{\text{thresh}}$ where K_{thresh} is a uniform thresh value, this forms SINO/NB problem.

2.3 Problem Analysis

Shields are used to reduce noise, while overabundance shields may waste the shielding area which is directly decided by the number of shields. Although, existing SINO algorithms [1] reduce both capacitive and inductive noise, there are still lots shields unnecessary. As greedy shield insertion operates [1] inefficiently not aiming at the key position influencing coupling most, we do lots of experiments to find the wires with max k value.

The coplanar interconnect structures containing 8, 16, 32, 64 s-wires with no shield are used to find the position of wires whose k value is the max in the block. We iterate the following sensitivity rates: 40%, 50% and 60% and run each condition under 50 random sensitivities. Table 1 shows the average position of wires having the max k value.

sensitivity rate	8 wires	16 wires	32 wires	64 wires
40%	3.10	6.05	15.42	31.24
50%	3.15	7.15	15.58	31.78
60%	3.10	7.45	15.60	31.68

Table 1. Average net position having the max value of k

The experimental results containing 64 s-wires under each 60%, 50%, 40% random sensitivities are provided in Figure 1. Here, x-axis indicates the experimental serial number of the 50 random sensitivities, and the y-axis indicates the wire order number from 0 to SIZE-1 (where SIZE is the number of wires).

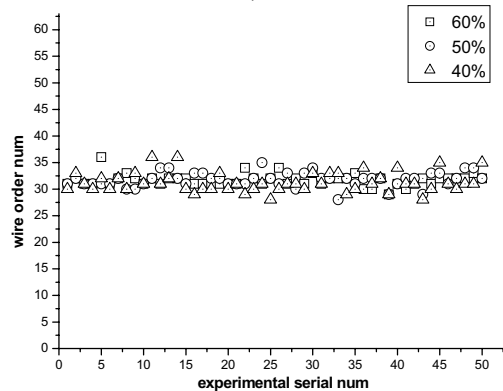


Fig. 1. The wire position of max k value (64 s-wires)

From the Figure 1, we find that k_{max} wire always appear from 30th to 32nd wire. So, the wire having the max k value mostly appears in the middle of the block, and by shielding these wires the k value in the block can be reduced efficiently. Finding this efficient way to reduce noise, fewer shields are needed and

the shielding area can be optimized. The efficient middle shield insertion algorithm (EMSI algorithm) is developed based on this discussion.

3. ALGORITHM FOR OPTIMAL SINO PROBLEMS

In shielding area optimization, capacitive noise free is defined if wire s_i is not adjacent to any other wires sensitive to it, and the inductive noise free is defined if sensitive wires do not share a block. We first introduce a Net Coloring algorithm (NC algorithm) to solve noise-free problem, which makes no sensitive wires adjacent to each other. As the SINO/NF problem is over-constrained and may lead to over-designed solutions not according to realistic design constraints, which may need a large number of shields. Also, the EMSI algorithm depends on the initial placement. So we combined NC and EMSI algorithms into NC+EMSI algorithm to solve SINO/NB problem. The number of shields can be reduced by first running net coloring algorithm to reorder nets so that no sensitive nets are adjacent to each other, then invoking the EMSI algorithm could reduce inductive coupling noise using shield as few as possible.

3.1 Net Coloring Algorithm

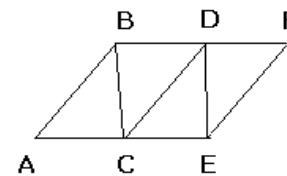


Fig 2. Sensitivity graph

The sensitivity of all wires could also be represented by graph shown in Figure 2, which is constructed as that a node corresponds to a wire and an edge exists if and only if the correspondent wires are sensitive to one another. By coloring the sensitivity graph, wires having the same color are not sensitive to each other.

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NC algorithm:
Input: placement P
Output: new placement with noise free
Operation:
Find max possible color  $C_i = \{c_1, c_2 \dots c_i\}$  for net i
for j from 0 to SIZE-1
    if  $c_j$  is the first in  $C_j$ 
        color  $c_j$  to net  $v_j$ 
        for k from j to SIZE-1
            if  $v_j$  and  $v_k$  sensitive
                eliminate  $c_j$  from  $C_k$ 
        endfor
    endfor
endfor
put wires having same color in the same block
end
    
```

Fig. 3. Net Coloring SINO/NF Algorithm

In Figure 3, we present the net coloring based SINO algorithm to solve noise-free problem. It attempts to color all s-wires sequentially so that wires in the same block have a single color. Assuming that the set of colors is numbered by

$\{c_1, c_2, \dots, c_i\}$, where c_i represents the i^{th} color. SINO/NC algorithm works in the following way: First, for each wire i enumerate the max available set of color C_i , where $C_i = \{c_1, c_2, \dots, c_i\}$. Then color the wires sequentially. Considering each wire, the first color in the set C_i of wire i is the final color to wire i . Meanwhile, in order to satisfy no wire sensitive to each other be colored the same, we delete the color from the set of other pending wires which are sensitive to the wire i considered. Finally, put the wires having the same color in the same block, so that wires in the same block are not sensitive to each other.

3.2 Efficient Middle Shield Insertion Algorithm

Efficient middle shield insertion algorithm is mainly about how to insert the shield to solve SINO/NB problem. To optimize the shielding area, we should use as fewer shields as possible to reduce the inductive coupling noise.

EMSI Algorithm:
Input: placement P, K_{thresh}
Output: new placement with noise bounded
Operation:
 Given a placement P
for each block in P
 if the k_{eff} value of block $> K_{\text{thresh}}$
 insert a shield in the middle of the block
 point to the new left block
 else
 point to the next right block
endfor

Fig. 4. Efficient Middle Shield Insertion SINO/NB Algorithm

As discussed in section 2, the wire having the max k value mostly appears in the middle of the block, and by shielding these wires inductive coupling in the block can be reduced efficiently. In Figure 4, we present the efficient middle shield insertion algorithm for SINO problem (SINO/EMSI algorithm). This algorithm is a recursive procedure. Run through all the blocks in the given placement; calculate the max k value of the block. After inserting a shield in the middle of one block, the algorithm recursively checks the K_{eff} value of the two newly-generated blocks. If any of these is still greater than K_{thresh} , no matter whose k value is the max, an additional middle shield is inserted in the new block.

3.3 NC+EMSI Algorithm

As discussed in section 2, we combined NC and EMSI algorithms into NC+EMSI algorithm to solve noise-bounded problem. Net coloring operation is first used to eliminate capacitive noise. While, different from the NC algorithm which inserts shields between every pair of wires in different colors, net coloring before EMSI algorithm only inserts shields between the adjacent sensitive wires not having the same color. Then efficient middle shield insertion is operated to reduce inductive noise using as fewer shields as possible.

4. EXPERIMENTAL RESULTS

In this section, we apply these three algorithms on a large number of examples. And the results obtained by these algorithms are compared to the existing algorithms [1].

We have implemented all algorithms in the C++ programming language on a SUN E450. And we use the coplanar interconnect structures containing 32 and 64 s-wires to determine the performance of the algorithms for different combinations of K_{thresh} and uniform sensitivity rate. We use four different K_{thresh} values as 0.5, 1.0, 1.5, 2.0 respectively, here $K_{\text{thresh}}=0.5$ represents the total inductive coupling coefficient for each net is less than 0.5. And the sensitivity rate is changed from 40%, 50% to 60%. That the sensitivity rate is 40% represents each net is sensitive to 40% of all nets, and these sensitive nets are selected randomly. For each combination of K_{thresh} value and sensitivity rate, we present the resulting number of shielding wires for different algorithms. We run each algorithm on the same initial placement for twenty different random sensitivities. And the average of these twenty runs is shown in italic style in table2.

number of net	Kthresh	GC[1]	NC	SI[1]	EMSI	NO+SI[1]	NC+EMSI
32	Net Sensitivity Rate :40%						
	0.5	8.50	<i>3.94</i>	16.70	<i>13.94</i>	6.30	<i>6.01</i>
	1.0			15.90	<i>12.46</i>	5.30	<i>4.72</i>
	1.5			15.40	<i>8.68</i>	4.40	<i>3.99</i>
	2.0			13.80	<i>6.56</i>	4.00	<i>3.44</i>
	Net Sensitivity Rate :50%						
	0.5	11.00	<i>4.72</i>	18.90	<i>13.96</i>	8.40	<i>6.53</i>
	1.0			18.40	<i>12.46</i>	5.70	<i>4.97</i>
	1.5			18.00	<i>8.14</i>	4.80	<i>4.60</i>
	2.0			17.50	<i>6.44</i>	4.40	<i>3.87</i>
	Net Sensitivity Rate :60%						
	0.5	12.00	<i>5.02</i>	22.80	<i>14.08</i>	6.60	<i>6.72</i>
1.0			22.10	<i>12.36</i>	6.00	<i>5.30</i>	
1.5			22.00	<i>8.22</i>	5.20	<i>4.60</i>	
2.0			21.50	<i>6.72</i>	4.50	<i>3.91</i>	
64	Net Sensitivity Rate :40%						
	0.5	15.60	<i>3.92</i>	30.10	<i>28.92</i>	11.30	<i>7.76</i>
	1.0			28.50	<i>25.96</i>	9.20	<i>6.88</i>
	1.5			26.20	<i>18.32</i>	7.50	<i>5.82</i>
	2.0			23.50	<i>14.00</i>	6.80	<i>5.30</i>
	Net Sensitivity Rate :50%						
	0.5	19.30	<i>4.78</i>	32.10	<i>29.12</i>	14.30	<i>8.17</i>
	1.0			31.30	<i>25.88</i>	9.80	<i>7.29</i>
	1.5			30.60	<i>17.52</i>	8.60	<i>6.55</i>
	2.0			31.50	<i>13.96</i>	7.90	<i>5.71</i>
	Net Sensitivity Rate :60%						
	0.5	21.60	<i>5.11</i>	39.70	<i>28.72</i>	12.80	<i>8.21</i>
1.0			39.20	<i>25.68</i>	11.40	<i>7.45</i>	
1.5			38.00	<i>17.36</i>	9.40	<i>6.73</i>	
2.0			36.80	<i>14.40</i>	8.10	<i>5.85</i>	

Table 2. Number of shields inserted by SINO algorithms

For each combination of k and sensitivity rate, we compare our algorithms investigated above to the existing algorithms [1], the EMSI algorithm is compared to the greedy shield insertion algorithm [1], and the NC+EMSI algorithm is compared to the NO+SI algorithm [1], respectively here.

We can see from table 2, the greedy shield insertion algorithm is significantly worse than the EMSI algorithm. For example, in 32 wires with sensitivity rate (60%) and K_{thresh} changes from 0.5, 1.0, 1.5 to 2.0, EMSI algorithm reduces 27.25%, 30.44%, 43.06%, 46.19% shields respectively compared to SI algorithm [1]. Furthermore, as we expected, the EMSI algorithm has a higher efficiency to reduce the inductive coupling noise, along with the increase of K_{thresh} , the number of shields by EMSI algorithm reduces obviously, while the result of SI algorithm [1] reduces insignificantly. See 64 s-wires, sensitivity rate=50%, when K_{thresh} increase from 0.5, 1.0, 1.5 to 2.0 separately, the number of shields in EMSI algorithm to the given size (64 s-wires) decreases from 45.50%, 40.44%, 27.38% to 21.81% respectively with 23.69% reduction, but the results of

SI algorithm are 50.16%, 48.91%, 47.81%, 49.22% with at most 2.35% reduction. So, middle shield insertion in EMSI algorithm may efficiently reduce the inductive coupling noise, and the shielding area reduces significantly.

Compared to the graph coloring algorithm [1], the net coloring algorithm also needs 18.25%, 22.69% and 25.77% less shields separately than SINO/GC algorithm [1] in 64 s-wires with sensitivity rate from 40%, 50% to 60%.

Considering separated net ordering and shield insertion operation [1], NC+EMSI algorithm not only follows the requirement of net ordering operation about eliminate the capacitive coupling noise, but also gathers wires not sensitive to each other into the same block by the greatest extent, which is helpful to the following shield insertion operation to reduce the inductive coupling noise. From the experimental results, NC+EMSI algorithm also shows a good performance. Take 64 s-wires with sensitivity rate 60% and K_{thresh} value increases from 0.5, 1.0, 1.5 to 2.0 as example, the NO+SI algorithm [1] needs 20.00%, 17.81%, 14.69%, 12.66% shields, while relatively, the NC+EMSI algorithm needs 12.83%, 11.64%, 10.52%, 9.14% shields to the given size 64, which means 7.17%, 6.17%, 4.17%, 3.52% less shielding area than the NO+SI algorithm[1].

	EMSI	NC	NC+EMSI
Runtime	0.013sec	0.00sec	0.004sec

Table 3. Approximate run times for SINO algorithms with sensitivity rate 60%

Finally, the runtime is showed in Table 3, where the times are for a single interconnect structures with a single run. SUN E450 is used to collect running time. From this table, all algorithms finished the examples in a few seconds. Therefore, large scale interconnect structures can be solved fast by algorithms we have proposed.

5. CONCLUSION AND DISCUSSIONS

As more and more high performance microprocessors and system-on-chip (SoC) operates in GHz+ scale, RLC crosstalk gains growing importance for signal integrity. In this paper, we have developed three efficient algorithms to solve the shielding area optimization. Extensive experiment results have shown that compared to the previous corresponding algorithms in [1] the proposed algorithms use less runtime while reduce the shielding area efficiently. SINO is a region based technique to reduce RLC crosstalk. Performing SINO within each region separately may introduce many dog-legs across regions. For full-chip routing optimization, we want to reduce the number of dog-legs as they deteriorate signal integrity [6]. We plan to study the row-based SINO problem with consideration of both shielding area and

dog-leg minimization in the future, and develop efficient algorithms correspondingly.

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