Performance Optimization Global Routing with RLC Crosstalk Constraints*

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Abstract: Performance optimization becomes an increasingly dominant factor in global routing. This paper presents a performance optimization global routing algorithm CEE-Gr with RLC crosstalk constraints, which to our knowledge, is the first to study coupling noise, timing performance, and routability simultaneously at global routing level. The CEE-Gr has been implemented and tested on MCNC benchmarks and the experimental results are promising.

1. Introduction

As VLSI/ULSI technology moves into very deep sub-micron (VDSM) device size and giga-hertz clock frequencies, performance optimization becomes an increasingly dominant factor in global routing [1]. It brings two major concerns for performance optimization. One is interconnect delay reduction. The other is coupling noise estimation and elimination.

Previous works [2-14] have various contributions to timing optimization for global routing, which includes timing models [2, 3], timing-driven Steiner tree algorithms [4, 5], interconnect design algorithms considering buffer insertion or/and wire sizing [6-8], and timing optimization global routing algorithms [9-15].

Increasing concerns have been raised regarding the coupling noise effects. There have been some works focusing on noise reduction. These approaches mainly fall into two categories, noise modeling [16-19] and noise minimization [20-25]. Among noise minimization algorithms, most optimizations are done after the process of global routing.

The noise minimization introduced in [20] and [21] is done after the detailed routing phase. Spacing algorithm proposed in [20] expands the distance between sensitive nets to reduce crosstalk. It uses Lagrangian relaxation technique and is efficient for non-congested routing regions. The track permutation algorithm [21] swaps tracks to avoid crosstalk for grid detail routing. It solves a mixed integer linear programming to decide which track should be permuted. Similar to the spacing algorithm, it is efficient for routing area with more unused tracks.

Ref. [22] and [23] introduced detailed routing algorithms to minimize crosstalk. Ref. [22] introduced the wire perturbation algorithm. By defining BPI (basic perturbation interval), it can accurately calculate the best wire position to minimize crosstalk. But to obtain optimal solution, this algorithm consumes much time. Crosstalk minimization algorithm for river routing was proposed in [23]. It minimizes crosstalk by converting two adjacent parallel wires into stair-shaped wires and using net flow method to distribute resource in the river routing region. With fixed pin on the top/bottom in the riverside, there is a limitation of its minimization capability.

Some algorithms reduce crosstalk after global routing. One is the two-part algorithm, region-based crosstalk risk estimation and crosstalk reduction, described in [24]. There is a high timing complexity in part two. Ref. [25] proposed the iSINO algorithm. It eliminates crosstalk by inserting shields.

Researchers find that it is more flexible if they reduce noise in the process of global routing. A few recent works [26-27] have addressed crosstalk avoidance techniques throughout global routing phase. In [26], global routing with crosstalk constraints has been studied. It constructs Steiner tree with a cost function including crosstalk consideration. If the crosstalk of initial routing solution still exceeds the given bound, then do rip up. Ref. [27] proposed the GSINO Algorithm. It gives a Steiner tree cost function containing the estimated shield number. Thus, the global router can reduce the total shield number and eventually reduce the total routing area. The objective of the two algorithms is to minimize crosstalk effects. Both of them do not take timing and congestion optimization into consideration. Among these approaches, there is still an absence of performance (including coupling noise, timing and routability) optimization algorithms for global routing.

This paper presents a performance optimization global routing algorithm CEE-Gr with RLC crosstalk constraints, which to our knowledge, is the first to study coupling noise, timing performance, and routability simultaneously at global routing level. The remainder of this paper is organized as follows. Section 2 formulates the global routing problem. In Section 3, the *LSK* model for RLC crosstalk is introduced. The algorithm is given in detail in Section 4. Section 5 discusses experimental results. Section 6 is an overall conclusion.

2. Problem formulation

We assume that the whole chip is divided into a rectangular array of $N_{row}*N_{col}$ cells called global routing

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cells (GRCs). Global routing graph (GRG) is the dual graph of GRCs, which is composed of the gridlines and crossings. Fig.1 shows an example GRG that holds 4*4 GRCs. Node v_i represents the center point of GRC_i. The edge links node v_i and node v_j is named as e. l is called the length of edge e, equals the distance between node v_i and node v_j. A non-negative number c_e, called edge capacity, is assigned to edge e. c_e indicates the number of available tracks between every two corresponding GRCs.

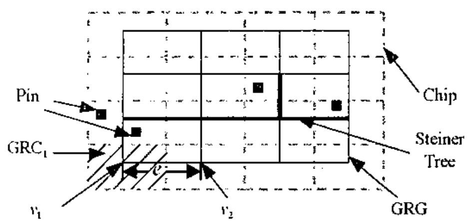

Fig.1. Global routing graph (GRG).

Thus, a net can be specified as a set of nodes in GRG. Then, the problem of routing a net in GRG can be described as a Steiner tree problem of specified nodes in GRG.

3. RLC noise model

The *LSK* model for RLC crosstalk [19, 27] is used in this paper. Different from earlier noise models [16, 17], the *LSK* model considers coupling inductance between adjacent and non-adjacent sensitive nets and points out coupling inductance could not be ignored while clock frequency is more than 1GHz.

For any two segments N_{it} and N_{jt} in region R_t, the inductive coupling coefficient between them is

$$k_{it,jt} = \frac{L_{it,jt}}{\sqrt{L_{it} \cdot L_{jt}}}$$

where $L_{it,jt}$ is the mutual inductance between N_{it} and N_{jt}, and L_{it} and L_{jt} are the self inductance for N_{it} and N_{jt}, respectively. A formula-based K_{eff} model has been developed in [19] to calculate the coupling coefficients $k_{it,jt}$. Furthermore, the total amount of inductive coupling induced on N_{it} can be represented by the sum of the inductive coupling coefficients

$$K_{it} = \sum_{j \neq i} k_{it,jt}$$

For all net segments N_{jt}'s that are sensitive to N_{it}.

To consider the effect of interconnect length and the general case where the total coupling is not uniform in all routing regions, a length-scaled K_{eff} (*LSK*) model was proposed in [27], where the *LSK* value is defined as

$$LSK = \sum_t l_t \cdot K_{it}$$

where l_t is length of R_t and K_{it} is total coupling for N_{it}.

4. The global routing algorithm CEE-Gr

A. The CEE-Gr Algorithm

The CEE-Gr algorithm consists of two parts: (1) Gr: timing and congestion optimization, (2) CEE: crosstalk estimation and elimination.

Gr firstly generates an initial routing solution considering congestion and timing optimization. Then, CEE eliminates the crosstalk from the solution by inserting shields and gets a mid-result. Finally, regard the mid-result as input and send it to Gr for iterations. The flow chart of CEE-Gr is shown in Fig. 2.

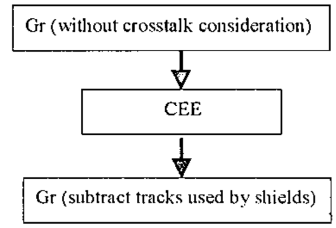

Fig.2. The flow chart of CEE-Gr.

B. Part One: Gr

The objective of Gr is wire length and the constraints are congestion and timing. The timing analysis and optimization method used in Gr follows critical-network-based technology introduced in [13].

To reduce congestion, Gr uses SSTT (search space traversing technology) [28] and considers independent of net ordering [29].

C. Part Two: CEE

The flow chart of CEE (crosstalk estimation and elimination) is shown in Fig. 3. This sub-section introduces CEE in detail.

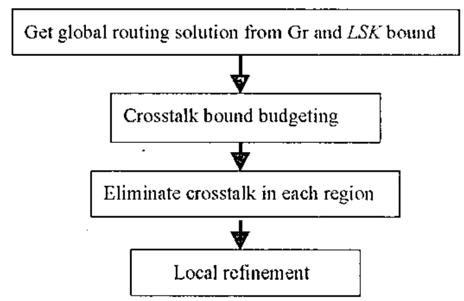

Fig.3. The flow chart of CEE.

1) *LSK* bound budgeting: We partition the *LSK* bound at each sink of a net into the GRG edges belonging to the source-sink paths. There are two strategies for budgeting as follows.

a) CBUD (uniform distributed crosstalk budgeting) strategy

This strategy uniformly partitions the *LSK* bound into edges according to their length. Let $\overline{LSK_{ij}}$ be the crosstalk bound at sink p_{ij} for net N_i, *len* be the total length from the source p_{i0} to sink p_{ij}, then each routing region (edges) R_t on the path is assigned a uniform crosstalk sub-bound $\overline{K_{it}}$:

$$\overline{K_{it}} = \frac{\overline{LSK_{ij}}}{len} \tag{1}$$

If segment N_{it} is shared by multiple paths starting from the same source to different sinks, we use the minimum value computed for these paths according to equation (1).

b) CBLP (linear programmed crosstalk budgeting) strategy

CBUD distributes *LSK* bound according to segment length without consideration of its congestion. To overcome this shortcoming, CBLP partitions the *LKS* bound by solving a linear programming problem.

We firstly consider the problem in one dimension. Assuming there are only horizontal wires routing in one row, let number of tracks used by nets, shields or obstacles in region R_t be h_t, and $h_{max} = \max\{h_t \mid \forall R_t \in RSET\}$, then the one dimensional problem could be described as:

Minimize h_{max}

Subject to

$$\sum_{N_{it} \in G_t} \alpha_t \cdot \overline{K_{it}} + \beta_t + |G_t| + O_t \leq h_{max} \quad \forall R_t \in RSET \tag{2}$$

$$\sum_{R_t \in H_{ij}} l_t \cdot \overline{K_{it}} \leq \overline{LSK_{ij}} \quad \forall p_{ij} \in P_i and \forall N_i \in NSET \tag{3}$$

$$\sum_{N_{it} \in G_t} \alpha_{it} \cdot \overline{K_{it}} + \beta_t \geq 0 \quad \forall N_{it} \in R_t and \forall R_t \in RSET \tag{4}$$

The left side of equation (4) is estimated shield number in R_t, so it couldn't be negative. Equation (3) guarantees that the sum of $\overline{K_{it}}$ is no more than $\overline{LSK_{ij}}$. Equation (2) reflects that no h_t should be greater than h_{max}.

For the two-dimensional problem, let CLM (ROW) be the set of routing regions in a column (row) for horizontal (vertical) wires, and CLMSET (ROWSET) be the set of all CLM's (ROW's). Then, h for CLM is defined as the total number of tracks used by nets, shields and obstacles in CLM, and the h_{max} of the total routing area is defined as the maximum h among all CLM $\in$ CLMSET. The w for ROW and w_{max} for the total routing area can be defined in the similar way. Then the two-dimensional problem could be described as:

Minimize $\gamma \cdot h_{max} + \theta \cdot w_{max}$

Subject to

$$\sum_{R_t \in CLM} \left(\sum_{N_{it} \in G_t} \alpha_t \cdot \overline{K_{it}} + \beta_t + |G_t| + O_t \right) \leq h_{max} \quad \forall CLM \in CLMSET \tag{5}$$

$$\sum_{R_t \in ROW} \left(\sum_{N_{it} \in G_t} \alpha_t \cdot \overline{K_{it}} + \beta_t + |G_t| + O_t \right) \leq w_{max} \quad \forall ROW \in ROWSET \tag{6}$$

$$\sum_{R_t \in H_{ij}} l_t \cdot \overline{K_{it}} \leq \overline{LSK_{ij}} \quad \forall p_{ij} \in P_i and \forall N_i \in NSET \tag{7}$$

$$\sum_{N_{it} \in G_t} \alpha_{it} \cdot \overline{K_{it}} + \beta_t \geq 0 \quad \forall N_{it} \in R_t and \forall R_t \in RSET \tag{8}$$

2) Crosstalk elimination in each region: According to each $\overline{K_{it}}$ computed in step 1), this step applies simulated annealing method in each region to insert shields, so that all region's crosstalk is within bound value.

3) Local Refinement: Check each net to eliminate possible remnant crosstalk and delete unnecessary shields so the final area is minimized.

First, eliminate remnant crosstalk, the net N_{it} with most critical crosstalk violation is chosen, and shield will be inserted in the least congested region R_t on N_i's path.

Second, to reduce total area, the most congested region R_j is chosen, and the slack K_i - K_{ti} of all nets in R_j is computed. If possible, shield could be deleted when K_{ti} increases properly.

5. Experimental results and discussions

The CEE-Gr algorithm has been implemented in the C language on a SUN V880 workstation with Unix. There are two running modes. T mode is timing-driven mode. W mode is non-timing-driven mode. We only reduce congestion in W mode, and optimize both congestion and timing performance in T mode.

A. Benchmark Data

We tested three MCNC benchmarks under 0.2*um* technology. Sensitivity rate of 0.5 is given to all nets and a random sensitivity matrix is created. *LSK* bound at each sink is set to be 1000. Table 1 summarizes the benchmark data sets.

Table 1. Benchmark data

Circuits	Number of nets	Grids
C2	745	9*11
C5	1764	16*18
C7	2356	16*18

B. Results

The experimental results are shown in table 2 and table 3.

C. Discussions

1) The crosstalk is serious in the initial routing solution of all these test cases. CEE-Gr can eliminate all crosstalk by adding shields. CEE-Gr is efficient in crosstalk estimation and elimination.

2) Row 4 in Table 2 shows that the increase in wire length of CEE-Gr is only from 2% to 4%, and when the circuit scale goes larger, the increase ratios get smaller.

3) The minimum redundancy of delay (*requiredDelay-currentDelay*), denoted as Min-R in Table 2 and showed in row 9 and raw 10 in Table 2, is almost unaffected. So CEE-Gr maintains the effectiveness in timing optimization of Gr.

4) We notice that the CBLP strategy consumes more routing area (see row 5 and row 10 in Table 3) than CBUD strategy since CBLP inserts more shields. The reason is that the objective function of the linear programming problem is to minimize the track utility of the most congested GRG edges. To do that, it must give such edges a relative high $\overline{K_{it}}$, so $\overline{K_{it}}$ of many other edges is set very low or even zero. In order to satisfy such low or zero crosstalk bounds, much more shields must be inserted in these regions. Thus, it makes CBLP uses much more shields than CBUD does.

5) Using simulated annealing method to insert shields in each region makes CEE-Gr require long running time, which is about 40 minutes for C2, and more longer for larger circuits.

6. Conclusions and future work

This paper studies coupling noise, timing performance and routability in global routing phase. A multi-constraint optimization global router CEE-Gr is presented in this paper. The experimental results are promising. The experimental results show that the CEE-Gr algorithm is able to (1) tackle coupling noise, timing performance and routability simultaneously, (2) take coupling inductance into consideration, (3) obtain good routing results. CEE-Gr efficiently eliminates crosstalk throughout the process of global routing by inserting shields, which has little influence on wire length and timing performance.

As future work, we plan to reduce the time complexity of CEE-Gr and find better strategies for bound partitioning.

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Table 2. Comparison between Gr and CEE-Gr with CBUD

Circuits		C2	C5	C7
W mode	(Gr) Wire length (*um*)	459786	1297814	1545454
	(CEE-Gr) Wire length (*um*)	473588	1336102	1564408
	Increase in wire length	3.00%	2.95%	1.23%
	Overflow edge number	0	1	0
T mode	(Gr) Wire length (*um*)	466288	1298210	1569038
	(CEE-Gr) Wire length (*um*)	468836	1326670	1570882
	Increase in wire length	0.55%	2.19%	0.16%
	(Gr) Min-R	-0.007417	0.006431	0.000910
	(CEE-Gr) Min-R	-0.006042	0.010355	0.003196
	Overflow edge number	0	1	0

Table 3. Comparison between CBUD and CBLP in CEE-Gr

Circuits		C2	C5	C7
Wire length of Gr in W mode (*um*)		459786	1297814	1545454
Sink number that violates the crosstalk bound		583	1570	1845
CEE-Gr (CBUD)	Shield number	158	483	595
	Area	154*200	273*298	346*380
	Wire length (*um*)	473588	1336102	1564408
	Increase in wire length	3.00%	2.95%	1.23%
	Overflow edge number	0	1	0
CEE-Gr (CBLP)	Shield number	422	1315	1769
	Area	150*229	267*343	344*448
	Wire length (*um*)	478240	1330950	1580938
	Increase in wire length	4.01%	2.55%	2.30%
	Overflow edge number	3	2	3