Simultaneous Signal and Power Routing under K_{eff} Model [*]

James D. Z. Ma
ECE Department
University of Wisconsin
Madison, WI 53706

Lei He
ECE Department
University of Wisconsin
Madison, WI 53706

ABSTRACT

In this paper, we study the min-area simultaneous signal and power routing problem under a given noise bound (i.e., the SPR/NB problem). The resulting SPR/NB solution is free of capacitive noise and satisfies a given inductive noise bound under the K_{eff} model. We first develop the pre-routing area estimation techniques for the min-area simultaneous shield insertion and net ordering (SINO) solutions. We then propose a two-phase approach to solve the min-area SPR/NB problem: in the first phase, we define a regular power/ground (P/G) structure according to the above area estimation; and in the second phase, we carry out SINO procedures to search for the best solution in a very limited neighborhood of the pre-defined P/G structure. Experimental results show that our approach is able to achieve the min-area SPR/NB solution efficiently by searching only the first-order neighborhood of the pre-defined P/G structure. Our ongoing work extends the interconnect estimation and two-phase algorithm to an explicit RLC noise model.

Keywords

on-chip inductance, interconnect design, shield insertion, net ordering, interconnect estimation

1. INTRODUCTION

Given the growing importance of interconnects in performance, reliability, cost, and power dissipation for high-performance and power-efficient circuits and systems, the interconnect synthesis becomes a critical design aspect [1, 2]. Even though most current research on interconnect synthesis uses the RC model, it is evident that the RLC model becomes more appropriate as the on-chip inductive effect gains increasing prominence in gigahertz designs [3].

Several previous studies have considered interconnect optimization under the RLC model for multiple coupled nets. In [4], a simultaneous shield insertion and net ordering (SINO/NB-k) problem was solved to find a min-area solution under the inductive coupling constraint using a K_{eff} model. Later on, a twisted-bundle layout scheme [5] was proposed to minimize the inductive coupling. Assuming that the current will return from the nearest shield, the loop inductance model is used in [4, 5]. However, the assumption is not true in general. Let a *block* denote the set of wires between two shields. The current often returns from quiet wires within the current block if there are plenty of quiet wires in this block. On the other hand, the current often returns from shields or quiet wires outside the current block when multiple wires in the current block switch simultaneously. A very recent article [3] removes the above assumption about the current return path. A table-based partial inductance model [6, 7] is adopted without pre-assuming any current return path; additionally, a coupling inductance screening rule [8] is employed to decide the scope of the current return path (i.e., the scope of inductive coupling). Further, different from the K_{eff} model used as a figure of merit for the noise bound in [4] and no noise bound considered in [5], a high-order RLC noise model is developed in [3] to compute the peak noise voltage for multiple coupled RLC interconnects. Then, the min-area simultaneous shield insertion and net ordering (SINO/NB-v) problem is solved under the RLC noise model.

The above two SINO formulations, however, do not consider pre-routed power/ground (in short, P/G) structures. As P/G wires are also shields to reduce the inductive and capacitive noise, the number of shields needed by the two SINO algorithms depends on the pre-routed P/G structure (see Table 1 later on). It is not clear how to define the best P/G structure and how to use the above two SINO formulations in the current global routing flow with pre-routed regular P/G wires.

As a first step to solve these concerns, especially on how to define the best P/G structure, we study in this paper the min-area simultaneous signal and power routing (SPR/NB) problem for given noise constraints. Our contributions include the following: (i) we develop simple yet accurate formulae to estimate the total number of shields needed by SINO/NB-k solutions without running SINO algorithms; (ii) we develop an efficient algorithm for a new SINO problem (herein referred to as the p-SINO/NB-k problem) with respect to the pre-routed P/G structure; (iii) we propose a two-phase solution to the min-area SPR/NB problem un-

---

[*] This research was partially supported by NSF CAREER Award CCR-0093273 and a grant from Intel Design Science and Technology Committee, and used computers donated by SUN Microsystems. Address comments to lhe@ece.wisc.edu.

SLIP'01 March 31 - April 1, 2001, Sibina, California, USA.

der the K_{eff} model: we first define a regular P/G structure according to the above area estimation, and then we carry out p-SINO/NB-k procedures with respect to the defined P/G structure and its first-order neighborhood. Experiments show that our two-phase approach is able to achieve the min-area SPR solution efficiently, satisfies the given noise bound and has a regular P/G structure.

The rest of this paper is organized as follows: Section 2 reviews the related research and presents the formulation and solution of the new p-SINO/NB-k problem considering pre-routed P/G structures. Section 3 derives formulae for pre-SINO/NB-k estimations and formulates and solves the new SPR/NB-k problem (i.e., the SPR/NB problem under the K_{eff} model). Section 4 concludes the paper, with discussions of ongoing and future work.

2. P-SINO/NB-K FORMULATION AND SOLUTION

2.1 Review of Previous SINO Work

According to [3, 4], we denote a signal net as *s-wire* and define that two nets s_1 and s_2 are *sensitive* to each other if a switching signal on s_1 causes s_2 to malfunction (due to extraordinary crosstalk or delay variation) and vice-versa. In this case, s_1 is an *aggressor* for s_2, and s_2 a *victim* of s_1. The *sensitivity rate* of s_i is defined as the ratio of the number of aggressors for s_i to the total number of nets. The sensitivity for all s-wires in a given problem can be represented compactly with a sensitivity matrix S of size $n \times n$, where n is the number of s-wires. An entry of 1,0 in location (i, j) indicates that s_i and s_j are sensitive or not sensitive, respectively, to one another. A *shield* is a wire directly connected to P/G wires. We use the terms "wire" and "net" interchangeably in this paper. By inserting a shield between two sensitive s-wires, we are able to eliminate the capacitive coupling and reduce the inductive coupling.

The simultaneous shield insertion and net ordering (SINO) problem has been studied under the K_{eff} model in [4], and under the explicit RLC noise constraint in [3]. As a SINO solution can be viewed as a *placement* of shields and signal nets to routing tracks, a SINO solution can be also called a placement. Then, the noise bounded SINO problem under the K_{eff} model (the SINO/NB-k problem) is defined as:

FORMULATION 1. *(Optimal SINO/NB-k problem): For a given set of signal nets, find a placement P with the minimum area by simultaneous shield insertion and net re-ordering such that any s_i in P is free of capacitive noise and its inductive coupling is less than a given bound using the K_{eff} model.*

The noise bound in the SINO/NB-k problem is given by the K_{eff} model, but not a noise voltage that is more intuitive and convenient to the designer. Additionally, the SINO/NB-k problem does not allow placing a victim adjacent to an aggressor, which may lead to over-design in practice. A more general SINO/NB-v problem is formulated as follows [3]:

FORMULATION 2. *(Optimal SINO/NB-v problem): For a given set of signal nets, find a placement P with the minimum area by simultaneous shield insertion and net re-ordering such that the peak noise of any wire s_i in P satisfies the given explicit noise constraint for wire s_i.*

A high-order RLC circuit model is developed in [3] to compute the peak noise that can be induced for the victim over all signal patterns of its aggressors. The partial inductance model [6] is used without assuming any current return path, and a wire is modeled in general by multiple RLC segments. Coupling capacitance is considered only for adjacent wires, while coupling inductance is considered for any two wires. Table-based models presented in [7] and [9] are used to obtain the capacitance and inductance. The scope of mutual inductance is decided by a screening rule [8, 3].

Compared to the RLC noise model, the K_{eff} model is less intuitive and convenient to the designer. However, it is easy to compute and keeps a high fidelity versus the SPICE-computed RLC noise voltage for SINO solutions. As shown in [10], a SINO/NB-k solution that has a higher coupling value under the K_{eff} model also has a higher SPICE-computed noise voltage using the table-based RLC circuit model. Therefore, we study in this paper the interconnect estimation and the simultaneous signal and power routing (SPR) problem, both under the K_{eff} model. Our ongoing work extends the interconnect estimation and SPR problem to the explicit RLC noise model, as discussed in Section 4 of this paper.

2.2 p-SINO/NB-k Formulation

Note that pre-routed P/G wires are also shields in the sense that they can eliminate the capacitive coupling and reduce the inductive coupling, but were not considered in [3, 4]. For differentiation, we call shields in [3, 4] as *g-wires* (or *movable shields*) that can be placed at any routing track in contrast to those pre-routed P/G wires (or *fixed shields*). In order to consider pre-routed P/G structures that are widely used in the current global routing flow, we formulate the new p-SINO/NB-k problem as follows:

FORMULATION 3. *(Optimal p-SINO/NB-k problem): Given a set of signal nets and a pre-routed P/G structure, find a placement P with the minimum area by simultaneous shield (g-wire only) insertion and net re-ordering such that any s_i in P is free of capacitive noise and its inductive coupling is less than a given bound using the K_{eff} model.*

For the simplicity of presentation, we assume that a SINO solution is found where the inductive coupling for each net meets the given noise bound under the K_{eff} model. We also assume that the P/G structure is regular, i.e., the *P/G pitch space*, defined as the number of tracks between a pair of adjacent P/G wires, is a constant. For the p-SINO/NB-k and SPR/NB-k problems, only a signal net or a movable shield, but not a fixed P/G wire, can be assigned to an arbitrary routing track.

2.3 p-SINO/NB-k Algorithm

It has been proved in [3, 4] that the optimal SINO/NB-k and SINO/NB-v problems are NP-hard, and heuristic methods have been developed to obtain high quality solutions with reasonable computational time. Figure 1 gives the framework of the simulated annealing algorithms used in [3] for the SINO/NB-k problem and in this paper for the p-SINO/NB-k problem. As highlighted in Figure 1, the two algorithms are different in terms of the random moves and scheduling scheme. Starting with an arbitrary initial solution, the random moves performed by [3] are:

```
Simulated Annealing Algorithm: Given a placement $P$:
Repeat
    $Temp$ = Initial_Temperature;
    Schedule Random_Move(P, P');
        $Candidate\_Cost = Compute\_Cost(P')$;
        $ds = Candidate\_Cost - Compute\_Cost(P)$;
        if ($ds < 0$)
            $P = P'$;
        else
            $r = RANDOM(0, 1)$;
            if ($r < exp(-ds/Temp)$)
                $P = P'$;
    Until equilibrium at $Temp$ is reached;
    $Temp = Temp * Temperature\_Adjustment$;
    /*($0 < Temperature\_Adjustment < 1$)*/
Until $Temp ==$ Freezing_Point;
```

Figure 1: Framework of simulated annealing algorithms for SINO/NB-k and p-SINO/NB-k problems

(i) Combine two random blocks. If the two random blocks are adjacent, this is equivalent to removing a g-wire. Removing a g-wire can be done by shifting left all its right-handed wires.

(ii) Insert a g-wire at a random track by shifting right all wires which are to the right of this track.

(iii) Move a single random s-wire to a new and random track. This should be done in two steps:

  (a) Remove this net from its original track, and shift left by one track all right-handed wires, ranging from this net's original track to the new random track.

  (b) Insert this net into the new and random track by shifting right all wires which are to the right of this track.

(iv) Swap two random s-wires.

The SINO/NB-k problem does not have pre-routed P/G structures and *all* shields can be moved freely. However, for the new p-SINO/NB-k problem, only g-wires can be moved during the simulated annealing procedure, but all P/G wires are assigned to *fixed* tracks. The above difference leads to more sophisticated random moves as follows:

(i') Combine two adjacent blocks divided by a g-wire by removing this g-wire, and shift left by one track all its right-handed s-wires and g-wires (but not P/G wires).

(ii') Insert a g-wire at a random track by shifting right all s-wires and g-wires (but not P/G wires) which are to the right of this track.

(iii') Move a single random s-wire to a new track not occupied by the P/G wire. This should be done in two steps:

  (a) Remove this s-wire from its original track, and shift left by one track all right-handed wires except P/G wires, ranging from this s-wire's original track to the new random track.

  (b) Insert this s-wire to the new and random track by shifting right all s-wires and g-wires (but not P/G wires) which are to the right of this track.

(iv') Swap two random s-wires.

Note that moves (i)-(iv) can be viewed as local moves in the solution space for the SINO/NB-k problem, but the new moves (i')-(iii') may be no longer local moves in the solution space for the p-SINO/NB-k problem. The simple scheduling scheme, performing random moves with equal weights for the SINO/NB-k problem, will lead to too many rejections for the p-SINO/NB-k problem. To reach a satisfactory solution with as few rejections as possible for the p-SINO/NB-k problem, we iterate through random moves (i')-(iv') with different weights. We always use move (iv') more than other moves. But as the temperature decreases, the number of move (iv') becomes smaller. Moves which create two adjacent shields in the placement are categorically rejected and a new move is tried. The starting temperature, freezing point, temperature adjustment and variance threshold factors are all determined experimentally, but they are fixed for all experiments in this paper.

2.4 Experimental Results

We have implemented an integrated toolset in the C/C++ programming language. The toolset includes the table-based models for capacitance and inductance proposed in [7] and [9], all shields insertion and net ordering algorithms proposed in [3, 4] and this paper, and the SPICE netlist generation to verify the interconnect optimization result. We have tested our algorithm and implementation using a large number of examples. In this paper, the sensitive nets are picked randomly with respect to a given s-wire and its sensitivity rate. The inductive noise bound K_{thresh} is set to 1.0. Note that the K_{eff} model is independent of the width, length, and spacing of s-wires and g-wires, as illustrated in [11]. We generate ten different sensitivity matrices and initial placements for each design combination of P/G structure and sensitivity rate. We report the average number of shields over the ten sensitivity matrices in this paper.

We present experimental results for various test cases for 32 signal nets in this subsection. The average number of shields is summarized in Table 1, and the min-cost solution is highlighted for each sensitivity rate in the table. The maximum and average coupling values for the resulting p-SINO/NB-k solutions are presented in Table 2. In Table 2, all maximum coupling values are smaller than 1.0, so that all p-SINO/NB-k solutions meet the specified noise bound K_{thresh}.

From Table 1, one can easily see that different P/G structures (i.e., different P/G pitch spaces) lead to SINO solutions with different costs. For example, in the case of 30% sensitivity rate, the best P/G structure has a P/G pitch space of 11 and leads to a min-area solution with a total of 4.0 shields on average. On the other hand, decreasing the P/G pitch space to 10 leads to a total of 6.2 shields on average, an increase of more than 50% compared to the min-area solution. This observation motivates us to study the simultaneous power and signal routing (SPR/NB) problem to find the best P/G structure that can achieve the min-area solution in the next section.

sensitivity rate	P/G pitch size of P/G structures					
	7	8	9	10	11	12
30%	7.6/3.6	7.0/3.0	8.4/5.4	6.2/3.2	**4.0/2.0**	4.8/2.8
50%	8.2/4.2	7.4/3.4	6.6/3.6	**5.4/2.4**	5.8/3.8	5.2/3.2
70%	8.8/4.8	**6.2/2.2**	8.8/5.8	7.8/4.8	7.4/5.4	6.6/4.6

Table 1: Summary of p-SINO/NB-k solutions for 32 signal nets with uniform sensitivity rate. In each cell of columns 2-7 in the table, the first value is the total number of shields, and the second value is the total number of g-wires. The K_{thresh} is 1.0.

sensitivity rate	P/G pitch size of P/G structures					
	7	8	9	10	11	12
30%	0.63/0.48	0.69/0.52	0.66/0.43	0.70/0.51	0.79/0.57	0.76/0.52
50%	0.62/0.45	0.65/0.47	0.73/0.54	0.80/0.55	0.76/0.51	0.84/0.57
70%	0.65/0.47	0.83/0.54	0.67/0.46	0.72/0.51	0.77/0.53	0.81/0.53

Table 2: Maximum and average coupling values for p-SINO/NB-k solutions with different P/G pitch sizes. In each cell of columns 2-7 in the table, the first value is the maximum coupling, and the second value is the average coupling.

3. SPR/NB-K FORMULATION AND SOLUTION

To find the min-area SINO solution with a regular P/G structure, we define the following simultaneous signal and power routing (SPR/NB-k) problem under the K_{eff} model:

FORMULATION 4. (**min-area SPR/NB-k problem**) *For a number of signal nets and a given inductive coupling constraint, the min-area SPR/NB-k problem decides a regular P/G structure, assigns signal nets to routing tracks, and inserts necessary g-wires (i.e., movable shields), such that the resulting SPR solution has a minimum area and has g-wires fewer than P/G wires. Further, any s-wire in the SPR solution is free of capacitive noise, and its inductive noise is less than the given bound under the K_{eff} model.*

Because g-wires have to be connected with P/G wires, g-wires (movable shields) bear implicit routing overhead and may alleviate the desired regularity of P/G structures. In order to explore the tradeoffs among noise, layout regularity, and area in terms of the total number of shields including both P/G wires and g-wires, a good SPR/NB solution should be able to define an optimal regular P/G structure and have as few g-wires as possible. We explicitly require that g-wires be fewer than P/G wires in our problem formulation, i.e., on average, there is at most one g-wire inserted between every pair of adjacent P/G wires. On the other hand, allowing only P/G wires leads to higher area overhead as we will show in Section 4. In the following, we will first develop the pre-SINO/NB-k area estimation, then propose a two-phase SPR/NB-k solution based on this area estimation.

3.1 Pre-SINO Estimation for SINO/NB-k Solutions

We first introduce the formula for the number of shields needed by the SINO/NB-k problem with uniform sensitivity, where each net has the same sensitivity rate. We show later on that this formula can be applied to the non-uniform sensitivity case with modest modifications. In the rest of this paper, we denote the number of shields as N_s, the number of nets N, and the uniform sensitivity rate S.

N	sensitivity rate			
	20%	40%	60%	80%
16	3.0	3.8	4.5	5.0
32	4.0	5.6	6.8	8.0
64	6.6	10.0	13.0	14.8

Table 3: Numbers of shields needed by the SINO/NB-k problem with $K_{thresh} = 1.0$

3.1.1 RLC Nets with Uniform Sensitivity Rate

From Table 3, we can know that N_s should be a monotonous increasing function of N and S. Figure 2 also shows that given the fixed S, N_s is a linear function of N with two unknown parameters:

$$N_s = a_1 \cdot N + b_1 \tag{1}$$

and given the fixed N, N_s is a two-order polynomial function of S with three unknowns:

$$N_s = a_2 \cdot S^2 + b_2 \cdot S + c_2 \tag{2}$$

Considering the two one-variable functions (1) and (2), parameters in one function can in fact be represented by the other function. Thus we may replace the parameters in either function with the form of the other function. In this work, we obtain the following function by representing the three parameters in function (2) with function (1) as follows:

$$N_s = (a \cdot N + b) \cdot S^2 + (c \cdot N + d) \cdot S + e \cdot N + f \tag{3}$$

We use a nonlinear regression analysis method [12, 13] to obtain the values (see Table 4) for these parameters. The rightmost column of the table shows the probability of that parameter to be zero. For the formula's simplicity without loss of accuracy, we omit the terms whose coefficients have more than 80% possibility to be zero. The final formula for

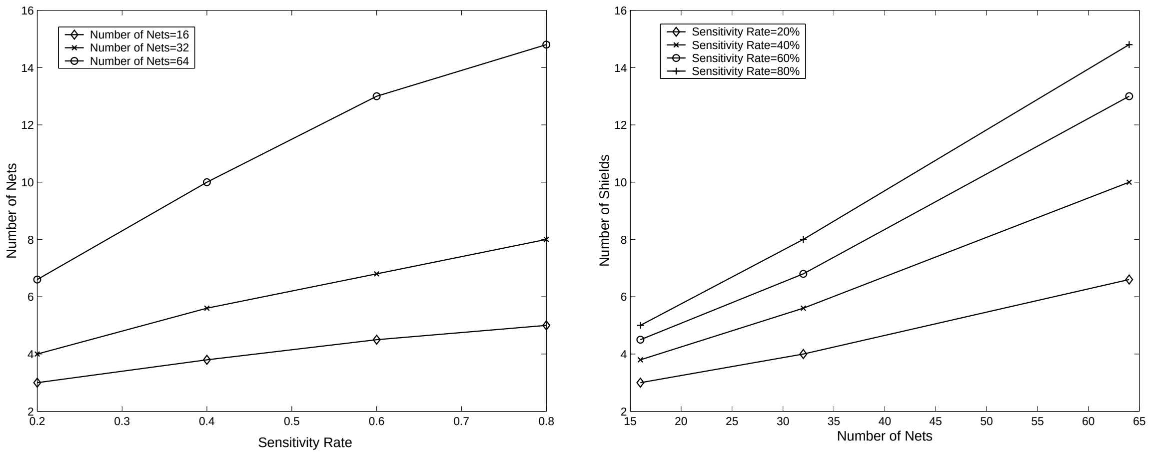

Figure 2: The function for the number of shields is linear with respect to the number of nets, and two-order polynomial with respect to the sensitivity rate.

parameter	final estimate	standard error	probability
a	-0.175343189	0.07760582	0.03580
b	1.1988973	3.153509	0.80803
c	0.378187878	0.07815248	0.00011
d	-0.341193692	3.175723	0.91557
e	0.0212514404	0.01713278	0.22993
f	0.806603546	0.6961897	0.26098

Table 4: Calculated parameters values

the number of shields with respect to $K_{thresh} = 1.0$ is:

$$N_s \;=\; -0.18 \cdot N \cdot S^2 + 0.38 \cdot N \cdot S + 0.02 \cdot N + 0.8 \quad (4)$$

We verify the formula in Table 5, where the number of shields given by the formula and that obtained by the SINO/NB-k program are compared. As shown in this table, the difference between the formula and the SINO/NB-k program is less than 10%.[1] Note that we can tune the constant f in function (3) to obtain a desired lower or upper bound of the number of shields required by SINO solutions.

Our estimation method is able to handle different K_{thresh} values. We derive the following formula (5) for K_{thresh}=1.5:

$$N_s \;=\; -0.23 \cdot N \cdot S^2 + 0.37 \cdot N \cdot S + 0.02 \cdot N + 0.6 \quad (5)$$

We further verify the estimation in Table 6. As shown in this table, the estimation error is less than 10%. In addition, same as shown in [4], when the K_{thresh} increases, the number of shields needed by SINO solutions decreases.

3.1.2 RLC Nets with Non-uniform Sensitivity Rates

Formulae (4) and (5) can be extended easily to the case with non-uniform sensitivity rates. When the sensitivity is not uniform, the number of shields is

$$N_s \;=\; -0.18 \cdot \sum_{i=1}^{N} S_i^2 + 0.38 \cdot \sum_{i=1}^{N} S_i + 0.02 \cdot N + 0.8 \quad (6)$$

for $K_{shresh} = 1.0$, and is

$$N_s \;=\; -0.23 \cdot \sum_{i=1}^{N} S_i^2 + 0.37 \cdot \sum_{i=1}^{N} S_i + 0.02 \cdot N + 0.6 \quad (7)$$

for K_{thresh}=1.5, where S_i is the sensitivity rate for s-wire s_i. We verify the above two formulae in Tables 7 and 8. The maximum difference between the estimation and the SINO/NB solution is 7.4% and 8.7% for K_{thresh}=1.0 and 1.5, respectively.

3.2 SPR/NB-k Algorithm

A brute-force solution to the min-area SPR/NB-k problem is to enumerate all possible P/G structures using the p-SINO/NB-k algorithm, and then find the SPR/NB-k solution with the minimum area. Using the newly developed formulae for the pre-SINO/NB-k estimation, we are able to propose the following two-phase SPR/NB-k algorithm: in the first phase, we define a single regular P/G structure according to pre-SINO/NB-k estimation; and in the second phase, we carry out p-SINO/NB-k procedures to find the best SPR/NB-k solution by searching the limited neighborhood of the pre-defined P/G structure. This two-phase algorithm is expected to be much more efficient compared to the brute-force solution.

Specifically, we speculate in the first phase that the optimal P/G structure that leads to the minimum number of shields should have a P/G pitch space (PS) given by

$$PS \;=\; \lceil \alpha \cdot \frac{N}{N_s} \rceil \quad (8)$$

where N is the number of signal nets, and N_s is the number of shields used in optimal SINO/NB-k solutions. Formulae from (4) to (7) for the SINO/NB-k estimation are used to compute N_s according to different K_{thresh} values and whether the distribution of the sensitivity rates is uniform or not. Furthermore, we speculate that the coefficient α is a constant and insensitive to different experiment settings. This speculation will be verified in the experiments later on.

To achieve the best SPR/NB-k solution in the second phase, we first apply the p-SINO/NB-k algorithm to assign signal nets into routing tracks and insert necessary g-wires

---

[1] As we will see from the comparison results in the following subsections, the error between each estimation and the corresponding SINO/NB solution is always within 10%.

N	sensitivity rate = 30%		sensitivity rate = 50%		sensitivity rate = 70%	
	estimation result	SINO/NB-k solution	estimation result	SINO/NB-k solution	estimation result	SINO/NB-k solution
16	2.7	3	3.4	4	4	4.4
32	4.6	3.0	6.1	6.4	7.2	7.6
64	8.3	8.4	11.4	11.6	13.5	14.2

Table 5: Comparison between the number of shields estimated by the formula and that obtained by the SINO/NB-k program. Here, uniform sensitivity is assumed, and K_{thresh} is set to 1.0. The maximum difference in this table is less than 10.0%.

N	sensitivity rate = 30%		sensitivity rate = 50%		sensitivity rate = 70%	
	estimation result	SINO/NB-k solution	estimation result	SINO/NB-k solution	estimation result	SINO/NB-k solution
16	2.4	2.2	3.4	3.4	4.1	4.2
32	3.7	3.6	4.8	5.0	6.2	5.7
64	6.3	6.0	8.1	8.4	10.5	10.2

Table 6: Comparison between the number of shields estimated by the formula and that obtained by the SINO/NB-k program. Here, K_{thresh}=1.5 and uniform sensitivity is assumed. The maximum estimation error is 8.8%.

	distribution of non-uniform sensitivity rates (N=32)	estimation result	SINO/NB-k solution
sample 1	$10\% \times 1 + 30\% \times 1 + 50\% \times 5 + 60\% \times 5 + 70\% \times 13 + 80\% \times 6 + 90\% \times 1$	6.6	6.6
sample 2	$30\% \times 4 + 40\% \times 11 + 50\% \times 6 + 60\% \times 10 + 70\% \times 1$	5.8	5.4
sample 3	$20\% \times 1 + 30\% \times 6 + 40\% \times 6 + 50\% \times 8 + 60\% \times 5 + 70\% \times 3 + 80\% \times 2 + 90\% \times 1$	5.9	5.8

Table 7: Comparison between the number of shields estimated by the formula and that obtained by the SINO/NB-k program. Here, K_{thresh}=1.0 and non-uniform sensitivity is assumed. The maximum estimation error is 7.4%.

	distribution of non-uniform sensitivity rates (N=32)	estimation result	SINO/NB-k solution
sample 1	$10\% \times 1 + 30\% \times 1 + 50\% \times 5 + 60\% \times 5 + 70\% \times 13 + 80\% \times 6 + 90\% \times 1$	5.6	5.0
sample 2	$30\% \times 4 + 40\% \times 11 + 50\% \times 6 + 60\% \times 10 + 70\% \times 1$	5.4	4.6
sample 3	$20\% \times 1 + 30\% \times 6 + 40\% \times 6 + 50\% \times 8 + 60\% \times 5 + 70\% \times 3 + 80\% \times 2 + 90\% \times 1$	5.1	4.6

Table 8: Comparison between the number of shields estimated by the formula and that obtained by the SINO/NB-k program. Here, K_{thresh}=1.5 and non-uniform sensitivity is assumed. The maximum error is 8.7%.

(movable shields) with respect to the regular P/G structure defined by the P/G pitch space PS in formula (8). We call the resulting SPR/NB-k solution the best among the *0-order neighborhood* (in short, *best of 0-neighbor*). We may then apply the p-SINO/NB-k algorithm with respect to two extra P/G structures defined by P/G pitch spaces $(PS + 1)$ and $(PS - 1)$, respectively. We denote the best solution among these three P/G pitch spaces $(PS+1)$, PS, and $(PS-1)$ as *the best of the first-order neighborhood* (in short, *best of 1st-neighbor*). Similarly, we may have the best of 2nd-neighbor, 3rd-neighbor, and etc.. We proceed to show in the next subsection that searching only the first-order neighborhood is capable of achieving the min-area SPR/NB-k solution.

3.3 Experimental Results

We apply our two-phase SPR/NB-k algorithm to four sets of examples: one set has 48 nets with uniform sensitivity rate ranging from 30% to 70%, and the other three sets contain the same non-uniform sensitivity cases as Table 7. For each example, we still use two different K_{thresh} =1.0 and 1.5, respectively. We first estimate the pre-routing area through formulae from (4) to (7), then define the regular P/G pitch space according to formula (8), and finally carry out p-SINO/NB-k procedures to find SPR/NB-k solutions as the best of 0-neighbor, 1st-neighbor, 2nd-neighbor, and 3rd-neighbor.

K_{thresh}	sensitivity rate	P/G pitch size		total shields/total g-wires				N_G
		estimated value	optimal value	best of 0-neighbor	best of 1st-neighbor	best of 2nd-neighbor	best of 3rd-neighbor	
1.0	30%	13	12	6.6/3.6	6.2/2.2	6.2/2.2	6.2/2.2	12
	40%	11	11	7.4/3.4	7.4/3.4	7.4/3.4	7.4/3.4	16
	50%	10	9	9.0/5.0	8.2/3.2	8.2/3.2	8.2/3.2	16
	60%	9	8	10.8/5.8	10.0/4.0	10.0/4.0	10.0/4.0	16
	70%	8	8	12.2/6.2	11.4/5.4	11.4/5.4	11.4/5.4	24
1.5	30%	14	13	6.4/3.4	5.8/2.8	5.8/2.8	5.8/2.8	7
	40%	12	12	6.4/2.4	6.4/2.4	6.4/2.4	6.4/2.4	8
	50%	11	11	7.0/3.0	7.0/3.0	7.0/3.0	7.0/3.0	9
	60%	10	10	8.0/4.0	8.0/4.0	8.0/4.0	8.0/4.0	12
	70%	9	9	9.8/4.8	9.8/4.8	9.8/4.8	9.8/4.8	12

Table 9: Summary of SPR/NB-k solution for 48 signal nets with uniform sensitivity rate. In each cell of columns 5-8 in the table, the first value is the total number of shields, and the second value is the total number of g-wires.

K_{thresh}	sensitivity rate	P/G pitch size		total shields/total g-wires				N_G
		estimated value	optimal value	best of 0-neighbor	best of 1st-neighbor	best of 2nd-neighbor	best of 3rd-neighbor	
1.0	case 1	9	8	7.8/4.8	7.2/3.2	7.2/3.2	7.2/3.2	11
	case 2	10	10	5.6/2.6	5.6/2.6	5.6/2.6	5.6/2.6	11
	case 3	10	9	6.2/3.2	5.8/2.8	5.8/2.8	5.8/2.8	9
1.5	case 1	10	10	5.6/2.6	5.6/2.6	5.6/2.6	5.6/2.6	9
	case 2	11	10	5.8/3.8	5.0/2.0	5.0/2.0	5.0/2.0	9
	case 3	11	10	5.4/3.4	4.8/1.8	4.8/1.8	4.8/1.8	8

Table 10: Summary of SPR/NB-k solution for 32 signal nets with non-uniform sensitivity rates. In each cell of columns 5-8 in the table, the first value is the total number of shields, and the second value is the total number of g-wires.

We present the total number of shields and g-wires in Tables 9 and 10, respectively for the uniform sensitivity case and the non-uniform sensitivity case. As shown in all these experiments, the best of 1st-neighbor is also the best of 3rd-neighbor. Further, our experiments show that a neighborhood higher than third-order does not lead to a better solution. Therefore, our two-phase SPR/NB-k algorithm is able to find the optimal P/G structure and routing solution by simply searching the first-order neighborhood of the estimated P/G pitch size given by formula (8). In addition, the total g-wires in all experiments are fewer than the total P/G wires, as required in our problem formulation. Moreover, as we speculated, the coefficient α can be set as a constant (=1.70 in all experiments here).

In Tables 9 and 10, we compare SPR/NB-k solutions and "SINO" solutions that use regular fixed P/G wires only. In the latter case, we enumerate all regular P/G structures by modifying our SINO algorithm to search for the best solution with the minimum area. In tables 9 and 10, these solutions are presented in the column "N_G". As movable shields are not used, only net ordering can be applied to minimize the coupling, hence leading to 30% to 120% larger area compared to min-area SPR/NB-k solutions.

Based on all these experiments, we summarize our two-phase SPR/NB-k algorithm in Figure 3 where the min-area SPR/NB-k solution is guaranteed by only searching the first-order neighborhood of the pre-defined P/G structure.

4. CONCLUSIONS AND DISCUSSIONS

For a number of coupled RLC signal nets, we have formulated the min-area simultaneous signal and power routing (SPR/NB) problem satisfying the given noise bound under the K_{eff} model. Further, we have developed a set of formulae to estimate the total number of shields needed by simultaneous shield insertion and net ordering (SINO) solutions; moreover, we have proposed a two-phase solution to the SPR/NB problem: in the first phase, we define a regular P/G structure based on the above interconnect estimation; and in the second phase, p-SINO/NB-k procedures are executed to achieve the best solution for the simultaneous signal and power routing problem by searching the first-order neighborhood of the estimated optimal P/G structure. Experimental results have shown that our SPR/NB-k solution satisfies the given noise bound under the K_{eff} model and needs fewer g-wires than P/G wires.

As described in Section 2, the explicit RLC noise voltage model proposed in [3] is more general and accurate than the K_{eff} model. Our ongoing work extends the interconnect estimation and the formulation and solution to the SPR/NB problem from the K_{eff} model to the explicit RLC noise model. We refer to them as the p-SINO/NB-v problem and SPR/NB-v problem, respectively. Same as [3], we apply the table-based partial inductance model, inductance screening rule, and higher-order RLC noise model to the two problems.

Preliminary results show that the frameworks proposed in this paper for the p-SINO/NB-k and SPR/NB-k problems

```
Two-Phase SPR/NB-$k$ Algorithm: Given a number of RLC nets, sensitivity rates, and $K_{thresh}$
    Phase One:
        Use formulae (4)-(8) to define a regular P/G pitch space.
    Phase Two:
        Carry out $p$-SINO/NB-$k$ procedures to find the the best SPR/NB solution
        in the first-order neighborhood of the pre-defined P/G pitch space.
```

Figure 3: Two-Phase SPR/NB-k Algorithm

are still applicable to the new p-SINO/NB-v and SPR/NB-v problems. These preliminary results, together with further development will be made available at the web site *http://eda.ece.wisc.edu*. In addition, we plan to incorporate our SPR/NB-v formulation into a global router with consideration of RLC signal integrity for both signal and power nets. We will explore optimal wire sizing and spacing, and the placement of decoupling capacitance in the context of our SPR problem.

5. ACKNOWLEDGMENTS

The authors would like to thank Mr. Kevin M. Lepak at University of Wisconsin, and Dr. Prashant Saxena and Dr. Mosur Mohan from Intel for helpful discussions.

6. REFERENCES

[1] J. Cong, L. He, C.-K. Koh, and P. H. Madden. Performance optimization of VLSI interconnect layout. *Integration, the VLSI Journal*, 21:1–94, 1996.

[2] J. Cong. Challenges and opportunities for design innovations in nanometer technologies. *SRC Design Sciences Concept Paper*, 1997.

[3] K. M. Lepak, I. Luwandi, and L. He. Simultaneous shield insertion and net ordering for coupled RLC nets under explicit noise constraint. *Accepted and to appear on Proc. Design Automation Conf.*, 2001.

[4] L. He and K. M. Lepak. Simultaneous shielding insertion and net ordering for capacitive and inductive coupling minimization. In *Proc. Int. Symp. on Physical Design*, 2000.

[5] G. Zhong, H. Wang, C.-K. Koh, and K. Roy. A twisted bundle layout structure for minimizing inductive coupling noise. In *Proc. Int. Conf. on Computer Aided Design*, 2000.

[6] A. Ruehli. Equivalent circuit models for three-dimensional multiconductor systems. *IEEE Trans. on MIT*, 1974.

[7] L. He, N. Chang, S. Lin, and O. S. Nakagawa. An efficient inductance modeling for on-chip interconnects. In *Proc. IEEE Custom Integrated Circuits Conference*, pages 457–460, May 1999.

[8] S. Lin, N. Chang, and O. S. Nakagawa. Quick on-chip self- and mutual-inductance screen. In *International Symposium on Quality of Electronic Design*, March 2000.

[9] J. Cong, L. He, A. B. Kahng, D. Noice, N. Shirali, and S. H.-C. Yen. Analysis and justification of a simple, practical 2 1/2-d capacitance extraction methodology. In *Proc. Design Automation Conf*, pages 627–632, 1997.

[10] K. M. Lepak, M. Xu, and L. He. Simultaneous shield insertion and net ordering for capacitive and inductive coupling minimization. *submission to IEEE Trans. on Computer-Aided Design of Integrated Circuits and Systems*, 2000.

[11] L. He and M. Xu. Characteristics and modeling for on-chip interconnects. In *University of Wisconsin, Technical Report, ECE-00-001*, 2000.

[12] C. Daniel, F. Wood, and J. Gorman. *Fitting equations to data: computer analysis of multifactor data.* New York: Wiley, 1980.

[13] P. Sherrod. *Nonlinear Regression Analysis Program*, 1997.