Post Global Routing Crosstalk Risk Estimation and Reduction*

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Abstract

Previous approaches for crosstalk synthesis often fail to achieve satisfactory results due to limited routing flexibility. Furthermore, the risk tolerance bounds partitioning problem critical for constrained optimization has not been adequately addressed. This paper presents the first approach for crosstalk risk estimation and reduction at the global (instead of detailed) routing level. It quantitatively defines and estimates the risk of each routing region using a graph-based optimization approach and globally adjusts routes of nets for risk reduction. At the end of the entire optimization process, a risk-free global routing solution is obtained together with partitions of nets' risk tolerance bounds which reflect the crosstalk situation of the chip. The proposed approach has been implemented and tested on CBL/NCSU *benchmarks and the experimental results are very promising.*

1 Introduction

Due to the scaling down of device geometry in deep-submicron technologies, the crosstalk noise between adjacent nets has become an important concern in high performance circuit design. If un-optimized, crosstalk may cause signal delay, logic hazards, and even malfunctioning of a circuit. The crosstalk noise is routing-dependent, since the coupling between nets is determined by the routes of interconnects on the chip. Therefore, crosstalk risk estimation and reduction can only be carried out after a feasible routing solution of the chip is obtained.

Previous approaches for crosstalk synthesis are mainly localized optimization methods at the detailed routing level[1, 2, 3, 4]. They are net-based approaches which estimate the crosstalk noise at each net in a region individually and reduce the coupling between adjacent nets via spacing[1, 2], track permutation[3] or track assignment[4]. Although these methods can achieve some reduction in crosstalk noise on a chip, they suffer from several drawbacks:

1. The optimization at the detailed routing level has very limited routing flexibility, since it can only adjust the routes of nets locally within a routing region, not globally among all regions on a chip. Consequently, its effectiveness depends heavily on the global routing solution, and it often fails to achieve satisfactory results especially for those regions having high densities of sensitive nets and limited routing resources.
2. Most previous approaches are not constraint-driven, but rather aim at coupling minimization. The crosstalk synthesis should be formulated as a constrained optimization process, since whether a net is subject to crosstalk violation depends not only on the couplings from its adjacent nets, but also on its *risk tolerance bound* - the maximum amount of crosstalk noise it can tolerate without affecting the functionality of circuit. The crosstalk noise at a net comes from all regions on its route, therefore, its risk tolerance bound must be partitioned appropriately among its routing regions. This critical problem has not been adequately addressed so far.

In this paper, we present a post global routing crosstalk optimization approach, which to our knowledge, is the first to estimate and reduce crosstalk risk at the global (instead of detailed) routing level. Given a feasible global routing solution, sensitivities and risk tolerance bounds of nets, our approach produces a risk-free global routing solution in which all regions on the chip are free of crosstalk risks. In addition, it generates partitions of nets' risk tolerance bounds which reflect the crosstalk situation of the chip.

The entire optimization process iterates among three key components (Fig. 1): crosstalk risk estimation, risk tolerance bound partitioning and global routes adjustment. The region-based crosstalk risk estimation first constructs a crosstalk risk graph for each routing region representing its crosstalk situation based on the initial partitions of risk tolerance bounds of nets. The crosstalk risk of the region, which indicates whether a risk-free routing solution is possible, is then quantitatively defined and estimated using a graph-based optimization approach. For accurate risk estimation, the impact of bound changes on regions' risks is analyzed and the current partitions of nets' risk tolerance bounds are adjusted via two-phase integer linear programming. If high risk regions still exist after bound partitioning, global routes adjustment is applied to reduce their crosstalk risks. First, nets whose removal leads to maximum risk reduction are identified, then they are ripped-up and rerouted with minimum cost alternative routes considering both the routing congestions and crosstalk risks of their routing regions. The entire iterative optimization process continues until a satisfactory solution is obtained.

*This research was sponsored by the Semiconductor Research Corp. (SRC) contract 94-DC-324.

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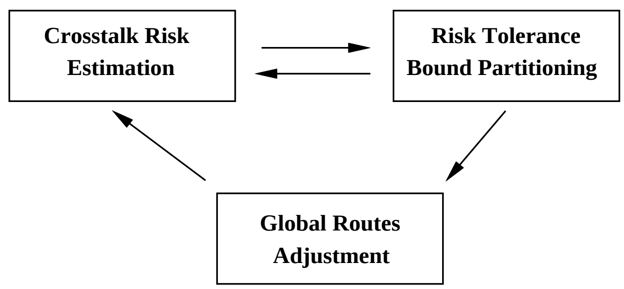

Fig. 1 Crosstalk Estimation and Reduction

The rest of the paper is organized as follows: Section 2 discusses the risk estimation method; Section 3 presents the risk tolerance bound partitioning algorithm; Section 4 explains the global routes adjustment approach; Section 5 shows experimental results which demonstrate the effectiveness of our approach.

2 Region-based Crosstalk Risk Estimation

2.1 Crosstalk risk representation

2.1.1 Definitions

The regular-grid global routing graph of the chip defines the horizontal or vertical routing regions. Denote E as the set of routing regions and N as the set of nets routed on the chip. Define $C(e)$ as the capacity (i.e., number of available routing tracks) of region $e \in E$ and $N(e)$ as the set of nets routed in e. The route of net $n \in N$, $route(n)$, is formulated as the embedding of topology of n on E, i.e., $route(n) \subseteq E$.

Although crosstalk noise between net pairs may cause delay and logic hazards in a circuit, a recent study[4] shows that not every pair of nets is subject to crosstalk concern in crosstalk optimization due to the logical and temporal isolations and *crosstalk sensitivity*, S_{ij}, can be specified for each net pair (i, j). For digital circuits, $S_{ij} \in \{0, 1\}$ and $S_{ij} = 1$ implies that net i, j are subject to crosstalk concern during optimization. According to the sensitivities of net pairs, $N_s \subseteq N$ is defined as the set of nets that are sensitive to other nets on the chip, and $N_s(e) \subseteq N(e)$ is the set of sensitive nets routed in region e. i.e., $N_s(e) = \{i | \exists j \in N(e), s.t.\ S_{ij} = 1\}$.

Since the coupling capacitance between a net pair (i, j) is directly proportional to their coupling wire length $len(i, j)$, the crosstalk noise $noise(i, j)$ between them can be measured by: $noise(i, j) = S_{ij} len(i, j)$. It is assumed that crosstalk noise exists only between net pairs in adjacent tracks and $Adj(i, e)$ is defined as the set of nets adjacent to net i in region e. For each sensitive net $i \in N_s$, its risk tolerance bound, $Bound(i)$, is defined as the maximum amount of crosstalk noise it can tolerate without affecting the functionality of the circuit. Thus, net i is "safe" under crosstalk noises from its adjacent nets if and only if:

$$\sum_{e \in route(i)} \sum_{j \in Adj(i,e)} noise(i, j, e) = \sum_{e \in route(i)} \sum_{j \in Adj(i,e)} S_{ij} len(i, j, e) < Bound(i) \quad (1)$$

where $len(i, j, e)$ and $noise(i, j, e)$ are the coupling length and crosstalk noise between net i, j in region e, respectively.

Although the crosstalk noise at each net in a region e can only be calculated exactly based on a detailed routing solution of e, we can identify whether a region is free of crosstalk violation once a global routing solution of e is obtained and the nets routed in e are known. Under global routing formulation, each net routed in region e counts for an entire track in the region either horizontally or vertically, i.e., no two nets share the same track in e. Therefore, we define a *routing solution of region* e at the global routing level as a routing order of nets in $N(e)$ in adjacent tracks of e from one side of the region to the other. If there exists a routing order of nets in e according to which each net is free of crosstalk violation, it is denoted as a risk-free routing solution of e and e is risk-free. If every region on the chip is risk-free, the current global routing solution of the chip is risk-free. The goal of our region-based crosstalk risk estimation process is to identify the existence of a risk-free routing solution for each region on the chip.

2.1.2 Crosstalk violations in global routing

Since crosstalk noise at net i comes from all routing regions on its route, $Bound(i)$ must be partitioned accordingly among $route(i)$ for crosstalk estimation. Denote $Bound(i, e)$ as the partitioned bound of i in region $e \in route(i)$, the partition of $Bound(i)$ can then be expressed as:

$$Bound(i) = \sum_{e \in route(i)} Bound(i, e) \quad (2)$$

Since each net occupies an entire track in a region under global routing formulation, it can be adjacent to no more than two nets in its above and below tracks within the region. Therefore, crosstalk violation may occur at net i in region e only in following two cases:

1. The noise from one of i's adjacent nets violates its risk tolerance bound in e, i.e., $\exists j \in Adj(i, e)$ s.t. $noise(i, j, e) \geq Bound(i, e)$.
2. The summation of noises from both of i's adjacent nets violates its bound, i.e., $\exists j, k \in Adj(i, e)$ s.t. $noise(i, j, e) + noise(i, k, e) \geq Bound(i, e)$.

These are referred to as crosstalk violation Case 1 and 2 in later discussions. Nets that cause crosstalk violations at i under these cases can not be placed adjacent to i in a risk-free routing solution of region e.

2.1.3 Crosstalk representation

Based on the analysis above, two graphs are defined for each routing region e, representing its crosstalk situation under risk violation Case 1 and 2.

A. **Crosstalk risk graph**

Define $CRG(e) = (N_s(e), E_s(e))$ (Fig. 2(a)) as the *crosstalk risk graph* of region e, which is a weighted graph having $Bound(i, e)$ as the weight of node $i \in N_s(e)$ and $noise(i, j, e)$ as the weight of edge $(i, j) \in E_s(e)$. Each node i in $CRG(e)$ represents a sensitive net routed in e, and each edge (i, j) satisfies: $noise(i, j, e) < Bound(i, e)$ and $noise(i, j, e) < Bound(j, e)$, i.e., the noise between i, j does not violate the risk tolerance bounds of both net i and j in region e. Therefore, $CRG(e)$ excludes crosstalk violations under Case 1 and it represents the compatibility between net pairs, i.e., each edge $(i,j) \in E_s(e)$ implies that net pair (i,j) can be placed in adjacent tracks in region e free of crosstalk violation under Case 1.

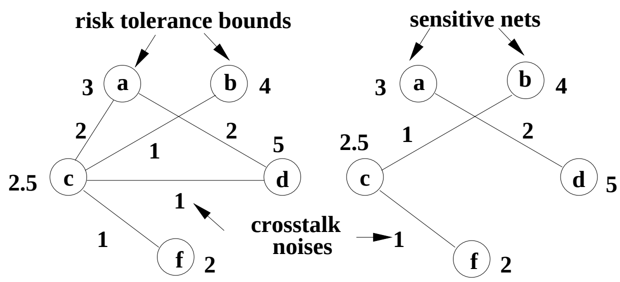

Fig. 2 (a) $CRG(e)$ **(b)** $CRG_{csp}(e)$

B. **Constrained simple path sub-graph**

The net compatibility represented in $CRG(e)$ is only pair-wise, i.e., the fact that net j,k are compatible with net i separately does not guarantee they can be placed adjacent to i at the same time, since the summation of noises from j,k may cause crosstalk violation at i under Case 2.

For further crosstalk representation, $CRG_{csp}(e) = (N_s(e), E_p(e))$ (Fig. 2 (b)) is defined as the *constrained simple path sub-graph* of $CRG(e)$ containing simple path segments only (isolated nodes are regarded as special path segments), i.e., $E_p(e) \subseteq E_s(e)$ and $degree(i) \leq 2$ holds for every node i in $CRG_{csp}(e)$. Furthermore, each simple path segment p in $CRG_{csp}(e)$ satisfies: $noise(i,j,e) + noise(i,k,e) < Bound(i,e), j,k \in Adj(i,e), \forall i \in p$, i.e., the total noise at each node i from its two adjacent nodes is less than its risk tolerance bound. According to this noise constraint, crosstalk violation under Case 2 is also excluded from $CRG_{csp}(e)$.

2.2 Region-based crosstalk risk definition

2.2.1 Risk-free routing solution

According its definition, each simple path segment $p = (n_1, \ldots, n_k) \in CRG_{csp}(e)$ corresponds to a risk-free routing order of nets on p. In other words, nets $n_1, \ldots, n_k$ are free of crosstalk violations under Case 1 and 2 if they are routed in region e in the same order as they appear on p. For example, path segment $p = (b,c,f)$ in Fig. 2(b) corresponds to a risk-free routing order of net b,c,f in the region. In graph theory, a *Hamiltonian path* in graph G is a simple path that visits every node in G exactly once. $CRG_{csp}(e)$ is equivalent to a Hamiltonian path if it contains just one simple path segment. According to the analysis above, a Hamiltonian path in $CRG_{csp}(e)$ corresponds to a risk-free routing solution of region e and the following proposition follows.

Proposition 1 *A routing region e is risk-free if $CRG_{csp}(e)$ has a Hamiltonian path.*

2.2.2 Shields

It is not always possible to find a $CRG_{csp}(e) \subseteq CRG(e)$ which contains a Hamiltonian path. When multiple simple path segments exist in $CRG_{csp}(e)$, the end nodes of these path segments can not be adjacent to each other in region e without causing crosstalk violations. To generate a risk-free routing solution of the region, we introduce the concept of *shield*. The shields in e are the non-sensitive nets or empty tracks in the region, each having zero crosstalk with other nets and infinite risk tolerance bound. They can be used to separate the end nodes of those simple path segments so that they are no longer subject to crosstalk violations. In other words, each shield s can "connect" two disjoint path segments, p_1 and p_2 in $CRG_{csp}(e)$ into a longer path segment, $p_1 \cup \{s\} \cup p_2$, which corresponds to a risk-free routing order of nets on both p_1 and p_2. Therefore, a risk-free routing solution of region e exists if and only if there are enough shields in e to connect all simple path segments in $CRG_{csp}(e)$ into one Hamiltonian path. An example of shield application is shown in Fig. 3:

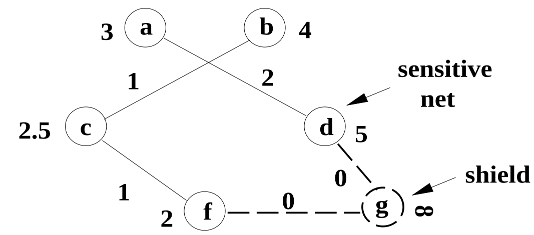

Fig. 3 Construction of Hamiltonian path

2.2.3 Crosstalk risk definition

Denote $P(e)$ as the number of simple path segments in $CRG_{csp}(e)$, $S_{avail}(e)$ as the number of shields available in region e and $S_{need}(e)$ as the number of shields needed in e to generate a risk-free routing solution. According to shield definition, $S_{avail}(e)$ equals the total number of empty tracks and non-sensitive nets in e and can be expressed as:

$$S_{avail}(e) = C(e) - |N_s(e)| \tag{3}$$

$S_{need}(e)$ is determined by the configuration of $CRG_{csp}(e)$ and can be calculated as follows:

Proposition 2 $S_{need}(e) = |N_s(e)| - |E_p(e)| - 1$, *where $N_s(e), E_p(e)$ are node and edge set of $CRG_{csp}(e)$, respectively.*

For risk estimation, $S_{need-min}(e)$ is denoted as the minimum number of shields needed in region e to generate a risk-free routing solution. Its corresponding $CRG_{csp}(e)$ having maximum number of edges, $|E_{p-max}(e)|$, is denoted by $CRG_{csp-max}(e)$. According to analysis above, the existence of a risk-free routing solution of region e is determined by the difference between $S_{need-min}(e)$ and $S_{avail}(e)$. Thus, the risk of region e, $Risk(e)$, is quantitatively as:

$$\begin{aligned} Risk(e) &= S_{need-min}(e) - S_{avail}(e) \\ &= 2|N_s(e)| - |E_{p-max}(e)| - C(e) - 1 \end{aligned} \tag{4}$$

$Risk(e)$ indicates whether region e is risk-free. $Risk(e) \leq 0$ implies there are more than enough shields in region e to generate a risk-free routing solution of e. If $Risk(e) > 0$, it is the number of extra shields needed in e, which should be minimized during the risk reduction phase. The current global routing solution of the chip is risk-free if and only if $Risk(e) \leq 0$ holds for every routing region e on the chip.

2.3 Crosstalk risk estimation

The key to the crosstalk risk estimation of region e is to construct the largest sub-graph of $CRG(e)$, $CRG_{csp-max}(e)$. This can be formulated as a generalized approach for finding a Hamiltonian path in a graph and the following proposition holds:

Proposition 3 *The crosstalk risk estimation problem is NP-complete.*

Proof:

The crosstalk risk graph $CRG(e)$ is an arbitrary graph with no restriction on its configurations. A Hamiltonian path in graph G is the largest possible maximum simple path sub-graph G_{sp-max} of G, i.e., if a Hamiltonian path exists in G, it is also a G_{sp-max} of G and can be found via G_{sp-max} construction. Therefore, the Hamiltonian path problem can be reduced in polynomial time to the problem of constructing $CRG_{csp-max}(e)$ from $CRG(e)$ by setting $CRG(e)$'s node weights to infinity and edge weights to 1, which effectively eliminates the noise constraints for $CRG_{csp-max}(e)$.

Since finding a Hamiltonian path in an arbitrary graph is known to be NP-complete, the construction of $CRG_{csp-max}(e)$, i.e., the risk estimation of region e, is also NP-complete.

□

There may exist multiple $CRG_{csp-max}(e)$s of $CRG(e)$, all having the maximum number of edges, $|E_{p-max}(e)|$. For crosstalk risk estimation, we aim at calculating the value of $|E_{p-max}(e)|$, rather than finding a specific $CRG_{csp-max}(e)$ of $CRG(e)$, i.e., we are interested in the existence of a risk-free routing solution of e, not in finding a specific one.

Due to the NP-complete nature of the crosstalk estimation problem, we develop a two-step algorithm for $CRG_{csp-max}(e)$ construction:

A. Initial $CRG_{csp-max}(e)$ construction

Define the degree of edge (i,j), $degree(i,j)$, as the summation of its node degrees in $CRG(e)$, i.e., $degree(i,j) = degree(i) + degree(j)$. For initial $CRG_{csp-max}(e)$ construction, edges are removed sequentially from $CRG(e)$ until the degree of each node is no more than 2 and the noise constraints for $CRG_{csp-max}(e)$ are satisfied. To minimize the number of edges that have to be removed, we adopt the following two heuristics:

1. Remove edges with largest degrees first.
2. Among edges with same degree, remove those having the largest weight (noise) first.

The initial $CRG_{csp-max}(e)$ is constructed as follows:

1. While there exists node i with $degree(i) > 2$:
   - 1.1 Compute degrees of edges in current $CRG(e)$.
   - 1.2 Remove edges from $CRG(e)$ according to Heuristics 1 and 2.
2. While crosstalk violations at nodes still exist: Remove edges according to Heuristics 2.

B. Iterative $CRG_{csp-max}(e)$ improvement

At Step A, the initial $CRG_{csp-max}(e)$ is constructed via sequential edge removal in a greedy fashion and the set of removed edges is denoted as $E_{rem}(e)$. To avoid local optimal solution, we design a two-phase improvement process which iterates until no further increase in $|E_{p-max}(e)|$ can be obtained.

Phase I:

Since edges are removed sequentially from $CRG(e)$ during the initial construction step, we check if any previously removed edges in $E_{rem}(e)$ can now be added back to the initial $CRG_{csp-max}(e)$ without violating the node degree and noise constraints. The complexity of this phase is bounded by the number of edges in $CRG(e)$, which is $O(|E_s(e)|)$.

Phase II:

To further improve the locally optimal solution obtained in Phase I, we apply the so-called *k-Opt* heuristics, which checks if more than k previously removed edges can be added back to the current $CRG_{csp-max}(e)$ when k edges randomly picked from it are removed. If *k-Opt* heuristics is applied with k ranging from 1 to $|E_s(e)| - 1$, a globally optimal $CRG_{csp-max}(e)$ can be found. However, this is not feasible in practice due to the $O(|E_s(e)|^{k+1})$ complexity of $k-Opt$. In our implementation, *1-Opt* and *2-Opt* are used and experiments show that they yield good results for $CRG_{csp-max}(e)$ construction.

2.4 Crosstalk risk reduction

Once the crosstalk risks of regions are estimated, those regions having positive risks can be identified. By definition, the total positive risk of these regions, P_{sum}, equals the total number of extra shields needed to generate a risk-free global routing solution of the chip. The basic goal of crosstalk risk reduction in global routing is to eliminate those positive risk regions so that no extra shields are needed and every routing region on the chip is risk-free.

The crosstalk risk reduction can be achieved by modifying the configuration of CRG. According to Eqn (4), the two adjustable variables in $Risk(e)$ of region e are:

1. The number of edges in $CRG_{sp-max}(e)$, determined by the routing solution of e, net sensitivity S_{ij}s and partitioned risk tolerance bounds $Bound(i,e)$s.
2. The number of sensitive nets $|N_s(e)|$ routed in region e, determined by the global routing solution.

These point to two ways of reducing the risks of those high risk regions on the chip:

- Increase their $|E_{p-max}(e)|$s by appropriately partitioning nets' risk tolerance bounds among their routing regions, which is discussed in Section 3.
- Reduce the $|N_s(e)|$s by globally adjusting the routes of nets, which is discussed in Section 4.

3 Risk Tolerance Bound Partitioning

3.1 An example

Given a global routing solution and sensitivities of nets, the crosstalk risk graphs of routing regions are determined by the partitions of risk tolerance bounds of nets as stated in Eqn (2). Different bounds partitions may result in different CRG configurations and risk estimations as shown in Fig. (4), which contains CRG_{sp-max}s of Region 1 and 2 under two different partitions of the risk tolerance bound of net f routed in both regions.

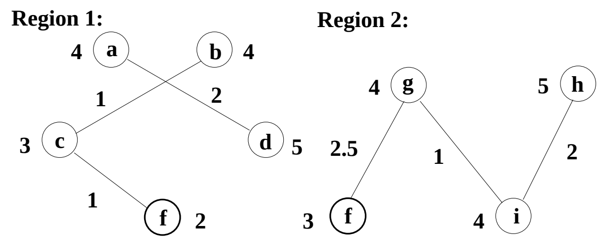

Fig. 4 (a) Partition One of $Bound(f)$

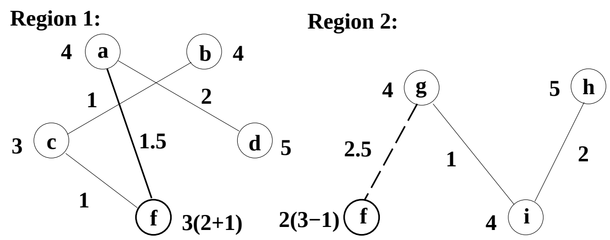

Fig. 4 (b) Partition Two of $Bound(f)$

Suppose that $C(1) = C(2) = 5$, $Bound(f) = 5$, and the risk bounds partitions of other nets routed in the two regions are fixed. Under Partition One of $Bound(f)$ (Fig. 4(a)), $Bound(f) = Bound_1(f,1) + Bound_2(f,2) = 2+3$, $Risk(1) = 1 > 0$ and $Risk(2) = -1 < 0$, i.e., Region 1 is not risk-free under Partition One. Under Partition Two (Fig. 4(b)), $Bound(f,1)$ is increased from 2 to 3, while $Bound(f,2)$ is reduced from 3 to 2. As the result, edge (a,f) which violates $Bound_1(f,1)$ (Case 2) under Partition One can now be added into $CRG_{sp-max}(1)$ without crosstalk violation and $Risk(1)$ is reduced from 1 to 0. On the other hand, edge (f,g) is removed from $CRG_{sp-max}(2)$ since it violates $Bound_2(f,2)$ (Case 1) under Partition Two. Still, $Risk(2) = 0$ is non-negative, since there is one empty track in Region 2 which can be used as a shield to connect the two path segments (f) and (g,i,h). Therefore, both regions are risk-free under Partition Two of $Bound(f)$. This example shows that the risks of positive risk regions can be reduced by partitioning the risk tolerance bounds of nets appropriately.

3.2 Impact of bound changes on risks

For risk tolerance bound partitioning, we first analyze the impact of risk bound changes on the crosstalk risk graphs and risk estimations of routing regions. An edge (i,j) in $CRG(e)$ cannot be included in $CRG_{sp-max}(e)$ of region e if placing i,j in adjacent tracks results in crosstalk violations in the following two cases:

1. Crosstalk violation under Case 1 or 2 happens at both i and j, edge (i,j) is denoted as "locked".
2. Crosstalk violation happens at one of i and j only, edge (i,j) is denoted as "half-locked".

Each edge (i,j) in $CRG_{sp-max}(e)$ is free of risk violation at both ends and is denoted as "free".

According to its definition, the crosstalk violation at net i,j can be eliminated by increasing $Bound(i,e)$ and $Bound(j,e)$ appropriately, which switches edge (i,j) from being "locked" to "half-locked" or from being "half-locked" to "free". In the later case, (i,j) may become a new edge in $CRG_{sp-max}(e)$ and $Risk(e)$ is reduced. On the other hand, decreases in bounds may result in fewer edges in $CRG_{sp-max}(e)$ and increase in $Risk(e)$. The change in $Risk(e)$ due to the adjustments in bounds can be characterized as follows:

Proposition 4 *The change in $Risk(e)$ of region e caused by adjusting $Bound(i,e)$ of net $i \in N_s(e)$ alone equals one of $\{-2,-1,0,1,2\}$.*

According to this proposition, the amount of increase in $Bound(i,e)$, $Inc(e)$, is characterized by:
$Inc_0(i,e)$: the amount of increase in $Bound(i,e)$ that does not affect $Risk(e)$ but may switch some edges from "locked" to "half-locked" or from "half-locked" to "free".
$Inc_{1,2}(i,e)$: the minimum amount of increase in $Bound(i,e)$ that can reduce $Risk(e)$ by 1 and 2 respectively.
Clearly, $Inc_0(i,e) < Inc_1(i,e) < Inc_2(i,e)$.

Similarly, the amount of decrease in $Bound(i,e)$, $Cut(e)$, can also be characterized as:
$Cut_0(i,e)$: the maximum amount of decrease in $Bound(i,e)$ that does not affect $Risk(e)$ but may switch some edges from "free" to "half-locked" or from "half-locked" to 'locked".
$Cut_{1,2}(i,e)$: the maximum amount of decrease in $Bound(i,e)$ that increases $Risk(e)$ by 1 and 2 respectively.
Again, $Cut_0(i,e) < Cut_1(i,e) < Cut_2(i,e)$. Since the increase in $Risk(e)$ caused by decrease in $Bound(i,e)$ can be no more than 2, $Cut_2(i,e) = Bound(i,e)$.

3.3 Risk tolerance bound partitioning

3.3.1 Problem formulation

Based on the above characterization, the bound partitioning problem can be formulated as:
Given initial partitions of risk tolerance bounds of nets, adjust the bounds of each net among its routing regions by Incs and Cuts so that the total positive risk of the chip is minimized and the chip's risk estimation becomes accurate.

Notice that $Risk(e)$s do not change continuously with respect to adjustments in $Bound(i,e)$s. Due to this discrete nature, the bound partitioning problem is formulated as an iterative two-phase integer linear programming (ILP):
Phase I: Switch maximum number of "locked" edges to "half-locked" so that they may become "free" in Phase II.
Phase II: Minimize the total positive risk of the chip by switching "half-locked" edges to "free".
The ILP formulation for these two phases are quite similar and can be integrated into one during the actual implementation. So only the formulation for risk minimization is discussed below.

3.3.2 ILP formulation for risk minimization

Define $x_{1-2}(i,e)$ and $y_{0-2}(e)$ as binary variables indicating whether $Risk(e)$ is reduced or increased by 1 or 2 respectively, i.e., $Bound(i,e)$ is increased by $Inc_{1-2}(i,e)$ or decreased by $Cut_{0-2}(i,e)$ respectively

during bound adjustment. This ILP phase aims at minimizing the total positive risk of the chip and is formulated as:
Minimize $\sum_e R(e)$
Subject to:

$$1. Risk(e) + \sum_{i \in N_s(e)} \sum_{k \in \{1,2\}} k(y_k(i,e) - x_k(i,e)) = R(e), \quad \forall e, Risk(e) > 0$$

$$2. \sum_{e \in route(i)} \sum_{k \in \{1,2\}} Inc_k(i,e) x_k(i,e) \leq \sum_{e \in route(i)} \sum_{k \in \{0,1,2\}} Cut_k(i,e) y_k(i,e) \quad \forall i \in N_s$$

$$3. \quad 0 \leq \sum_{k \in \{1,2\}} x_k(i,e) + \sum_{k \in \{0,1,2\}} y_k(i,e) \leq 1, \quad \forall e \in route(i), \forall i \in N_s$$

$$4. \quad x_1(i,e), x_2(i,e), y_0(i,e), y_1(i,e), y_2(i,e) \in \{0,1\}$$

The first constraint defines $R(e)$ as the updated risk of region e after bound adjustment. The second constraint enforces that the "demands" for risk bounds can be no more than the "supplies" for each sensitive net, i.e., the increases in $Bound(i,e)$s in some regions must be balanced by the decreases in $Bound(i,e)$s in other regions on $route(e)$. The third constraint indicates that $Bound(i,e)$ can be updated only once at a time. Notice that $R(e)$ is a linearized approximation of the actual risk of region e under the updated bounds partitions since the simultaneous bound adjustments at different nodes are not independent of each other. Nevertheless, minimizing $R(e)$ points to the right direction of bound adjustment for positive risk minimization and the accurate risks of regions can be estimated after each round of ILP during optimization.

3.3.3 Risk tolerance bound partitioning algorithm

The risk tolerance bound partitioning algorithm is designed as an iterative process. Initially, nets' bounds are partitioned uniformly among their routing regions. At each iteration, the current bounds partitions are adjusted for positive risk minimization and the regions' risks are updated accordingly. This process continues until the total positive risk of the chip is minimized.

Risk tolerance bound partitioning algorithm {

1. Initial bound partitioning:
   Partition the risk tolerance bound of each net uniformly among its routing regions.
2. Estimate the crosstalk risk of each region on the chip.
3. While reduction in positive risk is possible:
   3.1 Calculate Incs and Cuts for the current partitions of risk tolerance bounds.
   3.2 Solve two-phase ILP optimization for risk minimization.
   3.3 Update crosstalk risk graphs and regions' risks.

}

The positive risks of regions may be over estimated initially, since uniform bounds partitions do not reflect the actual crosstalk situation of the chip. After risk tolerance bound partitioning, the total positive risk of the chip is minimized, indicating fewer regions and nets are subject to global routes adjustment for crosstalk risk reduction. This speeds up the generation of a risk-free global routing solution of the chip.

4 Global Routes Adjustment

Once an accurate estimation of crosstalk risk situation on the chip is obtained after risk tolerance bound partitioning, the regions with positive risks can be identified and their risks can be decreased by reducing the number of sensitive nets routed in them. Since adjusting routes of nets globally may affect the quality of the current global routing solution in terms of routing density, total wire length and timing properties, the number of nets whose routes have to be adjusted for risk reduction should be minimized, and the global routes adjustment problem is formulated as:
Generate a risk-free global routing solution of the chip by ripping up and rerouting minimum number of nets from current positive risk regions.

4.1 Net ripping-up

For each positive risk region e, we define $N_r(e) \subseteq N_s(e)$ as the smallest set of nets need to be ripped-up from e for risk reduction, i.e., the removal of nets in $N_r(e)$ from e reduces $Risk(e)$ to 0. The relation between risk reduction and net ripping-up is stated by the following proposition:

Proposition 5 *The reduction in $Risk(e)$ of region e by ripping-up net i from e, $Risk_{dec}(i,e) \in \{0,1,2\}$; more precisely, $Risk_{dec}(i,e) = 2 - degree(i)$, where $degree(i)$ is the degree of node i in $CRG_{sp-max}(e)$.*

Ripping up a net from region e frees one track in e which can be used as a shield. According to the above proposition, ripping-up net with degree 0 and 1 in $CRG_{sp-max}(e)$ can reduce $Risk(e)$ by 2 and 1 respectively, while ripping-up net with degree 2 does not change $Risk(e)$. Therefore, $N_r(e)$ can be constructed based on $CRG_{sp-max}(e)$ as follows:

$N_r(e)$ Construction Algorithm {
While $\sum_{i \in N_r(e)} Risk_{dec}(i,e) < Risk(e)$:

1. Add nodes with degree 0 into $N_r(e)$ while they exist.
2. Add nodes with degree 1 into $N_r(e)$, break ties by selecting one which connects to a node also with degree 1. Go back to Step 1.

}

Nodes with degree 0 are chosen first at Step 1 since their removal can result in maximum reduction in $Risk(e)$. At Step 2, priority is given to node i which connects to a node j with $degree(j) = 1$, since j can become a new 0 degree node after the removal of i and its connecting edge. This iterative net selecting process continues until $Risk(e)$ can be reduced to 0 by ripping up nets in $N_r(e)$.

4.2 Net rerouting

Once nets in $N_r(e)$ are identified, they are ripped-up from region e and rerouted through other regions on the chip with a minimum cost alternative route. To this end, we adopt a modified version of the global router developed in [5]. The original router is extended to take the regions' crosstalk risks into consideration, in addition to other concerns in global routing such as densities, wire lengths, timing constraints, etc. Analogous to net ripping-up, the rerouting of nets may result in risk increases in regions on their new routes. To minimize the increase in positive risks, our router reroutes those ripped-up nets through regions having the lowest risks so that least number of new positive risk regions are created and fewest iterations are required to generate a risk-free routing solution.

4.3 Global routes adjustment algorithm

The global routes adjustment is formulated as an iterative optimization process, which updates the regions' risks and partitions of risk tolerance bounds after each round of net ripping-up and rerouting.

Global Routes Adjustment Algorithm {
While there exists region e with $Risk(e) > 0$:

1. Identify set of nets $N_r(e)$ to be ripped up from region e for risk reduction.
2. Reroute the ripped-up nets with minimum cost alternative routes.
3. Redo risk estimation and bound partitioning.

}

5 Experimental Results

Our post global routing crosstalk risk estimation and reduction approach has been implemented and tested on a DEC 5000/125 workstation. Four test circuits constructed from the CBL/NCSU building-block benchmarks, ami33, hp, xerox and ami49 are used. The specifications of these circuits are listed in Table 1, where G_{size} refers to the the size of regular-grid global routing graph of the chip.

The feasible global routing solution of these chips are generated by the performance-driven global router[5]. In our experiments, circuit ami33 and xerox are each tested under two different placement/global routing solutions, denoted as $*.1$ and $*.2$ respectively. The ILPs for bound partitioning are solved by *lp-solve* optimization tool. Since there are no standard benchmarks having crosstalk information, our crosstalk optimization approach is tested under all possible values of both net sensitivity ratio, which is the percentage of net pairs in the circuit that are subject to crosstalk risk concern, and risk tolerance bound of each net, specified as the percentage of total net length allowed for coupling with other nets.

Fig. 5 shows the testing results on ami33.1. Fig. 5 (a) illustrates how the average risk of regions on the chip varies with different net sensitivity ratios and risk tolerance bounds (partitioned uniformly in this test). It can be observed that crosstalk risk decreases as bound increases and sensitivity ratio decreases. This is due to the fact that nets having larger risk tolerance bounds are less vulnerable to crosstalk violation, and fewer shields are needed when fewer net pairs are subject to crosstalk concern.

Fig. 5 (b) compares the total number of extra shields needed (i.e., total positive risk) on the chip for a risk-free global routing solution under two different partitions of risk tolerance bounds: uniform and adjusted by our bound partitioning algorithm. Here, the results are measured under 100% sensitivity ratio. It can be seen that the risk estimation becomes more accurate under adjusted bounds partitions, and the number of shields needed is reduced drastically by over 50% for the entire range of bound specifications.

For crosstalk risk reduction, our main focus is on regions with positive risks on the chip. Table 2 and 3 show estimations of positive risk regions under uniform and adjusted partitions of risk tolerance bounds before and after global routes adjustment, respectively. Here, results are measured under 100% net sensitivity ratio, which corresponds to the most serious crosstalk situation, and risk tolerance bound at 50% of net wire length.

When applied before global routes adjustment (Table 2), bound partitioning reduces the numbers of positive risk regions, extra shields needed and nets to be ripped up for risk reduction by an average of 40%, 59% and 55% respectively, which means fewer nets need to be ripped-up and rerouted based on the accurate risk estimation. In case of circuit ami33.2, global routes adjustment is avoided since bound partitioning eliminates high risk regions on the chip. When applied after net ripping-up and rerouting (Table 3), bound partitioning reduces all those three numbers to 0 (for circuit ami33.1 and hp, nets' bounds partitions do not need to be adjusted), indicating that only one round of global routes adjustment is needed to generate a risk-free global routing solution for each circuit even under the worst crosstalk scenario. This also implies that our net ripping-up and rerouting method is very efficient for risk reduction. Our experiments show that there were little changes in routing densities and wire lengths of nets in the global routing solution due to limited global routes adjustments.

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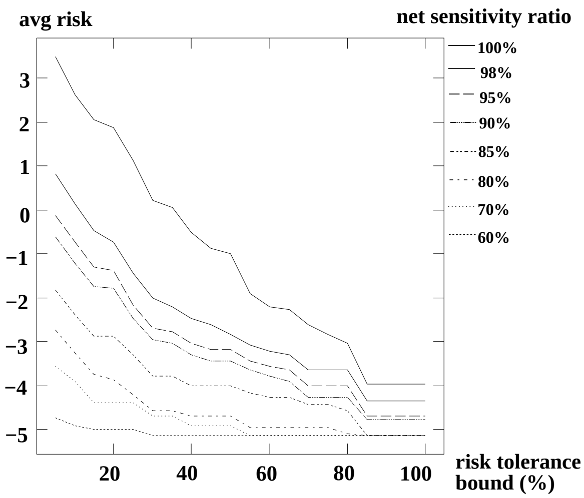

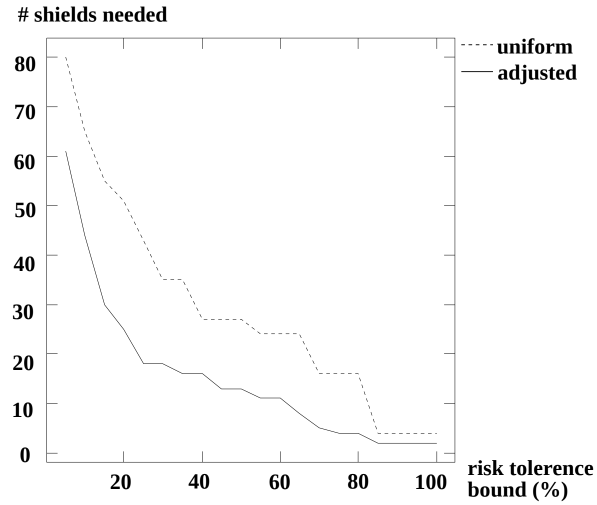

Fig. 5 (a) Risk estimation of Chip (b) Risk bound partitioning

Table 1. Benchmark specifications

Circuit	# macro cells	# nets	# pins	G_{size} (row x col)
ami33	33	123	442	28 x 23
hp	11	83	309	289 x 228
xerox	10	203	696	24 x 24
ami49	49	408	953	184 x 139

Table 2. Estimation of High Risk Regions Before Global Routes Adjustment

Testing Circuit	# positive risk regions			total # shields needed			# nets to be ripped-up		
	uniform	adjusted	-%	uniform	adjusted	-%	uniform	adjusted	- %
ami33.1	7	4	43	27	13	52	15	8	47
ami33.2	13	0	100	17	0	100	13	0	100
hp	39	39	0	105	59	44	72	48	33
xerox.1	12	5	58	44	10	77	24	5	79
xerox.2	53	43	19	175	88	50	103	60	42
ami49	214	166	22	375	270	28	232	166	28

Table 3. Estimation of High Risk Regions After Global Routes Adjustment

Testing Circuit	# positive risk regions		total # shields needed		# nets to be ripped-up	
	uniform	adjusted	uniform	adjusted	uniform	adjusted
ami33.1	0	-	0	-	0	-
hp	0	-	0	-	0	-
xerox.1	11	0	25	0	14	0
xerox.2	15	0	38	0	23	0
ami49	24	0	48	0	24	0