# Crosstalk-Constrained Performance Optimization by Using Wire Sizing and Perturbation *

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## Abstract

In this paper, we propose a unified wire sizing and perturbation algorithm for crosstalk-constrained performance optimization that is applicable to general routing structures. Our algorithm is based on a two-stage iterative technique: we first perturb *all* wires to the positions with the minimum delay, then we adjust the wire sizes to further optimize delay under crosstalk constraints. The unified wire sizing and perturbation technique has the property of unimodality, implying that there is a unique position resulting in the optimal delay and crosstalk. Applying these properties can dramatically reduce the search space and thus lead to a very efficient method to determine the best wire position and the optimal wire size. Experimental results show that our algorithm can achieve average improvements of 44.5% and 40.2% in delay without sacrificing area and crosstalk for the 0.18 $\mu m$ and 0.25 $\mu m$ process technologies, respectively. Further, we develop an effective incremental update technique that can substantially speed up the runtime. Empirically, this technique can reduce runtime by 10 times.

## 1 Introduction

As devices and interconnect are packed in ever-closer proximity in the deep sub-micron technologies, the crosstalk among adjacent wires is of comparable importance to area and performance in the high performance circuit design [1]. Crosstalk is a type of noises which is introduced by the coupling of wires. For example, two adjacent wires form a coupling capacitor and a mutual inductor that may affect the signal integrity and the delay of a net.

In this paper, we focus on the capacitive effects of crosstalk. We refer to the crosstalk as the coupling capacitance that is directly proportional to the coupling length between two adjacent wires and inversely proportional to the distance between them. Many heuristics and techniques try to reduce the crosstalk by minimizing the coupling length (e.g., track permutation [7, 8]) or maximizing the distance between two coupled wires (e.g., spacing/perturbation [2, 14, 16]).

Many techniques such as wire sizing have been proposed to optimize timing [3, 4, 11, 12, 16]. Some recent works focus on minimizing interconnect delay with the consideration of coupling capacitance [2, 3, 16]; however, these works only apply wire sizing at fixed positions [3] or spacing with fixed wire width [2, 16]. Thus, these works have less flexibility in optimizing timing and crosstalk simultaneously.

We propose a unified wire sizing and perturbation algorithm for crosstalk-constrained performance optimization. Our algorithm is based on a two-stage iterative technique: we first place all wires at their best positions with the minimum delay, then we adjust the sizes of the wires to further optimize delay under crosstalk constraints. The two stages are performed iteratively until no improvement is found. Unlike the algorithm presented in [14] that can perturb only horizontal segments, our algorithm can handle *both* vertical and horizontal segments by using a unified technique. The unified wire sizing and perturbation technique has the property of unimodality, implying that there is a unique best position resulting in the optimal delay and crosstalk. Applying these properties can dramatically reduce the search space and thus leads to a very efficient method to determine the best wire position and the optimal wire size. Experimental results show that our algorithm can achieve average improvements of 44.5% and 40.2% in delay without sacrificing area and crosstalk for the 0.18 $\mu m$ and 0.25 $\mu m$ process technologies, respectively. Further, we can incrementally update the delay and crosstalk of a net by considering only the perturbed or resized segments, which greatly improves the runtime of our algorithm. Experimental results show an average speedup of 10 times by applying the incremental update technique.

The remainder of this paper is organized as follows. Section 2 gives the crosstalk and delay models, notations, and the problem formulation. Section 3 and 4 present the effects of wire sizing and perturbation on delay and crosstalk, respectively. Section 5 presents a unified wire sizing and perturbation algorithm. Section 6 shows the experimental results, and finally concluding remarks are given in Section 7.

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## 2 Preliminaries

In this section, we introduce notations, the delay and crosstalk models, and formulate the crosstalk-constrained performance optimization problem.

### 2.1 Notations

We introduce some notations.

- $\hat{r}$: The resistance of unit size.
- $r_{i,j}$: The resistance of the $j$th segment of net $i$.
- $\hat{c}$: The capacitance of unit size.
- $c_{i,j}$: The capacitance of the $j$th segment of net $i$.
- $C_{i,j}$: The downstream capacitance of the $j$th segment of net $i$.
- $w_{i,j}$: The width of the $j$th segment of net $i$.
- $l_{i,j}$: The length of the $j$th segment of net $i$.
- $s_{i,j}$: The $j$th segment of net $i$.
- $S_{i,j}$: The set of downstream segments of $s_{i,j}$.
- $\hat{f}^k_{i,j}$: The unit coupling capacitance between segment $s_{i,j}$ and its neighbor $s_k$.
- $l^k_{i,j}$: The coupling length between wire $s_{i,j}$ and its neighbor $s_k$.
- $d^k_{i,j}$: The distance between wire $s_{i,j}$ and its neighbor $s_k$.
- $B^X_i$: The crosstalk bound of net $i$.
- $B^D_i$: The delay bound of net $i$.
- $\mu^k_{i,j}$: The crosstalk between wire $s_{i,j}$ and its neighbor $s_k$.
- $\mu_i$: The crosstalk in net $i$.
- $\alpha_i$: The crosstalk slack of net $i$.
- $\delta_{i,j}$: The delay of wire $s_{i,j}$.
- $\beta_i$: The delay slack of net $i$.
- $N(s_{i,j})$: The set of $s_{i,j}$'s visible neighbors. As shown in Figure 2(a), $N(s_{1,5}) = \{s_{2,1}, s_{3,1}, s_{4,1}\}$.
- $p_i$: The critical path of net $i$.

### 2.2 Delay Model

In this paper, we apply the $\pi$ model [13] to approximate wire behavior. Figure 1 illustrates the wire model. For a segment $s_{i,j}$ with size $w_{i,j}$ and length $l_{i,j}$, its respective resistance $r_{i,j}$ and capacitance $c_{i,j}$ are given by $\hat{r}l_{i,j}/w_{i,j}$ and $\hat{c}l_{i,j}w_{i,j} + \mu_{i,j}$, where $\mu_{i,j}$ is the sum of the coupling capacitance of $s_{i,j}$ due to its neighbors (the detail of coupling capacitance will be shown in Section 2.3). With the wire model, a net in a channel can be transformed to a tree with resistors and capacitors. Figure 2 illustrates the transformation of net $N_1$.

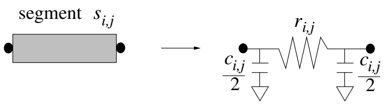


Figure 1: Wire Delay Model

In the transformed tree for net $i$, $S_{i,j}$ denotes the $s_{i,j}$'s downstream segments. For the example in Figure 2, $S_{1,1} = \{s_{1,2}, s_{1,3}, s_{1,4}, s_{1,5}, s_{1,6}, s_{1,7}\}$. We adopt the Elmore delay model [6] to calculate the delay of a net. The delay of segment $s_{i,j}$ equals $r_{i,j}(\frac{c_{i,j}}{2} + C_{i,j})$, where $C_{i,j}$ is the downstream capacitance of segment $s_{i,j}$. As shown in Figure 2(b), the delay of segment $s_{1,3}$ can be computed by $r_{1,3}(\frac{c_{1,3}}{2} + C_{1,3}) = r_{1,3}(\frac{c_{1,3}}{2} + c_{1,4} + c_{1,5} + c_{1,6} + c_{1,7})$.

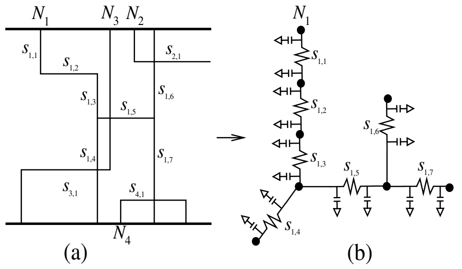

Figure 2: Net Delay Model

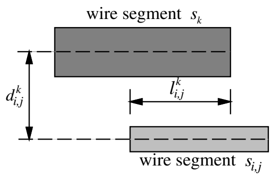


Figure 3: The coupling capacitance between segments $s_{i,j}$ and $s_k$.

## 2.3 Crosstalk Model

According to Figure 3, the coupling capacitance $\mu_{i,j}^k$ between segment $s_{i,j}$ and its neighbor $s_k$ is given as follows:

$$\mu_{i,j}^k = \frac{\hat{f}_{i,j}^k l_{i,j}^k}{d_{i,j}^k - \frac{w_{i,j}+w_k}{2}}. \quad (1)$$

Then, the crosstalk in each wire segment $s_{i,j}$ is expressed as the sum of the coupling capacitance due to its neighbors $s_k$. The total crosstalk $\mu_i$ in net $i$ is the sum of the crosstalk in its wire segments $s_{i,j}$.

Instead of minimizing the maximum crosstalk for each net in a circuit, we maximize the minimum *crosstalk slack*. The crosstalk slack is the difference between the maximum allowable crosstalk and the actual crosstalk of a net. We *perturb* the segments of various nets to increase the distance $d_{i,j}^k$ between segment $s_{i,j}$ and its neighbor $s_k$, and thus maximize the minimum crosstalk slack. The perturbation range for segment $s_{i,j}$ is bounded by the closest segments above or below it. This range can be divided into several sub-intervals. The end-points of each sub-interval are the end-points of segments which lie within the perturbation range. And these segments are visible from either of two perpendicular segments placed at the two ends of segment $s_{i,j}$. As shown in Figure 4, the perturbation range of segment $s_{1,2}$ is bounded by segments $s_{5,2}$ and $s_{4,1}$. The range of $s_{1,2}$ can be divided into three sub-intervals by segments $s_{6,1}$ and $s_{3,1}$. As presented in [14], the variation of crosstalk slack in any sub-interval is *unimodal* which means there exists a unique optimal solution for wire position over this sub-interval.

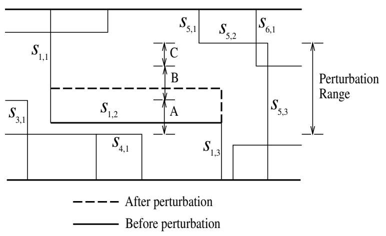


Figure 4: The perturbation range of segment $s_{1,2}$ can be divided into three sub-intervals.

## 2.4 Problem Formulation

Given a crosstalk bound $B_i^X$ for each net $i$ in a circuit, we shall optimize the critical path delay in the circuit by wire sizing and perturbation so that the crosstalk in each net $i$ does not exceed the crosstalk bound. The crosstalk-constrained performance optimization problem is formulated as follows:

- **Input:** A detailed routing instance, crosstalk bound $B_i^X$ for each net $i$, and the lower and upper bounds for wire sizes.
- **Objective:** Determine the optimal wire size and position for each segment in a net, so that the critical path delay is minimized and the crosstalk bound for each net is satisfied.

Note that the overall area remains the same after post-processing a detailed routing instance.

# 3 Effects of Wire Sizing and Perturbation on Delay Slack

We consider in this section optimizing the delay slack by wire sizing and perturbation. For easier presentation, we omit the terms for the effects of coupling capacitance on delay. However, the properties discussed in this section remains unchanged with or without the consideration of coupling capacitance.

## 3.1 Wire Sizing

Widening a wire makes the resistance decrease and the capacitance increase, since the resistance (capacitance) of the wire is inversely (directly) proportional to the size of the wire. The delay slack $\beta_i$ of net $i$ after sizing wire $s_{i,j}$ by $\Delta w_{i,j}$ in the critical path is given by

$$\begin{aligned}\beta_i &= B_i^D - \frac{\hat{r} l_{i,j}}{w_{i,j}+\Delta w_{i,j}}\left(\frac{\hat{c}(w_{i,j}+\Delta w_{i,j})l_{i,j}}{2} + C_{i,j}\right) \\ &- \sum_{s_{i,k}\in p_i\setminus\{s_{i,j}\}} r_{i,k}\left(\frac{c_{i,k}}{2} + C_{i,k} + \hat{c}\Delta w_{i,j} l_{i,j}|_{s_{i,j}\in S_{i,k}}\right) \quad (2)\end{aligned}$$

Here $f(x)|_y$ denotes that $f(x)$ is evaluated only under the condition $y$, and $f(x) = 0$ otherwise. Observe that Equation (2) has a pole (i.e., goes to $\pm\infty$) at $\Delta w_{i,j} = -w_{i,j}$, and is continuous elsewhere. However, $w_{i,j} + \Delta w_{i,j}$ must be larger than the minimum wire size. Thus, none of the poles lie within the sizing range. Differentiating Equation (2) twice, we have

$$\frac{d^2\beta_i}{d^2\Delta w_{i,j}} = \frac{-2\hat{r} l_{i,j} C_{i,j}}{(w_{i,j}+\Delta w_{i,j})^3}. \quad (3)$$

Because Equation (3) is always negative and finite, we can conclude that the variation of delay slack within the sizing range has the property of unimodality. For $a$ discrete points on the plane, it takes only $O(\lg a)$ time to find the optimal wire size for a wire by a binary search.

To compute the new delay slack of $i$ after sizing segment $s_{i,j}$, we only need to recompute the delay of segment $s_{i,j}$ and that of $s_{i,j}$'s upstream segments. Thus, we can significantly speed up our algorithm by incremental update.

## 3.2 Wire Perturbation

When we perturb a segment of net $i$ upwards or downwards, the total wire length of the net may not be changed; however, for each segment $s_{i,j}$ of the net, the downstream capacitance $C_{i,j}$ may be changed. As an example

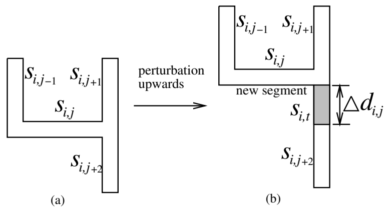


Figure 5: (a) The given net (b) perturbing wire $s_{i,j}$ upwards by $\Delta d_{i,j}$

shown in Figure 5(a)–(b), assume that the current flows from segment $s_{i,j-1}$ to segment $s_{i,j+2}$. After we perturb the segment $s_{i,j}$ upwards by $\Delta d_{i,j}$ (Figure 5(b)), a new segment $s_{i,t}$ is created, and the delay slack of net $i$ is given by

$$\begin{aligned}\beta_i &= B_i^D - \frac{\hat{r}\hat{c}(l_{i,j-1}-\Delta d_{i,j})^2}{2} - \frac{\hat{r}(l_{i,j-1}-\Delta d_{i,j})C_{i,j-1}}{w_{i,j-1}} \\ &- \frac{\hat{r}\hat{c}\Delta d_{i,j}(l_{i,j-1}-\Delta d_{i,j})(w_{i,t}-w_{i,j+1})}{w_{i,j-1}} \\ &- r_{i,j}\hat{c}\Delta d_{i,j}(w_{i,t}-w_{i,j+1}) - \frac{\hat{r}\Delta d_{i,j}}{w_{i,t}}\left(\frac{\hat{c}\Delta d_{i,j} w_{i,t}}{2} + C_{i,t}\right) \\ &- \sum_{s_k\in p_i\setminus\{s_{i,j-1}\}} r_{i,k}\left(\frac{c_{i,k}}{2} + C_{i,k} + \Delta C_{i,k},\right). \quad (4)\end{aligned}$$

where

$$\begin{aligned}\Delta C_{i,k} &= \hat{c}\Delta d_{i,j} w_{i,t}|_{s_{i,t}\in S_{i,k}} \\ &- \hat{c}\Delta d_{i,j}(w_{i,j-1}|_{s_{i,j-1}\in S_{i,k}} + w_{i,j+1}|_{s_{i,j+1}\in S_{i,k}}).\end{aligned}$$

$\Delta d_{i,j}$ must lie within the perturbation range $[d_{\min D} - \lambda,\ d_{\min U} - \lambda]$, where $d_{\min D}$ and $d_{\min U}$ denote the respective distance between segment

$s_{i,j}$ and its closest lower and upper neighbors, and $\lambda$ is the wire pitch. Thus, Equation (4) is continuous over the perturbation range. Differentiating Equation (4) twice, we have

$$\frac{d^2\beta_i}{d^2\Delta d_{i,j}} = -2\hat{r}\hat{c}\left(\frac{w_{i,j-1}+w_{i,j+1}-w_{i,t}}{w_{i,j-1}}\right). \quad (5)$$

For practical applications, the sizes of $s_{i,j}$'s upstream segments shall be larger than or equal to those of $s_{i,j}$'s downstream segments, i.e., $w_{i,t} \leq w_{i,j-1}$. Thus, Equation (5) is always negative and finite, and the variation of delay slack under wire perturbation has the property of unimodality when we perturb a segment upwards. Similarly, the property of unimodality still holds if we perturb a segment downwards. Thus, the variation of delay slack under wire perturbation has the property of unimodality in this case. For $a$ discrete points on the plane, it takes only $O(\lg a)$ time to find the optimal wire position for a segment by a binary search.

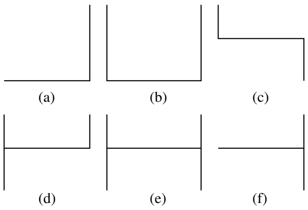


Figure 6: Six cases (a) Type-1 pattern (b) Type-2 pattern (c) Type-3 pattern (d) Type-4 pattern (e) Type-5 pattern (f) Type-6 pattern

As shown in Figure 6, we identify six primitive wiring patterns, and the property of unimodality holds in these six cases when we perturb the horizontal segments. It can be shown that every wiring pattern is formed by the six primitive wiring patterns.

**Lemma 1** *Every wiring pattern is induced by the six primitive wiring patterns.*

It suffices to consider the perturbation of horizontal segments. The reasons as given as follows. Any two wiring patterns are equivalent if they have the same pattern after a series of vertical and/or horizontal flips. For example, ⊓ and ⊔ are *equivalent*, since we can vertically flip ⊓ to get ⊔. Similarly, the example in Figure 5(a) and the case in Figure 6(d) are equivalent (by horizontal flip).

We classify a segment $s_{i,j}$ into these six cases according to $s_{i,j}$ and the set of segments perpendicular and adjacent to $s_{i,j}$, $S$, since perturbing a horizontal segment $s_{i,j}$ only makes the lengths of segments in $S$ change and does not affect other horizontal segments. As shown in Figure 2(a), perturbing segment $s_{1,2}$ only affects the segments $s_{1,1}$ and $s_{1,3}$ (and possible $s_{1,4}$ also), and the length of segment $s_{1,5}$ remains the same. Thus, we can classify the set of segments $s_{1,1}$, $s_{1,2}$, $s_{1,3}$ and $s_{1,4}$ as Type-3 pattern (see Figure 6(c)). Note that including or excluding $s_{1,4}$ does not affect the classification of the group or the property (unimodality) of the induced pattern. To perturb a vertical segment, the aforementioned technique still applies, and the property of unimodality still holds. For example, if we want to perturb the vertical segment in ⊐, we can rotate it by 90 degree, resulting in a Type-2 pattern.

After perturbing segment $s_{i,j}$, we only need to recompute the delays of $s_{i,j}$ and $s_{i,j}$'s upstream segments. Thus, we can incrementally update the net delay without recomputing the delays of all wire segments for all cases, which can significantly speed up the search of the optimal solution.

### 3.3 Unified Wire Sizing and Perturbation

Combining the discussions in Section 3.1 and 3.2, we have the following theorem:

**Theorem 1** *When a segment $s_{i,j}$ of net $i$ is perturbed and sized, the variation of the delay slack $\beta_i$ within the perturbation and the sizing ranges is continuous and unimodal.*

By the property of unimodality, for $a \times b$ discrete points on the plane, it takes only $O(\lg a \lg b)$ time to find the optimal wire position and size for a wire by a binary search. In Figure 7, the variation of delay slack $\beta_i$ of the example in Figure 5 is plotted as a function of the wire perturbation range $\Delta d_{i,j}$ and the sizing range $\Delta w_{i,j}$ based on the 0.18 $\mu m$ parameters described in Section 6.

## 4 Effects of Wire Sizing and Perturbation on Crosstalk Slack

As shown in Figure 8, when we enlarge the size of segment $s_{i,j}$, the distance between $s_{i,j}$ and its neighbor $s_k$ is reduced from $d$ to $d'$, and thus the crosstalk between the two segments is increased after wire sizing. The

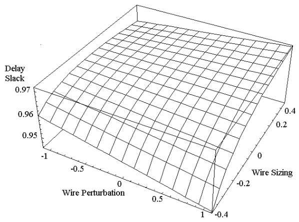


Figure 7: The effects of wire sizing and perturbation on delay slack.

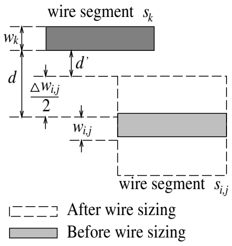


Figure 8: The influence of wire sizing on crosstalk.

crosstalk $\mu_{i,j}^k$ (from Equation (1)) is updated as follows:

$$\mu_{i,j}^k = \frac{\hat{f}_{i,j}^k l_{i,j}^k}{d_{i,j}^k - \frac{w_{i,j}+w_k+\Delta w_{i,j}}{2}}. \quad (6)$$

Let the number of segments of net $N_i$ be $m$. The crosstalk slack $\alpha_i$ can be computed by

$$\alpha_i = B_i^X - \sum_{s_k \in N(s_{i,j})} \mu_{(i,j)}^k - \sum_{n=1}^{j-1} \sum_{s_k \in N(s_{i,n})} \frac{\hat{f}_{i,n}^k l_{i,n}^k}{d_{i,j}^k - \frac{w_{i,n}+w_k}{2}} - \sum_{n=j+1}^{m} \sum_{s_k \in N(s_{i,n})} \frac{\hat{f}_{i,n}^k l_{i,n}^k}{d_{i,j}^k - \frac{w_{i,n}+w_k}{2}}. \quad (7)$$

Differentiating Equation (7) twice, we obtain

$$\frac{d^2\alpha_i}{d^2\Delta w_{i,j}} = -\sum_{j=1}^{m} \sum_{s_k \in N(s_{i,j})} \frac{2\hat{f}_{i,j}^k l_{i,j}^k}{\left(d_{i,j}^k - \frac{w_{i,j}+w_k+\Delta w_{i,j}}{2}\right)^3}. \quad (8)$$

Because Equation (8) is always negative and finite, the variation of crosstalk slack $\alpha_i$ has the property of unimodality.

After sizing, in particular, only the crosstalk of the segments in $N(s_{i,j})$ is changed. Therefore, we need to update only the crosstalk of the segments without recomputing the crosstalk for all wires. Thus, we can significantly speed up our algorithm by incremental update.

Combining the above discussion and the result presented in [14], we have the following theorem:

**Theorem 2** *The variation of crosstalk slack $\alpha_i$ within the perturbation and sizing ranges is continues and unimodal when one segment $s_{i,j}$ of net $i$ is perturbed or sized.*

By the unimodality property, for $a \times b$ discrete points on the plane, it takes only $O(\lg a \lg b)$ time to find the optimal position and size for a segment by a binary search. In Figure 9, the variation of crosstalk slack $\alpha_i$ is plotted as a function of the wire perturbation range $\Delta d_{i,j}$ and the wire sizing range $\Delta w_{i,j}$ based on the 0.18 $\mu m$ parameters described in Section 6.

## 5 A Unified Wire Sizing and Perturbation Algorithm

In practice, designers desire to determine the optimal size and the best position of a wire not to violate the crosstalk bound of the wire. Combining the discussions in Sections 3 and 4, we have the following theorem:

**Theorem 3** *The variation of delay slack $\beta_i$ subject to crosstalk constraint within the perturbation and the sizing ranges is unimodal.*

Thus, we can efficiently determine the optimal size and the best location of each wire by a binary search and the crosstalk constraint is satisfied.

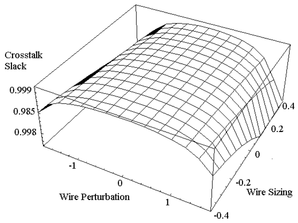


Figure 9: The effects of wire sizing and perturbation on crosstalk slack.

```
1 Initialize wire size for each net i.
2 repeat
3    Stage 1:
4       for each net i taken in order of decreasing β_i.
5          Path ← Find_Critical_Path(i).
6          s_{i,j} ← Find_Sink_Segment(Path).
7          repeat
8             perturb s_{i,j} to maximize β_i under the crosstalk constraint.
9             s_{i,j} ← Find_Predecessor(s_{i,j})
10         until all segments in Path are processed
11         for each segment s_{i,j} of net i, s_{i,j} ∉ Path
12            perturb s_{i,j} to maximize β_i under the crosstalk constraint.
13   Stage 2:
14      for each net i taken in order of decreasing β_i.
15         Path ← Find_Critical_Path(i).
16         s_{i,j} ← Find_Sink_Segment(Path).
17         repeat
18            size s_{i,j} to maximize β_i under the crosstalk constraint.
19            s_{i,j} ← Find_Predecessor(s_{i,j})
20         until all segments in Path are processed
21         for each segment s_{i,j} of net i, s_{i,j} ∉ Path
22            size s_{i,j} to maximize β_i under the crosstalk constraint.
23 until no improvement
```

Figure 10: The unified wire sizing and perturbation algorithm.

| Ckt name | Delay (fs) Int. | Fin. | Impr(%) | Time (min) $T_o$ | $T_u$ | Speedup |
|---|---|---|---|---|---|---|
| yk3a | 189.5 | 105.33 | 44.42 | 1 | 12 | 12 |
| yk3b | 238.38 | 158.25 | 33.61 | 2 | 10 | 5 |
| yk3c | 430.4 | 249.28 | 42.08 | 2 | 20 | 10 |
| yk5 | 317.44 | 183.69 | 42.13 | 4 | 48 | 12 |
| deutsch_1 | 1680.49 | 813.28 | 51.6 | 50 | 691 | 13.8 |
| deutsch_2 | 1306.99 | 659.80 | 49.52 | 32 | 430 | 13.4 |
| deutsch_3 | 1413.46 | 734.31 | 48.05 | 35 | 365 | 10.4 |
| average | | | 44.49 | | | 11 |

Table 1: Experimental results with .18 micron technology; $T_o$: incrementally compute only perturbed or sized segments; $T_u$: compute delay and crosstalk from the scratch.

In this section, we propose a unified algorithm to optimize delay subject to crosstalk constraint by wire sizing and perturbation. Whenever we perturb or size a wire of net $i$, if the crosstalk of net $i$ after wire perturbation or sizing is larger than the predefined crosstalk bound $B_i^X$, then the perturbation or sizing of the wire is not allowed. Thus, we can optimize delay under the crosstalk constraint. The unified wire sizing and perturbation algorithm is summarized in Figure 10.

Our algorithm can be divided into two stages. In the first stage, we perturb segments to maximize delay under the crosstalk constraint (Lines 8 and 12). In the second stage, we resize all segments to further optimize delay (Lines 18 and 22). Before we perturb or size the segments of a net, we first determine the critical path of the net, and find the sink segment of the path. Whenever we size or perturb segments of a net, we trace the critical path of a net from the sink to the source of the net, and size or perturb the unprocessed segments. Next, we size or perturb the unvisited segments. We repeat the whole process until no improvement is found. Note that we process nets in the decreasing order of delay slack. Sizing and perturbing a wire does not worsen the crosstalk and delay slacks in any other more critical nets (i.e., nets with slack less than that of the current net). This guarantees that no wire sizing and perturbation cause the crosstalk and delay of the nets to deteriorate in the more critical nets.

# 6 Experimental Results

We implemented our algorithm in the C language on a Sun SPARC Ultra-I workstation and tested on the detailed channel routes for Deutsch's Difficult Example in [5] and those in [17]. The unit capacitance $\hat{c}$ and unit resistance $\hat{r}$ of a wire were 0.023 $fF/\mu m$ (0.0206 $fF/\mu m$) and 0.09 $\Omega$ (0.053 $\Omega$) for the 0.18 $\mu m$ process (0.25 $\mu m$) technology, respectively. The upper and lower bounds for wire sizes were 1.2 $\mu m$ (1.6 $\mu m$) and 0.25 $\mu m$ (0.3 $\mu m$) for the 0.18 $\mu m$ (0.25 $\mu m$) process technology, respectively. Table 1 (Table 2) shows

| Ckt name | Delay (fs) Int. | Fin. | Impr(%) | Time (min) $T_o$ | $T_u$ | Speedup |
|---|---|---|---|---|---|---|
| yk3a | 25.54 | 18.16 | 28.90 | 1 | 17 | 17 |
| yk3b | 32.13 | 21.54 | 32.96 | 3 | 27 | 9 |
| yk3c | 58.01 | 32.47 | 44.03 | 3 | 22 | 7.3 |
| yk5 | 42.79 | 24.98 | 41.62 | 7 | 68 | 9.7 |
| deutsch_1 | 226.51 | 112.47 | 50.35 | 55 | 713 | 12.9 |
| deutsch_2 | 176.17 | 93.19 | 47.10 | 48 | 682 | 14.2 |
| deutsch_3 | 190.52 | 121.55 | 36.20 | 40 | 342 | 8.6 |
| average | | | 40.17 | | | 11.2 |

Table 2: Experimental results with .25 micron technology; $T_o$: incrementally compute only perturbed or sized segments; $T_u$: compute delay and crosstalk from the scratch.

the experimental results with 0.18 $\mu m$ (0.25 $\mu m$) technology, where "Init" denotes the initial delay before wire sizing and perturbation, "Fin" denotes the final delay after wire sizing and perturbation, "$T_o$" denotes the runtime for one iteration for our algorithm with the incremental updates for crosstalk and delay slacks after sizing and perturbing a segment, and "$T_u$" denotes the runtime for one iteration for computing the crosstalk and delay slacks from the scratch after sizing and perturbing a segment. In the experiments, we first extracted the maximum crosstalk in a net in the original benchmark and assigned the value as the crosstalk upper bound for each net. During the whole process, we tried to optimize the critical path delay without violating the crosstalk bound for *every* net.

The results show that our algorithm, on the average, improves the delays by 44.5% and 40.2% for the 0.18 $\mu m$ and 0.25 $\mu m$ process technologies, respectively. Further, the runtimes show that the incremental update techniques speed up the runtime by 10 times. These results show the effectiveness and efficiency of our algorithm.

# 7 Concluding Remarks

In this paper, we have presented a unified wire sizing and perturbation algorithm for crosstalk-constrained performance optimization. We have shown that the effects of wire sizing and perturbation on crosstalk and delay slacks have the property of unimodality within the perturbation and sizing ranges. Based on these properties, we can dramatically reduce the search space to locate the best position and size for each wire. Further, we can incrementally update the delay and crosstalk slacks of a net by recomputing only the perturbed and resized segments. Experimental results shows that our algorithm can effectively and efficiently improve delay under crosstalk constraints.

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