Optical Proximity Correction (OPC)-Friendly Maze Routing*

Li-Da Huang
Computer Sciences Department
University of Texas at Austin, Texas 78712
lida@mail.utexas.edu

Martin D. F. Wong
ECE Department, University of Illinois at Urbana-Champaign
Urbana, Illinois 61801
mdfwong@uivlsi.csl.uiuc.edu

ABSTRACT

As the technology migrates into the deep submicron manufacturing (DSM) era, the critical dimension of the circuits is getting smaller than the lithographic wavelength. The unavoidable light diffraction phenomena in the sub-wavelength technologies have become one of the major factors in the yield rate. Optical proximity correction (OPC) is one of the methods adopted to compensate for the light diffraction effect as a post layout process. However, the process is time-consuming and the results are still limited by the original layout quality. In this paper, we propose a maze routing method that considers the optical effect in the routing algorithm. By utilizing the symmetrical property of the optical system, the light diffraction is efficiently calculated and stored in tables. The costs that guide the router to minimize the optical interferences are obtained from these look-up tables. The problem is first formulated as a constrained maze routing problem, then it is shown to be a multiple constrained shortest path problem. Based on the Lagrangian relaxation method, an effective algorithm is designed to solve the problem.

Categories and Subject Descriptors: J.6: Computer-Aided Engineering

General Terms: Algorithms.

Keywords: micro-lithography, VLSI, maze routing, optical system, manufacturing, OPC.

1. INTRODUCTION

Microlithography has become one of the key techniques for the deep submicron technology. The improvements of IC device integration and fabrication have been facilitated by improving the stepper technology. Nowadays, integrated circuits (IC) are manufactured with features smaller than the lithographic wavelength [10]. The lithography technology with shorter wavelengths is still too costly and unstable. Any wavelength shorter than 185nm would be absorbed by the oxygen in the atmosphere. Furthermore, the photo resistance and development must react on a certain region of the wavelength. Therefore, the $0.25um$ and $0.18um$ technologies are still adopting the DUV scanner (wavelength=248nm). The $90nm$ process adopts the $193nm$ wavelength optical system, and major IC fabs have announced that the $65nm$ process will adopt the $193nm$ wavelength optical system to leverage the mass capital investment in the $90nm$ node.

The sub-wavelength lithography introduces a huge burden in the manufacturing process because the diffraction of light physically limits the critical dimension (CD), such as the shortest length of the gate channel. The distortions in optical lithography include corner rounding, pulling back at the end of the narrow line, and the wide variation of line width. To compensate for the distortion or cancel out the interference from the neighboring light diffractions, two techniques–Optical Proximity Correction (OPC) [5][6][12] and Phase Shift Masking (PSM) [2][3][9][7] have been demonstrated to show significant improvements in sub-wavelength lithography technology. OPC functions by adding or subtracting some fine features as serifs or line segments; and PSM operates by changing the phase of the transmitted light through certain regions on the mask. However, a rule-based OPC system that decides the added OPC features based on geometrical rules cannot handle rules that are too complicated; a model-based OPC system that requires many iterations of simulations takes a long time to choose the sizes and positions of the added features; and PSM increases the cost of the masks by introducing the phase shift mask.

The major goal of OPC is to keep the geometry printed on the substrate as close to the layout as possible. If the layout contains critical paths or regions, OPC cannot effectively improve the process window. Sometimes the situation becomes worse because the added feature narrows down the space between its neighbors. The original layout actually dominates the process variation allowances such as the exposure latitude (EL) and depth of focus (DOF), despite the fact that the post processes like OPC and PSM help reducing distortion. Generally, the quality of the aerial image determines the process window. If the aerial image has sharp edges on each polygon, then the layout would have a wide process window [8]. Since the design rules are the only guides for routing, and these simple spacing rules cannot reflect the light diffraction, the resulting layout often loses the yield rate or the compactness.

In modern technologies, such as the nodes beyond $130nm$,

*This work was partially supported by the National Science Foundation under grant CCR-0244236 and CCR-0306244. Li-Da Huang currently is working at Texas Insturments.

most of the metal layers need OPC to control the line width and length variations [11]. An OPC-friendly routing maximizes the effects of the corrections and reduces the efforts that these fine features require to be inserted. In this paper, we propose a maze routing algorithm that is aware of the optical effects. Since the maze routing is a sequential routing algorithm, only one signal net is routed at a time. The routed nets introduce some optical effects all over the routing grids on the same layer. In addition, when routing a new net, it also affects the previously routed nets. Based on the Lagrangian relaxation technique, a robust and effective algorithm that is able to be modified to accommodate more complicated models can be derived.

Section II reviews OPC technologies and defines the OPC-friendly routing problem. In section III, the OPC cost function derived from the models of optical systems and the methodology of building the look-up tables are described. In addition, an algorithm based on the Lagrangian relaxation is proposed to solve the problem. Experimental results are presented in section IV, and section V concludes the paper.

2. OPC TECHNOLOGIES AND PROBLEM DEFINITION

There are two major OPC technologies for the subwavelength processes: rule-based and model-based. Rule-based OPC extracts the geometrical measurements from the original layout. According to the pre-built OPC rules, OPC features are inserted to compensate for the distortion from the light diffraction. Model-based OPC simulates the optical system iteratively on many pre-determined points of the original layout. If the light intensity and the constrast at the checking point are below certain requirements, a small OPC feature would be added or subtracted from the original layout. Fig. 1 is an example of OPC.

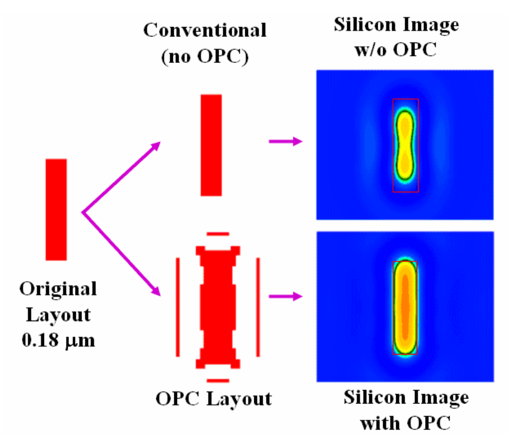

Figure 1: Optical proximity correction.

To simplify the problem description, we use a simple example to illustrate the OPC-friendly routing. Fig. 2 contains three nets on two conductor layers. All three nets are routed with minimum lengths. Since the line width and pitch are beyond the wavelength of the optical system, all of the grids contain the light diffraction from the routed nets. The extra light constructively or destructively affects the routed patterns with each other. These optical proximity effects can be compensated and corrected by adding fine features around the original patterns, as shown in Fig. 3. This technique is called optical proximity correction (OPC). OPC is not effective nor efficient for an OPC-unfriendly routing. Fig. 4 is the routing for the same nets, but it has different paths. Fig. 5 illustrates how the OPC features are added into Fig. 4. Obviously, less amount of OPC iterations are needed in Fig. 5, and the process window is broader for the OPC-friendly routing.

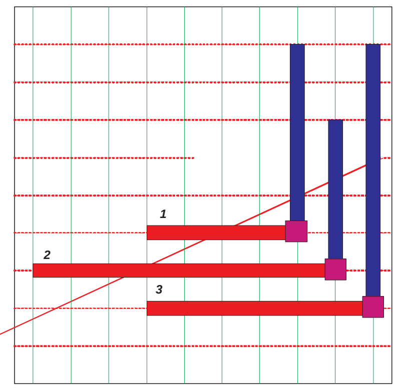

Figure 2: Three nets with shortest lengths on two conductor layers.

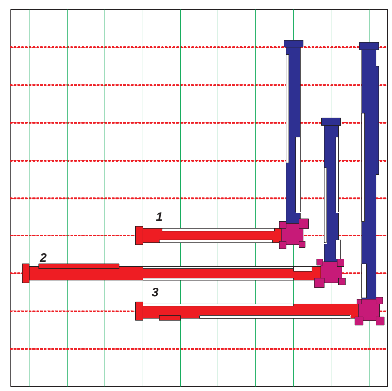

Figure 3: The optical proximity effects are compensated by adding fine features. This technique is called optical proximity correction (OPC). Depending on the patterns and space between them, the features added by OPC can be quite complicated, and they are considerable time-consuming. However, the effect is still limited by the quality of the original layout.

Note that the optical proximity effect would not be shielded by the neighboring routed patterns. However, it decays sharply beyond the distance of several wavelengths. The amount of the interference from other routing patterns is the error that would be corrected by OPC. We define the energy of the interference on a net as the OPC cost, which is the sum of the interference light intensity along the path of the net. If the cost is constrained, the routing result would be friendly for the OPC procedure later. Since the optical interference of the routing patterns only affects others on the same layer, the maze routing that is aware of the optical effects is formulated as the following problem.

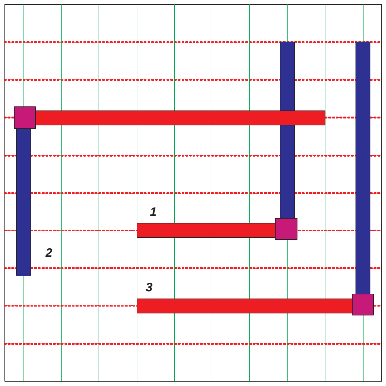

Figure 4: The same three nets with different paths.

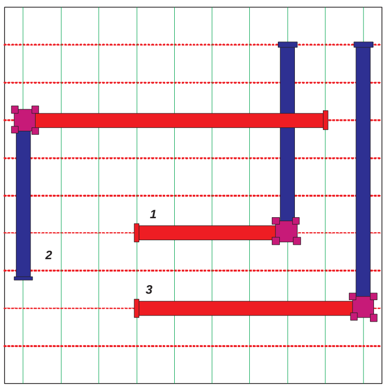

Figure 5: Fewer and less complicated OPC features are needed in the layout. The routing is more friendly to the OPC process, and the process window is wider.

Problem 1. OPC Constrained Maze Routing (OPCCMR)
Given a grid routing graph with $m-1$ nets routed on K conductor layers, find the shortest route for net m, such that $R_i^j \leq C_i^j$ for all $i = 1 \cdots m$, and $j = 1 \cdots K$. R_i^j is the cost of net i on layer j, and C_i^j is the constraint for net i on layer j.

Instead of minimizing the costs of all nets, the cost of each net is constrained and the total cost is balanced among the nets. This approach avoids an OPC critical net that narrows down the process window.

OPCCMR is a multi-constrained shortest path (MCSP) problem. In the next section, we propose an efficient method to calculate the OPC cost. Based on the cost, a vector-weighted graph is constructed, and a robust algorithm is adopted to route the multi-constrained nets on this graph.

3. OPC COST CALCULATION AND OPC-FRIENDLY MAZE ROUTING ALGORITHM

3.1 Optical System Models

Fig. 6 is a simple optical system in the microlithography. The numerical aperture (NA) is defined as $NA = \sin\alpha$. It

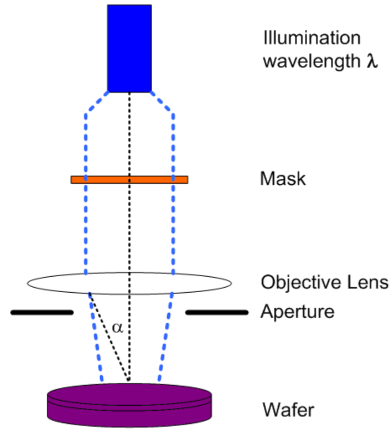

Figure 6: A simple optical system.

represents the quality of the lenses in the optical system. The smallest representable size in the optical system is proportional to $\frac{\lambda}{NA}$.

Let $f(r)$, where r is a two dimensional vector representing any position on a plane, be the mask for a certain layer of a layout. The $f(r)$ has a binary output: zero means the light is blocked, and one allows the light to go through the mask. The intensity of the output image $I(r)$ for an optical system with the amplitude-impulse-response $h(r)$ can be calculated by the following three models:

coherent illumination:

$$I(r) = |f(r) * h(r)|^2 \tag{1}$$

incoherent illumination:

$$I(r) = f(r)^2 * |h(r)|^2 \tag{2}$$

partially illumination:

$$I(r) = \sum_{i=1}^{n} \beta_i \, |f(r) * h_i(r)|^2 \tag{3}$$

where β_i is the scale factor. Partially coherent systems can be approximated as the sum of coherent systems as in Fig. 7.

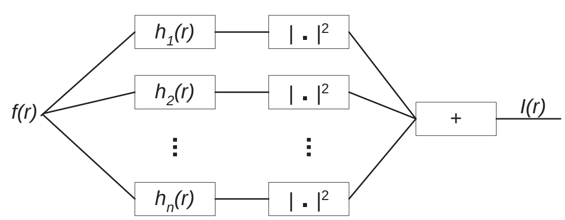

Figure 7: Partially coherent illumination model.

The ideal amplitude-impulse-response function $h(r)$ is a *sinc*-like function, as shown in Fig. 8. If the wavelength of the optical system is λ, with numerical aperture NA, the width W of the main lobes of $h(r)$ would be

$$W = \frac{\lambda}{NA} \tag{4}$$

The width of the side lobe would be $\frac{\lambda}{2 \cdot NA}$. Since the amplitude decays sharply beyond the first side lobe, we can think of the closest edges of the two adjacent patterns as the first order factor in the cost function. The rest of the edges on the patterns are second order, third order, and so on. If the edge falls beyond the first side lobe, its effects would be ignored. The design rules basically capture the first order factor from the geometry. However, since the CD is smaller than the wavelength nowadays, the second order or the third order edge would fall into the effective region and cannot be ignored.

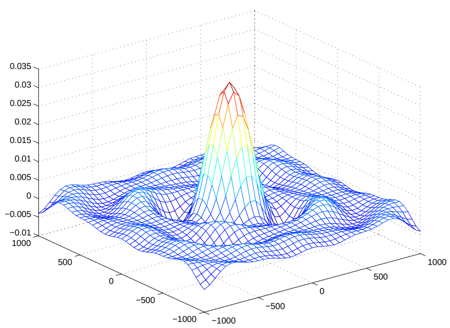

Figure 8: $h(r)$ of the coherent illumination system. $\lambda = 248nm, NA = 0.5$.

3.2 OPC Cost Calculation

The optical interference is limited within a region of several wavelengths. To calculate the interference on a certain edge from other routed patterns on the routing grid graph, only patterns within the effective region centered at the edge are necessary, as shown in Fig. 9. Note that the coordinates represent the center of each routing edge. All patterns within the effective region are marked with coordinates of the left-most edge and the lengths of the patterns. The optical interference on the routing edge is the summation of the interference from all effective patterns. As long as the relative positions stay the same, all of the optical effects would be equivalent. For example, to obtain the interference from pattern b shown in Fig. 9, the pattern would be shifted and mirrored, as shown in Fig. 10, Fig. 11, and Fig. 12. Thus, a look-up table is built as shown in Fig. 13. Let T_j be the table for the length j. T_j contains the results of two-dimensional convolution, $f_j(r) * h(r)$. $f_j(r)$ is the binary mask function for a bar with the length of j routing grids centered at the origin, and $h(r)$ is the amplitude-impulse-response of the optical system. For example, the light diffraction from the pattern b to edge e as shown in Fig. 12 is $T_7(-1, -2)$. Note that if the optical system does not have the symmetric property in certain axis, the mirror operation would not be allowed and the size of the table would be doubled.

The optical interferences from all effective patterns are looked up from the table. The sum of the values represents the total effect of the interferences. The energy of the total effect is the weight of the edge representing the cost from all effective patterns, written as:

$$(\sum w(e, p_i))^2$$

where p_i represents the effective patterns, and $w(e, p_i)$ is the optical interference obtained from the look-up table $T_{length(p_i)}$. For example, $w(e, p_b)$ in Fig. 9 is obtained from $T_7(-1, -2)$ as shown in Fig. 11. The other costs we need to obtain are

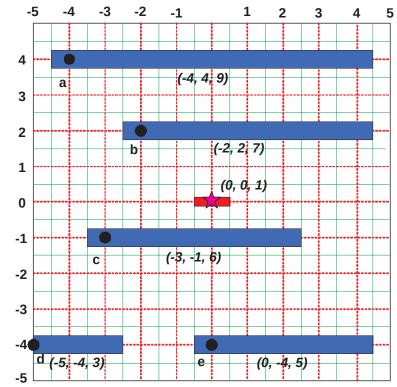

Figure 9: Five patterns are within the effective window of the edge $(0, 0)$. Each effective pattern is denoted by the left most edge coordinate and its length. For example, pattern a starts at $(-4, 4)$ with length 9.

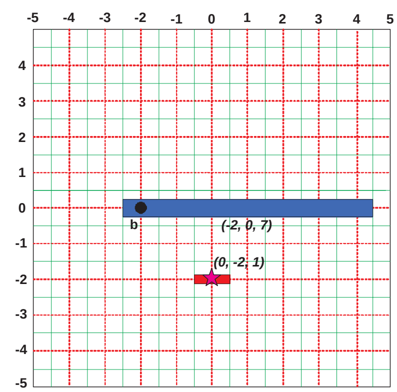

Figure 10: Pattern b is shifted to the horizontal axis.

the interferences from the routing edge to the effective patterns. This scenario is more complicated because the net to be routed does not exist yet. We evaluate the cost of the routing edge to a certain effective pattern as the maximum energy of the interference represented by:

$$\max_{g \in p_i} (w(e, g))^2$$

For example, the cost of the routing edge to b in Fig. 9 is the maximum interference energy on the 7 edges of b from the routing edge centered at the origin (the maximum of $T_1(-2, 2)^2, T_1(-1, 2)^2, \cdots, T_1(4, 2)^2$).

The vector-weighted graph can be constructed as follows: The grid nodes and edges that are occupied by routed nets or obstacles are removed from the grid graph. Assign the weight vector $(v_1^e, v_2^e, \cdots, v_m^e)$ on edge e, where $v_i^e, i = 1 \cdots (m-1)$ are the cost interferences from edge e to net i if net m is routed on edge e, and v_m^e is the sum of the interferences from all other nets on edge e. The entries of the vector are formulated as:

$$v_i^e = \max_{g \in p_i} (w(e, g))^2, \ \ i = 1 \cdots (m-1)$$

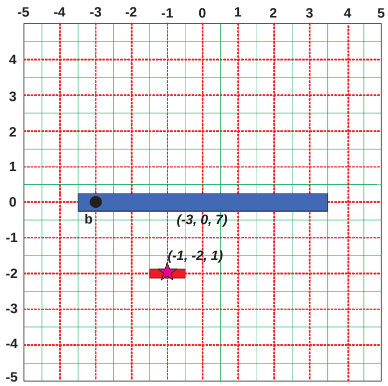

Figure 11: Pattern b is shifted to be centered at the origin.

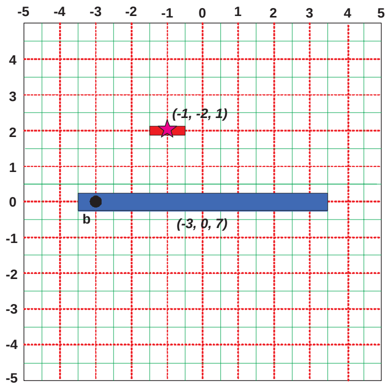

Figure 12: The evaluated edge can be mirrored to the upper part of the effective window if the optical system is symmetric on the horizontal axis.

$$v_m^e = (\sum_{i=1}^{m-1} w(e, p_i))^2$$

3.3 OPC-Friendly Maze Routing Algorithm

Given the vector-weighted graph, the OPCCMR is a MCSP problem on the graph. The Lagrangian relaxation method solves the MCSP by relaxing the constraints into the objective function after giving relative weights on the constraints. The Lagrangian relaxation method is usually presented as two sub-problems: Lagrangian Sub-Problem (LSP) and Lagrangian Multiplier Problem (LMP). The goal of the LSP is to find the shortest path for a given set of Lagrangian multiplier; and the LMP maximizes the lower bound of MCSP by adjusting the Lagrangian multipliers. The LSP of the OPCCMR is defined in the following problem.

Problem 2. The Lagrangian Sub-Problem of OPCCMR

Given the vector-weighted graph of OPCCMR and a set of non-negative constants $u_{i,j}, i = 1 \cdots m, j = 1 \cdots K$, find a path P in the graph such that $\sum_{j=1}^{K}\sum_{e_j \in P}(1+\sum_{i=1}^{m} u_{i,j}v_i^{e_j}) - \sum_{i=1}^{m}\sum_{j=1}^{K} u_{i,j}\, C_{i,j}$ is minimized, where e_j is the edge on layer j and $C_{i,j}$ is the constraint for net i on layer j.

Note that the second term, $\sum_{i=1}^{m}\sum_{j=1}^{K} u_{i,j}\, C_{i,j}$, in the above equation is a constant for fixed the Lagrangian multipliers. By assigning $1 + \sum_{i=1}^{m} u_{i,j}\, v_i^{e_j}$ as the weight on edge e_j, the LSP can be solved by using Dijkstra's shortest path algorithm [4]. Let $L(\mathbf{u})$ be defined as the optimal solution (i.e., the shortest path) to the LSP for a given $u_{i,j}, i = 1 \cdots m, j = 1 \cdots K$. That is:

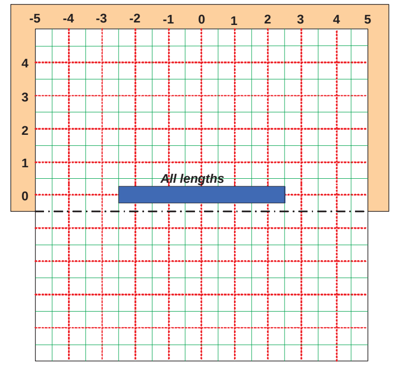

Figure 13: The optical interference is simulated for all lengths of patterns centered at the origin. The result is kept in a look-up table. Note that the routing grid size is different from the optical simulation grid size. The mean value within the grid size is recorded in the table.

$$L(\mathbf{u}) = \min_P\{\sum_{e \in P} 1 + \sum_{i=1}^{m}\sum_{j=1}^{K} u_{i,j}(\sum_{e_j \in P} v_i^{e_j} - C_{i,j})\}$$

The LMP of the OPCCMR is formulated as:

Problem 3. The Lagrangian Multiplier Problem of OPCCMR

$$Maximize\ L(\mathbf{u})$$

$$subject\ to\ \mathbf{u} \geq 0$$

Since $u_{i,j} \geq 0$, it is obvious that the solution to OPCCMR is:

$$\begin{aligned}
&\min_P\{\sum_{e \in P} 1 : \sum_{e_j \in P} v_i^{e_j} \leq C_{i,j}, \forall i,\, j\} \\
\geq\ & \min_P\{\sum_{e \in P} 1 + \sum_{i=1}^{m}\sum_{j=1}^{K} u_{i,j}(\sum_{e_j \in P} v_i^{e_j} - C_{i,j}) : \\
& \sum_{e_j \in P} v_i^{e_j} \leq C_{i,j}, \forall i,\, j\} \\
\geq\ & \min_P\{\sum_{e \in P} 1 + \sum_{i=1}^{m}\sum_{j=1}^{K} u_{i,j}(\sum_{e_j \in P} v_i^{e_j} - C_{i,j})\} \\
=\ & L(\mathbf{u}) \qquad (5)
\end{aligned}$$

Note that the above relationship exists for every $\mathbf{u}$. Therefore, the optimal solution to the LMP is the lower bound of the solution to OPCCMR:

$$\begin{aligned}
&\min_P\{\sum_{e \in P} 1 : \sum_{e_j \in P} v_i^{e_j} \leq C_{i,j}, \forall i,\, j\} \\
\geq\ & \max_{\mathbf{u}} L(\mathbf{u}) \qquad (6)
\end{aligned}$$

Ideally, if a path P meets all of the constraints (i.e., $\sum_{e_j \in P} v_i^{e_j} \leq C_{i,j}, \forall i, j$) and $\sum_{e \in P} 1 = L(\mathbf{u})$, then P would be the optimal solution to OPCCMR and $\mathbf{u}$ would be the optimal solution to the corresponding LMP.

Since the LMP is a convex programming problem, the sub-gradient method is an effective approach to solve this problem. The algorithm is described as:

Algorithm: *Sub-gradient Method for the LMP of OPCCMR Problem*

1. $t = 0; u_{i,j} = 0, i = 1 \cdots m, j = 1 \cdots K$;
2. Solve LSP by Dijkstra's shortest path algorithm;
3. Check constraints; If satisfied, halt;
4. Else $u_{i,j} = \max\{0, \theta_t(\sum_{e_j \in P} v_i^{e_j} - C_{i,j})\}, \ \forall i, j; \ t = t + 1$; goto step 2.

The above algorithm converges to the optimal solution if $\theta_t \rightarrow 0 \ and \ \sum_{i=1}^{t} \theta_t \rightarrow \infty \ as \ t \rightarrow \infty$ [1].

Since the number of iterations to get the optimal solution is undefined, the maximum number of the iterations is set to limit the execution time of each path routing. The feasible solutions are kept during the iterations. If the sub-gradient method did not generate the optimal solution, the shortest path in the feasible solutions would be adopted.

4. EXPERIMENTAL RESULTS

The OPC-friendly maze routing based on the Lagrangian relaxation is implemented in C++ on the Sun Ultra workstation. We perform the experiments on an industrial netlist that contains 350 nets. The parameters for the optical system are: $NA = 0.5$ and $\lambda = 193nm$. We use the simple coherent optical model to simulate the aerial image and build the look-up tables. The size of the optical grids is $14nm$. The aerial images are sampled at the optical grids. Higher precision of the simulation can be obtained by setting finer grids, but the simulation time would be longer. The line width and space are both $140nm$, which are obtained from the routing layers except the highest layer in the industrial $90nm$ process. The highest layer has a much wider space and line width for the global routing and special nets. Both the line width and space are more than one λ. Therefore, OPC is not required for the highest layer. However, OPC is necessary for the rest of the routing layers to compensate for the optical diffractions. The size of the routing grids is set as $140nm$.

We implement the router on two routing layers (i.e., H-V layers). The netlists are first routed to find the minimum lengths and obtain the costs. Afterwards, we set the constraints as 1%, 4%, 8%, 16%, 32%, 64%, and 85% of the maximum cost obtained in the conventional maze routing. The netlist is rerouted to meet the constraints by using the OPC-friendly maze router. The paths that violate the constraints are removed from the netlist. The amount of the routable nets in both routing results are shown in Fig. 14.

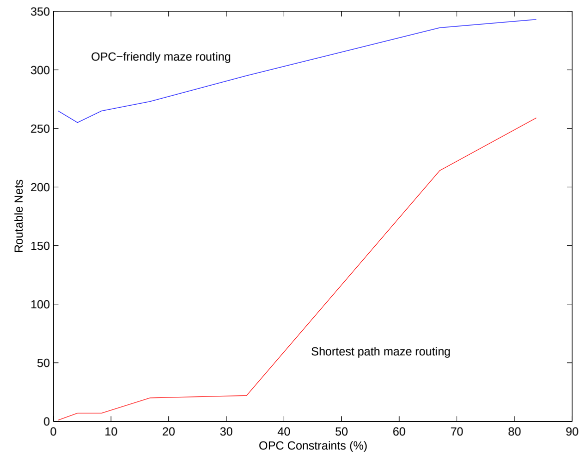

Figure 14: The routing results of the OPC-friendly maze router and the conventional maze router. Routable nets are the nets that meet the constraints.

5. CONCLUSIONS

The optical proximity costs are the energy of the light diffractions from other patterns. The costs of all nets are constrained during the sequential routing. The routing problem is shown to be a multi-constrained shortest path problem, and an effective routing algorithm based on the Lagrangian relaxation is proposed. As far as the authors' knowledge extends, this is the first routing algorithm that is aware of the optical effects of the sub-wavelength technologies. The implementation demonstrates considerable improvement on the routing quality.

5

6. REFERENCES

[1] R. K. Ahuja, T. L. Magnanti, and J. B. Orlin. *"Network Flows: Theory, Algorithms, and Applications"*. Prentice Hall, 1993.

[2] N. Cobb and A. Zakhor. "Large Area Phase-Shift Mask Design". *SPIE*, 2197:348–359, 1994.

[3] N. Cobb, A. Zakhor, and E. Miloslavsky. "Mathematical and CAD Framework for Proximity Correction". *SPIE*, 2726:208–222, 1996.

[4] T. H. Cormen, C. E. Leiserson, R. L. Rivest, and C. Stein. *"Introduction to Algorithms"*. MIT Press, 2001.

[5] C.-C. Fu, T. Yang, and D. R. Stone. "Enhancement of lithography patterns by using serif features". *IEEE Trans. Electron Devices*, 38(12):2599–2603, Dec. 1991.

[6] K. Harazaki, Y. Hasegawa, Y. Shichijo, H. Tabuchi, and K. Fujii. "High Accurate Optical Proximity Correction under the Influences of Lens Aberration in 0.15 um Logic Process ". In *International Microprocesses and Nanotechnology Conference*, pages 14–15, 2000.

[7] M. D. Levenson, N. Viswanathan, and R. A. Simpson. "Improving Resolution in Photolithography with a Phase-Shifting Mask". *IEEE Trans. Electron Devices*, 29(12):1828–1836, Dec. 1982.

[8] C. A. Mack. "Understanding focus effects in submicrometer optical lithography: a review". *Optical Engineering*, 32(10):2350–2362, Oct. 1993.

[9] Y. Pati, Y.-T. Wang, J.-W. Liang, and T. Kailiath. "Phase-Shift Masks: Automated Design and Mask Requirements". *SPIE*, 2197:314–327, 1994.

[10] F. Schellenberg. "Design for manufacturing in the semiconductor industry: the litho/ design workshop". *12th Internatioal Conference on VLSI Design*, pages 111–119, Jan. 1999.

[11] TSMC. In *U.S. Technology Symposium*, 2003.

[12] K. Yamamoto, S. Kobayashi, T. Uno, T. Kotani, S. Tanaka, S. Inoue, S. Watanabe, and H. Higurashi. "Hierarchical optical proximity correction on contact hole layers ". In *International Microprocesses and Nanotechnology Conference*, pages 40–41, 2000.