A Three-Layer Over-the-Cell Multi-Channel Routing Method for a New Cell Model

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Abstract— In this paper, we present a new cell model for over-the-cell routing and a new over-the-cell multi-channel routing method. In the proposed new cell model, terminals can be placed arbitrarily on the second layer of a cell so that each cell doesn't require the extra routing region on the first layer of a cell to align terminals. Unlike conventional cell models, some parts of the second layer are also utilized for the intra-cell routing in order to reduce the chip area. Therefore the size of the proposed cell model can be smaller than that of conventional cell model.

The proposed method consists of three phases. In order to utilize the proposed cell model, in phase 1, we simultaneously handle all channels to determine the most effective routing patterns from the set of possible routing patterns to minimize the chip area. In phase 2, for the effective routing patterns of nets selected in phase 1, over-the-cell routing nets are selected by a new greedy algorithm considering obstacles on over-the-cells. Finally, the conventional channel routing algorithm is applied for nets unrouted on over-the-cell. From the experimental results with MCNC benchmarks, the proposed cell model and algorithm produce smaller height of layouts as compared to those produced by conventional cell models and algorithms, and the effectiveness of the proposed method and cell model was shown.

I Introduction

Over-the-cell channel routing is one of the most effective methods in standard cell layout design to minimize the chip area, and many heuristic algorithms have been developed [8, 10, 11, 12, 14]. The basic idea of over-the-cell (in short, OTC) routing is to use the region over the cells for routing some nets. Since the number of nets to be routed in the channel is reduced by routing some nets over the cells, the number of tracks in the channel is also reduced, resulting the reduction of the chip area.

Efficient utilization of over-the-cell routing regions mainly depends on a routing model [1]. A cell model specifies the locations of terminals and Vdd/Gnd busses, the number of metal layers, and permissibility of vias on OTC regions. Normally, either two metal layers (M1, M2) or three metal layers (M1, M2, M3) are available for routing. Vdd/Gnd busses are located either in M1 or M2, either inside or outside of a cell. Usually, the cell models can be classified by the terminal location. Based on the terminal location five classes of cell models have been proposed and associated OTC routers have been developed [3, 4, 7, 9, 16, 17, 19, 20, 21]. Those five classes of cell models are: the Boundary Terminal Models (BTM) [7, 9], the Center Terminal Models (CTM) [21], the Middle Terminal Models (MTM) [3], the Target Based Cells (TBC) [4], and the cell model that we have proposed in Ref. [16] (we call this model the Column-dependent Capacity Model (CCM)). Table I shows characteristics of cell models and examples of OTC routing of these cell models, respectively.

TABLE I
Characteristics of cell models.

Model	Terminal	Vdd/Gnd	Feedthrough
BTM	boundary(M2)	center(M2)	M1
CTM	center(M2)	boundary(M1)	M2
MTM	middle(M2)	boundary(M1)	M2
TBC	middle(M2)	boundary(M1)	M2
CCM	boundary(M2)	center(M1)	M2

Model	Terminal alignment	Obstacles on cells	Vias on cells	Routing algorithm
BTM	○	×	×	[7, 9]
CTM	○	×	×	[21]
MTM	○	×	×	[3]
TBC	×	○	○	[4]
CCM	○	○	○	[16]

In most cell models except the TBC, terminals on the second layer of a cell row need to be assigned in line either at the boundary or the center of a cell row. Then, an extra routing region on the first layer is generally needed to align terminals. The extra routing region hinders the minimization of the chip area. Cell regions with multi-layers have been available for the OTC routing by the advance of semiconductor technology. It is desirable to increase the number of intra-cell routing layers without extending the cell area. This means that we need to use a part of the second layer as well as on the first layer for intra-cell routing. In the TBC, although terminals are placed on the second layer of a cell row arbitrarily, no part of the second layer is allowed to be used for intra-cell routing.

In this paper, we introduce a new cell model in which terminals are placed on the second layer of a cell row arbitrarily and a part of the second layer of a cell row is also used for the intra-cell routing. Since terminals are placed arbitrarily on the second layer of a cell row, no extra routing region is needed to align terminals on the first layer for the intra-cell routing. Since conventional routing algorithms are developed for the cell models in which terminals are aligned either at the boundary or the center of the second layer, those algorithms can't be applied effectively for a new cell model.

In order to utilize the proposed cell model, we develop a new OTC routing algorithm for the new cell model. The proposed routing algorithm consists of three phases: (1) Multi-Channel Net Assignment, (2) Over-the-Cell Routing Considering Obstacles, and (3) Terminal Reassignment and Channel Routing. In phase 1, we simultaneously handle all channels to determine the most effective routing patterns from the set of possible routing patterns to minimize the chip area. We formulate the problem as the 0-1 integer programming problem and solve it. In phase 2, for the effective routing patterns selected in phase 1, OTC routing nets are greedily selected for each track of OTC. Since the new routing algorithm performs not only routing for an entire net but also routing for a part of a net, the OTC region is utilized effectively. In phase 3, a set of nets that aren't selected for OTC routing nets in phase 2 is routed in a channel by using the conventional channel routing method [5].

The proposed algorithm has been implemented in C language on a SPARC server 1000 (135MIPS), and has been tested with several benchmarks. Experimental results show that the proposed algorithm can achieve results which are in a number of tracks of 55.1% better than an OTC H-V routing method with the BTM, 20.2% better than the conventional routing method in Ref. [21] with the CTM.

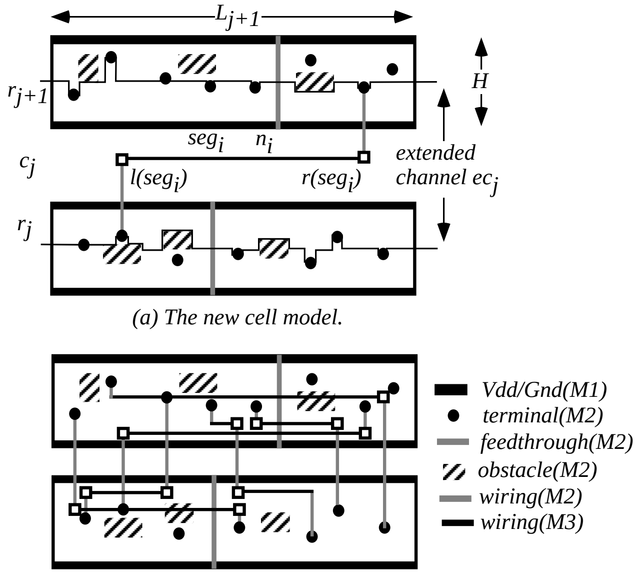
The rest of this paper is organized as follows. In Section II, we introduce a new cell model and formulate the OTC channel routing problem. In the Section III, we present a new OTC algorithm and show experimental results in Section IV. Finally, in Section V, we conclude this paper.

II Over-the-Cell Channel Routing

A. A New Cell Model

In conventional cell models, since terminals are aligned either at the boundary or at the center of the cell row, an intra-cell routing region on M1 layer is needed as the extra routing region to align terminals.

In order to eliminate this extra routing region, we propose a new cell model. Figure 1 shows a new cell model and an associated OTC routing, respectively. In the proposed cell model, it is assumed that three metal layers are available for routing and that there is a grid for each layer. A column and a track represent a vertical and a horizontal lines on a grid, respectively. The routing is performed on a grid. The connection of the same nets between adjacent layers can be realized by using vias that can be inserted at any grid point. As the routing model, we assume H-V-H routing in a channel and V-H routing in an OTC region. In the OTC region, it is assumed that vias are available. Vdd/Gnd busses are placed in the boundary of M1 layer of the OTC region. Feedthroughs are placed in M2 layer of the OTC region. In the conventional cell models, only the M1 layer is used for intra-cell routing. In our model, however, in order to reduce the chip area further, some parts of M2 layer are allowed to be used for intra-cell routing. A routing pattern for intra-cell routing on M2 layer is represented by a rectilinear



(a) The new cell model.

(b) A routing results.

Fig. 1. The new cell model and associated OTC routes.

polygon. Such a rectilinear polygon is regarded as obstacles for the OTC routing.

Terminals can be basically placed arbitrarily on M2 layer of an OTC. We assume that there exists at most one terminal for each column and a terminal can be routed vertically by using the column in which no obstacles exist from the terminal position to at least one side of boundaries of the cell row. Since the proposed cell model doesn't place Vdd/Gnd busses at the middle of the cell row in M2 layer, a net can cross the OTC regions and can be routed adjacent cell rows. Therefore there are much degree of the OTC routability in the proposed cell model than conventional cell models. In other words, since a net has many OTC routing patterns, we can route a net effectively by utilizing OTC of the adjacent cell rows in the new cell model.

B. Problem Formulation

We define some terminologies to explain the proposed algorithm. A set of cells forms a *cell row* in a chip. A set of cell rows, denoted as $R = \{r_1, r_2, \cdots, r_k\}$, is numbered from the bottom to the top cell rows. Similarly, a *channel* is a region between adjacent cell rows, denoted by $C = \{c_0, c_1, \cdots, c_k\}$, which is numbered from bottom to top of a chip. Let the *extended channel* $ec_j \in EC$ be the routing region extended from channel c_j to obstacles and/or terminals on the OTCs of cell rows r_j and r_{j+1}. Tracks on a cell row r_j are numbered from 1 to H according to track by track starting from the bottommost track, and is denoted by $T_j = \{t_1, t_2, \cdots, t_H\}$. Columns on a cell row r_j are numbered from 1 to L_j according to column by column starting from the leftmost column. Then L_{max} is the maximum column number of cell rows, that is, $L_{max} = max_{1 \leq j \leq k} L_j$.

It is assumed that a multi-terminal net is decomposed into a set of two terminal nets during global routing and a net already has the channel number to be routed with a conventional channel routing. The *netlist* is defined as $N = \{n_1, n_2, \cdots, n_{|N|}\}$. A set of nets to be routed in a channel c_j is defined as $N_j = \{n_1, n_2, \cdots, n_{q_j}\}$. The location of a terminal $p_l \in P$ on a cell row r_j is denoted by triple (x_l, t_l, j) where x_l, t_l, and j are the column, the track, and the row numbers, respectively. A net n_i can be denoted by a pair of terminals. The interval between the left and right terminal column positions of each net is defined as the *segment* $seg_i \in Seg$, and the segment list corresponding to the netlist is defined as $Seg = \{seg_1, seg_2, \cdots, seg_{|N|}\}$. The *horizontal length of the segment* seg_i is defined as, $x\_length(seg_i) = r(seg_i) - l(seg_i)$, where $l(seg_i)$ and $r(seg_i)$ are the column numbers of the left and right terminals of a segment seg_i, respectively.

Let the top (resp. bottom) OTC routing capacity at the column x in the cell row r_j, denoted as $cap^t_j(x)$ (resp. $cap^b_j(x)$), be the number of routable tracks between the top channel boundary c_j and a terminal/obstacle that exist at the column x. If no terminals or obstacles exist at the column x in the cell row r_j, $cap^t_j(x)$ and $cap^b_j(x)$ are the half height of the cell, that is, $cap^t_j(x) = \lfloor H/2 \rfloor$, $cap^b_j(x) = \lceil H/2 \rceil$. Let *cross_net(x)* be the number of segments crossing the column x. Then, *the local extended channel density* $d_j(x)$ at the column x of of a local extended channel ec_j is defined as, $d_j(x) = max\{0,\ cross\_net(x) - (cap^t_j(x) + cap^b_{j+1}(x))\}$. The *extended channel density* D_j is defined as, $D_j = \max_{1 \le x \le L} d_j(x)$. The *total extended channel density AD* in a chip is defined as, $AD = \sum_{j=0}^{k} D_j$. Now, we formulate of the OTC multi-channel routing problem as follows.

[The Over-the-Cell Multi-Channel Routing Problem]

Inputs: (1)A netlist N, (2)Obstacles on OTCs, (3)A set of extended channels EC

Outputs: Routing patterns on the channels and the OTCs

Objective: Minimization of the total number of tracks used for channel routing

Constraints: Do not violate the layout constraints □

III An Over-the-Cell Multi-Channel Routing Algorithm

A. *Outline of the Algorithm*

The proposed OTC multi-channel routing algorithm consists of three phases as shown below.

Phase 1: Multi-Channel Net Assignment: Since a terminal can be located arbitrarily on a cell, the OTC routing capacity at each column, which is derived from terminal positions, is not always uniform. In order to utilize all OTC regions of all cell rows effectively, we perform the multi-channel net assignment that selects the most effective routing pattern from possible routing patterns utilizing vacant columns, on which there exist no obstacles/terminals. Since the algorithm takes *not only* one routing patterns obtained from a result of global routing *but also* some routing pattern obtained by utilizing some channels (multi-channel) into consideration, whole OTC of all cell rows can be used effectively. We formulate the problem as the 0-1 integer programming problem and find the most effective routing patterns of nets with the minimum total extended channel density.

Phase 2: Over-the-Cell Routing Considering Obstacles: After phase 1, we obtained a net set N_j to be routed in an extended channel ec_j. The OTC routing algorithm is performed for each set of nets N_j independently. The algorithm constructs horizontal constraint graphs, and then performs selections of OTC routing nets greedily for each track t_k of an extended channel ec_j. Since the objective of OTC routing is the minimization of the extended channel density D_j, it is preferable to select nets as OTC routing nets such that the extended channel density D_j is reduced as much as possible.

Phase 3: Terminal Reassignment and Channel Routing: Phase 3 is performed for nets that have not been routed as OTC routing nets in phase 2. Firstly, terminals of unrouted nets are routed to the boundary of a cell row with vertical segments. Then, since all terminals of unrouted nets are located at the boundary of a cell row, we can assume that this model is like the BTM. Next, we apply the conventional greedy three layer channel routing method[5]. After we have performed the proposed algorithm from phases 1 to 3, OTC channel routing has been finished. In the following subsections, we describe each phase in detail.

B. *Multi-Channel Net Assignment (Phase 1)*

1. *The Multi-Channel Net Assignment Problem*

We proposed a new cell model in the previous section. If either terminals or obstacles don't exist at a column x of a cell row r_j, a net n_i can be routed at the adjacent extended channel ec_j or ec_{j-1} by passing the column x of the cell row r_j. In other word, a net can have another routing patterns in addition to the routing pattern to be routed in ec_j which is determined by global routing. Although a net can be routed several extended channels far from ec_j, it may make the total wire length of the net longer. Therefore, if terminals of a net exist in the adjacent cell rows r_j and r_{j+1}, it is assumed that the three routing patterns (within ec_{j-1}, ec_j, and ec_{j+1}) are available for the net n_i in maximum (Figure 2 (a)). On the other hand, if terminals of a net exist in the same cell row r_j, it is assumed that the net can have the four routing patterns (within ec_{j-2}, ec_{j-1}, ec_j, and ec_{j+1}) in maximum (Figure 2 (b)). We should select the most effective routing pattern to minimize the total extended channel

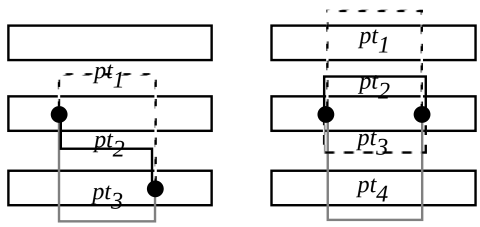


Fig. 2. Restriction of routing patterns.

density $AD = \sum_{j=0}^{k} D_j$. We define the selection of the most effective routing patterns in given possible routing patterns as the *Multi-Channel Net Assignment Problem (MCNAP)*. In phase 1, the routing pattern of a net n_i for the MCNAP is determined so as to minimize the total extended channel density AD.

The MCNAP has been shown NP-hard [9]. Therefore, in the proposed algorithm, the MCNAP is solved by applying the 0-1 integer linear programming(ILP). In order to formulate the MCNAP as the 0-1 ILP problem, we need to generate constraints concerning with an extended channel density D_j for each column x of a cell row r_j. However, in this case, the number of constraints will become large. Therefore, in order to figure out the critical area of an extended channel, we borrow an idea of *the zone representation* [22]. An advantage of the zone representation is that the number of constraints and variables of the 0-1 ILP can be reduced.

2. 0-1 Integer Programming Problem Formulation

In the MCNAP, we generate the following three constraints, (1) *the pattern incompatible constraint*, (2) *the vacant column constraint*, and (3) *the zone density constraint*.

(1) The Pattern Incompatible Constraint: First, we explain the pattern incompatible constraint. Figure 3 (a) shows an example of the pattern incompatible constraint. It is assumed that a net n_i has m_i (in our assumption, $m_i \leq 4$) routing patterns denoted by $PT_i = \{pt_{i1}, pt_{i2}, \cdots, pt_{im_i}\}$. To route a net without having inconsistency, for each net n_i only one routing pattern $pt_{ik} \in PT_i$ should be selected. We call this constraint as *the pattern incompatible constraint*. It is assumed that a routing pattern pt_{ik} of a net n_i corresponds to a variable y_{ik} ($y_{ik} \in \{0, 1\}$). If $y_{ik} = 1$, the net n_i is routed by the routing pattern pt_{ik}. Otherwise, i.e., $y_{ik} = 0$, the net n_i isn't routed by the routing pattern pt_{ik}. Then the pattern incompatible constraint is denoted by,

$$\sum_{k=1}^{m_i} y_{ik} = 1, \quad \forall n_i \in N. \tag{1}$$

(2) The Vacant Column Constraint: Next, we explain the vacant column constraint. We define a column x_l^j of cell row r_j with no obstacles/terminals as *a vacant column* vx_l^j of a cell row r_j. Now, we introduce a constraint for the vacant column vx_l^j. As shown in Figure 3 (b), if more than one routing patterns of nets can be considered at the vacant column vx_l^j, we must select one of these patterns to route without causing a wire-short. We call this constraint *the vacant column constraint* and denoted by,

$$\sum_{n_i \in N} \sum_{pt_{ik} \text{ which passes } vx_l^j} y_{ik} \leq 1, \quad \forall r_j \forall vx_l^j. \tag{2}$$

This constraint allows only one net to pass through a vacant column vx_l^j. Otherwise, more than one net are routed, making a wire-short.

(3) The Zone Density Constraint: Finally, we explain the zone density constraint (Figure 3 (c)). Considering the OTC routing capacities $cap_j^t(x)$ and $cap_j^b(x)$ of a cell row r_j by a terminal at a column x of a cell row r_j, we want to select the most effective OTC routing patterns so as to minimize the the extended channel density D_j. To formulate the degree of the contribution of a routing pattern to minimize the extended channel density D_j, we consider the zone density constraint for each zone $z_l^j \in Z_j$ in each ec_j. Let H be the number of tracks on an OTC region. Let $PT_i(z_l^j) \subset PT_i$ be the set of routing patterns of a net n_i in a zone $z_l^j \in Z_j$ of a ec_j. Let $Cap_t(z_l^j)$ (resp. $Cap_b(z_l^j)$) be the maximum of $cap_j^t(x)$ (resp. $cap_j^b(x)$) in the zone z_l^j of the ec_j. We have already discussed in Section II that the OTC routing capacity at a column x of ec_j is determined from $cap_j^t(x)$ and $cap_j^b(x)$. The OTC routing capacity of the zone z_l^j is determined by $Cap_t(z_l^j)$ and $Cap_b(z_l^j)$. Therefore, the zone density constraint is denoted by,

$$\sum_{n_i \in N} \sum_{pt_{ik} \in PT_i(z_l^j)} y_{ik} + (H - Cap_t(z_l^j)) + (H - Cap_b(z_l^j)) \leq D_j, \quad \forall ec_j \in EC, \forall z_l^j \in Z_j. \tag{3}$$

The reason of subtraction $Cap_t(z_l^j)$ from H is to prevent that the left hand side of the inequality becomes negative. Consequently, the MCNAP is formulated with the 0-1 ILP as shown below.

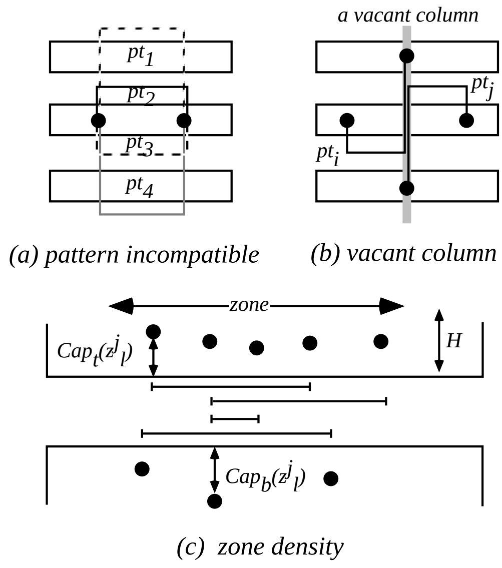


Fig. 3. Constraint of 0-1 ILP.

[The 0-1 ILP Formulation of the MCNAP]

minimize : $AD = \sum_{j=1}^{k} D_j$

subject to : $\sum_{k=1}^{m_i} y_{jik} = 1, \ \forall n_i \in N$

$$\sum_{n_i \in N} \sum_{pt_{ik} \text{ which passes } vx_l^j} y_{ik} \leq 1, \ \forall r_j \forall vx_l^j$$

$$\sum_{n_i \in N} \sum_{pt_{ik} \in PT_i(z_l^j)} y_{ik} + (H - Cap_t(z_l^j)) \\ +(H - Cap_b(z_l^j)) \leq D_j, \\ \forall ec_j \in EC, \forall z_l^j \in Z_j,$$

C. Over-the-Cell Routing Considering Obstacles (Phase 2)

In phase 2, we update a set $N_j = \{n_1, n_2, \cdots, n_{q_j}\}$ of nets for the OTC routing from the net set of the extended channel ec_j. We can solve the OTC routing problem, which generates over-the-cell routing patterns to minimize the extended channel density D_j, by treating independently each extended channel ec_j. Therefore, we only discuss the OTC routing of an extended channel ec_j in the following.

1. The Horizontal Constraint Graphs (HCGs)

Before describing the details of the phase 2, we define the *Horizontal Constraint Graphs* (HCGs) $G_j^s(t_k) = (V_j^s(t_k), E_j^s(t_k))$ $(s = t, b)$ used in the algorithm. Given a net set of a ec_j, $N_j = \{n_1, n_2, \cdots, n_{q_j}\}$, and the corresponding segment set $Seg_j = \{seg_1, seg_2, \cdots, seg_{q_j}\}$, the horizontal constraint graphs are constructed at each track t_k of a top and bottom cell rows in an extended channel ec_j and is defined $G_j^t(t_k)$ and $G_j^b(t_k)$, respectively. The horizontal constraint graphs $G_j^s(t_k)(s = t, b)$ for a track $t_k \in T_j$ on an OTC region are directed weighted graphs. Vertices $v_i \in V_j^t(t_k)$ in $G_j^t(t_k)$ (resp. $v_i \in V_j^b(t_k)$ in $G_j^b(t_k)$) consist of a segment set $Seg_j(t_k) \subset Seg_j$ where a segment in $Seg_j(t_k)$ can be H-V routable at the track t_k on an OTC region of the cell row r_{j+1} (resp. r_j). A directed edge $e_{im} = (v_i, v_m) \in E_j^s(t_k)(s = t, b)$ is inserted from a vertex v_i to a vertex v_m iff the two vertices $v_i, v_m \in V_j^s(t_k)$ corresponding to the segments seg_i, $seg_m \in Seg_j(t_k)$ satisfy the conditions that horizontal segments seg_i and seg_m don't overlap each other and satisfy the condition $r(seg_i) < l(seg_m)$. Figure 4 shows an example of $G_j^t(t_k)$. The horizontal constraint graph $G_j^t(t_k)$ in Figure 4 is constructed for a track t_k on the upper cell row r_{j+1}. Since the set of vertices $Vj^t(t_k)$ in $G_j^t(t_k)$ consists of the nets that can be routed at the track t_k on the OTC region of the cell row r_{j+1}, that is, the segments $seg_1, seg_2, \cdots, seg_6$ are selected in the example. For the directed edge, since the segments seg_1 and seg_2 overlap each other, the directed edge $e_{12} = (v_1, v_2)$ is not inserted between v_1 and v_2. On the other hand, the segments seg_1 and seg_3 do not overlap each other and satisfy $r(seg_1) < l(seg_3)$, then the directed edge $e_{13} = (v_1, v_3)$ is inserted from v_1 to v_3.

Next, we define the weights of the vertex v_i for the horizontal constraint graph $G_j^s(t_k)(s = t, b)$. The phase 2 consists of two stages, and the horizontal constraint graph $G_j^s(t_k)$ is employed for each stage. We define the weight of a vertex v_i in stages 1 and 2 as $w(v_i)$. The weight $w(v_i)$ corresponding to the segment seg_i is defined in the following expression.

$$w(v_i) = \alpha \times \max_{l(seg_i) \leq x \leq r(seg_i)} \frac{d_j(x)}{D_j} \\ +x\_length(seg_i), \quad (4)$$

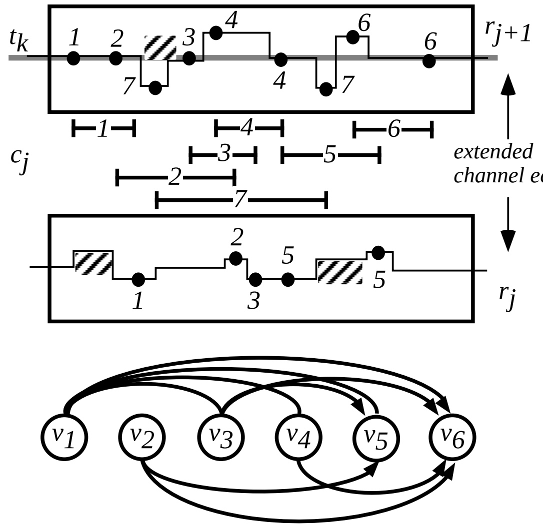


Fig. 4. The horizontal constraint graph $G_j^t(t_k)$.

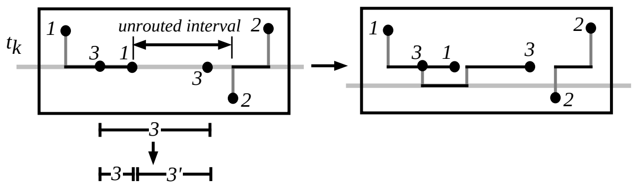


Fig. 5. Definition of an unrouted interval and a subsegment.

where α is a constant. In our experiment, we set α = 30. From the definition of this weight, a segment seg_i with a bigger value $w(v_i)$ is more effective to reduce the extended channel density D_j and easier to be selected as an OTC routing net.

2. An Over-the-Cell Routing Algorithm

The proposed algorithm consists of two stages. In stage 1, a segment seg_i of a net $n_i \in N_j$, which contributes to reduce the extended channel density D_j, is routed on the OTC region. In order to utilize the OTC regions which are not used for routing of stage 1, in stage 2, a segment seg_k of a net $n_k \in N_j$ which could not be routed in stage 1 is divided into subsegments. And then the subsegments are routed in unrouted interval on the OTC region. An unrouted interval is an interval that is not be used for routing at a track t_k on an OTC region (Figure 5). For example in Figure 5, the segment seg_1 and the segment seg_2 are routed at the track t_k, but the center region of the track t_k isn't used for routing. But the segment seg_3 can not be routed in the unrouted interval without dividing it. Dividing the segment seg_3 to two sub-segments, the right subsegment can be routable at the track t_k. This dividing procedure can be applied to the segment satisfying the condition that a subsegment can be routed at the track t_k on the OTC region.

The proposed algorithm selects OTC routing nets from finding the path $path(t_k)$ that has the maximum total weight on $G_j^s(t_k)(s = t, b)$ for stages 1 and 2. The total weight of vertices in a path $path(t_k)$ on $G_j^s(t_k)$ is denoted by,

$$w(path(t_k)) = \sum_{v_i \in path(t_k)} w(v_i). \quad (5)$$

Finding the path $path(t_k)$ with the maximum total weights on $G_j^s(t_k)$ means to find a set of nets that do not overlap each other and that reduce an extended channel density D_j. The detailed description of the proposed algorithm of phase 2 is as follows.

[Phase 2: Over-the-Cell Routing Algorithm]

(Stage 1)

Step1: Set the starting tracks, bt_j and tt_j at cell rows r_j and r_{j+1} to $bt_j = H - \max_{1 \le x_j \le L} cap_j^t(x_j)$, $tt_{j+1} = \max_{1 \le x_{j+1} \le L} cap_{j+1}^b(x_{j+1})$, respectively;

Step2: Calculate the weight $w(v_i)$ of $G_j^t(tt_{j+1})$ and $G_j^b(bt_j)$ for a segment $seg_i \in Seg_j$ of net set N_j, which can be routed at a track bt_j and tt_{j+1} on an OTC region, respectively;

Step3: Construct graphs $G_j^b(bt_j)$ and $G_j^t(tt_{j+1})$, and find the paths $path(bt_j)$ and $path(tt_{j+1})$ that have the maximum total weights, respectively;

Step4: If $w(path(bt_j)) > w(path(tt_{j+1}))$, then assign a set of segments on $path(bt_j)$ at the track bt_j;
Otherwise, assign a set of segments on $path(tt_{j+1})$ at the track tt_{j+1};

(Stage 2)

Step5: Perform the following **Steps5.1 - 5.4** to unrouted intervals at the track $st = \{bt_j \ or \ tt_{j+1}\}$ on the selected cell row from the leftmost positioned unrouted interval to the rightmost positioned unrouted interval;

Step5.1: Divide segments into subsegments to be routed on the current track st of the OTC region and calculate the weight $w(v_i)$ for a subsegment seg_i that can be routed within an unrouted interval;

Step5.2: Construct the graphs $G_j^s(st)(s = t, b)$ and find the path $path(st)$ with the maximum total weight;

Step5.3: Route subsegments of nets in the path $path(st)$ on the OTC region within the unrouted interval;

Step5.4: If this process has been performed for all unrouted intervals at the track st, then go to **Step6**;
Otherwise, go to **Step5.1** to perform the next unrouted intervals;

Step6: If $bt_j = H$, $tt_{j+1} = 0$, then terminate;
Otherwise, if a cell row r_j was selected in **Step4**, then $bt_j \leftarrow bt_j - 1$ and go to **Step2**, else $tt_{j+1} \leftarrow tt_{j+1} - 1$ and go to **Step2**; □

Next, we analyze the time complexity of the OTC routing algorithm described above. Let $|N_j|$ be the number of nets routed within the channel and H be the height of the cell row. In the OTC routing algorithm, the time complexity to construct the HCG and to find a path for each track is $O(|N_j|^2)$. This process is performed for the H tracks of the cell row. Therefore, the time complexity is $O(H \cdot |N_j|^2)$.

Figure 6 shows an example for an execution of the OTC routing algorithm. In this example, the OTC routing pattern of a cell row r_j is considered. Segments under the cell row in Figure 6 show the net set N_j. Figure 6 (a) shows an input of the

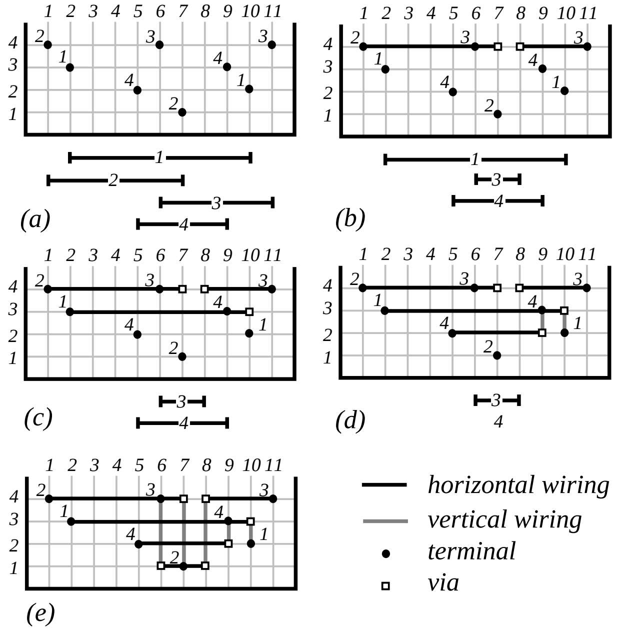


Fig. 6. An example of the OTC routing algorithm.

TABLE II
EXPERIMENTAL DATA.

Data	*#Nets*	*#Columns*	*#Rows*
PRIMARY	1266	477	19
mult16	1920	2086	14
struct	1920	1270	22
primarySC1	1266	646	28

OTC routing. It is assumed that the location with a column x and a track t is denoted by (x, t) and that a horizontal interval between (x, t) and (x', t) is denoted by $[x, x']_t$. The algorithm is performed from the track 4 far from the channel. In Figure 6 (b), the segments seg_2 and seg_3 are selected as the candidates for the OTC routing net. In this example, the segment seg_2 is selected as an OTC routing net and routed by using on M3 layer of the OTC. Furthermore, since the right terminal of the segment seg_3 is within the unrouted interval $[8, 11]_4$. The segment seg_3 is divided into sub-segments seg_3, seg_3' on the track 4. Then the segment seg_3' is routed from the right terminal to the point $(8, 4)$ where the segment seg_3' doesn't intersect the segment seg_2 within the unrouted interval $[8, 11]_4$. The right terminal position of the segment seg_3 is newly defined as $(8, 4)$, which is the location of the column at which no terminal exist. From this operation, the horizontal length of the segment seg_3, $x\_length(seg_3)$ is changed from $x\_length(seg_3) = 5$ into $x\_length(seg_3) = 2$. Similarly, in Figure 6(c), the algorithm is performed for the next track 3. However, in this case, since no net is selected in stage 2, only stage 1 is performed. Note that the candidates to be routed at this track 3 for the OTC routing net are not only the the segments seg_1 and seg_4 but also the segment seg_3. Similarly, the algorithm is performed as shown in Figures 6(d) and (e). When the algorithm has been performed for all tracks on the OTC region, the OTC routing algorithm has been finished.

TABLE III

Experimental results for conventional methods.

Data	*D*	$\sum T_{CR}$	$\sum T_{pro.}$	*#Tracks*					
				$\sum T_{PR}$	$\%R_{T_{PR}}$	$\sum T_{HV}$	$\%R_{T_{HV}}$	$\sum T_{CC}$	$\%R_{T_{CC}}$
mult16	188	99	40	52	23.1	58	31.0	53	24.5
struct	284	153	66	95	30.2	88	25.0	89	25.8
primarySC1	419	221	74	127	41.7	107	15.7	120	38.3

IV Experimental Results

We have implemented the proposed algorithm described in Section III on a SUN SPARCserver 1000 (135MIPS) in C programming language. Table II shows experimental data. We used the PRIMARY benchmark in Ref. [21], and the MCNC benchmarks of mult16, struct, and primarySC1. The placement and the global routing of the MCNC benchmarks were obtained from TimberWolfSC4.2c [18] and GLORIA [15], respectively. In benchmarks shown in Table II, terminals are placed at the boundary of a cell row and equi-potential terminals are on the vertical column, and hence the cell model is different from the proposed cell model. For the proposed algorithm, we transformed these data of the conventional cell model to the proposed cell model by randomly assigning track numbers of terminals and placing obstacles without changing column numbers of terminals(Figure 7). For the benchmark in Ref. [21], track numbers of terminals are randomly generated from the track t_1 to the track t_6 without changing original column number of terminals Capacities on the OTC region set to 6. Obstacles are placed at positions satisfying the condition that terminals can be routed by the routing patterns obtained from the global routing. For these experimental data, we have performed various experiments to make sure of the effectiveness of the proposed cell model and method. For phase 1 of the proposed algorithm, we have used the lp_solve1.5 [2] as the 0-1 ILP package.

In order to show the effectiveness of the proposed cell model, we firstly have compared four conventional methods with the proposed method, in which the multi-channel net assignment of phase 1 *does not* not apply. The four conventional methods are (1) *channel routing method for the BTM (CR)* [5], (2) *planar routing method for the BTM (PR)* [7], (3) *H-V routing method for the BTM (HV)* [19] and (4) *Ref.[16]'s routing method for the CCM (CC)* [16]. Table III shows the comparative results for conventional routing methods. In Table III, *D* denotes the original channel density with two layers. $\sum T_{pro.}$ denotes the total number of tracks in the proposed method. Similarly, $\sum T_{CR}$, $\sum T_{PR}$, $\sum T_{HV}$, and $\sum T_{CC}$ are defined as the total number of tracks for each routing method, respectively. $\%R_{T_{PR}}$, $\%R_{T_{HV}}$, and $\%R_{T_{CC}}$ denote the improvement ratio of the proposed method to each routing method, respectively. From the results of Table III, the proposed method can route nets in a number of tracks of 41.7% in maximum better than the PR for the BTM, and we can show the effectiveness of the proposed cell model and routing method.

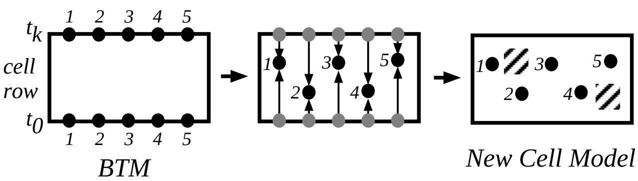


Fig. 7. Transformation of terminal positions.

TABLE IV

Experimental result for primarySC1 with H-V routing method.

channel	*D*	T_{CR}	T_{HV}	$T_{pro.}$	*diff*
1	16	8	5	1	4
2	10	5	2	0	2
3	9	5	3	0	3
4	11	6	3	1	2
5	9	5	2	1	1
6	12	6	3	2	1
7	10	6	2	1	1
8	14	7	3	2	1
9	17	9	6	2	4
10	15	8	3	2	1
11	23	12	8	3	5
12	19	10	5	3	2
13	19	10	5	3	2
14	22	11	5	4	1
15	21	11	6	2	4
16	16	9	5	3	2
17	17	9	5	2	3
18	21	11	7	3	4
19	16	8	4	2	2
20	19	10	5	3	2
21	21	11	5	2	3
22	12	7	3	2	1
23	17	9	4	1	3
24	13	7	3	1	2
25	14	7	2	1	1
26	17	9	3	1	2
27	9	5	0	0	0
Total	419	221	107	48	59

Next, in order to show the effectiveness of the proposed method, we compared the proposed method with the H-V routing method for the BTM. In this case, we apply the multi-channel net assignment of phase 1. Table IV shows the experimental results. In Table IV, *diff* denotes *diff* = $T_{HV} - T_{pro.}$. The conventional routing method in Table IV is to perform H-V routing on the OTC region with allowing vias for the BTM. Then, the OTC routing capacities on M2 and M3 layers are uniform, i.e., 6. From the results of Table IV, the proposed method can route nets in a total number of tracks of 55.1% better than the HV for the BTM.

Finally, we have compared the proposed method with the CTM routing method (CTMR) for the CTM in Ref. [21]. Table V shows the experimental results after the OTC routing. The experimental results of the CTM routing method are referred from Ref. [21]. We also compared with the planar and H-V routings. From the results of Table V, the number of tracks of the proposed method are locally bigger than the number of tracks of the CTM routing method. For example, in the channel

TABLE V
EXPERIMENTAL RESULTS FOR PRIMARY WITH CONVENTIONAL METHODS.

channel	D	T_{CR}	T_{PR}	T_{HV}	T_{CTMR}	$T_{pro.}$
1	11	6	3	0	3	4
2	16	9	6	4	6	4
3	21	11	7	7	8	5
4	24	15	9	9	10	9
5	20	11	9	8	8	6
6	23	12	8	8	10	9
7	22	14	7	6	7	7
8	21	16	8	7	9	7
9	21	13	5	6	7	7
10	14	8	6	6	7	5
11	16	12	4	4	6	4
12	14	8	5	4	5	3
13	13	8	4	4	4	2
14	13	7	4	3	4	3
15	10	6	3	3	3	2
16	11	6	3	2	3	2
17	13	7	4	3	3	3
18	6	3	1	0	1	1
Total	289	172	95	84	104	83

TABLE VI
IMPROVEMENT RATIO OF THE PROPOSED METHOD TO CONVENTIONAL METHODS.

$\%R_{CR}$	$\%R_{T_{PR}}$	$\%R_{T_{HV}}$	$\%R_{T_{CTMR}}$
51.7	12.6	1.2	20.2

number 1, the number of tracks of the proposed method are one more than the number of tracks of the CTM routing method. However, when we consider the total number of tracks in all channels, the total number of tracks of the proposed method are much smaller than the total number of tracks of the CTM routing method. Therefore, the proposed method utilizes OTCs of all cell rows more effectively than the CTM routing method. Table VI shows improvement ratio of the proposed method to the conventional methods. The proposed method can route nets in a number of tracks of 51.7% better than the CR for the BTM, 12.6% better than the PR for the BTM, 1.2% better than the HV for the BTM, and 20.2% better than the CCMR for the CTM, respectively. Therefore, we can conclude that the proposed method is effective in reducing the chip area.

V Conclusions

In this paper, we have introduced a new three-layer standard cell model in which terminals and obstacles are placed arbitrarily on M2 layer, and proposed an associated over-the-cell multi-channel routing algorithm considering terminal positions and vacant columns. In the proposed cell model, since terminals need not to be aligned and obstacles can be placed arbitrarily on M2 layer of a cell row, a routing region on M1 layer for an intra-cell connection is reduced. Therefore, the chip size with the proposed cell model has decreased. The proposed algorithm selects the most effective routing pattern from some routing patterns obtained by utilizing a vacant column of a cell row. Since the routing pattern is routed with not only an entire segment but also a part of a segment, the proposed algorithm can utilize an over-the-cell region effectively. We have performed experiments on benchmarks for this cell model. Experimental results show that the proposed cell model and algorithm are both effective in reducing the chip area.

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References

[1] P. Anne, A. Reddy, A. Panyam and N. A. Sherwani: "Cell width and delay analyses of OTC based standard cell libraries," Technical report, Western Michigan University (1993).

[2] E. Balas and T. Hull: "lp_solve," Technical report, A public domain linear and integer programming program. Available by anonymous ftp from ftp.es.ele.tue.nl in directory pub/lp_solve, file lp_solve1.5.tar.Z (1994).

[3] S. Bhingarde, A. Panyam and N. A. Sherwani: "Efficient OTC routing algorithm for via-less middle terminal models," Proc. of the European Conference on Design Automation, pp. 127–132 (1993).

[4] S. Bhingarde, R. Khawaja, A. Panyam and N. A. Sherwani: "Over-the-cell routing algorithms for industrial cell models," Technical report, Western Michigan University (1993).

[5] P. Bruell and P. Sun: "A greedy three layer channel router," Proc. of International Symp. on Circuits & Syst., pp. 298–300 (1985).

[6] J. S. Cherng, S. J. Chen and C. Changfan: "An efficient over-the-cell channel router," Proc. of the European Conference on Design Automation, pp. 133–137 (1993).

[7] J. Cong, B. Preas and C. L. Liu: "General models and algorithms for over-the-cell routing in standard cell design," Proc. of 27th ACM/IEEE Design Automation Conference, pp. 709–715 (1990).

[8] J. Cong, M. Hossain and N. A. Sherwani: "A provably good multilayer topological planar routing algorithm in IC layout design," IEEE Trans. Comput.-Aided Design of Integrated Circuits & Syst., 12, 1, pp. 70–78 (1993).

[9] J. Cong and C. L. Liu: "Over-the-cell channel routing," IEEE Trans. Comput.-Aided Design of Integrated Circuits & Syst., 9, 4, 4, pp. 408–418 (1990).

[10] S. C. Fang, W. S. Feng and S. L. Lee: "A new efficient approach to multilayer channel routing problem," Proc. of 29th ACM/IEEE Design Automation Conference, pp. 579–584 (1992).

[11] T. T. Ho: "New model for four- and five- channel routing," Proc. of 29th ACM/IEEE Design Automation Conference, pp. 589–593 (1992).

[12] T. T. Ho: "A density-based greedy router," IEEE Trans. Comput.-Aided Design of Integrated Circuits & Syst., 12, 7, 7, pp. 974–981 (1993).

[13] N. D. Holmes and N. A. Sarrafzadeh: "Utilization of vacant terminals for improved over-the-cell channel routing," IEEE Trans. Comput.-Aided Design of Integrated Circuits & Syst., 12, 6, 6, pp. 780–792 (1993).

[14] J. Kim and S. M. Kang: "A new triple-layer OTC channel router," Proc. of Custom Integrated Circuits Conference, pp. 647–650 (1994).

[15] T. Koide, S. Wakabayashi and N. Yoshida: "A new global routing algorithm for over-the-cell routing in standard cell layouts," Proc. of the European Conference on Design Automation with EURO-VHDL'93, pp. 116–121 (1993).

[16] T. Koide, M. Tsuchiya, S. Wakabayashi and N. Yoshida: "Three-layer channel routing for standard cells with column-dependent variable over-the-cell routing capacities," Proc. of Custom Integrated Circuits Conference, pp. 643–646 (1994).

[17] M. S. Lin, H. W. Perng, C. Y. Hwang and Y.-L. Lin: "Channel density reduction by routing over the cell," Proc. of 28th ACM/IEEE Design Automation Conference, pp. 120–125 (1991).

[18] C. Sechen and K. Lee: "An improved simulated annealing algorithm for row-based placement," Proc. of International Conference on Computer-Aided Design, pp. 478–481 (1987).

[19] N. A. Sherwani: "Algorithms for VLSI Physical Design Automation," Kluwer Academic Publishers (1993).

[20] T. C. Wang, D. F. Wong and Y. Sun: "On over-the-cell channel routing," Proc. of the European Conference on Design Automation, pp. 110–115 (1993).

[21] B. Wu, N. A. Sherwani, N. D. Holmes and M. Sarrafzadeh: "Over-the-cell routers for new cell model," Proc. of 29th ACM/IEEE Design Automation Conference, pp. 604–607 (1992).

[22] T. Yoshimura and E. S. Kuh: "Efficient algorithms for channel routing," IEEE Trans. Comput.-Aided Design of Integrated Circuits & Syst., CAD-1, 1, 1, pp. 25–35 (1982).