Planar constrained terminals over-the-cell router

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Indexing terms: Over-the-cell routing, Maximum weight independent chord set, Circle graph, VLSI

Abstract: The authors present a new routing model for over-the-cell channel routing. A graph theoretical algorithm is then proposed to solve the new problem. The algorithm has a complexity of $O(nk^2)$, where n is the number of nets and k is the number of columns in the channel. It achieved a routing area reduction of 71.5% for the PRIMARY 1 benchmark example from MCNC, using three-layer over-the-cell routing. To resolve a sub-problem, the authors also present an $O(mv)$ algorithm to find the maximum weight independent chord set in a circle graph with m chords incident to v vertices, where two chords may share a common vertex.

1 Introduction

One of the final steps in the physical design of a VLSI circuit is the interconnecting of the netlist. In the case of a design style using standard cells, this task appears as the channel routing problem (CRP), in which the routing of the netlist is performed in a rectilinear region between two rows of standard cells. It is preferable to reduce the channel height, thus reducing the total chip area. As circuits becomes more complex nowadays, more layers of interconnection materials have to be employed. Some of the more advanced IC products in the industry use more than four metal layers for interconnections.

With the added layers, it is now possible to route some of the netlist over the standard cells. This type of routing is classified as the 'over-the-cell channel routing problem' (OTC-CRP). Fig. 1 shows an example of an OTC-CRP. This problem has been studied rather extensively recently [1–16]. Previous works showed a reduction of routing area of up to 40% by employing this routing technique on standard cell layout design. In this paper, we present a new routing model to extend the routing capacity over the cell. We presented this new model previously, in [17] [Note 1], with an heuristic algorithm to solve the problem. However, the algorithm appeared to be rather *ad-hoc*. We shall present a new graph theoretical algorithm in this paper to solve the problem.

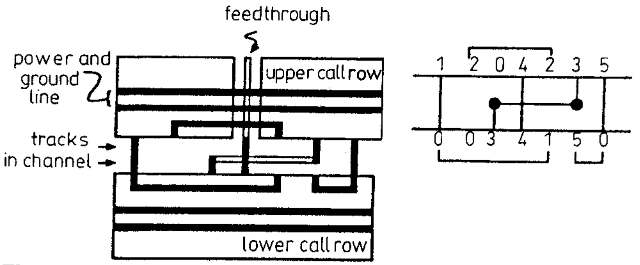
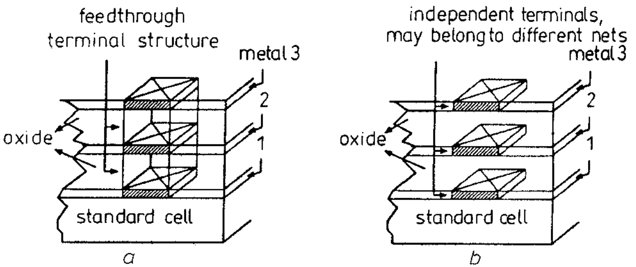


Fig. 1 *Example of an OTC-CRP and its symbolic representation*
□ Metal 1
■ Metal 2

Our research is motivated by the technology that allows circuits to have stacked active layers, sandwiched by improved insulating layers. As pointed out in [18], this structure not only improves the packing density but also reduces power consumption and improves high speed performance. A stacked structure is also possible for terminals along the edges of a standard cell. We call such structures 'constrained terminals'. Traditional channel routing approaches assume that each terminal on the cell edge is a through structure such that the net terminal is available on every routing layer. This is unnecessary, as we can assign the connection layer of each net and separate it from the above layers with insulating material. We illustrate this new routing model in Fig. 2, which compares the physical model of a conventional terminal and a constrained terminal.



a *b*

Fig. 2 *Traditional and constrained terminal structure*
a Traditional, *b* Constrained

Referring to Fig. 2, it is obvious that if we assign a net to be connected at the lower routing layers, the upper ones at the terminal position become available for other netlist connections. From another point of view, by constraining the connection layer of a net terminal, we can make it 'vacant' at the upper routing layers. We call such an induced 'vacant terminal' a

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Note 1: There was a typographical error in [17] semi-vacant terminal. As illustrated in a number of research works [10, 11, 14, 16], the presence of vacant terminals will increase the number of net segments routable over the standard cells. The introduction of semi-vacants will obviously augment the number of net segments routed over the cells. As a result, the application of this new routing model can reduce the channel height (and thus the total chip area) even further.

Our algorithm first finds a set of candidates for the OTC routing then, making use of a maximum weight independent chord set algorithm, we select the most suitable ones and assign them over the cells. At the end, those net segments not routed in the OTC routing phase will be routed in the channel by a conventional channel routing algorithm.

2 Physical model of constrained terminals

Over the years, a number of routing models have been proposed for over-the-cell (OTC) channel routing. For instance, the horizontally connected vertically divided (HCVD) model, the horizontally connected vertically connected (HCVC) model and the horizontally divided vertically connected (HDVC) model proposed in [1], the centre terminal model (CTM) proposed in [4], the middle terminal model (MTM) proposed in [5] and the target based cell model (TBC) presented in [6]. Each of the models needs a tailored algorithm to solve the routing problem. In this paper we present a new routing model to improve routing efficiency over the standard cells.

Our new model is similar to the traditional HCVD model. We assume the intra-cell connections are done in the polysilicon and the first metal (M1) layer. The feedthroughs are made in the M1 layer too. The power and ground lines are laid in the second metal (M2) layer along the centre of the area over the standard cells. These divide the OTC area into two halves. The OTC area in the third metal (M3) layer is not divided, but for simplicity we split it into two halves like the M2 layer (see Fig. 1). As the area over the standard cells is limited by the cell height, we assume that we can route six tracks on the M2 layer, and seven tracks on the M3 layer. The main difference between our model and the traditional one is the way nets are connected to the standard cells at the terminal positions.

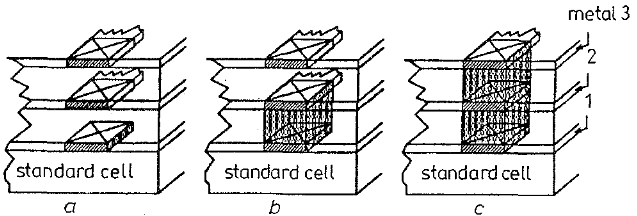

Fig. 3 *Three possible ways a constrained terminal is connected*

Fig. 3 shows three possible ways a constrained terminal can be connected. As mentioned earlier, the traditional channel routing approaches assume that each terminal on the cell edge is a through structure and the net terminal on the cell can be connected to the channel on any of the routing layers (similar to Fig. 3*c*). Obviously, if a net terminal is not connected to the OTC area (Figs. 3*a* and *b*), i.e. it is connected directly to the channel region, the upper metal layers may be treated as 'vacant' and we allow OTC routing to run through them. Note that a net is always available on M1, but is available on M2 or M3 only if the router has chosen to connect the net in such a way. When a net is connected in a lower metal layer, the upper metal layer(s) will be available for OTC routing. This poses a new channel routing problem which we call the constrained terminals over-the-cell channel routing problem (CTOTC-CRP). The OTC-CRP discussed in the previous research works are in fact a special case of the CTOTC-CRP. Since OTC-CRP is $\mathcal{NP}$-hard [19], so is the CTOTC-CRP.

Over the standard cell area, vias may or may not be allowed, depending on the fabrication technology used. It has been observed [14, 17] that vias may make the OTC routing very flexible. In this paper, however, we assume vias are not allowed and thus have to constrain ourselves to planar routing on the OTC area. In the channel region, we adopt the HVHV routing model, using the polysilicon, M1, M2 and M3 layers (also known as the three and a half reserved layer model).

3 Algorithm

We call our algorithm the 'planar constrained terminals over-the-cell' (PCTOTC) router. It treats a multi-terminal net as adjacent two-terminal net segments. From the set of net segments, it chooses a maximum weight independent subset and routes them over the cells. As PCTOTC relies heavily on a maximum weight independent chord set algorithm, we shall discuss the algorithm separately in the following Section.

3.1 Maximum weight independent chord set with chords sharing common vertices

As pointed out in [2], the selection of two-terminal net segments to be routed on one side of the OTC areas can be formulated as a selection of independent chord sets in a circle graph. The authors select the maximum independent chord set as a solution for the problem. This can be solved in $O(n^2)$ [20], where n is the number of chords in the circle graph. The multi-terminal nets can be transformed into two-terminal nets in $O(c^2)$, where c is the number of columns in the channel, and then be solved with the previous algorithm. Holmes *et al.* [10] used a weighted version of the maximum independent chord set and employed vacant abutments (to be discussed in the next Section) to achieve even better results.

Note that the dynamic programming algorithm employed by the aforementioned research only works for the case when no two chords on the circle share a common vertex. We shall demonstrate that such a consideration is necessary in solving the CTOTC-CRP. Cong [2] and Liu *et al.* [21] suggested that the problem with common chords can be solved in $O(n^3)$ using the dynamic programming approach. Chang *et al.* [22], however, have presented an $O(mv)$ algorithm to find a maximum independent set of m chords which are incident to v vertices in a circle. We shall present a similar algorithm to find a maximum weight independent chord set (MWICS) on a circle graph, i.e. to solve a problem when each of the chords is given a weight. Here we assume the chord set is given in C, and v_{ij} is a chord with vertices at i and j. We denote the weight of the chord v_{ij} by $W(i, j)$ and the sum of the independent chords between vertices i and j by $|MWICS(i, j)|$.

We also implement a linked adjacent matrix (similar to [22]), which is an upper-triangle matrix, to speed up

```
Algorithm MWICS
FOR $j \leftarrow 2$ TO $n$ DO
BEGIN
  FOR $i \leftarrow 1$ TO $j - 1$ DO
    FOREACH $k$ such that $v_{kj} \in C$ or $v_{jk} \in C$
      IF $i \le k \le j - 1$ and
        $|MWICS(i, k-1)| + W(i, j) + |MWICS(k+1, j-1)| > |MWICS(i, j-1)|$
      THEN $MWICS(i, j) \leftarrow MWICS(i, k-1) \cup \{v_{ij}\} \cup MWICS(k+1, j-1)$
      ELSE $MWICS(i, j) \leftarrow MWICS(i, j-1)$
END.
```

Fig. 4 *Maximum weight independent chord set (MWICS) algorithm*

the search in the FOREACH inner-loop. Each pointer points to the next '1' down the column, thus giving the next adjacent vertex in linear time. This adjacent matrix can be constructed in $O(n^2)$. Fig. 5 gives an example to illustrate the linked adjacent matrix. The example also shows how a one-sided planar routing on the OTC area can be formulated to find the maximum independent set on a circle graph as mentioned earlier. Without short-circuiting any of the different nets, we may choose the set $\{v_{15}, v_{24}\}$ for a maximum number of segments but have to choose $\{v_{35}\}$ for a maximum weight. This algorithm has the same complexity as $O(mv)$, where m and v are the number of chords and the number of vertices in the given circle graph. Readers are encouraged to refer to [22] for the proof which is applicable here.

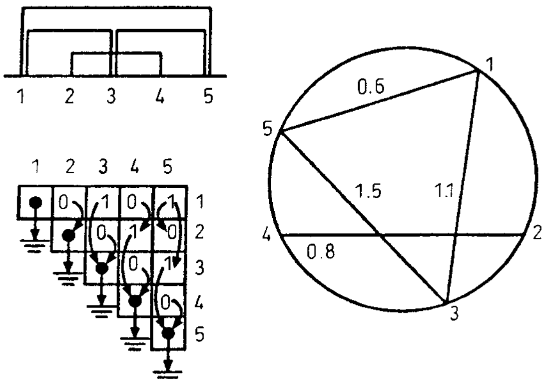

Fig. 5 *Linked adjacent matrix for a weighted circle graph*

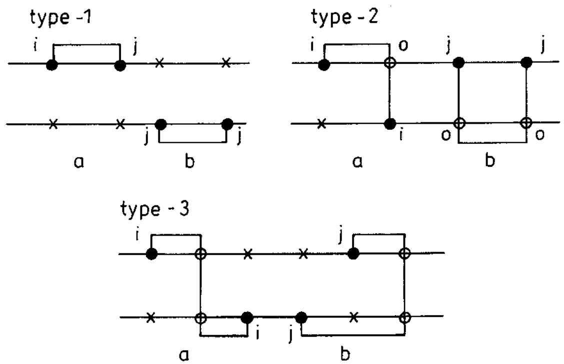

Fig. 6 *Three types of OTC routing candidates*

3.2 Types of OTC routing candidates

We classify all our considered OTC routing candidates into three types, as shown in Fig. 6. The symmetrical equivalence of the ones shown in the Figure (especially for type 2 and type 3) are also considered. In short, the candidates are classified such that a type 1 candidate has a net segment routable on one side of the OTC areas; a type 2 candidate has a net segment routable on either side of the OTC areas; and a type 3 candidate has a net segment to be routed on each side of the OTC areas. We denote the candidate sets of each type as $\mathcal{S}_I$, $\mathcal{S}_{II}$ and $\mathcal{S}_{III}$, respectively.

All the OTC routing candidates can be found in $O(k^2)$, where k is the number of column in the channel (i.e. the width of the channel). After finding all the candidates, we shall choose amongst them a maximum weight independent subset and route them over the standard cells. The weight assignment and the overall PCTOTC algorithm will be described in subsequent Sections. We shall further examine the type 3 candidates.

Since the MWICS algorithm can only consider candidates on one OTC area at a time, the algorithm will make an erroneous choice in cases like the one shown shown in Fig. 7 (note that in order not to complicate the figure, the type 3b candidates of net 1 and 3 are not shown). In particular, when considering the circle graph formed by the net segments on the top OTC area (i.e. net 1, 2 and 3), though the type 3 candidates of net 1 and 3 seem independent, they cannot be chosen at the same time, as they intersect each other on the bottom OTC area. Holmes *et al.* [19] refer to this problem as the vacant abutment assignment problem, and showed that this optimisation problem is $\mathcal{NP}$-complete. They handled this by defining three necessary conditions and applied a greedy approach to obtain an independent subset of candidates in $\mathcal{S}_{III}$. Their approach actually assigns a vacant column to only one candidate, heuristically, at the initial stage, and as a result, their algorithm deviates even further from the optimum.

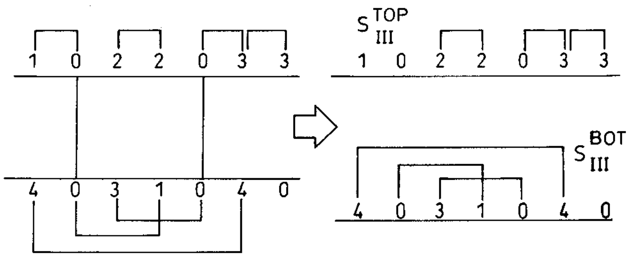

Fig. 7 *Choosing from type 3 candidates*

Formally, we shall denote the set of type 3 candidates, $\mathcal{S}_{III} \equiv \{(S^{TOP}_{III_i}, S^{BOT}_{III_i}) | 1 \le i \le p\}$, where $S^{TOP}_{III_i}$ and $S^{BOT}_{III_i}$ are the net segments of the ith candidate on the top and bottom OTC area, respectively, and p is the total number of type 3 candidates. We shall derive two subsets from $\mathcal{S}_{III}$, namely $\mathcal{S}^{TOP}_{III} = \{(S^{TOP}_{III_i}, S^{BOT}_{III_i}) | S^{BOT}_{III_i}$ is independent of $S^{BOT}_{III_j}$ if $i \ne j$, $1 \le i, j \le p\}$ and $\mathcal{S}^{BOT}_{III} = \{(S^{TOP}_{III_i}, S^{BOT}_{III_i}) | S^{TOP}_{III_i}$ is independent of $S^{TOP}_{III_j}$ if $i \ne j$, $1 \le i, j \le p\}$. It is obviously advantageous to have a set with maximum weight for each subset. They can be achieved with the following equations:

$$S_{III}^{TOP} = MWICS\left(\bigcup_{1\leq i\leq p} S_{III_i}^{BOT}\right) \tag{1}$$

$$S_{III}^{BOT} = MWICS\left(\bigcup_{1\leq i\leq p} S_{III_i}^{TOP}\right) \tag{2}$$

For the sake of conciseness, in the above equations (and from now on) we assume $MWICS(\cdot)$ returns the maximum weight candidate set rather than the chord set. Nevertheless, the mapping between the chord and the corresponding candidate is trivial. Note that $S_{III}^{TOP} \cap S_{III}^{BOT} \neq \emptyset$. Fig. 7 gives an example of obtaining the two subsets. Likewise, we divide S_I into two disjoint sets S_I^{TOP} and S_I^{BOT}, i.e., $S_I = S_I^{TOP} \cup S_I^{BOT}$ and $S_I^{TOP} \cap S_I^{BOT} = \emptyset$.

Another issue concerns searching for type 3b candidates. Since this type of candidate takes up OTC routing capacity outside the span of the net segment, it is not desirable to have too many of them. This fact is also taken care of in our weight assignment function, *AssignWeight*$(\cdot)$, which will be described in the next Section. Certainly *AssignWeight*$(\cdot)$ must be called before applying eqns. 1 and 2. In our implementation, we have a parameter, SEARCHLENGTH, to limit the search range for a vacant column left and right of the net interval. This will also reduce the actual run-time.

3.3 Weighting function

In the selection of candidates for the OTC routing, we use a weighting function to determine the order of merit for a candidate, c_i. This weighting function comprises four weights as listed below:

$$w_1 = \begin{cases} 0 & \text{if } c_i \notin L_{VG} \\ 1 - \frac{|2l_r - l_o - 1|}{l_o + 1} & \text{otherwise} \end{cases} \tag{3}$$

$$w_2 = \frac{d(v_i, G_{mh})}{|V'|} \tag{4}$$

$$w_3 = \frac{\sum_{r_i^l \leq j \leq r_i^r} d_r}{(r_i^r - r_i^l) d_o} \tag{5}$$

$$w_4 = \frac{r_i^r - r_i^l - e_i}{k} \tag{6}$$

The weights in eqns. 3 and 4 are taken from our previous work [16]. For a given channel, eqn. 3 considers the length of the longest path in the vertical constraint graph (VCG), L_{VG}. l_r is the relative position of the candidate net in the longest path, and l_o is the length of the longest path. eqn. 4 considers the modified horizontal constraint graph (MHCG), $G_{mh} = (V', E_{mh})$, of the channel. Here, v_i represents the net segment of c_i in the MHCG, and $d(v_i, G_{mh})$ is the degree of vertex v_i in the undirected graph G_{mh}. Readers can refer to [16] for a detailed discussion on these two weights and the relevant definitions.

Eqn. 5 considers the average local density over the span of the c_i, where d_j is the local density at column j in the given channel, r_i^l and r_i^r are the left and right column of c_i, and d_o is the channel density. w_4 adds weight for the consideration of the span of c_i and if it is of type 3, as mentioned in Section 3.2, a penalty is given for the exceeding span beyond the net interval of c_i. e_i is the exceeding span, either on the left or right, and k is the width of the channel. The weighting function implemented in the *AssignWeight*$(\cdot)$ function is given below.

$$\mathcal{F}(c_i) = C_1 \cdot w_1 + C_2 \cdot w_2 + C_3 \cdot w_3 + C_4 \cdot w_4 \tag{7}$$

where C_1, C_2, C_3 and C_4 are four constants which may be adjusted to suit different channel routing algorithm applied after the OTC routing.

```
Algorithm PCTOTC
FOR layer ← 1 TO MAXLAYER DO
BEGIN
    Candidates ← FindCandidate();
    AssignWeight(Candidates);
    tmp ← MWICS($S_{TOP} \cup S_{II}$);
    $S_1$ ← tmp ∪ MWICS(($S_{BOT} \cup S_{II}$) ⊖ tmp);
    tmp ← MWICS($S_{BOT} \cup S_{II}$);
    $S_2$ ← tmp ∪ MWICS(($S_{TOP} \cup S_{II}$) ⊖ tmp);
    IF $W(S_1) > W(S_2)$ THEN S[layer] ← $S_1$
    ELSE S[layer] ← $S_2$
    PlanarRoute( S[layer] );
    RouteFreeCandidates( S[layer] );
    UpdateGraph();
END.
```

Fig. 8 *Summary of the PCTOTC algorithm*

3.4 PCTOTC algorithm

Our algorithm PCTOTC can be summarised in Fig. 8. To begin with, it scans the channel for OTC routing candidates according to the types shown in Fig. 6. For type 3 candidates, we apply eqns. 1 and 2 to get S_{III}^{TOP} and S_{III}^{BOT}, respectively. Then we obtain the two following sets of candidates for applying the $MWICS(\cdot)$ algorithm.

$$S_{TOP} = S_I^{TOP} \bigcup S_{III}^{TOP} \tag{8}$$

$$S_{BOT} = S_I^{BOT} \bigcup S_{III}^{BOT} \tag{9}$$

To reiterate, since the $MWICS(\cdot)$ can only ensure the independence of the chords on one of the OTC areas at a time, we need to determine the set of chords (S_{TOP} and S_{BOT}) for the algorithm to enumerate the set of maximum weight candidates which are independent on both OTC areas. The advantage of this approach is that vacant terminals need not be assigned to the nets at too early a stage. Besides, the conversion of multi-terminal nets, as in [2], is avoided.

The *AssignWeight*$(\cdot)$ function is then applied to give an order of preference to each OTC routing candidate. Two possible solution sets, S_1 and S_2, are determined using the $MWICS(\cdot)$ function, as shown in Fig. 8. The one with a higher total weight (given by $W(\cdot)$) will be selected. The '$\ominus$' operator denotes a special set subtraction, in which the conflicting members will be excluded. As a result, not only the repeated (S_{II}) candidates are excluded but those minuend candidates which intersect with the subtrahend (S_{III}) candidates are excluded too.

The selected candidates are then routed on the OTC area followed by the routing of the free candidates. These are the adjacent candidates which are not selected by the $MWICS(\cdot)$ algorithm. For instance, in Fig. 7, the net 3 candidates on the top right corner may not be selected initially. However, it does not cause any design rule error to route it OTC too. Fortunately, there are not many adjacent candidates like these. The adjacent candidates of the same net must belong to a multi-terminal net, and it is known that in practical industrial examples, a multi-terminal net in a channel usually only has an average of three or four net segments. The free candidates are routed using a greedy approach. After the selected candidates are routed OTC, they are removed from the the graph representing the remaining net segments and hence will not be considered further. The column densities as well as the channel density of the remaining channel are updated too. Another important task is to label the terminals just routed to be semi-vacant so that they can be used for OTC routing on the upper metal layer. These are performed in the *UpdateGraph*(·) step. The algorithm then proceeds to the next layer and does likewise. At the end of the OTC routing, some net segments may remain not connected. They are then routed using a conventional channel routing algorithm.

The above OTC net segment selection is in fact a problem of finding 4 maximum weight independent chord sets on a circle graph. It is known that this problem is $\mathcal{NP}$-complete [23]. Our algorithm is an approximation algorithm which is able to obtain results at least 51% of the optimal solution. The proof shall be omitted here for the sake of brevity. The run time of the algorithm is bounded by $MWICS(\cdot)$ which is in $O(mv)$, where m and v are the number of chords and the number of vertices in the given circle, respectively. It is easy to verify that in our application, $m \le nk$ and $v \le k$ where n is the number of nets and k is the number of columns (i.e. the channel width) in the given channel. Hence our algorithm has a complexity of $O(nk^2)$.

4 Experimental results

To verify the efficiency of the PCTOTC algorithm, we conducted experiments on various benchmark examples, including the PRIMARY 1 example from MCNC. Our results are presented in Table 1. The results obtained by other algorithms are also listed for comparison. In our implementation, we assume vias are not permitted on the area over the standard cells and there are only six OTC tracks on the M2 layer and seven OTC tracks on the M3 layer.

The Greedy channel router [24] is a conventional channel routing algorithm not using the OTC routing. The WILMA algorithm [13] makes use of 45° routing segments on the OTC areas. O − V and O + V [11] are the improved algorithms from the same authors for two OTC layers, with and without vias, respectively. All the aforementioned algorithms deal with the conventional OTC-CRP. HERO [16], which belongs to the same class and has obtained the best result. The CTOTC [17] solves the CTOTC-CRP, though in a rather *ad hoc* manner. Note, however, that CTOTC allows vias over the standard cells. As shown, our algorithm is able to obtain a channel height reduction of 71.5% when compared to Greedy.

To make further comparison with the CTOTC [17] router, we conducted experiments using other benchmark examples, including the *ex*1, *ex*3*a*, *ex*3*b*, *ex*3*c*, *ex*4*b* and *ex*5 examples from [25], the Deutsch's difficult example, and the *reg*1, *reg*2 and *reg*3 examples taken from a register decoder circuit. Generally, these benchmark examples have less vacant terminals. Hence they pose as a more difficult benchmark for the routers. The results are shown in Table 2. Our algorithm achieved an improvement of 18.4% compared to CTOTC [17].

Table 1: Comparison with other routers for PRIMARY 1 benchmark example

Channel	Number of tracks						
	Greedy [24]	WILMA [13]	O-V [11]	O+V [11]	HERO [16]	CTOTC [17]	PCTOTC
1	6	2	1	2	1	0	0
2	9	5	5	4	4	3	3
3	11	6	6	5	5	5	5
4	15	9	6	4	7	6	6
5	11	7	6	4	5	4	4
6	12	7	7	5	6	5	5
7	14	5	4	5	4	5	4
8	16	7	7	8	6	6	6
9	13	6	6	6	5	5	4
10	8	5	4	4	4	4*	3
11	12	5	3	4	3	3	3
12	8	4	3	3	4	2	2
13	8	3	3	3	3	2	2
14	7	4	3	4	3	0	1
15	6	2	2	3	2	0	0
16	6	2	2	3	2	1	1
17	7	3	3	3	3	0	0
18	3	1	0	1	0	0	0
Total	172	83	71	71	67	51	49
Improve, %	—	51.7	58.7	58.7	61.0	70.3	71.5

* There was a typographical error in [17]

Table 2: Comparison with CTOTC for other benchmark examples

Example	CTOTC [17]	PCTOTC
Deutsch	7	6
ex1	4	3
ex3a	4	4
ex3b	4	4
ex3c	7	6
ex4b	5	4
ex5	5	3
reg1	6	4
reg2	4	3
reg3	3	3
Total	49	40

5 Conclusions

We have introduced a new over-the-cell routing model which produces a more efficient usage of the area over the standard cells. The new routing problem has been formulated as the constrained terminals over-the-cell channel routing problem. An algorithm in $O(nk^2)$ has been proposed to find a planar OTC routing solution, where n is the number of nets and k is the number of columns in the channel. The algorithm achieved a 71.5% channel height reduction on the PRIMARY 1 benchmark example from MCNC, as compared to the Greedy [24] traditional channel router which does not employ OTC routing. In order to resolve a sub-problem, an $O(mv)$ algorithm is also presented to determine the maximum weight independent chord set in a circle graph with m chords incident to v vertices, where two chords may share a common vertex.

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7 References

1 CONG, J., PREAS, B., and LIU, C.L.: 'General models and algorithms for over-the-cell routing in standard cell design'. Proceedings of 27th ACM/IEEE *Design automation* conference, 1990, pp. 709–715

2 CONG, J., and LIU, C.L.: 'Over-the-cell channel routing', *IEEE Trans. Comput.-Aided Des. Integr. Circuits Syst.*, 1990, **9**, pp. 408–418

3 TERAI, M., TAKAHASHI, K., NAKAJIMA, K., and SATA, K.: 'A new model for over-the-cell channel routing with three layers'. Proceedings of international conference on the *Computer-aided design*, 1991, pp. 432–435

4 WU, B., SHERWANI, A., HOLMES, N.D., and SARRAFZADEH, M.: 'Over-the-cell routers for new cell model'. Proceedings of 29th ACM/IEEE *Design automation* conference, 1992, pp. 604–607

5 BHINGARDE, S., PANYAM, A., and SHERWANI, N.: 'Efficient over-the-cell routing algorithm for general middle terminal model'. IEEE international symposium on *Circuits and systems*, 1993, pp. 1861–1864

6 BHINGARDE, S., KHAWAJA, R., PANYAM, A., and SHERWANI, N.: 'Over-the-cell routing algorithms for industrial cell models'. Proceedings of 7th international conference on *VLSI design*, 1994, pp. 143–148

7 LIN, M.S., PERNG, H.W., HWANG, C.Y., and LIN, Y.L.: 'Channel density reduction by routing over the cells'. Proceedings of 28th ACM/IEEE *Design automation* conference, 1991, pp. 120–125

8 PAI, R.R., and RAO, S.S.S.P.: 'An over-the-cell channel router'. Proceedings of IFIP TC10/WG 10.5 international conference on *VLSI*, 1991, pp. 327–336

9 CHANG, L.D., HSIAO, P.Y., YAN, J.T., and SHEW, P.W.: 'A robust over-the-cell channel router', *IEEE Trans. Comput.-Aided Des. Integr. Circuits Syst.*, 1993, **12**, pp. 1592–1599

10 HOLMES, N.D., SHERWANI, N.A., and SARRAFZADEH, M.: 'New algorithm for over-the-cell channel routing using vacant'. Proceedings of 28th ACM/IEEE *Design automation* conference, 1991, pp. 126–131

11 HOLMES, N.D., SHERWANI, N.A., and SARRAFZADEH, M.: 'Algorithms for three-layer over-the-cell channel routing'. Proceedings of IEEE international conference on the *Computer-aided design*, 1991, pp. 428–431

12 HOU, C.Y.C., and CHEN, C.Y.R.: 'A pin permutation algorithm for improving over-the-cell channel routing'. Proceedings of 29th ACM/IEEE *Design automation* conference, 1992, pp. 594–599

13 NATARAJAN, S., SHERWANI, N., HOLMES, N.D., and SARRAFZADEH, M.: 'Over-the-cell channel routing for high performance circuits'. Proceedings of 29th ACM/IEEE *Design automation* conference, 1992, pp. 600–603

14 STRUNK, T.W., and HOLMES, N.C.: 'VICTOR: A three-layer over-the-cell router'. Proceedings of third Great Lakes symposium on *VLSI design automation of high performance VLSI systems*, 1993, pp. 6–10

15 LIU, X., and TOLLIS, I.G.: 'Improving over-the-cell channel routing in standard cell design'. Proceedings of IEEE international conference on the *Computer-aided design*, 1994, pp. 606–609

16 SHEW, P.W., HSIAO, P.Y., and LIM, Y.C.: 'Efficient height reduction over-the-cell channel router', *IEE Proc., Comput. Digit. Tech.*, 1995, **142**, pp. 293–298

17 SHEW, P.W., SHEI, J.S., and HSIAO, P.Y.: 'A constrained terminals over-the-cell router'. Proceedings of IEEE Region 10 international conference on *Microelectronics and VLSI*, 1995, pp. 167–170

18 DETRY, D.J., and JAYASUMANA, A.P.: 'Three-layer router for channels with constrained terminals', *IEE Proc., Comput. Digit. Tech.*, 1993, **140**, pp. 333–340

19 HOLMES, N.D., SHERWANI, N.A., and SARRAFZADEH, M.: 'Utilization of vacant terminals for improved over-the-cell channel routing', *IEEE Trans. Comput.-Aided Des. Integr. Circuits Syst.*, 1993, **12**, pp. 780–792

20 SUPOWIT, K.J.: 'Finding a maximum planar subset of a set of nets in a channel', *IEEE Trans. Comput.-Aided Des. Integr. Circuits Syst.*, 1987, **CAD-6**, pp. 93–94

21 LIU, R., and NTAFOS, S.: 'On decomposing polygons into uniformly monotone parts', *Inf. Process. Lett.*, 1988, pp. 85–89

22 CHANG, R.C., and LEE, H.S.: 'Finding a maximum set of independent chords in a circle', *Inf. Process. Lett.*, 1992, pp. 99–102

23 SARRAFZADEH, M., and LEE, D.T.: 'A new approach to topological via minimization', *IEEE Trans. Comput.-Aided Des. Integr. Circuits Syst.*, 1989, **8**, pp. 890–900

24 RIVEST, R.L., and FIDUCCIA, C.M.: 'A 'greedy' channel router'. Proceedings of 19th ACM/IEEE *Design automation* conference, 1982, pp. 418–424

25 YOSHIMURA, T., and KUH, E.S.: 'Efficient algorithms for channel routing', *IEEE Trans. Comput.-Aided Des. Integr. Circuits Syst.*, 1982, **CAD-1**, pp. 25–35