

Efficient height reduction over-the-cell channel router

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Abstract: The authors present a new algorithm for both two-layer and three-layer over-the-cell channel routing in the standard cell VLSI design. The approach exploits vacant terminals on the channel boundary effectively. It considers the following factors simultaneously to select net segments for routing over the cells: density distribution in the channel, the longest path in the vertical constraint graph, elimination of cycles in the vertical constraint graph and reduction in maximum cliques in the horizontal constraint graph. With respect to the PRIMARY 1 benchmark examples, the router achieved a 41.3% improvement over the Greedy channel router (one without using over-the-cell area) for a two-layer routing model and a 61.0% improvement for a three-layer routing model. This outperforms all previous algorithms.

1 Introduction

In VLSI layout design using standard cells, channel routing is a crucial problem which has been studied extensively. A good routing solution should complete the connections in the channel with the minimum number of tracks. This will minimise the channel height, thus reducing the total chip area. Fig. 1a shows an example of

routing between two rows of standard cells (i.e. in the channel area) within a circuit.

Many channel routing algorithms have been proposed and they can produce solutions very close to optimum (e.g. the Greedy channel router [1]). Researchers have also proposed the use of the area over the standard cells for routing in second (M2) and third (M3) metal layers (the first metal (M1) is usually used for routing within the cell). Such routing style is known as *over-the-cell channel routing*. Fig. 1b illustrates such a routing style. Efficient utilisation of the area over the cells can reduce the layout area substantially. The reduction in chip area with this approach is even more significant in today's fabrication technology, as more metal layers are available for routing.

It has been shown that the channel routing problem is NP-hard [2]. Over-the-cell (OTC) channel routing is a more general case of the channel routing problem, hence it is obviously NP-hard too. A number of heuristics have been proposed [3-12] for either a two-layer (i.e. using only M2) or a three-layer (i.e. using both M2 and M3) OTC channel routing model. After the introduction of using vacant terminals in OTC routing [8], recent OTC channel routers can reduce the channel height by 30% for a two-layer model and 50% for a three-layer model (see Table 1).

In this paper we present a new algorithm which we have implemented for two-layer and three-layer OTC

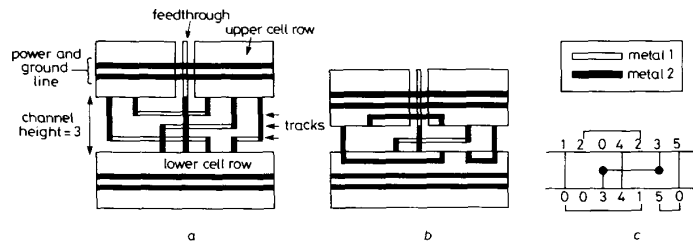


Fig. 1 Typical channel routing problem
a Traditional channel routing b Over-the-cell channel routing c Symbolic representation

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channel routing problems. We call our program HERO-V (HEight Reduction Over-the-cell channel router without using Vias over the cell area). The algo-

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Table 1: Comparison with other routers for PRIMARY 1

Channel	% Vacancy	Final channel height								
		Two-layer				Three-layer				
		Gr [1]	OTC-I [10]	WISER [8]	WILMA [12]	HERO-V	Gr [1]	WILMA [12]	O-V [11]	HERO-V
1	85	11	6	5	2*	4	6	2	1*	1*
2	75	16	14	12	11	10*	9	5	5	4*
3	64	21	16	16	16	14*	11	6	6	5*
4	60	24	20	21	20	18*	15	9	6*	7
5	64	21	17	17	17	13*	11	7	6	5*
6	53	23	17	18	17	16*	12	7	7	6*
7	58	22	14	14	13	12*	14	5	4*	4*
8	51	24	17	18	17	15*	16	7	7	6*
9	54	21	15	16	16	12*	13	6	6	5*
10	61	15	10	11	10	9*	8	5	4*	4*
11	64	17	11	12	11	10*	12	5	3*	3*
12	64	15	10	11	10	9*	8	4	3*	4
13	63	13	10	9*	9*	9*	8	3*	3*	3*
14	64	13	11	9	9	7*	7	4	3*	3*
15	63	11	7	7	6	5*	6	2*	2*	2*
16	68	11	8	7	6	4*	6	2*	2*	2*
17	68	14	9	8	8	7*	7	3*	3*	3*
18	92	6	4	3	3	1*	3	1	0*	0*
Σ	65	298	216	214†	201	175*	172	83	71	67*
Δ %	—	—	28.9	29.6	32.6	41.3*	—	51.7	58.7	61.0*

* Best result for each channel
 † Addition error in References 8 and 9

rithm has a generic nature in that it may be further extended to multiple-layer OTC channel routing. Our approach efficiently selects a subset of net segments to be routed over the cells with consideration of density distribution in the channel, and by making use of the vacant terminals it reduces the longest path in the vertical constraint graph, as well as the maximum cliques in the horizontal constraint graph. At the same time, cycles in the vertical constraint graph are eliminated as much as possible. We have tested our algorithm with a number of benchmark examples to verify its effectiveness. For the PRIMARY 1 example, our algorithm achieved 41.3% and 61.0% reduction in total channel height for two-layer and three-layer OTC routing models, respectively. It outperforms all previous algorithms.

2 Physical model for OTC routing

The OTC channel routing is restricted by the number of metal layers available in the IC fabrication. In this paper, we assume that the intracell connections are done in the polysilicon and the first metal (M1) layer. The feed-through is 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 lines divide the over-the-cell (OTC) area into two halves and the cell height permits us to route six tracks in the M2 layer over each half. The OTC area in the third metal (M3) layer is not divided, but for simplicity we split the area into two halves and only route, at most, seven tracks over each half. Vias may or may not be made in the OTC area, depending on the fabrication technology. In our current implementation, we assume vias are not allowed so OTC routing in M2 and M3 layers must be planar.

As for routing in the channel region, we adopt the traditional HV and HVH models for two-layer and three-layer channel routing. Under these channel routing models, horizontal and vertical wire segments are used exclusively in alternating metal layers. We make use of doglegs to complete the channel routing while keeping the final channel height as low as possible. Fig. 1b illustrates this physical routing model. Discussion on other

OTC routing models can be found in Reference 5. Fig. 1c shows a symbolic representation of the same problem as in Figs. 1a and b.

3 Terminology and notation

Amongst the N_{net} nets in a given channel, some may be multiterminal, i.e. a net consisting of more than two terminals. The approach in this paper first decomposes all multiterminal nets into modified two-terminal net segments adjacent at common terminal locations. Each pair of terminals defines a net segment which will either be routed in the channel or in the OTC area. Thus net $n_i = \{t_{i,1}, t_{i,4}, t_{i,7}\}$ (Fig. 2), after being decomposed, gives us the segments $s_i = \{s_{i,1}, s_{i,2}\}$, where $t_{s,c}$ refers to the terminal on row s (TOP or BOTTOM) at column c ; $s_{i,j} = (l_{i,j}, r_{i,j})$ where $l_{i,j}$ and $r_{i,j}$ denote the left and right column of the net segment $s_{i,j}$.

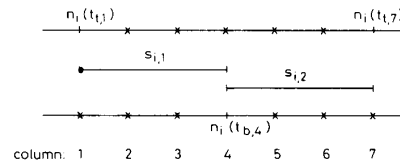


Fig. 2 Decomposing multiterminal net, n_i , into 2 two-terminal nets with net segments $s_{i,1}$ and $s_{i,2}$

Next we define the set of *critical columns*, $c_r = \{c_{r_i} : (1 \leq i \leq N)[D(c_{r_i}) = D_0]\}$, where N is the number of columns in the channel, $D(c)$ is the local density at column c (i.e. the number of net segments intersecting column c), and the channel density, $D_0 = \max [D(c)]$. Our approach considers the horizontal constraints in the channel by analysing the *modified horizontal constraint graph* (MHCG). MHCG is an undirected graph $G_{mh} = (V', E_{mh})$ where $V' = \{v_{i,j} : v_{i,j}$ represents the modified net segment $s_{i,j}\}$ and $E_{mh} = \{(v_{i,j}, v_{k,l}) : s_{i,j}$ intersects $s_{k,l}, i \neq k\}$. The vertical constraints, however, are considered by analysing the longest path in the *vertical constraint*

graph (VCG). VCG is a directed graph, $G_v = (V, E_v)$ where $V = \{v_i; v_i \text{ represents net } i\}$ and $E_v = \{(v_i, v_j); (\exists 1 \leq c \leq N) [\text{TopNet}(c) = i, \text{BottomNet}(c) = j, i \neq j]\}$. TopNet(c) and BottomNet(c) are the top terminal net and bottom terminal net at column c , respectively.

4 Reduction in channel height

As mentioned earlier, OTC channel routing can reduce the channel height of a circuit. Fig. 3 depicts nine valid OTC routing types for a net segment $s_{i,j}$. These types are not exhaustive but are the ones considered in our algorithm. Note that we allow combinations of these types for any net segment remaining in the channel. In Section 4.1, we discuss the factors which affect the channel height of a channel routing solution (without OTC routing). Then we describe the heuristic cost function befitting our consideration of all these factors in Section 4.2 and we give a summary of our algorithm in Section 5. To aid the description of our algorithm, we trace the execution of our program for a simple problem in Fig. 4.

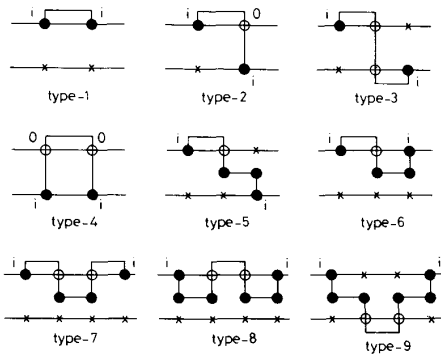


Fig. 3 Nine valid types of OTC routing

4.1 Lower bound for channel height

The first lower bound for channel height is the channel density d . In earlier algorithms (e.g. in References 4–7 and 10), the reduction in channel density was the ultimate goal. However, without considering other factors, they did not perform well. The second lower bound is the length of the longest path in VCG l . It is possible to reduce l by doglegging [13] or making OTC routing as illustrated in Fig. 4c. The weight w_2 in our heuristic cost function is improvised to achieve the lowest value of l . In addition to $\max(d, l)$, Brown and Rivest [14] have shown that for a two-terminal net routing problem $t \geq -(w-n) + \sqrt{\{(w-n)^2 + 2m\}}$ is a lower bound if nets are allowed to cross the initial routing window (w is the width of the window, n is the number of nets and m is the number of nontrivial nets, i.e. those that need to be 'moved'). Following the argument, it is easy to see that $t \geq m/(w-n)$ if the nets are not allowed to cross the window. With the concept of channel flux, Baker *et al.* [15] proposed $\max(f, d)$ to be the lower bound. Lee and Leong [16] suggested that for any path P in VCG, if S_p is the set of nets not in P but intersect every element in P , then $\tau = \max(|P| + |\text{clique}(S_p)|)$ is a tighter lower bound for the channel height. We shall re-examine the lower bound with zone representation [17] and VCG for a multiterminal net routing instance. Rigorous details are omitted in the following for the sake of brevity.

The zone representation does characterise the dogleg-free restricted Manhattan routing model for two-terminal nets but is not accurate enough for more general multiterminal net problems with doglegging. Adjacent subnets can either be routed on the same or different track (by adding doglegs), thus occupying one track for the former but two tracks for the latter. This can be represented more accurately by a reduced zone representation (RZR), as illustrated in Fig. 5b. The zone representation was originally defined for open interval $(z_1, z_2]$ where z_1 and z_2 are the positions of two terminal columns acting as the boundary of the zone. In RZR, the interval (z_1, z_2) is used instead. Observe that a pair of adjacent subnets which are not merged in the routing solution will have the right subnet appearing in the left zone, e.g. subnet 2b in Fig. 5b. Construction of the RZR requires a prior knowledge of whether each pair of adjacent subnets is merged in the final channel routing solution. Fortunately, we can obtain better insight from the VCG. Let us construct a reduced vertical constraint graph (RVCG) by merging all subnet nodes (belonging to the same net) on the VCG into a single node subject to the condition of not elongating the vertical constraint path. Fig. 5c shows the RVCG of the channel routing instance in Fig. 5a. Note that subnets 4a and 4b (not shown) are merged, but 2a and 2b are not. If we merge 2a and 2b, then l will increase from three to four. Whichever pair of subnets is merged in the RVCG, they will also be merged in the RZR. The RZR density d_R is then determined. Finally, we have $t_R = \max(d_R, \tau)$ as an improved lower bound. In fact this is the best known lower bound for the channel routing problem. In Fig. 5, $d_R = 4$ and $\tau = 3$ thus giving $t_R = 4$. Fig. 5a shows an optimal solution which requires four tracks to complete the routing.

As we allow doglegging, we consider the channel horizontal constraints with MHCG. To reduce the value of d_R , we introduce the cost w_3 in our heuristic cost function described in the following section. The combination of weights w_2 and w_3 attempts to lower the value of t_R in the final channel routing stage. Next, cycles may occur in a VCG. Without doglegging, a channel with a cyclic VCG does not have a routing solution. In fact cycles in the VCG pose a problem to many channel routers. Fig. 4b shows how OTC routing can provide a means of breaking a cycle. We give preference to candidates that can break any cycle. This is reflected by w_1 in our cost function.

4.2 Cost function for OTC routing

With all the valid OTC routing candidates, we construct a candidate set,

$$c_c = \{(s_{i,j}, p_{i,j}); (\exists c_n \in c_c)[l_{i,j} \leq c_n \leq r_{i,j}]\}$$

where $p_{i,j}$ is the OTC routing type for net segment $s_{i,j}$. Two candidates may be conflicting, i.e. routing both over the cells will cause a short circuit. For example, type-1 of Net 2 and type-2 of Net 3 in Fig. 1c are conflicting. We use $f_c(s_{i,j}, p_{i,j})$ to denote the number of candidates conflicting with the candidate $(s_{i,j}, p_{i,j})$. Minimal conflicts allow more net segments to be routed OTC. Now a proper candidate in c_c has to be selected for routing OTC in every iteration. To make this selection, we devise four weights below to calculate the criticality of each candidate.

$$w_1 = 1 \quad \text{if routing } (s_{i,j}, p_{i,j}) \text{ OTC will break a cycle} \\ = 0 \quad \text{otherwise} \quad (1)$$

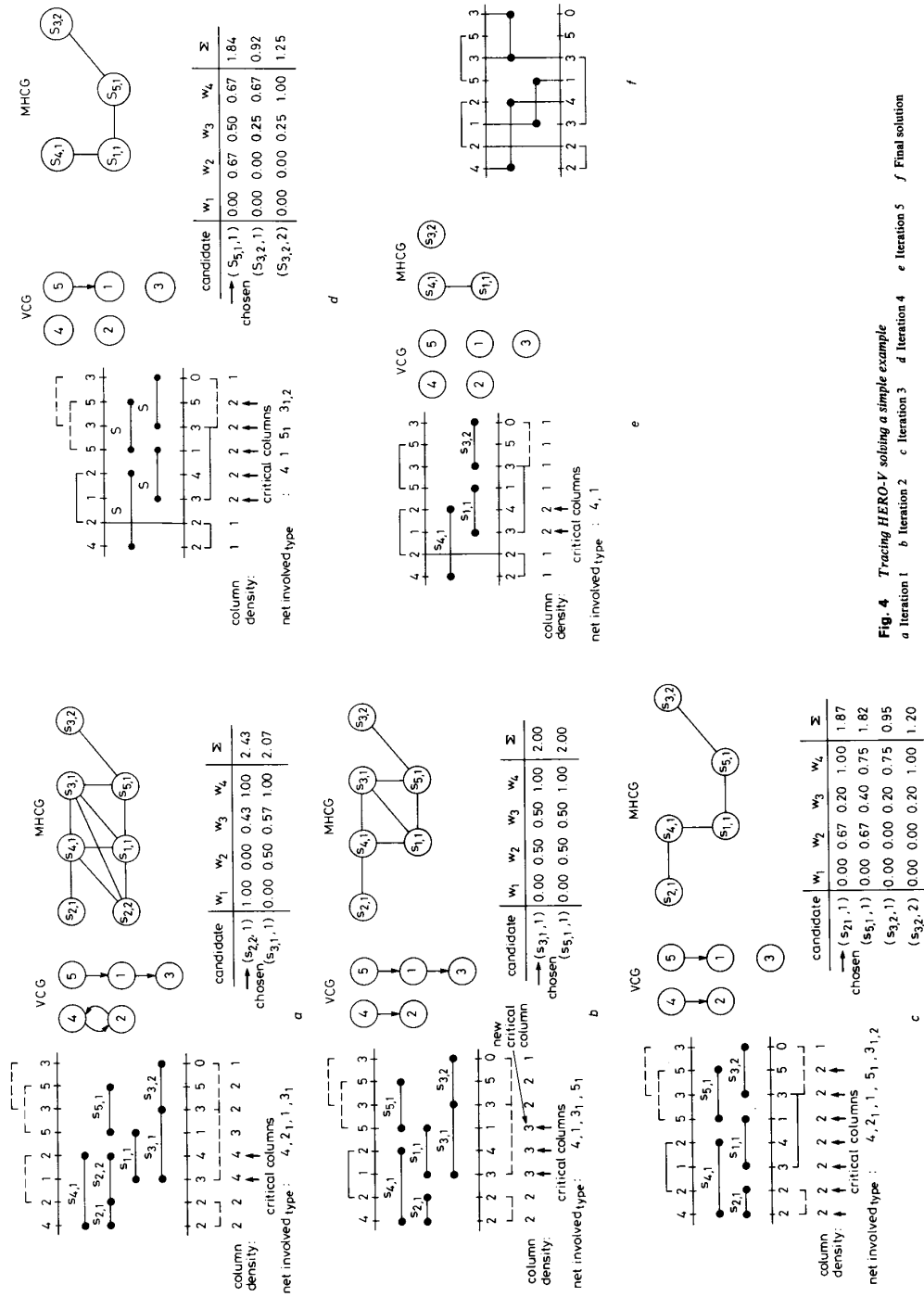


Fig. 4 Tracing HERO-V solving a simple example
a Iteration 1 b Iteration 2 c Iteration 3 d Iteration 4 e Iteration 5 f Final solution

$$w_2 = 0 \quad \text{if } n_i \notin L_{VG}$$

$$= 1 - \frac{|2l_r - l_0 - 1|}{l_0 + 1} \quad \text{otherwise} \quad (2)$$

$$w_3 = \frac{d(v_{i,j}, G_{mh})}{|V'|} \quad (3)$$

$$w_4 = 1 - \frac{f_c(s_{i,j}, p_{i,j})}{|c_c|} \quad (4)$$

Here L_{VG} is the longest path in the vertical constraint graph and l_0 is the length of the longest path, while l_r is the relative position of the candidate net in the longest path, $d(v, G)$ is the degree of vertex v in the undirected graph G .

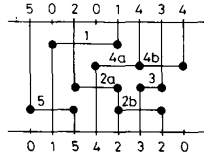


Fig. 5A Channel routing instance

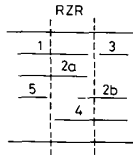


Fig. 5B Reduced zone representation

RVCG



Fig. 5C Reduced vertical constraint graph

5 Summary of our algorithm

The essence of our algorithm lies in the selection of net segments to be routed over the cells. The algorithm can be summarised in the following steps:

(a) *Decompose multiterminal nets*: All multiterminal nets are decomposed into two-terminal nets adjacent at common terminal locations thus giving us a set of two-terminal net segments.

(b) *Determine critical columns and OTC candidates*: The channel density is determined before the set of critical columns c_c is constructed. From the critical columns and based on the valid OTC routing types (see Section 4.1), we construct a set of OTC candidates which are not conflicting with those already routed OTC net segments. Conflicting ones are discarded and will not be considered further. When the corresponding net segment of the selected

candidate is removed from the channel in step (d), the column densities within its span are decreased by one and more columns become critical. Hence c_c and, similarly, the set of OTC candidates are updated in subsequent iterations.

(c) *Determine L_{VG} and find cycle-breaking nodes in VG* : We construct the vertical constraint graph VG and determine the set of longest path(s) L_{VG} . If cycles occur, we find the valid candidates that can break a cycle in VG , if they are routed OTC.

(d) *Weight assignment and OTC candidate selection*: The criticality of each OTC candidate is calculated by summing the four weights described in Section 4.1. The most critical net segment will be selected. In the case of equal weights, we choose the left-most candidate.

(e) *Track assign selected OTC candidate*: The selected candidate is then track-assigned in the OTC area. We do not perform the actual routing in this step because assigning a new selected net segment may involve shifting previously assigned segments. The final geometrical routing will be done in step (g). Next, the corresponding net segment of the selected candidate is removed from the channel.

(f) *Repeat step (b) until no more net segment can be routed over the cells*: Once a critical net segment is removed from the channel in step (e), we update the column (channel) densities. The VCG, as well as the MHCg will also be updated.

(g) *Route track assigned OTC net segments*: Assignment of geometrical track location for each OTC net segment is finalised after the above iteration. The OTC net segments are routed accordingly here. This step marks the end of the OTC routing phase.

(h) *Route remaining net segments in channel*: Net segments not routed OTC will be routed in this step using conventional channel routing techniques.

The differences between two-layer and three-layer OTC routing occurs mainly in steps (b) to (d). For each layer of metal available a disjoint candidate is selected, hence in three-layer OTC routing an M2 candidate and an M3 candidate will be selected. The enumeration of an OTC candidate set and its maintenance in step (b) contributes the highest computational complexity. The overall OTC routing is of the order of $O(n^2 k^2 l)$ where n is the number of net, k is the maximum number of net interval of a net and l is the maximum length (in terms of columns) of a net interval.

After the OTC routing phase, the remaining net segments are routed in the channel by a conventional channel router. We use an HV model for two-layer routing and an HVH model for three-layer routing in the channel. The routing problem left in the channel is much simplified as most cycles and vertical constraints are removed in the OTC routing phase.

6 Experimental results

We have implemented our algorithm in the C language on a Sun SPARC 10 station running SunOS 4.1.3. We call our program HERO-V. It was tested extensively on common benchmark examples for channel routing problem including the Deutsch's Difficult Example. Table 1 shows the results for the PRIMARY 1 benchmark compared to other algorithms, including the Greedy router [1] (denoted Gr in Table 1), OTC-1 [10], WISER [8, 9], WILMA [12] and O-V [11]. Results shown for a three-layer model assume vias are not permitted on the area

over the cells. The best result for each channel is marked with an asterisk. Table 2 shows the results compared to those in References 3 and 5. HERO-V is comparable to

Table 2: Comparison with other routers in References 3 and 5 for a two-layer model

Example	Channel length	% vacant terminal	Original density	Final channel height		
				[3]	[5]	HERO-V
Ex1	43	24	12	10	9	9
Ex3a	89	33	15	15	12	11
Ex3b	84	22	17	16	13	14
Ex3c	103	26	18	16	15	15
Ex4b	119	24	17	16	12	13
Ex5	128	35	20	14	12	11
Deutsch	175	14	19	20	17	17
Total	—	25	118	107	90	90

[5] on these benchmark examples. To check the performance on circuits with less vacant terminals, we tested the algorithm with three channels from a register decoder circuit. The results are shown in Table 3. The time taken for each execution is also indicated. With regard to the execution time, the average time taken in OTC routing one of the PRIMARY 1 channel was 19.15 s. Each of the PRIMARY 1 and our decoder benchmark examples has the channel length of 477 and 118, respectively.

Table 3: Results for decoder benchmarks and the execution times

Channel	Vacant	% Vacancy	Original density	Two-layer		Three-layer	
				Final channel height	Time (s)	Final channel height	Time (s)
D2	83	35	16	13	0.46	5	1.12
D3	103	44	15	10	1.23	4	3.81

Amongst the routers, the Greedy channel router does not use OTC are while the rest do. Comparison in Table 1 also illustrates the significance of routing over the cells. In terms of total channel height, HERO-V achieved a 41.3% improvement over the Greedy router for the two-layer model and a 61.0% improvement for the three-layer model. To emphasise this, we notice the total channel height obtained by HERO-V for two-layer routing (175 tracks) is approaching that obtained by Greedy channel router using three-layer routing (172 tracks). Note that the channels in PRIMARY 1, as in many practical layouts, have many vacant terminals (on the average 65% of the terminals are vacant). From our experience, the improvement in channel height is most promising when a channel has many vacant terminals as our approach can make use of them efficiently to reduce the channel height.

7 Conclusions

In this paper we have presented a new algorithm for the over-the-cell channel routing problem in standard cell

VLSI design. Our approach can efficiently reduce the channel height especially when there are many vacant terminals in the channel. It has achieved the best results in the PRIMARY 1 benchmark examples compared to previous algorithms.

Our algorithm is suitable for routing problems in which vias are not permitted on the area over the cells. We are currently developing algorithms for the case when vias are permitted. We hope the new algorithms will render better results in the future.

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