CONVERGE: A circular-assignment-based switchbox router with via reduction

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Abstract: The authors propose a new circular-assignment-based switchbox router, CONVERGE, based on segment assignment in circular routing. The CONVERGE router is divided into three phases: the iterative phase, the merging phase and the via reduction phase. In the iterative phase, circular routing will be applied to assign vertical or horizontal segments cycle by cycle. In the merging phase, if switchbox routing is successful, the routing result can be further improved by merging adjacent segments of the same routing net. Finally, in the via reduction phase, constrained layer assignment can further reduce the number of vias. As a result, many benchmarks have been tested on the switchbox router, and these benchmarks are successfully routed. In addition, the proposed switchbox router has better routing results than other switchbox routers on vias and wire length.

1 Introduction

The recent advances in VLSI technology allow the fabrication of a highly complex system to be implemented on a single chip. Thus, many sophisticated computer-aided design (CAD) tools are applied to design such complex systems. In particular, in building block design style, the layout problem originally consists of two subproblems: placement and routing. In general, the building blocks can be positioned on a chip in the placement phase, and the space between any two adjacent blocks is used for routing. In the routing phase, the routing region must be partitioned into channels and switchboxes. Because switchbox routing is critical for the routing phase, the switchbox routing problem must be efficiently solved in building block design style.

It is well known that the switchbox routing problem is NP-hard [1]. Hence, all of the routing knowledge has been applied to develop heuristic approaches, and many heuristic switchbox routers [2–9] have been proposed. For example, a set of five routing rules, which are applied in a specific order, successfully routes Burstein's difficult switchbox in MAREK [5]. WEAVER [6] uses the routing knowledge to develop a knowledge-based expert routing system. It seems to be a very successful rule-based switchbox router. However, the system establishes many experts and several hundred rules to make it very complex. On the other hand, it takes a long running time to solve the switchbox routing problem, and it cannot be efficiently used to route a real switchbox on the surface of a chip. MIGHTY [7] routes a detailed region based on routing modifications. The nets are put in a priority queue according to a very simple heuristical knowledge, and routed in that order. Whenever an existing shortest path is far from optimality or no path can be found for a net, these routing modifications are done: some segments of routed nets are relocated or removed. BEAVER [8], to the authors' knowledge, is the fastest switchbox router until now. It uses three different methods to connect the routing nets. The three methods are as follows: a corner router, a line sweep router and a thread router. During initialisation, a net is given control of the tracks and columns that extend out from its terminals. This control is heuristically set, and it gives the system a view of the interactions between nets still to route. CARIOCA [9] uses a net decomposition technique to route a switchbox. This decomposition is driven by the minimum Steiner tree. The nets are first divided into subnets and a subnet is the basic structure of the program. The system then gets into the following two-step loop until all subnets are routed:

(i) All subnets still to be routed are given priority by a set of heuristics, and one of them is selected and routed.

(ii) The routing of the subnet provides a new situation where priorities may have changed; another subnet is selected and routed etc.

In this paper, a new circular-assignment-based switchbox router, CONVERGE, based on segment assignment in circular routing, is proposed. The CONVERGE router is divided into three phases. First, circular routing will be applied to assign vertical or horizontal segments cycle by cycle. Again, if switchbox routing is successful, the routing result can be further improved by merging adjacent segments of the same routing net. Finally, constrained layer assignment can further reduce the number of vias. Experimental results show that the approach generates significant improvement for many benchmarks.

2 Problem description and definitions

A switchbox, S, is a rectangular routing region with four groups of fixed terminals, which are located on four sides

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of the rectangular region and are represented by an ordered top terminal set, T, an ordered bottom terminal set, B, an ordered left terminal set, L, and an ordered right terminal set, R, respectively. There exist four location functions, i.e. $t(i)$, $b(i)$, $l(i)$, and $r(i)$, in four sides of the switchbox, where $t(i)(b(i)$, $l(i)$, or $r(i))$ represents a net number on the ith terminal of top (bottom, left, or right) boundary of the switchbox.

Based on the Manhattan routing model, the main objective of the switchbox routing problem is successfully to route all of the nets, $N_1, N_2, \ldots, N_n$, in the switchbox. Furthermore, the second objective is to reduce the length of wire segments and the number of vias. Formally, the objective of a switchbox routing problem can be modelled as follows:

Obtain a successful routing $w = W(S, N_1, N_2, \ldots, N_n)$ with less length of wire segments and less number of vias,
constraint to the Manhattan routing model,
where $W(\cdot)$ is a routing function based on the location of the routing nets in a switchbox.

In Fig. 1, a standard switchbox is simply expressed by a rectangular region and four location functions. According to the assumptions on the Manhattan routing model, a feasible routing result for the switchbox can be further shown.

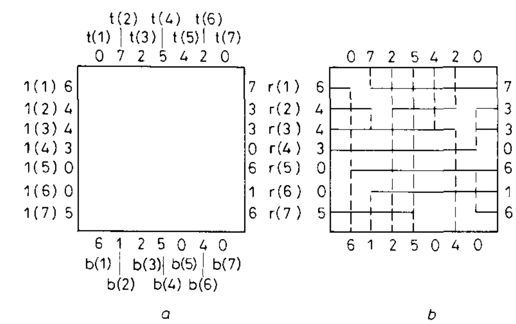

Fig. 1 *Switchbox routing*
a Standard switchbox
b Feasible routing result

Note that all of the routing nets, $N_1, N_2, \ldots, N_n$, whose endpoints are located on the boundary of the switchbox must be successfully routed in the switchbox. For a given net N_i, the horizontal (vertical) net interval H_i (V_i) is defined as an interval between the leftmost and rightmost (bottommost and topmost) terminals in the net N_i, such as $H_i = [L(N_i), R(N_i)]$ $(V_i = [B(N_i), T(N_i)])$, where $L(N_i)$ $(R(N_i), B(N_i), T(N_i))$ are the horizontal coordinate of the leftmost (rightmost, bottommost, topmost) terminal of a net N_i.

Definition 1: For a given switchbox, The vertical (horizontal) local density, VD_i (HD_i), at a vertical (horizontal) column i is defined as the number of horizontal (vertical) net intervals which cross the vertical (horizontal) column i, such as $VD_i = |\{N_j | L(N_j) \leqslant i \leqslant R(N_j), \; 1 \leqslant j \leqslant n\}|$ $(HD_i = |\{N_j | B(N_j) \leqslant i \leqslant T(N_j), 1 \leqslant j \leqslant n\}|)$, where $|S|$ represents the number of elements involved in a set S. Again, the vertical (horizontal) switchbox density, VD_{max} (HD_{max}), is defined as the maximal vertical (horizontal) local density for all virtual column lines, such as $VD_{max} = Max(VD_i)$, where $1 \leqslant i \leqslant w$ $(HD_{max} = Max(HD_i)$, where $1 \leqslant i \leqslant h)$.

In general, the vertical (horizontal) switchbox density in a switchbox seems to be seen as a low bound of the height (width) of switchbox routing. Because a switchbox is fixed and not extendible, clearly, some switchboxes are inherently unroutable.

Lemma 1: For a given switchbox, the switchbox on the Manhattan routing model is unroutable if it satisfies the following conditions:
(i) $VD_{max} > h$, or
(ii) $HD_{max} > w$

Based on the Manhattan routing model, any two vertical (horizontal) wire segments must not overlap at a vertical (horizontal) column. Hence, there exist some vertical (horizontal) constraints among vertical (horizontal) wire segments. These vertical (horizontal) constraints can further construct a vertical (horizontal) constraint graph in the switchbox.

Definition 2: A vertical (horizontal) constraint graph, G_{vc} (G_{hc}), is a directed graph G_{vc} $(G_{hc}) = G(V, E)$, where each node n_i in V is defined as a horizontal (vertical) net interval of a routing net N_i, and the directed edge $e_{i,j}$ connected from node n_i to node n_j represents that one terminal of N_i is located at the top (right) boundary of the switchbox, and one terminal of N_j is located at the bottom (left) boundary of the switchbox on the same column (row).

On the other hand, it is well known that any pair of intersected intervals cannot be assigned on the same track. Therefore, according to the intersect relation between two intervals, an interval graph for all net intervals will be further established.

Definition 3: A graph $G = (V, E)$ is called an interval graph if each vertex, v_i, in V can be represented by one nonempty interval on the axis, and the edge $e_{i,j}$ in E can be represented by the intersect relation between vertex v_i and vertex v_j.

3 Segment assignment for circular routing

In general, the routing region of a switchbox is composed of horizontal and vertical routing tracks. According to the construction of these routing tracks, the topmost horizontal track, the bottommost horizontal track, the leftmost vertical track and the rightmost vertical track can form an outer rectangular boundary called a circular track. Basically, circular routing is segment assignment on a circular track, and different track assignments can be generated by different heuristic approaches. A switchbox based on circular routing can be routed circle by circle until the routing region of the switchbox is empty. Hence, segment assignment in circular routing is a fundamental and important issue for the circular-assignment-based switchbox router. In the following, the construction of a candidate segment set for segment assignment is first discussed. A heuristic approach for segment assignment in circular routing is then proposed.

3.1 Construction of candidate segment set

Because a circular track is composed of a top horizontal track, a bottom horizontal track, a left vertical track and a right vertical track, a candidate segment set will be composed of a top segment set, a bottom segment set, a left segment set and a right segment set. In general, the construction of a horizontal (vertical) segment set depends on the vertical (horizontal) constraint graph and the locations of vacant terminals. First, according to the terminals on boundaries, the vertical and horizontal net intervals for all nets will be obtained by scanning all terminals on boundaries. Because the construction of a top segment is the same as the construction of a bottom segment set, a left segment set and a right segment set, we only discuss the construction of a top segment set in this Section.

For the construction of a top segment set, the topmost terminals on the left boundary and right boundary and the terminals on top boundary are applied to an input terminal set. Based on vertical constraint graph and vacant terminals on top boundary, each terminal in the input terminal set must be scanned from left to right for all nets and all possible segments will be decided. For any net with terminals in the input terminal set, while a vacant terminal or a same-net terminal is scanned, the horizontal net interval will be split into two segments and the two segments will be added into the top segment set. Therefore, a candidate segment set be obtained by a top segment set, a bottom segment set, a left segment set and a right segment set. For a top segment set, the set will be obtained by the algorithm Top_Segment_Set as follows.

Algorithm Top_Segment_Set

Step 1: $S \leftarrow \emptyset$

Step 2: For (each net, N_i, with terminals in the input terminal set)

Get the horizontal net interval, $\langle u_i, v_i \rangle$, for net N_i

While (there exists a vacant terminal or a same-net terminal, w in the input terminal set)

Split $\langle u_i, v_i \rangle$ into $\langle u_i, w \rangle$ and $\langle w, v_i \rangle$

$S \leftarrow S \cup \langle u_i, w \rangle \cup \langle w, v_i \rangle$.

Step 3: Return S.

3.2 Segment assignment

In general, segment assignment in circular routing is to choose a subset of the candidate set with maximal weight to satisfy routing constraints. For segment assignment, each segment in the candidate set will be assigned a weight, and an interval graph will be established according to the intersect relation between any two segments belonging to different nets. As a result, the maximum weight-independent set in the interval graph is a feasible subset of the candidate set for segment assignment. Although the maximum weight independent set (MWIS) problem is NP-complete, an interval graph has special graphical properties and the MWIS problem for an interval graph has been solved in $O(n)$ time by Hsiao [10], where n is the number of segments. Clearly, segment assignment in the proposed switchbox router will take $O(n)$ time to complete circular routing. Hence, the weight assignment and the construction of an interval graph are critical for segment assignment in circular routing.

Because the purpose of switchbox routing is to complete the routing problem, some routing heuristics of improving success probability will be used as the weight of a segment. In the weight assignment, the weight of each segment is a triple value, (W_1, W_2, W_3) and the priority of the weight is determined by comparing three weight elements sequentially. In the following, three weight element can be defined:

W_1 = span density, the maximal density under the span of the segment

W_2 = constraint reduction, the number of routing constraint reduction after assigning the segment

W_3 = span length, the sum of length of the segment.

From the definitions of the above weight elements, the physical meaning of weight W_1 is to guarantee the reduction of vertical or horizontal density in segment assignment. The physical meaning of weight W_2 is further to avoid the introduction of extra constraint cycles in the vertical and horizontal constraint graphs and to guarantee the reduction of vertical and horizontal constraints. The physical meaning of weight W_3 is to make use of the track space for segment assignment to increase success probability of switchbox routing.

Formally, segment assignment for circular routing can be divided into three steps. In the first step, four switchbox boundaries will be transformed into one horizontal boundary. Because the switchbox is a rectangular region, there exist four vacant corner-terminals, that is, upper-left corner-terminal, lower-left corner-terminal, upper-right corner-terminal and lower-right corner-terminal. The step can be completed by three substeps:

(i) Terminal exchange: two terminals next to any corner-terminal must be exchanged.

(ii) Circular track modification: owing to the terminal exchange, the circular track can be modified.

(iii) Switchbox split: the rectangular switchbox boundary can be split from one vacant corner-terminal and be stretched to one horizontal boundary.

In the second step, before segment assignment, the endpoints of all segments must be sorted from left to right and these segments are numbered as 1, 2, etc. according to the coordinates of the right endpoints of these segments. Segment assignment will be further obtained by Hsiao's MWIS algorithm [10] for the horizontal track. In the final step, the segment assignmnent of the horizontal track will be transformed into the segment assignment of the corresponding circular track. The segment assignment for a circular track can be shown in Fig. 2.

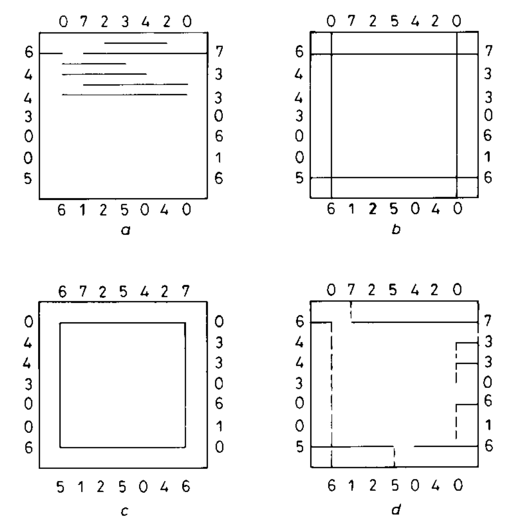

Fig. 2 *Segment assignment for a cicular track*

a Top segment set
b Circular track before terminal exchage
c Circular track after terminal exchange
d Segment assignment on a circular track

According to the steps of segment assignment for one circular track, the algorithm Segment_Assignment can obtain a feasible segment in the following:

Algorithm Segment_Assignment

Step 1: Sort the endpoints of all segments of the candidate segment set from left to right.

Number these segments as 1, 2, ..., etc. according to the coordinates of the right endpoints of these segments.

Assign a triple weight (W_1, W_2, W_3) for each segment.

Transform the switchbox boundaries into one horizontal boundary.

Step 2: Determine a subset of the candidate set by Hsiao's MWIS algorithm.

Step 3: Transform the horizontal boundary into the corresponding switchbox boundary.

Assign these feasible segments onto the circular switchbox boundary.

4 Circular-assignment-based switchbox router

Basically, the circular-assignment-based switchbox router is further divided into three phases: the iterative phase, the merging phase and the via reduction phase. According to the behaviour of circular routing in the iterative phase, the proposed switchbox router can be named CONVERGE. The three phases in detail will be described as follows.

4.1 The iterative phase

In the iterative phase, the main objective is to complete the given switchbox routing. For each iteration, a circular track along the switchbox boundary will be applied to segment assignment in circular routing. As mentioned above, based on segment assignment in circular routing, the circular track can be assigned by a subset of candidate segments. After each iteration, the remaining switchbox can be redefined as a new switchbox, and the terminals on the new switchbox are created by stretching the original terminals on to the processed circular track. Thus, a new switchbox cannot be further processed in the next iteration until a new switchbox is empty. If all of the nets are routed, the routing will succeed. On the other hand, if not, the routing will fail.

4.2 Merging phase

If the given switchbox is successfully routed, a rough routing result will be obtained after the iterative phase. Because the proposed switchbox router is based on segment assignment in circular routing, all of nets will be split into horizontal (vertical) segments and these segments will be assigned on the outer circular tracks to increase the success probability. As a result, a routing net can be divided into several horizontal and vertical segments assigned on different tracks, and there exist some unnecessary vias in the routing nets. The main objective in the merging phase is to reduce vias by merging any two adjacent segments into a segment without destroying any routing constraint. Any two adjacent horizontal (vertical) segments connected by a vertical (horizontal) segment can be tried to merge into one longer horizontal segment. Therefore, unnecessary vias will be reduced and wire length may be reduced.

4.3 Via reduction phase

Based on the Manhattan routing model, vertical segments are assigned on one layer and horizontal segments are assigned on the other layer. After the merging phase, the geometrical position of any segment is fixed and some unnecessary vias are still applied to connect these segments on different layers. In general, the via minimisation problem is called the constrained layer assignment (CLA) problem [11]. It is well known that the CLA is an NP-complete problem and no optimal approach can minimise the number of vias. In the via reduction phase, unnecessary vias can be further reduced by a greedy approach. In this approach, all of the vias in the routed switchbox will be tested. If two connected segments can be assigned on the same layer, the via between the pair of segments will be deleted. Although the approach is simple, most of unnecessary vias in a routed switchbox will be deleted. The greedy layer assignment approach can be applied to reduce vias in the via reduction phase, clearly, 20–40% of the vias will be deleted after the merging phase. The routing results of the given switchbox in Fig. 1 after the iterative phase, the merging phase and the via reduction phase are shown in Fig. 3.

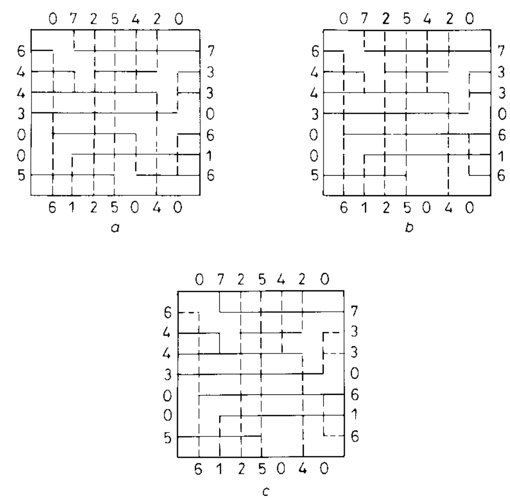

Fig. 3 *Routing result*
a After the iterative phase
b After the merging phase
c After the via reduction phase

4.4 Switchbox router

Basically, the input data is a netlist of switchbox routing and the output data is a complete switchbox routing result based on the Manhattan routing model. In the proposed switchbox router, it also checks unroutable conditions for a given switchbox. If the conditions are satisfied, the switchbox will be unroutable. The formal algorithmic description of our proposed switchbox router is listed as follows:

Algorithm Circular-Assignment-Based_Switchbox_Router

Step 1: Construct a vertical constraint graph, G_{vc}, and a horizontal constraint graph, G_{hc}.

Step 2: Judge the unroutable conditions. If the conditions are satisfied, then Return 'Routing Failure'.

{The Iterative Phase}

Step 3: Consider whether there exists a circular track or not. If not, then GoTo step 7.

Step 4: Find a candidate segment set.

Step 5: Call Segment_Assignment algorithm.

Step 6: Create new switchbox. Modify the vertical constraint graph, G_{vc}, and a horizontal constraint graph, G_{hc}. Goto step 3.

Step 7: Judge whether the routing result is complete on all of routing nets. If not, Return 'Routing Failure'.

{The Merging Phase}

Step 8: Clear unnecessary vias by merging possible horizontal (vertical) segments without destroying any routing constraint.

{The Via Reduction Phase}

Step 9: Clear unnecessary vias by layer assignment on horizontal (vertical) segments without destroying any routing constraint.

5 Experimental results

The circular-assignment-based switchbox router, CONVERGE, has been implemented using standard C language and run on a SUN workstation under the Berkeley 4.2 UNIX operating system. From applying the circular-assignment-based switchbox router to many benchmark switchboxes, it turns out that the proposed switchbox router successfully complete these switchboxes. These known benchmark switchboxes include Burstein and Pelavin's difficult switchbox [2–3], the variations Luk's dense switchbox, Luk's terminal intensive switchbox [4], Soukup's sample switchbox, Ho, Yun, and Hu's simple rectangular switchbox, and Doubois, Puissochet, and Tagant's cycle and random switchboxes [9]. In Fig. 4, the routing results of Burstein's (more) difficult switchbox with via reduction can be shown, the numerical comparison on the number of vias and the length of wires is also listed in Table 1.

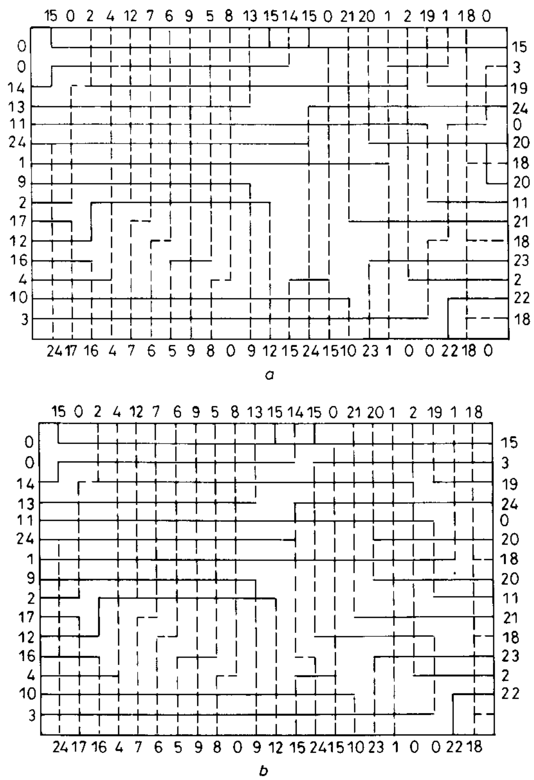

Fig. 4 *Routing results*
a Burstein's difficult switchbox *b* Burstein's more difficult switchbox

Table 1 : Comparison of Burstein's difficult switchbox

Router	Overlap	Row no.	Column no.	Via no.	Length	Time
LUK	No	15	23	58	577	1 s
MDR	NO	15	23	63	567	—
MAREK	No	15	23	58	560	5 s
GPR*	No	15	22	64	539	70 s
WEAVER	Yes	15	23	41	531	1390 s
MIGHTY	Yes	15	22	39	541	4 s
BEAVER	Yes	15	23	35	547	1 s
		15	22	34	536	1 s
CARIOCA	Yes	15	23	43	535	54 s
CONVERGE	No	15	23	34	539	3 s
		15	22	34	549	3 s

* with 45° wire

6 Conclusion

A new circular-assignment-based switchbox router, CONVERGE, based on segment assignment in circular routing, is proposed. Many benchmarks have been tested on the switchbox router and these benchmarks are successfully routed. In addition, the switchbox router has better routing results than other switchbox routers on vias and wire length.

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