An Evolutionary Constraint Satisfaction Solution for Over the Cell Channel Routing

Adnan Acan and Ahmet Unveren

Computer Engineering Dept., Eastern Mediterranean University, Gazimağusa,
T.R.N.C. Mersin 10, TURKEY
{adnan.acan, ahmet.unveren}@emu.edu.tr

Abstract. A novel combination of genetic algorithms and constraint satisfaction modelling for the solution of two and multi-layer over-the-cell channel routing problems is presented. The two major objectives of the optimization task are to find an optimal assignment of nets to over-the-cell and within the channel tracks, and to minimize the channel widths through a simple but effective iterative routing methodology. Two genetic algorithms cooperate in a nested manner to perform the optimization task. The results obtained using the benchmark problems published in literature indicate that, without any predefined fixed upper/lower channel widths, the implemented algorithm outperforms well-known channel routers.

1 Introduction

Well known conventional channel routers are developed to find a least-width channel sufficient to realize interconnection requirements in a rectangular region which carries fixed terminals along its two opposite sites (See Figure 1). In order to reduce the channel width below the channel density, some channel routers use the extra routing area over the cells, in addition to the channel area, for interconnections. Routers employing this approach are called over the cell (OTC) channel routers. In most cases, OTC channel routers can complete the interconnections using fewer tracks than the channel density. Since a large portion of the area of a VLSI circuit is used for wire routing, savings in channel area obtained by using OTC routers are usually significant. In fact, this is why OTC channel routers became attractive in research and practical applications [1], [2], [3], [4], [5].

In this paper, a novel OTC channel routing algorithm is presented. Two genetic algorithms (GAs) work together in a nested scheme in such a way that the outer GA tries to find an optimal assignment of nets to the available routing areas while the inner GA computes the fitness value of each generated assignment. Specific advantages of the proposed algorithm over the other well-known OTC channel routers are its simpler problem representation, more powerful optimization capability, low computational complexity, and consequently its low execution time. The presented algorithm can be used for any multi-layer OTC channel routing. On the one hand, it is an up-to-date routing method, which can

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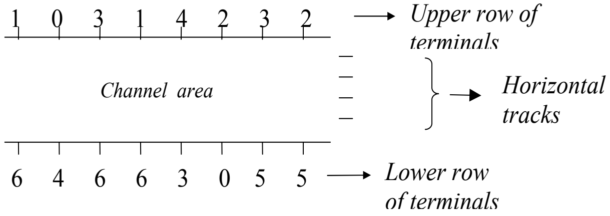


Fig. 1. A standard channel routing problem.

be implemented in the most recent cell-based design technologies for integrated circuits. On the other hand, the algorithm simultaneously optimizes the widths of over-the-cell and within the channel areas. That is, unlike the other OTC channel routers, which predefine and fix the number of tracks in over-the-cell areas, the implemented algorithm finds the widths of all channel areas through an evolutionary optimization procedure.

This paper is organized as follows. In Section 2, the basic definitions of constraint satisfaction modelling are introduced. In Section 3, constraint satisfaction modelling as applied to OTC channel routing problems is described in detail. The proposed nested genetic algorithms approach for two- and multi-layer OTC channel routing are presented with all implementation details in Section 4. The experimental results for two-layer benchmark problem instances are given in Section 5. Section 6 covers the results for multi-layer benchmark problem instances and related discussions. Conclusions and future research directions are given in Section 7.

2 The Constraint Satisfaction Modeling

Constraint satisfaction problems (CSPs) provide a general representation and solution model to a large class of combinational and other discrete structural problems. Those problems that can be represented as a CSP and solved with constraint satisfaction search techniques are those that involve one or more sets of entities (real world objects, variables, or concepts), a set of constraints (restrictions) on how entities are related to each other, and the range of values that each entity can take within a predefined domain [6].

The definition of a CSP includes the following features: a finite set of variables $V = \{V_1, V_2, V_3, \cdots, V_N\}$, finite sets of values, $D_i, i = 1, \cdots, N$, corresponding to domains of variables, and finite sets of constraints, $C_i, i = 1, \cdots, N$, that must be satisfied by any assignment of values to variables. Each variable can be assigned any of the values in its associated domain. Each constraint in the problem puts a restriction on the values that a group of variables can take in combination.

An assignment of a value to a variable is known as a binding or instantiation. The binding of a variable v to a value u is denoted as u/v. If the variable V_1 has a domain $\{u_1, u_2, u_3\}$, then its possible bindings are $u_1/V_1, u_2/V_1 and u_3/V_1$.

A constraint that can be explicitly enumerated is commonly represented by a set of possible legal substitutions. For example, a constraint C for variables V_1 and V_2 may be denoted by $C(V_1, V_2) = \{(u_1, u_2), (u_3, u_4)\}$. For V_1 and V_2 to have legal bindings according to this constraint, either u_1/V_1 and u_2/V_2 or u_3/V_1 and u_4/V_2 should be followed.

In order to find a solution for a CSP all variable assignments in the set of solutions must not violate any constraints. A solution is found only if a legal assignment can be made to all variables of the CSP.

3 A CSP Model for Multilayer OTC Channel Routing

A channel routing problem is traditionally described by a netlist. A predefined number of wiring layers are available for the routing of horizontal and vertical net segments. Layers dedicated to horizontally oriented wire segments are called horizontal layers (H-layers) and layers dedicated to vertically oriented wire segments are called vertical layers (V-layers). The two-layer routing of the problem presented in Figure 1 is given in Figure 2.

In order to represent physical constraints among net segments, graphs of vertical and horizontal constraints, VCG and HCG respectively, are used (See Figure 3). In this study, an OTC channel routing problem is defined as a constraint-satisfaction problem where the variables are nets to be routed. Constraints on net tracks (values to be assigned to nets) are extracted from VCG and HCG and are automatically transformed into a set of inequalities of net tracks. According to the described constraint satisfaction modelling, the representation of the problem in Figure 1 is illustrated in Table 1. A set D_i in Table 1 holds the possible routing tracks for *neti*, which are determined by using the constraints available in set C_i. Constraints in C_i are extracted from VCG and HCG.

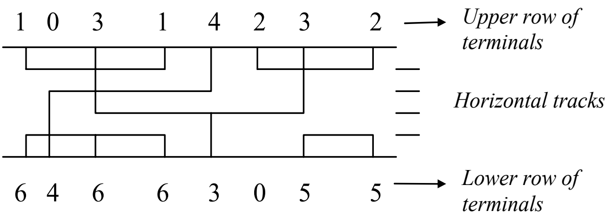


Fig. 2. A valid solution to the standard channel routing problem given in Figure 1.

For multi-layer channel routing, a router uses several H- and V-layers for the routing of horizontal and vertical net segments with no physical constraint

Table 1. Constraint function modelling of the problem given in Figure 1

$N = \{N_1, N_2, N_3, N_4, N_5, N_6\}$

$D_1 = \{1, 2, 3\}$ $\quad C_1 = \{d_1 < d_6, d_1 \neq d_3, d_1 \neq d_4\}$

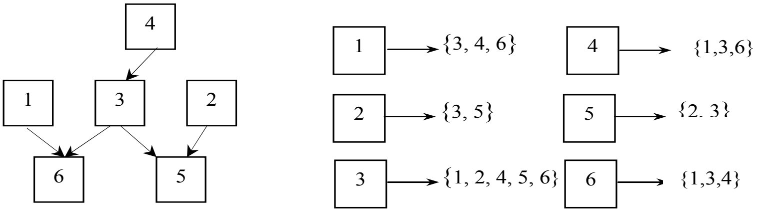
$D_2 = \{1, 2, 3\}$ $\quad C_2 = \{d_2 < d_5, d_2 \neq d_3\}$

$D_3 = \{2, 3\}$ $\quad C_3 = \{d_3 > d_4, d_3 < d_5, d_3 < d_6, d_3 \neq d_1, d_3 \neq d_2\}$

$D_4 = \{1, 2, 3\}$ $\quad C_4 = \{d_4 < d_3, d_4 < d_5, d_4 < d_6, d_4 \neq d_1\}$

$D_5 = \{3, 4\}$ $\quad C_5 = \{d_5 > d_2, d_5 > d_3, d_5 > d_4\}$

$D_6 = \{3, 4\}$ $\quad C_6 = \{d_6 > d_1, d_6 > d_3, d_6 > d_4\}$



a) b)

Fig. 3. a) Vertical constraint graph (VCG) of the problem in Figure 1, b) Horizontal constraint graph (HCG) of the problem in Figure 1.

violations. In this case, H-layers and V-layers are usually grouped in a way that the placement of each net's vertical and horizontal wire segments is simple and efficient. For this purpose, VH and HVH models are conventionally used for grouping the layers. The VH model allows using one horizontal layer and one vertical layer for routing, whereas the HVH model allows two horizontal layers and one in between vertical layer for routing. The presented algorithm makes use of a predefined number of H- and V-layers for OTC and within the channel areas as follows; let L be the total number of layers, for the cases $L = 2$ or $L = 3$, trivially the HV and HVH models are used for over the cell and within the channel areas respectively. For cases $L \geq 4$, over the cell routing uses one V-layer and $(L - 1)$ H-layers. As there is no vertical constraint available among nets in over the cell area, one V-layer is enough to route the nets assigned to this area. For example, HVH and HHVHH models are used for three- and five-layer routing for over the cell area respectively. For the cases $L \geq 4$, the presented algorithm uses one of the following cases to route the nets within the channel area [7], [8], [9], [10]:

- Case 1 $(L mod 3 = 0$ and $L \geq 4)$:
  The case has $2L/3$ H-layers and $L/3$ V-layers and
  the layers are grouped as HVH, HVH, ... , HVH.

- Case 2 ($Lmod3 = 1$ and $L \geq 4$):
  The case has $(2(L/3 - 1) + 2)$ H-layers and $((L/3 - 1) + 2)$ V-layers and the layers are grouped as, HVH, HVH, ... , HVH, VH,VH.
- Case 3 ($Lmod3 = 2$ and $L \geq 4$):
  The case has $((2L/3) + 1)$ H-layers and $(L/3 + 1)$ V-layers and the layers are grouped as, HVH, HVH, ... , HVH, VH.

4 Channel Width Optimization

The developed algorithm aims to find an optimal assignment of nets to upper, lower, and within the channel areas such that the number of upper, lower and within the channel tracks, hence the three channel widths, are minimized. The method employs a novel evolutionary optimization approach where two GAs cooperate in a nested manner [11], [12], [13], [14]. The outer GA tries to find an optimal assignment of nets to three available channel areas over a population of different assignments, and the inner GA, called by the outer GA for each net assignment, tries to minimize the channel width by optimally routing the area-assigned nets. In this way, the inner GA's results are used as the fitness values of the outer GA's individuals. Layer assignment of nets over the available multiple layers in over the cell and within the channel areas are made by outer and inner GAs. The algorithmic framework of the proposed approach is illustrated below:

```
Initialize $Outer\_Population$
For $i = 1$ $to$ $|Outer\_Population|$
  Fitness($Outer\_Population(i)$)=Inner_GA($Outer\_Population(i)$)
DONE=FALSE
While (NOT DONE)
  Mating_Pool=Selection($Outer\_Population$)
  $New\_Outer\_Population$=Crossover(Mating_Pool,$P_c$)
  Mutation($New\_Outer\_Population$,$P_m$)
  For $i = 1$ $to$ $|New\_Outer\_Population|$
    Fitness($New\_Outer\_Population(i)$)=Inner_GA($New\_Outer\_Population(i)$)
  $Outer\_Population$=$New\_Outer\_Population$
```

Chromosomes of individuals in the outer GA are vectors where each vector element holds a double containing two integer numbers. The two integer numbers determine the state and OTC layer of the corresponding net; the first integer identifies the routing state, either OTC or within the channel, while the second determines the routing layer. For the first integer number; '0' represents a net to be routed in over the cell area, and a '1' represents a net to be routed within the channel area. For example, $(0, k)$ represents a net to be routed in over the cell area and on the $k - th$ OTC H-layer. Since only one V-layer is available in over the cell area between H-layers, there is no need to identify this V-layer within each chromosome of outer GA. If a net is to be routed within the channel area, the first integer of the corresponding double is 1, then the second vector element is ignored because the inner GA will optimally make the layer assignment of these nets. For example, $(1, ?)$ represents a net to be routed within the channel area whose layer assignment will be made by the inner GA during its course of optimization procedure. The question mark indicates that the layer assignment for this net is currently a don't care. For example, the chromosome representation of the routing given in Figure 4 is $\{(0,1),(1,?),(1,?),(1,?),(0,1),(0,1)\}$.

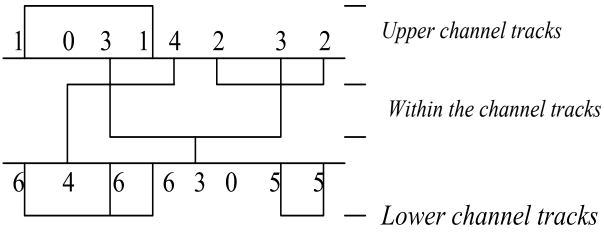


Fig. 4. Over the cell channel routing of the problem in Figure 1.

The initial population of the outer GA is easily formed by generating randomly initialized vectors of length N, where the vector elements are integer-valued doubles representing different area and layer assignments for each net. For OTC routing, the nets to be routed in OTC areas are identified from the first values of chromosome elements and, then, placed onto the appropriate tracks by checking their horizontal constraints within their H-layers, starting from the first track.

Routing within the channel area is critical in overall reduction of the channel width and it is carried out optimally by the inner GA. For each chromosome of the outer GA, first those nets to be routed within the channel area are determined. Then, chromosomes of the inner GA are randomly initialized as fixed-length vectors where each vector element is an integer-valued double; the first integer determines the horizontal routing layer (H-layer) whereas the second one corresponds to the horizontal routing track on this layer. V-layer assignments of the net segments are done according to the following cases automatically by using the H-layer numbers. Let h be the H-layer number of a net, H and V be the total number of H- and V-layers available, respectively, and L be the total number of layers.

- Case 1 $(L mod 3 = 0)$:
  If $(h mod 2 = 0)$, current net is assigned with $(h/2) - th$ V-layer.
  If $(h mod 2 = 1)$, current net is assigned with $h/2 - th$ V-layer.

- Case 2 $(L mod 3 = 1)$:
  For all $(h < H - 1)$, Case 1 is used for V-layer assignment.
  If $(h = H - 1)$, current net is assigned with $(V - 1) - th$ V-layer.
  If $(h = H)$, current net is assigned with $V - th$ V-layer.

- Case 3 $(Lmod3 = 2)$:
  For all $(h < H)$, Case 1 is used for V-layer assignment.
  If $(h = H)$, current net is assigned with $V - th$ V-layer.

An important feature of inner GA is that all optimizations are carried out over a population of feasible potential solutions. For an initial population of different feasible solutions, H-layer number is randomly assigned, and track numbers are quickly obtained using a modified form of the well-known left-edge algorithm [1], as illustrated in the following algorithm, MLEA(N_w, I_w, H_w).

```
1. Construct_VCG($N_w$).
2. Compute Max_Path_Length(VCG,$N_w$).
3. $d$=max(Max_Path_Length(VCG($N_w$)).
4. Let $T = \{T_1, T_2, \cdots, T_d\}$ denote the set of routing tracks from top to bottom.
5. Selected_Nets=Select_Nets(Max_Path_Length(VCG($N_w$), $N_w$).
6. If Selected_Nets={}
7.     Goto 24.
8. Sort_Selected_Nets(Selected_Nets, $I_w$).
9. For $i = 1$ to |Selected_Nets| {
10.    SUCCESSFUL=FALSE.
11.    For $j = 1$ to $d$ {
12.      H_Track(Selected_Nets($i$))=$j$.
13.      If (Check_Constrainst($j$, C(Selected_Nets($i$), $H_w$) == TRUE)
14.         SUCCESSFUL=TRUE.
15.   }
16.    If SUCCESSFUL==TRUE
17.      $N_w$=$N_w$ {Selected_Nets($i$).
18.    Else
19.      $d = d + 1$.
20.      H_Track(Selected_Nets($i$))=$d$.
21. }
22. Construct_VCG($N_w$).
23. Goto 5.
24. End.
```

For example, let $L = 5$ and $(3, 2)$ represents a net to be routed on third H-layer within the second track, then by the above cases it must use second V-layer. The inputs for the modified left-edge algorithm are a set of nets to be routed within the channel area $N_w = N_1, N_2, \cdots, N_m$, a set of intervals $I_w = I_1, I_2, \cdots, I_m$ corresponding to leftmost and rightmost terminal positions, and H-layer numbers of nets $H_w = H_1, H_2, \cdots, H_m$. First, this algorithm selects all the nets which are on the maximum length path of the updated VCG. Next, the selected nets are sorted in ascending order of their leftmost terminal positions. Then, they are assigned horizontal tracks, in order, within their H-layers without violating the constraints defined in problem representation. If a vertical constraints violation cannot be solved, additional tracks are used to complete the routing. After the selected nets are assigned to horizontal tracks, they are removed from the set Nw and the VCG is updated accordingly. This process is repeated until all the nets assigned within the channel area are routed. In this way, a population of different feasible solutions is formed.

The reproductive phases of outer and inner GAs are quite similar except the point that inner GA moves over feasible solutions only. The outer and inner GAs are employing uniform crossover and mutation operators with probabilities P_C and P_M, respectively. The outer GA recombines two vectors without any wonder of feasibility, however the inner GA recombines two channel routings such that the offspring produced are still feasible channel routings with different, and hopefully smaller, channel widths.

The uniform crossover and mutation operators applied on the chromosomes of outer and inner GAs are illustrated below where (↓) shows the crossover and mutation points:

Uniform crossover for outer GA:
  Parent 1: ↓(0,1) (1,?) ↓(1,?) ↓(0,2) (1,?)
  Parent 2: ↓(1,?) (1,?) ↓(0,2) ↓(1,?) (1,?)
  Offspring 1: (1,?) (1,?) (1,?) (1,?) (1,?)
  Offspring 2: (0,1) (1,?) (0,2) (0,2) (1,?)
Uniform crossover for inner GA:
  Parent 1: ↓(3,2) (1,2) ↓(2,2) ↓(1,2) (4,1) (4,2)
  Parent 2: ↓(2,1) (2,1) ↓(3,1) ↓(1,1) (4,2) (4,1)
  Offspring 1: (2,1) (2,1) (2,2) (1,1) (4,2) (4,1)
  Offspring 2: (3,2) (1,2) (3,1) (1,2) (4,1) (4,2)
Mutation for outer GA:
  Parent: (0,1) ↓(1,?) (1,?) (0,2) (1,?)
  Offspring: (0,2) (0,?) (1,?) (1,2) (1,?)
Mutation for inner GA:
  Parent: (3,2) ↓(1,2) (2,1) (1,2) (4,1) (4,2)
  Offspring: (3,2) (2,2) (2,1) (1,2) (4,1) (4,2)

The fitness values of individuals in the outer GA are the results of optimizations carried out by the inner GA. The inner GA takes the CSP representation of each individual in the outer GA and finds an optimal routing for it. The fitness function used in the inner GA is :

$$f(C) = W1 * No\_of\_Tracks + W2 * Total\_Vert\_Segments \tag{1}$$

where No_of_Tracks is the number of horizontal tracks used in the routing of an input area assignment, $Total\_Vert\_Segments$ is the total length of the vertical segments of nets in the obtained solution, and W_1 and W_2 are coefficients in (0,1). This fitness function is primarily directed to the minimization of the channel width and the total length of connections, which also helps to minimize upper and lower channel areas.

5 Experimental Results for Two-Layer Routing

For the seven benchmark channel routing problems collected from literature, the presented method is compared with the algorithms in [2] and [15] in Table 2. These two algorithms, 'A Permeation Router' [2] and 'Power Driven Routing Using GA' [15], are purposely selected because they both use evolutionary solution strategies. In Table 2, the presented algorithm is named as NGAR (Nested GA Router). It can easily be seen that NGAR outperforms its counterparts for all benchmark problem instances. For example, in row 6 of Table 2, the presented method found solutions with 7 / 7 tracks for the top and bottom over-the-cell areas respectively, compared to 18 / 15 and 12 / 9 tracks achieved for the same areas in [2] and [15]. Inside the channel, the presented method achieved a solution using 8 tracks compared with 15 and 11. The presented method is also compared with other powerful channel routers. Figure 5 illustrates the results for all benchmark problems for the comparison of NGAR with the method given in [4] which uses a planar over-the-cell channel routing technique. NGAR performed better or as good as [4] in all trials, which demonstrate the power of he presented GA approach.

6 Experimental Results for Multi-layer Routing

For further reducing the channel width, experiments are conducted with three and five layers within the channel area and two layers in top and bottom routing regions. Figure 6 and Figure 7 present the three-layer and five-layer routing results, respectively. The proposed method achieved routings with much smaller channel widths in all benchmark problem instances. Also, the results demonstrate both the success and generality of the proposed approach for multi-layer channel routing. Figure 8 illustrate the 5-layer routings of Yk3a, which clearly demonstrates the reductions in channel widths in all routing areas.

Table 2. Comparison of the proposed algorithm with the algorithms in [2] and [15]

		[2],[15]			NGAR		
Prob.	d	T	W	B	T	W	B
Yk1	12	11, 4	6, 6	7, 7	4	4	6
Yk3a	15	13, 9	15, 8	10, 6	8	8	5
Yk3b	17	8	15	8	8	7	8
Yk3c	18	18, 12	15, 11	15, 9	7	8	7
Yk4b	17	28, 8	6, 6	24, 11	7	9	8
Yk5	20	24,10	9,9	18,7	8	9	8
Deutsch	19	21, 14	12, 13	18, 14	6	13	9

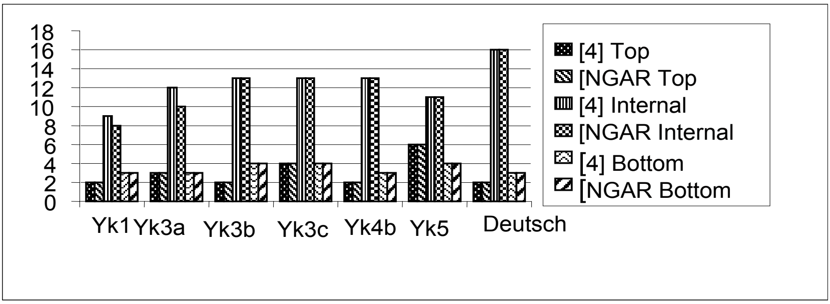


Fig. 5. Performance comparison of NGAR and [4].

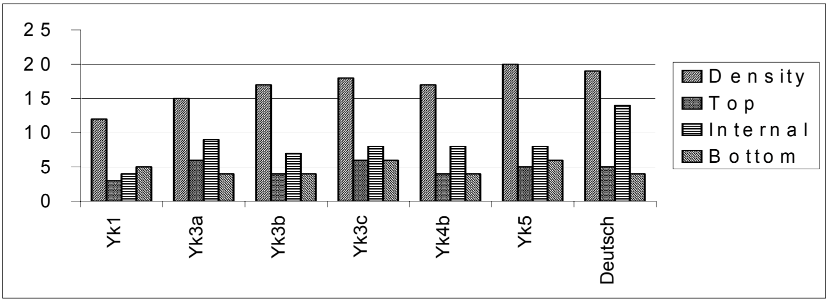


Fig. 6. Performance of NGAR in 3-layer OTC channel routing.

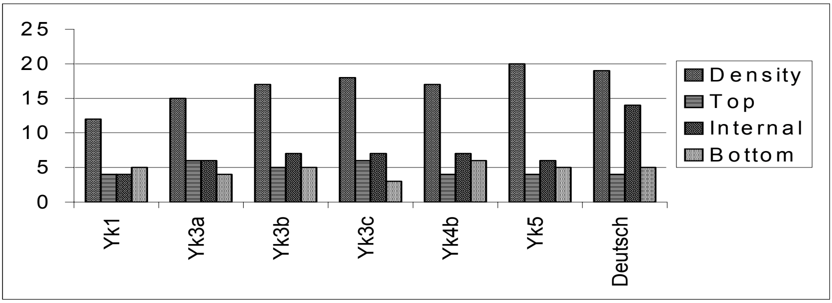


Fig. 7. Performance of NGAR for 5-layer OTC channel routing.

7 Conclusions

A constraint satisfaction modelling and a nested genetic algorithm approach is presented for the solution of well-known OTC channel routing problem. This problem is an interesting representative instance of NP-hard combinatorial opti-

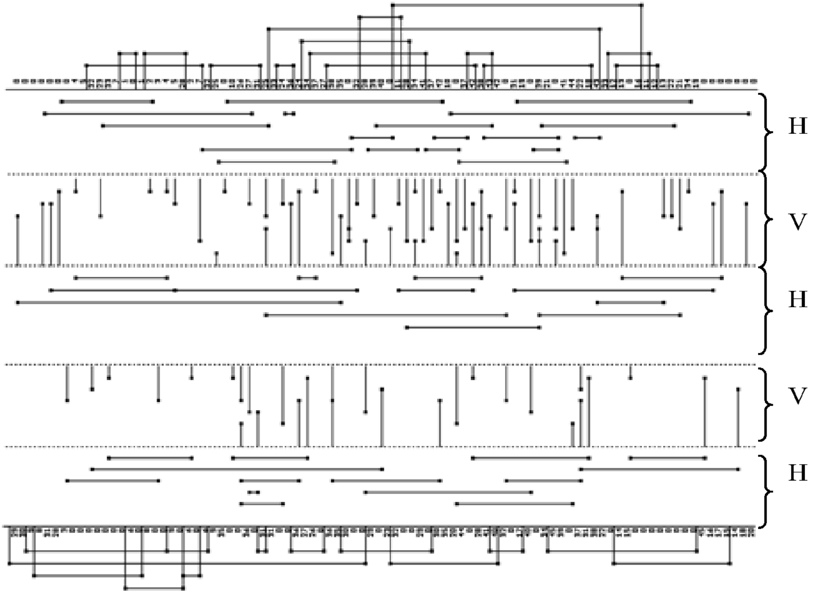


Fig. 8. Five-layer routing of Yk3a.

mization problems. The proposed algorithm combines the power of genetic evolutionary optimization with constraint satisfaction modelling to obtain a highly efficient and simple to implement method for the problem under consideration.

The novelties of the presented method can be stated in two ways. On the one hand, the proposed algorithm optimizes the assignment of nets to different routing areas using a GA which employs another GA for optimal routing of nets in their assigned areas such that the widths of routing areas are minimized. Unlike the other methods, there are no pre-specified restrictions on the widths of routing regions. On the other hand, the problem is modelled as a constraint satisfaction problem and using an evolutionary approach without passing through complicated heuristic value assignments and backtracking procedures.

The results obtained from the experiments demonstrate the success of the presented method compared to well-known OTC channel routers and its generality for the solution of two- and multi-layer problems. Simplicity of the proposed approach is another advantageous point to be stated because its implementation does not require any problem specific representations or heuristics to be used.

Further research currently undergoes in the development of evolutionary hybrid methods for the solution of well-known complex VLSI layout optimization problems.

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