Interactive Optimal Channel Router for Critical Nets

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Abstract

Presented router is an $O(n)$ computational complexity deterministic implementation of recent theoretical results. Theory shows that a net can have more than one minimum wiring length routing, and how all of them can be found. An obvious application of the rules is in critical net routing where main objectives are minimization of the wiring length, and the number of vias. Those objectives are usually met by prerouting critical nets before other signal nets, which then find prerouted wires as obstacles in the channel. Multiplicity of available optimal routings translates into flexibility of obstacles. Partitioning of a multi terminal net into flexible and non-flexible subnets provides a kind of computer vision for obstacle flexibility. Router is implemented in five modules, basic interactive module, net partitioning module, automatic and interactive initial routers, and the modification router. Examples of applications are included.

1: Introduction

Channel routing is considered by many as the most important and popular routing strategy in VLSI layout design. This approach to autorouting can be implemented on various levels of sophistication, and has proven to be useful for the regular structures of the standard cell, and gate array types, as well as in the custom chip design.

Critical nets carry signals whose propagation times can critically influence the correct operation of a whole digital system. Signal propagation times through the on chip wiring are proportional to the wire resistance, and capacitance to ground, which both increase with wiring length and the number of vias.

Majority of published channel routing algorithms have not considered critical net routing as a part of the problem to be solved. The fact that shortening critical net propagation delay times has been assigned a higher priority than to achieving minimal channel width, has been met so far by prerouting critical nets. To the best of author's knowledge, no results have been published on routing critical nets alone.

After prerouting, critical nets appear in the channel as obstacles for the subsequent channel routing step. Some recently reported channel routers [1,2,3,4] are capable of looking into the obstacle geometry. When faced with flexible obstacles, this class of channel routers could achieve better results, than in the cases when obstacles are rigid. The significance of non-rigidity in the results of design steps that precede channel routing is underlined in a recent survey article [5].

Paper describes a single net channel router whose deterministic strategy is based on theory [] that supports a set of rules for partitioning a multi terminal net into a set of subnets. Those subnets enjoy the property that their simple individual, single-track routings result in a minimal wire length, and optimal number of vias channel routing of the whole multi terminal net. Rules recognize all subnets that enjoy some degree of freedom with respect to the geometry of optimal routings. From the obstacle point of view, this introduces obstacle flexibility, because routings are determined as a set of routing alternatives, whenever they exist, rather than as a single solution.

Section 2 reviews some basic notions of the channel-type routing environment. Section 3 is an exposition of algorithmic foundations of the router. It starts with the single track per net (**STPN**) constraint on geometry of routing, and then introduces the rules for partitioning a multi terminal net into a set of subnets that can be routed using the STPN strategy while still providing an optimal routing for the whole net. Section 4 contains program description. Section 5 presents experimental results.

2: Definitions and problem formulation

Router is applicable to the classical channels, that consist of two parallel rows of equidistant terminals separated by a routing space. The geometry of routing is con-

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strained to the two-layer Manhattan model.

We define the grid of a classical channel to consist of routing columns and tracks. As shown in Fig.1, routing tracks are numbered 1 to r so that terminal rows have grid coordinates 0 and r+1. Columns are numbered 1 to n_c. Wiring pieces which coincide with columns/tracks will be called **jogs/segments.** A jog from track 1 to track r is called a **full switching jog (FSJ)**, and a jog from a terminal to the opposite outer track is called an **across the channel jog (ACJ)**.

Speaking of **terminals** in this paper, we mean channel grid coordinates of terminals. In a uniform width channel, all terminals inside the same terminal row have equal y-coordinates. As there are exactly two terminal rows, it is convenient to replace their y-coordinates 0 and r+1, by the signs - and + added respectively to their x-coordinates. The top and bottom row sets of terminals are then defined as, TT $= \{t_i | t_i \in \{1,2,...,n_c\}\}$ and $T_B = \{t_i | t_i \in \{-1,-2,..,-n_c\}\}$. Terminal weight $w_i \in \{-1,+1\}$ concept follows from the channel terminal set definition $T = \{t_i | t_i = w_i\, q_i\}$, where $q_i \in \{1,2,..,n_c\}$ is a column number. A **net** N_i is the set of terminals which must be maintained at the same potential. **Global weight** W_i of a net N_i is defined as the sum of N_i's terminal weights. Every column q_j in which a net N_i has one of its terminals is called a **terminal column** of N_i.

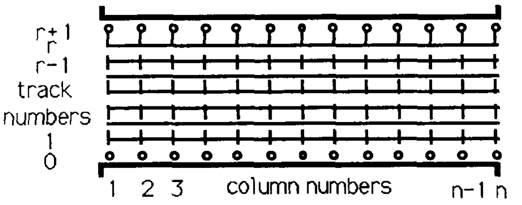

Fig.1 Channel grid numbering scheme

Horizontally monotonic routing of a net N_i is a routing that interconnects all terminals of N_i, and does not occupy two tracks in any two consecutive channel columns [14].

Channel side switching. One part of the critical net routing strategy consists of routing horizontal wires through specified channel intervals on tracks number 1, or r, exclusively. Terminal patterns in two adjacent net intervals may require routing on track 1 in interval I_i, and on track r in interval I_j. In such a case, one FSJ must interconnect the horizontal segments in I_i and I_j. From the point of view of a routing process, such a situation can be considered as one where horizontal routing switches between tracks 1 and r. It will be referred to in the sequel as channel side switching. Channel side switching is a special case of the general **track switching** that can take place between any two tracks.

The VLSI channel routing discipline has an established hierarchy of quality metrics for the general signal net routings. Minimal channel width is the primary requirement. Total wiring length is the second most important parameter, and the number of vias holds the third place. Critical net routing quality has one composite metric, the propagation delay time, which depends on the wiring length and the number of vias, which two can not be minimized simultaneously.

Critical net routing problem definition. We consider that a channel of some width d_M>1 has been set up by the building block placement geometry and the requirement to route the other nets. With the channel width minimization goal acting from the background, through the horizontal monotonicity constraint, minimization of the wiring length of critical nets takes precedence over the number of vias minimization. Hence, the following definition of the single critical net minimum wire length channel routing problem was adopted in [6], "given the channel of width d_M>1, and given a multi terminal net N_i, determine a horizontally monotonic geometry of routing that results in the minimum wiring length for N_i".

3: The algorithm

Necessary conditions for wire length optimization rely on a hierarchy of subnets: primitive (PS), constant weight (CWS), and meta subnets (MS), as defined in [6]. The method for minimizing wiring length offers options as to whether to keep the number of vias optimal, or to trade it for an increased flexibility in routing.

3.1: Single track per net algorithm

Single Track Per Net strategy is strictly applied to routing through some meta subnets. STPN was introduced by Hashimoto and Stevens [8] as a part of their "Left Edge" algorithm. It is characterized by the constraint on the geometry of routing, that the complete horizontal wiring of each individual net N_i must be routed along a single track only. Segment length is fixed under STPN; total jog length is optimized by the placement rule: Optimal track order number τ_{io} for placing the STPN segment of a net N_i is τ_{io}=r for W_i>0, τ_{io}=1 for W_i<0, and any track for W_i=0, where W_i is the global weight of N_i.

STPN was abandoned after it has been found that it prevents 100% routing in channels whose vertical constraint graph contains a directed cycle. STPN was first replaced by the **terminal column switching (TCS)** strategy, also referred to as *terminal dogleging* [9]. TCS introduced a limited freedom to switch horizontal wiring between two tracks, in terminal columns of N_i only. After it has been realized that

TCS constraint did not provide enough flexibility for routing difficult channels in optimal channel width, the **non-terminal column switching** (NTCS) was introduced.

3.2: Net partitioning algorithm

Net partitioning algorithm forms successively a hierarchy of three levels of subnets: primitive, constant weight, and meta subnets. Primitive subnet P_{jk} of a net N_i is a two-terminal net that contains two adjacent terminals of N_i, $q_p=w_p j$ and $q_q=w_q k$. To P_{jk} we assign a weight $w_{jk}=(w_p+w_q)/2$. Fig.2(b) shows the PS pattern of a net N_i with zero-weight PS's P_{ij}, P_{jk}, P_{lm}, P_{mn}, P_{no}, and P_{qr}, one positive-weight PS P_{kl}, and two negative-weight PS's P_{op} and P_{pq}. Constant weight subnets (CWS's) are formed by aggregation of adjacent PS's of equal weight. The length λ of a CWS C is defined as the number of PS's that have been aggregated into C. For example, in Fig.2 CWS's C_{ik} and C_{oq} have lengths $\lambda_{ik}=\lambda_{oq}=2$, and C_{lo} has $\lambda_{lo}=3$. Meta subnets (MS) forming rules require that a single MS is formed from: every zero-weight CWS of even-length and its adjacent weighted CWS's, and from a sequence of two or more odd-length zero-weight CWS's separated by weighted CWS's of length one; other CWS's are converted into MS's on a one-to-one basis. Application of MS forming rules is illustrated in Fig.2(d), where MS's M_{lo}, M_{oq}, and M_{qr} are formed on a one-to-one conversion basis, and the rest of them by aggregation.

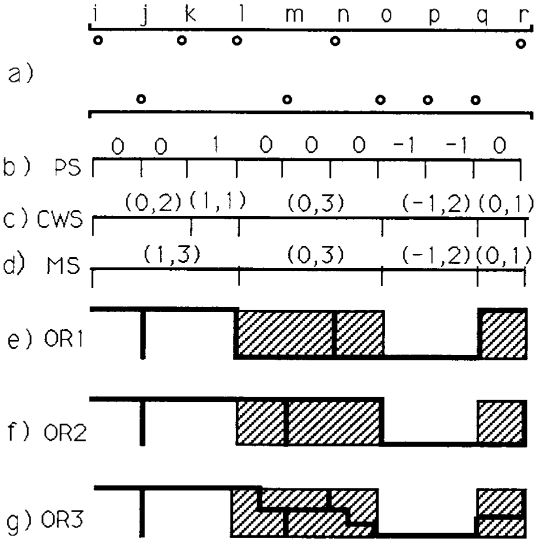

Fig.2. Hierarchy of subnets, and three optimal routings of a multi terminal net: (a) Topology of terminals. (b) Primitive subnets. (c) Constant weight subnets. (d) Meta subnets. (e) Optimal routing with switchings at the beginnings MS's. (f) Optimal routing with switchings at the ends MS's. (g) An optimal routing with partial switchings.

3.3: Basic critical net routing algorithm

It has been proven in [6] that a minimum wiring length routing of a single multi terminal net will be obtained if horizontal wires are routed in the topmost/bottommost track inside every positive/negative-weight MS, while channel side switchings must occur inside zero-weight MS's. Examples of minimum number of vias optimal routings are shown in Figs.2(e) and (f), 3(a) and 4(a); optimal routing using an optional switching column for a mandatory switching in Fig.3(b); using an optional switching in Fig.4(e); and using partial optional switchings in Figs.2(g), 3(c) and (d).

3.4: Considerations of flexibility in routing

In zero-weight meta subnets, STPN placement rule allows horizontal wires to be placed on any track, and additional degrees of freedom exist for vertical wires. In general, there are two main aspects of flexibility to be noted. First, channel side switchings that are mandatory can be accomplished in a number of different ways; second, optional switchings offer additional alternative routing patterns in meta subnets where no switchings are needed for achieving the minimum wiring length. In both cases, any channel-side-to-side switching can be accomplished in two ways, either in a single step, using up a whole single column by an FSJ, or through multiple partial switchings to/from internal tracks, where a number of columns are partially occupied by partial switching jogs. In the single step case, placement of FSJ's is flexible. That placement may be crucial, because it eliminates possibility for any other net to have even a partial track switching in that column. In the split switching case, the number of partial switchings, the jogs' placement, and the internal tracks between which the partial switchings take place, can be varied. Inside meta subnets which allow more than one switching, flexibility includes both, the number of channel side switchings and their placement.

For achieving maximal flexibility, while maintaining the minimum total wiring length and the optimum number of vias, additional insight into zero-weight MS structures is needed. Switching a critical net, from one channel side to the other, may be required and tolerated only inside zero-weight meta subnets. Among other issues, Fig.3 illustrates the need for differentiating between two classes of zero-weight MS's, the class-M and the class-O. When two nonzero-weight MS's M1 and M3 have the weights of opposite signs, $w_1=-w_3$, the MS M2 that they are separated by is a class-M MS, as shown in Figs.3(a), and 3(c). When M1 and M3 have equal weights , $w_1=w_3$, they are separated by a class-O MS, as shown in Fig.3(d).

3.5: Details of flexibility in mandatory and optional switchings

Channel side switching rules require recognition of two classes of zero-weight MS's that differ in the weight combinations of the two MS's adjacent to them. Fig.3 illustrates class-M in 3(a),(b) and (c), and class-O in 3(d). Basic switching rules specify, one mandatory channel side switching inside each class-M zero-weight meta subnet, no required switchings in class-O meta subnets, and absolutely no switchings inside weighted meta subnets. Mandatory switchings must occur inside odd-numbered primitive subnets, counting from an end of the MS. Figs.3(a) and (b) illustrate two basic aspects of flexibility in single-net minimum wiring length channel routing. Fig.3(b) illustrates the freedom in choosing the column for the FSJ that is needed for a mandatory switching; odd-numbered PS's, are indicated in it by the dashed line boxes, and a routing with an FSJ inside the third primitive subnet is shown.

Fig.3(a) illustrates the freedom in choosing the track on which to route the horizontal wire through a class-M MS. Routing on one of the outermost tracks requires a single FSJ in one of the end-of-subnet columns. Routing on any of the inner tracks would require two switching jogs, located in end-of-subnet columns, and having a total length of one FSJ. A combination of both basic degrees of freedoms, with switching jogs restricted to net terminal columns, is also possible and would result in a kind of monotonic channel side-to-side transition, as illustrated in Figs. 2(g) and 3(c). Fig.3(c) shows an optional monotonic switching, with two internal-track segments. Fig.3(d) shows that even vertically-non-monotonic routings can have minimal wire lengths; in both cases via minimization has been traded for increased flexibility.

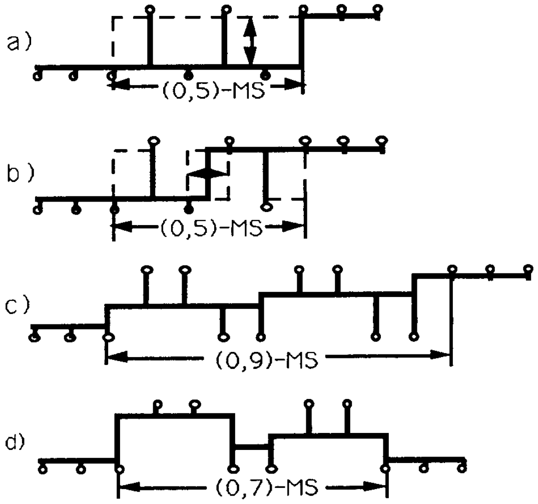

Fig.3. Illustrations of the flexibility aspects for the prerouted critical nets. (a) Level 1, jog position flexibility: single-jog, non-terminal column switching, minimal wire-length routing through a (0,5)-MS, with nFSJ=3. (b) Level 2, segment position flexibility: single-jog, EMI column transitions, minimal wire-length routing through a (0,5)-MS, with nFSJ=3. (c) Level 3, combined jog and segment position flexibility: monotonic transitions, minimal jog-length routing through a rule M2.2 derived class-A (0,9)-MS with k=4 and nFSJ=k+1=5. (d) Level 3 flexibility: non-monotonic, minimal jog-length routing through a rule M2.2 derived class-B (0,7)-MS with k=3 and nFSJ=k+1=4.

3.6: Algorithm complexity and further developments

An algorithmic implementation of the rules from Section 3 should consist of three steps, (1) determine MS structure; (2) place horizontal wires through MS's, applying the STPN placement rule, and the adopted set of constraints to each MS separately; (3) connect net terminals to horizontal wires. It is easy to show that this is an O(n) algorithm in the number of net's terminals, and independent of the numbers of tracks and columns in the channel. The described application is planned to be extended to the problem of routing two, or more, critical nets concurrently.

Considering critical and other signal nets together, the following should be observed. While flexibility in critical net routing is clearly defined by the theory [6], a need for exploiting that flexibility is not on the side of critical nets themselves, but results from the requirement that routing of other signal nets should be done minimizing the channel width. How the available flexibility of a critical net should be exploited, depends therefore on the geometry of terminals of other signal nets, and would consequently be a part of the strategy of a general channel router. In principle, any non-STPN channel router could be modified to include considerations, whether a vertical constraint should be resolved by adding a track to the channel, or the corresponding increase in channel width can be avoided by using, a segment of a track, or some column space, otherwise reserved for a flexible subnet of a prerouted critical net. This has not been implemented in the past because flexibility information was not available in a form visible by computers.

4: Program description

While designing this interactive router authors have continuously monitored the impact that their decisions would have on the user friendliness of the final product; no decision has been adopted that would trade user friendliness for a simplification it the programming task. Basic decision in that direction was, that users who require initial routings will always be provided with a valid one, irrespective of whether their specifications are acceptable, or not. Rejected specifications are accompanied by an explanation of the reason for rejection, and a hint how to proceed to obtain the desired routing details. Human errors are met with kindness.

Router has five modules, (1) the basic interactive module, (2) net partitioning module, (3) initial automatic router module, (4) initial interactive router, and (5) interactive modification router.

4.1: Basic interactive module

Basic interactive module provides for the most part of communication with users, and coordinates operation of other four modules. It first offers users the alternatives of initial net routing, or modifications of an existing critical net routing. It then prompts the user for further details. After routing has been done it displays a channel sketch, and offers a choice between redoing the existing design, or quitting.

4.2: Net partitioning module

Net partitioning module is an implementation of recent theoretical results that are described in Section 3. It partitions a multi terminal net into flexible and non-flexible subnets. Theory [6] provides complete routing specifications for non-flexible subnets only. As flexibility exists by the very virtue of not everything having been fixed, some details of routing through flexible meta subnets are not specified by theory. To obtain complete specifications, those details must be supplied by some arbitrary constraints on geometry of routing, that need to be adopted by the designers. Automatic router offers a menu of four simple constraint patterns, and the interactive initial router accepts detailed user specifications for flexible subnet routing patterns.

4.3: Automatic initial router

Automatic router performs mandatory switchings only. It offers the user a choice of four modes of routing through zero-weight meta subnets. Those four modes differ in the set of constraints that are adopted to provide the details left unspecified by theory. Routing patterns of the four modes are illustrated in Fig.3. Mode 1 provides mandatory switchings by placing FSJ's at the left end of class-M zero-weight MS's. Mode 2 provides the switchings by placing FSJ's at the right end terminal column of class-M meta subnets. Mode 3 places FSJ's at the median terminal column of class-M MS's that have internal terminals, otherwise it applies Mode 1 pattern. Mode 4 splits the FSJ into two halves that are placed, one in the right end terminal column, and the other in the left end terminal column of the class-M meta subnets.

4.4: Interactive initial router

Interactive router accepts detailed user specifications for a complete routing of a critical net from scratch. If net has already been routed, program will erase the existing routing after the user's confirmation that it can be erased. When user refuses that the existing routing be erased, he/she will be again given a choice between using modification router, or initial routers . Routing specifications are entered by the user as a sequence of column and track number pairs. For each column/track pair, column number specifies the position of a full, or a partial switching jog that will switch the horizontal routing to the right of the column into the specified track's position. All user specified routing details that violate minimum wiring length routing rules are re-

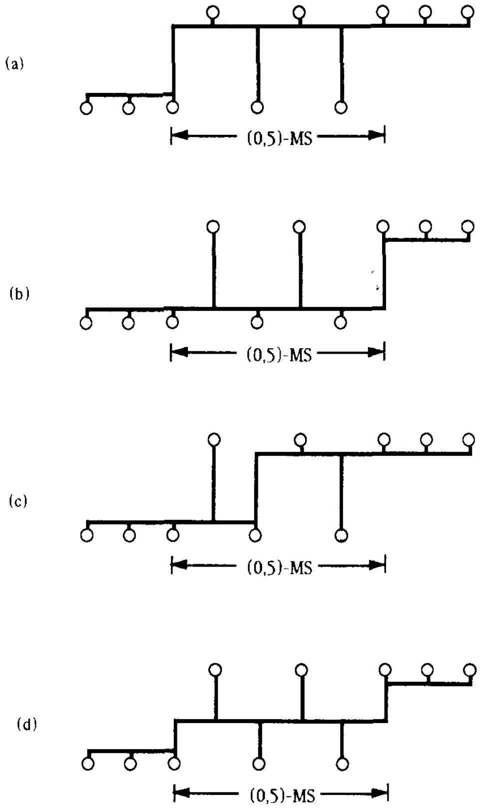

Fig.4 Four modes of mandatory switchings performed by the automatic initial router. (a)Mode-1 switching at the left end of zero-weight MS's. (b)Mode-2 switching at the right end of zero-weight MS's. (c)Mode-3 switching at a "middle" terminal column of zero-weight MS's. (d)Mode-4 switching to a "middle" track at the ends of zero-weight MS's.

placed, and all missing mandatory switching specifications are supplied by the router using the Mode 1 routing pattern of the automatic router. Warning information is displayed for the user in the cases when replacements have been introduced.

4.5: Modification router

Modification module performs partial changes on existing routings. It accepts a column/ track number pair at a time, checks conformation of the specified change with the minimum wiring length rules, and modifies the existing routing if the required change is acceptable. In order to make it easier for the users to correctly predict the changes that their specifications are going to cause, net interval that is to be affected by one column/track number specification had to be limited. After careful considerations it was first decided to allow modifications to affect only that part of the existing routing which lies to the right of the specified column. Later we came to the conclusion, that it would prove more convenient to constrain the modification from the other side also. In its present state modification router applies user's modification specification to the part of the existing routing which lies to the right of the specified column, up to the end of the primitive subinterval that contains the specified column. When the specified column/track number pair can not result in a modification that would preserve the minimum wiring length, it is rejected, and an explanation of the error in the specification is given, followed by a hint what should be done in order to make the required modification acceptable.

5: Experimental results

Single net initial routings shown in Figs.2(e) and (f), were produced by the automatic router using modes 2 and 1 respectively; those in Figs.2(g), 3(c) and 3(d) by the interactive initial router.

Fig.5(a) shows an incomplete routing of a channel where a prerouting of a critical net has caused a failure of the subsequent channel routing step. It is a good example of how even a trivially simple channel can be adversely affected by an unfavorable automatic prerouting. Figs.5(b) and (c) show that critical net has two positive-weight meta subnets, separated by a class-O zero-weight MS, which does not require a mandatory switching. As automatic router performs only mandatory switchings in order to keep the via number optimal, it has routed the critical net without any switchings, using the STPN strategy which places the complete horizontal routing on the topmost track. Two bottom row terminals of the critical net had to be connected in their columns by two ACJ's. One of them blocks the column needed for resolving a cyclic vertical constraint between nets 1 and 2, while the other causes a vertical constraint violation between net 4 and the critical net. Optional switching pattern shown in in Fig.5(d) would free up those two columns at the expense of two additional vias, and at no cost in the critical net wiring length. The unfavorable critical net prerouting from Fig.5(a) can be changed into the favorable prerouting shown in 5(e) using the modification router. Due to limitation of the subnet interval that can be affected by a modification, which was explained in Section 4.5, a three step intervention was required. In the preliminary first step a column/track-number pair specification (6,1) moves the horizontal segment through the primitive subnet between columns 6 and 8 to track number 1. The other two steps' specifications (4,1) and (8,1) can be entered in any order. Using any one of the latter in the first step would be rejected by the modification router, because they alone would cause an increase of the wiring length. The same prerouting from Fig.5(e) was obtained faster using the initial interactive router. Only two switching specification were needed (4,1) and (9,4), and they could be entered in any order, because the whole sequence of column/ track-number pairs is sorted before further processing.

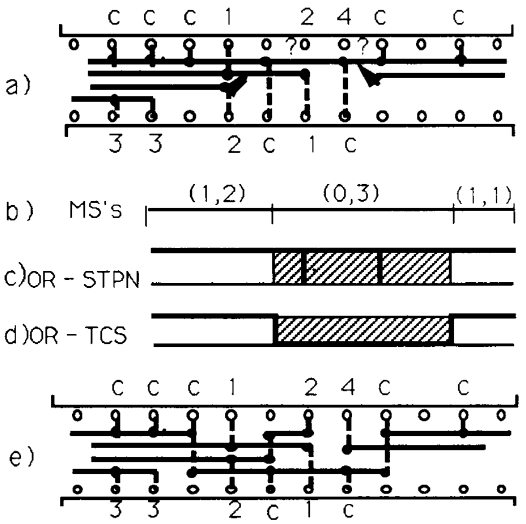

Fig.4 An example of optional switchings used to make a channel routable. (a) An unsuccessful routing attempt due to an unfavorable critical net prerouting. (b) MS structure of the critical net. (c) The unfavorable automatic prerouting without optional switchings. (d) An alternative optimal critical net routing with optional switchings. (e) Successful routing of the same channel using the favorable prerouting from (d).

6: Conclusion

Described routing tool uses a deterministic algorithm to solve the problem of minimum wiring length, and optimum via number channel routing for a single multi terminal net. Both the automatic and the interactive router options have computational complexity O(n) in the number of net terminals. An obvious application for this channel routing tool is the prerouting of critical nets, for which an algorithmic solution has not been published so far.

Of significance for the VLSI design automation is the optimal routing flexibility representation in terms of the meta subnet structure. Meta subnet structure creates a kind of computer vision for the topological properties of signal nets that were in the past only partially visible to an expert human eye, and that were totally invisible to computers. Examples of the flexibility property, and a demonstration of its possible usefulness in resolving some vertical constraint problems are included.

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