A METHOD OF MEASURING NETS ROUTABILITY FOR MCM'S GENERAL AREA ROUTING PROBLEMS

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ABSTRACT

A method for measuring routability/wireability is proposed for use in general area routing problems of MCM designs. The routability is measured by extending the counting method of Pascal's Triangle for potential routes of each net. Using this method, the number of potential routes can be obtained precisely in the presence of arbitrary obstacles including the possible limitations on the number of vias/bends to use. Experimental results of the technique proposed herein are presented.

1. INTRODUCTION

Traditionally, physical design of electronic modules consists of partitioning, placement and routing. The primary goal of this design phase is to produce a layout ready for fabrication. Whether designing PCBs, MCMs or ICs, a problem that frequently arises is determining if the layout will be routable at the end of the placement stage. This is the classical problem of predicting routability/wireability that has been known since the early days of physical design. Routability, as the name suggests, is a measure of the percentage of connections that can successfully be routed given the placement of modules, the amount of wiring space and the set of connections to be made [14].

In light of the routability prediction, obtaining a reasonable measure that insures a realizable interconnection during the early stage of the design phase has always been desired. However, due to the difficulty of quantifying the "real" routability measure, the average wire-length, or something similar, has been commonly used as a measure of routability. Most placement algorithms, for example, attempt to minimize wire-length based on the number of intra-module connections [14]. They achieve good routability this way by assuming that short connections will reduce congestion and will be easier to route than the long ones. The most reliable (but not very helpful) method of measuring the routability is to actually perform the place-and-route steps. Without going through the actual place-and-route, the average wire length can only serve as a very rough estimate. In fact, it would be difficult, if not impossible, to actually derive the mathematical relationship between the average wire length and the measure of routability.

Models for predicting routability have been developed in the context of traditional VLSI layout methodologies [13]. Roughly the approaches can be classified into two categories: (1) stochastic-based wiring space estimation and (2) computational geometric based algorithms. In the first category, initialized by works on wiring space estimation [15, 6], stochastic models were used for predicting the probability of successfully routing the placement within the allocated space [7]. Subsequent works [5, 14, 1, 3] proposed 2-D stochastic models to represent designs with regularly placed sub-circuits such as gate arrays or FPGAs. The second category is characterized by the idea of cut and capacity where the requirement of regularly placed sub-circuits was no longer necessary. The cut is a line segment connecting two visible end of features in the routing area and the capacity is the maximum number of wires which can cross the cut. The flow of a cut is then defined as the number of wires passing across a cut. One can then say that a design is routable when flows never exceed cuts. Here, the flow of wires crossing a cut was obtained by a pre-processing step. In [8] for example the pre-processing step was done by a global router, and in [12, 4] this was accomplished by a rough sketching process.

This work searches for a realistic way of measuring the nets' routability rather than relying on the average wire length. It focuses on general area routing problems [10, 2, 11] found in MCM designs. The proposed technique will be based on a simple Pascal's Triangle method to determine the number of possible paths in the bounding box formed by two terminals. This facilitates the possibility of considering arbitrary obstacles and precisely determines the number of potential interconnects that each net may have. A further development of the technique has made it possible to measure the potential routes when the number of vias allowed is limited.

In addition to providing feedback for improving the placement algorithm, the routability measure can also serve to feed forward information for routers. Routing usually is carried out in layer by layer basis [10, 2, 11]. Given a set of interconnect data, or a netlist, most routers attempt to connect the nets in the first layer or layer pair. Some of the nets may get routed and some may not. The unrouted nets will then be propagated to the second layer and so on. In a simplified example, consider a general area routing problem where all terminals, i.e. the end points of the nets, occupy the first layer of the routing planes. These terminals are basically obstacles to all potential interconnects. To some

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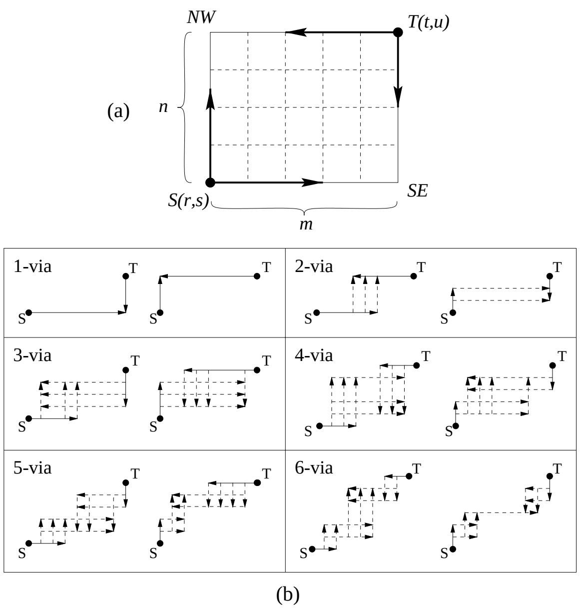

Figure 1. (a) A Net and The Bounding Box, (b) Route Types.

of the nets, the presence of the terminals alone could mean a blockage that prevents the router from completing the interconnects. In this case, the router should simply ignore such helpless nets and defer processing for the next layer. If one can identify which nets do not have the potential for routing in each layer, then the routers can make use of this information for improving the routing process.

2. A NEW ROUTABILITY MEASURE

This section starts the discussion with some observations on how one can route a net when the available space is limited to the net's bounding box. Then the method for calculating the number of possible routes when there exist some arbitrary number of obstacles inside the bounding box is introduced. The method is then developed further to include the ability to calculate the number of routes when the number of vias is limited.

2.1. Routability Inside a Bounding Box of a Net

The bounding box of a net is defined as the smallest rectangle enclosing the net's two end points [16]. Assuming a clean bounding box, the number of possible routes of a net can be calculated using a combinatorial analysis. The bounding box consists of evenly spaced grids where the route can go through or change directions. Routing starts at one end point of the net and always advances toward the other end point to form a path. This path consists of vertical and horizontal wire stubs/segments connecting the grids that the route goes through. The result is a minimum rectilinear path (MRLP) which is also known as a Manhattan route.

There are two styles of routing techniques for MCM designs: single-layer and x-y routing styles. The two differ in the way they support changing directions in each route. The former places the wires for the entire route for the net on one routing plane. The latter performs the routing on a pair of adjacent layers, with one layer for horizontal wires and the other for vertical wires. When a route needs to change direction, the horizontal wire and the vertical wire are connected by a via. Through out this paper only the x-y routing style is considered. In addition, it is assumed that the routing problems contain two-terminal nets only, i.e. the type of nets whose terminals are located at their two end points only. In many practical cases, however, some nets may contain more than two terminals which are also known as multi-terminal nets. In such cases they will be treated as a set of two terminal nets.

To begin, a single 2-terminal net is shown in Fig. 1a. The terminals are S (source) and T (target) located at (r, s) and (t, u), respectively. The two corners NW and NE are the conjugate corners. Two imaginary Euclidean lines exist in the bounding box of net $S - T$. The first is the main diagonal connecting the two terminals and the second is the conjugate diagonal connecting the conjugate corners. Given the locations of S and T, there are many possible MRLPs that can be established to connect the two terminals. One possible routing scheme (e.g. MCG [11]) is to trace the perimeter of the bounding box in both x and y directions from terminals S and T toward the two conjugate corners. When the traces intersect at the conjugate corners then there will be at most two MRLPs that can be established containing 1 via. In practical cases however, 1-via routes cannot always be found due to some obstacles that may be present on the perimeter. This forces the routing to change direction toward the inside of the bounding box in order to avoid the obstacles. Consequently, by assuming the x-y routing style one additional via must be introduced whenever the route needs to change direction.

The number of vias connecting a route determines the type of the route. Fig. 1b depicts a list of possible route types based on the number of vias. They are 1-via route type through 6-via route type. 0-via routes were not included in the list since a net from $S(r, s)$ to $T(t, u)$ can only have a 0-via route if $r = t$ or $s = u$. From these route types the following observations can be drawn: (1) route types with odd (even) number of vias start and end on different (the same) layers, (2) route types with a higher number of vias recursively contain lower via problems, (3) the maximum number of vias depends on how far apart the terminals are, (4) the larger the number of vias, the closer the path to the main diagonal.

In the next subsection, an analytical method is presented to answer to the following question. Given a net whose terminals are S and T, how many possible MRLPs are there from S to T?

2.2. Routability Measure by Combinatorial Analysis

In the absence of obstacles, the number of possible routes of a net can be obtained using a combinatorial analysis. Although the result doesn't seem to be applicable for practical purposes, the combinatorial analysis serves as an important basis for obtaining the new method of routability measure developed herein.

Consider a net with two terminals as described earlier and shown in Fig. 1a. It is assumed that all grids inside the net's bounding box are available for routing purposes or, in other words, there is no obstacle inside the bounding box. For a given net whose terminals are $S(r, s)$ and $T(t, u)$, let $m = |t - r|$ and $n = |u - s|$. The number of possible MRLPs connecting the two terminals is then given by

$$N(m, n) = \binom{m+n}{m} = \binom{m+n}{n} \tag{1}$$

This is also known as "the north-east paths" theorem where each possible MRLP can be thought of as a binary sequence of length $m+n$. Let 0 represent a horizontal segment, and 1 represent a vertical segment. The total number of possible MRLPs is basically the combinations containing m 0s and n 1s.

The number given by $N(m,n)$ can be enormous especially when the terminals are very far apart. This of course includes all of the possible MRLPs regardless of the multitude of vias. When one is interested in counting the MRLPs that change directions for only a certain number of times then it is often desirable to simply disregard the routes containing many vias. In such a case the combinatorial analysis can still easily be used to accommodate this interest as long as there is no obstacle in the bounding box.

As observed earlier, the maximum number of vias connecting an MRLP depends on how far apart the terminals are. The farther apart the terminals the more vias the MRLP can have. In contrast, a net whose terminals are in line ($r = t$ or $s = u$) will never have an MRLP containing even a single via. Indeed the multitude of vias to use should be set to a number no more than what an MRLP can have. This number can be obtained as follows. For a net with $m > 0$ and $n > 0$, the maximum number of vias that an MRLP can have is given by

$$V(m,n) = \begin{cases} 2m-1, & \text{if } m = n, \\ 2 \times \mathrm{Min}(m,n), & \text{otherwise.} \end{cases} \quad (2)$$

Again, an MRLP can be viewed as a binary sequence of length $m+n$ containing m 0s and n 1s. The first case is when $m = n$. If $m = n$ then the maximum number of transitions happens when 0 and 1 alternate in the sequence. The sequence that starts with 0 will end with 1 and vice versa. Consider now the sequence that starts with 0. In this sequence, each of the 1s represents 2 transitions except for the last 1 which represents only 1 transition. Thus the number of transitions in this sequence is $2n-1 = 2m-1$. The sequence that starts with 1 behaves similarly. The second case is when $m \neq n$. Consider $m > n$. The maximum number of transitions is obtained when each of the 1s is in between 0s. In this case each of the 1s represents 2 transitions or in other words the maximum number of transitions is equal to $2n$. If $n > m$ then the maximum number of transitions is $2m$. So if $m \neq n$ then the maximum number of transitions is $2 \times \mathrm{Min}(m,n)$.

Eq. 2 leads to two consequences. First, a router should not probe a net for possible routes with vias greater than $V(m,n)$. Second, $V(m,n)$ reflects the number of possible MRLPs since it basically represents the size of the bounding box which in turn determines $N(m,n)$.

Finally, one may also be interested in finding the MRLPs that go through a certain point located inside the bounding box. Suppose that this intermediate point is I located at (i,j). The number of paths from $S(r,s)$ to $T(t,u)$ that go through $I(i,j)$ can then be calculated using Eq. 1 as follows.

$$N^I(t-r, u-s) = N(i-r, j-s) \times N(t-i, u-j) \quad (3)$$

Or, if I is an obstacle then the number of MRLPs from S to T that don't go through I is simply the difference between $N(t-r,u-s)$ and $N^I(t-r,u-s)$. This is useful especially when there's only a single obstacle present inside the bounding box. However, as the number of obstacles becomes larger, it will be increasingly difficult to apply the formulation due to the combinatorial nature of the problem, not to mention if one wants to limit the number of vias that the net can have.

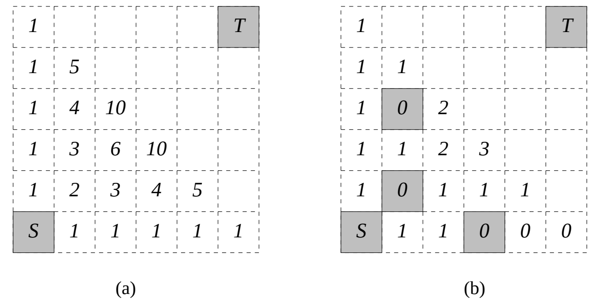

Figure 2. The Pascal's Triangle Method.

The above analysis applies only when there is no obstacle present inside the net's bounding box. In practice, obstacles will almost always be present inside the bounding box of a net. In fact, when the bounding box is free of any obstacle, there's no real need to find out how many MRLPs that the net can have. A good router would always route the net with the least possible number of vias which in this case is 1-via route type. On the other hand, the maximum number of vias given in Eq. 2 is probably a lot more useful in practice. Not only does it reflect the number of MRLPs, but it also needs less computation effort since no factorial calculation is involved in the equation.

In the following subsections, a more applicable method for calculating the number of possible MRLPs is presented. The method measures the routability of a net in the presence of an arbitrary number of obstacles. It is then developed further to include the ability to calculate the number of possible routes whose number of vias is limited.

2.3. Possible Routes by Pascal's Triangle

Given a net from $S(r,s)$ to $T(t,u)$, one can calculate the number of possible MRLPs using Eq. 1 as shown earlier by setting $m = |t-r|$ and $n = |u-s|$. Without loss of generality, suppose now that the net is enclosed in a square bounding box, i.e. $m = n$, as shown in Fig. 2. Then consider the conjugate diagonal of this bounding box. In order to connect the terminals, it is clear that all possible MRLPs from S to T must cross the conjugate diagonal. By Eq. 1, these routes are distributed among the grids lying on the diagonal according to the coefficients of a binomial distribution. The numbers of MRLPs from S to the grids lying on the conjugate diagonal are shown in Fig. 2a which indeed corresponds to the coefficients of a binomial distribution.

Algorithmically, the number of routes arriving at each grid of the conjugate diagonal can be obtained by using the method that has been used for finding the coefficients of a binomial distribution, namely the Pascal's Triangle Method. It is basically a 2D counting method starting from $(0,0)$ and advancing in the increasing order of the abscissas. Let us refer to the method as the Conventional Pascal's Triangle Method (CPTM) which is again applicable when the corresponding net contains no obstacle inside the bounding box. The method states that the entry of (i,j) is equal to the sum of the entries of $(i-1,j)$ and $(i,j-1)$. By definition, the entries of $(0,j)$ and $(i,0)$ are equal to 1, $\forall\, i,j$. Assuming that a net starts from $S(0,0)$, then the entry representing $I(i,j)$ found by CPTM is nothing else but the number of MRLPs from S to I. According to Eq. 1, it is equal to $N(i,j)$. And thus the entry found by CPTM at (m,n) is equal the total number of possible MRLPs from S to T.

Definition 1 *In* CPTM*, the number of* MRLP*s arriving at grid point* (i,j) *from the net's terminal of origin* $S(0,0)$ *is*

$$M(i,j) = M(i-1,j) + M(i,j-1) \quad (4)$$

where $M(i,0) = M(0,j) = 1, \ \forall \ i,j > 0$.

One important feature of CPTM is the fact that it can easily be extended to handle cases where obstacles are present inside the bounding box. The basic idea is to set an entry to a zero value if it corresponds to an obstacle in the bounding box. Fig. 2b depicts the new method for calculating the number of MRLPs from S to T in the presence of obstacles shown in grey. This extended method is referred to as the Obstructed Pascal's Triangle Method (OPTM).

Definition 2 *Let* $O(i,j)$ *be a function that tells whether or not grid point* (i,j) *inside the bounding box is occupied by an obstacle, or for* $r \le i \le t$ *and* $s \le j \le u$,

$$O(i,j) = \begin{cases} 1 & \text{if } (i,j) \text{ is free,} \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

Adopting Definition 1, the OPTM considers each entry similarly. The only addition is to evaluate whether the entry corresponds to an obstacle.

Definition 3 *Let* $P(i,j)$ *be an entry representing grid point* (i,j)*. It is located inside the bounding box of a net whose terminal of origin is* $S(0,0)$*. The bounding box contains an arbitrary number of obstacles which can be identified by* $O(i,j)$*. In* OPTM*, the entry representing grid point* (i,j) *is defined as*

$$P(i,j) = O(i,j)\,[P(i-1,j) + P(i,j-1)] \quad (6)$$

where $\forall \ i,j > 0 : P(i,0) = O(i,0)P(i-1,0)$ *and* $P(0,j) = O(0,j)P(0,j-1)$

In the above definition, the existence of every obstacle is taken into account for calculating the MRLPs. The existence of an obstacle in grid point (i,j) will prevent any MRLP from passing through. If grid point (i,j) is not free, then no path could pass through (i,j), consequently $P(i,j) = 0$. Otherwise the routes can simply pass the grid point. The MRLPs passing the grid point (i,j) are called *unblocked* when $P(i,j) \neq 0$.

Lemma 1 *The entry* $P(i,j)$ *given by* Eq. 6 *is an accumulation of the unblocked* MRLP*s from the previous entries.*

Proof: Suppose that grid point (i,j) is free and there exists an obstacle at grid point $(i-1,j)$ implying that $O(i,j) = 1$ and $O(i-1,j) = 0$. Applying Eq. 6 to grid point $(i-1,j)$ results in $P(i-1,j) = 0$ and consequently $P(i,j) = [0 + P(i,j-1)]$. In other words, only unblocked MRLPs can get through to (i,j). □

Theorem 1 *The number of possible* MRLP*s of a net from* S *to* T *is given by the OPTM entry representing* T.

Proof: By Lemma 1, the entry of *OPTM* representing T corresponds to the number of unblocked MRLPs that arrive at T recursively from S. □

Using the above theorem, OPTM is basically the same counting method as CPTM with additional features to handle obstacles. The entries of OPTM can be represented in two arrays. They correspond to the columns of the net's bounding box, one for even numbered columns and another for odd numbered columns. Counting starts from S and advances toward T.

In the final count, OPTM always includes all possible MRLPs that can be found regardless the number of vias. If one intends to calculate the number of possible routes using this method and simultaneously wants to limit the number of vias, then the method presented in the next subsection will be more appropriate. It's called the Extended Pascal's Triangle Method (EPTM).

2.4. Extended Pascal's Triangle Method for Limiting Number of Allowed Vias

In many cases, it is desirable to limit the number of vias that a route can have. In fact, routers (e.g. V4R[10], MCG [11]) do impose the limit for both algorithmic and technical reasons. In the earlier discussion, it was observed that routes with a large number of vias contain problems with a smaller number of vias. This implicitly expresses that routing procedures involving a large number of vias are potentially more tedious than those with a smaller number. Another important reason for limiting the vias is yield consideration. When a via is introduced, a connection from the x running wire to the corresponding y running wire has to be established physically in the fabrication process [10]. This process requires quite a degree of precision which affects yield. In addition, introducing vias also means decreasing the routing space since vias occupy both x and y layers and thus prevents additional nets from utilizing the space. Furthermore, each via corresponds to changing direction and thus introduces discontinuity in the electrical model of the wire.

Consider a net from $(0,0)$ to a grid point located at (i,j) as shown in Fig. 3. Let $w \le V(i,j)$ be the number of vias that the net is allowed to have. The net is to be routed using MRLP. According to Eq. 1, there are as many as $N(i,j)$ possible routes arriving at the grid point (i,j). They consist of those coming from the left and those from the bottom. Clearly, only a portion of these routes arrive at the grid point (i,j) with w vias.

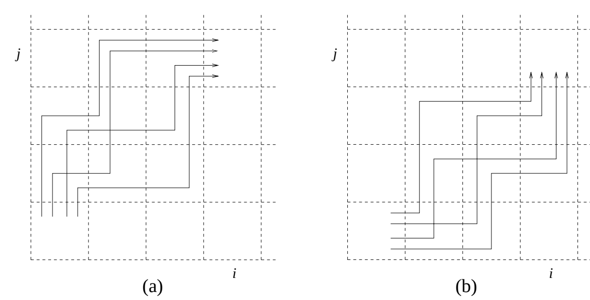

Figure 3. Example of 3-via MRLPs

Lemma 2 *The* MRLP*s arriving at grid point* (i,j) *with* w *vias consist of*

$$L^w(i,j) = \left[L^w(i-1,j) + B^{w-1}(i-1,j)\right] O(i,j) \quad (7)$$

$$B^w(i,j) = \left[B^w(i,j-1) + L^{w-1}(i,j-1)\right] O(i,j) \quad (8)$$

where $L^w(i,j)$ *and* $B^w(i,j)$ *are the numbers of* MRLP*s coming from the left and the bottom of* (i,j)*, respectively. By definition,*

$$L^w(i,j) = B^w(i,j) = 0, \quad \forall \ i,j \le 0$$

and

$$L^0(0,j) = O(0,j)L^0(0,j-1) \quad for \quad j > 0$$
$$B^0(i,0) = O(i,0)B^0(i-1,0) \quad for \quad i > 0$$

Proof: Eq. 7 shows the number of MRLPs with w vias which were coming from the left of grid point (i, j). These routes consist of those already having w vias coming from the left of $(i-1, j)$ and those having $w-1$ vias coming from the bottom of $(i-1, j)$. The latter turn right and end up with w vias. These MRLPs will pass through the grid point if there's no obstacle present. point (i, j). Eq. 8 can be proven similarly. □

In the example shown in Fig. 3, a set of MRLPs containing 3 vias is considered. In Fig. 3a, there are 4 possible 3-via routes which are coming from the left of grid point (i, j). These 3-via routes consist of those which already bend three times coming from the left of grid point $(i-1, j)$ and those which bend twice coming from bottom of grid point $(i-1, j)$. The MRLPs shown in Fig. 3b are basically the mirror of those in Fig. 3a.

Lemma 2 is inherently recursive since considering w-via routes requires also considering the ones with $w-1$ vias. This fact turns out to be quite useful since the routes will include all of MRLPs containing w vias or less. When a limit is set for the number of vias, one often wants to obtain any routes as long as the number of vias doesn't exceed the limit. In practice [10, 11], each route is allowed to have vias from 0 up to 4 or 6.

Theorem 2 *The number of* MRLP*s from* $S(0,0)$ *to a grid point* (i, j) *containing* v*-or-less vias is given by*

$$N^v(i,j) = \sum_{w=0}^{v} \left[B^w(i,j) + L^w(i,j) \right] \qquad (9)$$

Proof: This is a direct calculation using Lemma 2. □

The main disadvantage of the above theorem is the fact that it needs to maintain a set of arrays whose length depends on the value of v. The larger the number of limiting vias, the longer the arrays and thus the more space we need. However, since it maintains the number of routes for each possible via (0, 1, ..., v) in an array, the distribution of routes is automatically revealed.

2.5. Implementation Issue

The EPTM algorithm is probably best described through a small example such as shown in Fig. 4. The net is from S to T with three obstacles inside the bounding box. The terminals are identified in gray and the obstacles are drawn in solid black. In this example the MRLPs are allowed to only have up to three vias. Note also that the method would work as well for non-square bounding boxes.

The algorithm starts from $S(0,0)$ in the first column and ends at $T(4,4)$ at the last column. Each column of grids inside the bounding box is represented by an array of integers as shown in the top boxes. The array holds $B^u(i,j)$, $L^u(i,j)$ and $N^v(i,j)$. Although Fig. 4 shows the arrays representing all columns of the bounding box, in practice the method only needs a pair of these arrays in order for the EPTM to run: one for representing the even columns and another for the odd columns.

In the first column, each entry of the array is obtained using Eqs. 7 and 8 starting from grid point $(i, 0)$ advancing to grid point $(i, 4)$. The calculation continues for all entries in the next columns similarly. Final values of the entry that correspond to grid point $(4,4)$ will then represent the solution.

The top boxes from left to right in Fig. 4 show the entries as the algorithm proceeds. The final entries indicate a total of six possible routes consisting of four 3-via routes, one

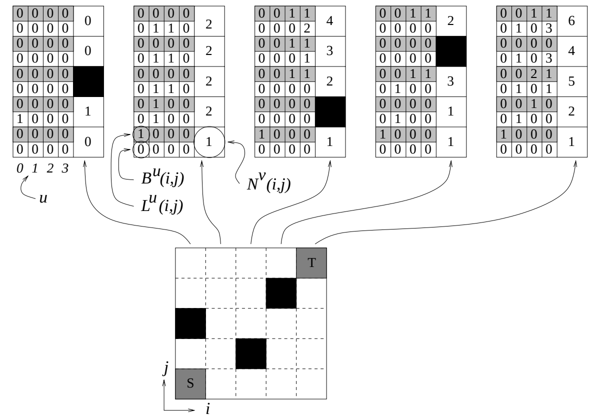

Figure 4. The EPTM Progress for A Single Net.

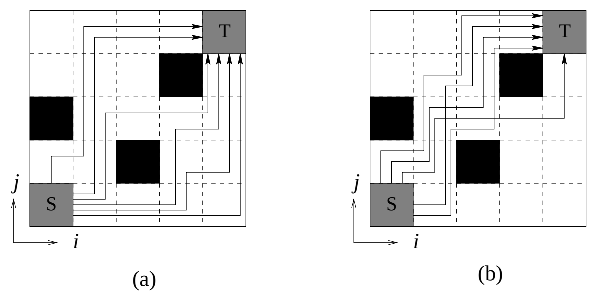

Figure 5. Possible Routes from S to T: (a) 3-via or less, (b) more than 3-via.

2-via route and one 1-via route. Fig. 5 illustrates all of the possible routes for the same net. The ones containing 3-via or less is shown in Fig. 5a and the rest of the routes are shown in Fig. 5b.

Having established the EPTM for measuring the routability of a net, the next step is to prepare a scheme for evaluating a set of nets when their terminals occupy the same routing surface. The goal is to measure the routability of each net in the presence of terminals that belong to the other nets. On the same routing surface, a terminal appears as an obstacle to a net when it resides inside the bounding box of the net. The scheme for calculating the MRLPs of the nets on the same routing surface is described below.

To describe the scheme, consider a small example whose terminal locations along with the data structure for use in measuring the routability is depicted in Fig. 6. There are 8 nets on the routing plane of size 7×7 grids. The nets consist of 5 nets going North East (NE nets) and 3 nets going North West (NW nets). These nets are stored in two different linked lists, the NE Net List and NW Net List, respectively. Terminals are sorted column wise and kept in a linked list called the Terminal List. An index is also used to identify the Terminal List according to the column number. This index is called Column Index.

The NE nets and NW nets are processed separately using a list called the Active List for bookkeeping. The Active List contains the instantiation of the EPTM data structure and the EPTM algorithm. When processing the NE nets, the Terminal List is scanned from left to the right to see whether the terminal is (a) a source terminal of an NE net, (b) a target terminal of an NE net, or (c) something that belongs to an NW net. When a source terminal of an NE

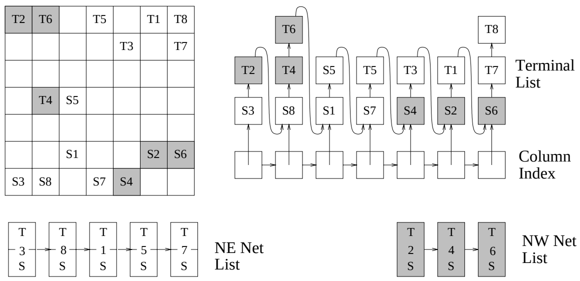

Figure 6. Data Structure for a Multi-net Problem.

Net	OPTM	EPTM ($v = 6$)							
		0	1	2	3	4	5	6	Total
1	15	0	0	1	6	4	3	1	15
2	57	0	0	2	5	9	9	12	37
3	13	0	1	2	4	3	1	2	13
4	2	0	0	1	0	1	0	0	2
5	4	0	2	2	0	0	0	0	4
6	88	0	0	1	1	10	9	15	36
7	25	0	0	3	3	9	6	4	25
8	0	0	0	0	0	0	0	0	0

Table 1. OPTM and EPTM Solutions to The Example Problem.

net is encountered then an EPTM instance is prepared and added to the Active List. If a target terminal of an NE net is encountered, then the instance of the corresponding net is scheduled for deletion from the Active List to be placed in a result list. The Active List grows and shrinks while the scanning of the Terminal List is progressing. Any terminal encountered will be used to update the EPTM instances in the Active List. To some nets, the terminal may appear as an obstacle. In this case the EPTM will act accordingly to the instances representing these nets. By the end of the Terminal List, EPTM will finish processing all of the NE nets and obtain the results.

Processing the NW nets is conducted similarly. Scanning is performed to the same Terminal List in the opposite direction. It goes from right to the left during which only the NW nets are scheduled for processing in the Active List. By the end of this scanning, the EPTM will obtain the solutions to the NW nets. Combining both solutions to NE and NW nets, a list of the number of possible routes for each net in question will be completed.

Table 2.5. shows the solution to the example problem. There are two types of solutions in the table. The OPTM lists the MRLPs regardless the number of vias and the EPTM lists the MRLPs with 0 to 6 vias.

3. EXPERIMENTAL RESULTS

The EPTM has been implemented in a Unix environment using C++ and tested on three industrial MCM designs commonly used as benchmarks for various MCM routers [10, 11, 2]. In addition, a test on a number of randomly generated examples has also been performed. This section reports the preliminary results of the test of EPTM.

The first test set was three of MCC's industrial MCM designs: MCC1-75, MCC2-75 and MCC2-45. The MCC1-75 consists of 6 chips with 75-micron pitch and substrate size of 45 × 45 mm^2 which is equal to a grid size of 599 × 599. It has 802 nets, 799 of which are signal nets (some are 3 to 7-pin nets), two power and one ground net. This results in a total of 1244 two-terminal-equivalent signal nets. Both MCC2-75 and MCC2-45 are 6 × 6 $inch^2$ substrates with 75-micron pitch and 45-micron pitch or equivalent to 2032 × 2032 and 3386 × 3386 grid size, respectively. They have 37 Honeywell VHSIC gate array chips and 18 connectors with a total 7118 nets and 14659 pins excluding the power and ground nets. This gives a total of 7541 two-terminal-equivalent signal nets.

The other set of test data was randomly generated and based on the MCC1-75 design. The terminals and their locations were taken from MCC1-75. Each new random design containing 2-terminal nets was then created by randomly making pairs of two terminals. A total of 10 random designs were prepared.

3.1. Experimental Setup

The test was conducted using both test data sets by allowing each net to have as many as 6 vias. The results reveal the number of unrouted nets as the number of maximum allowed vias increases. These nets are unroutable simply due to the presence of terminals that belong to other nets on the first routing layer pair. Here, EPTM can actually identify which nets are potentially routable and which are absolutely unroutable for each of the allowed number of vias. Intuitively, one would expect the number of unroutable nets to drop as the number of allowed vias increases. The test results also reveal a number which is considered to be acceptable for the maximum number of allowed vias.

To further confirm the test results with a more varied set of data, the random data was used. The test performed on the random data was the same as the one with the MCC data. However, only the statistical results, such as the average of unrouted nets, etc., are presented.

3.2. Test Results

The test results for the MCC data are shown in Table 3.2.. The list shows the number of unroutable nets when the number of allowed maximum vias is varied from 0 to 6. Fig. 7 shows the plot of percentage of unroutable nets for a varied number of vias. Fig. 8 shows a similar plot for the random data set for the minimum, the average and the maximum percentage of unroutable nets for the random data. For comparison, the plot for the original MCC1-75 is also included in Fig. 8.

vias	MCC1-75	MCC2-75	MCC2-45
0	1243	7540	7540
1	978	7213	7186
2	327	4348	3615
3	64	757	354
4	50	368	354
5	50	368	354
6	50	368	354

Table 2. Unroutable Nets of MCC Benchmarks for Several Numbers of Allowed Maximum Vias

All of the test results reveal that the number of unroutable nets drops significantly when the number of vias in each net is increased from 0 up to 4. Beyond 4-via routes, only about 5% of nets were left with unroutable flags. As the number of vias continues to increase, the percentage of unroutable nets doesn't seem to change very much. This suggests that, in this case, the general area routing problem can be solved by using 4-via or fewer route types. The

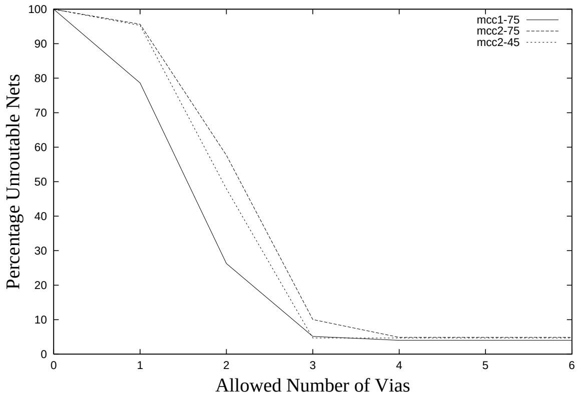

Figure 7. Percentage of Unroutable Nets of MCM Benchmarks

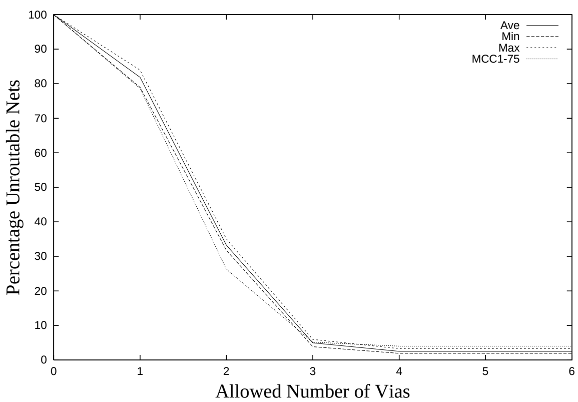

Figure 8. Percentage of Unroutable Nets of Random Designs

results confirm what was believed in [10] that the 4-via route type is enough for most practical purposes in MCMs.

The results also uncover the fact that more than 70% of the nets in MCC1 and more than 95% of the nets in MCC2 are unroutable by 1-via routes given that all terminals reside on the same layer pair. Thus a router should never try to find MRLPs for these nets using 1-via route type in the first layer pair. The same rule applies to more than 20% of the nets in MCC1 and more than 40% of the nets in MCC2 when using 2-via routes. Since EPTM identifies the routability of each net, the router could actually use this information to exclude the unroutable nets from processing with a certain type of routes. For a router such as MCG [11], this information is very valuable for improving the routing process.

4. CONCLUSION

A new method of measuring routability has been presented in this work. The experiments focusing on the first layer pair have been successful in identifying the number of potentially routable nets (as well as those absolutely unroutable) for some published MCM benchmarks. It also confirm that maximum 4-via routing is sufficient for most nets to be potentially routable in MCM general area routing problems. Further research is being conducted to extend this work to routing outside the bounding box and to gridless routing problems.

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