A New Multiple-Round DOR Routing for 2D Network-on-Chip Meshes

Binzhang Fu*†, Yinhe Han*, Huawei Li* and Xiaowei Li*
* Key Laboratory of Computer System and Architecture,
Institute of Computing Technology, Chinese Academy of Sciences, Beijing, China
†Graduate University of Chinese Academy of Sciences, Beijing, China

***Abstract*—The *Network-on-Chip* (NoC) meshes are limited by the reliability constraint, which impels us to exploit the fault-tolerant routing. Particularly, one of the main design issues is minimizing the loss of non-faulty routers at the presence of faults. To address that problem, we propose a new fault-tolerant routing, which has the following two distinct advantages: First, it keeps a network deadlock-free by utilizing restricted intermediate nodes rather than adding virtual channels (VC). This characteristic leads to an area-efficient router. Second, in the proposed routing algorithm, the rounds of DOR are not limited by the number of VC's anymore. As a consequence, the number of sacrificed non-faulty routers is significantly reduced. We demonstrate above advantages through extensive simulations. The experimental results show that under the limitation of VC's, the proposed routing algorithm always sacrifices the minimal number of non-faulty routers compared to previous solutions.**

***Keywords*-Mesh; Network-on-Chip (NoC); Fault-tolerant routing; Faulty Region; Sacrificed Router.**

I. Introduction

Network-on-Chip (NoC) Meshes offer an on-chip communication structure for its regularity and high bandwidth [1]. Furthermore, with the improvement of VLSI technology, a fault-tolerant routing algorithm is desirable for meeting the 20%-30% router failures estimated by Furber [2].

Generally, the main design issues of fault-tolerant routing include but not limit to: 1) reducing the sacrificed routers, 2) reducing the requirement of VC's. Reducing the sacrificed routers indicates that more functional cores are left for computing. Reducing the requirement of VC's, on other hand, leads to an area-efficient NoC router.

In general, there is a tradeoff between the above two objectives. For example, to reduce more sacrificed routers, more VC's are required by previous solutions [3] [4] [6] [10] [13] [17]. In the following, we review the previous solutions and also discuss the above tradeoff.

A. Intermediate Node Based Fault-Tolerant Routing

To route around failed routers, intermediate node based routing (IBR) first routes packets to several intermediate nodes, and then to the destination in a pipelined manner or not [10] [13].

Multiple round DOR (MR-DOR) [10] routing is a special case of IBR, in which DOR is implemented in each routing round. Given a number of intermediate nodes, Ho and Stockmeyer [10] first analyze the connectivity between any two routers, and disables at least one router for each unreachable pair. Hence, all left routers are guaranteed to be connected. Unlike the non-faulty router included into the faulty regions [4], the router sacrificed by IBR could be utilized to forward but not to send and receive packets. To avoid deadlock, Ho and Stockmeyer [10] assign each routing round with a separate VC. Hence, for a n-round routing, n VC's are required.

Gómez et.al. [13] also proposed a multiple round routing, where a fully adaptive routing is adopted in each round. To avoid deadlock, a separate escape VC is assigned to each routing around. Hence, for a n-round routing, $n + 1$ VC's are required.

B. Faulty Region Based Fault-Tolerant Routing

Faulty region is proposed to facilitate routing packets around failed routers. According to its different shapes, faulty region could be categorized into convex and concave regions [3] [4]. A faulty region P is convex iff any line segment is entirely in region P if its two ends lie in P, otherwise it's a concave region. In particular, if we ask the line segment to be horizontal or vertical, P is named as orthogonal convex.

Rectangular block faulty region is a typical convex region, and is commonly used in fault-tolerant routing [6] [7] [8]. Its simplicity and regularity facilitate routing with relatively few virtual channels, but it sacrifices too many non-faulty routers for constructing the faulty region.

To reduce the sacrificed routers, rectangular block faulty region is relaxed to orthogonal convex faulty region [4]. The new faulty region reduces the sacrificed routers to a very low level, but its relatively complex shape requires more VC's to avoid deadlock [5] [9] [17]. Furthermore, although the sacrificed routers have been reduced, the problem still exists.

Except orthogonal convex region, minimal-connected-component (MCC) faulty region is also widely adopted by researchers to design fault-tolerant routing [15] [16]. However, Wu [4] has already proved that MCC faulty region sacrifices more non-faulty routers compared to the orthogonal convex faulty region, so we omit the discussion about MCC in this paper.

C. Our Contributions

In this work, we proposed a new multiple round DOR (NMR-DOR) routing. Unlike [10] [13], proposed routing avoids deadlock by utilizing restricted intermediate nodes instead of adding VC's. The restricted, namely turn legally, intermediate nodes are selected under the direction of a turn model [11], so that inserting them doesn't introduce a deadlock. Hence, with a fixed number of VC's, proposed routing runs much more rounds of DOR than previous solutions [10] [13]. Therefore, more faults could be tolerated and fewer routers are sacrificed. We summarize our contributions in the following:

1) We proposed an area-efficient fault-tolerant routing by utilizing turn-legally intermediate nodes.
2) In the proposed NMR-DOR, the number of sacrificed routers is significantly reduced by running more rounds of DOR than previous solutions.

The rest of this paper is organized as follows: Sec. II shows the proposed routing in detail; Sec. III shows the simulations results; Sec. IV discusses the proposed technique; Sec. V concludes this work.

II. THE NEW MULTIPLE ROUND DOR ROUTING

In this section, we will show the main ideas of the proposed NMR-DOR, and give an algorithm to determine how many non-faulty routers should be sacrificed with given failed nodes.

Before discussion, we should note that the proposed algorithm is based on the global information about node failures as in [10]. This assumption is reasonable since our algorithm is part of the recovery process when node failure is detected and system is rolled back to a previous check point. Besides, we use the terms, router and node, interchangeably in the following of this paper.

A. The NMR-DOR

In NMR-DOR, a node I is an intermediate node between S and D iff it meets the following three conditions:

- I is reachable from S using DOR,
- I could reach D using DOR,
- the turns made by the adjacent two round DOR on node I (and the proceeding node if more than one intermediate node is inserted) should be allowed by the adopted turn model.

Particularly, this kind of node is named as turn legally intermediate node. Mathematically, if the set of nodes which are reachable from S is represented as τ_S, the set of nodes which could reach D is represented as τ_D, and the set of all turn legally intermediate nodes is represented as τ_L, then the set of all possible intermediate nodes τ_I is represented as:

$$\tau_I = \tau_S \cap \tau_D \cap \tau_L. \quad (1)$$

With the above equation, NMR-DOR is guaranteed to be deadlock free, and we prove it as the following theorem:

Theorem 1: NMR-DOR is deadlock free.

Proof: Without loss of generality, we assume west-first routing is adopted as the turn model. If no intermediate node is inserted, the original DOR network is deadlock free. First, if one turn legally intermediate node is inserted, the network is still deadlock free. The reason is that there is no turn forbidden by west-first routing existed in the original network, and no forbidden turn is introduced by the new intermediate node. Now, we assume the network with i turn legally intermediate nodes is deadlock free, so that the network with $i+1$ turn legally intermediate nodes is deadlock free too. The reason is that inserting one turn legally intermediate node into a deadlock free network doesn't introduce a deadlock. To Sum up, NMR-DOR is deadlock free. ■

B. Finding Turn Legally Intermediate Nodes

In general, finding a turn legally intermediate node is partially dependent on the adopted turn model. For example, the SW turn is forbidden by the west-first routing, but is allowed by the negative-first and north-last routing [11]. Therefore, the first step of the proposed technique is to determine which turn model is adopted. We summarize the rule as:

- In NMR-DOR, the adopted turn model doesn't forbid any turn taken by the DOR routing.

The above rule is straightforward, which means that any allowable turn of DOR should also be allowed by the adopted turn model. Thus, integrating them doesn't introduce any cycle. There is a counter-example shown in Fig. 1, DOR is assumed as xy routing, and negative-first is adopted as the turn model. According to Fig. 1, xy routing allows the turn ES, which is forbidden by negative-first routing. Therefore, if we incorporate them, a clockwise abstract cycle is formed as shown in Fig. 1.

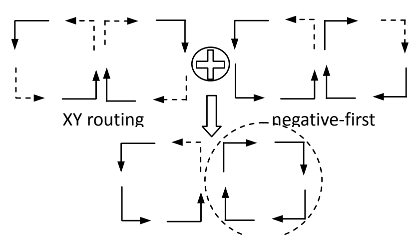


Fig. 1. Example of a wrong turn model.

Given the DOR and adopted turn model, whether an intermediate node is turn legally is determined by the relative position between nodes S, I and D. As shown in Fig. 2, if node I is selected, 2-round DOR makes a SE turn on it. According to west-first routing, SE is an allowable turn, so node I is said turn legally. If node F is selected, however, a forbidden turn SW is introduced. Hence, node F is not a turn legally intermediate node.

There is no need to check the turns taken on node S and D since the turns from/to local core are always allowed by turn model. However, if more intermediate nodes are inserted, inserting a new intermediate node also incurs a turn on the proceeding node, and that turn also should be checked. As shown in Fig. 3, if we insert node I, as the second intermediate node, between P and D, two turns are incurred. The first one happens on node P, which is an SE turn, and the second one happens on node I, which is an SE turn too. According

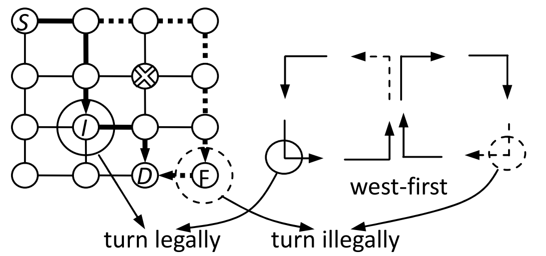


Fig. 2. Example of turn legally and turn illegally intermediate nodes: DOR is assumed as xy routing, west-first is adopted as the turn model. S represents source node, D represents destination node, I represents turn legally intermediate node and F represents turn illegally intermediate node.

to west-first routing, SE turn is legal, so that node I is viewed as turn legally. However, if node F is inserted as the second intermediate node between P and D, although the turn happens on node F is legal, node F is still viewed as turn illegally since the turn happens on node P, which is an SW turn, is a forbidden turn.

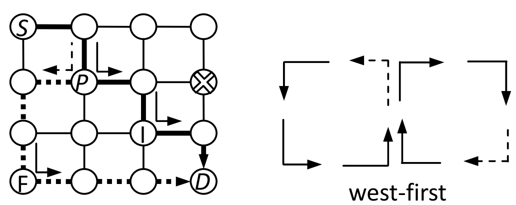


Fig. 3. Example of inserting more intermediate nodes: DOR is assumed as xy routing, west-first is adopted as the turn model. S represents source node, D represents destination node, I represents turn legally intermediate node and F represents turn illegally intermediate node, and P is their previous intermediate node.

By analyzing all possible relative positions between S, I and D, we summarize all possible turn legally intermediate nodes for DOR in Table I [14]. As shown in Table I, x and y denote the coordinates of turn legally intermediate node in x- and y-dimension respectively. Similarly, x_S, y_S, x_D and y_D are the coordinates of nodes S and D, and n_x and n_y are the width of network in x- and y-dimension respectively. For each node pair (i, j), as shown in eq. 2, we utilize a N-length T-vector to represent the results of Table I, where N is network size.

$$T_{i,j}(t) = \begin{cases} 1, & node\ t\ is\ turn\ legally\ or\ t \in \{i,j\}; \\ \\ 0, & otherwise. \end{cases} \quad (2)$$

As discussed above, if more than one intermediate node is inserted, determining whether a node is turn legally is partially determined by which node is the proceeding, and this requires the connectivity information between nodes. Thus, we will discuss it in the following.

C. Finding Sacrificed Routers

Two nodes are connected iff there is at least one path between them is not blocked by any faulty node, and we name them as a reachable pair. Otherwise, they are defined as unreachable pair. Hence, a network is fully connected iff no unreachable pair existed. To remove all unreachable pairs, at least one node of each pair should be disabled (sacrificed). Now, we show the method to find all unreachable pairs, which is equivalent with finding reachable ones.

If the maximal number of intermediate nodes is zero, NMR-DOR is reduced to be DOR. Determining whether two nodes are connected in DOR at the presence of failures is easy. It only requires us to check if there is any faulty node lies in the xy path between them. As shown in eq. 3, we use a $N*N$ matrix R, to represent the connectivity between nodes under DOR routing, where F refers to the faults set.

$$R_{i,j} = \begin{cases} 0, & \exists\ f,\ where\ f \in Fand \\ & (f_x = j_x and \min\{i_y, j_y\} \le f_y \le \max\{i_y, j_y\}) or \\ & (f_y = i_y and \min\{i_x, j_x\} \le f_x \le \max\{i_x, j_x\}), \\ 1, & otherwise. \end{cases} \quad (3)$$

If the maximal number is one, which means that NMR-DOR could route packet first to a turn legally intermediate node. In this situation, NMR-DOR is a 2-round DOR, and we extend the connectivity matrix to be $R^{(2)}$, where $R^{(2)}_{i,j} = 1$ indicates that there is a turn legally intermediate node, through which i could reach j. Mathematically, we calculate $R^{(2)}$ as shown in eq. 4.

$$R^{(2)}_{i,j} = (R_{i,*} \cap T_{i,j}) \times R_{*,j} \quad (4)$$

Let us reconsider the definition of $T_{i,j}$ shown in eq.2, R shown in eq.3, and the three conditions of the turn legally intermediate node discussed in Sec. II-A. The eq. 4 is reasonable since the right side of eq.4 indicates that there is a node t, where

- node t is reachable from i ($R_{i,t} = 1$),
- node t is a turn legally intermediate node for i and j ($T_{i,j}(t) = 1$),
- node t could reach j ($R_{t,j} = 1$).

Hence, $(R_{i,*} \cap T_{i,j}) \times R_{*,j} = 1$ means that node i could reach j through at most one turn legally intermediate node.

Now, we consider the situation when the maximal number of intermediate nodes is two. Without loss of generality, we assume the first turn legally intermediate node is p, and the second intermediate node is t. Node t is turn legally iff it meets the following four conditions:

- node k is reachable from i ($R_{i,k} = 1$),
- node k is a turn legally intermediate node for i and t ($T_{i,t}(k) = 1$),
- node k could reach t ($R_{k,t} = 1$),
- node t is a turn legally intermediate node for k and j ($T_{k,j}(t) = 1$),

Where, the first three conditions guarantee that node t could be reached from node i through a turn legally intermediate node, say node p. This indicates that inserting node t as the second intermediate node introduces a legal turn on its proceeding intermediate node. Furthermore, the last condition guarantees

TABLE I
EXAMPLE OF TURN LEGALLY INTERMEDIATE NODES IN 2D MESHES.

DOR	Turn Model	Turn legally intermediate nodes
XY routing	West-first	$\{(x,y) \| 0 \leq x \leq x_D,\ 0 \leq y \leq (n_y-1), x\ and\ y\ are\ integers\}$
XY routing	North-last	$\{(x,y) \| 0 \leq x < (n_x-1),\ y_S \leq y \leq (n_y-1),\ x\ and\ y\ are\ integers\}$
YX routing	South-first	$\{(x,y) \| 0 \leq x < (n_x-1),\ y_D < y \leq (n_y-1),\ x\ and\ y\ are\ integers\}$
YX routing	East-last	$\{(x,y) \| 0 \leq x \leq x_S,\ 0 \leq y \leq (n_y-1), x\ and\ y\ are\ integers\}$

that the incurred turn on node t is legal. According to the three conditions of the turn legally intermediate node discussed in Sec. II-A, node t is a turn legally second intermediate node. Mathematically, we extend $T_{i,j}$ to be $T_{i,j}^{(2)}$ as shown in eq. 5.

$$T_{i,j}^{(2)} = \bigcup_{k=1}^{N} R_{i,k} \cdot T_{i,t}(k) \cdot R_{k,t} \cdot T_{k,j}(t) \tag{5}$$

With vector $T_{i,j}^{(2)}$, the connectivity matrix for 3-round DOR, $R_{i,j}^{(3)}$ shown in eq.6, could be calculated in the similar way as $R_{i,j}^{(2)}$. Note that $T_{i,j}^{(2)}(t) = 1$ implies that $R_{i,t}^{(2)} = 1$ according to eq. 5. The reason of that we also include $R_{i,*}^{(2)}$ into eq. 6 is to keep compatible with eq. 4.

$$R_{i,j}^{(3)} = (R_{i,*}^{(2)} \cap T_{i,j}^{(2)}) \times R_{*,j} \tag{6}$$

In the following, we first generalize the T-vector to the situation that n turn legally intermediate nodes are utilized, and then generalize the R-matrix to the situation that n-round DOR is implemented (n-1 intermediate nodes). As in the way utilized to generate eq. 5, $T_{i,j}^{(n)}$ is shown in eq. 7. Similarly, as in the way utilized to generate eq. 6, $R_{i,j}^{(n)}$ is cacluated as shown in eq. 8. The proofs are similar with that discussed above, and are omitted due to space limitation.

$$T_{i,j}^{(n)}(t) = \bigcup_{k=1}^{N} R_{i,k}^{(n-1)} \cdot T_{i,t}^{(n-1)}(k) \cdot R_{k,t} \cdot T_{k,j}(t) \tag{7}$$

$$R_{i,j}^{(n)} = (R_{i,*}^{(n-1)} \cap T_{i,j}^{(n-1)}) \times R_{*,j} \tag{8}$$

With the n-round connectivity matrix $R^{(n)}$, a node pair (i,j) is unreachable iff $R_{i,j}^{(n)} = 0$. By now, the problem of finding sacrificed routers could be mapped to a WVC-problem [10]. Considering a weighted graph, as shown in Fig. 4, node represents the router, edge connects each unreachable pair, and node's weight denotes how many unreachable pairs it belongs to. Therefore, finding sacrificed routers is equivalent with finding minimal number of nodes, removing which all edges disappear from the graph. There are several mature algorithms to solve the WVC-problem, and we adopt the one proposed in [10]. The algorithm's detail is omitted.

III. EXPERIMENTAL RESULTS

In this section, we compared our solution with the MR-DOR in [10], and faulty-region solutions in [3] [4] in terms of average, maximal number of sacrificed routers, under the limitation of various number of VC's for 4x4 and 8x8 mesh networks respectively. These average and maximal results are got from over 1'000 simulations for different fault distributions. In these simulations, NMR-DOR adopts north-last routing as the turn model, and utilizes one turn legally intermediate node in all VC's provided.

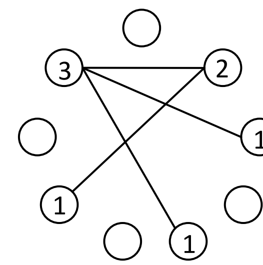
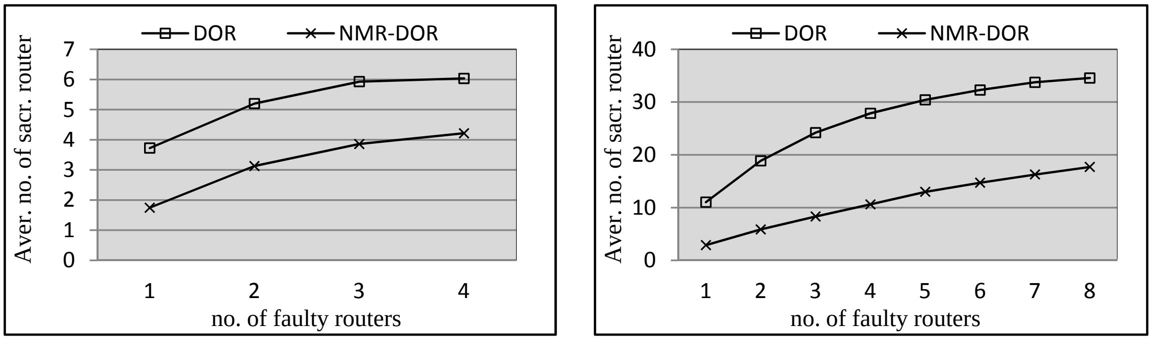


Fig. 4. Unreachable node graph: each line connects an unreachable pair; weight is represented by the labeled number.

With the limitation of one VC, we only compared our results with that of DOR since MR-DOR doesn't work in this situation [10], and faulty-region solutions either only tolerate one faulty block [8] or put much limitations on faulty regions, such as [5] requires the faulty region to be at least two hops away from network vertical boundaries. As shown in Fig. 5, using one turn legally intermediate node, NMR-DOR dramatically reduces the number of sacrificed routers compared to DOR. Specially, the results of NMR-DOR are attractive if low faulty rate is assumed. With the increasing of faulty rate, sacrificed routers increase very fast. The reason is that the number of available turn legally intermediate nodes is limited by the adopted turn model. This problem could be well alleviated by adding one VC as shown in the next simulation.

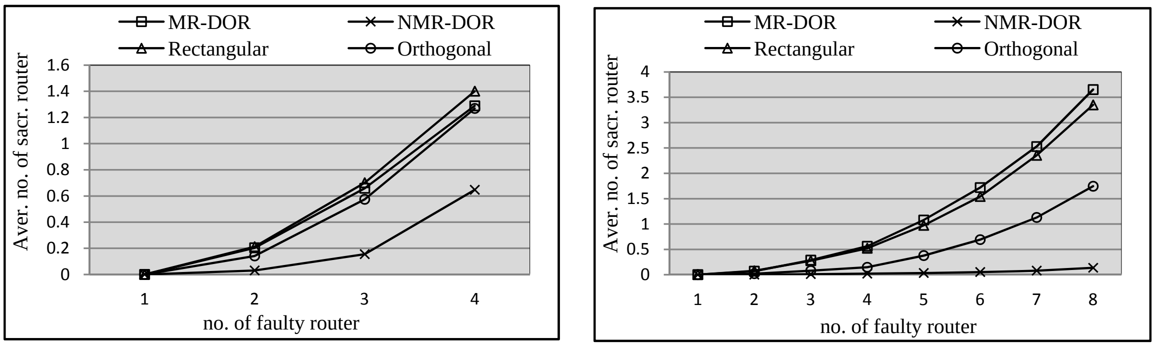
With the limitation of two VC's, we compared our results with that of MR-DOR, and rectangular block and orthogonal convex faulty region solutions. Note that the connectivity matrix using two VC's is got by multiplying the two connectivity matrixes in each VC. The average number of sacrificed routers is shown in Fig. 6. If only one failed router is assumed, all solutions could tolerate it, and no router is sacrificed. With the increasing of faulty routers, sacrificed routers, in MR-DOR and rectangular faulty region solutions, increase quickly. Compared to them, NMR-DOR and the solution based on orthogonal faulty regions have much better results. Specially, NMR-DOR is superior to others, and never sacrifices more than one router averagely in all situations. The average results of orthogonal faulty region solution are also attractive, but its worst case performance is much worse than NMR-DOR, as



(a) (4×4 mesh)

(b) (8×8 mesh)

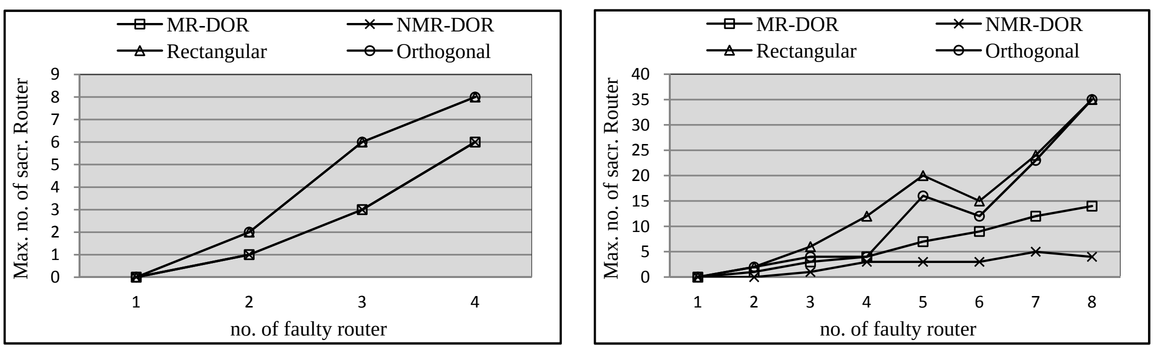
Fig. 5. Aver. no. of sacrificed routers without adding VC.



(a) (4×4 mesh)

(b) (8×8 mesh)

Fig. 6. Aver. no. of sacrificed routers with two VCs.



(a) (4×4 mesh)

(b) (8×8 mesh)

Fig. 7. Max. no. of sacrificed routers with two VCs.

shown in Fig. 7.

Next, we discuss the question that whether NMR-DOR could get better performance if more VC's are provided. We compared the number of sacrificed routers in average between NMR-DOR using two VC's and that using three VC's for a 16x16 mesh. The results are shown in Fig. III, and tell us that NMR-DOR, with two VC's, gets good enough results which couldn't be further improved by using more VC's at most times. The reason is that most of the routers sacrificed by NMR-DOR, with two VC's, are surrounded by faulty routers and can't be saved even arbitrary number of VC's are provided.

We summarize simulation results as that NMR-DOR could get promised results without adding any VC when low faulty rate is assumed, and if tolerating large number of failed routers is expected, two VC's at most are required. Besides, compared to other solutions, NMR-DOR sacrifices minimal non-faulty routers when same number of VC's is provided.

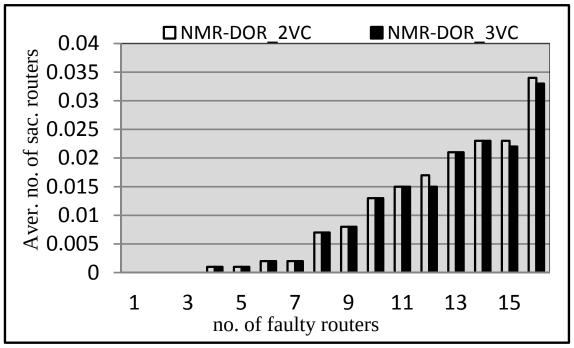


Fig. 8. Aver. no. of sacrificed routers with two and three VCs.

IV. DISCUSSION

Compared to MR-DOR, NMR-DOR is superior to that since:

- NMR-DOR could be implemented without adding VC,
- NMR-DOR significantly reduces the number of sacrificed routers as in MR-DOR.

Compared to faulty region solutions, especially with those based on orthogonal convex faulty regions, the conclusion is complicated. Faulty region solutions utilize local information, but NMR-DOR is based on global information. However, NMR-DOR implements DOR in each round, which means that router is simpler and faster than that used in faulty region solutions. Furthermore, as proved by the experimental results, NMR-DOR always sacrifices fewer non-faulty routers.

V. CONCLUSION

In this paper, we proposed a new multiple round DOR routing, namely NMR-DOR, which is kept deadlock free by using restricted intermediate nodes. These intermediate nodes are selected under the limitation of an adopted turn model, guaranteing that the network with turn legally intermediate nodes is deadlock free. With the limitation of VC's, NMR-DOR runs much more rounds of DOR routing than MR-DOR. Thus, more faulty nodes are tolerated, and much fewer non-faulty routers should be sacrificed to keep network fully connected. Except MR-DOR, we also compared NMR-DOR to other solutions based on faulty regions in terms of average and maximal sacrificed non-faulty routers. Simulation results show that, with the limitation of VC's, NMR-DOR achieves better performance than its counterparts in both average and worst cases.

ACKNOWLEDGMENT

This paper is supported in part by National Natural Science Foundation of China (NSFC) under grant No.(60633060, 60806014, 60831160526), in part by National Basic Research Program of China (973) under grant No.(2005CB321604), and in part by High-Tech Research and Development Program of China under grant No.(2007AA01Z113, 2007AA01Z476, 2007AA01Z109).

REFERENCES

[1] W. Dally and B. Towles, "Principles and Practices of Interconnection Networks", *Morgan Kaufmann Publishers*, 2004.

[2] S. Furber. "Living with Failure: Lessons from Nature?", *IEEE European Test Symposium*, pp. 4-8, 2006.

[3] J. Wu and Z. Jiang, "On Constructing the Minimum Orthogonal Convex Polygon for the Fault-Tolerant Routing in 2-D Faulty Meshes", *IEEE Transactions on Reliability*, vol. 54(3), pp. 449-458, Sep. 2005.

[4] J. Wu, "A Distributed Formation of Orthogonal Convex Polygons in Mesh-Connected Multicomputer", *Proceeding of International Parallel and Distributed Processing Symposium*, pp. 23-28,2001.

[5] J. Wu, "A Fault-Tolerant and Deadlock-Free Routing Protocol in 2D Meshes Based on Odd-Even Turn Model", *IEEE Transactions on Computers*, vol. 52(9), pp. 1154-1169, 2003.

[6] R. Boppana and S. Chalasani, "Fault-Tolerant Wormhole Routing Algorithms for Mesh Networks", *IEEE Transactions on Computers*, vol. 44(7): pp. 848-864, 1995.

[7] A. Chien and J. Kim, "Planar adaptive routing : low cost adaptive networks for multiprocessors", *Proceeding of International Symposium on Computer Architecture*, pp. 268-277, 1992.

[8] Z. Zhang, A. Greiner, and S. Taktak, "A Reconfigurable Routing Algorithm For A Fault-tolerant 2D-mesh Network-on-chip", *Proceedings of Design Automation Conference*, pp. 441-446. 2008.

[9] S. Chalasani and R. V. Boppana, "Communication in Multicomputers with Nonconvex Faults." *IEEE Transactions on Computers*, vol. 46(5), pp. 616-622, May 1996.

[10] C. Ho and L. Stockmeyer, "A New Approach to Fault-Tolerant Wormhole Routing for Mesh-Connected Parallel Computers", *IEEE Transactions on Computers*, vol. 53(4), pp. 427-438, 2004.

[11] C. Glass and L. Ni, "The turn model for adaptive routing", *Proceeding of International Symposium on Computer Architecture*, pp. 278-287, 1992.

[12] Intel Corporation, "A Touchstone DELTA system description", 1991.

[13] M. Gómez, N. Nordbotten, J. Flich, P. López, A. Robles, J. Duato, T. Skeie, and O. Lysne, "A Routing Methodology for Achieving Fault Tolerance in Direct Networks", *IEEE Transactions on Computers*, vol. 55(4), pp. 400-415, April 2006.

[14] Binzhang Fu and Yinhe Han, "A New Fault-Tolerant Routing Based on Turn Model for Network-on-Chip", *Workshop on Diagnostic Services in Network-on-Chips*, 2009.

[15] D. Wang, "A Rectilinear-Monotone Polygonal Fault Block Model for Fault-Tolerant Minimal Routing in Mesh", *IEEE Transactions on Computers*, vol. 52(3), pp. 310-320, Mar. 2003.

[16] D. Xiang, Y. Zhang, Y. Pan, and J. Wu, "Deadlock–Free Adaptive Routing in Meshes Based on Cost-Effective Deadlock Avoidance Schemes", *Proceeding of International Conference on Parallel Processing*, pp. 41-48, 2007.

[17] D. Xiang, Y. Zhang, and Y. Pan, "Practical Deadlock-Free Fault-Tolerant Routing in Meshes Based on the Planar Network Fault Model", *IEEE Transactions on Computers*, vol. 58(5), pp. 620-633, May, 2009.