Restricted Turn Model Fault Tolerant Routing Techniques for 3D Mesh Network-on-Chip: An Evaluation

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Abstract Communication plays a crucial role in design and performance of multi-core system-on-chips (SoCs). Recent development in nanoscale has opened an alternative option to conventional on-chip communication network with uniform stackable multi-chip modules in three dimensions. As the feature size continues to shrink, transient failures or permanent physical damages of on-chip network links are becoming a critical issue. To overcome these failures, network-on-chip (NoC) routing scheme can be enhanced by adding fault tolerant capabilities. In this paper, we analyze the performance of restricted turn model-based routing for the 3D mesh NoC, namely partially adaptive fault tolerant odd even (FTOE3D) routing, fault tolerant negative first (FTNF3D) routing, and fault tolerant XYZ (FTXYZ) routing. As compared to other two routing algorithms, FTOE3D gives the promising results. This document is in the required format.

Keywords Reliability · Fault tolerant routing · 3D mesh

1 Introduction

System-on-chip (SoC) consists of multiple shareable resources that need to communicate at very high speed. An alternate reliable, scalable, and efficient communication infrastructure is required with the shrinking of feature size and higher scaling of cores in SoC. In terms of simplicity and ease of implementation, the bus-based architectures have obvious advantage, but lack scalability and higher bandwidth required. To overcome these limitations, a new communication infras-

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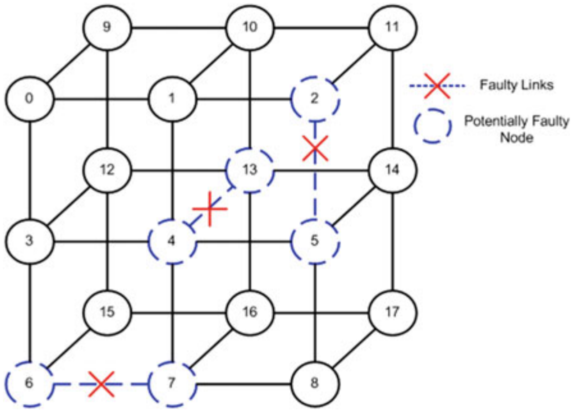

Fig. 1 3 × 3 × 2 3D mesh showing faulty links and potentially faulty nodes

tructure is needed for multi-core chips. Network-on-chip is emerging as an alternate solution to deal with complex system design in SoC [1, 2].

However, increasing the number of cores over a 2D plane is not efficient due to long network diameter and overall communication distance [3]. Three-dimensional (3D) integration is a viable design paradigm to overcome the existing interconnect bottleneck in integrated systems to enhance system performance characteristics [4]. 3D mesh NoC architecture comprises multiple homogeneous and heterogeneous cores interconnected through routers as shown in Fig. 1. The complex 3D NoC architecture is more vulnerable to the faults such as link failure or processing element (PE) or router failure. Every router must be aware of the faults in channels or adjacent nodes. A higher degree of tolerance is desirable in a routing algorithm without any deadlock or livelock condition. An efficient algorithm with fault tolerance exhibits higher degree of tolerance while exploring multiple paths to deliver the packet to the destination.

This paper is organized as follows: Sect. 2 presents related work in 3D NoC routing. Section 3 explores the restricted turn model routing for 3D NoC. Experimental setup, results, and performance analysis of fault tolerant algorithm is discussed in Sect. 4, and finally we end the paper with conclusion and future work in Sect. 5.

2 Related Work

In [5], a fault resilient routing algorithm for vertically partially connected 3D NoC is discussed where each node in network does not have a vertical link in order to deliver a packet to the destination layer. The routing algorithm requires two virtual channels along the *Y* dimension while one each in *X* and *Z* dimensions. In [6], authors address a low-cost solution to improve fault tolerance in horizontal interconnections only, in order to minimize the fault susceptibility in 3D NoCs.

Whereas, reliability issues are discussed in [7] on the aggregated faults that affect through silicon vias (TSV) links in 3D NoC.

A traffic distributing routing algorithm for the 3D mesh network by limiting bandwidth in the vertical dimension is discussed in [8]. In this algorithm, routing decision is taken on the basis of distance between current and the destination node along with the congestion information from the neighboring nodes. However, algorithm focuses solely on congestion avoidance.

Another fully adaptive routing algorithm 3D FAR for homogeneous networks is presented in [9]. This algorithm requires two virtual channels along the *X*, *Y*, and four along *Z* direction that affects area and cost. In their proposed architecture, the network is divided into four disjoint networks and packets are routed using shortest paths between the source and destination nodes as long as there is no fault. In case of any fault non-minimal routes are used. An efficient router structure is suggested for 3D NoC called true NoC architecture by [10]. The architecture consists of vertical links that are embedded in the crossbar and extend to all vertical layers.

3 FTOE3D and FTNF3D Routing Algorithms

Minimal path routing algorithms are advantageous as delays are smaller compared to other adaptive routing algorithms. FTOE3D and FTXYZ are minimal, whereas FTNF3D is non-minimal. The restricted turns of FTOE3D and FTNF3D are shown in Fig. 2a, b, respectively.

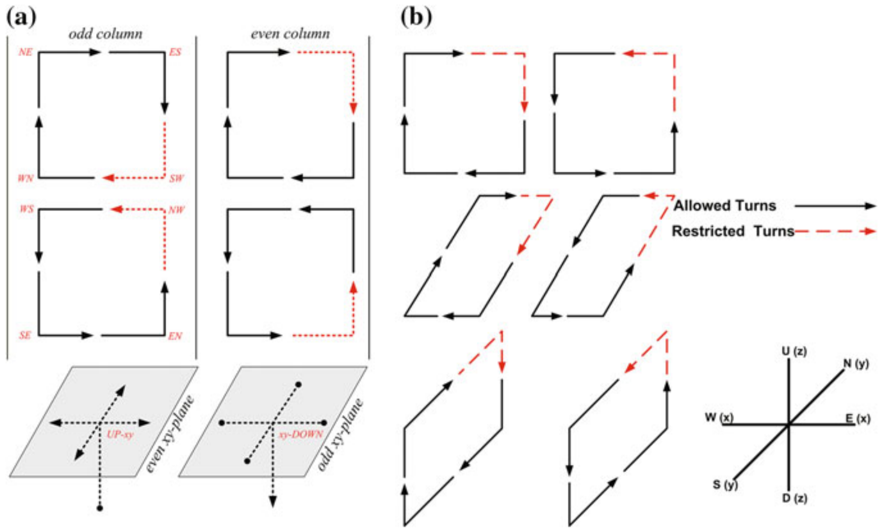

Fig. 2 Turns allowed in **a** FTOE3D and **b** FTNF3D for 3D mesh

Odd-even turn model for adaptive routing is proposed by Chiu [11], which is further extended by Nizar et al. [12]. Turn restrictions are made on the basis whether the current node is in even column or odd column and even slice or odd slice as listed below and shown in Fig. 2a.

1. In odd column, packets are not allowed to take North-West and South-West turns.
2. In even column, packets are not allowed to take East-North and East-South turns.
3. Up-*XY* turns are not allowed in an even *XY*-plane, and *XY*-down turns are not allowed in an odd *XY*-plane. Also, down-*XY* turns are not allowed in an even *XY*-plane, and *XY*-up turns are not allowed in an odd *XY*-plane.

FTOE3D routing algorithm is partially adaptive, and even in the presence of multiple faults it always follows minimal path from source to destination node. As FTOE3D routing prohibits turns to break any waiting cycles hence, prevent deadlocks. Further, it adheres to shortest path in cuboid of interest from source to destination making it free from livelock also. The algorithm is shown in Algorithm 1.

Algorithm 1. Fault Tolerant Odd Even (FTOE3D) Routing Algorithm for 3D Mesh NoC

procedure ► (FTOE3D Routing Algorithm)

Case 1: If current node is having Even column and Even plane.
- If input direction of current node is East.
  - If links attached except North and South are failed, drop the packet.
  - Else, send in any one direction depending on congestion.
- If input direction of current node is Rear
  - If minimal direction contains Rear and link not failed, send packet in Rear direction
  - Else, drop the packet.
- Otherwise
- If all links failed, drop the packet.
- Else, send packet in any one direction depending on congestion.

Case 2: If current mode is having Even column and Odd plane:
- If input direction of current node is East:
  - If links attached except North, South and Front failed, drop the packet.
  - Else send in any one direction depending on congestion.
- If input direction of current node is West or North or South:
  - If links attached except Front failed, drop the packet.
  - Else, send in any one direction depending on congestion.
- Otherwise
- If all links failed, drop the packet.
- Else, send packet in any one direction depending on congestion.

Case 3: If current node is having Odd column and Even plane:
- If input direction of current node is North or South:
  - If links attached except West failed, drop the packet.
  - Else, send in any one direction depending on congestion.
- If input direction of current node is Rear:
  - If minimal direction contains Rear and link not failed, send packet in Rear direction.
  - Else, does not contain Rear or contains Rear but Rear link is failed, drop the packet.
- Otherwise
- If all links failed, drop the packet.
- Else, send packet in any one direction depending on congestion.

Case 4: If current node is having Odd column and Odd plane:
- If input direction of current node is North or South:
  - If links attached except West and Front failed, drop the packet.
  - Else, send in any one direction depending on congestion.
- If input direction of current node is West or East:
  - If links attached except Front failed, drop the packet.
  - Else, send in any one direction depending on congestion.
- Otherwise
- If all links failed, drop the packet.
- Else, send packet in any one direction depending on congestion.

end procedure

Algorithm 2. Fault Tolerant Negative First (FTNF3D) Routing Algorithm for 3D Mesh NoC

Procedure ► (FTNF3D Routing Algorithm)

Case 1: If all the three minimal directions of current node are negative and input direction at current node is west or south or front or current node is source node.

If all the links are failed, drop the packet.

Else, send the packet in any of these directions depending on congestion.

Case 2: Else if the minimal direction of current node has any two negative directions and input direction at current node is west or south or front or current node is source node.

If Link in minimal negative direction fail, check for non-minimal negative direction.

If this link fails, drop the packet.

Else, send the packet in that direction.

Else, send in any of those directions depending on congestion.

Case 3: Else if the current node contains only one minimal negative directions and input direction at current node is west or south or front or current node is source node

If link in minimal negative fails, check for the remaining two non-minimal negative directions.

If all the links fail, drop the packet.

Else, send the packet in these directions depending on congestion.

Else, send the packet in that minimal negative direction.

Case 4: Else

If all links attached with the current node in minimal negative directions fail

Send the packet in any of non-minimal negative directions, if not failed.

Else drop the packet.

Else

If some or all links attached with the current node in minimal negative directions are not failed, send the packet in any of these directions depending on congestion.

end procedure

FTNF3D is partially adaptive, and non-minimal fault tolerant routing algorithm based on turn restricted routing algorithms is proposed by Glass [13]. Six turns are restricted in this algorithm as shown in Fig. 2b. This algorithm implies that all turns from positive direction to negative direction, i.e., West, South, and Front are prohibited. Forwarding packet is first routed toward West or South or Front until offset is zero and then, turned toward East or North or Rear direction. The FTNF3D is described in Algorithm 2, where packets from source to destination node are routed through minimal path until there is no fault in network. If all links in minimal negative direction are failed, then packets are routed through non-minimal negative direction paths.

4 Experimental Setup and Results Analysis

4.1 Experimental Setup

In order to evaluate the efficiency of the proposed routing algorithms, cycle accurate simulator written in SystemC [14] is used. Simulation parameters are taken as listed in Table 1. We have evaluated performance of proposed routing method with random and transpose traffic patterns using bursty data, with the burst length of 4 at an interval of 3 cycles. To evaluate effectiveness of FTOE3D, FTNF3D, and FTXYZ, we have introduced 10 link failures across the network.

4.2 Results Analysis

For 64 nodes (4 × 4 × 4) uniform 3D mesh NoC, load ranging from 5 to 50% with the increase of 5% each time is applied for initial 2000 cycles and simulated for 10,000 cycles. Every 20 bytes packet is fragmented by wormhole routing in 4 bytes flits. Experiment is executed 10 times with a different load values to achieve a better level of confidence. Table 2 shows the path taken by routing algorithms for single source and destination pair. Every time, a new fault is injected in the current path to see the degree of tolerance.

The graph is plotted for the latency at different load conditions for FTOE3D, FTNF3D, and FTXYZ shown in Fig. 3a, b, respectively. FTOE3D performs better as it tends to find the minimal path from source to destination in multilink failure environment. After 20%, load congestion starts building, causing the higher latency and more failure of packet delivery. Both FTOE3D and FTXYZ routing prohibit

Table 1 Simulation parameters

Parameter	Values
Mesh size	4 × 4 × 4; total 64 nodes
Packet size	20
Buffer size	8
Flit size	4
Simulation cycles	10,000
Test gen. number	2000
Traffic patterns	Random and transpose
Load in %	5–50 with 5% steps
Data pattern	Data pattern bursty data with burst length 4
No. of simulation	10 times with different load and traffic pattern for FTOE3D, FTNFD, and FTXYZ

Table 2 Path for single source to destination pair in the presence of multiple faults

No of links fail	Failed links for FTOE3D	FTOE3D path taken from source (3) to destination (60)	Failed links for FTNF3D	FTNF3D path taken from source (3) to destination (60)
0	Nil	3 → 19 → 18 → 22 → 26 → 30 → 29 → 28 → 44 → 60	Nil	3 → 7 → 11 → 15 → 14 → 13 → 12
1	3 → 19	3 → 2 → 6 → 10 → 14 → 13 → 12 → 28 → 44 → 60	3 → 7	3 → 2 → 6 → 10 → 14 → 13 → 12
2	3 → 19, 2 → 3	3 → 7 → 23 → 22 → 26 → 30 → 29 → 28 → 44 → 60	3 → 7, 2 → 3	3 → 19 → 18 → 17 → 16 → 0 → 4 → 8 → 12
3	3 → 19, 2 → 3, 22 → 23	3 → 7 → 23 → 39 → 55 → 54 → 58 → 62 → 61 → 60	3 → 7, 2 → 3, 16 → 17	3 → 19 → 18 → 17 → 21 → 20 → 4 → 8 → 12
4	3 → 19, 2 → 3, 22 → 23, 54 → 58	3 → 7 → 23 → 39 → 55 → 54 → 53 → 52 → 56 → 60	3 → 7, 2 → 3, 16 → 17, 4 → 8	3 → 19 → 18 → 17 → 21 → 20 → 4 → 5 → 9 → 13 → 12
5	3 → 19, 2 → 3, 22 → 23, 54 → 58, 23 → 7	3 → 7 → 11 → 27 → 26 → 30 → 29 → 28 → 44 → 60	3 → 7, 2 → 3, 16 → 17, 4 → 8, 20 → 21	3 → 19 → 18 → 17 → 21 → 25 → 24 → 8 → 12
6	3 → 19, 2 → 3, 22 → 23, 54 → 58, 23 → 7, 26 → 30	3 → 7 → 11 → 27 → 26 → 25 → 24 → 28 → 44 → 60	3 → 7, 2 → 3, 16 → 17, 4 → 8, 20 → 21, 24 → 25	3 → 19 → 18 → 17 → 21 → 25 → 29 → 28 → 12

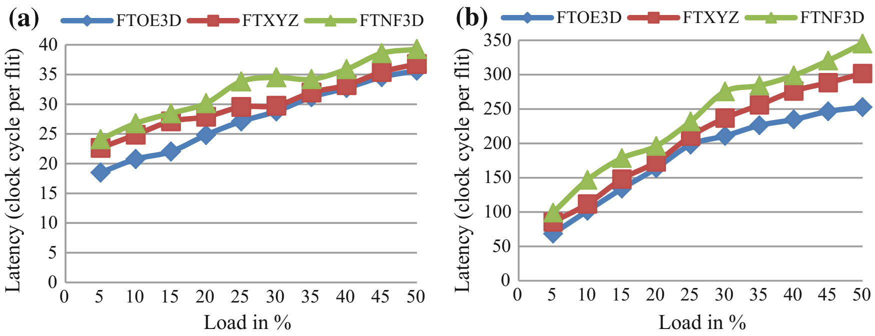

Fig. 3 Latency of **a** random traffic and **b** transpose traffic in the presence of 10 faulty links with load ranging from 5 to 50%

turns to break any waiting cycles and prevent deadlocks as a result virtual channels are not required (Fig. 3).

Average latency in FTOE3D under random and transpose traffic is observed to be lower than FTNF3D and FTXYZ under different load conditions. FTNF3D and FTXYZ use non-minimal path to route the packet form source to destination, whereas FTOE3D uses minimal path to route the packets to surrounding cuboid of interest. FTNF3D selects non-minimal path but less congested. By comparative analysis, we can observe that FTOE3D is giving the best latency results in comparison with FTNF3D and FTXYZ. This may be owing to the facts that turn restrictions in the FTOE3D results in uniform distribution of load. More realistic pattern is observed in transpose traffic pattern, and it is clear that FTOE3D outperforms compared to other routing algorithms making it more reliable for the 3D mesh NoC.

5 Conclusion and Future Work

In this paper, we explored FTOE3D, FTNF3D, and FTXYZ routing algorithms with the fault tolerant under the different traffic with bursty data patterns. Results are indicative that FTOE3D exhibits better performance in terms of latency than FTNF3D and FTXYZ. This is because routing always following a minimal path that does not include faults. In future, robustness of these algorithms is evaluated under more complex and realistic traffic and data patterns like bit shuffle, NED, and multimedia or MPEG4, respectively.

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