Low-Cost Adaptive and Fault-Tolerant Routing Method for 2D Network-on-Chip

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SUMMARY This letter presents a Preferable Mad-y (PMad-y) turn model and Low-cost Adaptive and Fault-tolerant Routing (LAFR) method that use one and two virtual channels along the X and Y dimensions for 2D mesh Network-on-Chip (NoC). Applying PMad-y rules and using the link status of neighbor routers within 2-hops, LAFR can tolerate multiple faulty links and routers in more complicated faulty situations and impose the reliability of network without losing the performance of network. Simulation results show that LAFR achieves better saturation throughput (0.98% on average) than those of other fault-tolerant routing methods and maintains high reliability of more than 99.56% on average. For achieving 100% reliability of network, a Preferable LAFR (PLAFR) is proposed.

key words: Network-on-Chip (NoC), fault tolerance, adaptive routing, turn model

1. Introduction

Designing a fault-tolerant routing method, deadlock is a major challenge. Virtual channels are mainly used in the fault-tolerant routing method for avoiding deadlock [1], improving performance and tolerating faults, but they introduce the additional area and increase the complex control logic of the router. Another fault-tolerant routing method without virtual channels avoids deadlock by using turn model [2], decreasing hardware costs, but it lowers performance because of less adaptivity. So a fault-tolerant routing method should introduce fewer virtual channels and have more adaptivity that packets are delivered through multiple paths to destinations. Aiming to introduce fewer virtual channels, the TFLR [3] and HiPFeR [4] fault-tolerant routing algorithms employ one and two virtual channels along the X and Y dimensions. They use the Mad-y and Double-y turn model to avoid deadlock, respectively. However, TFLR and HiPFeR are only able to tolerate a single faulty link or router. With the increasing of faults, they will result in the loss of a number of packets.

To address above problems, we propose a Preferable Mad-y (PMad-y) turn model which supports the prohibited turns in Mad-y turn model and provides a high degree of adaptiveness. Based on PMad-y and the link status of neighboring routers within 2-hops, we propose a Low-cost Adaptive and Fault-tolerant Routing (LAFR) method. LAFR can tolerate any number of faulty links and routers, and improve the successful arrival rate of packet. LAFR requires only one and two virtual channels along the X and Y dimensions, which is the minimum amounts of virtual channels to design an adaptive routing method. Still, 0% packet loss cannot be achieved in LAFR. For reducing the number of lost packets, we propose a Preferable LAFR (PLAFR) method that the Virtual Source and Echo mode [5] are added to LAFR method.

2. Turn Model

For every router in a 2D mesh NoC, a destination router may be located in eight different positions of a source router as north, south, east, west, northeast, northwest, southeast, and southwest. If the destination of a packet is in the northwest (resp., northeast, southwest, southeast, east, west, north, and south) position of the source router, we call the packet a northwest (resp., northeast, southwest, southeast, eastward, westward, northward, and southward) packet.

Mad-y turn model [3] utilizes a double-Y network where the X and Y dimensions have one and two virtual channels, respectively (Fig. 1(a) shows a double-Y router). In order to avoid deadlock, Mad-y prohibits one turn in each cycle like S1-W, N1-W, E-N2 and E-S2 which is shown in Fig. 1(b). Based on this turn model, the northeast packets can take E-N1 (i.e. a packet moving to the east direction makes a turn to the north direction with the first virtual channel), N1-E, and N2-E turns. Northwest packets can take W-N1, N2-W, and W-N2 turns. Southeast packets can take S1-E, S1-W, and S2-W turns. Finally, southwest packets can take W-S1, S1-W, and S2-W turns. The prohibited turns like E-N2, E-S2, S1-W and N1-W in Mad-y model make TFLR to tolerant a single faulty router or link.

To improve the adaptivity and fault-tolerance of routing method in the double-Y network, PMad-y permits the prohibited turns in Mad-y and imposes some constraint to
the prohibited turns to avoid deadlock. The prohibited turn is called constraint turn.

In PMad-y, the routing method obeys three rules:

**Rule 1:** The E-N2 and E-S2 turns can be replaced by E-N1 and E-S1 turns, respectively.

**Rule 2:** If packets take the S1-W turn in current router, the E-W, E-N2, E-N1 and E-S2 turns are prohibited in the west neighboring router of the current router, such as in Fig. 2(a).

**Rule 3:** If packets take the N1-W turn in current router, the E-W, E-N2, E-S1 and E-S2 turns are prohibited in the west neighboring router of the current router, such as in Fig. 2(b).

Since Mad-y model is deadlock-free, we only prove that the rule 2 and rule 3 cannot lead to deadlock in the network. In PMad-y, some constraint turns like S1-W and N1-W turns are employed, which are prohibited in Mad-y model to avoid deadlock. However, according to rule 2 and rule 3, PMad-y prohibits some turns in the west neighboring router of the current router to avoid the forming of the clockwise and counter-clockwise cycles, so that the PMad-y is deadlock-free.

### 3. Proposed Routing Method

#### 3.1 LAFR Method

In this letter, we adopt the fault distribution mechanism [6] for the analysis and simulation that each router knows the status of 16 links within 2-hops like E, EE, EN, ES, W, WW, WN, WS, N, NN, NE, NW, S, SS, SE, and SW paths in total, as shown in Fig. 3.

Since the 2-hops link statuses known are still not enough for each router to discover all component faults in the network, LAFR employs the priority of ports to avoid gambling on unknown component status. For each position of the destination router to the current packet, each router shows three ports and numbers mean priority of ports. 1 is the highest priority while 3 is the lowest. One of the aims of LAFR is to tolerate faults using the available minimal paths. A non-minimal route is necessitated when all of the minimal paths are faulty.

Starting from the highest priority direction, router scans each direction excluding the backward incoming link direction in the strict ascending order. For each direction, the router first checks whether the corresponding output link is both existent and healthy. And then packet is routed inside the network using the following three rules. The C and D represent current router and destination router, respectively.

**Rule 4:** The destination of a packet is located in the northeast, northwest, southeast and southwest position of the current router. In this case, the greater-distance dimension has higher priority about the two minimal paths. When the two minimal paths are faulty, the northeast and northwest (resp., the southwest and southeast) packets are routed to south (resp., north) direction, as shown in Fig. 4.

**Rule 5:** The destination of a packet is located in the east and west position of the current router. In this case, when the only one minimal path is faulty, the eastward (resp., westward) packets use the E-N1, N1-E and E-S1, or E-S1, S1-E and E-N1 (resp., W-N2, N2-W and W-S2, or W-S2, S2-W and W-N2) turns to bypass faults, as shown in Fig. 5.

**Rule 6:** The destination of a packet is located in the north and south position of the current router. In this case, the west direction has higher priority than the east direction. According to rule 2-3, the routing process is dived in two situations: the input channel of the current router is S1 (resp., N1) and S2 (resp., N2), as shown in Fig. 6.

According to rule 4-6, when all the minimal paths are faulty, packets bypass faults using the set of allowable turns, so there is not deadlock in LAFR. There are two cases that packets route using rule 5-6 will be ended, one case is that the packets are routed at the 1-hop column as destination and the other case occurs when the packets reach the network edge router. Thus LAFR is livelock-free.
3.2 PLAFR Method

For reducing the number of lost packets, PLAFR adds the Virtual Source and Echo mode [5] to LAFR.

Rule 7 (Virtual Source): Each router adds an additional Virtual Source (VS) buffer. If the packets may even have no usable direction but to take the prohibited turns in rule 4-6, the complete packets are stored in the VS buffer, thus eliminating the dependencies on previously visited buffers. Then, the packets are re-emitted starting from this router. For avoiding infinite looping, the packets keep track of the traversed routers (i.e., each router used by the packet is stored with it), and avoid them in following routing decisions.

Rule 8 (Echo mode): If there is no usable direction in rule 4-7 to route the packets to the destination router, the Echo mode is applied. The Echo Mode enables the packets to rewind until them find another path or reach the source router.

In Fig. 7(a), a packet is routed from the source router A(2,2) to destination router B(4,3). According to rule 4-6, firstly the packet is routed to router (4,1) using S2 channel by rule 4-6. At router (4,1), the W, SS, SW, E and SE paths are faulty, so there is no usable direction and then the Echo mode is activated. The packet is returned to the source router B and then is routed towards north direction by rule 8. The packet eventually reaches the destination router A by rule 4-6.

4. Simulation Results

We use BookSim2.0 [7] to evaluate LAFR in average network latency with TFLR [3] and HiPFaR [4]. We assume that the network topology size is $8 \times 8$, and simulate the cases with 5%, 10%, and 15% link faults of the total links. The packet size is randomly selected between 2 and 5 flits, 1 and 2 input queuing buffers with the depth of 6 flits in a router, respectively. Table 1 and Table 2 show the saturation throughput and the undelivered packet ratio of three routing methods under three standard traffic patterns, respectively. We adopt the saturation throughput [8], which is the throughput where the average latency equals to twice of the zero-load latency, as the evaluation metric.

When the network is under uniform traffic, the three routing methods behave similarly for 5% fault rate. With the fault rate increasing, LAFR decreases the saturation throughput by 3.16%, 2.24% over TFLR and 2.12%, 1.13% over HiPFaR for 10% and 15% fault rates, respectively. However, from Table 2, LAFR reduces the undelivered packet ratio by 4.13%, 4.88% and 5.6% over TFLR and 5.03%, 5.43% and 5.9% over HiPFaR for 5%, 10% and 15% fault rates, respectively. This is mainly because HiPFaR and TFLR only tolerant the faults in the minimal paths to deliver the packets, therefore many packets are lost and the numbers of received packets decrease significantly with the fault rates increasing. These lost packets are not counted in the average network latency calculation; therefore the HiPFaR and TFLR has higher saturation throughput than LAFR at a high fault rate. However, LAFR first tries to find an alternative healthy minimal path; otherwise it selects a non-minimal path in some cases. In cases where the minimal path is not available, a non-minimal path needs to be taken. So a number of lost packets are survived in LAFR.

For transpose traffic, HiPFaR has the worst perfor-


Table 1 The saturation throughput (flits/cycles/router)

<table>
<thead>
<tr>
<th>Traffic Patterns</th>
<th>TFLR</th>
<th>HiPFAK</th>
<th>LAFR</th>
<th>PLAFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>uniform</td>
<td>0.0495</td>
<td>0.0475</td>
<td>0.0445</td>
<td>0.0494</td>
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<tr>
<td>transpose</td>
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<td>0.0313</td>
<td>0.0375</td>
</tr>
<tr>
<td>hotspot</td>
<td>0.0295</td>
<td>0.0272</td>
<td>0.0255</td>
<td>0.0285</td>
</tr>
</tbody>
</table>

Table 2 The undelivered packet ratio (%)

<table>
<thead>
<tr>
<th>Traffic Patterns</th>
<th>TFLR</th>
<th>HiPFAK</th>
<th>LAFR</th>
<th>PLAFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>uniform</td>
<td>4.2</td>
<td>4.95</td>
<td>6.7</td>
<td>6.1</td>
</tr>
<tr>
<td>transpose</td>
<td>0.06</td>
<td>0.7</td>
<td>1.6</td>
<td>1.9</td>
</tr>
<tr>
<td>hotspot</td>
<td>2.25</td>
<td>3.1</td>
<td>3.6</td>
<td>4.1</td>
</tr>
</tbody>
</table>

performance among three routing methods. Compared with TFLR, LAFR increases the saturation throughput by 1.72%, 3.7% and 4% and reduces the undelivered packet ratio by 0.06%, 0.7% and 0.8% for 5%, 10% and 15% fault rates network, respectively. This is due to the fact that LAFR reduces the congestion around faults, in which LAFR uses more fault information of links to make routing selection than TFLR (i.e., TFLR knows the fault statuses of 8 surrounding links).

In hotspot traffic, the three routing methods behave similarly when the packet injection rate is very low. When the injection rate and fault rate are increased and links get congested, the LAFR and TFLR lead to smaller average network latency, with LAFR being the absolute best. LAFR can reduce the undelivered packet ratio to 0, 0, and 0.16% for 5%, 10% and 15% fault rates network, respectively.

As shown in Tables 1 and 2, PLAFR achieves 0% packet loss, but it decreases the saturation throughput by 1.22%, 2.17% and 7.34% over LAFR for 5%, 10% and 15% fault rates, respectively. This is due to the fact that the lost packets in LAFR are survived and the Echo mode makes some survived packet to route more paths to destination router.

5. Conclusion

We present a PMad-y turn model that allows more turns than other turn models. Based on PMad-y and the link status of neighbor routers within 2-hops, we present a minimal/ non-minimal LAFR routing method to tolerate multiple faulty links and routers in more complicated faulty situations. LAFR requires only one and two virtual channels along the X and Y dimensions, which is the minimum amount of virtual channels to design an adaptive routing method. Simulation results demonstrate that LAFR improves performance and reduces undelivered packet ratio. PLAFR guarantees that the destination router is always reached if a path exists.

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References


