PDA-HyPAR: Path-Diversity-Aware Hybrid Planar Adaptive Routing Algorithm for 3D NoCs

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Abstract

3D Network-on-Chips (NoCs) is an efficient solution to multi-core communications. The routing algorithm has become a critical challenge for higher performance of NoCs. Performance of traditional methods based on the turn models degrades when the network gets saturated. To improve network stability after saturation, in this paper, a novel deadlock-free Path-Diversity-Aware Hybrid Planar Adaptive Routing (PDA-HyPAR) algorithm without using virtual channels is proposed. In this method, different routing rules are exploited in different XY-planes. And planar adaptive routing strategy is proposed to balance the network loads. We analyze path diversity theoretically and utilize path-diversity-aware selection strategy properly. Experimental results show that PDA-HyPAR is effective even if network load becomes heavy.

Keywords

Path-Diversity-Aware, deadlock, routing algorithm, 3D NoCs, multiprocessing systems

1. Introduction

In NoCs, the system performance mainly depends on a topology structure and a routing algorithm. A routing algorithm determines the path which a packet travels through. Path diversity is defined as the number of alternative paths provided by the routing algorithm. And deadlock paralyzes the network when several packets are waiting for each other in a cycle to release the required resources. Path diversity and deadlock avoidance put routing algorithm designing in a dilemma.

In a deterministic routing algorithm, there is only one path for packet transmission. Conversely, fully adaptive routing is able to provide maximum path diversity. However, virtual channels are necessary to avoid deadlocks for fully adaptive routing. In order to avoid deadlocks without extra area and power overhead and to achieve high path diversity to some degree, partially adaptive routing, such as the conventional 2D Odd-Even (OE) turn model [1], was proposed where the concept of illegal turn sets were introduced and some certain turns are not allowed while routing packets. Thus, turn models have been an efficient and simple solution to NoC routing.

In large-scale NoCs, uneven path diversity by the previous turn models has become a severe problem that limits the network performance. Some turn models show saturation instability and even perform worse than deterministic routing. Moreover, there have been fewer studies that investigated routing problems on large-scale NoCs considering saturation stability. Therefore, in this paper, we try to propose a tentative and holistic solution to address saturation stability issues.

In [2], we have proposed Hybrid Planar Adaptive Routing (HyPAR) to achieve higher saturation stability for large-scale networks. Considering packet flow, deterministic routing and adaptive routing are exploited in different XY-planes so that network loads are balanced and network congestion is alleviated. However, there still remain some problems on HyPAR. One is the relationship between path diversity and performance improvement is unclear. Another problem is that, throughput of HyPAR may decrease after saturation under some traffic patterns. In this paper, we modify HyPAR by optimizing output direction strategy, where global path diversity is carefully analyzed and combined with local congestion information to determine the transmission direction. Experimental results show that our method has significant improvement in terms of throughput under uniform and non-uniform traffic patterns compared to other traditional routing algorithms.

2. Proposed Routing Algorithm

2.1. Proposed Turn Model

In PDA-HyPAR routing algorithm, deterministic XY routing is applied in even XY-planes while adaptive 2D Hamiltonian-based Odd-Even (HOE) routing [3] is applied in odd XY-planes. They are described as Rule 1 and Rule 2 below. And furthermore, to guarantee deadlock freeness in the turns involving vertical directions, Rule 3 is added. Actually, Rule 3 corresponds to the conventional 2D OE turn model applied to XZ-planes and YZ-planes respectively.

[Rule 1] XY routing: North (N) or South (S) transmission is not allowed unless the current node and the destination node have the same x-dimension coordinate value.

[Rule 2] 2D HOE routing: East-South (ES) and North-West (NW) turns are prohibited in even rows, while North-East (NE) and West-South (WS) turns are prohibited in odd rows.

[Rule 3] XY-Down turns are not allowed in an odd XY-plane while Up-XY turns are not allowed in an even XY-plane.

2.2. Planar Adaptive Routing Strategy

In [4], Planar Adaptive Routing (PAR) was proposed to route packets in a series of 2D planes. Decreased path diversity helps to reduce the hardware complexity and improve router speed. However, two virtual channels in each direction are required to avoid deadlock in this method.

In planar adaptive routing strategy, the packet will firstly be routed in the current XY-plane if possible, until it reaches the XZ-plane or YZ-plane where the destination node is located. And then the routing will take place in the corresponding XZ-plane or YZ-plane adaptively.

It should be noted that, for the packet to be transmitted downward into lower XY-planes, according to Rule 3, it is not allowed to traverse in the odd XY-plane firstly. In this case, PDA-HyPAR routes the packet downward and planar adaptive strategy will be applied at the next routing step.

Obviously, planar adaptive routing strategy tends to route packets through XY-planes and then XZ-planes or YZ-planes, rather than considering all the possible directions. Thus, routing freedom is limited and path diversity decreases. However, it is conductive to more regular packet flow and high path diversity can be maintained.

2.3. Packet Flow Analysis

We explain the proposed PDA-HyPAR method by two examples illustrated in Figure 1. The possible paths are marked as solid arrows. For a source-destination pair (0,47), the packet is firstly routed along x-dimension because Node 0 is in an even XY-plane. After reaching Node 3, four possible paths are available towards the destination node. Due to the vertical turn restrictions by Rule 3, Up-XY turns, such as 19-35-39, are not allowed in the destination XY-plane. For another source-destination pair (20,41), the up direction at Node 20 is not available based on Rule 3. Therefore, 2D HOE routing takes place in the current XY-plane until the packet reaches Node 25. There remain two available paths by applying the proposed method while fully adaptive routing can provide six available paths.

Here packet flow in the network needs further consideration.

For XY routing in even XY-planes, the packet will be firstly routed to the east or west direction until the current node and the destination node have the same x-dimension coordinate value. This fact causes that those packets sent from even XY-planes will be routed to YZ-planes where the destination node is located.

For 2D HOE routing in odd XY-planes, 2D HOE is such a row-based turn model that the turn constraints mainly restrict the usage of x-dimension links. Figure 2 illustrates packet flow pattern when 2D HOE routes packets to northeast regions. In 2D HOE routing, path diversity decreases faster in y-dimension than in x-dimension. The difference on path diversity attenuation in each direction contributes to uneven packet flow. This is an inherent problem of the previous turn models

For instance, from Source Node 0 to Destination Node 12, the number of allowable paths remains two if the east output direction is chosen. On the contrary, if the packet is routed through the north output direction at Node 0, the packet has to be transmitted to Node 10 at the next routing step and there is only one path to reach the destination. In other words, assuming the transmission direction is determined randomly, the distance of source-destination pair in y-dimension is more likely to decrease into zero earlier while routing packets. As a consequence, 2D HOE routing tends to guide packets to XZ-planes.

By combining XY routing and 2D HOE routing, the main forms of routing paths are regulated as from odd XY-planes to XZ-planes and from even XY-planes to YZ-planes. In this way, packets are staggered to two sets of continuous 2D planes. As the result, congestion can be relieved.

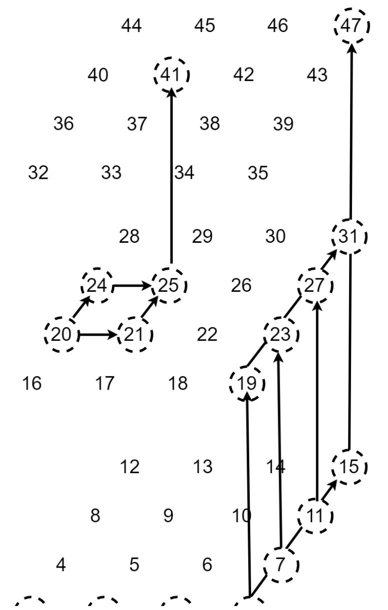


Figure 1: Examples of the proposed PDA-HyPAR routing

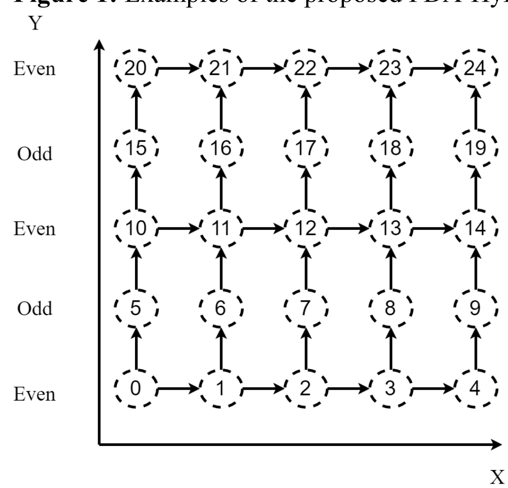


Figure 2: Packet flow in 2D HOE routing

2.4. Deadlock and Livelock

Deadlock occurs when some packets are waiting for each other to release the required channel so that they cannot make progress any more.

Specifically, the deadlock freeness needs to be ensured in the intra-plane and inter-plane scenarios. The proving method is similar to [3].

Lemma 1: Deadlock in each XY-plane can be avoided.

Proof: Since XY routing and 2D HOE routing have been proven to be deadlock free, deadlocks in each XY-plane can be avoided.

Lemma 2: Deadlock between XY-planes can be avoided.

Proof: Because no 180° turn can be allowed in the networks, Rule 3 guarantees that either Up-XY turns or XY-Down turns are allowed in any XY-plane. In other words, in the Channel Dependency Graph (CDG), horizontal channels are independent of either Up channels or Down Channels. No abstract dependency cycle could be constructed and deadlock would not occur between XY-planes as well.

In conclusion, the proposed PDA-HyPAR is a deadlock-free routing algorithm without virtual channels.

Unlike deadlock, livelocked packets continue to move through the network, but never reach their destination. Since PDA-HyPAR routes packets through minimal paths, every packet is able to reach the final destination by finite hops. As a result, livelock never occurs as well.

2.4. Analysis of Path Diversity

Path diversity is one of useful metrics for evaluating adaptive routing algorithms [1]. It is defined as the number of allowable minimal paths to transmit packet from the source node to the destination node. In a 3D mesh, let $S(x_s, y_s, z_s)$ and $D(x_d, y_d, z_d)$ denote the addresses of the source node and the destination node of a packet. Moreover, let $dx = |x_d - x_s|$, $dy = |y_d - y_s|$ and $dz = |z_d - z_s|$.

We further define the operation functions to determine the path diversity conversion coefficient in y-dimension and z-dimension as cy(int) and cz(int), respectively. Generally, this kind of path diversity conversion works according to whether the turn model is column-based or row-based. Take Figure 2 as an example. Due to uneven path diversity of 2D HOE mentioned above, the effective hops for path diversity calculation in y-dimension cy(dy) will be equal to $\left\lceil \frac{dy}{2} \right\rceil$ or $\left\lceil \frac{dy-1}{2} \right\rceil$ depending on parity of y_s and dy. For convenience of analysis and calculation, we assume that after reaching the XZ-plane or YZ-plane where the destination node lies, upward or downward transmission must be taken at first. Therefore, based on Rule 3, the effective hops in z-dimension cz(dz) will be equal to $\left\lceil \frac{dy-1}{2} \right\rceil$ or $\left\lceil \frac{dy-2}{2} \right\rceil$ depending on parity of z_s and dz.

Hence, path diversity of 2D HOE is given by:

$$PD_{2d-hoe} = \frac{\left(dx + cy(dy)\right)!}{dx!\,cy(dy)!} \qquad (1)$$

and then the analysis of path diversity of PDA-HyPAR can be divided into the following three cases:

Case 1: Packets Sent from Even XY-planes

Due to planar adaptive routing strategy, the multiple minimal paths will appear only in the YZ-plane where the destination node lies. According to Rule 3, its path diversity is equal to that of the conventional 2D OE routing in the YZ-plane as shown in Equation (2).

$$PD_{Case1} = \frac{\left(dy + cz(dz)\right)!}{dy!\,cz(dz)!} \qquad (2)$$

Case 2: Upward Packets and Intra-plane Packets Sent from Odd XY-planes

Here we discuss in two ways: transmission through XY-planes and then XZ-planes, or through XY-planes and then YZ-planes.

For the first situation, assume the coordinate value of the intermediate node is $I(x_{intermediate}, y_d, z_s)$ which is at the boundary of XY-planes and XZ-planes. Since $x_{intermediate}$ is in the range of x_s to x_d, $i = |x_{intermediate} - x_s| \in [0, dx]$.

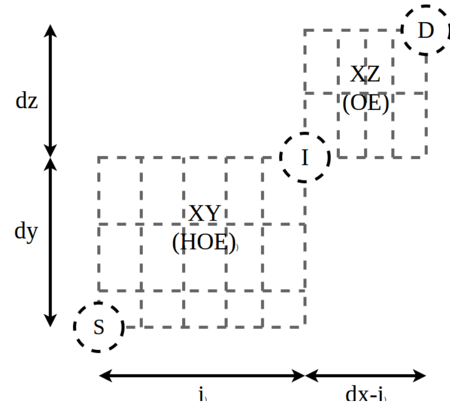


Figure 3: Path diversity calculation of Case 2

Figure 3 shows the surface development of XY-plane and XZ-plane while routing a packet. As shown in Figure 3, path diversity from the source node $S(x_s, y_s, z_s)$ to the intermediate node $I(x_{intermediate}, y_d, z_s)$ can be expressed as:

$$PD_1 = \frac{\left(i + cy(dy)\right)!}{i!\,cy(dy)!} \qquad (3)$$

Similarly, path diversity from the intermediate node $I(x_{intermediate}, y_d, z_s)$ to the destination node $D(x_d, y_d, z_d)$ is:

$$PD_2 = \frac{\left(dx - i + cz(dz)\right)!}{(dx - i)!\,cz(dz)!} \qquad (4)$$

Thus, the path diversity of the first situation will be:

$$PD_{C2-xy-xz} = \sum_{i=0}^{dx} PD_1 PD_2 = \sum_{i=0}^{dx} \frac{\left(i + cy(dy)\right)!}{i!\,cy(dy)!} \frac{\left(dx - i + cz(dz)\right)!}{(dx - i)!\,cz(dz)!} \qquad (5)$$

Likewise, given that $j = |y_{intermediate} - y_s|$ for the intermediate node $I(x_d, y_{intermediate}, z_s)$, the path diversity of the second situation can be expressed as follows:

$$PD_{C2-xy-yz} = \sum_{j=0}^{dy} \frac{\left(dx + cy(j)\right)!}{dx!\,cy(j)!} \frac{\left(dy - j + cz(dz)\right)!}{(dy - j)!\,cz(dz)!} \qquad (6)$$

Considering repetitive computation, the paths where the intermediate node is $I(x_d, y_d, z_s)$ are doubly included in both Equations (5) and (6). It should be deducted during calculation. In conclusion, the formula to calculate the total path diversity of PDA-HyPAR in Case 2 is shown as Equation (7).

$$PD_{Case2} = \sum_{i=0}^{dx} \frac{\left(i + cy(dy)\right)!}{i!\,cy(dy)!} \frac{\left(dx - i + cz(dz)\right)!}{(dx - i)!\,cz(dz)!} + \sum_{j=0}^{dy} \frac{\left(dx + cy(j)\right)!}{dx!\,cy(j)!} \frac{\left(dy - j + cz(dz)\right)!}{(dy - j)!\,cz(dz)!} - \frac{\left(dx + cy(dy)\right)!}{dx!\,cy(dy)!} \qquad (7)$$

Case 3: Downward Packets Sent from Odd XY-planes

In Case 3, the packet will be routed through the down direction, after which it will reach an even XY-plane. Thus, the total path diversity is equal to that of routing packets from $S(x_s, y_s, z_s - 1)$ to $D(x_d, y_d, z_d)$. Thus, the path diversity calculation of Case 3 has the following expression:

$$PD_{Case3} = \frac{\left(dy + cz(dz-1)\right)!}{dy!\,cz(dz-1)!} \quad (8)$$

2.5. Path-Diversity-Aware (PDA) Selection Strategy

Based on Rule 1-3, all the available directions are added to a direction set. And then a more efficient selection strategy is required to determine the final transmission direction from the direction set.

In general buffer selection strategy, local congestion information, such as free slot in the neighboring routers, is used to determine the output direction at each routing step. However, due to obsession of local balance, the packet may be routed to another much greater congestion area while only considering the local congestion condition [5].

In [6], a path-diversity-based latency model for selection was presented. When all the output ports are available, Effective Buffer Length (EBL) is utilized to predict the latency and choose a better path to deliver a packet. EBL is defined as the product of path diversity and free slot in the next router.

As mentioned in Sect.2.4, path diversity of PDA-HyPAR is determined by the coordinate values of the current node and the destination node according to Equations (2) (7) and (8). Among several available directions, PDA-HyPAR will choose the direction with bigger EBL.

As shown in Figure 4, both north direction and east direction are available for Current Node 0. Suppose the number of free slots of south input buffer at Node 3 is 8 while that of east input buffer at Node 1 is 6. If general buffer selection strategy is used, the packet is routed to Node 3, after which it is forced to traverse two highly congested links. On the contrary, PDA selection can avoid the worst case in Figure 4. EBL of the east direction $6 \times 2 = 12$ is greater than EBL of the north direction $8 \times 1 = 8$, thus, the packet will be routed along the east direction.

The number of free buffer in the next router can provide the local information while path diversity provides the global information of the network. Therefore, this combination contributes to lower latency.

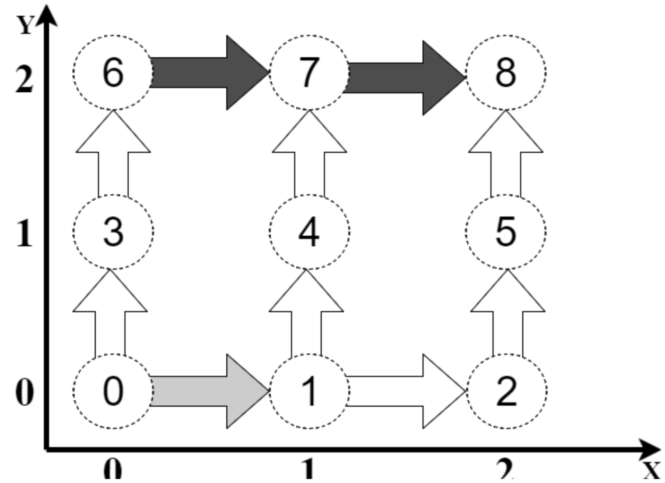


Figure 4: An example of PDA selection in 2D HOE routing

3. Experiments and Evaluation

The performance of PDA-HyPAR is evaluated by using an open source simulator Noxim [7]. The buffer size for each channel is set to 4 flits while each packet is divided into 8 flits. Each simulation is conducted for 10,000 clock cycles. Note that, the simulator has been warmed up for 1,000 clock cycles. In this period, the simulation results are excluded due to instability of the work condition upon initialization.

We execute consecutive simulations where the packet injection rate varies from 0.01 to 0.29. PDA-HyPAR is compared with the conventional 3D OE extended from [1], 3D Hamiltonian-based Odd-Even Algorithm (3D HOE) [8] and HyPAR [2] in terms of Global Average Latency (GAL), throughput, reliability and stability.

In the conventional 3D OE, the same conventional 2D OE turn model is applied in each XY-plane, XZ-plane and YZ-plane. And in 3D HOE, 2D HOE routing rules and its complementary rules are applied for different XY-planes respectively. For the turns involving vertical channels, Minimal Adaptive Routing (MAR) is utilized to restrict turns according to Hamiltonian-based node labelling. In addition, the routing function of HyPAR is the same as that of the proposed PDA-HyPAR method.

All the three routing algorithm for comparison use general buffer selection strategy while PDA-HyPAR uses PDA selection strategy. In general buffer selection strategy, direction decision among all the possible directions is based upon the local congestion level. The congestion level of each input port can be examined and then the direction to forward packets is determined.

As shown in Figure 5 and Figure 6, the four routing algorithms are compared on different sized networks under different traffic patterns for illustrations.

3.1. Experimental Results on 4×4×3 Mesh Network

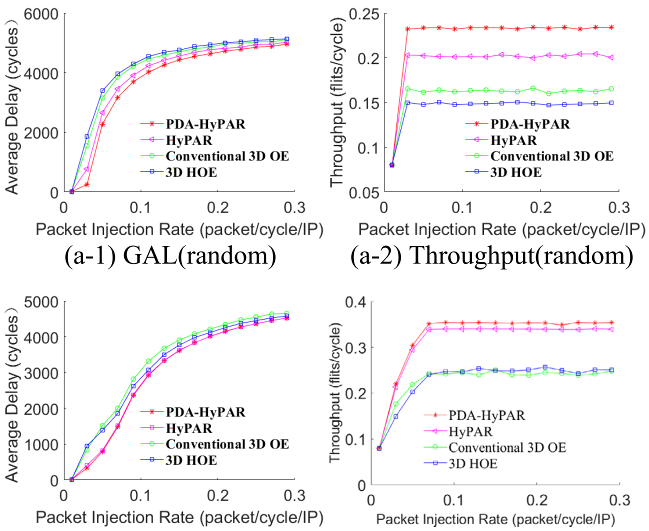
To evaluate the performance of the proposed PDA-HyPAR method, we firstly implement the simulations on a 4×4×3 mesh network with random and transpose traffic.

3.1.1. Random Traffic

Under random traffic pattern, each source node is equally likely to send packets to other destination nodes. Our proposed algorithm increases 15.92%, 43.83% and 57.43% saturation throughput compared with HyPAR, the conventional 3D OE and 3D HOE, respectively.

3.1.2. Transpose Traffic

For the most applications, certain nodes communicate with some other nodes very frequently. Therefore, we also evaluate PDA-HyPAR at transpose traffic. In transpose traffic mode, Node (i,j,k) only sends packets to Node $(M_x-1-j, M_y-1-i, M_z-1-k)$, where $\mathrm{M_x}$, $\mathrm{M_y}$ and $\mathrm{M_z}$ are the mesh dimension of x, y and z directions, respectively [9]. Transpose traffic pattern leads to heavy traffic for the central nodes of the mesh. Therefore, close to the center of the network hot spots may be created by using the conventional 3D OE and 3D HOE. In regard to throughput, our method gets 3.05% throughput improvement compared with HyPAR, 46.86% throughput improvement for the conventional 3D OE and 44.44% throughput improvement for 3D HOE.



(a-1) GAL(random) (a-2) Throughput(random)

(b-1) GAL(transpose) (b-2) Throughput(transpose)

Figure 5: Network performance comparison on a 4×4×3 mesh network

3.2. Experimental Results on 8×8×4 Mesh Network

We also implement the simulations on an 8×8×4 NoC. Random traffic, transpose traffic and bit reversal traffic are used.

3.2.1. Random Traffic

In the aspect of throughput, PDA-HyPAR outperforms HyPAR, the conventional 3D OE and 3D HOE by 55.62%, 135.91% and 108.43%, respectively, as shown in Figure 6(a-2). The main reason is that, XY routing in even XY-planes helps spread uniform traffic as evenly as possible through channels [10].

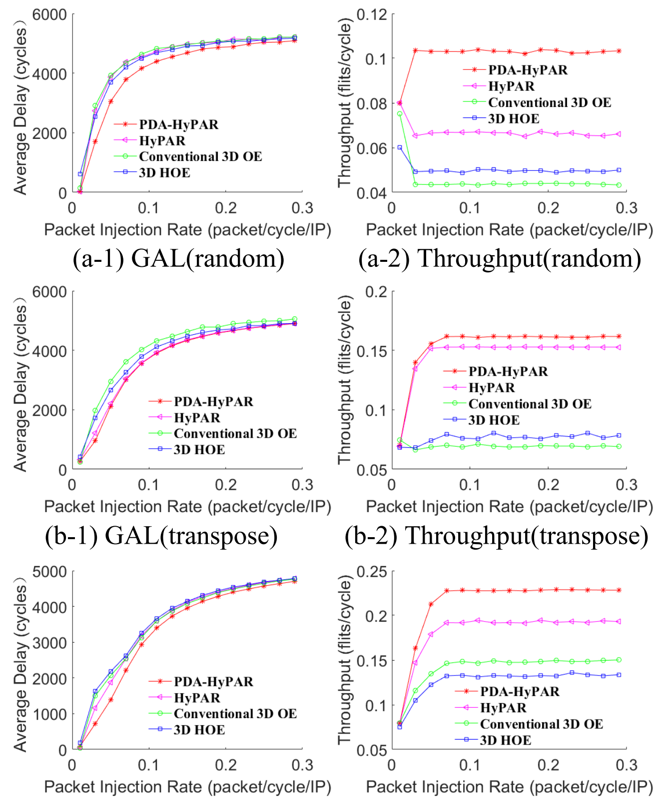
3.2.2. Transpose Traffic

From Figure 6(b-1) (b-2), PDA-HyPAR shows the lowest global average latency and the highest throughput beyond saturation by balancing loads in each XY-plane. Throughput gets improved by 5.50%, 130.00% and 101.25% on average compared with HyPAR, the conventional 3D OE and 3D HOE, respectively. The results confirm that PDA-HyPAR is more suitable for tackling the congested areas of the network.

3.2.3. Bit reversal Traffic

Bit permutations are a subset of permutation in which the destination address is computed by permuting and selectively complementing the bits of the source address. In bit permutations, $\mathrm{s_i}$(or $\mathrm{d_i}$) denotes the i_{th} bit of the source (or destination) address and the bit length of address is $\mathrm{b}=\log_2\mathrm{N}$, where N is the number of nodes in the network. For bit reversal traffic in a 4×4 network, if the four-bit source address is $s_3\, s_2\, s_1\, s_0$, the destination address will be $s_0\, s_1\, s_2\, s_3$.

During the simulations, when the network is unsaturated, the proposed PDA-HyPAR shows better performance in both global average latency and throughput compared to other routing algorithms. When the network reaches the saturation state completely, the throughput of PDA-HyPAR averagely reaches 0.23 and outperforms HyPAR, the conventional 3D OE and 3D HOE by 18.65%, 54.44% and 71.28%, respectively.



(a-1) GAL(random) (a-2) Throughput(random)

(b-1) GAL(transpose) (b-2) Throughput(transpose)

(c-1) GAL(bit reversal) (c-2) Throughput(bit reversal)

Figure 6: Network performance comparison on an 8×8×4 mesh network

3.3. Reliability Analysis

Beside of GAL and throughput, reliability R is a more direct criterion assessing how many packets arrive at the destination. In this paper, it is also out of realistic applications. We take it to supplement the analyses on simulation results. It is defined as the equation below [11]:

$$\mathrm{R}(\%)=\frac{\#\text{ of received packets at the destination node}}{\#\text{of total injected packets}}$$

The simulations are carried out on an 8×8×4 mesh. The reliability of PDA-HyPAR, HyPAR, the conventional 3D OE and 3D HOE under different traffic patterns is shown in

Table 1. Packet injection rate is set to 0.03, where the network congestion is not serious. It is clear that PDA-HyPAR shows the highest reliability in all the cases. It should be mentioned that due to the limitation of simulation cycles, some packets received after the simulation cycle will be neglected and the measured reliability is always lower than 100%.

As the packet injection rate exceeds the transmission ability of the network, the number of received packets stops rising, thus reliability decreases. And when the network gets saturated, for example at packet injection rate of 0.19, the number of received packets of the three algorithms is shown in Table 2. Even in the congested situations, PDA-HyPAR can transmit more packets than the other three algorithms.

3.4. Performance and Stability Analysis

From experimental results above, PDA-HyPAR performs better than the other three traditional routing algorithms. Comparing HyPAR with the conventional 3D OE and 3D HOE, the effectiveness of guiding packet flow is verified. Comparing PDA-HyPAR with HyPAR, we can find that PDA selection strategy works to further improve NoC performance.

Table 1: Reliability comparison at packet injection rate of 0.03

Traffic Pattern	Random	Transpose	Bit reversal
PDA-HyPAR	39.08%	44.22%	55.49%
HyPAR	24.64%	39.64%	52.08%
Conventional 3D OE	17.13%	23.21%	42.73%
3D HOE	18.83%	20.66%	37.92%

Table 2: Comparison of received packets at packet injection rate of 0.19

Traffic Pattern	Random	Transpose	Bit reversal
PDA-HyPAR	30020 (2.023)	33310 (1.999)	51667 (1.440)
HyPAR	19338 (1.303)	31502 (1.890)	46447 (1.294)
Conventional 3D OE	12969 (0.874)	18321 (1.099)	40804 (1.137)
3D HOE	14841 (1.000)	16664 (1.000)	35888 (1.000)

PDA-HyPAR shows lower global average latency in most cases. Planar adaptive routing strategy and PDA selection strategy may increase hardware complexity of arbitrators in the routers. Hence, the routing service time for selecting the output port will be longer. However, the balanced packet flow helps to reduce network congestions, thus, the transmission delay between routers decreases. Totally, GAL can be reduced by using the proposed method.

Improvement of throughput performance can be attributed to improvement of network stability. As the traffic increases, throughput eventually reaches saturation. It means the network is not able to deliver packets as fast as they are being generated. Throughput falls after saturation, which suggests that the network may have unfair flow control. In small-scale network (Figure 5), throughput does not decline after reaching saturation, thus, the network is stable. However, stability becomes worse as the mesh size becomes larger.

Saturation stability problem is highly related with the designing of routing rules. Besides, it is also affected by the traffic patterns.

In the 8×8×4 network under random and transpose traffic pattern, the conventional 3D OE routing appears instability. This is due to uneven path diversity of turn models and its unfair load distribution.

Since 3D HOE is still a row-based or column-based turn model, throughput decreases under random traffic pattern as well. However, 3D HOE shows good stability under transpose traffic. It is because the vertical turn restriction rule of 3D HOE is based on Hamiltonian path. The direction of the Hamiltonian path in two adjacent planes is reverse, thus, the vertical turn restrictions are symmetric and instability does not occur under some symmetric traffic patterns.

Note that, the proposed PDA-HyPAR can solve instability problem under all the three traffic patterns by regulating packet flow.

4. Conclusion

In this paper, a performance enhanced adaptive routing algorithm for 3D NoCs is proposed. Our proposed PDA-HyPAR takes advantage over the traditional PAR [4] to guide the packet flow in the network. And sophisticated PDA selection method is introduced to effectively determine the output direction. Furthermore, experimental results show that throughput is significantly improved compared to the conventional 3D OE and 3D HOE.

Although fault tolerance has not been discussed in this paper, PDA-HyPAR is possible to tolerate link faults to a certain degree, since path diversity of PDA-HyPAR is high and balanced.

Furthermore, the proposed PDA-HyPAR guarantees deadlock freeness without using virtual channels. The idea of guiding packet flow can be applied to other routing algorithms with virtual channels. The discussion on applicability and analysis of power and area overhead is our future work.

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