BHOE: Balanced Hamiltonian-Based Odd-Even Routing Algorithm for 3D Networks-on-Chip

Hong-Yi HUANG¹,a, Jin-Dun DAI¹, Lian ZENG¹, Xin JIANG¹, Liang TAO¹ and Takahiro WATANABE¹,b*

¹Graduate School of Information, Production and Systems, Waseda University, Wakamatsu, Kitakyushu 808-0135, Japan
a huanghongyi@fuji.waseda.jp, b watt@waseda.jp
*Corresponding author

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Abstract. In this paper, we propose a novel deadlock-free adaptive routing algorithm for 3D NoCs. The proposed method, named Balance-HOE, is based on 2D Hamiltonian-based Odd-Even turn model. Applying well-designed turn models for different layers can achieve balanced flow with maximal degree of adaptiveness. In this paper, the basic principle of this routing algorithm is described and theoretical analysis proves its efficiency. Furthermore, simulation results show lower latency and 13% throughput improvement compared to the previous works under non-uniform traffic pattern.

Introduction

Recently, with the increase of cores on a chip, the design of 2D NoCs is getting more complex, traditional bus-based architectures in Multi-Processor Systems-on-Chip (MPSoCs) are not useful anymore, and new raised Networks-on-Chip (NoCs) has become a promising solution for on-chip interconnection due to its reusability and scalability [1]. Due to this trend, the design of 2D NoCs is getting more complicated, 3D NoCs is proposed to decrease wire length and chip size [2].

Generally, the performance of NoCs is highly related with network topology and routing algorithm. Routing algorithms can be classified into deterministic and adaptive. In deterministic routing algorithm, once source and destination is set, the routing path is determined as well [3]. Deterministic routing algorithms perform well under uniform traffic pattern, however, they are ineffective under non-uniform traffic patterns. Thus we mainly focus on adaptive routing algorithm.

To maximize system performance, a routing algorithm should be free from deadlock and livelock, turn models and virtual channels (VCs) are the two main techniques to guarantee deadlock-free [4]. Due to the additional buffer space and complex control logic to routers of VCs, turn model routing algorithms are useful for handling deadlock without extra overhead.

In this paper, we propose a routing algorithm called BHOE to extend 2D Hamiltonian-based Odd-Even routing algorithm [5] into 3D and improve it to achieve high-balance without sacrificing adaptiveness. Experimental results show that BHOE is more efficient compared to traditional routing algorithm.

Related Works

OE Turn Model in 3D

The routing rules in Odd-Even turn models are as follows:

[Rule 1] In a layer, NW and SW turns are prohibited in odd columns; EN and ES turns are prohibited in even columns.
[Rule 2] In a layer, WN and EN turns are prohibited in odd columns; SW and SE turns are prohibited in even columns.

[Rule 3] In vertical direction, UP-XY turns are prohibited in even layers and XY-DOWN turns are prohibited in odd layers.

![Figure 1. Vertical constraints.](image)

Rule 1 is used in the traditional OE turn model for 2D case, it can be extended into 3D mesh by applying Rule 3 in z direction [6]. The extension of OE turn model provides better evenness of routing adaptiveness comparing with the previous well-known turn model.

**Plane-Balanced 3D OE Routing**

Plane-Balanced Odd-Even routing algorithm (BOE) was proposed in [7], in which Rule 1 and Rule 2 are used in odd and even xy-planes respectively. Rule 3 is applied as 3D vertical constraints as well (Figure.1).

**Proposed Approach**

Deadlock-free adaptive routing algorithm is effective approach to realize low latency and high throughput. We take advantage of HOE to propose a new 3D turn model called Balanced Hamiltonian-based Odd-Even routing algorithm (BHOE) which possesses high adaptiveness and balanced packet flow.

**Previous HOE Turn Model**

The 2D HOE turn model was proposed to increase the adaptiveness of Adaptive Column-Path (ACP) routing algorithm. Its rule can be established as Rule 4.

**[Rule 4]** ES and NW turns are prohibited in even rows; WS and NE turns are prohibited in odd rows.

HOE was extended to 3D mesh routing algorithm. Turns consisting of vertical directions are managed by Rule 3 as well. HOE and complementary HOE rule are applied in even and odd XY planes respectively, the latter can be regulated as:

**[Rule 5]** WN and SE turns are prohibited in even rows; WS and NE turns are prohibited in odd rows.

**[Rule 6]** WS and NE turns are prohibited in even rows; ES and NW turns are prohibited in odd rows.

**[Rule 7]** ES and NW turns are prohibited in even columns; EN and SW turns are prohibited in odd columns.

**[Rule 8]** EN and SW turns are prohibited in even columns; ES and NW turns are prohibited in odd columns.

![Balanced-HOE Routing Algorithm](image)

Balanced-HOE Routing Algorithm

For further improvement of the traffic flow balance compared with the 3D HOE, the HOE (Rule 4) and its three variants (Rule 6-8 corresponding to HOE1, HOE2, HOE3, respectively) are adopted in layer 4N, 4N+1, 4N+2, 4N+3 (N ≥ 0) in order, as shown in Figure.2, where dotted lines represent prohibited turns.

**[Rule 6]** WS and NE turns are prohibited in even rows; ES and NW turns are prohibited in odd rows.

**[Rule 7]** ES and NW turns are prohibited in even columns; EN and SW turns are prohibited in odd columns.

**[Rule 8]** EN and SW turns are prohibited in even columns; ES and NW turns are prohibited in odd columns.
And vertical link involved turns obey Rule 3. We can build BHOE with high degree of adaptiveness in this way.

Fig. 3 shows the BHOE pseudo code. Line 10 and Line 26 mean that we need to judge the current layer and then call corresponding plane routing algorithm. Line 16 and Line 17 guarantee that UP-XY turns do not occur in even layers, while Line 19 and Line 20 avoid the case that the packet can't enter this layer when it arrives the final layer (because its final layer and Rule 3 forbidden the UP-XY turn, the packet has nowhere to go in minimal routing algorithm). Finally, Line 25 and 26 prohibit XY-DOWN turns in odd layers. By using function \( c_2 \mod 4 \), we can choose the corresponding plane routing algorithm.

Here is an example of two source-destination pairs, marked with red and blue respectively as shown in Fig. 4. In the first pair (blue), node 63 is source and node 44 is destination node. Firstly, source node has three choices to approach destination, node 32, 56 and 62. However, due to the
vertical constraint and the location in odd xy plane, it can only be forwarded into node 32. Since it has been in the same plane with destination node, and Rule 3 doesn't forbid other turns any more in this case, it only needs to obey HOE2 Rule. Our packet is to EN (NE) direction, therefore, the packets can't enter odd columns until it reaches the same row with destination node. All the analytical allowed paths above are marked with blue arrows.

As for the second pair (red), which is from node 13 to node 62, packets can't make an UP-XY plane turns in even layer due to vertical constraints. It cannot be routed in layer 2. In layer 0, HOE Rule prohibits WS turn in odd rows, thus the path of node 13 to node 14 and node 5 to 6 can't be selected. In layer 1, WS turn is prohibited in even rows, the path from node 21 to node 22 will not happen due to this constraints. In layer 3, SW turn is prohibited in even columns, thus it must be forwarded to node 49 in advance. All possible paths is shown as red arrows in Fig.4.

Livelock-Freeness and Deadlock-Freeness

[Definition 1] Livelock occurs when the resources needed by the transmission of some packets are occupied by other packets. Thus these packets are looking for the resources and revolving around the destination node perpetually.

[Lemma 1] Minimal routing algorithm guarantees the packets to get closer to destination by every step, hence all the packets will definitely reach their destination without spinning, it's livelock-free.

[Theorem 1] Since BHOE is a minimal routing algorithm, it’s livelock-free.

[Definition 2] Deadlock is the situation that two or more packets are always waiting for one another to release the occupied resources in a cycle and thus none of the packets can arrive at the destination.

[Lemma 2] When there is no cycle, there is no abstract dependency cycle in Channel Dependency Graph, its deadlock-free [8].

[Theorem 2] Since there is no cycle in BHOE, this algorithm is deadlock-free.

Proof We need to prove it both in inter-plane and intra plane. In the aspect of intra-plane, there are four variant HOE models. Since 180-degree turns are prohibited in the routing algorithm, a complete cycle is consist of rows and columns. HOE and HOE1 are lack of north-most row, HOE2 and HOE3 are lack east-most columns to form a cycle in the xy-plane by prohibiting certain turns respectively. Similarly, for the xy inter-plane, Rule 3 can guarantee the lack of up-most plane to form a cycle in 3-D scenarios, because neither odd nor even layers can accept both of the UP-XY and XY-DOWN turns.

Comparison with Previous Turn Models

Same vertical direction rule is applied, and plane turn model can be classified into OE-type and HOE-type. When we set the same mesh size in x and y direction, their adaptiveness is equal. The vital factor to influence the performance of these turn models is the degree of evenness of adaptiveness. To show the flow process of packets, we take 8x8 plane as an example, where (3, 3) is source and the four corners are destinations. By using exhaustive method to list all possible paths, packets flows in BOE [8], HOE and BHOE are shown in Fig. 5, 6 and 7 respectively. The links with blue ‘x’ in figures are the forbidden links. For example, there are 28 forbidden links in Fig.5 (a).

After overlapping four consecutive plane layers of each routing algorithm as a group respectively and counting the distribution of these forbidden links in four layers, we conclude them as shown in Table 1. For example, the times of repetitive forbidden links in Fig.7 are marked in their position instead of blue ‘x’, most of them only appear once at the same place of layer, and ten positions where forbidden links appearing twice are marked with ‘2’ which has same color respectively. Because OE turn model uses same plane routing in four layers, all of forbidden links appear at the same place. As a result, 28 links repeated four times indicates that OE is highly uneven. BHOE is the most balanced turn model, because most of the forbidden links spread evenly and only 10 forbidden links are repeated once in two layers.
Table 1. Comparison of forbidden links distribution.

| Repetition  | Once | Twice | Four times | Total |
|-------------|------|-------|------------|-------|
| OE          | 0    | 0     | 28         | 112   |
| HOE         | 0    | 22    | 17         | 112   |
| BOE         | 0    | 48    | 4          | 112   |
| BHOE        | 94   | 10    | 0          | 114   |

Simulation Results

3D-Noxim simulator [9] is used to evaluate the performance, reliability and overhead of the proposed routing scheme. Simulation data is shown in Table 2.

Table 2. Data set for simulation.

| Parameters       | Settings               |
|------------------|------------------------|
| Topology         | 4x4x4 3D Mesh          |
| Packet Size      | 8 flits                |
| Buffer depth     | 8 flits                |
| Warm-up Time     | 2000 cycles            |
| Simulation Time  | 10000 cycles           |
| Repetitions      | 30                     |

Figure 8 shows that BOE and OE have higher performance than HOE and BHOE although delay is close. The reason is that comparing with HOE-based turn model (Figure 6), OE-based routing algorithm is similar with xy routing, it has less choice in y direction comparing to x direction, the algorithm reduces time in selecting directions in this way, which is more efficient in uniform traffic pattern. However, when applying in more usual case: non-uniform traffic pattern such as transpose traffic, BHOE outperforms all the other schemes as shown in Fig 9. This is the benefit of balanced routing. Our proposed routing algorithm has nearly 13% improvement in throughput than the previous HOE routing algorithm.
Conclusion

In this paper we propose a novel routing algorithm called BHOE, which is deadlock-free and livelock-free. Compared with classical turn models, the proposed BHOE improves the balance degree while maintaining high degree of adaptiveness. It's noteworthy that BHOE has better performance than the traditional HOE method.

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