A Deadlock-Free Routing Algorithm Requiring No Virtual Channel on 3D-NoCs with Partial Vertical Connections

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***Abstract*— Elevator-first routing algorithm has been introduced for partially connected 3D network-on-chips, as a low-cost, distributed and deadlock-free routing algorithm using two virtual channels. This paper proposes *Redelf*, a modification of the elevator-first routing algorithm on a 3D mesh topology. The proposed algorithm requires no virtual channel to ensure deadlock-freedom.**

***IndexTerms*—NoC, deadlock, routing algorithm, 3D stacking**

I. Introduction

Among the efforts to deal with high cost of TSVs, [1] introduced *elevator-first* algorithm for an architecture that connected layers of 2D NoCs with arbitrary partial connections of TSV links. Proof was shown that, with any network topology and any deadlock-free 2D routing algorithms, a deadlock-free algorithm could be built using two virtual channels. Later in [2], its detailed architecture was described and its cost analysis was given.

In this work, we present a routing algorithm named "*Redelf,*" and show that when we focus on layered mesh architecture, it can be deadlock-free even without using virtual channel while maintaining the original benefits of elevator first routing algorithm.

II. Original Elevator-first Algorithm

Because our algorithm is based on the elevator-first algorithm [1], knowledge about the algorithm is essential to understand ours. The algorithm has been proposed as an algorithm that connects several layers of 2D networks that use deadlock-free algorithms. The key point of the algorithm is that it is deadlock-free even though there are only partial, arbitrary vertical connections, while only two virtual channels are needed.

In elevator-first routing, when a packet is destined to a node located on another layer, it is first routed to a vertical link (an *elevator*) using the routing algorithm inside the 2D network (e.g., *XY* routing). When it arrives at the elevator, the packet is sent upward or downward (towards the destination). When the packet reaches the next layer, the destination is checked. If the destination is on the current layer, then it is routed to the destination using the routing algorithm of the new layer. If it is not, the same process is repeated until it reaches the layer of the destination node. The routing is deadlock-free with two virtual channels only inside the 2D networks (vertical links do not require virtual channels).

III. Proposed algorithm

A. Target architecture

The elevator-first algorithm allows low cost distributed routing for 3D NoC where planar deadlock-free networks are

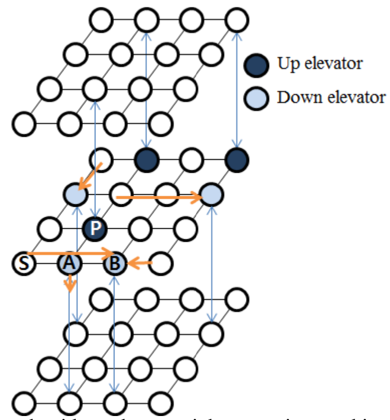

Fig. 1. 3D mesh with random partial connections and its *down* elevator selection.

partially connected by vertical channels. In this work, we decided to focus only on mesh topology for planar networks, which is probably the most popular one among wide variety of NoC topologies [3][4][5]. Thus, it would be meaningful to focus on layers of meshes instead of arbitrary topologies. We use *dimension ordered* (*XY*) routing as in examples of [1]. In the remainder of this section, we show that, by composing some rules for choosing elevators (vertical channels), elevator-first algorithm can be made deadlock-free even without any virtual channel.

B. Proposed routing algorithm for 3D mesh with partial irregular vertical links

Our algorithm uses the original elevator-first algorithm (*Elf*) as baseline. In Elf, the algorithm can choose any elevator when the destination and the source are located in different z planes. In our algorithm, certain rules are applied when an elevator is to be taken. Before introducing the rules, we first define some special nodes called "pivots".

Definition 1: An up (down) *pivot* elevator of a plane is the up (down) elevator that has no more upward (downward) elevator to the south-or-due-east of it in the plane.

By the definition, only one up pivot and only one down pivot exist for each layer. Using this definition, the rules for selecting elevators are as follows.

- Rule 1: When the destination is on a different layer, take the nearest elevator among the south-or-due-east ones of the source (including the self-node).
- Rule 2: If there is no south-or-due-east elevator of the source in the desired direction, take the pivot elevator.

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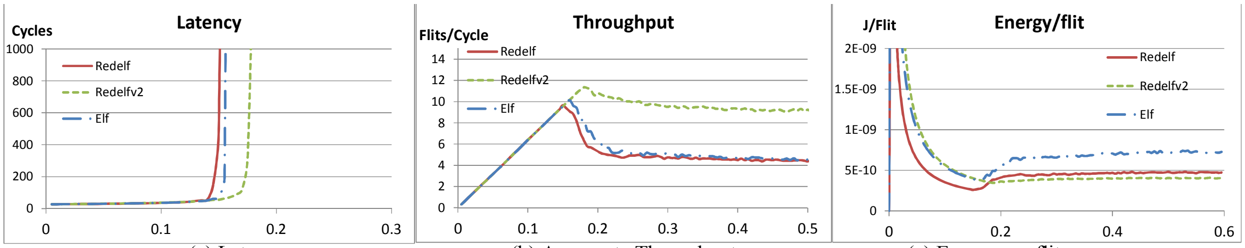

(a) Latency (b) Aggregate Throughput (c) Energy per flit

Fig. 2. Experimental result. X axis represents injection ratio (Flits/node/cycle).

- Rule 3: Assume a down elevator is chosen by Rule 1 and it is not at the self-node. Also assume that it is located to the south or due east of the up pivot elevator. Then, instead of taking that down elevator, take the down pivot elevator on the same plane. Same rule applies when up direction and down direction are switched.

The thick arrows in Fig. 1 show an example of elevator selection. Normally, packets having node “S” as their source would take node “A” as its *down* elevator by Rule 1. However, because node “P” has an *up* pivot elevator and “A” is located to the south of “P”, the *down* pivot elevator at node “B” is selected instead by Rule 3. On the other hand, packets having “A” as their source takes the *down* elevator at the self-node “A” by Rule 2. This routing algorithm is deadlock-free without any virtual channel. Detailed description and proofs are omitted due to space reason.

IV. Evaluation

A. Experimental setup

To examine performance of our routing algorithm, we used an in-house, cycle-accurate NoC simulator integrated with DSENT [7], an NoC power modeling tool. 3D NoC architectures consisting of four layers of 4x4 mesh with various vertical connections (25%, 50%, and 75%) were used. The routers are 3-stage pipelined and each port has 8-flit buffers with buffer-bypass technique applied.

Our algorithm was compared with the original elevator-first algorithm. However, because the original elevator-first algorithm uses two VCs (virtual channels) for the planar links, direct comparison with our algorithm using no virtual channel wouldn’t be fair. So we also tested our algorithm on the same architecture with two planar VCs.

Four kinds of traffic patterns were used: uniform random, hotspot random, bit complementary, and tornado. Under the traffics, three metrics, average latency, aggregate throughput, and energy consumption per flit were measured. The results are shown in Fig. 2. For space reason, only the result under uniform random traffic with 25% of vertical connections is shown. In the legend, “Elf” means the baseline original elevator-first routing. “Redelf” means the proposed algorithm with no virtual channel and “Redelfv2” means the proposed algorithm using two planar VCs as in the baseline elevator-first algorithm.

B. Performance comparison.

To make a quantitative comparison, we can define “saturation point” as the point where the latency reaches over 500 cycles. On average[1], saturation point of “Redelfv2” is 8.4% higher than “Elf”, and that of “Redelf” is 4.5% lower than “Elf”. In average peak throughput, “Redelfv2” is 13.7% higher than “Elf” and “Redelf” is 6.0% lower than “Elf”. In average saturated throughput, “Redelfv2” is over 31.2% higher than “Elf” and “Redelf” is only 10.6% lower than “Elf”. In terms of average energy per flit at the lowest point, “Redelf” consumes 27.9% less energy than “Elf” and “Redelfv2” consumes 8.0% less than “Elf”. For saturated energy per flit, “Redelf” is 17.7% lower than “Elf” and “Redelfv2” is 27.7% lower than “Elf”. This implies that, when designing for low-power, “Redelf” has advantage in energy efficiency when the network is expected to work at relatively low load, and “Redelfv2” should be better when there is high stress in the network.

V. Conclusion

In this paper, we have proposed a routing algorithm for 3D NoC with partial vertical connections. Compared to elevator-first algorithm, the proposed algorithm achieves lower power consumption, higher performance, or both.

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[1] Average of four traffic patterns over three vertical connections (total 12 cases).