Improving Hamiltonian-based Routing Methods for On-chip Networks: A Turn Model Approach

Poona Bahrebar and Dirk Stroobandt

Department of Electronics and Information Systems (ELIS), Ghent University
Sint-Pietersnieuwstraat 41, B-9000 Ghent, Belgium
{poona.bahrebar, dirk.stroobandt}@ugent.be

Abstract—The overall performance of Multi-Processor System-on-Chip (MPSoC) platforms depends highly on the efficient communication among their cores in the Network-on-Chip (NoC). Routing algorithms are responsible for the on-chip communication and traffic distribution through the network. Hence, designing efficient and high-performance routing algorithms is of significant importance. In this paper, a deadlock-free and highly adaptive path-based routing method is proposed without using virtual channels. This method strives to exploit the maximum number of minimal paths between any source and destination pair. The simulation results in terms of performance and power consumption demonstrate that the proposed method significantly outperforms the other adaptive and non-adaptive schemes. This efficiency is achieved by reducing the number of hotspots and smoothly distributing the traffic across the network.

I. INTRODUCTION

Nowadays, the conventional interconnection architectures such as shared buses and ad-hoc wiring solutions, have become the limiting factors for achieving the operational goals of the Multi-Processor Systems-on-Chip (MPSoCs). As a result, Networks-on-Chip (NoCs) have been proposed as a promising solution for the high communication demands required by such complex multicore architectures [1], [2]. On-chip communication which plays a determinant role in the performance of the network is controlled by the routing algorithms. For maximum system performance, a routing algorithm should have high throughput and low latency, avoid deadlocks and livelocks, and be able to work well under various traffic patterns [4]. Deadlock is one of the potential problems in designing efficient routing methods [2]. It has been proved in [5] that a routing function for an interconnection network is deadlock-free if and only if there are no cycles in the Channel Dependency Graph (CDG). Breaking the cycles in the CDG is either realized by restricting the routing algorithm to avoid the prohibited paths or splitting each physical channel along a cycle into a number of Virtual Channels (VCs) [5]. However, adding VCs imposes extra hardware requirements and a complex control logic to the routers [6]. Therefore, it is highly desirable to design deadlock-free routing algorithms without using VCs.

Among the factors associated with the design of an efficient routing algorithm, adaptivity [6], [3] appears to be of crucial importance. Adaptivity determines the ability of the routing algorithm to provide alternative paths between each pair of source and destination nodes. Compared to the deterministic routing schemes, adaptive routing methods achieve better performance by sending the packets through alternative paths, and

thereby avoiding congested or faulty regions of the network. In this paper, a highly adaptive path-based unicast/multicast routing method is presented for wormhole-switched 2D mesh NoCs. The proposed method is deadlock- and livelock-free and requires no VCs. It has also been exploited to increase the adaptivity in the Multi-Path (MP) routing algorithm [7].

The remainder of this paper is organised as follows. Section II gives an overview of the Hamiltonian path-based routing algorithms. The proposed routing method, and the deadlock avoidance in this scheme are presented in Section III. Section IV is devoted to the simulation results and discussion. Finally, the conclusions are drawn in the last section.

II. RELATED WORK

The Hamiltonian strategy [7] is a well-known path-based method used for multicast routing. In this method, each router is assigned a label between 0 and $N-1$ (N is the number of routers in a 2D mesh network). Starting from the first router with $(0,0)$ coordinates, the routers in even rows are given labels from left to right, and the routers located in odd rows are labelled from right to left. Such a labelling in a 3×4 mesh is illustrated in Fig. 1. Based on the labelling, two disjoint subnetworks (or directed Hamiltonian paths) could be identified in the network: the high-channel subnetwork (H_H) and the low-channel subnetwork (H_L) which are specified by the solid and dashed arrows in the figure, respectively. If the label of the destination is greater (smaller) than that of the source, the routing takes place in the H_H (H_L) subnetwork and the nodes are visited in an ascending (descending) order. Although the vertical channels are not parts of the Hamiltonian paths, they can also be utilized accordingly in order to shorten the paths in routing. The Hamiltonian path-based routing strategy guarantees deadlock- and livelock-free routing [4], [7].

1) Multi-Path (MP) Routing Algorithm: In the MP routing method, first, the set D of destination nodes is partitioned into two discrete subsets, D_H and D_L. D_H (D_L) is composed of
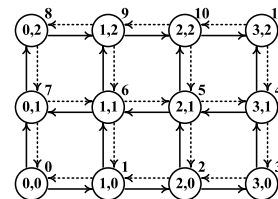

Fig. 1. A 3×4 mesh with corresponding Hamiltonian labelling. The solid and the dashed arrows represent the H_H and H_L subnetworks, respectively.

the destination nodes with greater (smaller) labels compared to the source. In the second step, D_H and D_L are also partitioned further into left and right subsets to form (at most) four disjoint subsets. The source, afterwards, generates (at most) four multicast packets with the sorted destinations in their headers. The packets are forwarded through the network using the corresponding Hamiltonian path [7].

2) Adaptive Multi-Path (AMP) Routing Algorithm: Deterministic routing methods (such as MP) suffer significantly from the degraded performance in congested networks. The AMP routing algorithm was proposed in [8] to improve the performance of MP by exploiting the alternative minimal paths during routing. AMP is based on the Hamiltonian Adaptive Multicast Unicast Model (HAMUM) [9]. AMP (or HAMUM, in general) is associated with two groups of rules:
For the low-channel subnetwork,
Rule 1: South and West directions are allowed in even rows.
Rule 2: South and East directions are allowed in odd rows.
And for the high-channel subnetwork,
Rule 1: North and East directions are allowed in even rows.
Rule 2: North and West directions are allowed in odd rows.

The behaviour of this algorithm is shown in the 8×8 mesh of Fig. 2. As can be seen in the figure, the destinations are partitioned such that four copies of the message are prepared and sent from the source (i.e. node 35) to accomplish the desired multicast operation. Consider the multicast message originating from the source node which attempts to reach the destinations in D_{L_2}. The AMP alternative paths have been shown with solid arrows in the figure. In order to route the message from node 27 (which is located in an odd row) to node 7, the second rule of HAMUM for the H_L subnetwork is applicable. The router at this node has to decide whether to route the packet to the south (node 20) or to the east (node 26). The decision is based upon the congestion level of the north and west input buffers of the aforementioned routers, respectively. In fact, by comparing the Congestion Flags (CFs) [8], the proper direction towards which the packet has to be forwarded is determined. Compared to the MP, the number of available paths to be taken from node 27 to node 7 is increased to 4. For the packets being routed from the source node to the destinations in D_{L_1}, D_{H_1}, and D_{H_2}, the number of available paths has been increased to 2, 3, and 2, respectively.

III. Proposed Routing Method

Adaptivity in routing algorithms has a high impact on the network's overall performance. Therefore, the main motivation for this study was to increase the adaptivity of HAMUM by taking advantage of the unused minimal paths in this scheme, and propose a new routing method based on that.

A. Routing Mechanism

The permitted and prohibited turns formed in even and odd rows using HAMUM rules can be regulated by the cycles of Fig. 3(a). Note that a 90-degree change of the travelling direction is called a turn [10]. As it is evident from the figure, two of the four possible turns in each cycle are prohibited using HAMUM routing method. But it is possible to preserve one of the two prohibited turns in each cycle and change the other one to a permitted turn, to ensure the deadlock-freedom and an
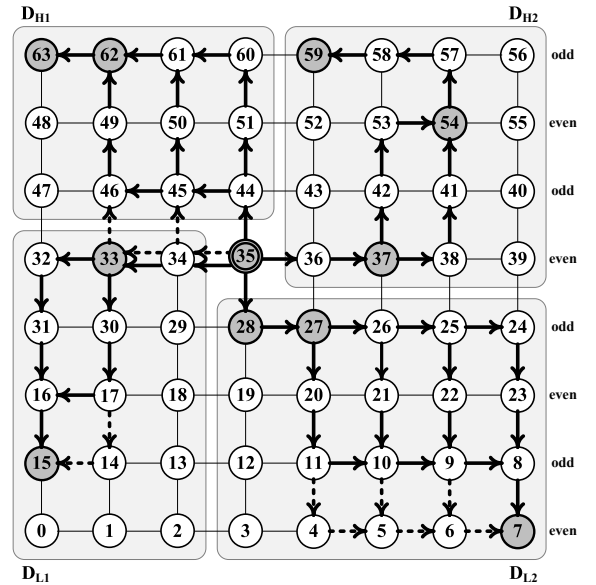

Fig. 2. AMP and HOEMP routing algorithms. The solid arrows represent the AMP paths, and the dashed arrows indicate the paths added by HOE.

increased adaptivity at the same time. In fact, the restrictions in HAMUM (and particularly AMP) that confine the packets to necessarily follow the Hamiltonian paths are relaxed by the proposed routing mechanism. This is achieved by carefully choosing the prohibited turns so that every possible cycle is broken and the deadlock is avoided.

Of the 16 different possibilities to modify the prohibited turns in each cycle of Fig. 3(a), 14 result in deadlock. The permitted and prohibited turns in one of the deadlock-free routing possibilities is shown in Fig. 3(b). As it is obvious from the figure, in each cycle, one of the prohibited turns in HAMUM is allowed and the other one remains forbidden to prevent deadlock. The rules of the proposed routing method can be established as follows:
Rule 1: *East-South and North-West turns are prohibited in even rows.*
Rule 2: *North-East and West-South turns are prohibited in odd rows.*
According to the above rules, ES and NE turns do not take place in the same row. Furthermore, NW and WS turns cannot be taken at the nodes in the same row. Note that similar to the OE turn model [10], 180-degree turns are prohibited. The order of the turns in the above two rules may also be interchanged.

The proposed scheme, which is called Hamiltonian-based Odd-Even (HOE) routing method, is able to outperform HAMUM in terms of adaptivity. This is evident in Fig. 2 where HOE rules are applied to the MP method (HOEMP). The paths added by the HOE are shown with the dashed arrows in the
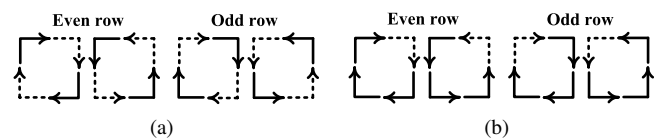

Fig. 3. Permitted (solid) and prohibited (dashed) turns using (a) HAMUM, and (b) HOE routing methods in even and odd rows.

figure. Consider the case when the packet originating from the source node and heading to node 7 in D_{L_2}, has arrived at router 10 via 11. By exploiting the rules added by HOE, this packet can be forwarded to 9 (the same as AMP), or to 5 by taking an ES turn which is allowed in odd rows. Once it reaches 5 which is located in an even row, the packet can take a SE turn to reach the destination. Compared to the AMP, the number of alternative paths in this particular case has been raised from 4 to 10. Also, it has been doubled for the packets travelling to node 62 in D_{H_1}. For the destinations located in D_{L_1}, the number of alternative paths has been raised to 3. But as can be seen in the figure, the proposed rules cannot be employed for forwarding the packets to the destinations in D_{H_2} and the number of alternative paths remains unchanged. Note that the destination partitioning is identical to the AMP and MP.

B. Deadlock Avoidance

1) Unicast Mode: The following argument is based on the proof given in [10] which justifies that the OE turn model is deadlock-free.

Theorem. *Any unicast routing algorithm that follows the HOE rules is deadlock-free as long as* 180-*degree turns are not allowed.*

Proof: We need to prove that the uppermost row which is a necessary part of a circular waiting path can never be formed. Suppose by contradiction that there exists a set of packets $p_1, p_2, ..., p_k$ that are deadlocked in a circular waiting path. This waiting path must be comprised of both row and column channels because 180-degree turns are prohibited. Consider RS_u which is the uppermost row segment in the waiting path. The channels of RS_u could be either West-East or East-West, which are both shown in Fig. 4. The beginning and the end nodes of RS_u are also designated as A and B. In Fig. 4(a), there must be some p_i, $1 \leq i \leq k$, taking a NE turn at node A, and also some p_j, $1 \leq j \leq k$, taking an ES turn at node B on the waiting path. Here the contradiction arises because NE and ES turns cannot occur at the nodes in the same row according to the rules of HOE. A similar contradiction can be obtained for the westward channels in RS_u, utilizing the rules of HOE. Thus, it is proved that HOE is deadlock-free. ∎

2) Multicast Mode (for MP Algorithm): Here, we show that with some restrictions, using the HOE method for the multicast traffic in MP does not threaten the deadlock-freedom in this algorithm. The Degree of Adaptiveness (DoA) determines the number of minimal paths that an algorithm offers from a source node to a destination node [6]. Based on the location of the destination with respect to the source node, eight different states (four in each subnetwork) could be identified such that the DoA of the HOE is higher than that of the HAMUM. In these states which are shown in Fig. 5, both HAMUM paths (solid arrows) and the additional paths offered by HOE (dashed arrows) are illustrated. Utilizing the HOE method for
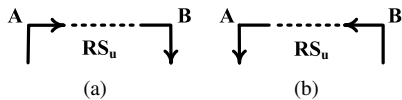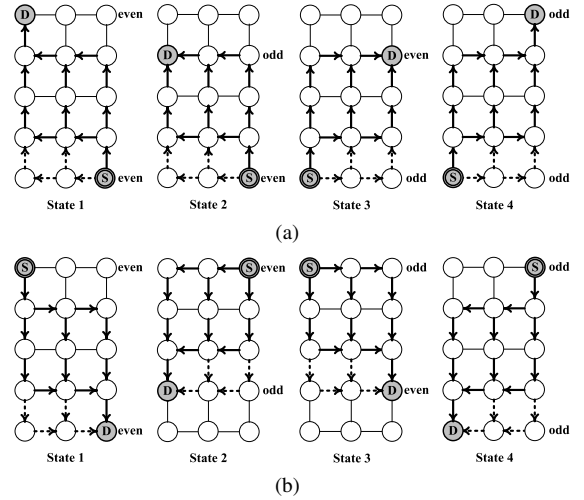

Fig. 5. Possible states with different DoAs for HAMUM and HOE routing methods in the (a) high-channel, and (b) low-channel subnetworks.

the multicast messages dispatched from the source node to the first destination in the H_H subnetwork does not jeopardize the deadlock freedom in the MP algorithm. In other words, there is no risk of a 180-degree or prohibited turn in such situations. This is also true for the multicast packets travelling to the last destination in the H_L subnetwork. For the remaining situations in both subnetworks, HOEMP has to be restricted to behave the same as AMP in order to avoid the risk of deadlock.

IV. RESULTS AND DISCUSSION

The efficiency of the proposed method is evaluated using a modified version of BookSim 2.0 cycle-based network simulator [3] and Orion 2.0 [11] power library. The packet switching technique being used is wormhole. Details of the simulation parameters are listed in Table I. First, the simulator has been warmed up for 10,000 cycles and then the results are averaged over the next 100,000 cycles. All of the values reported in this section are obtained by averaging the results from 50 simulation samples, each with a distinct random starting seed, to ensure a fair comparison between the algorithms.

A. Performance Analysis

Simple traffic models such as uniform random and hotspot are useful for NoC designers in acquiring insights by stressing the network with a regular, predictable traffic pattern. However, they do not represent realistic traffic loads which are necessary in assessing the networks. In fact, placing two highly communicating blocks on opposite ends of a chip is as undesirable as mapping two highly communicating tasks to the tiles located at opposite ends in a NoC. That's why the locality of tasks is required in NoCs analogous to the classical logic placement

Fig. 4. (a) West-East (eastward), and (b) East-West (westward) channels of the uppermost row segment in the waiting path.

TABLE I.   SIMULATION PARAMETERS

Parameter	Value
Network size and Topology	8×8 2D mesh
Number of destinations	10 and 25
Data width	32 bits
Buffer (FIFO) and Message size	8 and 16 flits
Congestion threshold	60% of the total buffer capacity

in circuits [12]. For this reason, we have implemented a Rentian [13] traffic generator which mimics the real traffic distribution in a network. The implementation is based on the Communication Probability Distribution (CPD) introduced in [14]. CPD is the probability that a processor sends packets to another processor at a particular distance in the network: the farther the distance, the smaller the probability. The formula for CPD and implementation details are described in [14].

The average latency for the MP, AMP, and HOEMP routing algorithms as a function of the message injection rate is shown in Fig. 6 under the mixed Rentian traffic profile. This pattern represents the traffic in distributed shared-memory multiprocessors, in which cache misses are performed using unicast messages, and updates and invalidations are served by multicast messages [4], [8]. In our simulations, the mixture of multicast and unicast traffic has been implemented such that 80% of the injected messages are unicast, and the remaining 20% are multicast. The Rent's exponent (p) has also been set to 0.75. As is apparent from the figure, HOEMP excels in reaching the lowest average latency even in high injection rates and larger number of destinations. The average performance gain that HOEMP offers near the saturation points (0.27 and 0.2) is about 38% and 54% compared to the AMP and MP, respectively. This efficiency is mainly due to the fact that adaptive routing methods try to minimize the congestion in the network by offering alternative paths to route the packets, thereby reducing the average communication delay. On the contrary, deterministic routing methods (such as MP) are highly vulnerable to the congestion since they have no mechanism to tackle the congested areas of the network. Although AMP is also adaptive, the results confirm that HOEMP is able to outperform that in terms of adaptiveness. In fact, the simulation results confirm that HOEMP is less vulnerable to the numerous number of hotspots being created around the sources under a nonuniform traffic pattern.

B. Power Analysis

The power consumption has also been calculated using the UMC 90 nm technology, with an operating point of 1 GHz and supply voltage of 1 V. The results in terms of average power consumption near the saturation points have been shown in Fig. 7. These results support our conclusion that HOE excels the other methods in diminishing the number of hotspots, and consequently, the power consumption in the network.
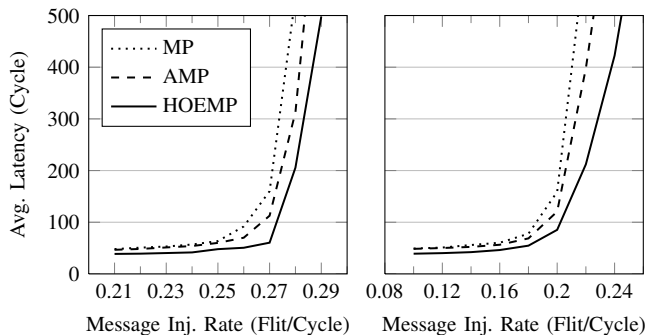

Fig. 6. Performance comparison of an 8×8 mesh with 10 (left) and 25 (right) destinations under mixed Rentian traffic profile.
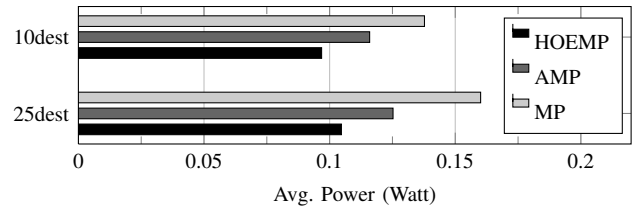

Fig. 7. Average power consumption of an 8×8 mesh with 10 and 25 destinations near the saturation points under mixed Rentian traffic profile.

V. Conclusion and Future Work

In this paper, a deadlock-free and highly adaptive path-based routing method (HOE) is proposed. By prohibiting the minimum number of turns, HOE strives to reach a high degree of adaptiveness, without using VCs. Applying the HOE rules to the MP routing method has also been studied in the paper. The results in terms of performance and power consumption validate the flexibility of our approach in choosing the appropriate routing path based on the congestion condition of the network. We plan to evaluate the performance of HOE under other workloads and traffic patterns. Moreover, the area of the router required by HOE remains to be examined in the future.

References

[1] A. Jantsch and H. Tenhunen, Eds., *Networks on Chip*. Hingham, MA, USA: Kluwer Academic Publishers, 2003.

[2] J. Duato, S. Yalamanchili, and L. M. Ni, *Interconnection Networks: An Engineering Approach*. San Francisco, CA, USA: Morgan Kaufmann Publishers Inc., 2003.

[3] W. J. Dally and B. P. Towles, *Principles and Practices of Interconnection Networks*. Morgan Kaufmann Publishers, 2004.

[4] R. V. Boppana, S. Chalasani, and C. S. Raghavendra, "Resource deadlocks and performance of wormhole multicast routing algorithms," *IEEE Trans. Parallel Distrib. Syst.*, vol. 9, no. 6, pp. 535–549, 1998.

[5] W. J. Dally and C. L. Seitz, "Deadlock-free message routing in multiprocessor interconnection networks," *IEEE Trans. Comput.*, vol. 36, no. 5, pp. 547–553, 1987.

[6] C. J. Glass and L. M. Ni, "The turn model for adaptive routing," *Journal of Assoc. Comput. Mach. (JACM)*, vol. 41, no. 5, pp. 874–902, 1994.

[7] X. Lin, P. K. McKinley, and L. M. Ni, "Deadlock-free multicast wormhole routing in 2-D mesh multicomputers," *IEEE Trans. Parallel Distrib. Syst.*, vol. 5, no. 8, pp. 793–804, 1994.

[8] M. Daneshtalab, M. Ebrahimi, T. C. Xu, P. Liljeberg, and H. Tenhunen, "A generic adaptive path-based routing method for MPSoCs," *Journal of Syst. Architect. (JSA)*, vol. 57, no. 1, pp. 109–120, 2011.

[9] M. Ebrahimi, M. Daneshtalab, P. Liljeberg, and H. Tenhunen, "HAMUM - A novel routing protocol for unicast and multicast traffic in MPSoCs," in *Proc. Euromicro Int. Conf. on PDP*, 2010, pp. 525–532.

[10] G.-M. Chiu, "The odd-even turn model for adaptive routing," *IEEE Trans. Parallel Distrib. Syst.*, vol. 11, no. 7, pp. 729–738, 2000.

[11] A. B. Kahng, L. Bin, L.-S. Peh, and K. Samadi, "ORION 2.0: A power-area simulator for interconnection networks," *IEEE Trans. Very Large Scale Integr. (VLSI) Syst.*, vol. 20, no. 1, pp. 191–196, 2012.

[12] D. Greenfield, A. Banerjee, J.-G. Lee, and S. W. Moore, "Implications of Rent's rule for NoC design and its fault-tolerance," in *Proc. 1st Int. Symp. on NOCS*, 2007, pp. 283–294.

[13] P. Christie and D. Stroobandt, "The interpretation and application of Rent's rule," *IEEE Trans. Very Large Scale Integr. (VLSI) Syst.*, vol. 8, no. 6, pp. 639–648, 2000.

[14] G. B. P. Bezerra, S. Forrest, M. Moses, A. Davis, and P. Zarkesh-Ha, "Modeling NoC traffic locality and energy consumption with Rent's communication probability distribution," in *Proc. ACM/IEEE Int. Workshop on SLIP*, 2010, pp. 3–8.