Computers and Electrical Engineering 45 (2015) 386–401

Contents lists available at ScienceDirect

Computers and Electrical Engineering

journal homepage: www.elsevier.com/locate/compeleceng

The Hamiltonian-based odd–even turn model for maximally adaptive routing in 2D mesh networks-on-chip ☆

Poona Bahrebar *, Dirk Stroobandt

Department of Electronics and Information Systems (ELIS), Ghent University, Sint-Pietersnieuwstraat 41, 9000 Ghent, Belgium

ARTICLE INFO

Article history:
Received 15 February 2014
Received in revised form 4 December 2014
Accepted 8 December 2014
Available online 14 January 2015

Keywords:
Network-on-Chip (NoC)
Adaptive routing methods
Deadlock
Turn model
Hamiltonian path-based routing strategy

ABSTRACT

Networks-on-Chip (NoCs) have emerged as a promising solution for the communication crisis in today's high-performance Multi-Processor System-on-Chip (MPSoC) architectures. Routing methods have a prominent role in taking advantage of the potential benefits offered by NoCs. As a result, designing high-performance and efficient routing algorithms is highly desirable. In this paper, the Hamiltonian-based Odd–Even (HOE) turn model is proposed for both unicast and multicast routing in wormhole-switched 2D mesh networks. HOE is able to maximize the degree of adaptiveness by minimizing the number of prohibited turns, such that the algorithm remains deadlock-free without adding virtual channels. By increasing the number of alternative minimal paths, the hotspots are less likely to be created and the traffic is efficiently distributed throughout the network. The simulation results in terms of latency and power consumption indicate the better performance of the proposed method in comparison with the existing routing methods.

1. Introduction

Nowadays, bus-based and ad-hoc interconnects can no longer support the high communication demands of the complex Multi-Processor Systems-on-Chip (MPSoCs) according to the continuously increasing number of cores. As a result, Networks-on-Chip (NoCs) have been proposed as a promising solution to take advantage of the inherent parallelization offered by these multicore architectures [1,2]. Routing algorithms are responsible for the on-chip communication and traffic distribution across the network. Since on-chip communication plays a major role in the performance of the system, designing efficient routing methods is of significant importance.

According to [3], there are several properties that an ideal routing method should possess for maximum system performance, namely, high-throughput and low-latency message delivery, avoidance of deadlocks and livelocks, and ability to work well under various traffic patterns. Deadlock occurs when two or more packets are blocked forever due to the cyclic dependencies of resources such as links or buffers [4]. Livelock is a state when a packet keeps circulating in the network without ever reaching its destination [5].

In the wormhole switching technique, a packet is decomposed into small units called FLITs (FLow control digIT) which are then routed consecutively through the network [2]. Wormhole flow control has been increasingly advocated and used as a means of reducing latency and buffering requirements in various multicomputers [2,5]. But since it is prone to deadlock [5],

☆ Reviews processed and recommended for publication to the Editor-in-Chief by Associate Editor Dr. M. Daneshtalab.

* Corresponding author.
E-mail addresses: poona.bahrebar@ugent.be (P. Bahrebar), dirk.stroobandt@ugent.be (D. Stroobandt).

http://dx.doi.org/10.1016/j.compeleceng.2014.12.009
0045-7906/

additional precautions are necessary to guarantee the deadlock-freedom. It has been proven in [2] that a routing function for an interconnection network is deadlock-free if and only if there are no cycles in the Channel Dependence Graph (CDG). Breaking the cycles in the CDG is realized by either (1) restricting the routing algorithm in path selection such that an acyclic CDG is formed, or (2) splitting each physical channel along a cycle into a number of Virtual Channels (VCs) [2].

Among the factors contributing to the design of an efficient routing method, adaptivity [4] is an important one. Adaptivity determines the ability of the routing algorithm to provide alternative paths between each pair of source and destination nodes. In terms of adaptivity, the routing algorithms are classified into two main categories [2,4]: A *deterministic* (non-adaptive) routing algorithm always supplies the same fixed path between a given source–destination pair. On the contrary, a (minimal) *adaptive* routing algorithm adapts to the state of the network to select a route among alternative (shortest) paths to the destination. Note that a *fully adaptive* routing algorithm allows the packets to choose from any path. However, a *partially adaptive* routing algorithm is capable of routing packets through multiple paths, but some paths are prohibited for deadlock-freedom. A partially adaptive routing algorithm that maximizes the number of routing options while avoiding deadlock is referred to as *maximally adaptive* [5]. Compared to the deterministic methods, adaptive routing algorithms are able to avoid congested or faulty regions, and achieve a better load balance by distributing the traffic across the network.

VCs can also be incorporated to design highly adaptive routing methods that are deadlock-free. In fact, designing deadlock-free fully adaptive routing algorithms without VCs is impossible [2,5]. However, adding VCs to the network is costly because of the extra hardware requirements and the complex control logic imposed to the routers which can potentially increase the area overhead and network latency [2,4]. Thus, designing adaptive deadlock-free routing algorithms without using VCs is highly desirable.

In this paper, a maximally adaptive unicast/multicast routing method is presented targeting wormhole-switched two-dimensional (2D) mesh on-chip networks. The proposed Hamiltonian-based Odd–Even (HOE) turn model is deadlock- and livelock-free and requires no VCs. It has also been exploited to increase the adaptivity of the Column-Path (CP) [6] and Multi-Path (MP) [7] routing algorithms.

The remainder of this paper is organized as follows. After a brief overview of related works in Section 2, the path-based multicast routing algorithms are further studied in Section 3 because of their important role as an infrastructure for the proposed routing scheme. Section 4 presents the proposed routing method in both unicast and multicast modes, its degree of adaptiveness, and the deadlock avoidance in this model. Section 5 is devoted to the simulation results and discussion. Finally, the conclusions are drawn and some possible directions for future work are outlined in Section 6.

2. Background and related work

In general, the routing algorithms can be classified as either *unicast* (one-to-one) or *multicast* (one-to-many) [8,9], depending on the number of destination nodes.

2.1. Unicast routing methods

The turn model was proposed in [4] as a systematic approach to design partially adaptive and deadlock-free unicast routing algorithms without using VCs. The turn model is based on analyzing the directions in which packets can turn in a network and the cycles that the turns can form. By prohibiting the smallest number of turns to break all of the cycles, maximally adaptive routing algorithms could be designed which are deadlock-free. The algorithm should not prohibit more turns than necessary. Otherwise, its adaptivity is reduced [4].

The two cycles in Fig. 1(a) represent the eight turns formed using the four directions, East (E), West (W), North (N), and South (S) in a 2D mesh. Note that a 90-degree change of the travelling direction is called a turn [10]. The permitted and prohibited turns using the XY routing method are shown in Fig. 1(b) by the solid and dashed arrows, respectively. XY is deadlock-free since the four permitted turns cannot form a cycle, but neither do they allow any adaptivity [5]. In fact, only two turns, one from each cycle, need to be prohibited in order to provide some degree of adaptivity in routing. However, the prohibited turns must be chosen carefully since prohibiting any two turns does not guarantee deadlock-freedom [4]. The West-First (WF), North-Last (NL), and Negative-First (NF) routing algorithms presented in [4] based on the turn model, prohibit just one turn in each cycle. The permitted and prohibited turns of these maximally adaptive unicast methods are illustrated in Fig. 1(c)–(e), respectively.

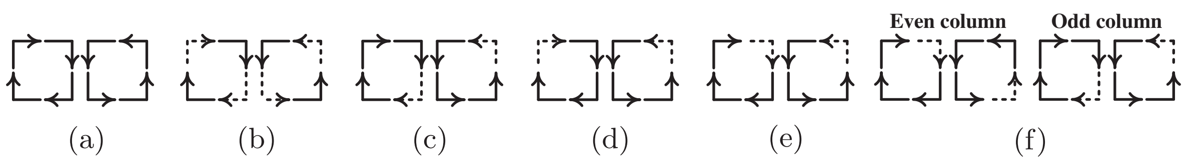

Fig. 1. (a) Clockwise and counter-clockwise cycles forming eight possible turns in a 2D mesh. Permitted and prohibited turns using (b) XY, (c) WF, (d) NL, (e) NF, and (f) OE routing methods [4,10].