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Adaptive wormhole routing in tori with faults

S. Chalasani
R.V. Boppana

Indexing terms: Adaptive routing, Deadlocks, Fault-tolerant routing, Multicomputer networks, Message routing, Performance evaluation, Torus networks, Wormhole routing

Abstract: The authors present a method to enhance wormhole routing algorithms for deadlock-free fault-tolerant routing in tori. They consider arbitrarily-located faulty blocks and assume only local knowledge of faults. Messages are routed via shortest paths when there are no faults, and this constraint is only slightly relaxed to facilitate routing in the presence of faults. The key concept used is that, for each fault region, a fault ring consisting of fault free nodes and physical channels can be formed around it. These fault rings can be used to route messages around fault regions. We prove that, at most, four additional virtual channels are sufficient to make any fully-adaptive algorithm tolerant to multiple faulty blocks in torus networks. Simulation results are presented for a fully-adaptive algorithm showing that good performance can be obtained with as many as 10% links faulty.

1 Introduction

Point-to-point torus and related networks are being used in many recent experimental and commercial multicomputers and multiprocessors [1–3]. A (k,n)-torus network has an n-dimensional grid structure with k nodes (processors) in each dimension such that every node is connected to two other nodes in each dimension by direct communication links. The *wormhole* (WH) switching technique by Dally and Seitz [8] has been used in many recent multicomputers [1–4]. In the WH technique, a packet is divided into a sequence of fixed-size units of data, called *flits*. If a communication channel transmits the first flit of a message, it must transmit all the remaining flits of the same message before transmitting flits of another message. To avoid deadlocks among messages, multiple virtual channels are simulated on each physical channel and a predefined order is enforced on the allocation of virtual channels to messages.

For fault-free networks, important issues in the design of a routing algoritlim are high throughput, low-latency message delivery, avoidance of deadlocks, livelocks and starvation and ability to work well under various traffic patterns. Given a network with faults, our approach is to use the existing network rather than recreate the original network using spare nodes and links. Therefore, for networks with faults, a routing algorithm should exhibit the following additional features: graceful degradation of performance and ability to handle faults with only a small increase in routing complexity and local knowledge of faults.

The well-known *e*-cube or dimension-order routing algorithm is an example of nonadaptive routing algorithms, since always a particular path is used in routing messages between a pair of nodes even when multiple shortest paths are available. With the *e*-cube, even a single fault disrupts communication between multiple pairs of nodes. With increase in adaptivity, a message is more likely to find a less congested path or fault-free path. Therefore, the issue of adaptivity, the extent of choice in selecting a path between a pair of nodes in routing a message, plays an important role in designing fault-tolerant routing algorithms.

1.1 Description of the problem and results

We present a technique to enhance minimal, fully-adaptive routing algorithms for fault-tolerant routing in tori. A minimal fully-adaptive algorithm routes messages along any of the shortest paths available. We consider routing methods that use only local knowledge of faults. We assume that faulty processors are confined to one or more rectangular blocks.

For each fault region, there exist one or more paths that pass through fault-free nodes and links and encircle the fault. For a fault in a 2D torus, there is an undirected ring of fault-free nodes and links; we refer to this ring as *fault-ring*. In this paper, we show that fault rings can be used to route messages around the fault regions using only local knowledge of faults and without introducing deadlocks and livelocks.

1.2 Related results

Adaptive, fault-tolerant routing algorithms for WH and virtual cut-through switching techniques has been the subject of extensive research in recent years [5–10]. Reddy and Freitas [11] use global knowledge of faults, spare nodes, and routing tables to investigate the performance limitations caused by faults. Gaughan and Yalamanchili [12] use a pipelined circuit-switching mechanism with backtracking for fault-tolerant routing. These two results are applicable to networks with arbitrarily-shaped faults. Our interest in this paper, is to design fault-tolerant wormhole routing algorithms that can be applied with local knowledge of faults. One important criterion is that the fault-free performance should not be sacrificed for fault-tolerant routing.

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There are no previous results specifically on fault-tolerant wormhole routing in tori. Often, the results developed for meshes [5,8,13] can be extended to tori with suitable modifications, since meshes and tori are closely related. The wraparound links in tori lead to extra deadlock possibilities, however. Therefore, if the results developed for meshes are applied with few changes, the number of virtual channels required to avoid deadlocks may be doubled [5]. Furthermore, meshes have edges, for example, the top row in a 2D mesh, and faults on edges are complicated to handle [13]. But this case never arises in tori, since they are node symmetric. Hence, extending efficient mesh routing techniques to tori in a straight forward manner may not necessarily yield efficient routing algorithms for the latter networks.

In terms of adaptivity and performance comparisons, the results by Dally and Aoki [8] are the most relevant to ours. With the dimension-reversal schemes of Dally and Aoki, a message may lose its adaptivity, if its number of dimension reversals equals the number of virtual channel classes. A message that has lost adaptivity is routed by the *e*-cube algorithm and is not guaranteed to be delivered to its destination if there are faults in the network. Thus the number of virtual channels needed and the number of faults tolerated is highly dependent on the number of virtual channels and the location of faults. In contrast, our algorithms can tolerate any number and combination of rectangular faulty blocks with simple logic, and require only four virtual channels more than that required for the original adaptive algorithm. (Throughout this paper we indicate the number of virtual channels on per physical channel basis). This result compares well with our earlier result that four extra virtual channels are sufficient for routing in meshes with faults [13].

2 Preliminaries

A (k,n)-torus (also called k-ary n-cube) has n dimensions, numbered from 0 to $(n-1)$, and $N = k^n$ nodes. Each node is uniquely indexed by an n-tuple in radix k. Each node is connected via communication links to two other nodes in each dimension. The neighbours of the node $x = (x_{n-1}, ..., x_0)$ in dimension i are $(x_{n-1}, ..., x_{i+1}, x_i \pm 1, x_{i-1}..., x_0)$, where addition and subtraction are modulo k. A link is said to be a wraparound link if it connects two neighbours whose addresses differ by $k-1$ in dimension i, $0 \le i < n$. A (k, n)-mesh is a (k, n)-torus with the wraparound connections missing. We assume that each communication link represents two unidirectional physical communication channels. The link between nodes x and y is denoted by $<x, y>$. To simplify presentation, we discuss the concept of fault-rings for two dimensional (2D) tori. We label the sides of a 2D torus as North, South, East and West.

2.1 Fault model

We consider both node and link faults. All the links incident on a faulty node are considered faulty. We assume that faults are permanent and nonmalicious faults. Therefore, messages are generated by and for nonfaulty processors only. We develop fault-tolerant algorithms, for which it is sufficient if each nonfaulty processor knows the status of the links incident on it.

A *fault set* is defined as the set F of faulty nodes and faults and two link faults in the two-dimensional network shown in Fig. 1. We assume that faults in a 2D torus have *rectangular* shapes. A set F of faulty nodes and links in a 2D torus is said to have a rectangular shape if there is a rectangle in the torus such that: (*a*) there are no faulty components on the boundary of the rectangle, (*b*) the interior of the rectangle† includes all faulty components in F and (*c*) the interior of the rectangle contains no component that is not present in F.

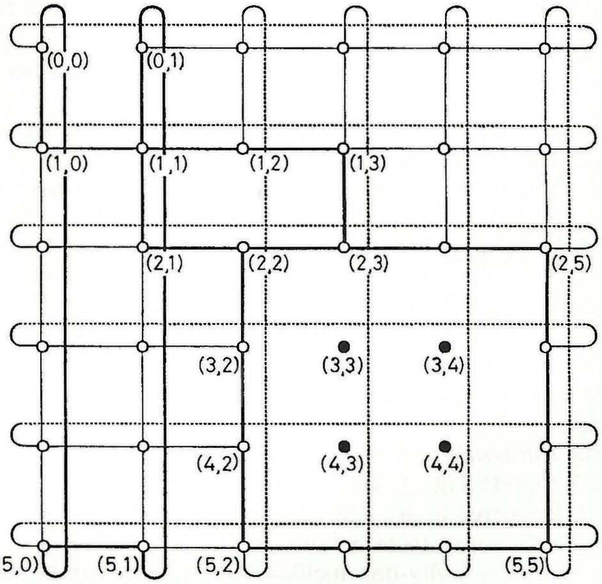

Fig. 1 *Three fault regions and their associated fault rings in a 6 × 6 torus*

For example, the set {(3,3),(3,4),(4,3),(4,4)} of faulty nodes shown in Fig. 1 is rectangular, since the interior of the rectangle – with corners (2,2),(2,5),(5,2), and (5,5) – includes all faulty components in F and no nonfaulty component (recall that a processor fault implies that all links incident on it are faulty). However, the set of faulty links {<(1,1),(1,2)>, <(1,2),(2,2)>, <(2,2),(2,1)>, <(2,1),(1,1)>} in a 6 × 6 torus is not rectangular, since any rectangle with nonfaulty elements on its boundary contains at least one-element not in F. The faulty link <(1,2), (2,2)> is an example of a rectangular fault region, since the interior of the rectangle with corners (1,1), (1,3),(2,1), and (2,3) contains only the faulty link. The faulty link <(0,0),(0,1)> in Fig. 1 is considered rectangular; the rectangle that covers the faulty link has processors (1,0),(1,1),(5,1) and (5,0) as its corners.

An *f*-region is the fault region of the torus given by a block-fault. Under the *block-fault* model, the fault-set in a 2D torus can be written as a union of disjoint smaller fault sets, each of which denotes an *f*-region. For example, the fault set F in Fig. 1 is in fact the union of three disjoint *f*-regions {(3,3),(3,4),(4,3),(4,4)}, {<(0,0),(0,1)>} and {<(1,2),(2,2)>}. We assume that faults do not disconnect the network.

There are many reasons to consider block faults. First, they model several common fault scenarios such as faults of isolated nodes and links and consecutive nodes in a row or column. Second, an arbitrarily-shaped fault can be modelled as a block-fault, albeit by labelling some nonfaulty processors and/or links as

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