

## Abstract

Interconnection networks play an important role for the performance of modern high performance computing systems. It consists of a series of nodes and links. Each node interacts with each other for communications through links. The interconnection network is a requirement of any parallel computer because parallel system shows high performance by providing reliable and quick communication over the networks. In this context, components failures have an extremely high impact because most of the routing algorithms have not been designed to tolerate faults. Since, one link and/or node failure may halt the entire computing system and stop the scientific applications running on them.

In this thesis, we present fault-tolerant routing algorithms based on adaptive protocols. Adaptive routing protocols can use alternative paths between communicating nodes. Multipath networks and adaptive routing protocols dynamically adapt to network conditions, thus capable of serving interconnection networks affected by a large number of node/link failures. Three contributions are presented throughout this thesis, namely: fault-tolerant distributed node-to-node routing, fault-tolerant node-to-set disjoint-path routing, and reliable broadcasting via independent spanning trees.

The aim of this thesis is to study, implement and evaluate fault-tolerant routing algorithms for the hypercube interconnection network. We have addressed and designed fault tolerant routing algorithms in the presence of high number of node and/or link faults. We addressed this issue by designing adaptive routing protocols for hypercube interconnection networks. This technique addresses network latency and bandwidth utilization for parallel architectures. Adaptive routing algorithms exploit gains of path redundancy in  $n$ -cube.

The first contribution of this thesis is the adaptive fault-tolerant routing algorithm for hypercube topology. This algorithm has been designed in such a way that they can use alternative path available in hypercube topology, making more efficient use of network bandwidth and allowing hypercube networks to perform in the presence of large number of faults. The proposed algorithm is a simple uniform distributed algorithm that can tolerate a large number of process failures, while delivering all  $n$  messages over optimal-length disjoint paths. However, no distributed algorithm uses acknowledgement messages (*acks*) for fault tolerance. So, for dealing the faults, acknowledgement messages (*acks*) are included in the proposed algorithm for routing messages over node-disjoint paths in the hypercube network. Simulation results confirm that the proposed node-to-node routing algorithm provides an average of 10% improvement in the performance of hypercube network in comparison with the previously proposed routing algorithms—depth first search algorithm and unsafety vectors algorithm.

The second contribution is the node-to-set node-disjoint routing algorithm for the hypercube networks with faulty nodes. This algorithm has been designed to the problems of the disjoint shortest paths routing. The proposed algorithm can tolerate maximum  $n - 1$  faulty nodes, where  $n$  is the dimension of the hypercube. The proposed NoSeRo algorithm used the subcube property of the  $n$ -dimensional hypercube. It adapts divide-and-conquer approach to take full advantage of the regularity of the hypercube. Hence, proposed algorithm generates fault-free node-disjoint paths in a faulty environment. The proposed fault tolerant routing algorithm for faulty hypercube networks which finds  $n$  disjoint paths from source process  $s$  to  $n$  destination processes in  $n$ -dimensional hypercube in  $O(n^2)$  time with optimal path lengths at most  $n + f + 1$ , where  $n$  is the number of destination node and  $f$  is the number of faulty nodes. Then simulation results showed that the proposed algorithm reduce the average path length by about 20% in comparison of Bossard's algorithm in 8-dimensional hypercube ( $H_8$ ).

The third contribution is the reliable data broadcasting scheme by generating Independent Spanning Trees (ISTs) on hypercubes. The proposed

scheme can be useful for secure message transmission. Using  $n$ -IST-based broadcasting from same root  $r$  on hypercube network ( $N = 2^n$ ) provides  $n$ -degree fault tolerance. The proposed algorithm can be easily implemented in parallel or distributed systems. Using ISTs one can enhance the fault-tolerance, bandwidth, and security. In this chapter, we study the existence and construction of  $n$  ISTs rooted at an arbitrary vertex in  $H_n$  ( $n \geq 1$ ). A parallel algorithm with the time complexity  $O(n)$  is proposed to construct  $n$  ISTs on  $H_n$ , where  $n \geq 1$ .

In this thesis, we have designed, implemented and evaluated the different algorithms for fault-tolerant routing. The methodologies of all the algorithms are based on existing theories, knowledge and observations. The algorithms proposed in this thesis were developed on a theoretical basis and were implemented practically. With the help of relevant books and related research papers, we have focussed on the design, implementation, and evaluation of similar algorithms with efficient complexity. We have analysed the effectiveness of all the proposed fault-tolerant routing algorithms through simulation. For this, we have developed simulation models for experimental evaluation of our propositions.

All of the proposals made in this thesis are suitable (without hardware modification) to be implemented on currently personal computing systems and all the proposed algorithms are able to tolerate dynamically a reasonable number of faults.

**Keywords:** Hypercube interconnection networks, Fault tolerance, Fault-tolerant routing, Node-disjoint paths, Independent spanning trees, Multicasting, Broadcasting.