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It is further certified that the student has fulfilled all the rquirements of Comprehensive, Candidacy and SOTA.

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DECLARATION BY THE CANDIDATE

I, Lokendra Singh Umrao, certify that the work embodied in this thesis is my own bona fied work and carried out by me under the supervision of Dr. Ravi Shankar Singh from July 2012 to November 2015 at the Department of Computer Science and Engineering, Indian Institute of Technology, Varanasi. The matter emboded in this thesis has not been submitted for the award of any degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully lifted up any other's work, paragraphs, text, data, results, *etc*., reported in journals, books, magazines, reports dissertations, theses, *etc*., or available at websites and included them in this thesis and cited as my own work.

Date : 06/11/2015

Place : Varanasi LOKENDRA SINGH UMRAO

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It is certified that the above statement made by the student is correct to the best of my knowledge.

Dr. Ravi Shankar Singh
(Supervisor)

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Preface

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.

Interconnection networks play an important role in the performance of modern high performance computing systems. It consists of a series of nodes and links. Nodes interact with each other for communication through links. The interconnection network is a requirement of any parallel computer as it helps parallel systems in showing high performance by providing reliable and quick communication over the networks. Since most routing algorithms for parallel computers are not being designed to tolerate faults, component failures impact these systems terribly. Thus, one link and/or node failure may halt the entire computing system altogether and stop the scientic 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 further study parallel computing, interconnection networks, routing, fault tolerance and node-disjoint paths. The scope of research given in this thesis is to design, implement and evaluate fault-tolerant routing strategies for the hypercube topology which can be utilized to frame the supercomputers.

Chapter 1 introduces parallel computing. It deals with the need for high performance computing and discusses the hypercube interconnection networks. General introduction to other related topics in parallel computing is covered to provide the span of the field.

Chapter 2 explains the basic terminologies of fault tolerance, then background on interconnection networks for HPC systems including topologies and routing. Then the concepts about hypercube interconnection networks and their routing methods and previous related works that explain routing strategy for both cases, routing without failures and routing in the presence of failures. The chapter provides complete theoretical and practical implementation of designing simple routing algorithms.

Chapter 3 describes in detail the first adaptive fault-tolerant node-to-node routing algorithm over all shortest node-disjoint paths in n-dimensional hypercube interconnection networks. It is designed in such a way that it can handle large number of node and link failures, while delivering all n messages over disjoint-paths in the presence of maximum permissible node/link failures. The chapter develops the idea from nodes and /or links failures in hyper networks towards fault tolerating interconnection networks.

Chapter 4 presents a node-to-set node-disjoint fault-tolerant routing algorithm based on subcubes of the hypercube networks. The n-dimensional hypercube can tolerate maximum n-1 faulty nodes. The proposed algorithm generates node disjoint-paths which maximise the probability of setting up non-faulty path in a faulty

environment.

Chapter 5 introduces data broadcasting on parallel computers through multiple independent spanning trees (ISTs). The n-IST based broadcasting from common root r on the hypercube network can provide n-degree fault tolerance. The designed fault-tolerant broadcasting algorithm using ISTs may increase message security in hypercube network.

Chapter 6 concludes the thesis and presents future directions in the research. This chapter also gives initiation to a broad range of open lines for fault-tolerant routing and further work.

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.

Most of the concepts in the thesis are illustrated by several examples. This thesis can be useful to students and engineers who are interested in routing algorithms of high speed interconnection networks.

November, 2015 **Lokendra Singh Umrao**
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Abstract

Interconnection networks plays an important role for the performance of modern high performance computing systems. It consists of a series of nodes and links. Each node interact 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.

To my family. They give me the solid basis that always me to reach here.

and

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