

ADAPTIVE ROUTING ALGORITHMS FOR
FAULT-TOLERANT TOPOLOGIES

by

NIDHI AGRAWAL
Department of Electrical Engineering

Submitted

in fulfillment of the requirements of the degree of
Doctor of Philosophy
to the



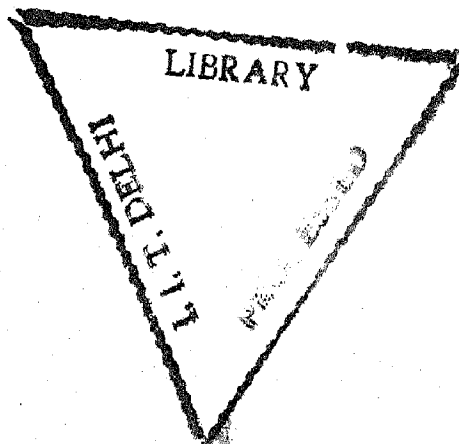
Indian Institute of Technology, Delhi

New Delhi-110016, India.

July, 1998

681.3 : 510.5
AGR - A

I. I. T. DELHI.
LIBRARY
Acc. No. 5TH-2625



Certificate

This is to certify that the thesis entitled “Adaptive Routing Algorithms for Fault-Tolerant Topologies” which is being submitted by Ms. Nidhi Agrawal to the Department of electrical Engineering, Indian Institute of Technology, Delhi, for the award of the degree of Doctor of Philosophy, is a record of bonafide research work she has carried out under my supervision and guidance, and in my opinion, it has reached the standard fulfilling the requirements of the regulations relating to the degree.

The results obtained in this thesis have not been submitted to any other university or institute for the award of a degree or a diploma.



Dr. C.P. Ravikumar

Dept. of Electrical Engineering,
Indian Institute of Technology,
Delhi.

Acknowledgements

For me, it is a great privilege to write a few lines here on this page to express my sincere gratitude to the people who guided me, motivated me and constantly inspired me to carry out my research.

First of all, I express my indebtedness to my supervisor Dr. C.P.Ravikumar for his constant encouragement and incomparable guidance. He introduced me to the world of research and taught me the art of writing. Without his enthusiastic participation and guidance, this work would not have been in its present shape. I shall remain grateful to him and his family throughout my life.

I am grateful to the faculty members and other staff members of Electrical Engineering department, IIT Delhi, for their help and support. My special thanks to the Computing Lab and Computer Service Center staff for providing me the help and support.

My sincere thanks to family friends at IIT campus and my other associates who helped me during my research work. I am very much indebted to my parents at Jabalpur, in-laws at Ghaziabad and my brothers and sisters, without whose cooperation and help I would not have pursued my studies.

Finally, I am proud of my small family, my husband Ajai and my son Saumil, who provided me unbelievable support, motivation and encouragement. They sacrificed their personal priorities to cope up with my studies.

Nidhi Agrawal
Nidhi Agrawal

Abstract

Multicomputers are used for running complex scientific programs and other compute-intensive applications. Interprocessor communication is the bottleneck in achieving high performance of the order of tera-flops in multicomputers. This bottleneck is the prime motivation for research on interconnection networks and related issues. When multicomputers are used in reliability-critical applications, fault-tolerance becomes an important issue. However, as the number of nodes (processors and other system components) increases, the probability of fault occurrence increases as well. In such cases, the prime requirement of the interconnection network and the underlying routing algorithm is fault-tolerance. This thesis addresses the problem of "adaptive routing" in fault-tolerant interconnection topologies like the hypercube, k-ary n-cube and a variation of hypercube called Multiply Twisted Cube(MTC). Adaptive routing ensures that routing is possible in the presence of node faults, link faults and congestion that may arise due to non-uniform traffic conditions. The following algorithms are proposed in this thesis :

- *Fault-tolerant routing on MTC*
- *Adaptive, deadlock-free randomized routing using virtual channels*
- *Adaptive routing based on Deadlock recovery*
- *Adaptive, deadlock-free multicasting based on Euler paths*

Contents

1	Introduction	1
1.1	Motivation	1
1.2	Preliminaries	4
1.2.1	Interconnection network	4
1.2.2	Topology	6
1.2.3	Routing	6
1.2.4	Switching and Flow Control	8
1.2.5	Virtual Channels	9
1.2.6	Deadlocks and Livelocks	10
1.3	Fault-tolerance	11
1.4	Example Multicomputers	12
1.5	Communication patterns	14
1.6	Unicast Communication: state-of-the-art	15
1.6.1	First generation	16
1.6.2	Second generation	16
1.6.3	Third generation	18
1.7	Multicasting	18
1.8	Organization of the Thesis	20
1.8.1	Organization	20
1.8.2	Work carried-out	22

1.9	Conclusions	23
2	Routing: An overview	25
2.1	Interconnection Network Topology	27
2.1.1	Hypercube	28
2.1.2	k-ary n-cube	29
2.1.3	Multiply Twisted Cube	31
2.2	Switching and Flow Control	33
2.2.1	Switching Technique	33
2.2.2	Flow Control	38
2.3	Deadlocks: Avoidance and recovery	40
2.3.1	Deadlock Avoidance	41
2.3.2	Deadlock recovery schemes	43
2.4	Livelock avoidance	45
2.5	Taxonomy of routing algorithms	46
2.5.1	Limited information based routing	48
2.5.2	Self Routing	49
2.5.3	Deterministic Routing Algorithms	51
2.5.4	Partially Adaptive Routing	53
2.5.5	Fully-Adaptive Routing	58
2.6	Multicasting	60
2.6.1	Path-based multicasting	61
2.7	Performance metrics and Cost model	66
2.7.1	Performance metrics	66
2.7.2	Traffic models	68
2.7.3	Chien's Cost Model	69
2.7.4	Distance optimality	71
2.8	Conclusions	72

3	Routing on Multiply Twisted Cube	74
3.1	Introduction	74
3.2	Hierarchical Routing Algorithm	75
3.3	Adaptive, Fault-tolerant hierarchical Routing	82
3.4	Performance Evaluation	85
3.4.1	Network description	85
3.4.2	Simulation Model	88
3.5	Conclusions	91
4	Fully Adaptive Routing	94
4.1	Introduction	94
4.2	Routing Probability Matrix	96
4.3	Randomized Routing Algorithm	98
4.3.1	Effect of α and β	101
4.3.2	Congestion Measurement	102
4.4	Router Design	103
4.5	Deadlock Free Adaptive Randomized Routing	105
4.6	Conclusions	107
5	Adaptive Routing based on deadlock-recovery	108
5.1	Introduction	109
5.2	Detection of deadlocks	114
5.3	Deadlock-Recovery	115
5.3.1	Recovery Scheme 1	115
5.3.2	Recovery Scheme-2	120
5.4	Livelock Avoidance	125
5.5	Simulation based performance analysis	126
5.5.1	Finding optimum <i>TimeOut</i> and $\frac{\alpha}{\beta}$	127
5.5.2	Comparison	130

5.6	Conclusions	134
6	An Euler path based technique for deadlock-free multicasting	135
6.1	Introduction	136
6.2	Euler Circuits and Channel Numbering	138
6.2.1	Reachability Conditions	140
6.3	Routing Algorithm	142
6.3.1	Header Preparation	142
6.3.2	Routing function	145
6.4	Deadlock-free Multicast without Virtual Channels	147
6.4.1	Necessary and sufficient condition	147
6.4.2	Multicasting on Hamiltonian Graphs	148
6.4.3	Multicasting on Eulerian Graphs	150
6.4.4	Multicasting on other Graphs	151
6.5	Simulation Experiments and Results	152
6.5.1	Synchronous Model	153
6.5.2	Poisson Model	156
6.6	Conclusions	156
7	Conclusions and Future Work	161
7.1	Overview	161
7.2	Future Work	164