Chapter 6

Summary and Conclusions

Since the failure rate in HPC systems is high, so developing fault tolerance methods in these systems is highly required. In particular, the time needed by fault tolerance methods for tolerating the failures is decisive, because it increases the traffic load as long as it increases. Hence, the methods should be transparent for the applications running on the systems.

This thesis provides a simple and efficient solutions to the problem of dynamic faults in hypercube networks. We have designed and implemented sufficient and satisfactory solutions by multipath routing methods for large number of node/link failures in high performance computing systems. We have developed three multipath fault-tolerant routing algorithm for solving large number of dynamic node/link failures. These proposed algorithms allow messages to arrive at destination even in the presence of large number of node/link failures. The strongest point of all the algorithms are that they provide significant information about network's fault tolerance and they are able to work in the presence of faults. Apart from handling node/link failures, these algorithms are also capable to handle with congestion problems. These algorithms do not degrade the system performance at all in the presence of failures.

We have presented the design, implementation and evaluation of the contributions of this thesis among the Chapter 3, Chapter 4 and Chapter 5. Throughout this thesis, we have been following the requirements of scientific research method. The proposed methods fulfil two extra necessities. Firstly, in any situation, the network traffic is never halt by the methods. Secondly, the proposed methods seek to be transparent to

the application running on the system with respect to the network performance (e.g., latency, throughput, and QoS requirements) as much as possible.

6.1 Conclusions

Firstly, an adaptive multipath algorithm is proposed that determines the shortest node-disjoint paths from a source node to any destination node. This algorithm allows to find all the paths between source to destination and is independent of the number of faulty nodes and links in a hypercube networks. For dealing with faults, acknowledgement messages (*acks*) are included in the proposed algorithm for routing messages over node-disjoint paths in a hypercube network. The task of the algorithm may be finished after determining the first path, the length of which is equal to Hamming distance. The algorithm is effective to provide fault tolerance for the hypercube system, which may have a great number of faulty nodes and/or links. This approach may be applied to the routing algorithm with local information about faulty nodes and links, to broadcasting and multicasting algorithms and task allocation problems.

We have described an optimal node-to-set fault-tolerant routing algorithm in hypercubes, which finds disjoint paths from single source node to multiple destinations nodes in $O(n^2)$ time with optimal path length at most $n+f+1$. The proposed NoSeRo algorithm can tolerate maximum $n-1$ faulty nodes. Experimental results showed that applying NoSeRo algorithm approach reduce path length about 20% in H_8.

The basic idea of hypercubes and their contribution to the improvement of spanning tree protocols in broadcasting was discussed. This chapter proposed a fault-tolerant broadcasting protocol by means of multiple independent spanning trees (ISTs) in a hypercube network H_n. Fault tolerance can be achieved by sending n copies of the message along n independent spanning trees rooted at the same root r. If the source node r is fault free, then this strategy can tolerate up to $n-1$ faulty nodes/links. The proposed algorithm is applied to solve any node broadcast problem for hypercubes and all independent spanning trees, constructed by the algorithm presented in this chapter broadcast the data in $O(n)$ time.

This thesis has covered all types of routing algorithms (Unicast, Multicast, Broadcast) for the hypercube topology. All of them are simple and provide satisfactory solutions to the problems of dynamic faults in hypercube network. To this end, we

have designed and implemented adaptive routing protocols for hypercube interconnection networks. In HPC systems, these protocols can handle large number of network components failures.

6.2 Scope for Further Work

This thesis is intended to be complete and entirely closed within a certain field of science. However, this thesis also yields some open lines and further work. These open lines are reported below according to the contribution.

In node-to-node routing algorithm, one of the point that can be improved is the simultaneously handling the components failures and congestion problems. In this point of view, it is necessary to conduct a complete study of the relation among the various parameters of the problem like network topology, the maximum permissible failures, maximum number of alternative paths, and the traffic load.

In node-to-set routing algorithm, solving routing problems with similar approach to other interconnection networks should be considered. Since recursive features of interconnection networks can reduce the time complexity.

Using ISTs one can design fault-tolerant broadcasting schemes and increase message security in a network. There are many variants of hypercube topology like crossed cubes, twisted cubes, folded cubes and hierarchical cubes. Thus, one can apply the proposed methodology in variants of hypercube topology since the problem of ISTs on graphs has been received much attention.

6.3 List of Publications

The work presented in this thesis has been published in the following papers.

1. Lokendra Singh Umrao and Ravi Shankar Singh. **Fault-tolerant routing over shortest node-disjoint paths in hypercubes**. *International Journal of Parallel, Emergent and Distributed Systems*, 2015 (taylor and francis). DOI: 10.1080/17445760.2015.1057587

2. Lokendra Singh Umrao and Ravi Shankar Singh. **Fault-Tolerant Optimal Broadcast Algorithm for the Hypercube Topology**. *International Journal of*

Computer, Electrical, Automation, Control and Information Engineering, 9(2):576–580, 2015 (waset).

3. Lokendra Singh Umrao, Dharmendra Prasad Mahato and Ravi Shankar Singh. **Fault Tolerance for Hypercube Networks Via Independent Spanning Trees**. In *Proceedings of the* 3^{rd} *International Conference on Parallel, Distributed and Grid Computing*, pages: 191–195, Solan (HP), December 2014, Publisher: IEEE. ISBN: 978-1-4799-7682-9.

6.4 List of Accepted Papers

The work presented in this thesis has been accepted in the following workshop.

1. Lokendra Singh Umrao and Ravi Shankar Singh. **Fault-Tolerant Routing over All Shortest Node-Disjoint Paths in Hypercube Networks**. In IEEE Workshop On Computational Intelligence: Theories, Applications and Future Directions. December 14–17, 2015 organised by Indian Institute of Technology Kanpur, India.

6.5 List of Communicated Papers

The work presented in this thesis has been communicated in the following journals.

1. Lokendra Singh Umrao, Dharmendra Prasad Mahato and Ravi Shankar Singh. **Fault-Tolerant Routing over All Shortest Node-Disjoint Paths in Hypercube Networks**. IETE Journal of Research.

2. Lokendra Singh Umrao, Dharmendra Prasad Mahato and Ravi Shankar Singh. **Broadcasting via Independent Spanning Trees on Hypercubes**. Parallel Processing Letters (World Scientific Publishing Company).