

**STUDIES ON REVERSE, BI-DIRECTIONAL AND 4X4
DATA VORTEX OPTICAL MULTISTAGE
INTERCONNECTION NETWORK**

BY

SANGEETHA R.G.

Department of Electrical Engineering

Submitted

In fulfillment of the requirements of the degree of
DOCTOR OF PHILOSOPHY

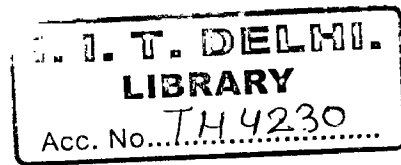
to the



**INDIAN INSTITUTE OF TECHNOLOGY, DELHI
INDIA
May 2012**

Interconnection networks ; Network architecture

TH
621.391
SAN-S

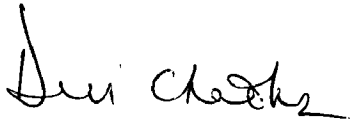


Dedicated to My Father, whose blessings will always guide me!

Sangeetha R.G.

CERTIFICATE

This is to certify that the thesis entitled “**Studies on Reverse, Bi-directional and 4x4 Data Vortex Optical Multistage Interconnection Network**” being submitted by Sangeetha R.G. to the Department of Electrical Engineering, Indian Institute of Technology, Delhi, for the award of degree of Doctor of Philosophy is the record of the bona-fide research work carried out by her. She has worked under our supervision and guidance. The thesis, in our opinion has reached the standards fulfilling the requirements of the regulations relating to the degree. The results contained in this thesis have not been submitted either in part or in full to any other university or institute for the award of any degree or diploma.



Professor D. Chadha

Department of Electrical Engineering
Indian Institute of Technology, Delhi
New Delhi – 110016

14/5/12



Professor Vinod Chandra

Department of Electrical Engineering
Indian Institute of Technology, Delhi
New Delhi - 110016

14/5/2012

Acknowledgements

First and above all, I praise God, the almighty for providing me this opportunity and granting me the capability to proceed successfully. It would not have been possible to write this doctoral thesis without the help and support of the kind people around me, to only some of whom it is possible to give particular mention here.

I would like to express my sincere gratitude wholeheartedly to my supervisors Prof. Devi Chadha and Prof. Vinod Chandra, for their support and ever-ready to help nature, not to mention their sagacious counsel and guidance both in this area of research and beyond. Most of all, I would like to thank them for their extreme patience in handling my queries, which at times bordered on the side of ignorance. Their wide knowledge and the logical way of thinking have been of great value for me. Their understanding, encouraging and personal guidance have provided a good basis for the present thesis. I would like to offer my due respects to my Gurus, who have consciously moulded me to be what I am today. The impression that they have left on me would be long cherished and carried forward for years to come in my life.

I would also like to express my thanks to my Student Research Committee members Prof. Subrat Kar, Prof. Arun Kumar, Prof. Swades De and Prof. M.R.Shenoy for providing their valuable comments and suggestions.

I would like to thank the staff of the Optical Laboratory, Dept. of EE – Mrs. Neeru Asija , Mr. Jagdish Naudiyal, Mr. Naveen Nautiyal and Mr. G.S. Negi for their kindness, friendship and support.

I would like to acknowledge the financial, academic and technical support of the Indian Institute of Technology, Delhi and its staff, particularly in the award of a teaching assistantship that provided the necessary financial support for this research. I feel extremely fortunate to have been a part of this prestigious institution.


On a personal note, I would like to place my sincere gratitude for the generosity and encouragement of Mrs. Shanta K. Chandra, which cannot be expressed in words. I would like to recall and place my special gratitude to Vishnu Pratap, whose invaluable help with his expert computing skills played an essential role during the most difficult period of my research.

Among my fellow and senior postgraduate students in the Dept. of Electrical Engineering, I would like to place my special thanks to Dr. Neha Sharma, Rahul Pandya, Rajesh Chari, N.J. Khumancha, Divyoattama Nagesh, and innumerable others who were instrumental in promoting a stimulating and welcoming academic and social environment during the course of my study. I would like to thank Dr. Selvaraj and Packiam, who were a constant source of motivation in their own ways, which helped me tide over the most difficult of waves with ease.

I would like to thank my spouse, Venkata Krishnan, my pillar of strength and my daughter, Souparnika for their unwavering support and great patience at all times. I would like to reiterate their constant encouragement and the innumerable sacrifices made by them during the last five years, which motivated me towards achieving this milestone. My mother, Sulochana and sister, Sahidhya have given me their unequivocal support throughout, as always, for which my mere expression of thanks likewise does not suffice.

Last but not the least, I would like to recall the constant source of encouragement received from my family members – my in-laws, Shantha and Rangarajan, Bharath, Radha and Akshara, which helped me to maintain a sense of balance in life and recuperate during the most trying times of my research.

Date: 14.05.12


(Sangeetha R.G.)

ABSTRACT

In this thesis we have proposed three interconnection networks: *Reverse Data Vortex (RDV)* network, *Bi-directional Data Vortex (BDV)* network and *4x4 Optical Data Vortex (4x4 ODV)* network. The prior art to these networks is *Data Vortex (DV)* packet switch, which is reported as the more recent optical multistage interconnection network. The DV network with size $H=4$ and $A=3$ has been demonstrated in the test bed and proven to overcome the limitations of optical buffering using fiber delay lines and optical bit level processing. The DV network is a highly scalable multistage interconnection network which also shows low latency, low crosstalk, and high capacity suitable to be implemented in high performance parallel computations.

In this thesis, hardware model of a RDV node, self routing procedure of the RDV network, bit level processing and priority schemes to have contention-less networks have been suggested. The performance of RDV network has been discussed in terms of throughput, latency and latency distribution both in the symmetric and asymmetric modes. The results have been compared with DV network. The fault tolerance, reliability issues of RDV has been discussed. The feasibility of a RDV node has been verified using Rsoft. Inc. Optsim Simulator. The bit error rate (BER) has been measured for 70 such cascaded nodes.

The DV is essentially a unidirectional network. The multistage interconnection network to connect along with other optical devices needs to be bi-directional. To exploit the bi-directional optical environment, Bi-directional Data Vortex has been proposed. The possible hardware model and self routing procedure of BDV have been suggested to

make the existing DV bi-directional. The performances in terms of throughput, latency and latency distribution, fault tolerance and terminal reliability have been discussed. The feasibility of a BDV node has been verified using Rsoft. Inc. Optsim Simulator. The bit error rate (BER) has been measured for 70 such cascaded nodes.

The fault tolerance of a multistage interconnection network can also be improved by increasing the number of links. In order to improve the fault tolerance further, we have suggested 4×4 ODV network. Closed form expressions for fault tolerance, network reliability and a new algorithm for the calculation of terminal reliability have been analysed through numerical simulations. These results have been compared with DV, ADV networks.

CONTENTS

1 INTRODUCTION

1.1	Optical Interconnection Networks	1
1.1.1	Generalized Multiprotocol Label Switching (GMPLS)	2
1.1.2	Optical Burst Switching (OBS)	3
1.1.3	Optical Packet Switching (OPS).....	4
1.2	Literature Survey.....	5
1.2.1	Optical switch architectures.....	5
1.2.2	Data Vortex architecture (DV)	8
1.3	Motivation.....	14
1.4	Organisation of the thesis.....	15

2 REVERSE DATA VORTEX INTERCONNECTION NETWORK

2.1	Introduction.....	19
2.2	Possible Hardware Model	24
2.2.1	Switching node	24
2.2.2	Switch at the input level of the interconnection network	25
2.2.3	Control logic and priority scheme of RDV	26
2.3	Performance Analysis	28
2.3.1	Symmetric mode.....	29
2.3.1.1	<i>Injection rate</i>	29
2.3.1.2	<i>Latency</i>	32
2.3.1.3	<i>Latency Distribution</i>	34
2.3.1.4	<i>Asymmetric mode</i>	36
2.4	Conclusions and Discussions.....	40

3 RELIABILITY ANALYSIS AND HARDWARE SIMULATION FEASIBILITY STUDIES OF RDV

3.1	Introduction.....	43
3.2	Reachability and Fault Tolerance Analysis of DV and RDV	44
3.3	Multiplexing Input Nodes for Improved Fault Tolerance.....	45
3.4	Terminal Reliability	50
3.5	BER Characteristics of RDV.....	55
3.5.1	Simulation results of cascaded nodes	57
3.6	Conclusions and Discussions.....	61

4 BI-DIRECTIONAL DATA VORTEX INTERCONNECTION NETWORK

4.1	Introduction.....	63
4.2	Hardware model and Priority Scheme of BDV.....	64
4.2.1	Hardware Model.....	64
4.2.2	Deflection routing.....	68
4.2.3	Control logic and priority scheme for the data flow.....	71
4.2.4	Data flow in BDV.....	74
4.3	Performance Evaluation of BDV	76
4.3.1	Symmetric mode: Injection rate	78
4.3.2	Latency	81
4.3.3	Latency distribution.....	82
4.3.4	Asymmetric mode.....	83
4.3.5	Unequal data on both the sides of BDV: 75% data in forward direction and 25% data in reverse direction	83
4.3.6	25% data in forward direction and 75% data in reverse direction.....	88

4.4	Performance Evaluation of Alternate Bi-directional DV Setup.....	91
4.4.1	Injection rate	92
4.4.2	Latency	92
4.5	Bi-directional Operation using Single DV.....	96
4.6	Conclusions and Discussions.....	98

5 TERMINAL RELIABILITY AND HARDWARE FEASIBILITY SIMULATION STUDIES OF BDV

5.1	Introduction.....	101
5.2	Terminal Reliability Analysis of BDV.....	102
5.2.1	Reliability of the node	103
5.2.2	Reliability of the external switch.....	106
5.2.3	Improved reliability with redundant external switches	107
5.2.4	Voting redundancy	108
5.2.5	Terminal reliability of parallel DV for bi-directional operation.....	109
5.3	Simulation of BDV Hardware Model	113
5.4	Conclusions and Discussions.....	118

6 4x4 OPTICAL DATA VORTEX INTERCONNECTION NETWORK

6.1	Introduction.....	121
6.2	Architecture of 4x4 Optical Data Vortex network.....	122
6.2.1	Routing procedure of 4X4 optical data vortex network	124
6.2.2	Two-Dimensional equivalent planar diagram	125
6.2.3	Hardware implementation and priority scheme.....	126
6.3	Fault Tolerance Analysis.....	130
6.3.1	Fault model and fault tolerance evaluation.....	130
6.3.2	Input elements of level, $c=0$ (stage 1) with multiplexed nodes.....	131

6.3.2.1	<i>Intermediate level elements ($c=\log_2H-1$)</i>	133
6.3.2.2	<i>Output elements of output level ($c=\log_2H$)</i>	133
6.4	Cost Analysis.....	135
6.5	Survival Probability Analysis.....	135
6.5.1	Survival probability of input level ($c=0$).....	136
6.5.2	Survival probability of intermediate levels ($c=0-\log_2H-1$).....	137
6.5.3	Survival probability of output level($c=\log_2H$).....	139
6.5.4	Expected number of faults in the entire network (\bar{k}).....	140
6.6	Network Reliability.....	140
6.7	Terminal Reliability.....	142
6.7.1	Enumeration of all possible paths between the terminal pair.....	143
6.7.2	Evaluation of terminal reliability.....	144
6.8	Conclusions and Discussions.....	147

7 CONCLUSIONS AND SCOPE FOR FUTURE WORK

7.1	Summary of Contributions.....	149
7.2	Scope for Future Work.....	152