UNIVERSITI PUTRA MALAYSIA

CROSSTALK-FREE SCHEDULING ALGORITHMS FOR ROUTING IN OPTICAL MULTISTAGE INTERCONNECTION NETWORKS

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April 2009

Chairman : Associate Professor Mohamed Othman, PhD

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Multistage Interconnection Networks (MINs) have been used in telecommunication networks for many years. Significant advancement in the optical technology have drawn the idea of optical implementation of MINs as an important optical switching topology to meet the ever increasing demands of high performance computing communication applications for high channel bandwidth and low communication latency. However, dealing with electro-optic switches instead of electronic switches held its own challenges introduced by optics itself.

Limited by the properties of optical signals, optical MINs (OMINs) introduce optical crosstalk, as a result of coupling two signals within each switching element. Therefore, it is not possible to route more than one message simultaneously, without optical crosstalk, over a switching element in an OMIN. Reducing the effect of optical crosstalk has been a challenging issue considering trade-offs between performance and hardware and software complexity. To solve optical crosstalk, many scheduling

algorithms have been proposed for routing in OMIN based on a solution called the time domain approach, which divides the *N* optical inputs into several groups such that crosstalk-free connections can be established.

It is the objective of the research presented in this thesis to propose a solution that can further optimize and improve the performance of message scheduling for routing in the optical Omega network. Based on Zero algorithms, a Modified Zero algorithm is developed to achieve a crosstalk-free version of the algorithm. Then, the Fast Zero (FastZ) algorithm is proposed, which uses a new concept called the symmetric Conflict Matrix (sCM) as a pre-scheduling technique. Extended from the FastZ algorithms, another three new algorithms called the FastRLP, BRLP and FastBRLP algorithms are developed to achieve different performance goals. Lastly, a comparison is made through simulation between all algorithms developed in this research with previous Zero-based algorithms as well as traditional Heuristic algorithms since equal routing results can be obtained between all algorithms.

Through simulation technique, all three FastZ, BRLP and FastBRLP algorithms have shown the best results when the average execution time is considered. The FastRLP and FastBRLP algorithms on the other hand have shown the best results when the average number of passes is considered. It is proven in this thesis that the new approach has by far achieved the best performance among all the algorithms being tested in this research.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

ALGORITMA PENJADUALAN BEBAS CAKAP SILANG UNTUK PENGHALAAN DI DALAM RANGKAIAN OPTIK SALING BERHUBUNG BERBILANG PARAS

Oleh

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Rangkaian optik saling berhubung berbilang paras (MINs) telah digunakan di dalam rangkaian telekomunikasi selama beberapa tahun. Dengan perkembangan yang signifikan di dalam teknologi optikal, telah menarik ide implementasi optikal MINs sebagai topologi pensuisan optikal yang penting untuk memenuhi keperluan permintaan yang sentiasa bertambah untuk aplikasi pengkomputeran prestasi tinggi bagi lebar jalur saluran tinggi dan kependaman komunikasi rendah. Walaubagaimanapun, penggunaan suis elektro-optik berbanding suis elektronik mempunyai cabarannya yang tersendiri yang disebabkan oleh optik itu sendiri.

Terhad oleh ciri-ciri signal optikal, optikal MINs (OMINs) memperkenalkan cakap silang, hasil dari gandingan dua signal di dalam setiap elemen pensuisan. Oleh itu, adalah mustahil untuk menghalakan lebih dari satu mesej secara serentak, tanpa cakap silang, melalui sesuatu elemen pensuisan di dalam OMIN. Mengurangkan kesan dari

cakap silang telah menjadi suatu isu yang mencabar dengan mengambil kira *trade-off* di antara prestasi dan kompleksiti perkakasan dan perisian. Untuk menyelesaikan cakap silang, banyak algoritma penjadualan telah dicadangkan untuk penghalaan di dalam OMIN berdasarkan kepada suatu penyelesaian yang dipanggil pendekatan *time domain*, yang membahagikan *N* input optikal kepada beberapa kumpulan supaya sambungan bebas cakap silang boleh dibina.

Adalah objektif penyelidikan yang diajukan di dalam tesis ini untuk mencadangkan suatu penyelesaian yang boleh menambahbaik dan mamperbaiki dengan lebih lanjut prestasi penjadualan mesej untuk penghalaan di dalam rangkaian Omega optikal. Berdasarkan kepada algoritma Zero, suatu algoritma Modified Zero adalah dibangunkan untuk mencapai versi bebas cakap silang algoritma tersebut. Kemudian, algoritma Fast Zero (FastZ) adalah dicadangkan, yang menggunakan konsep baru yang dipanggil *symmetric Conflict Matrix* (sCM) sebagai teknik pra-penjadualan. Lanjutan daripada algoritma FastZ, tiga lagi algoritma baru yang dipanggil algoritma FastRLP, BRLP dan FastBRLP adalah dibangunkan untuk mencapai matlamat prestasi yang berbeza. Akhir sekali, suatu perbandingan dibuat melalui simulasi di antara kesemua algoritma-algoritma yang dibangunkan di dalam penyelidikan ini dengan algoritma-algoritma sebelumnya yang berdasarkan kepada algoritma Zero dan juga algoritma-algoritma Heuristic kerana hasil penghalaan yang sama boleh diperolehi di antara kesemua algoritma-algoritma tersebut.

Melalui teknik simulasi, ketiga-tiga algoritma FastZ, BRLP dan FastBRLP telah menunjukkan hasil yang terbaik apabila purata masa pelaksanaan diambil kira. Algoritma-algoritma FastRLP dan FastBRLP pula telah menunjukkan hasil yang terbaik apabila mengambil kira purata bilangan laluan. Adalah dibuktikan di dalam tesis ini bahawa pendekatan yang baru telah sehingga kini mencapai prestasi yang terbaik di antara kesemua algoritma-algoritma yang diuji dalam penyelidikan ini.

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Last but not least, to all my friends and colleagues who have helped me in any possible way, I express my warmest thanks and may we all succeed in life.

DECLARATION

I hereby declare that the thesis is based on my original work for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

TENGKU DIAN SHAHIDA BT RAJA MOHD AUZAR

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BIZ	Bitwise Improved Zero
BIZ_X	Bitwise Improved ZeroX
BIZ_Y	Bitwise Improved ZeroY
BIZ_XY	Bitwise Improved ZeroXY
BRLP	Bitwise Remove Last Pass
BWM	Bitwise Window Method
CMP	Chip Multi Processor
FastBRLP	Fast Bitwise Remove Last Pass
FastXBRLP	Fast ZeroX with Bitwise Remove Last Pass
FastYBRLP	Fast ZeroY with Bitwise Remove Last Pass
FastRLP	Fast Remove Last Pass
FastXRLP	Fast ZeroX with Remove Last Pass
FastYRLP	Fast ZeroY with Remove Last Pass
FastZ	Fast Zero
FastZ_X	Fast ZeroX
FastZ_Y	Fast ZeroY
FastZ_XY	Fast ZeroXY
sCM	Symmetric Conflict Matrix
IN	Interconnection Network
IWM	Improved Window Method
IZ	Improved Zero
IZ_X	Improved ZeroX
IZ_Y	Improved ZeroY
IZ_XY	Improved ZeroXY
MCN	Maximal Conflict Number
MIN	Multistage Interconnection Network
MZ	Modified Zero
MZ_X	Modified ZeroX

MZ_Y	Modified ZeroY
MZ_XY	Modified ZeroXY
NoC	Network on Chip
OMIN	Optical Multistage Interconnection Network
OON	Optical Omega Network
RLP	Remove Last Pass
SA	Simulated Annealing
SE	Switching Element
SoC	System on Chip
WM	Window Method

CHAPTER 1

INTRODUCTION

1.1 Background

Emerging of multicore systems has witnessed the trend towards powerful machines with higher computing power available at the reach of fingertips. Future telecommunication systems are expected to provide seamless support for higher transmission capacity and faster switching technology to connect these high-end systems, in line with the explosive growth of the Internet. Interconnection Networks (INs) is faced with greater challenge as the direction in computing systems is fast moving towards advanced architectures such as Chip MultiProcessors (CMPs), Systems on Chip (SoC) and Network on Chip (NoC) (Owens *et al.*, 2007).

Multistage Interconnection Networks (MINs) have long since been proposed as interconnecting structures in various types of communication applications ranging from parallel systems (Yang *et al.*, 2003 and Abdullah *et al.*, 2005), switching architectures (Lu *et al.*, 2004), to multicore systems (Tutsch *et al.*, 2003). The main advantage of MINs is that it allows for simultaneous one-to-one permutation connections to be established between each input and output port of the network.

As far as speed is concerned, with the introduction of optical switching, it is most feasible to apply MINs in the architecture for building electro-optical switches with a capacity at the rate of terabits per second. Optical MINs (OMINs) are an attractive solution that offers a combination of high bandwidth, low error probability, and large transmission capacity in the design of high-speed communication networks and switches (Lu *et al.*, 2003).

However, dealing with electro-optic switches instead of electronic switches held its own challenges introduced by optics itself. A major drawback is that of optical crosstalk problem. Limited by the properties of optical signals, it is not possible to route more than one message simultaneously, without optical crosstalk, over a switching element (SE) in an OMIN. Optical crosstalk causes performance degradation of OMINs in terms of reduced signal-to-noise ratio and limits the size of the network (Shen *et al.*, 2001).

Under the constraint of avoiding crosstalk, three approaches, space domain, time domain and wavelength domain have been proposed (Sharony *et al.*, 1993; Qiao *et al.*, 1994 and Qiao, 1996). In this research, crosstalk-free scheduling algorithms are proposed and developed based on the time domain approach to schedule messages for routing more efficiently in the optical Omega (Wu *et al.*, 1980) multistage interconnection networks. The interest of these algorithms is to find a permutation that uses a minimum number of passes and minimum execution time.

The time domain approach, avoids optical crosstalk by ensuring that only one signal pass through each of the SEs at any given time in the network. Messages with conflicting paths is determined and arranged into crosstalk-free groups with each group consists of only crosstalk-free connections. These independent crosstalk-free groups are then routed to the intended destination at different time slots to eliminate crosstalk.

1.2 Problem Statement

High-speed photonic switching networks can switch optical signals at the rate of several terabits per second (Deng *et al.*, 2006). The topology of an OMIN is similar to its electronic peer except that electro-optic switches are used instead of electronic switches. The basic SE is a directional coupler with two active inputs and two active outputs. At any given time, the switching connections in each SE can be of two types (refer to Figure 2.2(a)); either straight or cross connection scheme (Lu *et al.*, 2003 and Qiao *et al.*, 1994).

Considering the switching of optical signals rather than electronic signals in conventional electronic systems, one significant problem associated with these directional coupler-based electro-optical switches in OMINs is the optical crosstalk which is caused by undesired coupling between optical signals carried in two waveguides such that two signals channels interfere with each other (Vaez *et al.*, 1998; Chau *et al.*, 2005 and Deng *et al.*, 2006).

In the event of optical crosstalk occurrence, a small fraction of the input signal power may be detected at another output disregard of the actual signal injected to the appropriate output port. As a result, the input signal will be distorted at the output due to loss and crosstalk accumulated along connection path.

In this thesis, scheduling algorithms are developed based on the previously proposed Zero algorithms (Al-Shabi, 2005) for solving optical crosstalk in OMINs. Based on analysis performed on all Zero-based algorithms (Al-Shabi, 2005 and Abed, 2007), it can be concluded that for some permutation, crosstalk may still occur between scheduled messages for routing.

Furthermore, in terms of performance evaluation of previous time domain algorithms such as the Remove Last Pass (RLP) algorithm, there are tradeoffs in the performance between the execution time to schedule permutations and the number of passes generated to route a permutation. Algorithms that schedule messages with less number of passes for routing are most likely to result with higher execution time vice versa.

1.3 Research Objectives

The goal of the research described in this thesis is to develop crosstalk-free scheduling algorithms based on the Zero algorithms (Al-Shabi, 2005), that efficiently decompose a given permutation set and schedule the messages into its crosstalk-free subsets for routing with minimum execution time and number of passes. In order to achieve the goal, the following objectives are defined.

- To develop the symmetric Conflict Matrix (sCM), to map conflicts between messages with conflicting path in the network.
- To develop the Modified Zero (MZ) algorithms, to resolve possible crosstalk in Zero-based algorithms.
- To develop the Fast Zero (FastZ) algorithms, to improve the execution time for scheduling permutations.
- To develop the FastZ with Remove Last Pass (RLP) (FastRLP) algorithms, to reduce the total number of passes to route a permutation.
- To develop the Bitwise RLP (BRLP) algorithm, to improve the execution time of the RLP algorithm.
- To develop the FastZ with BRLP (FastBRLP) algorithms, to improve the execution time for scheduling permutations and reduce the total number of passes to route a permutation.

1.4 Research Scope

In order to solve optical crosstalk in OMINs, we are interested on the time domain approach (Qiao *et al.*, 1994), adopted to realize crosstalk-free scheduling for routing in the optical Omega network topology. Furthermore, this research focuses on the algorithm development but not on the physical issues pertaining to the structure of the SE and does not cover the mathematical modeling of the proposed algorithms.

The Omega network was selected among other topologies because it is a class of self-routable networks; that is topologically equivalent to many other topologies such as the Baseline, Butterfly and Cube networks (Wu *et al.*, 1980 and Feng, 1981). Since many other topologies are equivalent to the Omega network topology, performance results obtained for the Omega network are also applicable to other OMIN topologies (Abdullah, 2005).

Based on the time domain framework, messages in the network can be routed simultaneously in smaller crosstalk-free subsets, also referred as partial permutations, to utilize the high bandwidth offered by the optical communications. In view of the fact that the paths realizing a partial permutation for a given OMIN does not share any SE in the network, the time domain approach also solves the link contention problem that would normally cause conflicts in blocking OMINs such as the Omega network itself. In this thesis, the term conflict and crosstalk will be used interchangeably to refer to both link and SE contentions in the optical Omega network. In essence, avoiding conflicts means avoiding crosstalk vice versa.

1.5 Research Contributions

In this research, time domain scheduling algorithms are designed and developed based on the Zero framework (Al-Shabi, 2005) to achieve the best in network performance. The performance is categorized according to two types of performance measures; the average execution time and the average number of passes. The following lists the major contributions of this research according to the abovementioned performance category.

- Developed the sCM, to map conflicts between messages with conflicting path in the network.
- Developed the MZ algorithms, to resolve possible crosstalk in Zero-based algorithms.
- Developed three new FastZ algorithms called the Fast ZeroX (FastZ_X), Fast ZeroY (FastZ_Y) and Fast ZeroXY (FastZ_XY) algorithms, to improve the execution time for scheduling permutations.
- Developed two new FastRLP algorithms called the Fast ZeroX with RLP (FastXRLP) and Fast ZeroY with RLP (FastYRLP) algorithms, to reduce the total number of passes to route a permutation.
- Developed the new BRLP algorithm, to improve the execution time of the RLP algorithm.
- Developed two new FastBRLP algorithms called Fast ZeroX with BRLP (FastXBRLP) and Fast ZeroY with BRLP (FastYBRLP) algorithms, to improve the execution time for scheduling permutations and reduce the total number of passes to route a permutation.

1.6 Thesis Organization

This thesis is organized into seven consecutive chapters. Chapter one provides the overview of the research, its objectives, scope and contributions. The optical crosstalk