UNIVERSITI PUTRA MALAYSIA

A FAST SCHEDULING ALGORITHM FOR WDM OPTICAL NETWORKS

CHEAH CHENG LAI

FK 2000 22

A FAST SCHEDULING ALGORITHM
FOR WDM OPTICAL NETWORKS

By

CHEAH CHENG LAI

Thesis Submitted in Fulfilment of the Requirements for the Degree of Master of Science in Faculty of Engineering
Universiti Putra Malaysia

July 2000

To Siew Yeng and Zhiyi

Abstract of the thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science.

A FAST SCHEDULING ALGORITHM FOR WDM OPTICAL NETWORKS

By

CHEAH CHENG LAI

July 2000

Chairman : Associate Professor Borhanuddin Mohd. Ali, Ph. D.

Faculty : Engineering

Wavelength Division Multiplexing (WDM) is emerging as the most promising approach to exploit the huge bandwidth of optical fibre. This approach divides the optical spectrum into many different channels where each channel corresponds to a different wavelength. Single-hop WDM networks are attractive in local area environment where all the nodes can be connected to a single broadcast facility. In a single-hop WDM broadcast network, the transmitter must know when to transmit a packet and at which wavelength, while the receiver must know when to tune to the appropriate wavelength to receive the packet. This process requires some form of coordination. Many researches have focused on the scheduling algorithms that perform this kind of coordination.

This thesis proposes a scheduling algorithm for the WDM broadcast networks. The algorithm employs a theory in graph, known as edge colouring of bipartite multigraph to produce the transmission schedule, which is free from collision due to the nature of the edge colouring. An optimal edge colouring of bipartite multigraph can be found in $O(M \log^2 N)$ time, where M is number of

packets selected for scheduling, and N is the number of the nodes. This time complexity can be improved to $O(\log^3 N)$ by parallel processing using $O(M)$ processors.

Two variations of implementation of the scheduling algorithm have been proposed, namely the Variable Frame Size (VFS) and Limited Frame Size (LFS) schemes. These schemes use different criteria to select packets from the nodes for scheduling. The VFS scheme is simple, but supports only best effort transmissions. The LFS scheme ensures the frame size of the transmission schedule is bounded, thus enabling it to support bandwidth guarantee to the nodes up to a node's fair share of the network capacity. The LFS scheme is capable of supporting constant bit rate and unspecified bit rate service categories, analogous to the Asynchronous Transfer Mode (ATM) services.

The results show that the LFS scheme performs better than the VFS scheme in terms of channel utilisation, packet loss probability and network throughput for all the simulated traffic patterns, especially at heavy loads. Besides, the LFS scheme respects any level of bandwidth guarantee, while the unused bandwidth can be used for best effort transmissions. The results also show that the VFS and LFS schemes are future-proof as they are able to capitalise on the increase in the number of wavelength channels.

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

SUATU ALGORITMA PENJADUALAN PANTAS UNTUK RANGKAIAN-RANGKAIAN OPTIK WDM

Oleh

CHEAH CHENG LAI

Julai 2000

Pengerusi : Profesor Madya Borhanuddin Mohd. Ali, Ph. D.

Fakulti : Kejuruteraan

Pemultipleksan pembahagian panjang gelombang (WDM) sedang muncul sebagai pendekatan yang terjamin untuk mengeksploitasi lebar jalur optik gentian yang amat besar. Pendekatan ini membahagikan spektrum optik kepada beberapa saluran yang berbeza, di mana setiap saluran mewakili satu panjang gelombang yang berlainan. Rangkaian-rangkaian WDM satu lompatan adalah menarik dalam persekitaran tempatan di mana semua nodnya boleh disambungkan kepada satu kemudahan penyiaran. Dalam satu rangkaian WDM satu lompatan, penghantar perlu tahu bila hendak menghantarkan satu paket pada panjang gelombang yang tertentu, sementara itu penerima perlu tahu bila hendak menala pada panjang gelombang yang sesuai untuk menerima paket tersebut. Proses ini memerlukan beberapa bentuk koordinasi. Banyak penyelidikan telah ditumpukan pada algoritma-algoritma penjadualan dalam melaksanakan koordinasi ini.

Tesis ini mencadangkan satu algoritma penjadualan untuk rangkaian-rangkaian WDM satu lompatan. Algoritma ini menggunakan satu teori graf yang dikenali sebagai perwarnaan pinggir dalam graf dwibahagian untuk menghasilkan

jadual penghantaran, yang bebas dari pelanggaran disebabkan oleh tabii perwarnaan pinggir. Satu perwarnaan pinggir yang optimum untuk graf dwibahagian boleh diperolehi dalam masa $O(M\log^2 N)$, di mana M adalah bilangan paket yang terpilih untuk penjadualan dan N adalah bilangan nod. Kompleksiti masa ini boleh dipertingkatkan kepada $O(\log^3 N)$ dengan proses selari dengan menggunakan $O(M)$ pemproses.

Dua variasi pelaksanaan algoritma penjadualan telah dicadangkan, iaitu skima Variable Frame Size (VFS) dan Limited Frame Size (LFS). Skima-skima ini menggunakan kriteria yang berbeza dalam pemilihan paket dari nod-nod untuk penjadualan. Skima VFS adalah mudah tetapi ia cuma boleh menyokong penghantaran usaha terbaik. Skima LFS memastikan saiz bingkai jadual penghantarannya adalah terbatas, dengan demikian ia dapat menampung lebar jalur jaminan kepada nod-nodnya sehingga satu nod mempunyai bahagian adil kapasiti rangkaian. Skima LFS berupaya menyokong kategori perkhidmatan kadar bit malar dan kadar bit tidak ditetap, beranalog dengan perkhidmatan mod penghantaran tak segera (ATM).

Keputusan menunjukkan bahawa skima LFS berprestasi lebih baik daripada skima VFS dari segi penggunaan saluran, kebarangkalian hilang paket dan daya memproses untuk semua corak trafik yang diselakukan, terutamanya pada bebanan yang berat. Selain itu, skima LFS sesuai untuk sebarang paras lebar jalur jaminan, manakala lebar jalur yang tidak digunakan boleh diguna untuk penghantaran usaha terbaik. Keputusan juga menunjukkan bahawa skima VFS dan LFS adalah tahan untuk masa depan kerana ia dapat mengambil kesempatan pada penambahan bilangan saluran jarak gelombang.

ACKNOWLEDGEMENTS

I would like to take this opportunity to thank everyone who has directly or indirectly contributed to this thesis. The following list, by no means exhaustive, is an attempt to acknowledge at least a few of them.

First and foremost, I wish to express my deepest gratitude and appreciation to Associate Prof. Dr. Borhanuddin Mohd. Ali, the chairman of my supervisory committee for his guidance and inspiration throughout the research period.

I am also grateful to my supervisor Dr. Veeraraghavan Prakash for his kind supervision and invaluable suggestions for carrying out the work properly.

My sincere thanks to my supervisor Dr. Selvakennedy Selvadurai for his earnest discussions and constructive suggestions. He has suggested and helped on the development of the simulation system and provided comments on the results.

My sincere thanks also to Prof. Dr. Malay Raj. Mukerjee for ideas and suggestions he has contributed to this work. He was my supervisor before he left Malaysia in March 2000.

Lastly, I wish to take this opportunity to express my sincere gratitude to all my fellow friends in ATM & Broadband Research Group for their help, friendship and insightful discussion, especially Mr. Ali Mohamed Abdelrahman and Mr. Choong Khong Neng.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ARPA	-	Advanced Research Project Agency
ARPA AON	-	ARPA sponsored All Optical Network
ATM	-	Asynchronous Transfer Mode
CBR	-	Constant Bit Rate
CRCW	-	Concurrent Read, Concurrent Write
CREW	-	Concurrent Read, exclusive Write
EDFA	-	Erbium-Doped Fibre Amplifier
EREW	-	Exclusive Read, Exclusive Write
FT-FR	-	Fixed Transmitter(s) and Fixed Receiver(s)
FT-TR	-	Fixed Transmitter(s) and Tuneable Receiver(s)
LAN	-	Local Area Network
LFS	-	Limited Frame Size
IP	-	Internet Protocol
MAN	-	Metropolitan Area Network
MIMD	-	Multiple-Instruction, Multiple-Data stream
NC	-	Nick (Pippenger)'s Class
NP	-	Non-deterministic Polynomial
OT	-	Optical Terminal
PE	-	Processing Element
PRAM	-	Parallel Random Access Machine
QoS	-	Quality of Service
SCMA	-	Subcarrier Division Multiple Access

SIMD	-	Single-Instruction, Multiple Data stream
TDMA	-	Time Division Multiple Access
TT-FR	-	Tuneable Transmitter(s) and Fixed Receiver(s)
TT-TR	-	Tuneable Transmitter(s) and Tuneable Receivers(s)
UBR	-	Unspecified Bit Rate
VC	-	Virtual Circuit
VFS	-	Variable Frame Size
WAN	-	Wide Area Network
WDM	-	Wavelength Division Multiplexing
WDMA	-	Wavelength Division Multiple Access

LIST OF NOTATIONS

Δ	-	Maximum degree.
λ	-	Wavelength channel.
λ_c	-	Control channel.
χ	-	Chromatic number.
f	-	Frame size.
$f_{\max}$	-	Maximum frame size of the LFS scheme.
C	-	Set of colours.
CG	-	Coloured edges.
CU	-	Channel Utilisation.
e	-	Edge.
E	-	Set of edges.
k	-	Packet selection factor.
G	-	Graph.
l	-	Burst length of 2-state traffic.
M	-	Number of packets selected for scheduling.
N	-	Number of nodes.
p	-	Probability.
PG	-	Total number of packets generated.
PL	-	Total number of packets lost.
p_{PL}	-	Packet loss probability.
PS	-	Total number of packets been transmitted.

SG - Subgraph.

t_A - Interarrival time of the packets of Poisson traffic.

TP - Network throughput.

TS - Total number of time slots.

u - Source node.

U - Set of source nodes.

UG - Uncoloured edges.

v - Destination node.

V - Set of destination nodes.

W - Number of wavelength channels for data transmission.

CHAPTER 1

INTRODUCTION

WDM Optical Networks

The demand for bandwidth in networks is increasing at a tremendous rate. The high demand for bandwidth is driven by the emergence of new services and requirements such as high-definition television, digital audio, medical-imaging, supercomputer interconnect and digital library (Li and Stone, 1999). Optical fibre has evolved to become the transmission medium of choice for high-speed communications. The emergence of optical fibre as the transmission medium stems from several key attributes, which are low bit error rates, enormous bandwidth and low cost.

In optical networks, the end-user equipment are based on electronic, thus the maximum rate at which each end-user can access the networks is limited by the electronic speed. The key in designing the optical networks in order to exploit the huge bandwidth of fibre optic is to introduce concurrency among multiple-user transmissions into the network. There are many approaches to introduce this concurrency, such as Time Division Multiple Access (TDMA), Subcarrier Multiple Access (SCMA) and Wavelength Division Multiple Access (WDMA).

TDMA divides the optical bandwidth into sequential time slots. Time slots may be pre-assigned to users or they may be allocated on a demand basis, depending on the type of transfer mode being used. SCMA uses different electrical subcarrier frequencies to multiplex separate data streams. The different subcarriers then modulate an optical carrier. TDMA and SCMA have been investigated by a number of authors (Green, 1993), and their limitation is due to the electronic front-ends employed at the network nodes, which are limited by the peak electronic rate of a few gigabits per second (Mukherjee, 1992).

WDMA divides the optical spectrum into many different channels, where each channel corresponds to a different wavelength. The technique used in this approach is known as Wavelength Division Multiplexing (WDM). The WDM networks may comprise from several channels up to several tens of channels at different wavelengths, each could be operated at the peak electronic rate. To date, WDMA appears to be the most promising approach to exploit the huge bandwidth of fibre optic (Mukhejee, 1992), since all the end-user equipment needs to operate only at the bit rate of a single channel.

Figure 1 shows an illustration of the WDMA concept. It shows an optical network where connections between different node-pairs are established at different wavelengths, which are λ_1, λ_2 and λ_3.

Fibre optic has two low-loss wavebands of approximate widths of 100 nm and 150 nm in the 1.3 μm and 1.5 μm waveband regions, respectively (Green, 1993). A direct conversion from wavelengths to frequencies yields an aggregate bandwidth of these regions to be approximately 30 THz. Using a modulation rate of 1 b/Hz, this bandwidth translates to 30 Tb/s. Parallel and concurrently operating WDM channels can be derived by having end-users transmit into and receive from the non-overlapping portions of the fibre low loss spectrum.

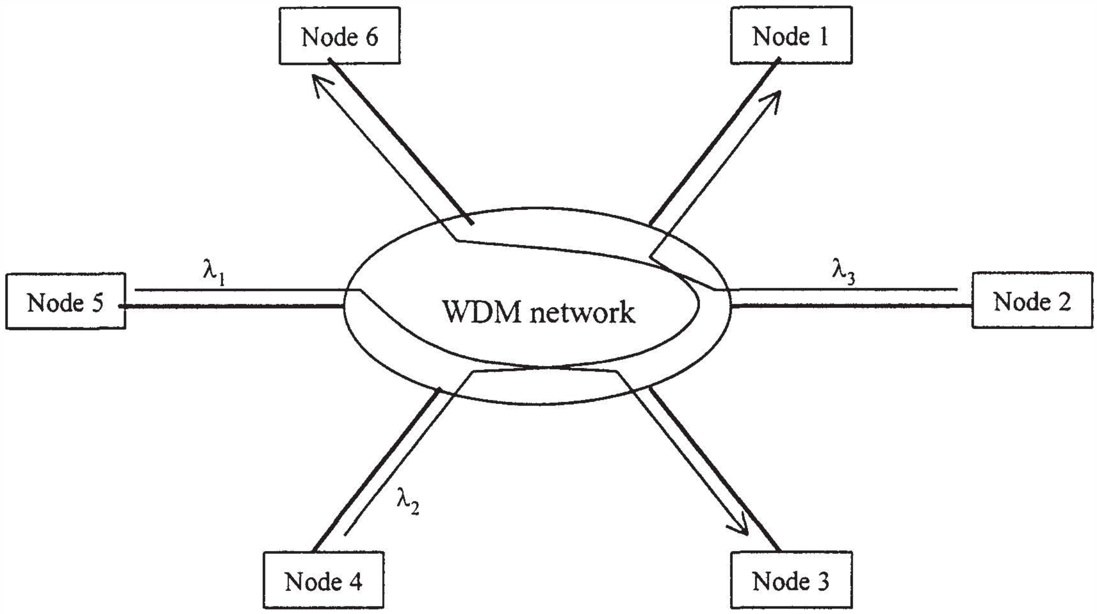

Figure 1: An illustration of the WDM network concept.

WDM Broadcast-and-Select Optical Networks

A simple physical architecture to implement a WDM network is based on broadcast-and-select approach. In this approach, the transmission from a node is broadcast to all the nodes in the network. At the receiver end, the desired signal is then extracted from the entire signal spectrum. These networks are "all optical" in nature, whereby once information enters the networks, it remains in the optical domain until it is delivered to its destination. The WDM broadcast-and-select optical networks sometimes are also known as WDM broadcast networks.

Physical Layer Architectures

The WDM broadcast networks' fabric can be totally passive, consisting of optical couplers (combiners and splitters) that formed various physical topologies. Figure 2 shows two of the most common topologies, which are star and bus. The star topology is configured as a broadcast-and-select network in which all of the inputs from various nodes are combined in a passive star coupler, and the mixed optical information is then broadcast to all outputs. In the bus topology, each node transmits into the bus through a coupler and receives from the bus via another coupler.

The star topology is attractive because it is more efficient in distributing the optical power due to the logarithmic splitting loss in the coupler, since the splitter portion of the star coupler is essentially a binary tree structure (Mukherjee, 1992). In addition, an $N \times N$ star coupler can be considered to consist of an $N \times 1$ combiner followed by a $1 \times N$ splitter. Thus, a signal strength incident from any input can be (approximately) equally divided among all the N outputs.

Single-Hop and Multihop

The WDM broadcast networks may be categorised into single-hop or multihop (Mukherjee, 1992). In the single-hop networks, each node has a direct link to every other node, while in the multihop networks, two nodes may communicate via one or more intermediate nodes.

The multihop networks have the advantage that not every node has to be capable of accessing every channel of the networks, reducing the requirements of its transceivers. However, messages may have to be routed through one or more