İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

VIRTUAL TOPOLOGY RECONFIGURATION ON OPTICAL WDM NETWORKS CONSIDERING TRAFFIC GROOMING

M.Sc. Thesis by
İlker AKGÜN, B.S.

Department : Computer Engineering

Programme: Computer Engineering

JANUARY 2004

İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

VIRTUAL TOPOLOGY RECONFIGURATION ON OPTICAL WDM NETWORKS CONSIDERING TRAFFIC GROOMING

M.Sc. Thesis by

İlker AKGÜN, B.S.

(504001573)

Date of submission :	**22 December 2003**
Date of defence examination:	**13 January 2004**
Supervisor (Chairman):	**Assist.Prof.Dr. Feza BUZLUCA**
Members of the Examining Committee	**Prof.Dr. Emre HARMANCI (İTÜ.)**
	Prof.Dr. Cem ERSOY (BÜ.)

JANUARY 2004

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

TRAFİK GRUPLAMAYI GÖZÖNÜNE ALARAK OPTİK WDM AĞLARDA SANAL TOPOLOJİ YENİDEN DÜZENLEŞİMİ

YÜKSEK LİSANS TEZİ

Müh. İlker AKGÜN

(504001573)

Tezin Enstitüye Verildiği Tarih : 22 Aralık 2003

Tezin Savunulduğu Tarih : 13 Ocak 2004

Tez Danışmanı : Y.Doç.Dr. Feza BUZLUCA

Diğer Jüri Üyeleri Prof.Dr. Emre HARMANCI (İTÜ.)

Prof.Dr. Cem ERSOY (BÜ.)

OCAK 2004

To my wife; Gülsün N. AKGÜN

FOREWORD

I would like to express my sincere gratitude to Assist. Prof. Dr. Feza BUZLUCA due to his supervision and motivating suggestions throughout this study.

I would like to thank to Prof. Dr. Emre HARMANCI and Assist. Prof. Ayşegül GENÇATA for their support, kindness and time.

Special thanks go to Dilek YAMAN and Mehmet GÜMÜŞ for their support and the materials they supplied to me.

Thanks to my family for their patience.

December, 2003 İlker AKGÜN

TABLE OF CONTENTS

ABBREVIATIONS

ANOVA	: Analysis Of Variance
GR	: Grooming Ratio
GRWA	: Grooming, Routing and Wavelength Assignment Algorithms
Gb\s	: Gigabit\seconds
ISP	: Internet Service Provider
MILP	: Mixed Integer Linear Program
PM	: Performance Measure
PT	: Physical Topology
VT	: Virtual Topology
VTR	: Virtual Topology Reconfiguration
VTRA	: Virtual Topology Reconfiguration Algorithms
VTRT	: Virtual Topology Reconfiguration Triggering
WDM	: Wavelength Division Multiplexing
R&D	: Research and Development
OC	: Optical Channel
OC-n	: Data rate of n*51.84 megabits per second

LIST OF TABLES

LIST OF FIGURES

TRAFİK GRUPLAMAYI GÖZÖNÜNE ALARAK OPTİK WDM AĞLARDA SANAL TOPOLOJİ YENİDEN DÜZENLEŞİMİ

ÖZET

Optik teknolojilerindeki son zamanlardaki gelişmeler, optik WDM ağlarda hem dinamik sanal topoloji yeniden düzenleşimine (STYD) ve hem de trafik gruplamaya imkan vermektedir. Optik WDM ağların artan ağ yönetimi kabiliyeti sayesinde sanal topoloji değişen trafik koşullarına göre yeniden düzenlenebilir. Ve trafik gruplama kabiliyeti sayesinde düşük hızlı bağlantı talepleri yüksek kapasiteli kanallara multiplekslenerek anahtarlanabilir. Hem STYD'nin hem trafik gruplamanın daha kabiliyetli ve işlevsel optik WDM ağlar sağlamakta önemli rolleri vardır.

Bu çalışmada, bu iki önemli konu tekrar gözden geçirilmiş ve STYD problemi üzerinde, trafik gruplama etkeni gözönüne alınıp yeni STYD yöntemleri önererek çalışılmıştır. İlk olarak, genel STYD problemi birbirinden bağımsız iki alt problem olarak ele alınmıştır; STYD tetikleme problemi ve STYD problemi. Uygun STYD tetikleme ve STYD algoritmaları değerlendirilmiş ve yeni STYD yöntemleri önerilmiştir. Bu temel "böl ve feth et" yaklaşımı bize bu iki alt problemin karşılıklı etkileşimlerinin ve ilişkilerinin açıkça analşılmasını sağlamıştır.

İkinci olarak tanımlanan STYD problemi yeni değişken ve kısıtlarla KTDP olarak formüle edilmiştir. Bu problemi ele alabilmek için, yeniden düzenleşimin avantaj ve dezavantajları; ağ kaynak kullanım verimliliği ve ağ bağlantı aksaması incelenmiş ve ölçülebilir parametreler cinsinde sayısallaştırılmıştır. Bu performans ölçütleri önerilen STYD tetikleme yöntemleri ve STYD algoritmalarının karşılaştırılması ve değerlendirilmesinde kullanılmıştır.

Görülmüştür ki önerilen STYD algoritmalarından sadece trafik gruplamayı gözönüne alanının STYD işleminde özellikle de ağ bağlantı aksaması performansında belirgin etkisi vardır. Fakat sanal topolojiyi farklı STYD algoritmalarıyla yeniden düzenlemenin STYD işleminin toplam performansında belirgin etkisi olduğu ve farklı performans ölçütleri arasında; ağ kaynak kullanım verimliliği ve ağ bağlantı aksaması zıt denge durumu olduğu gözlemlenmiştir. STYD algoritmalarının performans ölçütlerine etkisi incelendiğinde, bir performans ölçütünü iyileştiren STYD algoritmasının diğer performans ölçütlerinin değerlerinin düşmesine sebep olduğu gözlemlenmiştir. Daha iyi toplam STYD performansı sağlamak için, tümleşik yeniden düzenleşim algoritması adında çok amaçlı hedef fonksiyonlu STYD algoritması önerilmiştir. Bu yeni önerilen algoritma önceki çalışmalardan farklı olarak üç ana etkeni; ışık yolunun trafik yükü, ışık yolunun trafik gruplama oranı ve ışık yolunun uzunluğunu tek bir hedef fonksiyonunda birleştirir ve yeniden düzenleşim esnasında tüm bu etkenleri gözönüne alır.

Simülasyon sonuçları göstermiştir ki önerilen STYD yöntemi; periyodik STYD tetikleme yöntemli tümleşik yeniden düzenleşim algoritması toplam STYD performansında artışlar sağlamaktadır.

Anahtar kelimeler: optik WDM ağları, sanal topoloji yeniden düzenleşimi, trafik gruplama

VIRTUAL TOPOLOGY RECONFIGURATION ON OPTICAL WDM NETWORKS CONSIDERING TRAFFIC GROOMING

SUMMARY

Recent advances in optical technology allow both dynamic virtual topology reconfiguration (VTR) and traffic grooming on optical WDM networks. By the help of increasing networking capability of optical WDM networks; virtual topology can be reconfigured for changing traffic conditions. And by the help of traffic grooming capability; a set of low speed connection requests can be multiplexed and switched onto high capacity channels. Both VTR and traffic grooming have an important role to provide more intelligent and operational optical WDM networks.

In this study these two important issues are reviewed and VTR problem is studied considering traffic grooming factor by proposing new VTR policies. Firstly, general VTR problem is categorized and handled in two independent sub problems as VTR triggering problem and VTR problem. Possible VTR triggering policies and VTR algorithms are evaluated and new VTR policies are proposed. This common “divide and conquer” approach also provides clear understanding of interaction and interrelation of these two sub problems.

Secondly, defined VTR problem considering traffic grooming is formulated with new variables and constraints by MILP. In order to handle this problem, the advantages and disadvantages of reconfiguration; network resource utilization and network disruption are examined and quantified in terms of measurable parameters. These performance measures (PM) are used to compare and evaluate proposed VTR triggering policies and VTR algorithms.

It is seen that proposed VTR algorithm considering only traffic grooming factor has a significant effect on VTR process especially on network disruption performance. But it is observed that reconfiguring the VT by different VTR algorithms has a significant effect on the overall performance of VTR process and there are tradeoffs between different performance measures; network resource utilization and network disruption. When effects of selected VTR algorithm on PMs are evaluated, it is observed that any VTR algorithm optimizing one PM can decrease the optimal value of other PMs. In order to provide better overall VTR performance, multi objective VTR algorithm called Integrated Reconfiguration (IR) algorithm is proposed. This newly proposed VTR algorithm different from previous studies combines three main factors; traffic load of lightpaths, traffic grooming ratio of ligthpaths and route length of ligthpaths into one single objective and considers all of them when reconfiguring. The results of simulations indicate that proposed VTR policy; periodic VTR triggering policy with IR algorithm achieves performance improvements for overall VTR performance.

Keywords:optical WDM networks, virtual topology reconfiguration, traffic grooming

1. INTRODUCTION

1.1 Optical Communication Networks

Optical communication networks are high capacity telecommunication networks based on optic technology. Telecommunication networks consist of three basic networks; access network, metropolitan-area network and backbone network. The access network connects end-users to the network infrastructure, e.g., dial-up modems. The metropolitan-area network covers metropolitan region, e.g., SONET ring networks. The backbone network covers long distances like national or global distances, e.g., stacked SONET ring networks. In the past few years due to advances in optics, electronics and software; optic technology is one of the most promising solutions for these three basic networks.

The potential research and development (R&D) challenges for optical communication networks are very large and still maturing. Optics is excellent for transmission due to its high bandwidth capacity, low signal attenuation, low signal distortion, low power requirement, low material usage, small space requirements and low cost, but its signal processing capability continues to be a bottleneck [1].

The maximum rate at which an end user can access the network is limited by electronic processing speed up to a few Gb/s. In order to utilize full bandwidth capacity of fiber-optic efficiently, multiplexing; multiple concurrent transmissions must be supported by network architectures and protocols. There are three methods for multiplexing: Wavelength Division Multiplexing (WDM), Time Division Multiplexing (TDM) and Code Division Multiplexing (CDM). TDM needs synchronization and CDM needs processing speed higher than data rate of users. So WDM optical network is the technology of choice in today’s optical backbone network technology for the exponentially growing bandwidth requirements of information society.

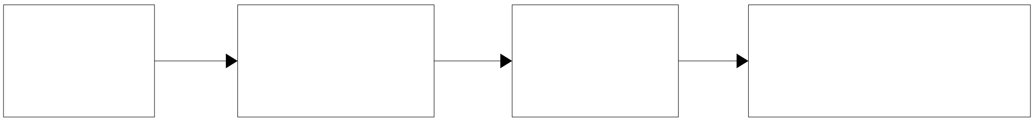

Figure 1.1 WDM Network Evolution

In Figure 1.1 evolution of WDM network architectures from simple point-to-point systems to advanced rings and arbitrary mesh networks with traffic grooming capability are shown. At first, WDM technology is being deployed for point to point communications. In order to expand bandwidth capacity, applying WDM technology to existing fibers is more cost effective compared to laying more fibers [2]. Then broadcast and select WDM network; primitive local WDM network is constructed by connecting network nodes via two way fibers to a passive star. A node sends optical data stream to the star using one available wavelength. The optical data stream from multiple nodes are combined by star and split to all nodes. In order to receive data, the optical filter of destination node or nodes must be tuned to the wavelength of source node [1, 3].

Recent advances in optical devices; optical switches have led to WDM technology with networking capabilities. Lightpath (LP) is the basic mechanism of communication in a wavelength routed network. “A lightpath is an all-optical communication channel between two nodes in the network and may span more than one fiber link. The intermediate nodes in the fiber path route the lightpath in the optical domain using active switches. The end nodes of the lightpath access the lightpath with transmitters and receivers that are tuned to the wavelength of lightpath operates.” [1, 3]. Virtual topology (VT) is a set of lightpaths and lightpaths are set of physical links that sets up physical topology (PT). Independence between VT and PT is an important characteristic of WDM networks. Configurable components allow VT to be reconfigured. In today’s optical technology optical devices have still low signal processing capability. But sooner or later, R&D and standardization activities for optical control methods and optical switching devices will allow dynamic switching and dynamic VT. By the help of this reconfiguration capability; virtual topology can be reconfigured dynamically for changing traffic conditions.

A single optical fiber strand has the potential bandwidth of 50 THz or higher. By using WDM, this bandwidth can be divided into multiple non-overlapping frequency or wavelength channels. However, there still exists a large bandwidth gap between a wavelength channel’s transmission speed (e.g., OC-48, OC-192 or OC-768) and the bandwidth requirement of a typical connection request (e.g., STS-1

(51.84Mbps), OC-3, OC-12 or up to full wavelength channel capacity) for backbone applications. In order to use network resources efficiently, low speed traffic streams need to be efficiently multiplexed or “groomed” onto high-speed lightpaths. Traffic grooming is one of the most important traffic engineering issues in optical WDM mesh networks. The traffic grooming refers to the problem of efficiently multiplexing a set of low speed connection requests onto high capacity channels and intelligently switching them at intermediate nodes [4-8].

1.2 General Problem Definition

In this thesis, Virtual Topology Reconfiguration (VTR) problem for wavelength routed WDM optical mesh networks with traffic grooming capability is studied. If there are unlimited network resources; e.g. unlimited wavelengths on all fiber links, every node pair could be connected by an all-optical LPs and there should be no problem to solve. Technological constraints limit WDM channels that can be supported in a fiber, number of transceivers and grooming capability at each node. So, there could be only limited number of LPs set up on the network. Since the traffic pattern is changing rapidly in real life applications, it is important to reconfigure the VT according to the traffic changes. In order to handle this problem, the benefits and costs of reconfiguration must be examined and quantified in terms of measurable parameters.

Disruption is a common penalty owned by VTR algorithms. Frequent changes to VT are disruptive because traffic at higher than gigabit per second transmission rates must be rerouted to new path on VT with buffering, tuning and switching delays during reconfiguration. For those transmission rates even a short period of disruption can’t be tolerated. The reconfiguration process disrupts both existing traffic and network performance by degrading the Quality of Service. So, frequent reconfiguration is not needed and it is necessary to minimize the network disruption when reconfiguring.

But postponing a required reconfiguration also has bad effects on the overall network performance and network resource utilization. Network performance may decrease since some connection requests could be blocked because of inefficient network resource utilization, e.g. there could be no wavelength available while some grooming ports are available. Bandwidth is also an important network resource and commodity. Since bandwidth can be sold, purchased or leased on a universal scale, this new market place called bandwidth markets have started to appear. So limited network resources must be utilized efficiently and this problem is also a variation of common optimal resource allocation problem.

On the other hand, if the VTR decisions are made only by considering the load balancing, even small changes in traffic pattern lead to reconfiguration and impact network performance.

It is vital to develop a methodology that can handle and optimize these tradeoffs and to reconfigure the network when the benefit of reconfiguration outweighs the costs of reconfiguration. In the literature, this active R&D area is called “Virtual Topology Reconfiguration”.

The problem is formulated as mixed integer linear program (MILP) in chapter 3 and an ILP solver like GAMS, CPLEX or LINDO will solve this problem for small networks. But the number of variables and constraints increase with the size of network. The related problems; Virtual Topology Design problem, Routing and Wavelength Assignment problem (RWA) and Traffic Grooming problem in a mesh network are known to be NP-complete problems [1,6,9].

1.3 Motivation

Since backbone networks are evolving from SONET/WDM ring networks to WDM mesh networks, more studies are needed on this problem. Reconfiguration is an important capability and VTR has an important role to provide more intelligent and operational WDM optical networks. It is required to analyze and develop efficient VTR algorithms for WDM optical mesh networks with grooming capability under dynamic traffic. Assessment of optical WDM network performance is also necessary in the phase of network planning, budgeting and system evaluation for optical communication network designs.

1.4 Objective

Network Resource utilization efficiency and network disruption are most important and conflicting objectives in reconfiguration process. The main objective of this thesis is to adapt virtual topology better for dynamic traffic conditions considering traffic grooming by minimum disruption to existing groomed traffic and maximum network resource utilization efficiency without increasing the complexity of problem. The second objective is to design a simulation model for WDM Optical Networks and analyze the proposed Virtual Topology Reconfiguration algorithms with defined performance measures.

1.5 Research Questions

In this thesis the following questions are considered:

- How frequently and when to reconfigure a Virtual Topology in WDM optical mesh networks with traffic grooming capability?
- How to reconfigure Virtual Topology in WDM optical mesh networks with traffic grooming capability?
- What factors have main effects on Virtual Topology Reconfiguration?
- How can the effectiveness of Virtual Topology Reconfiguration algorithms be improved?
- What should the best Virtual Topology Reconfiguration policy in dynamic traffic be?
- What is the influence of proposed Virtual Topology Reconfiguration policies on the network performance?
- Can proposed Virtual Topology Reconfiguration policies improve the network performance?

1.6 Methodology

In this study, first optical WDM network simulation model is constructed and tested using discrete event simulation techniques based on realistic assumptions. Second the simulation model is integrated with a program module that applies proposed Virtual Topology Reconfiguration algorithms. Then simulation results are used to evaluate different Virtual Topology Reconfiguration algorithms on selected network configurations. 12 different scenarios are considered and simulation was run 15 times per scenario adding up to 180 replications to analyze the results. In the simulation model dynamic network traffic is used. The model is implemented using SIMAN in Rockwell Arena software [23] and Microsoft Visual Basic. Proposed reconfiguration policies are evaluated and the benefit of each VTR is demonstrated by simulation results. The problem is formulated as MILP and solved by proposed VTR policies.

1.7 Scope

Virtual Topology Reconfiguration problem described in this thesis is a special case of the more general optimal resource allocation problem. A problem specific optimization algorithm is designed and tested on this real problem by using heuristic and multi objective optimization techniques. This is not a solution of the virtual topology design problem by mathematical optimization. Effectiveness of this algorithm can be understood better by analyzing the simulation data. Grooming routing and wavelength assignment (GRWA) phase and signaling phase of the problem is not considered and GRWA algorithms in the literature are implemented in the simulation model.

1.8 Literature Survey

A brief description of important studies in VTR category, referred in the literature, is summarised in this section. In [1, 4-8,10,11] VT design problem and traffic grooming problem has been studied in great detail. The VTR problem has been mainly studied for SONET/WDM ring networks [12]. There are two main approaches to handle the VTR problem. One approach is solving the VT design problem for current traffic pattern by MILP and applying it, the other approach is optimizing selected VT related objective function and applying it.

In [12] iterative VT reconfiguration algorithms for load balancing are proposed to track rapid changes in traffic pattern. The proposed algorithm is an iterative local search algorithm that starts with a given VT and makes small changes to VT that reduce the load on the most heavily loaded link.

Hitless reconfiguration is defined as reconfiguration process without the loss of any data during the transition between topologies in [13]. Hitless reconfiguration is achieved by first establishing new links of new topology without removing old ones, second rerouting the existing traffic in old topology to new topology and finally removing the old topology. But network disruption can not be eliminated completely because of transition phase.

In [14] VT design problem is formulated as mixed integer optimization problem with the objective of minimizing the maximum link flow in the network. In [15], moving from initial VT to target VT in minimum steps of branch exchange operations is studied. VTR is executed as a sequence of reconfiguration operations. Three polynomial-time greedy algorithms are proposed to find the shortest sequence with minimum reconfiguration duration. Results show that length of sequence increases with the size of network. It tries to minimize traffic loss by reducing the number of steps required in reconfiguration.

In studies [14] and [15], target VT is computed by the algorithm proposed in [14] for the given traffic and shortest branch and exchange sequence is calculated by heuristic algorithms proposed. In these studies VT design problem is solved from the beginning at every reconfiguration step. This kind of multi step reconfiguration process can take long time and results in obsolete VT topologies when completed because of dynamic traffic patterns.

In [15-17] have been suggested that the new virtual topology was known a priori, and concerned with the cost and sequence of branch-exchange operations to transform from the original VT to new VT.

In [18] VT design problem is formulated and three objective functions are proposed for finding the optimal VT for a given traffic pattern. Tradeoffs between amount of reconfiguration steps and optimization of proposed objective function are considered.

In [10] the best virtual topology for a given network traffic matrix is calculated by ILP formulations. This methodology is based on both optimizing a given objective function and minimizing the changes required to obtain new VT to the current VT. The closest VT is chosen for reconfiguration but reconfiguration procedure is not considered.

In [10] and [18], best VT for a given network traffic using MILP formulation and heuristic techniques is shown but reconfiguration procedure; transition from the old VT to new one, is not studied.

In [19] three reconfiguration schemes are proposed that attempt shift from one VT to another while keeping the network availability as much as possible. Proposed reconfiguration algorithms arrange a reconfiguration sequence to minimize mean number of disrupted transceivers.

In [20] the problem is formulated as a Markov Decision Process. Results from Markov Decision Process theory is applied to obtain optimal reconfiguration policies for a network of large size.

Previous studies on reconfiguration proposed heuristic algorithms to determine the best VT for given traffic pattern and migrate to that topology using a series of reconfiguration steps. But for dynamically changing traffic patterns, reconfiguring the full VT by every change in traffic may be very disruptive.

In [21, 22], a bandwidth allocation and reconfiguration method called capacity allocation using time zones (CATZ) is proposed. This method exploits the daily traffic fluctuations and time-zone based traffic shifts to cost-effectively operate a WDM backbone network. This approach monitors the traffic load on each link. Periodically; a single link may be added if links exist with traffic loads above upper threshold value called high watermark. Otherwise, a link may be deleted if links exist with traffic loads below lower threshold value called low watermark. This study is different from other studies because it does not solve the VT design problem from the beginning at every reconfiguration step.

The recent study [22] has focused on addition/deletion of one lightpath per decision interval. A lightpath is taken as the basic unit of VTR. Reconfiguration decision; addition/deletion of one lightpath depends on the actual traffic load on lightpaths. The VTR schemes proposed in the literature are summarised in Table 1.1.

Table 1.1 Comparison of VTR Related Papers

Reference:	Objective Functions:	Reconfiguration Method:
Ref[10]	• Minimize average hop distance • Minimize topology change	Multi step
Ref[12]	• Minimize the maximum link load	Multi step
Ref[14-16]	• Minimize reconfiguration duration with shortest sequence	Multi step
Ref[18]	• Minimize average hop count • Minimize total ligthpaths • Minimize total number of physical link channels used	Multi step
Ref[19]	• Minimize mean number of disrupted transceivers	Multi step
Ref[20]	• Optimize the degree of load balancing • Optimize the degree of network unavailability	Multi step
Ref[21,22]	• Optimize traffic load balancing	Single step

This study can be classified into single step reconfiguration with the objective of both maximizing the network resource utilization and minimizing network disruption.

1.9 Contribution

In this thesis, a new approach to Virtual Topology Reconfiguration problem for wavelength routed WDM optical networks with traffic grooming capability under dynamic traffic is proposed. VTR problem is formulated with new variables and constraints for wavelength routed WDM optical mesh networks with traffic grooming capability. Mathematical formulation of VTR with traffic grooming is studied with heuristics finding sub-optimal solutions by reasonable assumptions. In previous studies for VTR problem, traffic grooming factor is not taken into account.

In this thesis different than previous studies, the problem is handled in two independent sub problems:

1. VTR Triggering (VTRT) Policies: Timing is an important issue for reconfiguration process since continuously monitoring the network is best but has signaling costs. Possible VTR triggering policies are considered with their costs and benefits and classified as Event Triggered and Time Triggered.
2. VTR Algorithms (VTRA): New factor affecting Virtual Topology Reconfiguration problem is considered and compared with previous factors in the literature. Then multi objective optimization of these factors is applied considering the cost and benefits of reconfiguration process.

1.10 Summary of Chapters

This study is presented in six chapters. The preceding sections of this chapter outline the motivation, methodology, literature survey, research questions and objective as well as general problem definition.

The remaining chapters are summarized as follows:

- Chapter 2 describes the WDM Optical Network briefly.
- Chapter 3 explains Virtual Topology Reconfiguration algorithms.
- Chapter 4 describes the simulation process in detail.
- Chapter 5 presents design of experiments and analysis used to evaluate simulation results.
- Chapter 6 makes necessary conclusions and recommendations for future study in this area.