İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF INFORMATICS

# A NEW HEURISTIC ALGORITHM FOR VIRTUAL TOPOLOGY RECONFIGURATION IN OPTICAL WDM NETWORKS

M.Sc. Thesis by
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Programme : Computer Science

SEPTEMBER 2004

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ BİLİŞİM ENSTİTÜSÜ

# OPTİK WDM AĞLARDA SANAL TOPOLOJİNİN YENİDEN DÜZENLENMESİ İÇİN YENİ BİR SEZGİSEL ALGORİTMA

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# FOREWORD

I would like to thank to Assist. Prof. Dr. Feza BUZLUCA for all support, supervision, and motivation during my graduate studies.

I would like to thank to Research Assistant Çiçek ÇAVDAR and Assist. Prof. Dr. Ayşegül GENÇATA for their contributions to this study.

Thanks to my family for their patience and endless support throughout all of my education life.

To the memory of my father; Halil Sıtkı KOÇAK.

Okan KOÇAK

August, 2004

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## ABBREVIATIONS

| | |
|---|---|
| **Gbps** | : Gigabit/seconds |
| **Mbps** | : Megabit/seconds |
| **PT** | : Physical Topology |
| **VT** | : Virtual Topology |
| **VTR** | : Virtual Topology Reconfiguration |
| **WDM** | : Wavelength Division Multiplexing |
| **OC** | : Optical Channel |
| **OC-n** | : Data rate of n*51.84 megabits per second |
| **NLC** | : Number of lightpath changes |
| **AHD** | : Average Hop Distance |

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## ÖZET

Internet kullanımında son zamanlarda oluşan artış, Internet servisi sağlayıcılarını daha yüksek bant-genişliği ve hızı kullanıcılara sağlamasını gerektirmektedir. Kullanıcılar Internetten video izlemek, çevrimiçi konferanslar yapmak istemektedirler. Bu gibi çok yüksek bant-genişliğine ihtiyaç duyan uygulamalar, bilgisayar ağlarının şu anki yapısı yüzünden kolaylıkla gerçekleştirilememektedir.

Optik WDM ağlar bu bant-genişliği ve hız problemini çözecek en önemli adaydır. Şu anki en hızlı bant-genişlikleri onlarca Gbps düzeyinde iken, optik ağlar Tbps bant-genişliği sunmaktadırlar. Optik WDM teknolojisi, yüksek dalgaboylarına imkan veren, dalgaboyu bölüşümlü çoğullama yöntemini kullanmaktadır. Aynı fiber birden çok dalgaboyunu taşıyabilmektedir. Böylece fiberin kullanılma kapasitesi artmaktadır.

Optik ağlar, ağdan en yüksek kapasiteyi alabilmek için, fiziksel topolojinin üstünde, sanal topoloji kullanırlar. Zaman geçtikçe, sanal topoloji o anki trafik koşullarına karşı verimliliğini yitirmiş olabilir. Bu yüzden sanal topolojide değişiklikler yapabilmek için sanal topoloji yeniden düzenleme algoritmaları kullanılır. Böylece sanal topoloji daha verimli hala getirilir.

Bu çalışmada sanal topolojinin yeniden düzenlenmesi için yeni bir içgüdüsel algoritma önerilmektedir. Algoritma optimum sanal topolojiye ulaşmak için, temel ve gelecek vaat eden bir yaklaşım kullanmaktadır. Bu çalışmada yeniden düzenlemenin amacı en yüksek yüklü ışıkyolunun yükünü azaltmaktır. Bu amaca ulaşmak için, algoritma en yüklü ışıkyolunun yükünü artırmadan ışıkyollarını koparmaktadır. Daha sonra en yüklü ışık yolunun yükünü azaltmak için ışıkyolları kurmaktadır. Algoritmanın avantajları şunlardır: Gelecekteki trafik örüntüsünü bilmeye gerek duymamaktadır. Karmaşıklığı azdır, bu nedenle çevrimiçi çalıştırılabilir. Ayrıca ağ yöneticisi yeniden düzenlemeden ağın ne kadar etkileneceğini ayarlayabilir.

**A NEW HEURISTIC ALGORITHM**
**FOR VIRTUAL TOPOLOGY RECONFIGURATION**
**IN OPTICAL WDM NETWORKS**

## SUMMARY


Recent growth in the Internet usage forces for Internet Service Providers to provide higher bandwidths, speeds, to the users. Users would like to view streaming video, make online conferences over the Internet. This bandwidth hunger applications are not currently being used easily because of the limitations of the current network infrastructure.

Optical WDM networks are the leading candidate to solve this bandwidth and speed problem. They offer up to Tbps bandwidth which is much higher than the current fastest bandwidths which are up to tens of Gbps. Optical WDM technology is based on wavelength division multiplexing which made these Tbps bandwidths feasible. Same fiber can carry many wavelengths so that usage of fiber is growing with the number of wavelengths used.

On top of the physical topology, Optical WDM Networks use Virtual Topology in order to get the most from the network. Many studies have been made for designing Virtual Topologies. As time passes, the initial Virtual Topology of a network may become inefficient for the current traffic conditions. Therefore virtual topology reconfiguration algorithms are used in order to make changes to the current virtual topology so that it fits to changing conditions.

In this study a new heuristic algorithm for Virtual Topology reconfiguration is proposed. Heuristic uses a basic and promising approach to achieve optimal virtual topology. In our study, the objective of reconfiguration is to minimize the load of the maximally loaded lightpath. In order to achieve minimization of the load on the maximally loaded lightpath, our algorithm tears down lightpaths without increasing the load on the maximally loaded lightpath. Then, it sets up lightpaths in order to decrease the load of the maximally loaded lightpath. The advantages of our algorithm are: It does not need to know the future traffic pattern. Its complexity is low so that it can be run online. Moreover the network administrator can decide how much the network will be interrupted.

# 1. INTRODUCTION

In the 1990s, networking research and development made significant advances in the areas of high speed wide area computer networks and local area networks. The computer networks researchers struggled with the problems of defining and implementing new network protocols for traffic requiring real time constraints, such as continuous media applications. The need for fast and manageable network infrastructure became more important as applications which require high bandwidth increased and computer networks became the central component of the world's telecommunications infrastructure.

Internet is a Wide Area Network (WAN) which is the core network of the world. It cuts across continents and countries for the purpose of connecting hundreds, or even thousands, of small networks such as Metropolitan Area Networks (MAN) and Local Area Networks (LAN). These small networks are also called access networks which upload or download data to or from Internet.

Internet has changed our world and life. Also it has changed the computer and communications industry. One can publish information to the all world by using Internet. People and computers can share information, work together and communicate although they are at different locations of the world. As Internet became more important, network infrastructure importance increased.

Recent growth in the Internet usage forces for Internet Service Providers to provide higher bandwidths, speeds, to the users. Users want to view streaming video, make online conferences over the Internet. This bandwidth hunger applications are not currently being used easily because of the limitations of the current network infrastructure.

Optical networks research area became the most popular networks research in the 1990's which will overcome the struggle of providing high bandwidth to the world. Optical networks involve a number of technologies, from the physics of light through protocols. The basis of first generation optical networks is Synchronous Optical Network (SONET) and Synchronous Digital Hierarchy (SDH) techniques. SONET defines interface standards at the physical layer of the computer networks. SONET establishes Optical Carrier (OC, speed of fiber optic networks) levels from 51.8 Mbps to 2.48 Gbps while Optical WDM Networks provides speeds up to Tbps. Because of the high speed it provides, in the next generation networks Optical WDM technology will be the dominant one.

Optical networks can be configured point-to-point, linear, ring, or mesh topology. First generation networks, were deployed before techniques to manage complex mesh networks were developed. Consequently, first generation optical networks are primarily rings, although point-to-point and linear networks are utilized for certain applications. Now optical networks are mostly complex mesh networks.

The current trend in the computer networks area is towards optical WDM networks. The goal is to take advantage of the capacity of optical fibers better, which is much greater than single wavelength systems can utilize. Whereas current systems provide several hundred Mbps to a few Gbps, WDM systems promise capacities on the order of several Tbps without dramatic electronic speed improvements. Thus, a new era of cheap, massive bandwidth is beginning.

## 1.1 Motivation

In an Optical network an arbitrary virtual topology (VT) can be embedded on a physical topology. The virtual topology is set up to exploit the relative strengths of both optics and electronics [1]. Virtual topology is formed by lightpaths and nodes of the network.

Traffic is carried on lightpaths optically from source to destination. If there is not a lightpath between source and destination, electronic conversion occurs in order to switch a lightpath to another lightpath. The type of this architecture where electronic conversion may occur is called “almost-all-optical” [2]. If there is no electronic conversion occurs between source and destination in a network, this architecture is called “all-optical”. Since wavelengths are limited in an optical network, electronic conversion is inevitable. To minimize this type of conversions and average distance that data travels, to provide load balancing, virtual topology is designed and used.

The virtual topology designed at the beginning may be inefficient when time passes. In a real network environment, traffic may change unpredictably. Research on networks traffic shows that, traffic fluctuates in a day. In order to benefit most from the virtual topology, it needs to be reconfigured to fit the traffic of the network and optimize the network. Researchers have worked on Virtual Topology Reconfiguration (VTR) algorithms and methods which change and optimize the VT.

In this thesis the aim is to get the most from the VT by applying a heuristic reconfiguration problem. This is actually an optimization problem and the linear formulation of the optimization problem is given in the thesis. Since simpler versions of this optimization problem is known to be NP-hard[1], we use heuristic approaches to reconfigure the virtual topology.

## 1.2 Problem Statement and Proposed Solution

The problem that is studied in this work is the reconfiguration of virtual topology of an optical WDM network in order to use the networks resources optimally and to provide more resources to the future traffic needs. We think that the problem is a real time problem, since computer network's traffic is dynamically changing and the changes to the system can be done only in real time. So it should be handled with on-line approaches.

The proposed solution is an on-line heuristic VT reconfiguration algorithm. The VTR algorithm works periodically and makes changes to the network in each period. These changes can be kept small or large according to the needs of the network and network administrator's choice.

The advantages of the algorithm are:

- Network administrator can determine the amount of disruption to the network by setting the number of lightpath change.
- It does not need to know the future traffic pattern.
- It deletes ineffective used lightpaths from the network.

The heuristic VTR algorithm works in two phases. In the first phase predetermined number of lightpaths, which have minimum load, are deleted. The objective in the first phase is to free up some resources which are used inefficiently. Deletions of the lightpaths are done if the load of maximally loaded lightpath does not increase. In

[1] Definition of NP-hard: The complexity class of decision problems that are intrinsically harder than those that can be solved by *a* nondeterministic Turing machine in polynomial time [3].

the second phase predetermined numbers of lightpaths are established. Additions of the lightpaths are done according to the minimum of the maximum loads which will happen after their additions. The lightpaths which have the lowest maximum load are established.

## 1.3 Summary of Chapters

This study is presented in six chapters. Following chapters are summarized as follows:

- Chapter 2 describes optical WDM networks, virtual topology design problem and reconfiguration problem, previous studies on VT design and reconfiguration.
- Chapter 3 gives the linear formulation of the virtual topology reconfiguration problem and explains the proposed virtual topology reconfiguration heuristic algorithm.
- Chapter 4 presents simulation and results of the heuristic VT reconfiguration algorithm.
- Chapter 5 gives necessary conclusions and recommendations for future study in this area.
- Appendix A. This section gives additional individual simulation result graphs for different simulation periods and NLC (number of lightpath changes). These graphs are there to show them separately. They are also drawn in the comparison figures in the thesis.

# 2. VIRTUAL TOPOLOGY DESIGN AND RECONFIGURATION IN OPTICAL WDM NETWORKS

Today computer networks and Internet are one of the best platforms of communications and information sharing. *Computer network is a* connected independent computers collection which helps communication in several ways [1]. These computers are connected to each other via copper cable, fiber optics, microwaves or satellites. People need more and more from this communication platform as their need and request to information, entertainment and communication increase. Therefore there should be new types of computer networks which accomplish very high bandwidths. *Optical WDM networks* are expected to accomplish these demands.

Idea of constructing optical networks first started in 1980's with the advances in fiber optics and opto-electronics [18]. In the beginning most of the focus was on access networks such as Fiber Distributed Data Interface (FDDI) and Synchronous Optical Network (SONET). They have various nice properties such as traffic engineering, protection and failure recovery.

Next generation optical Internet is expected to be a WDM mesh network. Between each pair of nodes there will be multiple fibers. With this architecture network researchers have new research topics which they have never before. Since WDM technology increased the bandwidth in a single fiber, we now need new techniques to make the most use of this revolutionary improvement in the hardware. By using these new techniques and new infrastructure, hundreds of terabit per-second will be attained.

In order to fully utilize optical networks, virtual topologies are designed over the physical topology. Moreover virtual topology reconfiguration algorithms are designed in order to use virtual topologies optimally. In this chapter, Optical WDM Networks, virtual topology design and reconfiguration problems are described in detail.

## 2.1 Optical WDM Networks

*Optical WDM Networks* are the leading candidate today which meets the needs of networks users. It provides very high bandwidth up to 2-3 Tb/s which is the highest speed in the computer networks history [2]. In the coming years optical networks are expected to be used all over the globe, and will dominate over other types of networks such as ATM and SONET. Computer networks will be two layered: IP over WDM. Optical WDM networks will be the next generation computer network framework.

Optical WDM networks are one type of computer networks which uses fiber optic cables as the physical medium. Before fiber optic cables, copper cables were being used in computer networks. Then fiber optics are preferred over copper cables and used for a long time in the history. Fiber optics offers high bandwidth and low transmission errors. In theory fiber optic cable's capacity is up to 25 THz [1]. However, computer networks could not go to that much speed because of the lower speeds of the end user's receivers such as their personal computer.

Optical Networks comprises of units like the Optical Amplifiers, Wavelength Converters, Wavelength Add/Drop Multiplexers and Optical Cross Connects for its operation. The concept of the optical transport network implies that the service provider should have optical access to traffic at various nodes in the network (like the SONET layer for SONET traffic). All these components ensure not to require any other electrical accessory.

*Optical Amplifiers* (OA) are devices used to amplify a weak, distorted signal with the aim of generating a good signal. It operates in the optical domain, without converting the signal into electrical pulses. It is usually found in the long haul networks, where the cumulative loss is huge. The Noise Figure, Automatic gain control, Bandwidth and Gain Flatness characterize the optical amplifier used in a system. Erbium Doped Fiber Amplifier (EDFA) is a common amplifier found in most networks.

The performance of the optical amplifier has improved tremendously over the past few years. Current amplifier systems provide very low noise and flatter gain, which proved advantageous to the WDM system. The amplifier throughput has steadily increased onto nearly +20db, which is many a time powerful than the primitive model.

A wavelength converter's function is to convert data on an input wavelength onto a possibly different output wavelength within the operation bandwidth of the system. This component is used in the routing devices when the wavelength, which marks the route to be followed, is to be changed. An ideal wavelength converter should be transparent to bit-rates and signal formats. It has many other physical requirements governing its operation - like fast setup time, large signal-to-noise ratio, moderate input power levels, insensitivity to input signal polarization etc. Wavelength conversion can be opto-electronic (or) all-optical, based on the strategy employed. Usage of a particular scheme depends on the requirements of the system. Nevertheless the all-optical wavelength conversion is more future oriented and advantageous.

Wavelength Add/Drop Multiplexer is the optical sub-system that facilitates the evolution of the single wavelength point-to-point optical network to the wavelength division multiplexed networks. It is responsible for managing the WDM traffic in the fiber. The WADM serves as the entry point to the optical layer in many other aspects. The practical utilization of the fiber bandwidth is achieved by being able to selectively remove and reinsert individual channels, without having to regenerate the all of the WDM channels.

A WADM is characterized in terms of the total number of input, through, drop and add channels (virtual fibers). The system maintains each connection as sequential ports and performs manipulations on them. The channels to be added or dropped can either be pre-assigned or reconfigured automatically based on the type of implementation. The former is called as Fixed WADM and the latter is known as Reconfigurable WADM.

The Optical Cross Connect (OXC), which is shown in Figure 2.1, is a WDM system component that provides cross-connect functionality between N input ports and N output ports, each handling a bundle of multiplexed single-wavelength signals. The bandwidth management flexibility is obtained with the introduction of an Optical Cross Connect (OXC).

An OXC will support network reconfiguration and will allow network providers to transport and manage wavelengths efficiently at the optical layer. An OXC is most efficient when it contains a bit-rate & format independent optical switch. These attributes help the OXC cross connect over multiple bit-rates - such as OC-3, OC-12, OC-48 and OC-192 and other formats like SONET, ATM.

The optical gateway is a common transport structure that must groom and provision traffic entering the optical layer. These blocks are essential for maintaining protocol transparency and for a maximum bandwidth capacity. The emerging basic format for high-speed transparent transport is ATM, and optical gateways will allow a mix of standard SONET and ATM services. By providing a link between the variety of electrical protocols and allowing flexible deployment of any mix of them, optical gateways provide networks the maximum benefits of optical networks. The optical gateway will be the key element to allow smooth transition to optical networks.

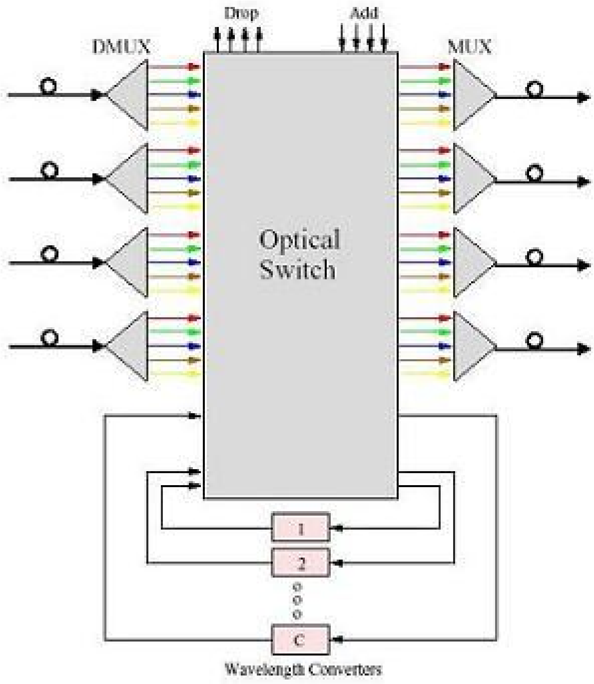


**Figure 2.1:** Optical Switch / Optical Cross Connect (OXC)

### 2.1.1 Wavelength Division Multiplexing

In fiber optic cable, Optical Network uses one of the best ways of carrying data which is Wavelength Division Multiplexing. *Wavelength Division Multiplexing* uses several numbers of wavelengths in the same fiber optic cable to carry the data. So the capacity of the fiber optic cable is highly utilized. Through this operation, it creates many virtual fibers each capable of carrying a different signal. At its simplest, WDM system can be viewed as a parallel set of optical channels, each using a slightly different light wavelength, but all sharing a single transmission medium. This new technical solution can increase the capacity of existing networks without the need for expensive re-cabling and can tremendously reduce the cost of network upgrades.

In a WDM network data is routed to their destination by using wavelengths. This routing is called wavelength-routing and optical WDM networks are wavelength-routed networks. In order to route wavelengths there are wavelength switching capable routers which are connected by fibers. Some routers are connected to access networks where their data are multiplexed in the router. At these routers also Optical to Electronic (O/E) conversion or Electronic to Optical conversion (E/O) occurs since data is in the electronic domain in the access networks while it is in optic domain in the optical networks. If in a network no intermediate O/E conversion occurs, it is called an *all-optical network*.

Internet Protocol (IP) over WDM is the concept of sending data packets over an optical layer using WDM for its capacity and other operations. In the modern day world, the optical layer has been supplemented with more functionality, which was once in the higher layers. This creates a vision of an all-optical network where all management is carried out in the photonic layer. The optical network is proposed to provide end-to-end services completely in the optical domain, without having to convert the signal to the electrical domain during transit.

Instead of WDM, we can use many fibers between the nodes, but this is not the best economical solution and there will be many maintenance problems of fibers which can be cut accidentally by outside effects. Or we can use TDM (Time Division Multiplexing) which distribute data to time slots. However in current technology we can not go beyond 10 Gb/s with TDM technology.

WDM technology is essentially similar to FDM (Frequency Division Multiplexing), which is used in radio systems [19]. Although they are same, WDM is used in optical communication and FDM is used in radio communication. The reason might be that WDM was invented by physicists while FDM was invented by electronics engineers. In FDM data is sent with different frequencies (or equivalently, wavelengths or colors) in the same fiber optic cable. The same principle holds for WDM too. These wavelengths do not interfere with each other if they are far enough. By this way a fiber acts like multiple fibers with each carrying a single data stream. Today each wavelength can carry up to 2.5 Gb/s, 10 Gb/s data and 40 Gb/s will be available in the near future.

In Figure 2.2 there is a wavelength routed Optical WDM network. Routing of wavelengths is done by Optical Crossconnects (OXC, Optical Switch). As seen from the figure same wavelengths can not be used on the same link and many wavelengths are available on the same link, so that there can be two or more virtual links between nodes of the network.

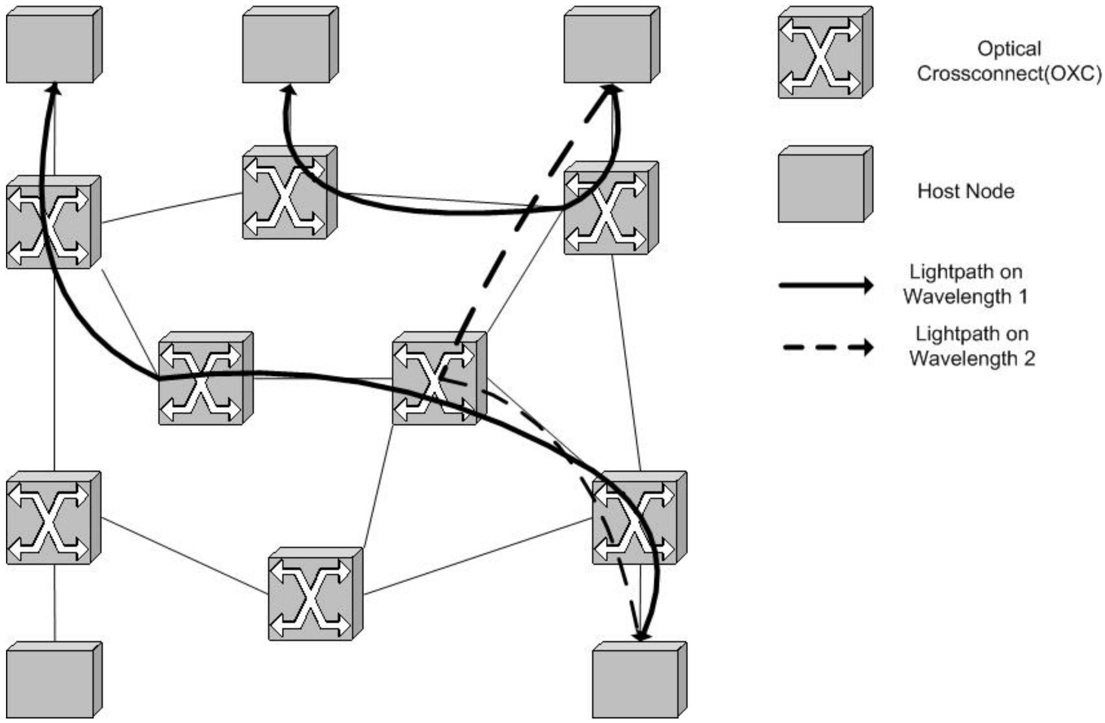


**Figure 2.2:** Wavelength routed Optical WDM Network

## 2.2 Virtual Topology Design Problem

A network can be physically structured in the form of a ring or a mesh based on the connection between the various nodes. A connected network of arbitrary topology, in which the node degree is typically more than two, is regarded as a Mesh. Above the mesh based or ring physical topology, there is a Virtual Topology.

Virtual Topology is a key feature in an Optical WDM network which optimizes the traffic on the network so that network performs higher and users can benefit more from the network. Optical networks are formed by nodes and switching elements which are connected by physical links (optical fibers). This topology is the physical topology of the optical network. Virtual topology is formed by lightpaths over physical topology of the network. The lightpaths are the links of virtual topology and the nodes of physical topology are also the nodes of virtual topology. A virtual path is formed by lightpaths. Data is carried on virtual paths between the source and destination. In Figure 2.3 there is a sample virtual topology. The nodes A and D are neighbors since they have a lightpath which connects them and therefore they are 1 hop away from each other. The same is true for node A and C, B and D.

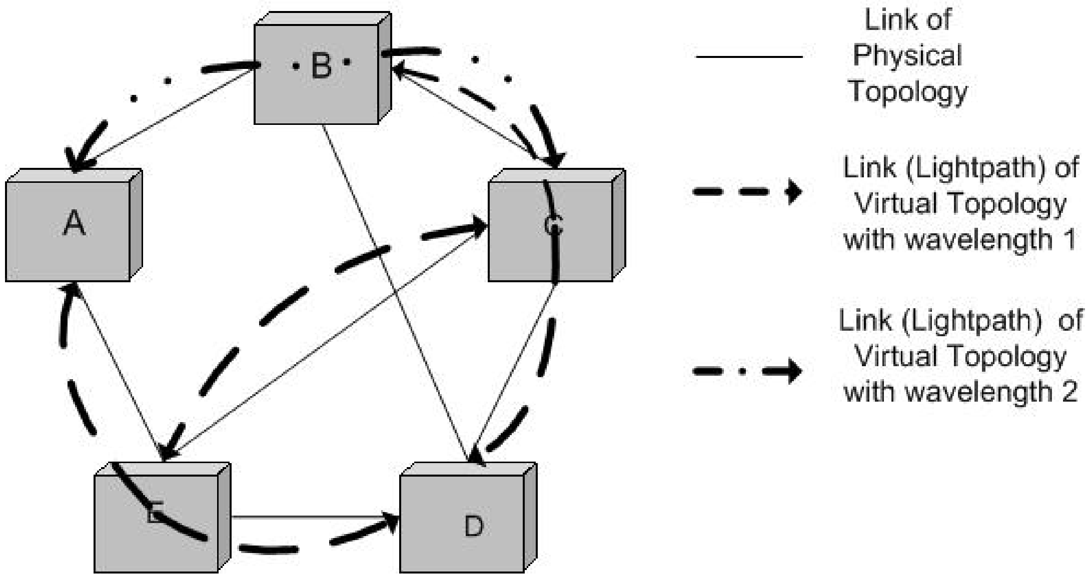


**Figure 2.3:** Virtual Topology

A virtual topology indicates the lightpaths from one node to another. This arises from a logical view all connections in the network (and not the physical structure). The virtual topology will comprise N x N connection. Hence, determining a lightpath constitutes an $N^2$ -scaling problem. An efficient algorithm needs to be devised to calculate an optimal virtual topology based on the traffic pattern. There exist many algorithms for dynamically reconfiguring the virtual topology of the system. In most cases, knowing the physical structure would help reducing overheads, by keeping the number of fiber links traversed to a minimum.

Forming lightpaths over physical topology in order to make a virtual topology is called the Virtual Topology Design (VTD) problem. If there were unlimited transmitters, receivers and wavelengths, there will be no VTD problem. If that is the case, any traffic can go from any source to destination with one hop. So there will be no delay. However, in real world, there are limited resources. Transmitters, receivers and wavelength converters are still expensive. As wavelengths are limited, not all lightpaths can go to its destination with one hop, they may use multi hops. When they are going from one hop to another, they are under Optical-Electrical-Optical (O-E-O) conversion. This conversion is a big delay factor. Therefore the aim of virtual topology design is to effectively use the resources and to achieve the objective of their design. This objective might be minimizing network delay, congestion and traffic weighted average hop distance.

### 2.2.1 Virtual Topology Design Algorithms

In the past 10 years many research have been made for Virtual Topology Design problem in Optical WDM Networks. VTD is the main feature of Optical Network which determines the efficiency of the network. VTD determines the lightpaths which are the links of the data over the network. So any algorithm, which makes total number of links shorter, will be successful. This optimization parameter is traffic weighted average hop distance. The other objectives, minimizing congestion and delay also help to make the road shorter.

One of the most important papers on VTD in the literature is [3]. They propose various VTD heuristic algorithms. Since VTD is an NP-complete problem, heuristic algorithms are used. These algorithms are:

- HLDA (Heuristic Logical Topology Design Algorithm): This algorithm tries to establish lightpaths between nodes according to the traffic. The nodes with the highest traffic between will get the lightpath first. This approach is trying to give 1 hop route to highest traffic so that congestion could be lowered in the network.

- MLDA (Minimum Delay Logical Design Algorithm): This algorithm is designed for networks where $\Delta_l$ (maximum out degree of a node) is bigger than the physical out degree of the node. If this is the case, lightpaths are established between nodes. The other lightpaths are established according to the HLDA. MLDA provides shortest paths for traffic so that delay of the network is minimized.

- TILDA (Traffic Independent Logical Topology Design Algorithm): TILDA does not consider the traffic of the network while establishing the logical topology. Firstly it establishes lightpaths between 1 hop neighbor nodes. Secondly it establishes lightpaths between 2 hop neighbor nodes. Finally it establishes lightpaths between 3 hop neighbor nodes. This way TILDA attempts to minimize the number of wavelengths used. If traffic is unknown or uniform TILDA is a good choice for VTD.

- RLDA (Random Logical Design Algorithm): This algorithm places lightpaths randomly. This is used to compare the results with the other algorithms.

In the above algorithms when we consider all constraints, throughput, delay, wavelengths, MLDA is better than the others.

As optical networks have limited number of resources like wavelengths, receivers, transmitters, some of the current researches have been focused on the problems caused by these limitations. These limitations increase network delay, congestion and number of hops which data travel.

In [4] authors have proposed a new algorithm for VTD which takes into account these limitations. O-E-O conversions have a big delay factor in optical networks. However when signal travels long distances, bit-error rate (BER) and noise occur in the signal. Their algorithm tries to minimize BER and the length that the data travels. As the signal goes to long distances the BER increase in the signal. They give a formula to calculate the BER when a lightpath is requested so that when designing VTD this formula can be used. Although O-E-O conversions cause delay, they propose to use O-E-O conversion in order to decrease BER in the signal.

In other VTD algorithms physical problems such as BER have not been considered. They have tried to achieve the optimization objective by using a heuristic multihop connection establishment algorithm which takes into account the BER constraint. By simulations they have showed that this algorithm decreases BER in the lightpaths and BER should have taken into account in VTD.

In [5] authors have addresses the electronic bottleneck problem in VTD. Problem arises because of O-E-O conversions in the OXC's of nodes. Conversions mean delay which is a fallback of high speed optical networks. This conversion is very slow when compared to speed of optical networks. So they saw a need to address this problem, which is congestion on the nodes. This seems as important as congestion of lightpaths. They have given a new formulation for VTD which takes account the electronic data processing at the nodes. This formulation tries to minimize the congestion at the nodes. The formulation is an MILP (Mixed Integer Linear programming) formulation. By using MILP one can find the optimum virtual topology. Since as number of nodes increases, running time of MILP increases a lot, previous studies on VTD has proposed heuristic algorithms for VTD. Their MILP formulation is called Multi-Hop Minimization Model (MHTmin) model which tries to minimize the congestion on the nodes. Previous MILP formulations are called Lightpath Congestion Minimization (LCmin) model. MHTmin is low in complexity than the LCmin model and takes into account the delay parameter.

There are many objective functions in VTD. In [6] authors have investigated the effect of objective functions on VTD. In previous studies on VTD, different researchers used different objective functions while ignoring other important objectives of VTD. These objective functions are lightpath congestion on a link, congestion on the maximally loaded lightpath and traffic weighted average hop distance. They have observed the other objective functions while optimizing an objective function. Their study showed that if one focuses on one objective function, the other objectives become worse. Therefore they have stated that in VTD, multi-objective functions should be used so that while optimizing one parameter, also the other parameters are not much affected badly.

### 2.3 Virtual Topology Reconfiguration Problem

Reconfiguration of Virtual Topology is an important property of Optical WDM networks. Virtual topology has lightpath as a link which can be torn down and set up. In a physical topology one can not generally change the links of the network. Tearing down lightpaths which are no longer necessary and setting up new lightpaths is called Virtual Topology Reconfiguration (VTR). Reconfiguration in an optical WDM network is done to dynamically optimize the network by rearranging the lightpath connections. All lightpaths makes a virtual topology in an optical network. So when lightpaths are changed, this means also virtual topology is changed to a new virtual topology.

Virtual topologies are designed to get the maximum and optimum performance from the network. As time passes the conditions of the network, such as traffic rate, conditions of links, changes. These new conditions force the network to have a new virtual topology. In some lightpaths congestion occurs because of high load on the lightpaths. Also link failures may occur in the network which will disrupt the network and the virtual topology. In order to protect network from these kinds of changes in the conditions of network, VTR should be applied to the old virtual topology.

Although we need to make VTR in order to get optimum performance from the network, changes that will be done causes disruption to the network. The traffic and connections on the lightpaths will be rerouted when lightpaths are deleted or established. This rerouting is a cost of VTR process. This cost should be kept at a minimum level. So there is a tradeoff between the objective of VTR and the cost of VTR which is the disruption of the traffic and connections.

There are two approaches to the Virtual Topology Reconfiguration problem in the literature. These are: On-line and Off-line approaches [7]. On-line approaches make the virtual topology reconfiguration dynamically. Off-line approaches firstly find a new virtual topology according to the current and future conditions of the network. Then it defines a process for transition to the new virtual topology from the old virtual topology. Off-line approaches are very costly since it makes a lot of changes to the topology. Because of this higher cost, they are applied to the network in long periods. In this long period network continues with a static virtual topology which may not be good for the conditions of the network for that long period.

In a highly dynamic environment, where traffic conditions are unpredictable, and traffic fluctuates highly, on-line approaches should be applied to the network. On-line approaches make small changes to the topology in small intervals so that the network is not disrupted too much. Since it is applied in small intervals, topology continuously adapts itself to the new conditions and traffic.

### 2.3.1 Virtual Topology Reconfiguration Algorithms

Virtual topology reconfiguration has been studied by many researchers in the literature. VTR has been studied in two approaches: on-line and off-line. In the recent years most of the studies focused on on-line dynamic VTR.

In [8] authors have proposed a new VTR algorithm which takes into account the network disruption and number of reconfiguration steps. These parameters are important for network administrators. They can set the upper bound of network disruption and number of reconfiguration steps. In the previous studies these parameters were not seen as a constraint in the algorithms.

A two phase approach for VTR which sees VTR as an on-line process was proposed in [9]. When applying VTR to a network, network disruption should be kept at minimum since lightpaths carry data in the order of gigabits per second. They assume that traffic disrupted is proportional to the number of changes to the current topology. Their approach takes into account the optimality of the virtual topology, a balance between the number of changes and the objective function value of the virtual topology, and quick finding of lightpaths to be modified. In the first phase in order to quickly make some changes to the VT, a few numbers of lightpaths are determined to be added and deleted. The second phase is the fine tuning phase. After the first phase VT may not be optimal so a new VT is determined in the second phase which is near to optimal. Their objective in the second phase is maximizing single hop traffic.

In [10] authors have proposed a Balanced Alternate Routing Algorithm (BARA) which is based on a genetic algorithm. The objectives of the algorithm are maximizing the network throughput, minimizing the average propagation delay, and minimizing the network reconfiguration cost. This algorithm works in two phases. In the first phase, alternate routes for each source and destination node pair is calculated. In the second phase, optimal route for each lightpath between source and destination nodes are calculated. The optimal route decision is made according to the constrains and the objectives of the algorithm. Since constraints and objectives make the computation complexity very high, they use a genetic algorithm in order to decrease the complexity and increase the computational efficiency.

A new approach to VTR which is Virtual Topology Adaptation (VTA) was introduced in [11]. In this approach reconfiguration is seen as an on-line process and an adaptation process. By using the VTA heuristic algorithm, VT continuously adapts itself to the changing dynamic traffic conditions and network conditions. The advantage of this algorithm is it makes only 1 lightpath change at a time so that the disruption of the network is kept at minimum. The objective of the algorithm is to minimize the load of the maximally loaded lightpath.

The algorithm uses watermarks to decide to do the lightpath addition or deletion. Two watermarks $W_H$ and $W_L$ is used. When the load of the maximally loaded lightpath increases above $W_{H,}$ a new lightpath is established. When the load of the minimally loaded lightpath decreases below $W_L$, the least loaded lightpath is deleted. Lightpath addition and deletion is done periodically and only 1 ligthpath change is allowed at a time. The algorithm achieves keeping the loads on the lightpaths between the $W_H$ and $W_L$ values.

# 3. A NEW HEURISTIC FOR VIRTUAL TOPOLOGY RECONFIGURATION

In this chapter, a new heuristic algorithm for virtual topology reconfiguration is proposed. This algorithm is an effective, efficient, basic and a promising one. The algorithm is using the basic idea of removing inefficient lightpaths and instead of those deleted lightpaths, adding efficient lightpaths. By this way the algorithm is trying to achieve its optimization objective which is minimizing the load of the maximally loaded lightpath.

Firstly a linear formulation for the problem and the algorithm is given. This formulation gives all of the variables, constraints and formulas about the heuristic reconfiguration algorithm. Secondly, the heuristic reconfiguration algorithm is described by using pseudo code and flowcharts. Heuristic reconfiguration algorithms are important since the linear formulation can not be solved in a small time [12]. Moreover for real time reconfiguration, heuristic reconfiguration algorithms are the best choice to be used.

## 3.1 Virtual Topology Reconfiguration Linear Formulation

In this part linear formulation of the VTR problem is given. In the formulation the proposed heuristic algorithm is also introduced and formulized. The formulation is a linear optimization formulation.

In the formulation we consider an N node Optical WDM network which has limited wavelengths on each physical fiber link. Each node of the network has wavelength conversion capability. The physical topology can be any topology and the number of nodes N can be any amount.

The traffic of the backbone network is assumed as dynamically changing as a real backbone network. It fluctuates in the day and the future traffic matrix can not be guessed and known beforehand. As traffic fluctuates and changes dynamically, the designed virtual topology at the beginning will not be optimum virtual topology as time passes. Therefore a need of virtual topology reconfiguration arises.

The formulation of the VTR is an optimization problem. The formulation which is given in the following sections, gives the best selection of lightpaths to be added and deleted from the VT.

### 3.1.1 Parameters of the Linear Formulation

The notation of the optimization problem is:

- s and d denote source and destination of a packet.
- i and j denote originating and terminating nodes of a lightpath.

**Given:**

- Number of nodes in the network = N
- Capacity of each wavelength channel = C (bits/s)
- Number of transmitters and receivers at node i: $T_i$ and $R_i$ respectively
- Number of wavelengths on each fiber = W
- Physical network topology represented as a bidirectional graph P = $\{P_{mn}\}$ where $P_{mn}$ indicates the number of fibers between nodes m and n.
- Current virtual network topology represented as a directed graph V = $\{V_{ij,q}\}$. q takes a binary value denoting $q^{th}$ lightpath between nodes i and j.
- $\Lambda_{sd}$ is the traffic matrix which denotes the average rate of traffic flow ( in packets/second) from node s to node d.
- $\lambda_{ij}^{sd}$ is the traffic flowing from source s to destination d on the lightpath from node i to node j.

### 3.1.2 Variables of the Linear Formulation

- $L_{Max}$ is the load of the maximally loaded lightpath in the network.
- Physical routing binary variable $P_{mn}^{ij,q} = 1$ if the $q^{th}$ lightpath from node *i* to node *j* is routed through the physical fiber link (m,n).
- Variable $P_{mn}^{ij}$ denotes the number of lightpaths between nodes *i* and *j* being routed through physical fiber link (m,n).
- V′ is the new virtual topology. $V' = \{V'_{ij,q}\}$
- Sorted list of possible maximum loads $L_d = \{L_{i,j,q}\}$ where $L_{i,j,q}$ is the maximum load in the network when we delete lightpath q from node i to j.
- Sorted list of possible maximum loads $L_a = \{L_{i,j,q}\}$ where $L_{i,j,q}$ is the maximum load in the network when we add lightpath q from node *i* to *j*.

- NLC (number of lightpath changes) is the number of lightpaths that will be added or deleted in each period of the heuristic algorithm.

### 3.1.3 Linear Formulation

**Objective**

Minimize $L_{Max}$ (1)

In the algorithm we are trying to decrease the load of the maximally loaded lightpath. This objective provides load balancing and efficient use of resources, lightpaths, and wavelengths in the network. Moreover it makes the resources more available to the future requests by decreasing the maximum load on the network.

**Constraints**

In the linear formulation, various constraints which are explained in detail below can be used.

- On virtual topology connection matrix $V_{ij}$:

$$\sum_j \sum_q V'_{ij,q} \le T_i \quad \forall i \tag{2}$$

$$\sum_i \sum_q V'_{ij,q} \le R_j \quad \forall j \tag{3}$$

Above equations are based on conversation of resources. Equations (2) – (3) limit the total of lightpaths originating from and terminated at a node to the total number transmitters and receivers at that node.

- Multi-commodity flow equations:

$$\sum_m p^{ij}_{mk} = \sum_n p^{ij}_{kn} \tag{4}$$

$$\sum_n p^{ij}_{in} = V'_{ij} \tag{5}$$

$$\sum_m p^{ij}_{mj} = V'_{ij} \tag{6}$$

$$\sum_j \lambda^{sd}_{sj} = \lambda_{sd} \tag{7}$$

$$\sum_i \lambda^{sd}_{id} = \lambda_{sd} \tag{8}$$

$$\sum_i \lambda^{sd}_{ik} = \sum_j \lambda^{sd}_{kj} \quad \textit{if} \quad k \ne s, d \tag{9}$$

The multi-commodity flow equations are based on conversation of flows in each node and in virtual topology. Also they prevent the conflicts on wavelengths such as on the same fiber, a wavelength can not be used more than once. Equations (4) - (6) manages the routing of lightpaths from source to destination. Equations (7) - (9) manage the flow of traffic through the virtual topology and responsible for the packet traffic on the virtual topology. They take into account that total traffic flowing on a channel can not exceed the capacity of the channel.

- Other physical topology constraints:

$$\sum_{ij} p_{mn}^{ij} \le W \times P_{mn} \tag{10}$$

$$\forall m,n,i,j,q \quad p_{mn}^{ij,q} \le V'_{ij,q} \tag{11}$$

Number of wavelengths flowing through every physical link is limited to W. Equation (10) – (11) limits the number of lightpaths on a fiber to the number of wavelengths in a fiber.

- Lightpath deletion - addition constraints.

where $D_{ij,q} = \begin{cases} 1, L_{ij,q} \le L_{\max} \\ 0, else \end{cases}$ (12)

$$\sum_{i}\sum_{j}\sum_{q} D_{ij,q} \le NLC \tag{13}$$

$$\sum_{i}\sum_{j}\sum_{q} V'_{ij,q} = \sum_{i}\sum_{j}\sum_{q} V_{ij,q} - \sum_{i}\sum_{j}\sum_{q} D_{ij,q} \tag{14}$$

$$\sum_{i}\sum_{j}\sum_{q} A_{ij,q} \le NLC \tag{15}$$

$$\sum_{i}\sum_{j}\sum_{q} V'_{ij,q} = \sum_{i}\sum_{j}\sum_{q} V_{ij,q} + \sum_{i}\sum_{j}\sum_{q} A_{ij,q} \tag{16}$$

where $A_{ij,q} = 1$ if $L_{ij.k}$ is in the range of first NLC elements of $L_a$,

else $A_{ij,q} = 0$

Equations 12 - 16 manage the constraints of our rules of additions and deletions from the VT. A lightpath is deleted or added if it does not increase $L_{max}$. Predetermined numbers of lightpaths are deleted or added.

### 3.2 Heuristic Reconfiguration Algorithm

The pseudo code of the heuristic VT reconfiguration algorithm is given in Figure 3.1 and its corresponding flow chart is given in Figure 3.2 – 3.3. This VTR algorithm changes and reconfigures an initially designed virtual topology in two phases. In the first phase lightpaths are deleted and in the second phase new lightpaths are established. The changes are done by taking into consideration the load of the maximally loaded lightpath. In every step, the algorithm tries to keep the maximum load at the same level or decrease the maximum load. This algorithm is an improved and revised version of the algorithm in [13]. The former algorithm is a optical WDM network Protection algorithm, but the idea with some improvements and revisions can be applied to virtual topology reconfiguration problem.

The algorithm starts with an initial virtual topology. Initial VT might be designed with any VT design algorithm in the literature. Initial VT design does not affect the VTR algorithm. Then the traffic is routed using shortest path routing algorithm along the lightpaths of VT. Traffic is distributed on all shortest paths. All lightpath loads are calculated. From the lightpath loads, the maximum load of the lightpaths is found. After these initial configurations, Phase 1 and Phase 2 of the algorithm are applied to the optical WDM network periodically and in real time. In each period both of the phases of the algorithm are applied.

In the first phase our heuristic algorithm tears down lightpaths without increasing the load on the maximally loaded lightpath which is the bottleneck lightpath of the network where congestion occurs. Algorithm uses a lightpath list which is a sorted list of all lightpaths in the virtual topology in increasing order according to their load. The first lightpath with the minimum load in the list is removed and the algorithm tears down that lightpath.

Then the traffic is rerouted and the new maximum load of the lightpaths is calculated. If the load of maximally loaded lightpath increases, that lightpath is restored. Otherwise the lightpath stays as deleted. If the lightpath is removed a new lightpath list is prepared which has one less lightpath than the previous one. New lightpath is formed as follows. Traffic is rerouted along the remaining lightpaths and the loads of all lightpaths are calculated. From new lightpath loads, new lightpath list is formed. If the lightpath could not be removed, old lightpath list is used and next lightpath in the list is removed. This loop continues until a pre-determined number of lightpaths are deleted.

In the second phase, a new lightpath list, which contains all possible lightpaths that can be established and their corresponding maximum loads of the network, is prepared. The algorithm sets up one lightpath at a time in order to decrease the load of the maximally loaded lightpath and use the free resources which are gained in the phase 1. So the first item in the list which has the least maximum load if set up, is established. Then the traffic is rerouted and lightpath list is recalculated. This loop continues until a pre-determined number of lightpaths are added or there is no more lightpaths to be established.

The algorithm is deleting the lightpath which has smallest load and if its deletion does not increase the load of the maximally loaded lightpath. Then it sets up new lightpaths which will decrease the load of the maximally loaded lightpath. As it is intuitive to see that the algorithm is achieving the objective: decreasing the load of the maximally loaded lightpath ( $L_{\max}$ ). It is said intuitive since both of the deletions and additions are done after calculating $L_{\max}$ . If $L_{\max}$ decreases, reconfigurations are done. We tested our heuristic VTR algorithm in the simulations and the results are given in the next chapter.

```
Variables:

V, Virtual topology
δij, Load of lightpaths
NLC, maximum number of lightpath changes in each phase
ij, lightpath between node i and node j

Algorithm:

At the end of each observation period:
find max(δij), maximum link load

// Phase 1
lightpath_list=sort_lightpaths_by_load(V)
while (number_of_changes < NLC)  and (lightpath_list not empty) {
  if possible tear down and remove first lightpath of
  lightpath_list
  reroute traffic
  if (new max (δij)>max(δij) {
    restore lightpath
  }
  else {
    lightpath_list=sort_lightpaths_by_load(V)
  }
}
// Phase 2
for (all node pairs) {
  if (setup(ij, V)) {
    reroute traffic
    find max(δij), maximum link load
    add max(δij), i, j to new_lightpath_list
    tear down ij
  }
}
new_lightpath_list=sort_lightpaths_by_load(new_lightpath_list)
while (number_of_changes < NLC) and (new_lightpath_list not empty) {
  remove first lightpath of new_lightpath_list
  if (setup(ij, V) is success) {
    for (all node pairs) {
      if (setup(ij, V)) {
        reroute traffic
        find max(δij), maximum link load
        add max(δij), i, j to new_lightpath_list
        tear down ij
      }
    }
  }
  new_lightpath_list = sort_lightpaths_by_load(new_lightpath_list)
}
```

**Figure 3.1:** Pseudo-code of heuristic reconfiguration algorithm

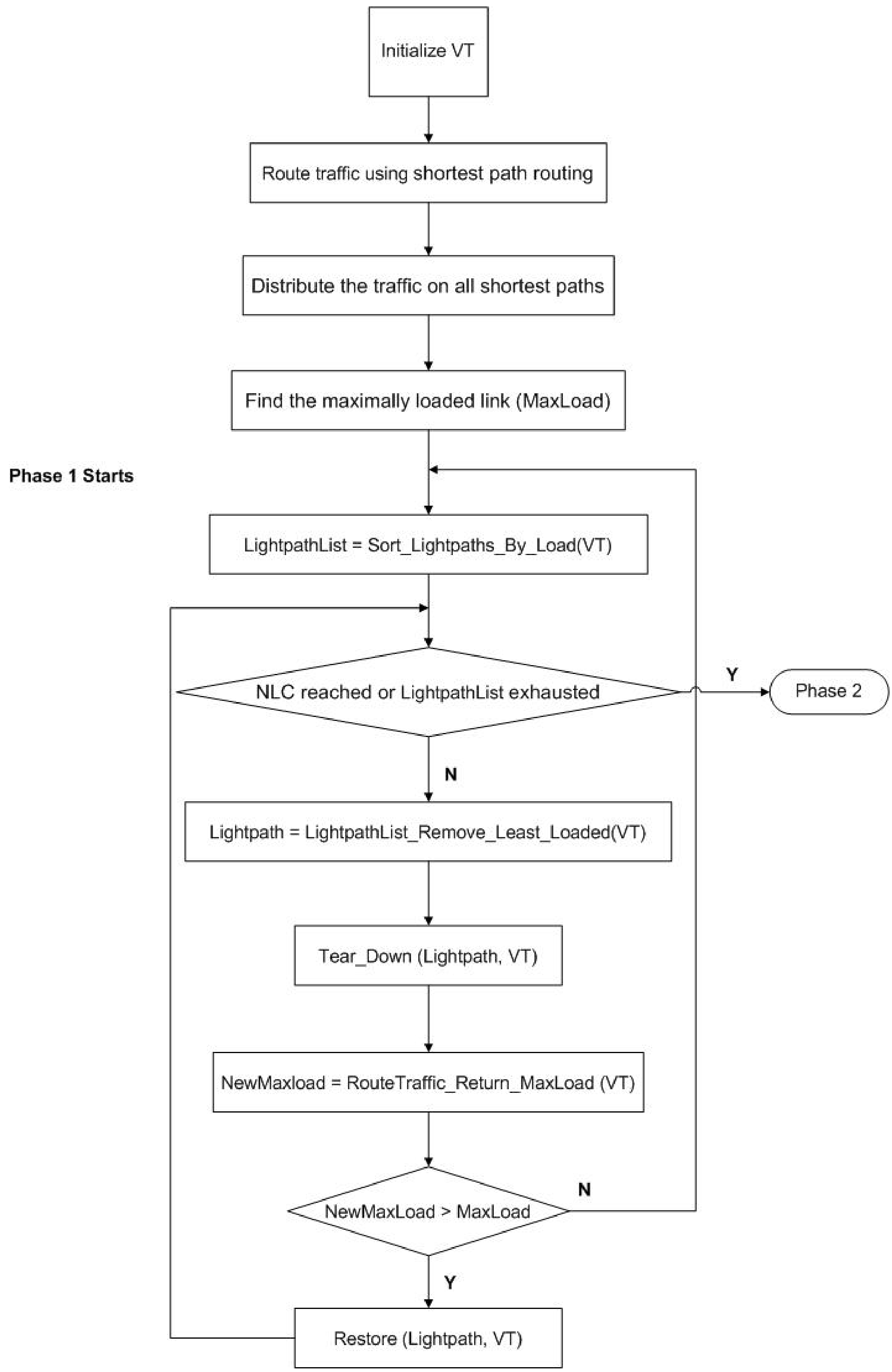


**Figure 3.2:** Flowchart of Initialization and Phase 1 of Heuristic VTR Algorihtm

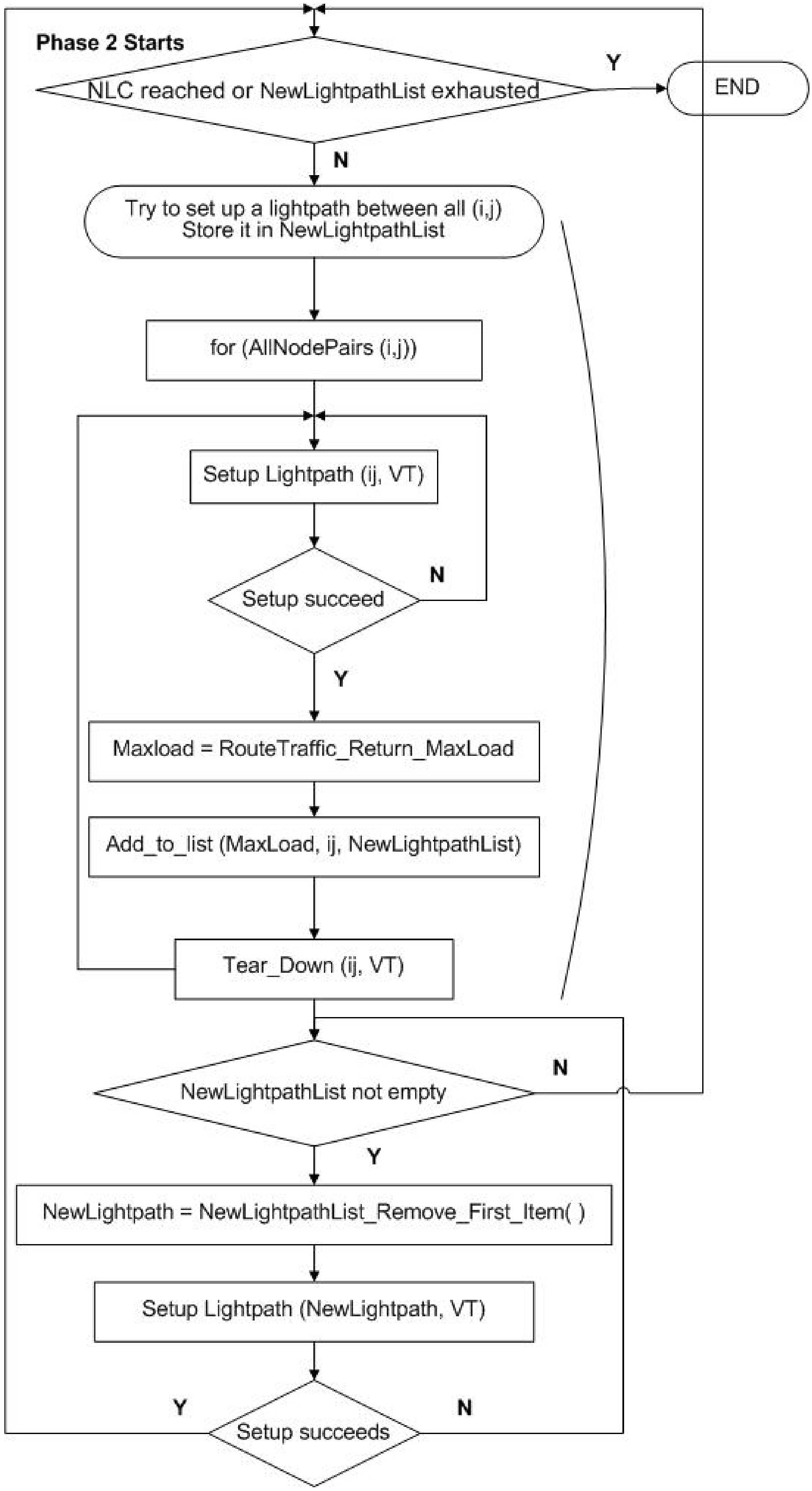


**Figure 3.3:** Flowchart of Phase 2 of Heuristic VTR Algorihtm

### 3.2.1 Disadvantages of the Heuristic VTR algorithm

In [17], the disadvantage of a VTR algorithm is seen as the lightpath disruption caused by the algorithm. Lightpath disruption is the additions and deletions of lightpaths. When a lightpath is added or deleted, the traffic is rerouted and this causes some packet losses, and delay of traffic. While designing a VTR algorithm one of the important points to be taken care of is to minimize the network disruption. The lightpath disruption between nodes i and j can be quantified as:

$$U(V_{ij}(t) - V_{ij}(t+\Delta t)) \text{ where } U(x) = |x| \quad (17)$$

Each deletion or addition between nodes i and j means a cost of the algorithm since it disrupts the traffic.

In our algorithm at each period predefined number of lightpaths is deleted and added. The number of deletions and additions are equal and is typically between 1 and 10. If more than 10 lightpaths are added and deleted, according to our cost formula (17), the disruption is very high. So it is better to keep this number small.

## 4. SIMULATIONS AND RESULTS

This chapter includes several simulation results of the proposed heuristic virtual topology reconfiguration algorithm. After introducing the simulation environment, simulation results are given.

Simulation experiments were done to investigate the success of the reconfiguration algorithm and to find the effect of various system parameters like period of the simulation and the number of lightpath changes at each period. In the experiments, we implemented the new heuristic algorithm in an event-driven simulation.

### 4.1 Simulation Environment

A telecommunication mesh network of 19 nodes interconnected by 31 bidirectional links was used as the physical topology for the numerical examples shown in this section (Fig. 4.1). A typical backbone network like NSFNET (National Science Foundation Network) have 14 nodes and 21 links and ARPA2 physical network have 21 nodes and 26 links [20]. That’s why we have chosen a network which has similar number of nodes and links with typical backbone networks in the world. For the examples, we assume that the number of wavelengths is 16 per fiber link and equal for all links. Each node is assumed to have 8 transmitters and 8 receivers.

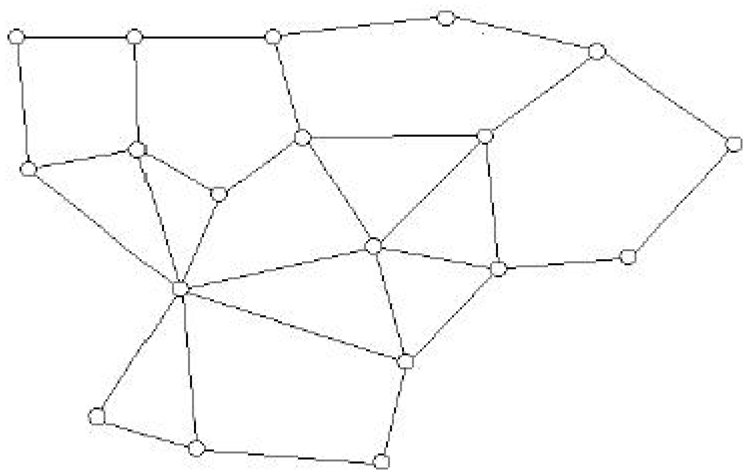

**Fig 4.1** The physical topology of a backbone network used in the simulations

Since this study is focused on backbone networks, a traffic model is derived based on the observations on several backbones' link loads. Backbone traffic is the aggregation of several end systems' traffic, and the aggregation process filters out the short-term variations. Long-term variations (on a scale of hours) remain and repeat their pattern in one-day periods. To obtain a realistic model, we sampled some representative link traffic rates real networks over a 24-hour period. The sampling allows us to represent the traffic rate as a function of time. The average traffic rate at a point in time between two sampling points of the rate function was calculated by a linear interpolation to represent the continuous change in traffic. These traffic-rate functions are used to generate the simulated traffic between any node pair in the network.

In this study, the following performance metrics are calculated: The traffic-weighted average hop distance, the maximum and minimum loads of the lightpaths

### 4.2 Simulation Results

In order to evaluate the performance of the algorithm many simulation studies have been done. In the first group of simulations VTR was simulated with different periods. The periods were 5 – 10 - 20 min. In each period the algorithm was applied to the virtual topology so that it is reconfigured according to our VTR algorithm. Also at each period maximum, minimum loads and traffic weighted average hop distance values were recorded in order to see the performance of the algorithm. Second one is the simulation of the VTA algorithm and its comparison to the VTR algorithm. Third one is the simulation in which virtual topology reconfiguration is not applied. Finally, the effect of number of lightpath changes in the VTR algorithm was simulated. The simulations have been conducted in a 24 hour period.

An example for the simulation result of the algorithm is shown in Fig 4.2 and 4.3. This simulation was done with 10 min period for 24 hours. The lightpath loads are normalized to 100 which mean that the data shows the percentage load of the lightpaths.

From Fig 4.2 we can obtain that maximum lightpath load stays approximately at 70 and does not go over that. Minimum lightpath load stays between 10 and 20. At fig 4.3, traffic weighted average hop distance (AHD) values are plotted. This value is also an important result of virtual topology reconfiguration algorithms. Although it is not our explicit aim and optimization objective, for an VTR algorithm it is important to keep that value low. As can be seen from the graph, the AHD value gets lower as time passes and VTR is applied to the VT. At the beginning it increases up to 2.1 and then it stays approximately at 1.6.

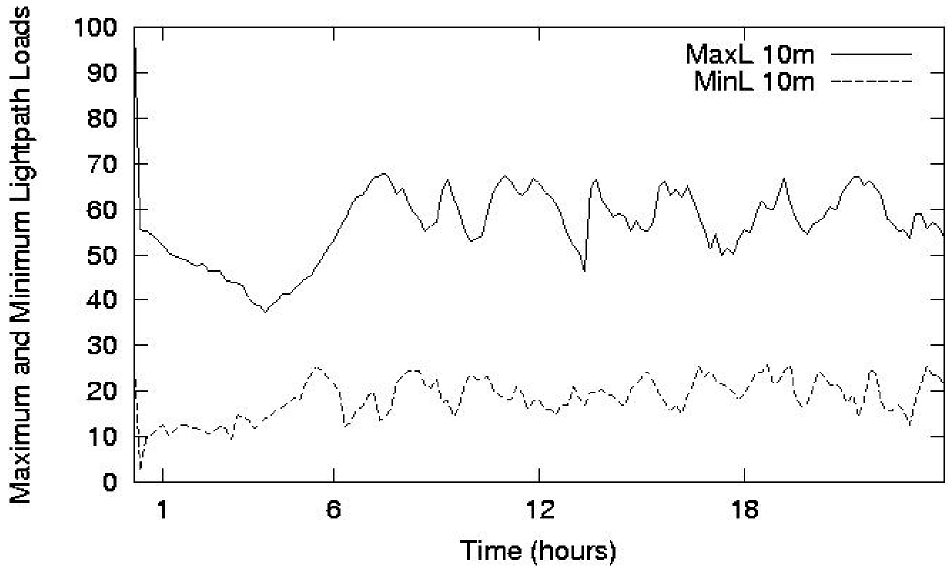


**Fig 4.2** Maximum and minimum lightpath loads. VTR Period = 10 min.

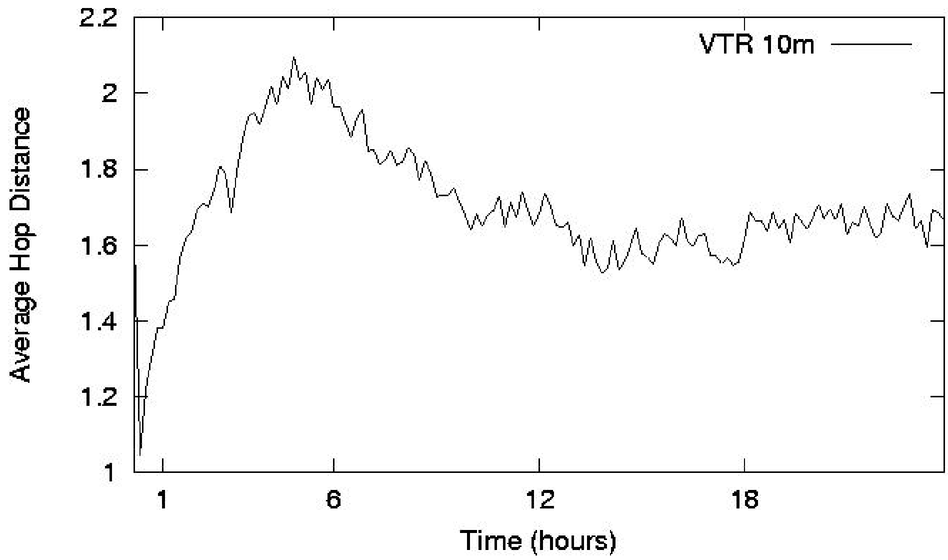


**Fig 4.3** Traffic weighted average hop distance.

### 4.2.1 Effect of Reconfiguration Period

In this part of the simulation the effect of the reconfiguration period is observed. Three periods are tested. Durations of these periods are: 5 – 10 – 20 minutes.

In Fig 4.4 we see the maximum and minimum lightpath loads under different reconfiguration periods. From the graph it is seen that the lowest maximum load is achieved at 10 minute period. Also the highest minimum load is achieved at that period. 20 minute and 5 minute periods are close to each other. 20 minute period performs a little bit better than the 5 minute period.

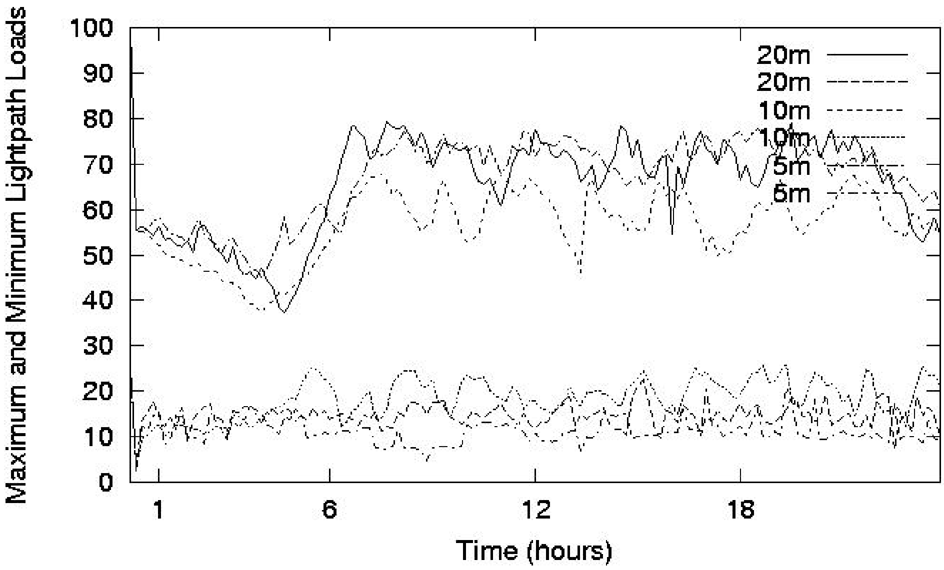


**Fig 4.4** Maximum and minimum lightpath loads for different reconfiguration periods: 5 – 10 – 20 min.

**Table 4.1:** Comparison of lightpath loads for different periods.

| Algorithm | Max Load | Min Load | Average Max Load | Average Min Load |
|---|---|---|---|---|
| VTR (5 m) | 78.1 | 20.8 | 66.6 | 11.2 |
| VTR (10 m) | 68 | 25.8 | 56.1 | 18.3 |
| VTR (20 m) | 79.3 | 22.4 | 65.1 | 14.4 |

In both 20 and 5 minute period, maximum load is approximately 75 – 80 while it is 70 in 10 minute period.

In Fig 4.5 AHD values are plotted for different reconfiguration periods. AHD value increases to 2.2 for 20 minute period and 2.4 for 5 minute period and 2 for 10 minute period. Then it stays at 1.7 for 5 min, 1.95 for 20 min and 2.05 for 5 min.

From maximum load values and AHD values of different periods it is seen that 10 minutes period performs better than the other 2 periods. The 5 minute period performs worse so this shows frequent reconfiguration of the VTR algorithm is not efficient and does not give desired results. Also frequent VTR means more disruption to the network so it should be avoided. The 20 minute period performs worse than 10 minute period. If the VTR algorithm is not applied for a long time to the virtual topology it becomes worse as seen from the simulation results. An optimum value which is not very low or high should be chosen as a reconfiguration period.

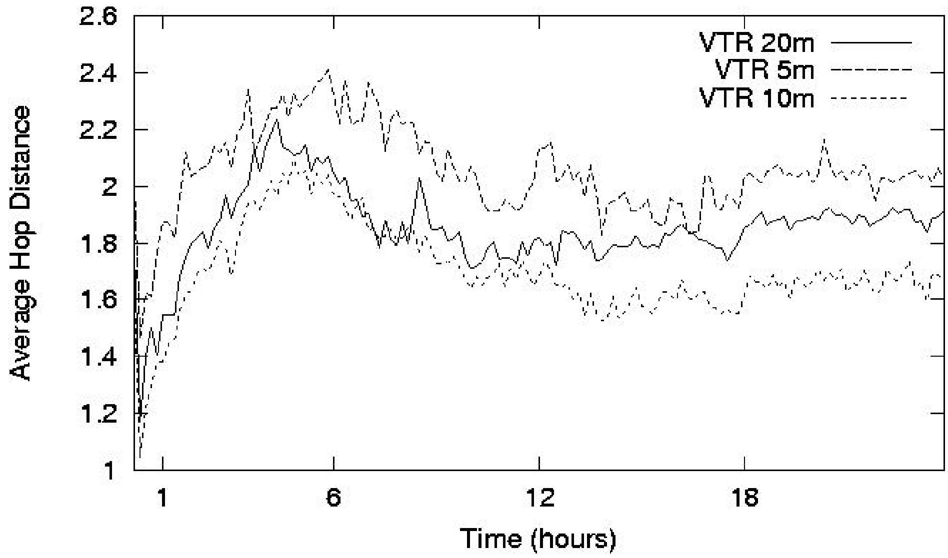


**Fig 4.5** Average weighted traffic hop distance for different reconfiguration periods: 5 – 10 – 20 min.

### 4.2.2 Effect of Number of Lightpath Changes in a Reconfiguration Period

In this part of the simulation the effect of the allowed number of lightpath changes per configuration period was observed. The simulation was performed for four different values, which are 1, 3, 5 and 7. These values represent allowed numbers of lightpath additions and deletions in a period.

In Fig 4.6 we see the maximum and minimum lightpath loads under different number of lightpath changes (NLC). From the graph it is seen that the lowest maximum load is achieved at 5LC. Also the highest minimum load is achieved at 5LC. Highest maximum load is at 7LC and lowest minimum loads are at 7LC and 1LC.

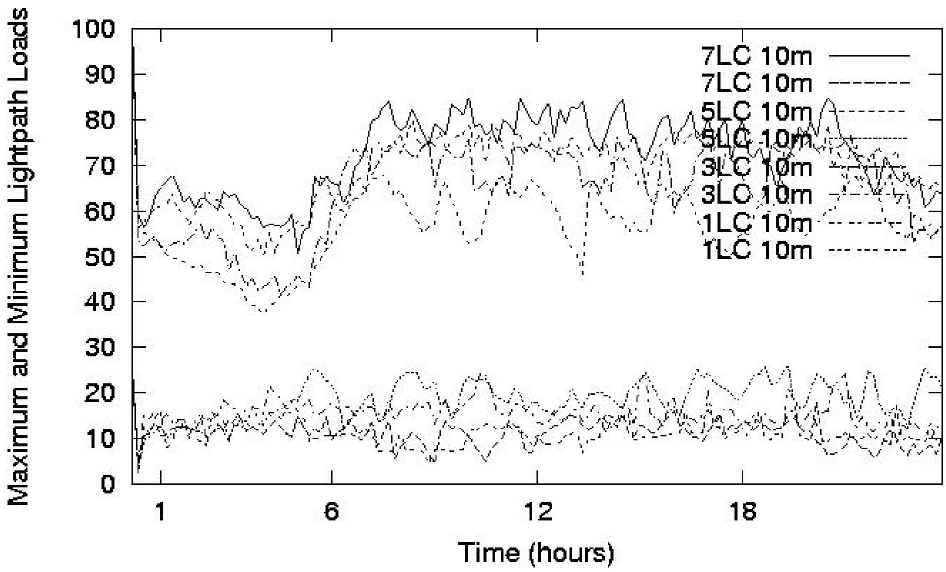


**Fig 4.6** Maximum and minimum lightpath loads for different number of lightpath changes.

In Fig 4.7 AHD values are plotted for different NLC. Lowest AHD values are at 5LC which stabilizes at ~1.7 during the simulation. AHD value for 3LC and 7LC are close to each other and stabilizes at ~1.9 during the simulation. AHD value for 1LC is highest and stabilizes at ~2.1.

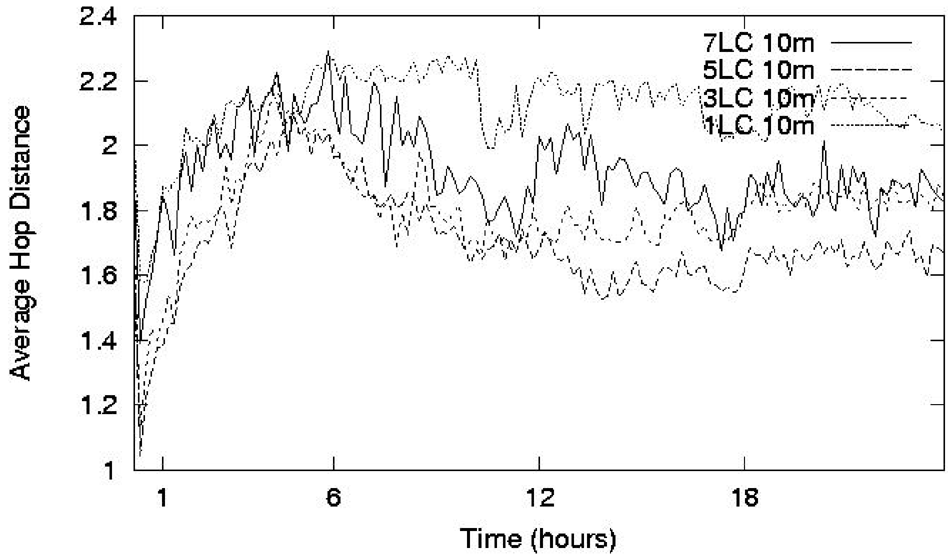


**Fig 4.7** Average weighted traffic hop distance for different number of lightpath changes.

In table 4.2 there is a summary of maximum and minimum loads of different NLC. Minimum average maximum load and maximum average minimum load are achieved at 5LC. Worst values are observed for 1LC and 7LC.

**Table 4.2:** Comparison of lightpath loads for different number of lightpath changes.

| Algorithm | Max Load | Min Load | Average Max Load | Average Min Load |
|---|---|---|---|---|
| VTR (1LC) | 80.3 | 20.8 | 68.8 | 11.2 |
| VTR (3LC) | 77.5 | 25.4 | 64.3 | 16.3 |
| VTR (5LC) | 68 | 25.8 | 56.1 | 18.3 |
| VTR (7LC) | 85 | 16 | 71.7 | 11.1 |

As can be seen from the graphs and table it is better not to do a lot NLC at a time since the values of objective parameters becomes worse. Also it is better to not keep that NLC small. Since high NLC disrupts the traffic and network it should be avoided.

### 4.2.3 Comparisons with a VTR Algorithm and No VTR Case

In this part two comparisons are done to show the performance of VTR algorithm. First comparison is done with another VTR algorithm. Second one is done with No-VTR case at which no VTR algorithm is applied to the VT during the simulation.

In [14] a virtual topology reconfiguration algorithm is proposed which is online and makes small changes to the virtual topology at each period. It makes 1 lightpath change at a time. The algorithm is called virtual topology adaptation algorithm (VTA) since it adapts the virtual topology slowly to changing traffic conditions. The algorithm works as follows. There is a threshold value which is called a watermark. If maximum load goes over high watermark, then a new lightpath is established in order to decrease maximum load. If minimum load goes below low watermark, then the lightpath with lowest load is deleted. Our VTR algorithm is also online and makes small changes to the topology at each period. That's why we compare our VTR algorithm to the VTA algorithm.

Second comparison is done with No-VTR case. A simulation is done without applying a VTR algorithm to the VT. This comparison is made to show the use and need of VTR algorithm.

Two simulations are shown in the Figure 4.8. In simulation with VTA maximum load is higher than the simulation with VTR. Minimum load is lower at VTA.

In Figure 4.18 traffic weighted average hop distance of the network in the two simulations are plotted. The average weighted hop distance of VTA algorithm is 1.9 while it is 1.65 for VTR algorithm. This shows a better performance of VTR algorithm.

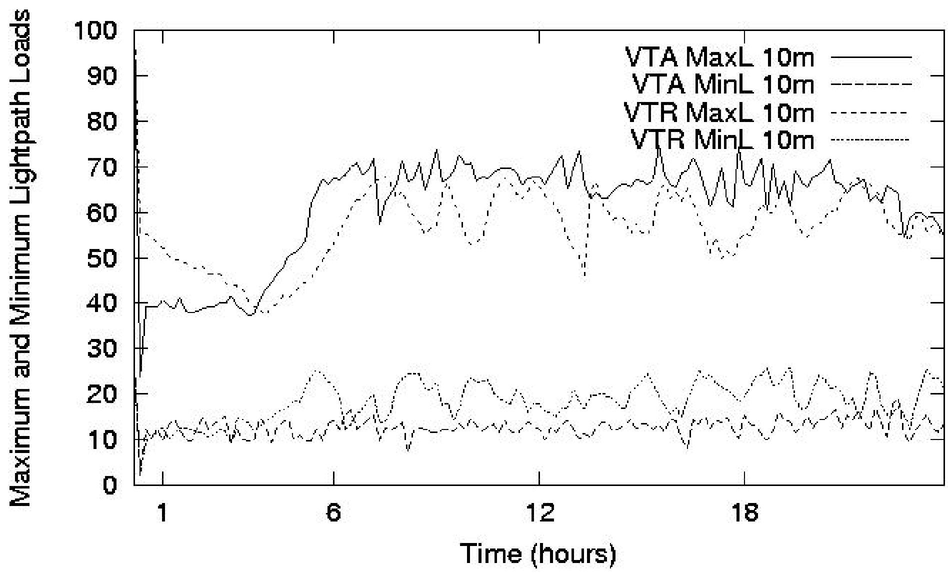


**Fig 4.8** Comparison of maximum and minimum loads of VTR and VTA. algorithms. VTR Period = 10 min.

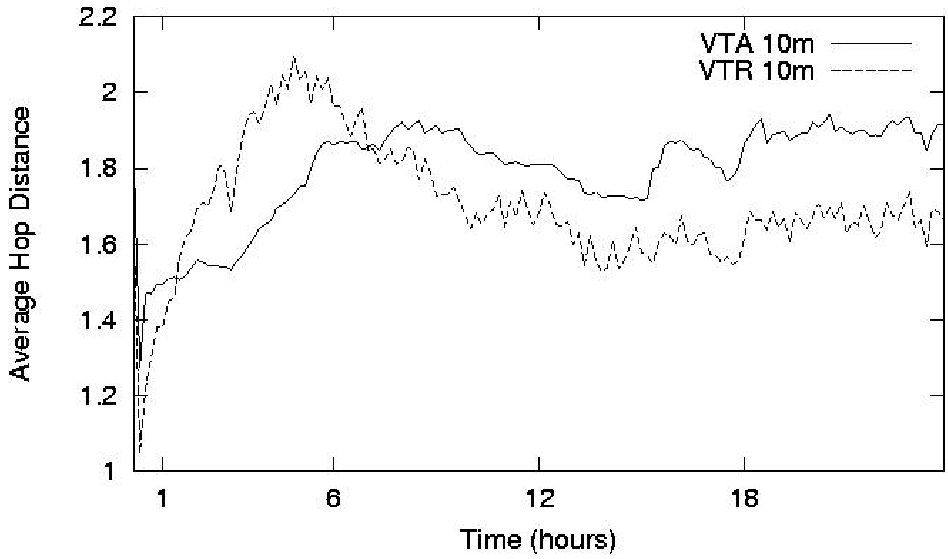


**Fig 4.9** Comparison of traffic weighted average hop distance of VTR and VTA algorithms. VTR Period = 10 min.

Two simulations are shown in the Figure 4.10 In simulation without VTR maximum load increases up to 80-90 while it increases up to 70 in VTR. As seen from the results and figure, maximum load is lower as a result of the virtual topology reconfiguration algorithm. Also minimum load is higher in VTR simulation which means more effective use of lightpaths.

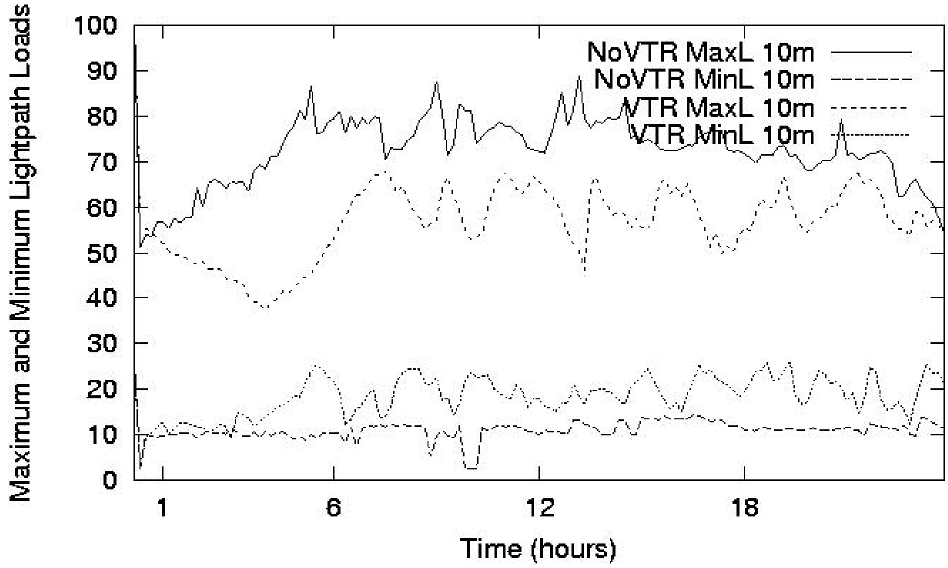


**Fig 4.10** Comparison of maximum and minimum loads of VTR algorithm and No-VTR (No VTR is applied to the network).

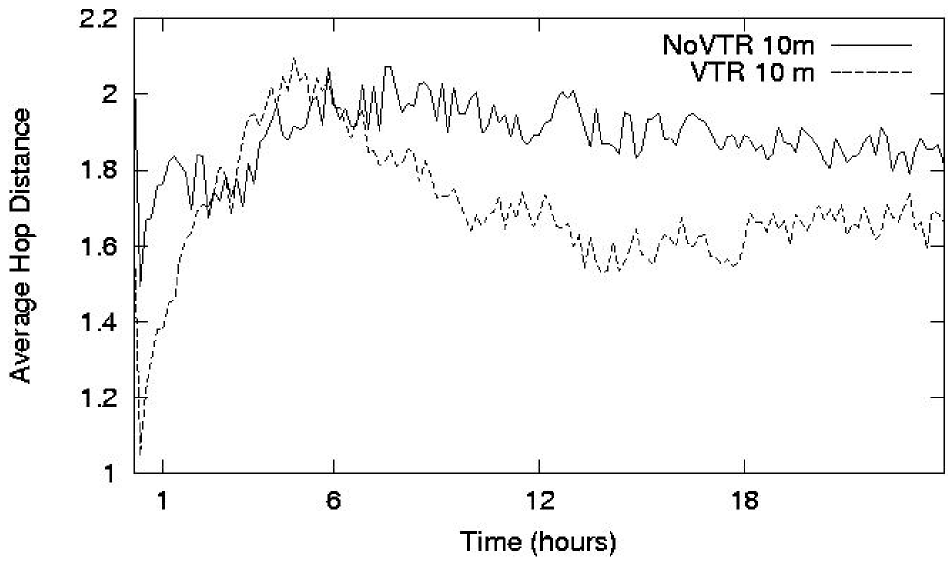


**Fig 4.11** Comparison of traffic weighted average hop distance of VTR and No-VTR case. VTR Period = 10 min.

In Fig. 4.11 traffic weighted average hop distance values of VTR and No-VTR case is plotted. AHD is ~1.65 for VTR while it is ~2 for No-VTR case.

**Table 4.3:** Comparison of lightpath loads for different algorithms and simulations.

| Algorithm | Max Load | Min Load | Average Max Load | Average Min Load |
|---|---|---|---|---|
| VTR (10 m) | 68 | 25.8 | 56.1 | 18.3 |
| VTA (10 m) | 75 | 19.1 | 60.7 | 12.5 |
| No-VTR (10 m) | 89.1 | 14.3 | 72 | 10.8 |

As can be seen from Table 4.3 VTR algorithm performs comparable with the VTA algorithm and slightly better than that. Also it performs better than No - VTR case.

## 5. CONCLUSION

Optical Networks are the future's networks which will provide high bandwidths and speeds (Terabit per second) to the world. Internet will be faster and users will access Internet easily than never been before. Many researches on Optical networks have been done in order to design new protocols, algorithms and solutions. New methods are needed in order to get the maximum benefit from this revolutionary network. One of the main and significant research areas in Optical Networks is Virtual Topology Design and Reconfiguration.

In this thesis, a heuristic Virtual Topology Reconfiguration algorithm is purposed. Reconfiguration algorithms are important in order to keep the network optimized. In optical networks in the beginning a Virtual Topology is designed. As time passes, traffic and many other conditions changes, so Virtual Topology becomes inefficient. So this Virtual Topology should be changed, reconfigured in order to fit the current conditions and become optimal.

Purposed reconfiguration algorithm is a two phase algorithm. We consider this two phase approach as a basic and promising approach to the Virtual Topology Reconfiguration problem. The aim of a Virtual Topology Reconfiguration is to use the lightpaths at optimum load. Our heuristic algorithm deletes unnecessary loaded lightpaths and adds lightpaths to decrease the load in the other lightpaths. By this way traffic weighted average hop distance of the network and the load of maximally loaded lightpath can be decreased; load balancing can be achieved.

Our algorithm has many advantages. It does not need to know the future traffic pattern. Its complexity is low so that it can be run online. Moreover the network administrator can decide how much the network will be interrupted by adjusting the pre-determined value of the loop counter which determines the number of deletions and additions of lightpaths.

## 5.1 Simulations

In the simulations performance of the algorithm was tested. Effect of reconfiguration period, effect of number of lightpath change was investigated. Comparison to another VTR algorithm and No – VTR case is done.

Optimization objective of the algorithm is to minimize the load of the maximally loaded lightpath. So, one of the performance parameter is the load of the maximally loaded lightpath. Another common performance parameter in Virtual Topology Reconfiguration algorithms, the traffic weighted average hop distance was also observed. Results are as follows:

- As seen from the simulation results, load of the maximally loaded lightpath and traffic weighted average hop distance decrease as a result of VTR.
- Effect of the reconfiguration period is an important parameter in the algorithm. If it is kept low, there will be many deletions and additions which affect negatively the network and decrease in the load is low in this case. If it is high, reconfiguration becomes ineffective and again decrease in the maximum load is low.
- If the number of lightpath change is low, the effect of reconfiguration algorithm becomes low. If the number of lightpath change is high, there will be many additions and deletions which will interrupt the network and decrease in the maximum load is low.
- When our VTR algorithm is compared to another VTR algorithm which is in the same category as ours, we see that our algorithm performs better. The decrease in the maximum load is higher and we get low traffic weighted AHD values.
- When our VTR algorithm is compared to No-VTR case, it is seen that maximum load and traffic weighted AHD decreases significantly.

## 5.2 Future Work

In our VTR algorithm at each period pre-determined number of additions and deletions are done without looking into any condition. In the VTA algorithm which we used to compare our algorithm, there is a threshold value which is called watermark.

This watermark can also be used in our algorithm to trigger the additions and deletions. If maximum load goes above $W_H$, additions can be done. If minimum load goes below $W_L$, deletions can be done. If the algorithm works like that, interruption of the network will decrease.

## REFERENCES


[1] **Mukherjee B., Banerjee D., Ramamurthy S. and Mukherjee A.,** "Some principles for designing a wide-area WDM optical network", IEEE/ACM Transactions on Networking, pp 684-696, 1996.

[2] **Dutta R., Rouskas G. N.**, "A survey of virtual topology design algorithms for wavelength routed optical networks", Optical Networks Magazine, pp 73-89, 2000.

[3] 2003, http://www.nist.gov/dads/HTML/nphard.html.

[4] **C.S.R. Murthy and M. Gurusamy**, "WDM Optical Networks", Prentice Hall, 2002.

[5] Corvis, March 2004, http://www.corvis.com/Corvis/media/rl/ON_LR.pdf

[6] **R. Ramaswani, K. Sirajavan,** "Design of logical topologies for Wavelength-Routed Optical Networks", IEEE Journal on Selected Areas in Communications, pp.840-851, June 1996.

[7] **J.Y. Youe, S.W. Seo,** "An algorithm for virtual topology design in WDM optical networks under physical constraints", IEEE International Conference on Communications, pp. 1719 – 1723, June 1999.

[8] **R.T.R. Almeida, K. Potratz, L.C. Bueno, M.E.V. Segatto, E. Oliveira, L.C. Calmon,** "Addressing the electronic bottleneck to virtual topology design of optical networks", Proceedings of the 2003 SBMO/IEEE MTT-S International, Sept. 2003.

[9] **Manohar P., Manjunath D., Shevgaonkar R. K.,** "Effect of Objective Function on Virtual Topology Design in Optical Networks", Proceedings of the National Conference on Communications at Indian Institute of Technology, Jan 2002.

[10] **Sreenath N., Murthy C.S.R.,** "On-line reconfiguration of virtual topologies in wavelength-routed WDM networks", Journal of High Speed Networks, pp 141-169, January 2002.

[11] **Ramamurthy B., Ramakrishnan A.,** "Virtual topology reconfiguration of wavelength-routed optical WDM networks", IEEE Global Telecommunications Conference, pp 1269 - 1275, Dec. 2000.

[12] **Sreenath N., Panesar G.R., Murthy C. S. R.,** "A two-phase approach for virtual topology reconfiguration of wavelength-routed WDM optical networks",

Proceedings of Ninth IEEE International Conference on Networks, pp 371 – 376, October 2001.

[13] **Zhou B., Zheng J., Mouftah, H.T.,** “Dynamic reconfiguration based on balanced alternate routing algorithm (BARA) for all-optical wavelength-routed WDM networks”, IEEE Global Telecommunications Conference, pp 2706 - 2710, Nov. 2002.

[14] **Gençata A., Mukherjee B.,** “Virtual Topology Adaptation for WDM Mesh Networks Under Dynamic Traffic", Proceedings of IEEE INFOCOM, Jun. 2002.

[15] **Banarjee D., Mukherjee B.,** “Wavelength-Routed Optical Networks: Linear Formulation, Resource Budgeting Tradeoffs, and a Reconfiguration Study”, IEEE/ACM Transactions on Networking, vol. 8, no. 5, pp. 598-607, Oct. 2000.

[16] **Sahasrabuddhe L., Ramamurthy S., Mukherjee B.,** “Fault Management in IP-Over-WDM Networks: WDM Protection Versus IP Restoration”, IEEE Journal on Selected Areas in Communications, vol 20, no. 1, pp. 21-33, Jan. 2002.

[17] **Ramamurty B., Yang X.,** “An Analytical Model for Virtual Topology Reconfiguration in Optical Networks and A Case Study”, Proceedings of IEEE ICCCN 2002, Oct. 2002.

[18] **Mouftah H. T., Ho P.,** “Optical networks : architecture and survivability”, Boston : Kluwer Academic, 2003

[19] **Ramaswami R., Sivarajan K. N.,** “Optical networks: a practical perspective”, San Francisco: Morgan Kaufmann Publishers, 2002.

[20] **Crochat O., Boudec J.Y.L,** “Design Protection for WDM Optical Networks”, IEEE Journal on Selected Areas in Communications, pp. 1158 - 1165, Sep. 1998.

## APPENDIX A: SIMULATION RESULTS

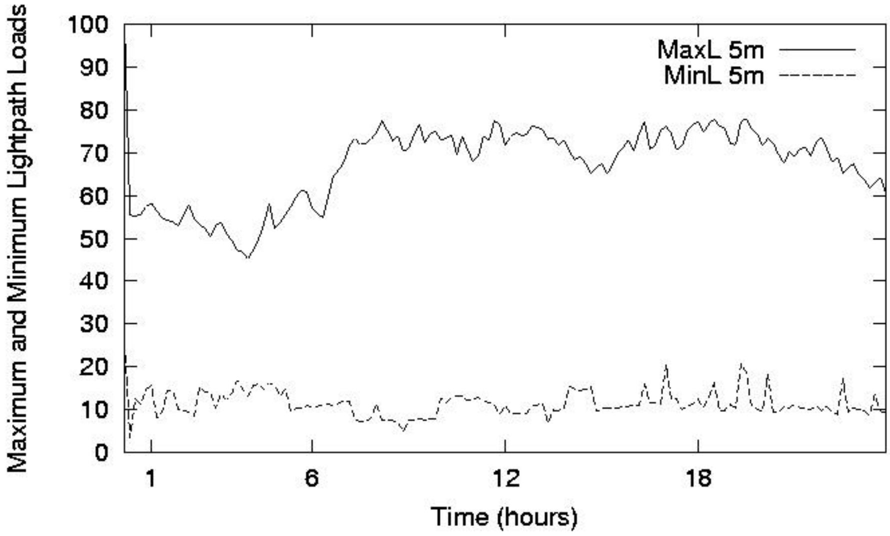


**Fig A.1** Maximum and minimum lightpath loads. VTR Period = 10 min.

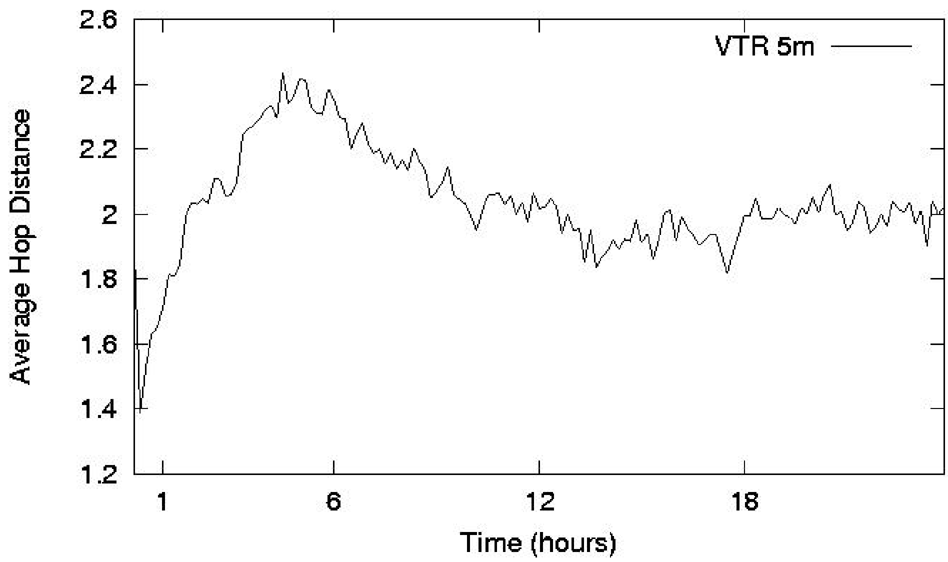


**Fig A.2** Traffic weighted average hop distance.

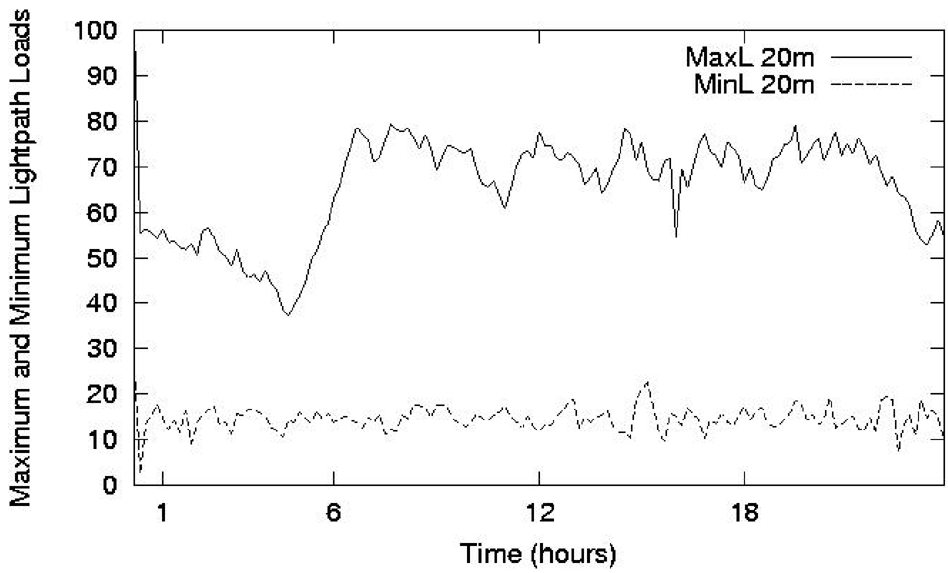


**Fig A.3** Maximum and minimum lightpath loads. VTR Period = 20 min.

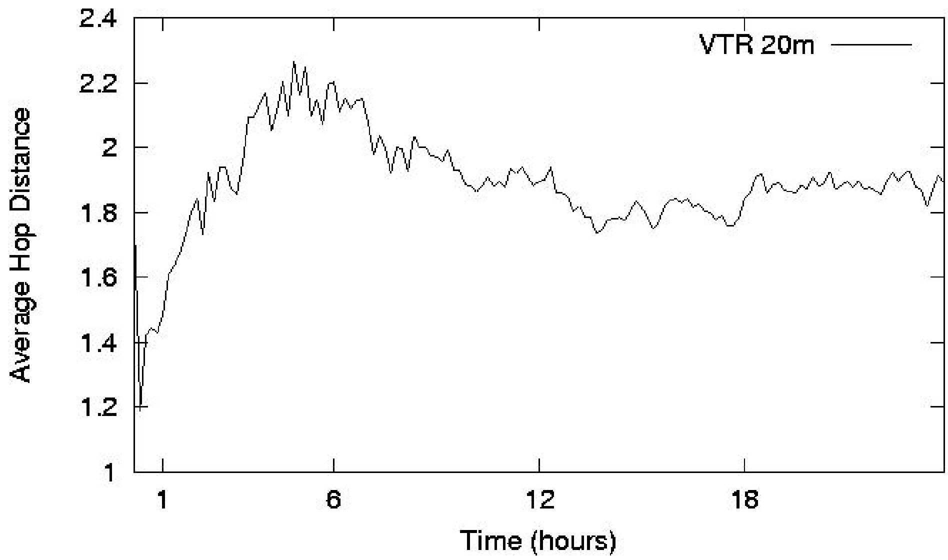


**Fig A.4** Traffic weighted average hop distance.

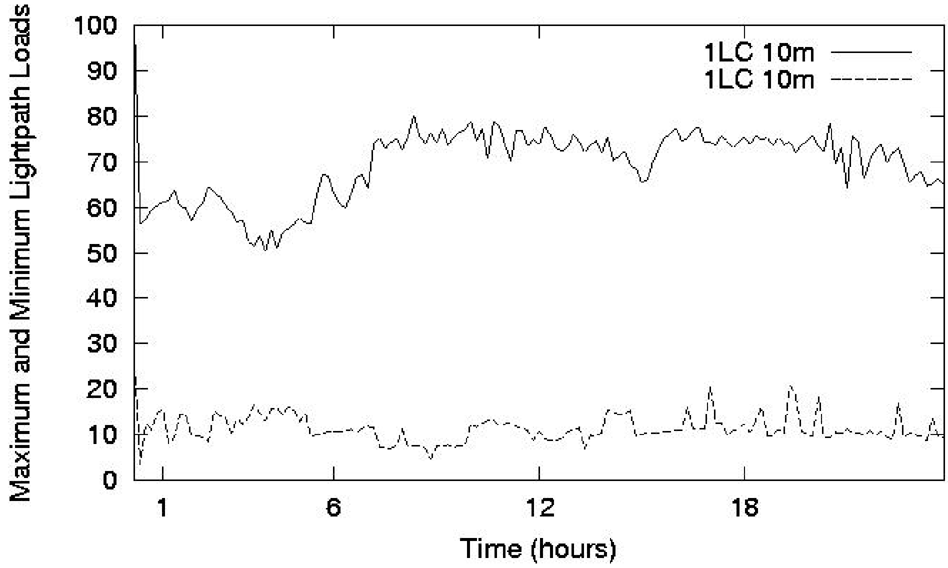


**Fig A.4** Maximum and minimum lightpath loads.
VTR Period = 10 min. NLC = 1.

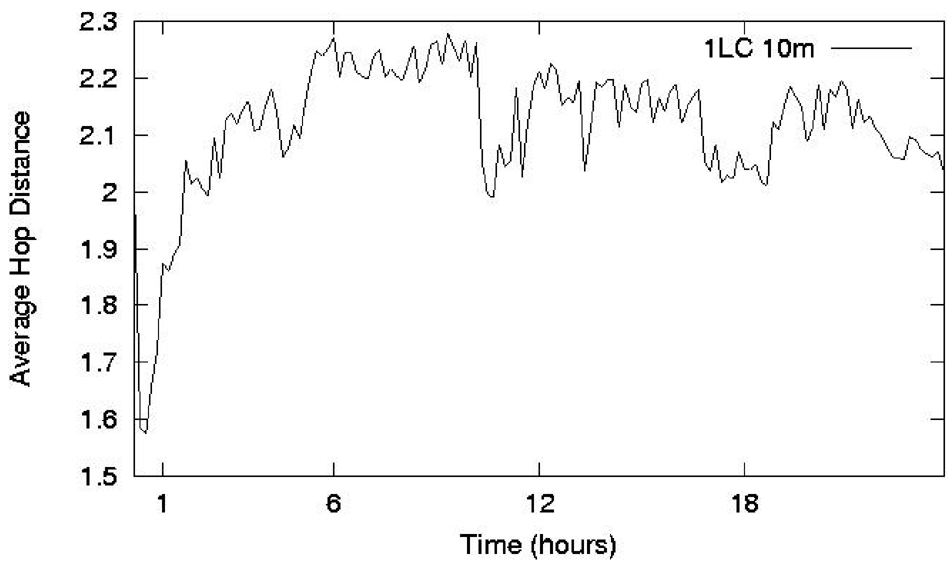


**Fig A.5** Traffic weighted average hop distance.

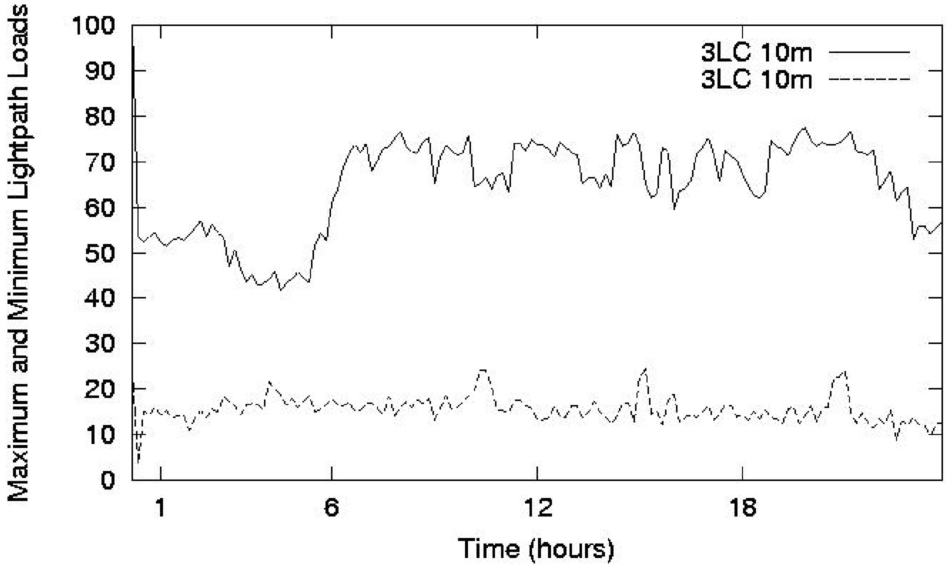


**Fig A.6** Maximum and minimum lightpath loads.
VTR Period = 10 min. NLC = 3.

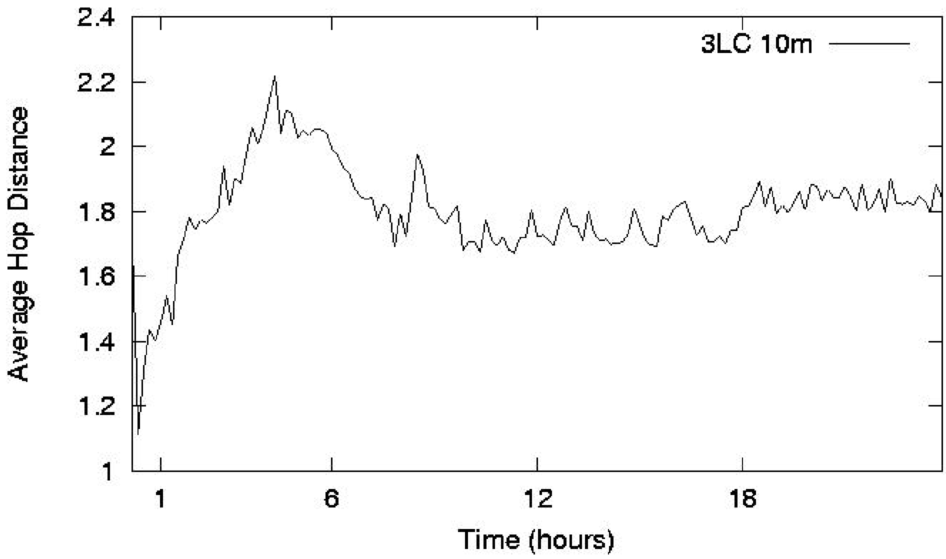


**Fig A.7** Traffic weighted average hop distance.

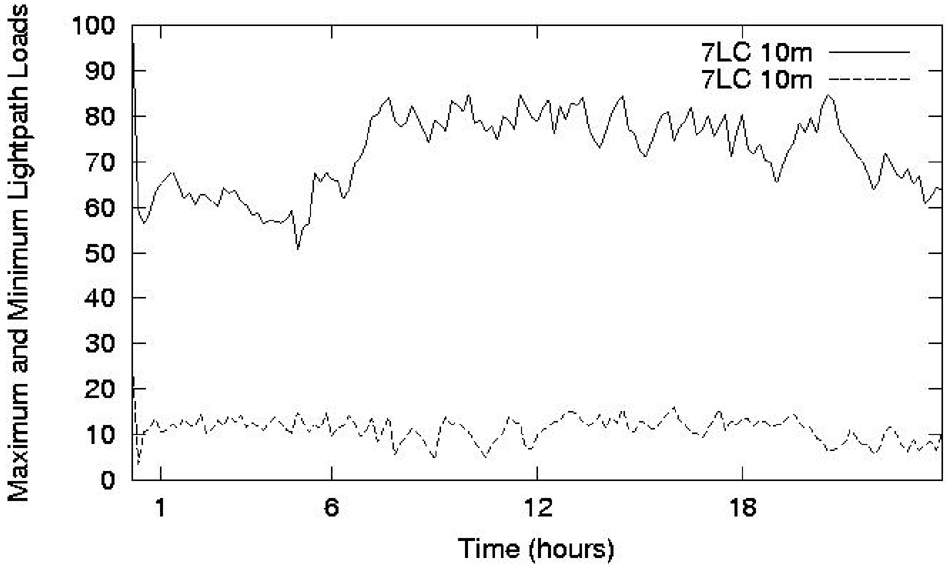


**Fig A.8** Maximum and minimum lightpath loads.
VTR Period = 10 min. NLC = 7.

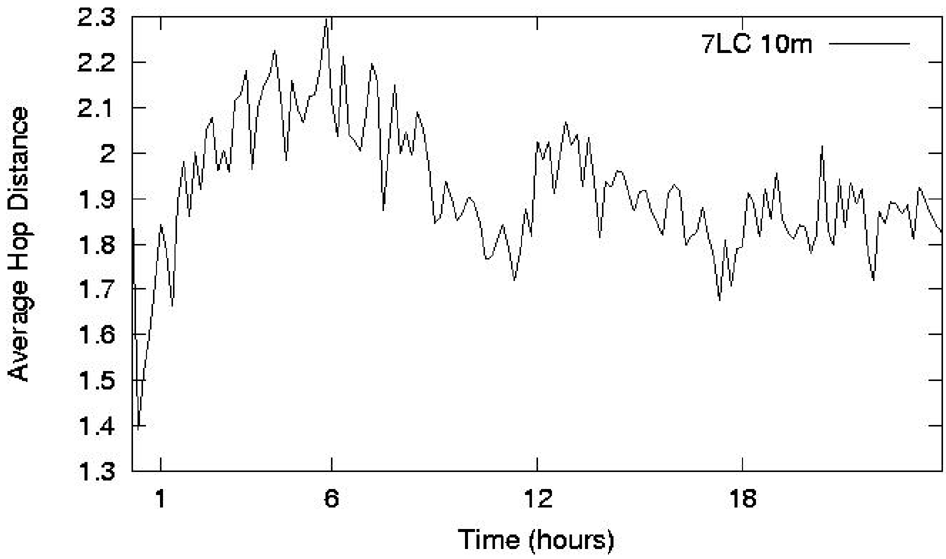


**Fig A.9** Traffic weighted average hop distance.

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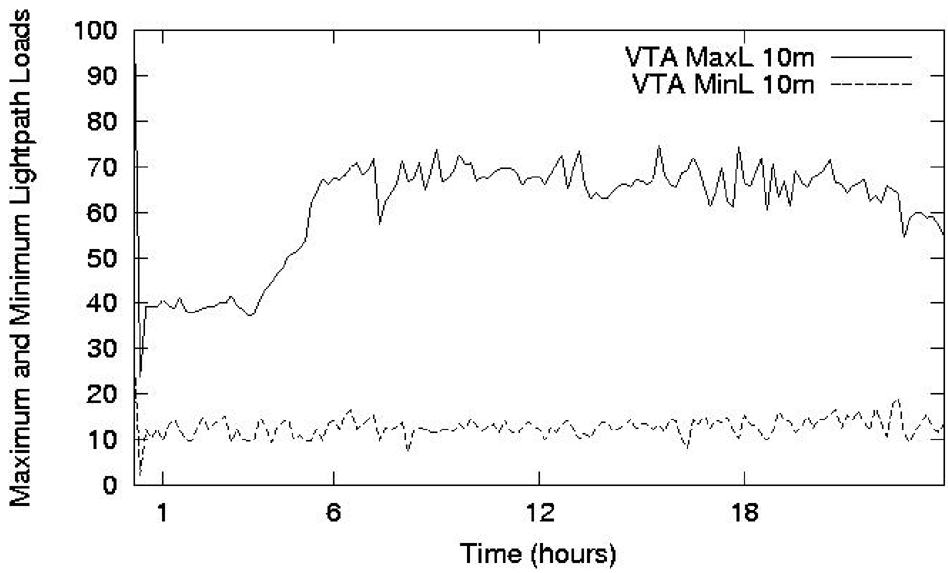


**Fig A.10** Maximum and minimum lightpath loads.
VTA Period = 10 min.

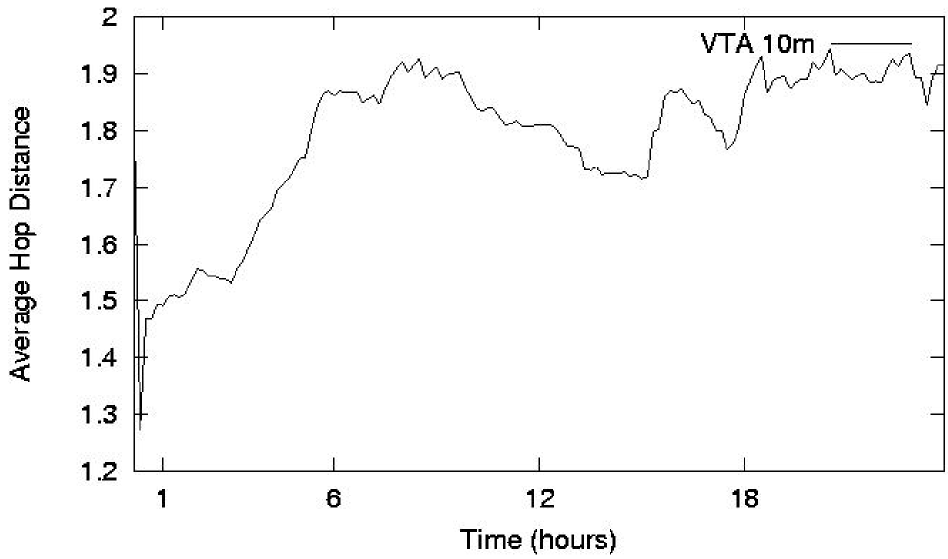


**Fig A.11** Traffic weighted average hop distance for VTA.
Period = 10 min.

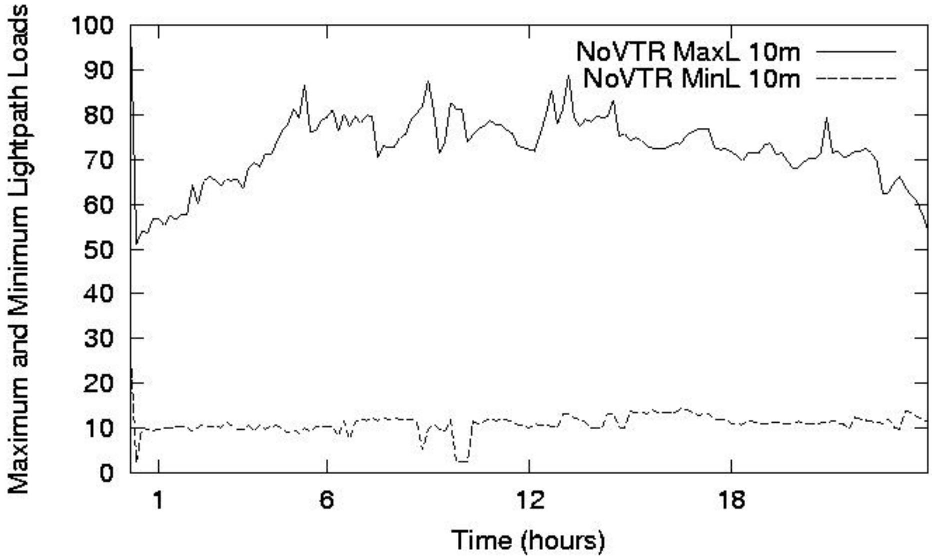


**Fig A.12** Maximum and minimum lightpath loads for No-VTR Case. Period = 10 min.

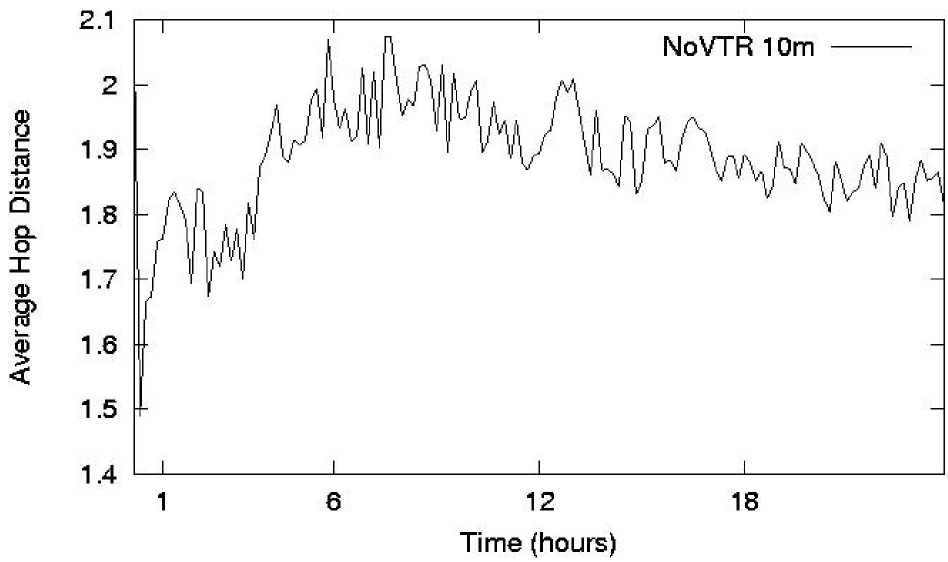


**Fig A.13** Traffic weighted average hop distance for No-VTR Case. Period = 10 min.

**BIOGRAPHY**

Okan Koçak received his B.Sc. degree in Electrical and Electronics Engineering from Bilkent University in 2001. He has begun his M.S. Computer Science Studies in Istanbul Technical University (ITU) in 2001. Also he has worked as a Research Assistant from 2001 to 2003 in Computer Science program of Institute of Informatics, ITU. He is now working as a Researcher at TUBITAK National Institute of Electronics and Cryptology (UEKAE).