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TRAFFIC ENGINEERING AND REGENERATOR PLACEMENT IN MPLS AND GMPLS NETWORKS WITH RESTORATION

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By
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I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

TRAFFIC ENGINEERING AND REGENERATOR PLACEMENT IN MPLS AND GMPLS NETWORKS WITH RESTORATION

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January 2002

Label switching technologies, standardized under the name MultiProtocol Label Switching (MPLS), provide performance advantages for core networks. MPLS enables traffic engineering and QoS support on conventional IP networks. Since MPLS uses the common control plane of IP protocol, it simplifies network management and decreases maintenance costs. Generalization of MPLS, called GMPLS, is seen as an important step in the evolution of architectures of optical transport networks. In this thesis, we discuss the problem of traffic engineering of restorable paths in MPLS networks and study four working and restoration path design methods. Each method is formulated as an Integer Linear Programming (ILP) model, and relative performances of these methods are compared based on a proposed traffic uncertainty model.

For optical networks, we study the traffic engineering problem taking into account the physical layer impairments and optical layer constraints. These factors limit the range of optical signals and necessitate placement of signal regenerators. This, in turn, affects the path selection process for each demand. We present an ILP formulation for the regenerator placement problem with the objective of using minimum number of regenerators. Since the resulting formulation has a huge size making it impractical for large networks, we also develop two heuristic algorithms for the same problem. We compare the efficiencies of these algorithms in terms of the number of regeneration points needed. For the design of working and restoration paths in GMPLS networks, we develop an ILP formulation for path set creation which considers optical layer constraints and locations of regenerators. We use traffic engineering models to demonstrate the effect of these algorithms on network performance. As in the MPLS case, performances of traffic engineering methods are compared for the optical network using the traffic uncertainty modeling.

Keywords: MPLS, GMPLS, traffic engineering, restoration, regenerator placement, working and restoration path design

ÖZET

MPLS VE GMPLS AĞLARINDA RESTORASYONLU TRAFİK MÜHENDİSLİĞİ VE REJENERATÖR KONUMLANDIRILMASI

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MultiProtocol Label Switching (MPLS) adı altında standartlaştırılan etiket anahtarlama teknolojileri, çekirdek ağlar için performans avantajları sunmaktadır. MPLS geleneksel IP ağlarında trafik mühendisliği ve QoS desteğine imkan vermektedir. MPLS, IP protokolünün ortak kontrol düzlemini kullandığından dolayı, ağ yönetimini kolaylaştırmakta ve bakım maliyetlerini düşürmektedir. GMPLS olarak adlandırılan MPLS'in genellemesi, optik taşıma ağlarının yapısal evriminde önemli bir aşama olarak görülmektedir. Bu tez çalışmasında, MPLS ağlarında onarılabilir yolların trafik mühendisliği problemini ele almakta ve dört aktif ve onarım yolu tasarımı metodu üzerinde çalışmaktayız. Her bir metot Tamsayılı Doğrusal Programlama (ILP) modeli olarak formüle edilmekte ve bu metotların relatif performansları öne sürülen bir trafik belirsizliği modeline göre karşılaştırılmaktadır.

Optik ağlar için, trafik mühendisliği problemini fiziksel katman uyumsuzlukları ve optik katman kısıtlamalarını göz önüne alarak incelemekteyiz. Bu etkenler optik sinyallerin menzilini sınırlamakta ve sinyal rejeneratörlerinin yerleştirilmesini gerekli kılmaktadır. Bu da her bir talep için yol seçimi sürecini etkilemektedir. Rejeneratör konumlandırılması problemi için en az sayıda rejeneratör yerleştirmeyi amaçlayan bir ILP formülasyonu sunmaktayız. Elde edilen formülasyonun büyük ağlarda kullanılamayacak büyükte olmasından dolayı aynı problem için iki de buluşsal algoritma geliştirmekteyiz. Bu algoritmaların etkinliklerini gerekli rejeneratör nokta sayısı açısından karşılaştırmaktayız. GMPLS ağlarında, aktif ve onarım yolları tasarımı için, yol kümesi oluşturmak üzere optik katman kısıtlamaları ve rejeneratörlerin yerlerini göz önüne alan bir ILP formülasyonu geliştirmekteyiz. Bu algoritmaların ağ performansı üzerindeki etkilerini ortaya koymak için trafik mühendisliği modellerini kullanmaktayız. MPLS durumunda olduğu gibi, trafik mühendisliği metotlarının optik ağlardaki performansı, trafik belirsizliği modeli kullanılarak karşılaştırılmaktadır.

Anahtar Kelimeler: MPLS, GMPLS, trafik mühendisliği, onarım, rejeneratör konumlandırılması, aktif ve onarım yolları tasarımı

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To My Family. . .

Chapter 1

INTRODUCTION

Since the initial deployment of the original ARPANET, Internet architecture has evolved in response to technological progress and user needs. The explosive growth in traffic fed by the increase in the number of users and resources consumed by modern applications has put an ever increasing load on the Internet. A report from the U.S. Department of Commerce [1] suggests that the rate at which the Internet has been adopted has surpassed all other technologies preceding it, including radio, television, and the personal computer. A common expectation is the convergence of voice, video, and data communications to happen over the Internet. Hence, capacity, performance and Quality of Service (QoS) become the critical requirements. To respond the challenge of Internet growth Internet service providers (ISPs) employ three complementary technical instruments:

- Network architecture
- Capacity expansion
- Traffic engineering

Network architecture is the abstract structure of the network. It involves the components or object classes of the network, their functions and the relations between them.

Expansion of capacity and network infrastructure is employed as a response to the traffic growth by the large ISPs. In 1996 most large ISPs in the United States operated backbones with DS3 (44.736 Mb/s) links. In 1997 and 1998, OC-12c (622 MB/s) links became pervasive. In 1999 a number of major ISPs upgraded to OC-48c (2.488 Gb/s). By the year 2000, some ISPs began deployment of IP backbones with OC-192c (9.953 Gb/s) links, provisioned directly over dense wavelength-division multiplexing (DWDM) facilities.

The third instrument used to address the Internet growth is the traffic engineering, which has attracted significant attention at recent times. The motivation for traffic engineering is the fact that architectural paradigms and simple capacity expansions are not sufficient alone to deliver high quality Internet service. Internet traffic engineering addresses the issue of performance and resource utilization optimizations of the operational networks. It also aims application of knowledge and techniques to achieve specific performance objectives, and planning network capacity.

In this context, MultiProtocol Label Switching (MPLS) has both architectural and traffic engineering aspects. The evolution of routing architecture and need for traffic engineering lead to the development of MPLS as a technology that aims to respond to aforementioned challenges faced in Internet today .

Internet routing architecture has evolved over time. ARPANET which is the predecessor of today's Internet, was structured as a single flat link layer based on packet switches. But this architecture became insufficient with the rise of other link layers, like Ethernet. This situation required a protocol such as IP in order to traverse different link layers and a system that could pass packets between such link layers. Such a system was called a gateway, which is now better known as a router. Gateways had complete knowledge of all connected IP networks and used Gateway-to-Gateway Protocol to exchange routing information. Thus, a two-level hierarchical routing architecture has evolved where some gateways are designated as core gateways, and the remaining ones as exterior gateways. Exterior Gateway Protocol was used to exchange the reachability information between the core and exterior gateways. Each site, known as an autonomous system or domain, used an Interior Gateway Protocol (IGP) for routing within the site. After the creation of NSFNET, EGP is replaced with Border Gateway Protocol (BGP) to overcome the problems and limitations of EGP. With the growth of the Internet, the routing and addressing architectures of the Internet were again changed in order to support tremendous amount of data required by the routing protocols. The new architecture, which is known as the Classless Interdomain Routing (CIDR), replaced the two-level hierarchical addressing with a multilevel hierarchical addressing.

Meanwhile, in parallel with the evolution of Internet, which is a datagram network, connection-oriented architectures have continued to evolve. In connection-oriented link layers, such as ATM, Frame Relay, and X.25, a logical connection must exist between endpoints prior to data exchange in contrast to the situation in Internet where packets can be sent without such a connection. Since control information is required at each network element, connection-oriented architectures enable services that are intractable within a pure datagram network. First, connection-oriented architecture is advantageous in supplying certain QoS features, since all data traveling along a specific connection can be treated in the same way, with no need of analysis on each individual packet. Besides, each connection can be delivered along a unique path through the network. Thus, two packets with the same destination can follow completely different paths starting from the same point in the network. This is not possible in a datagram network, since packets with the same destination are forced to follow the same path. This feature is also a useful tool for traffic engineering, since the traffic can be shifted from congested links to uncongested links, allowing better resource utilization. It can also be used as a policy tool, for example to prevent certain type of traffic using specific links.

Connection-oriented services are also advantageous from the restoration point of view. For loss-sensitive services high-speed restoration can be done by redirecting the traffic from a failed connection to an alternative connection to the same destination. The restoration time is much lower than the one necessary in a datagram network, where the routing protocol must converge before the restoration of service. These advantages of connection-oriented networks made them a suitable choice as the infrastructure for datagram networks. IP over ATM networks proved the usefulness of this approach. But due to the separation between the connection oriented layers and datagram layer, the benefits of connection-oriented networking can not be fully utilized.

The MPLS approach is presented as a solution for this problem. MPLS establishes a virtual connection between two points in a datagram network, and this connection carries datagram traffic. By using MPLS connections, called LSPs, in a manner similar to connection-oriented networks, MPLS can provide much of the advantages of connection-oriented networks while still keeping the efficiency and operation of a datagram network.

With the continuous growth of the Internet, and the introduction of real-time applications service predictability is getting more important. But the traditional IP networks do not offer a predictable performance which is often unacceptable for such applications. At this point traffic engineering is a key solution to enable the networks to offer performance predictability. Effective traffic engineering is difficult to achieve in public IP networks due to the limited functional capabilities of IP networks. One of the limitations is the fact that, inadequate measurement functionality of conventional IP technology prevents the construction of a traffic matrix, which is a basic need for traffic engineering. Another issue is the limitations of intradomain routing control functions. The protocols used to route traffic in an autonomous system are topology-driven and require per-packet processing. Each router makes an independent routing decision on the packet based on shortest path computations using simple additive link metrics. Although this approach is highly distributed and scalable, it ignores the characteristics of the traffic, and network capacity constraints. Hence they result in an inefficient resource utilization; while some paths become congested, the others are underutilized.

To overcome these challenges, the overlay model is used, where a secondary technology with virtual circuit and traffic management capabilities, such as ATM, is introduced into the IP infrastructure in an overlay configuration. The virtual connections of this technology serve as point-to-point links between IP routers. Although this approach enables efficient traffic engineering to be done, it has important drawbacks. The need to build and manage two networks with dissimilar technologies, and the increased complexity of the network architecture are the fundamental disadvantages of this solution. Besides, the scalability problems and the overhead of quantization and encapsulation in ATM present technical difficulties. Therefore, instead of the overlay model more integrated solutions are needed, which is now possible with MPLS. With the developments in MPLS, new possibilities are opened for traffic engineering. Although it is a relatively simple technology based on label swapping paradigm, it enables the use of sophisticated control functionality that advances the traffic engineering in IP networks.

There are ongoing studies and standardization efforts on various aspects of MPLS. Most of the work published in several papers focus on the architecture and signaling mechanisms of MPLS networks. Although the advantages of MPLS in the areas of traffic engineering and reliable networking are discussed in many publications, a compact and detailed analysis on the practical traffic engineering approaches and algorithms have not been studied. In this thesis, we discuss the traffic engineering with restoration problem and present several methods for maximizing the traffic carrying capacity of the network.

First we present a method to build a candidate path set for a given demand, and formulate it as an Integer Linear Programming (ILP) problem. Next, we discuss four different optimization approaches for the design of working and restoration paths for a given traffic projection and develop corresponding ILP models. The goal of optimization is to use the available network capacity in an efficient manner and to increase the robustness of the network design in response to the uncertainties in the traffic projections, while satisfying all the demands, that is assigning each demand a pair of paths; one for working and the other for restoration traffic.

In the most primitive design strategy separate design of the working and restoration paths in order to minimize the resource utilization is considered. In this method, working paths are designed first, to minimize the capacity utilization. Afterwards corresponding restoration paths are designed again to minimize the used capacity. Second design approach aims to evenly distribute the capacity usage through the network in order to enhance the robustness feature. This method again treats the working and restoration path designs as separate problems and tries to minimize the capacity usage as a second objective. Similar to the first approach, the working paths are designed to minimize the capacity usage while balancing the capacity utilization over the network. Then on the residual network restoration paths are designed to achieve the same objective.

Last two methods use a joint optimization approach, where both working and restoration paths are designed concurrently. The goal of these methods is to minimize the capacity usage while distributing the load over the network in a balanced fashion. The difference between these two methods is that the last method uses weights for each link in the network which indicate the relative importance of links, and the objective becomes the minimization of used capacity while distributing the weighted residual link capacity evenly.

To evaluate the relative efficiency of each design approach, we develop and formulate the traffic uncertainty modeling again as an ILP. As a performance measure, we use the robustness of the network design to the uncertainties in the traffic projections. Afterwards, we obtain numerical results on a sample network using the CPLEX optimization software package. We use these results in order to determine the best design approach and the effects of load balancing, joint optimization and link weights on the efficiency of design methods.

The idea of extending MPLS to the optical networking is called Generalized Multiprotocol Label Switching (GMPLS). It is seen as an important step in the evolution of Optical Transport Networks. With GMPLS it is possible to have a simpler and more manageable network architecture. Recently, many studies have been published on the topic of GMPLS and the challenges in applying MPLS on optical networks. Most of these work deal with the signaling enhancements and architectural aspects of GMPLS networks. Besides, optical layer impairments are considered in some publications. But traffic engineering over optical networks using GMPLS is not studied at all. Moreover, the effects of optical layer impairments on the design and traffic engineering are not considered in an algorithmic approach. Although the necessity of signal regeneration is discussed, efficient regenerator placement problem is not dealt with.

In this thesis, we formulate the regenerator placement problem as an ILP. Since the solution of this problem, due to its size, is very hard, we develop two heuristic approaches. We obtain numerical results for these approaches on a sample network, and compare their efficiencies. Next, we develop the ILP formulation for the path set creation problem in the optical networks, taking into account the constraints imposed by optical impairments. Then we use the working and restoration path design methods and compare their performances on the optical network. The impacts of the regenerator placement algorithms are discussed from a traffic engineering point of view. Numerical results obtained using CPLEX based on which we compare the efficiency of design methodologies, are presented.

Chapter 2

BACKGROUND INFORMATION

In this chapter, an overview of the basic concepts used in this thesis is presented as a background information. The evolution of MPLS technology and the motivations behind it are discussed. The architectural and operational principles of MPLS networks are explained. Restoration and traffic engineering aspects of MPLS networks are presented. The extension of MPLS to the optical networking, GMPLS, is explained and optical layer constraints are discussed. Related work in these areas are also considered in this section.

2.1 MultiProtocol Label Switching

In the mid-1990's, several companies developed new switching/forwarding technologies using a different paradigm. The most well-known approach of this type is the *IP Switching* invented by Ipsilon. Other similar technologies are, *Cell Switching Router (CSR)* of Toshiba, Cisco's *Tag Switching* and *Aggregate Route-Based IP Switching (ARIS)* by IBM. A detailed analysis and comparison of these approaches are provided in [2,3]. [4] compares MPLS and IP technology from a design point of view with particular emphasis on issues specific to MPLS networks.

All of these approaches are based on similar ideas. First, they all use a simple label swapping technique for forwarding data packets, which is similar to the idea used in Asynchronous Transfer Mode (ATM). But unlike ATM, these approaches use the control paradigm of the Internet Protocol (IP) suite. That is, they use IP addresses and standard Internet routing protocols, such as Open Shortest Path First (OSPF) and Border Gateway Protocol (BGP).

To standardize these new ideas Internet Engineering Task Force (IETF) chartered a working group and picked the name *Multiprotocol Label Switching (MPLS)* for this group. The architecture of this framework along with signaling protocols is explained in detail in [5]. All of these approaches are collectively known as *Label Switching* technologies.

There are important motivations behind the development of Label Switching. First of all, the well-known exponential growth of the Internet has placed an increasing demand especially on the networks of the Internet Service Providers (ISPs). To meet this growing bandwidth demand higher performance switching and routing products are needed. And scalability is also an important issue, since networks have to deal with increased number of nodes and more flows. Another reason that makes label switching attractive is that, the forwarding algorithm is fixed and new control paradigms can be implemented without making any modifications on it. In the conventional IP routing, evolving the routing functionality is hard due to the strong coupling between the routing and forwarding. For instance, deployment of Classless Interdomain Routing (CIDR), which enables the usage of variable length IP network prefixes (which had previously been 8, 16 or 24 bits long) requires changes also in the forwarding algorithm of

IP routers. But making changes to the forwarding algorithms, which are crucial to the performance of routers, are typically expensive and time consuming.

Routers are the key components of any network which is based on IP protocol suite. The main task of a router is to forward IP packets (datagrams) across the network which is a complex operation. In addition, many other functions such as filtering the flow of packets between different parts of a network are performed by routers. Switch is another network component, which is a layer-2 device and uses limited number of protocols mainly for forwarding packets. Hence switches are simpler and cheaper devices compared to routers. As a result, switches have higher level of performance in terms of forwarding speed. Thus, one of the important motivations behind label switching is to use a simple device similar to a switch to fulfill the most important task of a router, namely the forwarding of IP packets, hence to obtain a higher performance/price ratio.

Another motivation for label switching is the desire to integrate IP and ATM. ATM has a significantly different architecture compared to IP. It is based on a connection-oriented or virtual-circuit model whereas IP uses a datagram or connectionless model for data delivery. Besides, IP and ATM have completely separate addressing schemes and many other incompatibilities such as different models of multicast communication and resource allocations. In short, IP and ATM have control planes which significantly differ from each other. Currently, the most widely used integration technique is the *overlay model*, where IP network is overlaid onto an ATM network. In this case, the ATM network provides a core of high speed connectivity to IP routers which in turn provide the intelligence to forward IP datagrams. But this approach has a number of complex problems which stem from the fact that ATM and IP protocols are developed without any regard to each other. As a result two different protocol architectures with completely different addressing, routing protocols and resource allocation schemes are used by these protocols. The label switching approach proposes to use ATM hardware to forward packets by using label swapping while the IP control protocols are used for setting up forwarding tables and for allocating resources. Thus ATM switches effectively become IP routers from the control point of view, and the need to map between IP and ATM control models is eliminated. Label switching approach also solves the problem of scalability (the undesired rapid increase of router adjacencies) which is an important problem of the overlay model.

Finally, label switching enables new functionality which is not available with existing IP routing techniques. The standard destination-based routing of the IP routing can be extended, so that traffic engineering can be done easily in the network in order to use network resources more efficiently. Other abilities gained by label switching include easy formation of Virtual Private Networks (VPNs) and support for Quality of Service (QoS).

2.1.1 MPLS Overview

In a connectionless network layer protocol, such as IP, data packets are routed at each router independently. Upon receipt of a packet, the router examines the header of that packet and runs a network layer algorithm. The next hop for each packet is chosen independently by each router as a result of the analysis of the packet's header and using the routing algorithm. Therefore the process of choosing the next hop can be viewed as the composition of two functions: The first function partitions packets into sets of *Forwarding Equivalence Classes (FECs)*, and the second one maps each FEC to a next hop at each node. So, all packets belonging to the same FEC follows the same path.

In conventional IP forwarding, the packets are partitioned into FECs typically based on some address prefix in the router's routing table. Each router determines the *longest prefix match* between the entries in its table and the destination address of the data packet, and forwards the packet to the corresponding output port. Each router, similarly, reexamines the packet header and assigns it to the FEC, as the packet travels in the network.

In MPLS, the packet is assigned to a particular FEC just once when it enters network. This FEC is encoded as a short, fixed length value known as a *label* and the packet is forwarded to the next hop with its label appended. At subsequent nodes, the network layer header is not further analyzed, instead the label is used as an index into a table which specifies the next hop and a new label. Old label is replaced with the new one before the packet is forwarded to its next hop.

The basic difference in the MPLS forwarding paradigm is the fact that, once a packet is assigned to a particular FEC, its network layer header is not further analyzed by subsequent routers, and all the forwarding decisions are given based on the labels. This approach has several advantages compared to the conventional network layer forwarding.

The packets can be labeled based on the router from which the packet enters the network called the *ingress router*. Hence, forwarding can be easily extended to include decisions related to the ingress router of the packet. Since the information about the ingress router is not included in the packet header, this is not possible with conventional forwarding.

Since each packet is assigned to a FEC in the entry to the network, the ingress router may use any information about the packet in deciding the FEC for that packet. For instance, the packets can be assigned to FECs based on the number of the port they are received. The process of mapping packets into FECs can be complicated as much as desired without any impact on the routers that only forward packets. In contrary, conventional forwarding is not capable of using any information that is not contained in the packet header.

As a matter of policy or to support traffic engineering it is sometimes desirable to explicitly specify the path that a packet should follow. In conventional routing this is accomplished by adding an encoding of the explicit route to the packet, called *source routing* which complicates the operation of routers. But in MPLS, the identity of the explicit route need not be carried with the packet, since a path can be represented by a sequence of labels.

2.1.2 MPLS Architecture

MPLS forwarding framework provides efficient designation, routing, forwarding and switching of traffic flows through the network.

Main functions MPLS performs include:

- specification of mechanisms to manage the traffic flows of various granularities (e.g., flows between different hardware, machines, or even flows between different applications)
- independence from the layer-2 and layer-3 protocols
- providing a means to map IP addresses to simple, fixed-length labels used by different packet-forwarding and packet switching technologies
- interfacing to existing routing protocols, such as OSPF.

In MPLS, data is transmitted over virtual paths called *Label Switched Paths (LSPs).* LSP is simply a series of nodes and corresponding labels from the source to the destination node. LSPs can be established before data transmission by appropriate signaling (control-driven) or upon detection of a certain data flow (data-driven).

Label Switching Router (LSR) is a high-speed router that participates in the establishment of LSPs using the appropriate signaling protocols and it is capable of high-speed switching of the traffic based on the established LSPs. LSRs that operate at the boundary of the access network and MPLS network are called the edge LSRs. Edge LSR supports multiple ports connected to different networks (e.g., frame relay, ATM or Ethernet) and forwards traffic to the MPLS network after establishing LSPs using signaling protocols. Since traffic enters and exits from edge LSRs, they play an important role in the assignment and removal of labels. The LSR at which an LSP exits an MPLS domain is called the *egress router* for that LSP.

LSPs can be set up in two different ways: In *hop-by-hop routing*, each LSR independently determines the next hop for a given FEC which is similar to current IP networks. In *explicit routing*, the ingress LSR specifies the nodes which the LSP will traverse. The resources along the path may be reserved to ensure QoS. Using Explicitly Routed LSPs (ER-LSPs) traffic engineering can be easily done, and differentiated services based on policies or network management methods can be provided.

All the packets in the same FEC are treated in the same way by the LSRs on their paths. As described above, the assignment of the FEC to a particular packet is just done at the ingress router as opposed to conventional IP forwarding. FECs can be assigned based on service requirements or simply using the address prefix of the packet. Each LSR keeps a table that specifies how a packet from any FEC is to be treated.

A data packet may carry more than one label organized in a last-in first-out manner which is called a *label stack*. This stack mechanism allows for the hierarchical operation in MPLS domain which in turn supports a tunneling mode of operation (LSP Tunnel). The labels can be pushed or popped to create the label stack. The processing of the packet is solely determined by top label, without regard to other labels below it.

When layer-2 is ATM or Frame Relay, MPLS label is carried in the layer-2 header. For link types which cannot accommodate labels in the link layer header (i.e., for all link types except ATM and Frame Relay), MPLS uses a shim header consisting of a stack of 32-bits. This shim label header is inserted between the link layer and the network layer headers. The format of the shim header is illustrated in Figure 2.1.

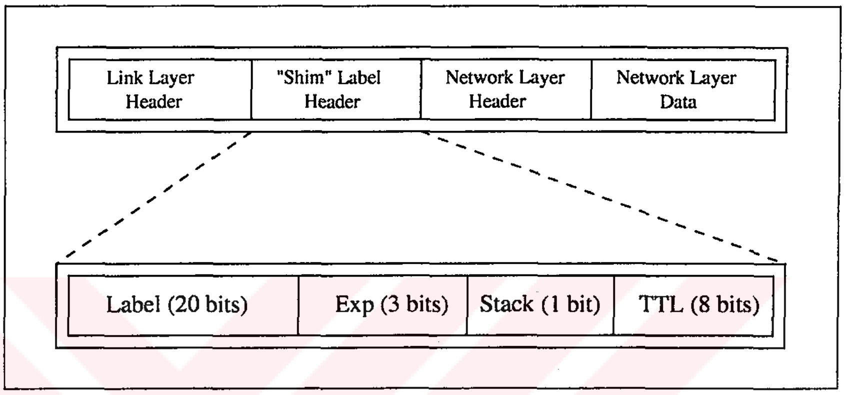

Figure 2.1: Generic Label Format.

The Time-to-Live (TTL) field is used for the same purposes as in IP. For consistency, at the entry to the MPLS domain, the TTL value in the IP header is copied to the TTL field of the MPLS header. TTL value is decremented at each LSR, and copied back to the IP header at the exit of the MPLS domain. So, TTL value is decremented by the number of hops the packet travels in the MPLS network. Alternatively, TTL value can be decremented only at the egress router when the MPLS header is removed. Thus, the MPLS network is seen as a single hop. The advantage of this approach is that the details of the network topology is hidden from an outside observer.

The stack bit is used to indicate whether another label exists below the top label for hierarchical operation. It is set to 1 if the bottom of the label stack is reached. At the time of standardization, there is no definite usage of the three bits, hence they are named experimental (Exp). Since then several ways of using these bits to support quality of service have been defined.

The set of procedures by which one LSR informs another of the label/FEC bindings it has made, is called the Label Distribution Protocol (LDP). There is no single label distribution protocol mandated by MPLS architecture. Existing routing protocols can be extended to be used for label distribution. For example BGP have been enhanced to piggyback the label information, and also RSVP has also been extended to support label distribution. Furthermore, a specific protocol, called *Label Distribution Protocol (LDP)*, is developed by IETF for explicit signaling and management of label space. LDP is also extended to support explicit routing based on QoS and Class of Service (CoS) requirements, and it is called Constraint-Based Routing LDP (CRLDP). For different needs, different protocols are used. For mapping unicast IP destinations into labels LDP can be used. RSVP and CR-LDP may be used for traffic engineering and resource reservation purposes. For Virtual Private Networks, BGP can be used to exchange external labels.

2.1.3 MPLS Operation

The MPLS operation consists of two main steps. First, an LSP is created and then the flow is forwarded through this LSP. These steps are illustrated on a sample network shown in Figure 2.2. In this figure, LSR1 is the ingress and LSR6 is the egress router for the MPLS network shown.

Label Switched Path Creation

For the creation of LSP through which the packets will be forwarded, the routers bind a label to a specific FEC and build their tables prior to forwarding any traffic. For LDP it is the responsibility of downstream routers to initialize the distribution of labels and the label/FEC bindings. In addition, traffic requirements and network capabilities are negotiated using LDP. For reliable and ordered transport, LDP uses Transport Control Protocol (TCP). In Figure 2.2,

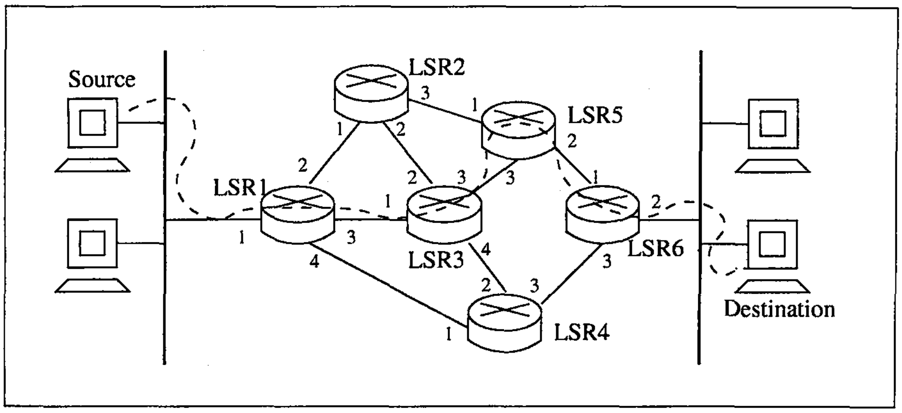

Figure 2.2: Sample MPLS Network.

when the packet is first received by the ingress router (LSR1), it initializes a label request toward the egress router (LSR6). The next router can be determined by hop-by-hop routing. If traffic engineering is needed to ensure QoS/CoS or administrative requirements, CR-LDP can be used in determining the explicit route. This request propagates to LSR6 through LSR3 and LSR5. When the request reaches the egress router, it assigns a label to this flow and sends its label mapping to the upstream router. Each intermediate router assigns a label to this flow so the mapping propagates back to LSR1 following the path that the request follows in the reverse direction, i.e., LSR6-LSR5-LSR3-LSR1.

Meanwhile, upon reception of label bindings each LSR creates the corresponding entry in its Label Information Base (LIB) table. This table keeps the mapping of labels to FECs. It specifies the output port and output label for an input port and input label pair. A simple example of the LIB table for LSR3 is given in Table 2.1. The LSP established between the ingress and egress routers in the MPLS domain is plotted as the dashed line in Figure 2.2.

Input Port	**Incoming Label**	**Output Port**	**Outgoing Label**
1	A	3	B

Table 2.1: Forwarding Table for LSR3.

Label Swapping/Packet Forwarding

LSR1 uses its LIB table to find the next hop and label for the incoming packet of a specific FEC. After inserting the appropriate label to the packet, LSR1 forwards the packet to the next hop specified in its table. Subsequent routers examine the label of the incoming packet and determine the next hop and the outgoing label. Then they simply swap the label and forward the packet to the next hop, using the appropriate entries in their LIB. When the packet reaches LSR6, the label is removed and the packet is send out of the MPLS domain as the original packet taken by the ingress router.

After we discuss MPLS networks, the restoration problem in high-speed multilayer networks is presented in the next section.

2.2 Restoration

Connectivity is the major concern of the network routing protocols deployed today and typically one class of service, the best effort class, is supported. An important component of QoS is the ability of the network to transport data reliably and efficiently. With the incredible increase of real-time and high priority traffic presented to the IP network, network survivability has become crucial for future IP networks. Even though current routing algorithms are robust and survivable, the amount of time they need to recover from a failure can be significant, e.g., in the order of several seconds to minutes, which can cause serious service disruptions. This is not suitable for many of the services that require high reliability and recovery times in the order of tens of milliseconds.

There are inherent limitations to improving the recovery times of current routing algorithms. For this aim, path-oriented technologies such as MPLS can be used to enhance the reliability of IP networks. The fact that MPLS networks establish LSPs, potentially allow pre-establishment of protection LSPs for working LSPs and achieve better protection switching times than those in conventional IP networks. Furthermore, a protection priority can be used as a means of differentiation for premium services that require higher reliability.

There are several advantages of MPLS based protection. First, MPLS is able to give faster response to faults compared to traditional IP routing. Moreover, it eliminates the need for intervening SONET layer by enabling IP traffic to be put directly on Wavelength Division Multiplexing (WDM) optical channels. This feature enables construction of IP-over-WDM networks. Furthermore, in SONET-based protection or optical layer restoration the granularity of the protected traffic may be coarse compared with MPLS-based mechanisms.

MPLS provides several options for the protection of traffic. First, the recovery can be established using layer-3 rerouting or using MPLS protection switching or rerouting actions. MPLS based recovery allows more flexibility in choosing the recovery mechanism and granularity at which traffic is protected. So, a variety of protection mechanisms can be offered by network operators. Specific types of traffic can be chosen to be protected in order to give network operators more control over the reliability/cost trade-off. Using MPLS different classes of services can be given different levels of protection. For example, real-time applications like VoIP may be protected by MPLS, while the best effort traffic may simply rely on IP rerouting or application layer recovery mechanisms.

General considerations for label switched path restoration are studied by IETF and published in several Internet Drafts. The framework for MPLS-based recovery is explained in [6]. The aspects of bandwidth reservation in protection are presented in [7] and a path protection/restoration mechanism is introduced in [8]. [9] deals with the shared backup LSP path restoration and [10] describes the necessary extensions to RSVP protocol for MPLS path protection.

2.2.1 Recovery Models

Recovery methods are classified according to the principles used for *Initiation of Path Setup*, *Initiation of Resource Allocation* and *Scope of Recovery.* There are two options for the initiation of the recovery path setup. In *Pre-Established* case, recovery path(s) is established prior to any failure on the working path. On the other hand, in *Established-on-Demand* case, a recovery path is established after a failure on the working path is detected and notified.

A recovery path may or may not need to support the same QoS as the working path. If the recovery path is capable of replacing the working path without degrading the service, it is called an *equivalent recovery path*, else it is called a *limited recovery path.* Based on this differentiation there are two options for the Initiation of Resource Allocation. In *Pre-Reserved* case, the resources required on the recovery path are reserved during the establishment of the working path. Thus, the service quality on the recovery path can be guaranteed. In the *Reserved-on-Demand* case, resources required to recover the working path are reserved after a failure on the working path is detected and notified. Hence there is always the possibility of degrading the service quality since the required resources may not be available when needed.

Recovery methods can also be classified based on the scope of the recovery action. *Local Repair* aims to protect against single link or neighbor node failures. In local recovery, the node immediately upstream of the fault initiates the recovery action using either rerouting or protection switching. Local repair can be in the form of link recovery/restoration and node recovery/restoration. In link recovery, the recovery path can be configured to route around a certain link deemed to be unreliable (in the case of protection switching), or a failed node (in the case of rerouting). Similarly, in the node recovery, an alternate path is selected to route around a neighbor node which is failed or deemed to be unreliable. In both cases the recovery path shares overlapping portions with the working path. *Global Repair* which is also known as the *Path Recovery* or *Path Restoration* aims to protect against any link or node failure on the working path, except failures in the ingress or egress nodes. In path recovery, the ingress node which may be distant from the failed link or node initiates the recovery process. In many cases the restoration path may be selected to be link and/or node disjoint from the working path to protect against all link and/or node failures on the working path. Global repair is potentially more optimal in resource usage than the local repair. However, it can be slower in some cases, since the fault notification message takes longer time to get to the ingress node to trigger the recovery action. Link restoration and path restoration are demonstrated in Figure 2.3.

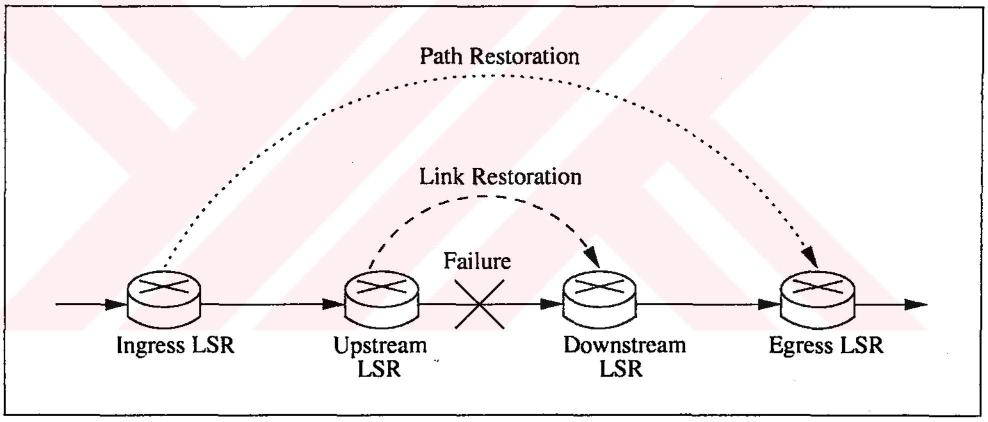

Figure 2.3: Link Restoration and Path Restoration.

Recovery models can be separated into two basic classes: re-routing and protection switching.

1 Rerouting

In rerouting, new restoration paths or path segments are established on-demand after the occurrence of a failure. In this type of recovery, signaling is needed to establish paths or path segments to bypass the failure. The fault information, network topology and routing policies may be taken into account in this process. Naturally, rerouting is slower than the protection switching mechanism. On the other hand, this method is simpler and conserves the capacity since no resources are committed until the occurrence of the fault, and fault can be located by signaling. Rerouting employs paths established on-demand with resources also reserved-on demand.

2 Protection Switching

In protection switching, a recovery path or path segment is pre-established according to network routing policies, the restoration requirements of the traffic and administrative constraints. The recovery path does not have to be link- or node-disjoint from the recovery path, but the overall reliability of protection degrades as the source sharing increases. Upon detection of the failure, the traffic is switched to the recovery path(s). Protection switching employs pre-established recovery paths. The resources may or may not be pre-reserved depending on the application.

There are two subtypes of protection switching: In 1+1 protection the recovery path carries a copy of the working path traffic. In 1:1 protection the recovery path may carry low priority traffic which is preempted when a protection switching occurs.

In 1+1 protection scheme, the resources (bandwidth, buffers, processing capacity, etc.) on the recovery path are fully reserved and the same traffic as in the working path is carried on the recovery path. The Path Merge LSR (PML) selects between the traffic on the working and recovery paths depending on signal quality.

In 1:1 protection, the resources, if any allocated, on the recovery path can be fully used to carry preemptible low priority traffic. When a failure occurs on the working path, the low priority traffic is dropped and the resources are used to carry the protection traffic. Thus, the protected traffic only travels on the working path unless a fault occurs, and the traffic is switched to the recovery path once the failure is detected. Since, the low priority traffic is preempted only when a failure occurs on the protected path, resources are used more efficiently.

These models may also be used together. For example, in order to restore quickly, the protection switching may be used, and later rerouting may be employed to find a more optimal network configuration by re-arranging the paths. Restoration in MPLS networks is analyzed in several papers. An overview of the reliable services in MPLS is given in [11].

2.3 Traffic Engineering

The rapid growth of the Internet has made the IP protocol suite the most predominant networking technology. Moreover, the convergence of voice and data communications over a single network infrastructure is expected to happen over IP-based networks [12]. But conventional IP offers little predictability of service which is unacceptable for many applications, such as Internet telephony and other real-time applications. Current Interior Gateway Protocols (IGPs) always use the shortest-paths to forward traffic. This approach conserves network resources but may cause two performance problems. First, the shortest paths from different source-destination pairs may overlap at some links, causing congestion on those links. This problem is illustrated in Figure 2.4. The second problem occurs when the traffic from a source to a destination exceeds the capacity of the shortest path, while a longer path remains underutilized. So, there is a need to provide dependability and service differentiation in the networks. In order to enable such capabilities, the basic traffic forwarding paradigm of IP must be enhanced to support *Traffic Engineering.* Traffic engineering can be defined as the process of controlling how traffic flows through the network in order to optimize resource utilization and network performance. The required capabilities include the provisioning of a guaranteed QoS, improving the utilization of network resources by spreading traffic evenly in the network (load balancing), and providing features for quick recovery when a node or link fails.

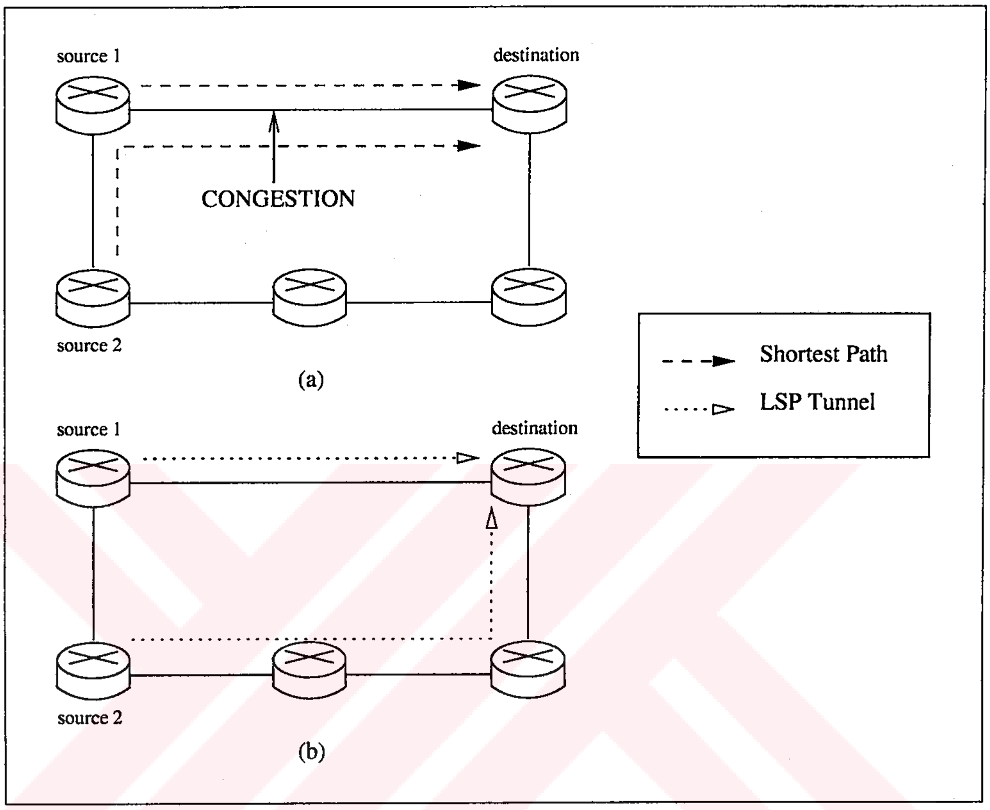

Figure 2.4: Addressing congestion problems with MPLS: a) congestion caused by intersecting shortest paths; b) traffic redistribution using LSP tunnels.

Recent developments in MPLS provide possibilities to overcome the limitations of IP in the area of traffic engineering. MPLS combines scalability and flexibility of routing with performance, QoS and traffic management of layer-2 switching, hence many capabilities which were only existed at layer-2, become available at the IP layer. The most important capability of MPLS from a traffic engineering point of view is the ability of specifying explicit LSPs at the origination node. This path may be independent of the destination based IP shortest path routing model. Although explicit paths can also be specified by IP using source routing, explicit LSP creation is easier and more efficient in MPLS.

Moreover, the deployment of MPLS in IP over SONET, or IP over DWDM configurations promises less operational cost, queuing delays and number of network elements while increasing the reliability. MPLS aggregates the traditional layer-2 and layer-3 functionality in one network element, the LSR. Since MPLS maps the traffic trunks, i.e., the aggregation of traffic belonging to the same class, on explicit LSPs, it presents capabilities for optimizing the performance and capacity usage of the network. For example, LSP tunnels can be explicitly routed to avoid congestion problem. Traffic between two nodes can be divided among multiple LSP tunnels according to some local policy to prevent congestion and to spread the traffic over the network. Moreover, LSP tunnels permit the introduction of flexible and cost-effective survivability options. Statistics, which is an important part of traffic engineering, can be collected from LSP tunnels and be used to construct a traffic matrix. The advantages of MPLS from a traffic engineering point of view are discussed in [13].

MPLS traffic engineering model has four basic functional components: path management, traffic management, network state information dissemination and network management.

Path Management component deals with all aspects of explicit route selection and maintenance of LSP tunnels. Path management includes three primary functions: path selection, path placement and path maintenance. The path selection function determines the explicit route for an LSP tunnel at the origination node of the tunnel. Explicit routes can be defined administratively or computed automatically by a constraint-based routing algorithm. The path placement function instantiates the LSP tunnels using a signaling protocol, which also serves as a label distribution protocol. And the path maintenance component sustains and terminates already established LSPs.

Traffic Assignment component deals with the allocation of traffic to the established LSP tunnels. It consists of two primary functions. The partitioning function partitions the ingress traffic according to some principle of division, and the apportionment function allots the partitioned traffic to established LSP tunnels according to some principle of allocation. Thus there is a great flexibility in traffic engineering in MPLS. LSP tunnels may be viewed as shortcuts through the IGP domain. Additional attributes may be introduced and filtration rules may be applied, e.g., for differentiated services. Load distribution across multiple LSP tunnels between two nodes is an important issue in traffic assignment, and it can be easily implemented by assigning weights to each tunnel and apportioning the traffic in proportion with weights.

Network State Information Dissemination deals with the distribution of topology state information throughout the MPLS domain. To achieve this, conventional IGPs are extended to propagate additional network state information in link state advertisements (LSAs). The additional information may include, maximum link bandwidth, maximum allocation multiplier, default traffic engineering metric, reserved bandwidth per priority class and resource class attributes. This information is used by constraint-based routing to select feasible routes for LSP tunnels.

Network Management deals with functions related to the observation and control of the network. These functions include the configuration management, performance and accounting management and fault management. Point-to-point traffic flows, path loss and path delay characteristics can be estimated. In turn, these statistics can be used for analysis and capacity planning purposes.

Because optimizing the performance of large-scale networks is an intractable problem, off-line traffic engineering support tools may be required to augment the online capabilities of MPLS. Such offline tools may be interfaced with the MPLS network management system to provide external feedback control [1]. The principles and advantages of traffic engineering in MPLS networks are studied in [13, 14]. The signaling protocols for traffic engineering are considered in [12].

In [1] the architectural aspects of the traffic engineering approach in MPLS is considered. In [15] a new algorithm for dynamic routing of restorable bandwidth guaranteed paths is presented.

2.4 Generalized Multiprotocol Label Switching (GMPLS)

Today's data network architecture typically consists of four layers: IP for carrying applications and services, ATM for traffic engineering, SONET/SDH for transport and WDM for capacity increase. Since any one layer can limit the scalability of the entire network as well as add to the cost of the network, such a complex multi-layered approach does not scale well for very large volumes of traffic and is fairly cost-inefficient.

Effective transport of data can be achieved as a result of optimizing the data multiplexing and data switching for a wide range of traffic volumes. WDM is a cost-effective multiplexing technique, since it increases the carrying capacity of a single fiber while leveraging the existing fiber infrastructure. On the other hand, Optical Cross Connects (OXCs) are likely to be the preferred option for switching, since they can handle multigigabit data streams by avoiding electronic per packet switching. Detailed information on optical networking can be found in [16,17].

It is widely expected that IP-based traffic will continue to be the predominant traffic carried in the network. And as the capabilities of both routers and OXCs grow rapidly, it is becoming possible to bypass ATM and even SONET layers. This approach results in a simpler and more cost-effective network architecture which is capable of carrying a wide range of data-streams and very large volumes of traffic. The expected technology layer evolution of core IP networks from IP over ATM over SONET over fiber to IP with MPLS over SONET over WDM, and finally to IP with MPLS over an adaptation layer interfacing with an transport network (OTN) is illustrated in Figure 2.5.

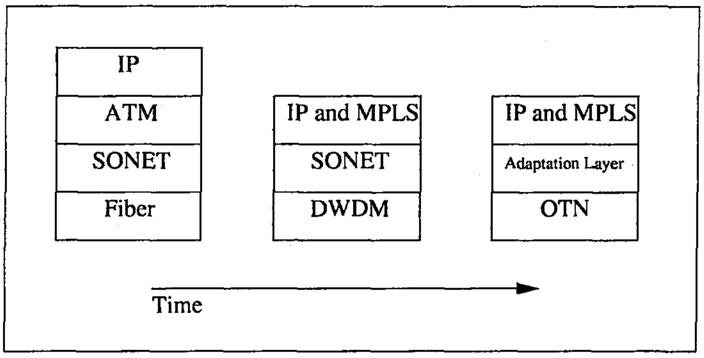

Figure 2.5: Technology Layer Evolution.

The idea of extending MPLS as a control plane that can be used not only with routers, but also with legacy equipment (e.g., SONET, ADMs) and newer devices such as OXCs is called the *Generalized Multiprotocol Label Switching(GMPLS)* or *Multiprotocol Lambda Switching (MPλS)*. GMPLS stems from the fact that this approach generalizes the concept of label in traditional MPLS, and MPλS is also used since wavelengths are used instead of labels as in traditional MPLS. The idea of a common control plane is essential in the evolution of open and interoperable optical networks, and has many advantages. First, a common control plane simplifies operations and management, thus reduces the cost of operation. Next, it provides a wide range of deployment scenarios ranging from overlay model to peer model. Besides, building the common control plane from a proven signaling and routing protocol minimizes the risk and reduces the time to market.

Naturally, to adopt to the non-ideal behavior of photonic switches, some modifications and additions to the MPLS routing and signaling protocols have to be made and these are being standardized by IETF under the concept of GMPLS. The basic principles for GMPLS are considered in [18, 19]. And [20] examines the issues and challenges involved in developing a standardized optical network control plane.

The major additions and modifications needed can be listed as follows:

- A new link management protocol (LMP), which resolves the issues related to link management in optical networks using photonic switches,
- Enhancements to Open Shortest Path First (OSPF)/Intermediate System to Intermediate System (IS-IS) routing protocols to disseminate the state of optical resources in the network, e.g., bandwidth of wavelengths, link protection type and fiber identifiers,
- Scalability enhancements including hierarchical LSP formation, link bundling and unnumbered links.

An overview of signaling, routing and management enhancements for GMPLS are given in [19, 21–23]. [24, 25] deal with the architectural aspects for IP over Optical Networks approach.

The working principles of GMPLS are very similar to the MPLS protocol. The optical channels in the optical network are used in a similar fashion with the usage of labels in the MPLS. Hence OXCs in GMPLS resemble LSRs in the MPLS domain. The information about the network topology and resource availability is disseminated through the signaling network between the neighboring OXCs. Then a constraint-based routing algorithm computes the routes for the flows using this information. Once the path is determined, the LSP is established by using similar protocols used in MPLS, i.e., RSVP and/or CR-LDP.

Traffic Engineering in GMPLS is studied in [26], and restoration in GMPLS is considered in [14].

2.5 Optical Network Constraints

Although GMPLS has many advantages, there are several issues that must be considered while applying MPLS to the optical layer. These are considered in [27] from a restoration performance point of view, and the physical layer limitations are presented in [28].

First, the major differences between routing in optical and IP datagram networks must be taken into account. In conventional IP networks, packets are forwarded on a hop-by-hop basis while in optical networks, an end-to-end connection or lightpath is established based on network topology and available resources. In optical networks, routing protocols are used to update network topology and resource status information, but are not involved in data forwarding. Besides more detailed information must be included in LSA updates. Another difference is the separation of the control plane from the data plane. In IP networks control channels are embedded in the same data-bearing channels, i.e., in-band control signaling. On the other hand, optical networks have greater separation between the data and control domains. Control information is carried in an out-of-band fashion, e.g., via either a time division multiplexing (TDM) circuit or an optical supervisor channel (OSC).

There are also physical layer constraints imposed by various analog transmission concerns that affect the routing in optical networks. These impairments can be classified in two categories: linear and nonlinear. Linear effects are independent of the signal power and affect wavelengths individually. Amplifier Spontaneous Emission (ASE), Polarization Mode Dispersion (PMD) and chromatic dispersion are examples for the linear impairments. Nonlinear effects are more complicated since they not only generate dispersion on each channel but also crosstalk between channels. PMD constraint requires that the time-average differential time between two orthogonal state of polarizations be less than a fraction of the bit duration, hence it limits the total length of the transparent segments in the optical network. ASE is a linear effect which degrades the signal to noise ratio. Since a minimum amount of SNR level must be satisfied at the receiver, ASE limits the size of the domain of transparency in the optical network by dictating a maximum number and length for spans. Nonlinear impairments are hard to be modeled and thus they are not likely to be used in routing algorithms. Several assumptions can be made to ease the modeling. For instance, nonlinear effects can be assumed to be bounded and a margin for these affects can be added to the required SNR value.

All of these effects must be considered while choosing a physical path for a flow. Hence a number of physical layer parameters should be included in the routing protocol advertisements and, they should be taken into account by the routing algorithms in the process of route computation.

Wavelength continuity is another constraint specific to optical networks. If wavelength conversion is not available at each node, wavelength continuity has to be preserved along the path or path-segment. This complicates the Routing and Wavelength Assignment (RWA) computation and increases the size of the state information since wavelength resource information must also be considered in the routing process.

In optical networks, since a higher degree of multiplexing is done and much more traffic is carried over a single link, failures can affect much more users. Thus, survivability is a crucial issue in optical networking. Diversity routing is a common technique and an important requirement used to provide fast protection or restoration capability. Diversity refers to the situation where two lightpaths have no single point of failure. For diversity routing, fiber, conduit and right-of-way diversity requirements can be considered. For this aim, a new link attribute called *Shared Risk Link Group (SRLG)* is introduced to support diversity routing. SRLG information is used to denote all links subject to similar type of failure at a lower layer. For example, it is evident that a fiber cut affects all the fibers in the same conduit, thus there is no point in using a recovery path on a fiber which is in the same conduit with the fiber that is carrying the working traffic. In other words, single points of failure should be included in the same SRLG so that by selecting SRLG disjoint working and restoration paths, the possibility of one failure affecting both paths is eliminated. Typical single points of failure include:

- Conduit or right of way where fiber cables pass through,
- Places where fiber cables cross,
- Locations where fibers are interchanged between fiber cables.

The fiber cable is defined as the uniform group of fibers contained in a sheath, and conduit is the buried honeycomb structure through which fiber cables may be pulled or buried in a right of way (ROW). Figure 2.6 shows an example for the first case, where separate fiber cables are routed through the same ROW, which may be a tunnel or a bridge. Although these two links seem to be independent of each other in the fiber cable topology, since XY segment is shared by both fibers in the physical topology, they should be considered in the same SRLG. Thus, in the computation of diverse lightpaths, SRLG information should be taken into account to ensure that two lightpaths are completely disjoint with respect to their SRLG values.

In IP networks, LSPs may be established such that no bandwidth is consumed as long as no packets are switched into links along the path. The switching of packets onto these predefined paths at their endpoints is simple and rapid. On the other hand, an Optical Transport System (OTS) multiplexes a number of optical signals onto a common fiber which introduces the concept of a channel. An optical connection is provisioned by cross-connecting channels within individual

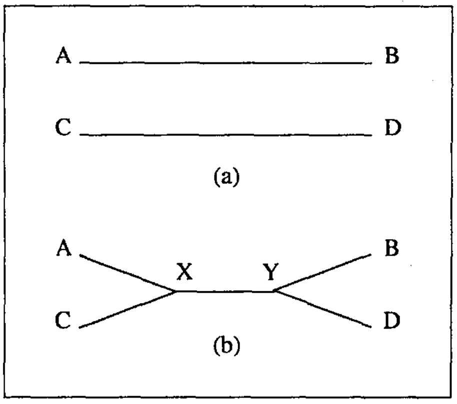

Figure 2.6: Fiber Cable vs. ROW Topologies: a)Fiber Cable Topology, b)Right-of-Way/Conduit Topology.

OTSs along its path. Hence, this fact implies that zero-bandwidth paths can not be established for later use.

Although an OXC resembles an LSR in many ways from a control point of view, there are some important distinctions stemming from the structure of the optical domain. One difference is that, since wavelengths are used instead of labels, there are no analogs of label merging in the optical domain. This fact means that an OXC can not merge several wavelengths into one wavelength. Because of the same reason, an OXC can not perform the equivalent of label push and pop operations in the optical domain.

There are many recent papers which emphasize the advantages of MPLS for traffic engineering and restoration in networks. But most of these work concentrate on the functional or signaling features and the optimization of network resources problem considering restoration is not dealt with in a practical fashion. An algorithm for routing bandwidth guaranteed tunnels with restoration while sharing the restoration capacity as much as possible is presented in [31], but this work does not give the optimal solution since it employs an online approach. However, an offline method for the initial design of working and restoration paths for aggregate demands based on traffic projections is an important step for obtaining solutions close to optimum. Moreover, efficient capacity usage does not necessarily imply minimum capacity usage: A balanced distribution of the residual capacity is also an important parameter. Traffic engineering for resilient connections in an MPLS network is studied in Chapter 3. The resulting offline routing algorithms are formulated and their relative efficiencies in coping with traffic uncertainties are compared via numerical results obtained through simulations.

Extending MPLS to optical networks in order to have simpler and manageable networks, is another popular topic on which many studies have been done. The physical layer constraints are stated in several studies, but the effects of these impairments on routing algorithms are not dealt with. For instance, a solution for the regenerator placement problem has not been proposed. Besides, the problem of routing working and restoration paths under the constraint of regeneration also has not been worked on. The regenerator placement problem is studied in Chapter 4, and the traffic engineering approach we developed for MPLS networks is extended to GMPLS case taking into account the constraints imposed by the physical layer.

Chapter 3

TRAFFIC ENGINEERING WITH RESTORATION IN MPLS NETWORKS

One of the main purposes of traffic engineering is to use the available network capacity in an efficient manner in order to carry as many demands as possible. This requires appropriate routing of all working paths and their corresponding restoration paths. In this section four different methods for calculating working and restoration path pairs are presented. These methods are formulated as Integer Linear Programming (ILP) models. The numerical results obtained by using the optimization software CPLEX and comparison of methods based on these results are given.

These traffic engineering methods are not intended to be used as an online calculation or for micro flows. Instead, these methods are used for routing aggregate demands in the core of the network which uses MPLS as a means of fast forwarding. These computations are done in an offline fashion using projected demand and traffic information. The uncertainty of the traffic projections is addressed in Section 3.6.

In this work, only single link failures are considered, and the generalization to multiple link and/or node failures is shown to be simple extensions of the model. The protection is based on 1:1 protection switching, discussed in Section 2.2. For each working path the corresponding restoration path is pre-established. The resources needed for recovery on this path are pre-reserved. The capacity needed for restoration on each link is calculated taking into account the possible capacity sharing between the restoration paths of different link disjoint working paths, since only single link failures are considered. An end-to-end restoration (global repair) is used in which the restoration path is completely link disjoint from the working path. The effects of physical layer constraints on routing are not considered in this chapter.

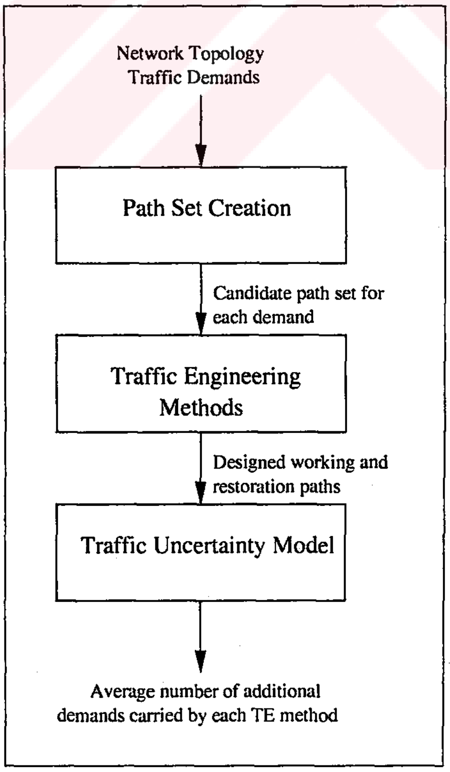

Figure 3.1: Flow Chart for Traffic Engineering with Restoration in MPLS Networks

The methodology followed in this section is given in Figure 3.1. Given the network topology and traffic demands, for each demand a maximal set of link disjoint paths is determined. Using these sets, traffic engineering methods select a working and restoration path pair for each demand. The efficiency of each method is determined using the traffic uncertainty model, which gives the number of additional demands carried by each design method.

3.1 Path Set Creation

In a typical network, which has at least tens of nodes and tens of links, there are a large number of different paths between any source and destination pair. The number of possible paths increases exponentially with the number of nodes and links. Hence, consideration of all possible paths limits the scalability of any optimization approach which aims to determine the best working and restoration path pair for each demand.

To overcome this difficulty, for each source and destination pair a maximal set of candidate paths is determined in this work. This set consists of maximum possible number of link disjoint paths. The paths are selected so that the sum of the lengths of these paths is minimum. This problem is formulated as a max-flow min-cost optimization problem as described below.

Suppose the network topology is represented by a graph $G = (V, E)$ where V is the set of nodes and E is the set of links. The ILP formulation for the path creation problem is given below for node pair (s, d).

Objective:

$$\textit{Maximize} \quad D - \alpha \sum_{(i,j) \in E} (x_{ij} + x_{ji})$$

Subject to:

$$\sum_j x_{ij} - \sum_j x_{ji} = \begin{cases} D, & i = s \\ -D, & i = d \\ 0, & i \neq s, d \end{cases} \qquad \forall i \in V$$

$$x_{ij}, x_{ji} \in \{0, 1\}, \qquad \forall (i,j) \in E$$

$$D \in Z^+$$

where x_{ij} is the decision variable defined as

$$x_{ij} = \begin{cases} 1, & \text{if link } (i,j) \text{ is included in the path set} \\ 0, & \text{otherwise.} \end{cases}$$

In the above ILP formulation, the binary variable x_{ij} denotes the directed flow from node i to node j. Hence, a link can be used at most once in the path set for source destination pair (s, d). The main objective of the above formulation is to maximize the number of link disjoint paths between s and d, which is denoted as D. The second term in the objective function ensures that the optimization not only maximizes D, but also minimizes the total number of hops in the path set. This term is needed since otherwise the optimal solution may include unnecessarily long paths as long as the number of disjoint paths is maximized. The scalar α is a small positive number to ensure that the maximization of D takes higher priority. The link disjoint paths are constructed using the binary decision variables x_{ij} by forming paths along the links with $x_{ij} = 1$. In this manner for each demand a set of possible paths is determined. The set of all paths is denoted by $P = \{P_{ki}\}$ where P_{ki} is the i^{th} path for demand k.

In this formulation, simple link disjoint paths constraint is imposed in calculating the candidate paths, since only single link failures are considered. This approach can easily be generalized to deal with node or multiple link failures, by appropriately defining Shared Risk Link Groups (SRLGs) which was discussed in Section 2.5. For this purpose, the above ILP formulation can be modified by adding an additional constraint that will limit the total flow on links belonging to the same SRLG to 1. This constraint can be written as

$$\sum_{(i,j)\in S_m} (x_{ij} + x_{ji}) \leq 1, \quad \forall m$$

where S_m is the set of links belonging to SRLG m.

After the determination of path sets, methods for choosing the best path pairs for each demand are presented in the following four sections.

3.2 Separate Design of Working and Restoration Paths

For the design of working and restoration paths, the simplest and straightforward approach is to first determine the working paths in such a way that these paths use the minimum amount of network capacity. Then, in the residual network, i.e., the network where each link capacity is decreased by the amount that is used by working paths on that particular link, restoration paths are determined. Once again the aim is to minimize the network capacity utilization. In other words, in this approach, the problems of working and restoration paths designs are treated separately. The goal in designing the working and restoration paths is to minimize the total used capacity in the network while all of the demands are satisfied.

First, working paths are chosen to minimize the total capacity used, or equivalently to maximize the total residual capacity. The total capacity used is defined as the sum of all capacities used on all links in the network, where total residual capacity is the sum of spare capacities on each link in the network. ILP formulation for this problem is given below.

Objective:

$$\textit{Maximize} \quad \sum_l z_l$$

Subject to:

$$\sum_i x_{ki} = 1, \quad \forall k$$

$$\sum_k \sum_i x_{ki} r_k \delta_{ki}^l + z_l \leq C_l, \quad \forall l$$

$$x_{ki} \in \{0,1\}, \quad z_l \geq 0$$

where x_{ki} is the decision variable denoting the selected working path for demand k defined as

$$x_{ki} = \begin{cases} 1, & \text{if } P_{ki} \text{ is chosen as working path for demand } k \\ 0, & \text{otherwise.} \end{cases}$$

The other decision variable z_l denotes the amount of residual capacity on link l. The input parameter r_k is the bandwidth requested by demand k, C_l is the capacity of link l, and δ_{ki}^l is the path-link incidence function defined as

$$\delta_{ki}^l = \begin{cases} 1, & \text{if } P_{ki} \text{ passes through link } l \\ 0, & \text{otherwise.} \end{cases}$$

The objective in the above ILP formulation is to maximize the total residual capacity in the network. The first constraint implies that all demands are satisfied. The second constraint is the link capacity constraint which ensures that the total capacity used on link l does not exceed C_l. The solution of this problem gives the selected path for each demand and the residual capacity on each link after all the demands are routed.

Similarly, restoration paths are chosen such that the total unused capacity in the network is maximized. The set of all possible restoration paths for each demand is obtained by excluding the selected working path from the set of paths found in Section 3.1. In other words, path set P^* is obtained from the path set P by deleting the paths chosen as working paths in the first part of this design. The difference in the design of the restoration paths is that the capacity reserved for restoration on a link can be shared by working paths that are link disjoint. This is possible since only single link failures are considered which implies that two link disjoint working paths cannot fail simultaneously and hence at most one of them will use the reserved restoration capacity. The ILP formulation is given by

Objective:

$$\textit{Maximize} \quad \sum_l z_l$$

Subject to:

$$\sum_i y_{ki} = 1, \quad \forall k$$

$$\sum_k \sum_i y_{ki} r_k \varepsilon_{lkil'} + z_{l'} \le C^*_{l'}, \quad \forall l, \forall l'$$

$$y_{ki} \in \{0,1\}, \quad z_l \ge 0$$

where the decision variable y_{ki} denotes the restoration path chosen for demand k defined as

$$y_{ki} = \begin{cases} 1, & \text{if } P^*_{ki} \text{ is chosen as restoration path for demand } k \\ 0, & \text{otherwise.} \end{cases}$$

Auxiliary variable z_l denotes the residual capacity on link l, and $\varepsilon_{lkil'}$ is an indicator function defined as

$$\varepsilon_{lkil'} = \begin{cases} 1, & \text{if } k^{th} \text{ demand uses link } l \text{ on its active path and } i^{th} \text{ backup path} \\ & \text{uses link } l' \\ 0, & \text{otherwise.} \end{cases}$$

In this formulation the capacity of link l, C_l^*, is obtained after reducing C_l by the total capacity used by working paths on link l. The objective is again to maximize the total residual capacity which is the sum of residual capacities on all links. The first constraint ensures that a restoration path for each demand is selected. The second constraint is the link capacity constraint which inherently takes into account possible sharing of capacity between different restoration paths. This constraint states that in case of failure of link l bandwidth used on all other links do not exceed their available capacities.

The separate design of working and restoration paths aims minimum capacity usage for working and restoration paths. One possible drawback of this approach is that the network capacity may be used in an unbalanced manner, that is some links may be congested while other links are underutilized. As a result, the residual network with an unbalanced load distribution may face problems with routing additional demands and/or increased amount of traffic which may result from uncertainties or demand growth. Furthermore, heterogeneous residual capacity distribution left after the design of working paths may lead to inefficient restoration capacity usage, since capacity sharing probability decreases.

3.3 Separate Design of Working and Restoration Paths With Load Balancing

One solution for balancing uneven distribution of the network residual capacity is considered in this section. The idea is to distribute the load for working paths in a fashion that will guarantee at least some amount of residual capacity on each link and then to design the restoration paths again in a similar manner on the residual network. More formally, the minimum residual capacity (minimum taken over all links) is maximized separately for both working and restoration path design problems. Thus a two step optimization is employed for working and restoration path design problems similar to the previous method.

In the first stage working paths are designed such that the minimum residual capacity is maximized. The ILP formulation for the first step is as follows.

Objective:

$$Maximize \quad z + \alpha \sum_{l} z_l$$

Subject to:

$$\sum_{i} x_{ki} = 1, \quad \forall k$$

$$\sum_{k} \sum_{i} x_{ki} r_k \delta_{ki}^{l} + z_l \leq C_l, \quad \forall l$$

$$z \leq z_l, \quad \forall l$$

$$x_{ki} \in \{0, 1\}, \quad z \geq 0, \quad z_l \geq 0$$

where x_{ki} is the decision variable denoting the selected working path for demand k defined as

$$x_{ki} = \begin{cases} 1, & \text{if } P_{ki} \text{ is chosen as working path for demand } k \\ 0, & \text{otherwise.} \end{cases}$$

Auxiliary variables z_l and z denote the residual capacity on link l, and the minimum residual capacity, respectively, and δ_{ki}^{l} is the path-link incidence indicator function defined as

$$\delta_{ki}^{l} = \begin{cases} 1, & \text{if } P_{ki} \text{ passes through link } l \\ 0, & \text{otherwise.} \end{cases}$$

The objective is to maximize the minimum residual capacity while simultaneously maximizing the total residual capacity in the network. The parameter α is chosen small such that the maximization of z has higher priority. The first constraint ensures that for all demands exactly one working path is chosen. The second constraint states that the capacity used on each link does not exceed the capacity of that link. And the last constraint is used to set z to the minimum of the residual link capacities. The solution for this problem gives the selected working paths for each demand.

Restoration paths are selected in a similar way. The path set P is updated so that the working paths chosen above for each demand are discarded and a reduced path set, P^*, is obtained. And the capacity of each link is reduced by the total capacity used by all working paths on that link, so the set of modified link capacities, $\{C_l^*\}$, is obtained. The ILP formulation for the restoration path design problem is given as

Objective:

$$\textit{Maximize} \quad z + \alpha \sum_l z_l$$

Subject to:

$$\sum_i y_{ki} = 1, \quad \forall k$$

$$\sum_k \sum_i y_{ki} r_k \varepsilon_{lkil'} + z_{l'} \leq C_{l'}^*, \quad \forall l, \forall l'$$

$$z \leq z_l, \quad \forall l$$

$$y_{ki} \in \{0,1\}, \quad z \geq 0, \quad z_l \geq 0$$

where the decision variable y_{ki} denotes the selected restoration path for demand k defined as

$$y_{ki} = \begin{cases} 1, & \text{if } P_{ki}^* \text{ is chosen as restoration path for demand } k \\ 0, & \text{otherwise.} \end{cases}$$

Auxiliary variables z_l and z denote the residual capacity on link l, and the minimum residual capacity, respectively, and the indicator function $\varepsilon_{lkil'}$ is defined as

$$\varepsilon_{lkil'} = \begin{cases} 1, & \text{if the working path for } k^{th} \text{ demand uses link } l \text{ and } P_{ki}^* \text{ uses link } l' \\ 0, & \text{otherwise.} \end{cases}$$

The objective is to maximize the minimum residual capacity while simultaneously maximizing the total residual capacity in network. The first constraint states that for each demand only one path is chosen as the restoration path. The second constraint is the capacity constraint which ensures that in case of failure of link l, the restoration capacity used on each link l' does not exceed the capacity $C^*_{l'}$. This approach is used in order to take into account the possible capacity sharing between restoration paths. And the last constraint sets z to the minimum of the residual capacities. As a result, restoration paths for all demands are selected in a way that aims to balance residual capacities on all links.

3.4 Joint Design of Working and Restoration Paths With Load Balancing

Both design methods described in Sections 3.2 and 3.3 solve the working and restoration paths design problems separately. But it is clear that the two problems interact with each other. Thus, separate solution of these problems may lead to inefficiencies in the overall design. As a simple example, the design of restoration paths can be more efficient if the working paths are designed so that maximum sharing between the restoration paths is obtained. Previously discussed design methods try to minimize the used capacity for working and restoration paths independently. This does not guarantee that the total used capacity is minimized. The reason is that by designing working paths in a suitable manner, possibly using more capacity, the capacity needed for restoration paths can be reduced. Thus the total used capacity for working and restoration paths can be less than the separate design models. In this section a design method which jointly optimizes the working and restoration path design problems with load balancing, is introduced. The ILP formulation for this method is given as

Objective:

$$\textit{Maximize} \quad z + \alpha \sum_{l} z_l$$

Subject to:

$$
\begin{aligned}
&\sum_{i}\sum_{j} v_{kij} = 1, \quad \forall k \\
&v_{kij} = 0, \quad \text{if} \quad i = j, \quad \forall i, \forall j, \forall k \\
&\sum_{k}\sum_{i}\sum_{j} v_{kij} r_k \delta_{ki}^{l'} + \sum_{k}\sum_{i}\sum_{j} v_{kij} r_k \delta_{kj}^{l'} \delta_{ki}^{l} + z_{l'} \leq C_{l'}, \quad \forall l, \forall l' \\
&z \leq z_l, \quad \forall l \\
&v_{kij} \in \{0,1\}, \quad z \geq 0, \quad z_l \geq 0
\end{aligned}
\tag{3.1}
$$

where v_{kij} is the decision variable denoting the working and restoration paths chosen for demand k defined as

$$
v_{kij} = \begin{cases} 1, & \text{if } P_{ki} \text{ and } P_{kj} \text{ are chosen as working and restoration paths,} \\ & \text{respectively, for demand } k \\ 0, & \text{otherwise.} \end{cases}
$$

Auxiliary variables z_l and z denote the residual capacity on link l, and the minimum residual capacity, respectively, and δ_{ki}^{l} is the indicator function defined as

$$
\delta_{ki}^{l} = \begin{cases} 1, & \text{if } P_{ki} \text{ uses link } l \\ 0, & \text{otherwise.} \end{cases}
$$

The objective is to maximize the minimum residual capacity while simultaneously maximizing the total residual capacity in the network in order to evenly distribute the residual capacity as discussed in Section 3.3. In the objective function, the parameter α is chosen small so that the maximization of z takes higher priority. The first constraint ensures that one working and one restoration path is chosen for each demand. The second constraint states that the same path cannot be chosen as both working and restoration path for any demand. The third constraint is the capacity constraint on link l' stating that in the case of failure of link l, the capacity used for working (first term) and restoration paths (second term) on link l' cannot exceed its capacity $C_{l'}$. The last constraint is used to set z to the minimum of the residual link capacities.

3.5 Joint Design of Working and Restoration Paths With Weighted Load Balancing

In a typical network, the traffic injected to the network from some nodes may be much more than the others. Besides, demands between particular source and destination pairs may be higher than the other node pairs. As a result, some links in the network may face more traffic depending on the network topology and traffic distribution.

In the case where all link weights are equal, as in the previous method, the goal of the optimization is to distribute the residual capacity as uniform as possible over the network, neglecting the relative importance of each link. This approach may cause some links to become bottlenecks since the capacity usage on links vary depending on the factors stated above. It may be a better design approach to have more residual capacities on links that are candidates of being overloaded, e.g. links with high estimated utilization levels. This is accomplished by assigning each link a weight which is inversely proportional with the estimated utilization level on that link. The links with high probability of usage are given less weight, so that maximizing the minimum of the weighted residual capacities ensures that these links will have more residual capacities. Hence, the residual capacity on each link will be proportional with the importance of that link, which may increase the traffic that can be carried over the network. The link weight can also be used to increase the reliability of the network by assigning higher weights to links with better reliability.

This design approach is similar to the joint optimization formulation given in Section 3.4. The difference is that, in order to take into account the relative importance of each link, the constraint stated in (3.1) is replaced by

$$z \leq \omega_l z_l$$

where ω_l denotes the relative weight of link l. Thus, this method is a generalization of the method in Section 3.4, since giving all links unity weights results in that method.

In this work, link weights are determined based on the expected utilization levels on each link. For each source and destination pair a demand with 1 unit capacity requirement is created and the corresponding path set is determined. The capacity used on each link by these demand sets are taken as the expected utilization level, since it is assumed that the demands between any node pair is equi-probable. Then each link is given a weight which is inversely proportional with the expected utilization level.

3.6 Traffic Uncertainty Modeling

The demands on a network are not deterministic quantities. They are typically obtained from some traffic measurements and forecasts, and link capacities are designed based on traffic projections. These capacities are expanded typically every few years in order to cope up with increasing traffic demand and to relieve bottlenecks in some part of the network occurring as a result of deviations from traffic projections. Hence, there is always an uncertainty in the demand structure. An important performance measure of any working and restoration paths design methodology is its robustness against traffic uncertainty. The designed network should be able to delay the trivial and expensive solution of capacity expansion as much as possible by efficiently using the available capacity.

To compare the relative efficiencies of four methods developed in this work, traffic uncertainty is modeled as additional demands on top of the given demands. We then compare the design approaches by calculating the number of additional demands that can be carried for each design. In all methods designed working paths are not allowed to be reconfigured in order to minimize the effect of reconfiguration on carried traffic. But the existing restoration paths can be re-optimized in order to maximize the number of carried new connection requests. The performance measure is taken as the number of additional demands the network can carry under each design.

The ILP formulation for traffic uncertainty modeling is given below. The subscript k is used for already routed demands and k_e is used to denote the additional demands. The path set P is updated so that the working paths for existing demands are discarded, and the reduced path set P^* is obtained. P^e is the path set for additional demands. The capacity of each link is reduced by the total capacity used by all working paths on that link, so the set of modified link capacities, $\{C_l^*\}$, is obtained.

Objective:

$$Maximize \quad \sum_{k_e} \sum_i \sum_j v_{k_e ij}$$

Subject to:

$$\sum_i y_{ki} = 1, \quad \forall k$$

$$v_{k_e ij} = 0, \quad \text{if} \quad i = j, \quad \forall i, \forall j, \forall k_e$$

$$\sum_i \sum_j v_{k_e ij} \leq 1, \quad \forall k_e$$

$$\sum_{k_e} \sum_i \sum_j v_{k_e ij} r_{k_e} \delta^{l'}_{k_e i} + \sum_{k_e} \sum_i \sum_j v_{k_e ij} r_{k_e} \delta^{l'}_{k_e j} \delta^{l}_{k_e i} +$$

$$\sum_k \sum_i \varepsilon_{lkil'} y_{ki} r_k \leq C^*_{l'}, \quad \forall l, \forall l'$$

$$v_{k_e ij} \in \{0, 1\}, \quad y_{ki} \in \{0, 1\}$$

where v_{k_eij} is the decision variable denoting the working and restoration paths chosen for demand k_e defined as

$$v_{k_eij} = \begin{cases} 1, & \text{if } P^e_{k_ei} \text{ and } P^e_{k_ej} \text{ are chosen as working and restoration paths,} \\ & \text{respectively, for demand } k_e \\ 0, & \text{otherwise} \end{cases}$$

and y_{ki} is the decision variable denoting the restoration path chosen for demand k defined as

$$y_{ki} = \begin{cases} 1, & \text{if } P^*_{ki} \text{ is chosen as restoration path for demand } k \\ 0, & \text{otherwise.} \end{cases}$$

The indicator function δ^l_{ki} is the path-link incidence function defined by

$$\delta^l_{k_ei} = \begin{cases} 1, & \text{if } P^e_{k_ei} \text{ uses link } l \\ 0, & \text{otherwise} \end{cases}$$

and $\varepsilon_{lkil'}$ is the indicator function defined as

$$\varepsilon_{lkil'} = \begin{cases} 1, & \text{if the existing working path for } k^{th} \text{ demand uses link } l \text{ and } P^*_{ki} \\ & \text{uses link } l' \\ 0, & \text{otherwise.} \end{cases}$$

The objective is to maximize the number of additional demands that are carried. The first constraint ensures that a restoration path is selected for each existing demand. The second constraint states that the restoration paths cannot be the same with the working paths for additional demands. The third constraint ensures that at most one working and restoration path pair is chosen for each additional demand k_e. The last constraint is the capacity constraint for link l' stating that in case of failure of any link l the capacity constraint on link l' is not violated. The first term on the left-hand side is the necessary capacity for working paths on link l' corresponding to additional demands, and the second and the third terms are the restoration capacities required for additional and existing demands respectively, in case of failure of link l.

3.7 Numerical Results

To compare the relative efficiency of each design method based on traffic uncertainty modeling, simulations using the CPLEX optimization toolbox are performed. The capacity usage characteristics and robustness to the traffic and demand variability are determined for each method. The number of constraints and variables for the seperate and joint design problems are given in Table 3.1, for a typical simulation. For separate design methods there are two parts. Number of variables are 241 and 211 for active path and backup path design problems, respectively. Number of constraints are 130 and 2630 for these two parts. Joint design methods formulate the active and backup path design problems as a single problem, and there are 271 variables and 2630 constraints in these formulations.

Design Method	paths	# variables	# constraints
Separate Design (method1, method2)	active paths backup paths	241 211	130 2630
Joint Design (method3, method4)	both paths	271	2630

Table 3.1: Number of variables and constraints for the seperate and joint design approaches

For simulation purposes, the mesh network shown in Figure 3.2 is used. The network has a planar topology with 32 nodes and 50 links. Links are thought to be bidirectional. Demand from any source to any destination node is assumed to be equi-probable. The capacity of each link is determined based on this assumption. Paths for all source and destination pairs are found, and the number of usage of each link is determined. Proportional to this number each link is assigned a capacity. In addition to this capacity assignment a fixed amount of capacity is added to each link for robustness.

Afterwards, a demand set is created to be imposed on the mentioned network topology. This demand set consists of 80 demands with randomly chosen

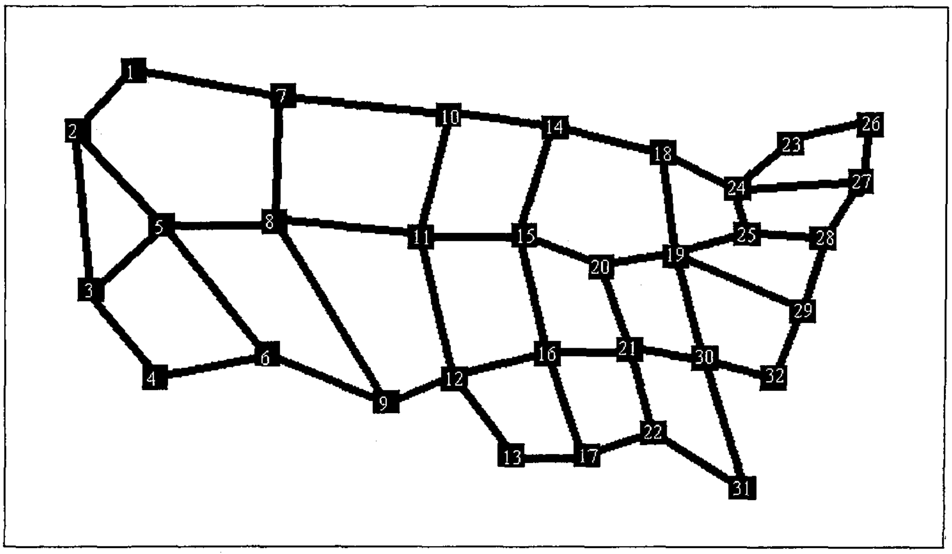

Figure 3.2: Network topology used in simulation.

source and destination pairs, to be consistent with the assumption made in capacity planning. Each demand has a capacity requirement selected randomly from the set {1,2,3} unit capacities. Based on this demand set, the working and restoration paths are designed using four aforementioned design methods, namely Separate Design of Working and Restoration Paths (method 1), Separate Design of Working and Restoration Paths with Load Balancing (method 2), Joint Design of Working and Restoration Paths with Load Balancing (method 3), and Joint Design of Working and Restoration Paths with Weighted Load Balancing (method 4).

Typical capacity usage characteristics for these methods are demonstrated in Figure 3.3, for a particular demand set. Bottom and the middle rectangles denote the network capacity used for working and restoration paths, respectively. Top rectangles show the resulting residual network capacity. The first method, as expected, uses the minimum capacity for working paths. With the load balancing approach of the second method the capacity usage for working paths increases, but the capacity needed for restoration paths decreases much more. Hence, more

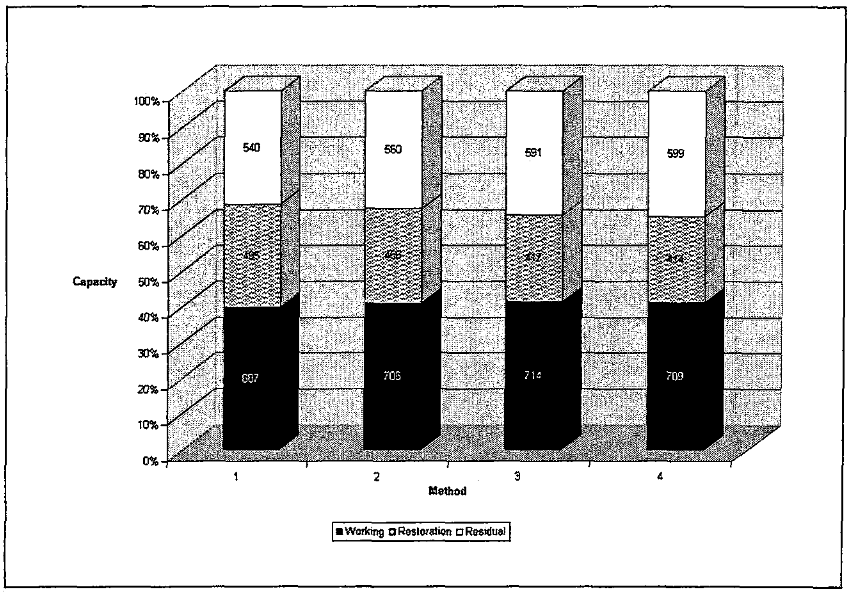

Figure 3.3: Comparison of capacity usage for design methods.

residual capacity is left with the second method, which demonstrates the advantage obtained with load balancing from a capacity usage perspective. Similarly, the third and the last method use still more capacity for working paths, which again decreases the restoration capacity requirement and hence increases the total network residual capacity. These enhancements caused by joint design show the strong relationship between working and restoration path designs. Therefore, one can conclude that, from a total capacity usage point of view, there is significant enhancements going from method 1 to method 4.

Efficient capacity usage does not necessarily imply minimum capacity usage. The distribution of the residual capacity over the network is also an important issue, since uneven distribution may lead some links to become bottlenecks. Such a situation will naturally degrade the robustness to the traffic uncertainties. In order the compare the design approaches from this point of view, histograms of capacity usage on links are plotted in Figure 3.4 for a typical case. The first row of figures show the amount of residual capacity left versus the number of links which have this amount of capacity after each design approach. For the first method, the residual capacity distribution is unbalanced since several links have no residual capacity, while some others have much capacity left. Second method results in a better capacity distribution by eliminating the zero residual capacity links. Third method performs the best in terms of residual capacity distribution, since the minimum residual link capacity is much more than the ones attained by the first two methods. The result of the last method seems to be close to the third method. Another approach to evaluate the ability of evenly distributing the residual capacity may be to look at the residual capacity ratio distribution. The idea behind this approach is the fact that, since the links with higher capacities may subject to higher traffic demand, having residual capacities that are proportional with the link capacities may increase the robustness to the demand uncertainties. To evaluate the performance of each method from this perspective, the second row of Figure 3.4 plots the residual capacity ratio (i.e., residual capacity of a link divided by its capacity) distributions obtained by each method. Last two methods again have better residual capacity distributions, since the variance of the residual capacity ratio decreases going from the first to last method.

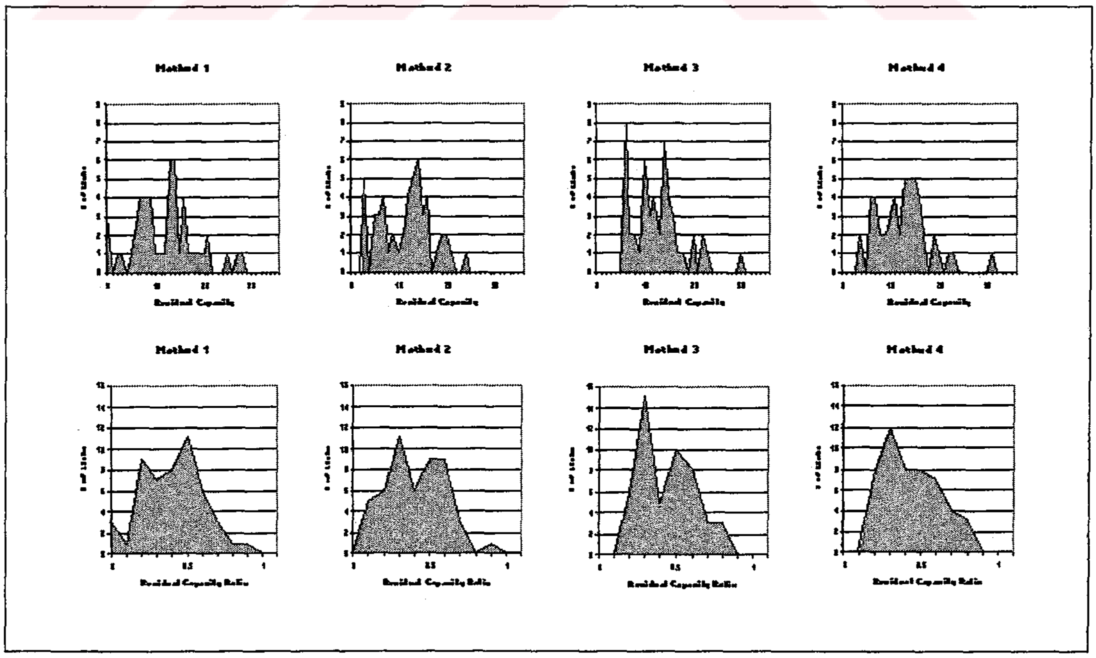

Figure 3.4: Distribution of residual capacity for each method.

Next, these methods are compared in terms of their abilities to cope up with carrying additional demands occurring as a result of traffic uncertainty. For each set of existing demands 20 demand sets are created where each set contains 20 or 25 additional demands. These demands have also randomly chosen source and destination nodes, and capacity requirements of 1, 2 or 3 unit capacities. This simulation is repeated with 10 different original demand sets. The average number of additional demands carried by each method for each demand set is tabulated in Table 3.2.

Demand Set	# demands	Method 1	Method 2	Method 3	Method 4
1	25	19.45	20.15	21.55	21.80
2	25	19.80	20.70	21.75	22.20
3	20	18.75	19.10	19.55	19.55
4	20	18.10	18.50	19.00	18.75
5	20	18.05	18.00	18.60	18.65
6	20	17.25	17.95	17.95	18.10
7	20	16.50	18.10	18.00	18.40
8	20	18.85	19.60	19.65	19.65
9	20	17.20	17.35	19.05	19.35
10	20	17.55	18.60	18.60	18.75

Table 3.2: Number of additional demands carried by each method.

These results clearly show the relative performance of each design method. The robustness against traffic uncertainty increases going from method 1 to method 4. These results are in parallel with capacity usage results. But the improvement in the additional demand carrying capability is much more pronounced than the increase in the residual network capacity. This fact verifies that the distribution of residual capacity over the network is at least as important as the size of total residual capacity. A more clear understanding of relative performance can be extracted by plotting the average percentage of additional demands rejected by each method, which is shown in Figure 3.5.

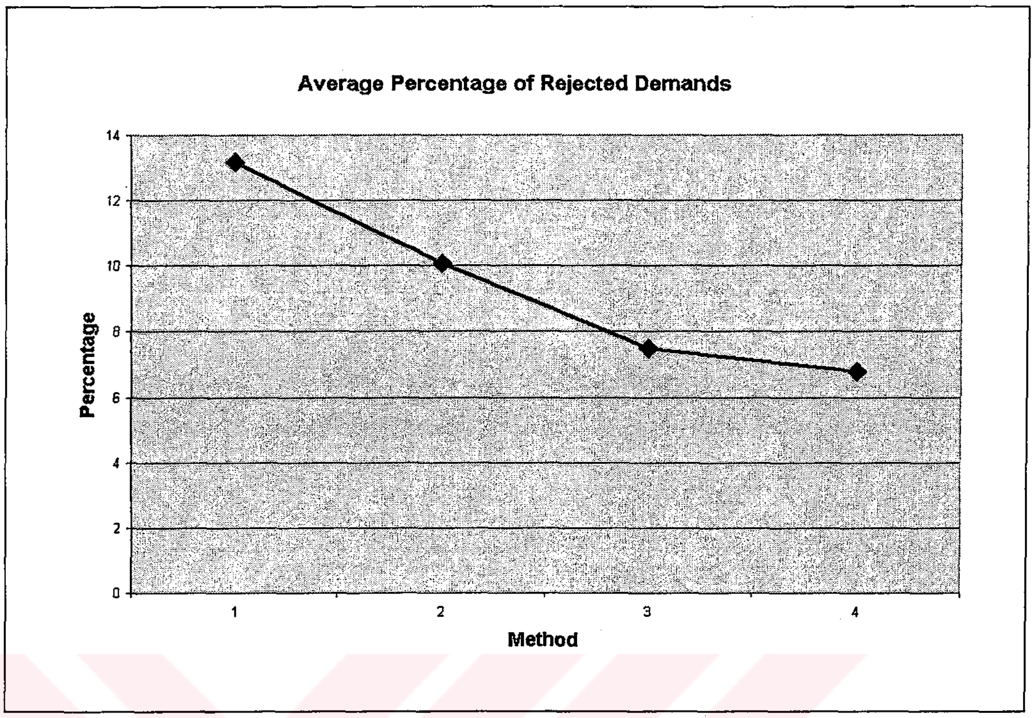

Figure 3.5: Percentage of rejection for each method.

In this figure it is apparent that the worst performance belongs to the first method, and there is a 3% decrease with the second method. Another 3% decrease in rejection is obtained with the third method and the last method still decreases the rejected additional demands by nearly 1%. To sum up, moving from the first method to the last method there are significant improvements in the network capacity usage and robustness to traffic uncertainty.

In this chapter, traffic engineering and performance comparison methods are developed for MPLS networks. Since GMPLS, as described in Section 2.4, has a similar architecture with MPLS, these methods are also valid on optical networks using GMPLS as a forwarding technology. In the next chapter, traffic engineering algorithms are extended to the case of GMPLS, with some modifications that are needed to take into account the optical layer constraints.

Chapter 4

REGENERATOR PLACEMENT AND TRAFFIC ENGINEERING WITH RESTORATION IN GMPLS NETWORKS

The methods and results obtained in Chapter 3 can be extended to the optical networks with some modifications. Traffic Engineering for optical networks also aims efficient capacity usage to enhance the traffic carrying capacity of the network. The methodology used in this section follows the one used in the last section. Same routing methods are studied and corresponding ILP models are used. Based on the numerical results which are obtained using CPLEX optimization software package, method comparisons are discussed.

As in the previous chapter, the methods are intended to be usable for aggregate demands on a core network with offline calculation. The demand uncertainty is modeled, and performances of design methods are compared based on this model.

The restoration mechanisms are the same as described in Chapter 3. Namely, single link failures and generalization to node or multiple link failures are considered. The protection scheme is 1:1 protection switching which uses pre-established and pre-reserved restoration paths to establish global repair of the failed path.

The nature of the optical physical layer imposes some modifications for the methods used in MPLS networks. First, with current technology at hand, the physical layer constraints limit the maximum transmission range for optical signals without regeneration. Beyond this length, the optical signals are degraded, and the SNR becomes too low to be usable. Hence optical or electrical signal regeneration is needed in some nodes in the network. In an optical network, the determination of efficient points for placing regenerators is an important problem. It is economically advantageous to place regenerators at selected nodes instead of using regeneration at all nodes. Once regenerators are located, path sets should be determined subject to the optical transmission constraints.

SRLG, explained in Section 2.5, is an important concept in survivable optical networking. In this section, path selection subject to optical layer constraints is developed, and possible extension of using SRLG information is presented. The placement of regenerators problem is addressed, and two different algorithms are developed and compared with each other. Finally, four traffic engineering approaches are studied for optical networks, and their relative efficiencies are compared again using the traffic uncertainty modeling.

4.1 Path Set Creation in the Optical Network

For a particular demand, finding the maximum number of link disjoint paths is a more complex operation in an optical network with physical constraints compared to the case without such constraints which was formulated in Section 3.1. The main reason is the existence of signal regenerators in the network that affect the path set creation process. The maximum range constraint which limits the length of any path segment between the regeneration points must also be taken into account in this process.

For this approach the exact number of link disjoint paths must be known before the selection of paths. In order to determine the maximum number of link disjoint paths between any source and destination pair subject to the optical transmission limitations, the formulation in Section 3.1 is used to generate a starting value. Then, this number is decremented at each step until the following ILP has a feasible solution.

Objective:

$$\textit{Minimize} \quad \sum_i \sum_j \sum_k y_{ijk} + \alpha \sum_i \sum_j \sum_k y_{ijk} r_i$$

Subject to:

$$\sum_j y_{ijk} - \sum_j y_{jik} = \begin{cases} 1, & i = s \\ -1, & i = d \\ 0, & i \neq s, d \end{cases} \qquad \forall i, \forall k \qquad (4.1)$$

$$\sum_k (y_{ijk} + y_{jik}) \leq 1, \quad \forall i, \forall j \qquad (4.2)$$

$$w_{ik}^{+} - w_{jk}^{-} + y_{ijk}(d_{ij} + M) \leq M, \quad \forall i, \forall j, \forall k \qquad (4.3)$$

$$w_{ik}^{+} = w_{ik}^{-}(1 - r_i), \quad \forall i, \forall k \qquad (4.4)$$

$$w_{ik}^{-} \leq R_{max}, \quad \forall i, \forall k \qquad (4.5)$$

$$w_{sk}^{+} = w_{sk}^{-} = 0, \quad \forall k \qquad (4.6)$$

$$y_{ijk} \in \{0, 1\}$$

where y_{ijk} is the decision variable defined as

$$y_{ijk} = \begin{cases} 1, & \text{if } k^{th} \text{ path uses link } (i,j) \\ 0, & \text{otherwise} \end{cases}$$

and the indicator function r_i denotes whether the i^{th} node is a regeneration point or not, i.e.,

$$r_i = \begin{cases} 1, & \text{if regeneration exists at } i^{th} \text{ node} \\ 0, & \text{otherwise.} \end{cases}$$

The length or alternatively the attenuation of link (i,j), is given by d_{ij}, and D is the number of link disjoint paths between the source and destination nodes. w_{ik}^{-} and w_{ik}^{+} denote the path lengths for k^{th} flow into and out of node i, respectively. R_{max} is the maximum allowable length (attenuation) of a path segment.

In this formulation, the objective is to minimize the total number of hops in the path set. The secondary objective is to minimize the total number of regenerators that any path passes through. This is established by using a small number, α as a coefficient for the second summation in the objective function.

Constraint (4.1) is used to ensure path continuity for each path. Constraint (4.2) states that any link can be used at most once in the path set. The second term in the summation is needed since the links are bidirectional. Constraint (4.3) is used to determine the length of the path segment from the last regeneration or source node to any node on the path. M is a big number used to include the effects of only selected links, while others are ignored. Constraint (4.4) sets the length of the path segment to zero if regeneration occurs. Constraint (4.5) limits the length of any path segment to be smaller than the maximum range, and constraint (4.6) is used to initialize the w values at the source node.

If this problem turns out to be infeasible, the number of link disjoint paths, D is decremented, and the same problem is solved with this new value. The solution of this problem gives the set of links each path uses, and with appropriate ordering of the links desired path set is obtained.

The ILP formulation for the path set generation problem can be extended such that other additive optical transmission impairments can be incorporated into the formulation by adding extra constraints similar to (4.3)-(4.6). SRLG information can be included in the path set creation formulation by adding a constraint that will limit the total flow on links belonging to the same SRLG to 1. This constraint can be written as

$$\sum_{k} \sum_{(i,j) \in S_m} (y_{ijk} + y_{jik}) \leq 1, \quad \forall m$$

where S_m is the set of links belonging to SRLG m.

In this section, we have assumed that regenerator locations are known. In the next section, regenerator placement problem is studied.

4.2 Regenerator Placement

Due to the optical physical layer impairments, the length of path segments are limited. Hence regeneration of optical signals by either optical or electrical means is inevitable. It is economically beneficial to have regeneration at some selected nodes instead of regeneration at all nodes. In this section we study the problem of determining where regenerators should be placed. The requirement is to have at least two feasible link disjoint paths (one for working path and the other for the restoration path) between each source and destination pair in the network such that both paths satisfy optical transmission constraints.

In this problem there is a trade-off between the number of regenerators and the average path length used by working and restoration paths. Having less number of regenerators causes the paths to be longer since some traffic have to pass through regenerators which are not on their shortest path. On the other hand, in order to be able to use shortest paths, a large number of regenerators have to be placed in various nodes. In this work, the cost of regeneration is assumed to be the dominant factor in determining the total network cost.

For the exact solution of this optimization problem the formulation given in Section 4.1, can be extended to determine the r_i coefficients such that for each source and destination pair with number of paths D is set equal to 2, there is a feasible solution. The ILP formulation corresponding to this problem is given by

Objective:

$$\textit{Minimize} \quad \sum_i r_i$$

Subject to:

$$\sum_j y_{ijk}^{sd} - \sum_j y_{jik}^{sd} = \begin{cases} 1, & i = s \\ -1, & i = d \\ 0, & i \neq s,d \end{cases} \qquad \forall i, \forall k, \forall (s,d)$$

$$\sum_k (y_{ijk}^{sd} + y_{jik}^{sd}) \leq 1, \quad \forall i, \forall j, \forall (s,d)$$

$$w_{ik}^{sd+} - w_{jk}^{sd-} + y_{ijk}^{sd}(d_{ij} + M) \leq M, \quad \forall i, \forall j, \forall k, \forall (s,d)$$

$$w_{ik}^{sd+} = w_{ik}^{sd-}(1 - r_i), \quad \forall i, \forall k, \forall (s,d)$$

$$w_{ik}^{sd-} \leq R_{max}, \forall i, \quad \forall k, \forall (s,d)$$

$$w_{sk}^{sd+} = w_{sk}^{sd-} = 0, \quad \forall k, \forall (s,d)$$

$$y_{ijk}^{sd} \in \{0,1\}, \quad r_i \in \{0,1\}$$

where y_{ijk}^{sd} is the decision variable defined as

$$y_{ijk}^{sd} = \begin{cases} 1, & \text{if } k^{th} \text{ path between } (s,d) \text{ nodes uses link } (i,j) \\ 0, & \text{otherwise} \end{cases}$$

and r_i denotes the decision variable defined as

$$r_i = \begin{cases} 1, & \text{if regeneration exists at } i^{th} \text{ node} \\ 0, & \text{otherwise.} \end{cases}$$

The length or alternatively the attenuation of link (i, j), is given by d_{ij}. w_{ik}^{sd-} and w_{ik}^{sd+} denote the path lengths for k^{th} flow between s and d nodes into and out of node i, respectively. R_{max} is the maximum allowable length (attenuation) of a path segment. M is a big number used to neglect the effects of links which are not selected.

In this formulation, the objective is to minimize the number of regenerators needed to obtain at least two feasible paths between any source and destination pair. The constraints are the same with the ones in the formulation given for path set creation in Section 4.1, except the fact that here the constraints are duplicated for each source and destination pair.

But this problem has a very large size, hence this approach is not applicable except for very small networks. Therefore, heuristic approaches are needed for the solution of regenerator placement problem. In this section we present two heuristic algorithms and compare their performances.

4.2.1 Heuristic Algorithm 1

This method is similar to the maximum-descent algorithm. At each iteration, a regenerator is placed at the node which eliminates maximum number of infeasible paths between all source and destination pairs. The method aims to place minimum number of regenerators needed to guarantee at least two link disjoint paths between each source and destination pair. The algorithm for this method is described below where N corresponds to the number of nodes in the network.

1. Initialization: $r_i = 0$ for $1 \leq i \leq N$, $n_{reg} = 0$, $done = 0$, $g_{ij} = 0$ for $i \neq j$ and $1 \leq i, j \leq N$.

2. Solve the path set creation formulation given in Section 4.1 for each source and destination pair with number of paths $D = 2$. Set $g_{sd} = 1$ for the source and destination pairs for which a feasible solution exists.
3. If $g_{ij} = 1$ for all $i \neq j$, set *done* $= 1$.
4. While not *done* and $n_{reg} < N$,
    - 4.1 Set $f_i = 0$ for $1 \leq i \leq N$.
    - 4.2 For all nodes i with $r_i = 0$ do
        - 4.2.1 Set $r_i = 1$.
        - 4.2.2 Solve the path set creation formulation for all source and destination pairs (s, d) for which $g_{sd} = 0$.
        - 4.2.3 Set $f_i =$ number of feasible solutions.
        - 4.2.4 Set $r_i = 0$.
    - 4.3 Set $r_i = 1$ for i which maximizes f_i; increment n_{reg}; set $g_{sd} = 1$, for which feasible solutions for source-destination pairs (s, d) are obtained by setting $r_i = 1$.
    - 4.4 If $g_{ij} = 1$ for all $i \neq j$, set *done* $= 1$.
5. If not *done*, there is no feasible solution for this problem.

   Else the solution is the set of nodes for which $r_i = 1$.

Since the paths are symmetric, i.e., the path from node s to node d is the reverse of the path from node d to node s, half of the paths can be calculated to decrease the amount of computation.

This algorithm requires the solution of the optimization formulation for each source and destination pair for each candidate node of regeneration. Hence it has a computational complexity of $O(N^3)$ for determining the location of each regenerator. In the next section, a more efficient algorithm is developed to solve the regeneration placement problem.

4.2.2 Heuristic Algorithm 2

The second method uses a different approach: Instead of trying all nodes for each regenerator placement, which is computationally inefficient, the paths are determined so that the number of required regeneration is minimized. Then the regenerator is placed at the most demanding node. Hence the computational complexity of this approach is $O(N^2)$ for determining the location of each regenerator. The algorithm for this method is given below.

1. Initialization: $r_i = 0$ for $1 \le i \le N$, $n_{reg} = 0$, *done* $= 0$.
2. While not *done* and $n_{reg} < N$,
    2.1 For each source-destination pair (s, d), calculate two link disjoint paths, using the following ILP formulation:

Objective:

$$\textit{Minimize} \quad \sum_{i \in R_{sd}} \sum_{k} m_{ik} + \alpha \sum_{i \in R_{sd} \setminus \{d\}} \sum_{j} \sum_{k} y_{ijk}$$

Subject to:

$$\sum_{j} y_{ijk} - \sum_{j} y_{jik} = \begin{cases} 1, & i = s \\ -1, & i = d \\ 0, & i \neq s, d \end{cases} \quad \forall i, \forall k \tag{4.7}$$

$$\sum_{k} (y_{ijk} + y_{jik}) \le 1, \quad \forall i, \forall j \tag{4.8}$$

$$w_{ik}^{+} - w_{jk}^{-} + y_{ijk}(d_{ij} + M) \le M, \quad \forall i, \forall j, \forall k \tag{4.9}$$

$$w_{ik}^{+} = w_{ik}^{-}(1 - r_i), \quad \forall i, \forall k \tag{4.10}$$

$$\frac{1}{R_{max}} \, w_{ik}{}^{-} - m_{ik} \le 1, \quad \forall i \in R_{sd}, \forall k \tag{4.11}$$

$$w_{sk}^{+} = w_{sk}^{-} = 0, \quad \forall k \tag{4.12}$$

$$y_{ijk} \in \{0, 1\}, \quad m_{ik} \ge 0, \quad m_{ik} \in Z$$

In this formulation y_{ijk}, r_i, d_{ij}, w_{ik}^{-}, w_{ik}^{+}, R_{max}, and M are same as defined in Section 4.2.1, and R_{sd} is the set of nodes defined as

$R_{sd} = \{i : i = d \text{ or } r_i = 1\}$.

The auxiliary variable m_{ik} denotes the minimum number of regenerators required to make the section of the k^{th} path between s and d up to node $i \in R_{sd}$ feasible. For instance, if a path length into some node i is smaller than R_{max}, m_{ik} is 0, which indicates that there is no need to place a regenerator on this path segment. On the other hand if $w_{ik}^{-} = 2.5 \times R_{max}$, then $m_{ik} = 2$, which implies that at least two regenerators have to be placed on this path segment to make it feasible.

The objective of this formulation is to minimize the sum of minimum number of regenerators needed to make each path feasible. As a secondary objective, the total number of hops in the path set is minimized. This is accomplished by weighting the first term in the objective function by a small number, α.

Constraint (4.7) is used to ensure path continuity for each path. Constraint (4.8) states that any link can be used at most once in the path set. The second term in the summation is needed since the links are thought to be bidirectional. Constraint (4.9) is used to determine the length of the path segment from the last regeneration or source node to any node on the path. Constraint (4.10) sets the length of the path segment to zero if regeneration occurs. Constraint (4.11) is used to set m_{ik} to the minimum number of regenerators required to make the path feasible, and constraint (4.12) is used to initialize the w values at the source node.

2.2 Determine $\{t_i\}$, where t_i is the number of regeneration points assigned to node i by calling $ComputeRegenerationPoints(i)$.

2.3 Set $t_{max} = \max_i\{t_i\}$.

2.4 If $t_{max} = 0$, set *done* $= 1$,

Else, set $r_i = 1$, for node for which $t_i = t_{max}$, increment n_{reg}.

```
3. If not *done*, there is no feasible solution for this problem.
   Else, the solution is the set of nodes $i$ for which $r_i = 1$.
```

Upon calculation of the path set using the above formulation, the best node for regeneration is determined. For this aim, at step 2.2 each node i is assigned a t_i value which is initially 0. For each path, at the i^{th} node where the length of the path just exceeds the maximum allowable length R_{max}, the value of t_i is incremented. As a result, the node with the maximum value of t_i is chosen as the best node for regeneration. Regenerator placement is continued until all source and destination pairs have at least two feasible link disjoints paths.

The algorithm used by $ComputeRegenerationPoint(i)$ for computing t_i in Step 2.2 is given by

```
2.2 For each path do
    2.2.1 Set length $d = 0$
    2.2.2 For each link $l = (i, j)$ on the path
        2.2.2.1 Set $d_{last} = d$, and $d = d + w_l$ where $w_l$ is the length of link $l$.
        2.2.2.2 If $d > R_{max} > d_{last}$, $t_i = t_i + 1$ and then set $d = 0$.
```

4.3 Numerical Results on Regenerator Placement

Using the heuristic methods developed for regeneration placement, numerical results are obtained for the network shown in Figure 3.2. In these simulations three different values for R_{max} are used, namely R_{max} = 1500, 2000 and 2500. The results are tabulated in Table 4.1, where the nodes selected for regeneration are written in the order they are selected by the algorithms.

R_{max}	Algorithm 1	Algorithm 2
2500	11, 15	7, 15
2000	11, 8, 21, 9	8, 10, 16, 12, 15
1500	21, 11, 9, 5, 19, 7	11, 5, 9, 21, 7, 14, 19

Table 4.1: Regeneration nodes obtained by heuristic algorithms.

For a maximum range of 2500, both algorithms find two regeneration points. For other R_{max} values the second method results in one more regeneration node than the first method. Both algorithms find similar nodes for all R_{max} values. Efficiencies of the two algorithms from a traffic engineering point of view are evaluated in the next section.

4.4 Design of Working and Restoration Paths with Regenerators

Although the path set creation in optical networks significantly differs from its counterpart in the last chapter, same traffic engineering approaches can be applied without any modification after the path sets for each demand are determined. Using the traffic engineering methods developed in Chapter 3, the performance of each method subject to the optical layer impairments and regeneration constraints is determined. Traffic uncertainty modeling of Section 3.6 is used to compare the robustness of each method to uncertainties in the demand structure.

The network topology given in Section 3.7 is used in order to compare the design methods over an optical network under optical layer constraints. 10 different demand sets, each consisting of 80 demands with randomly chosen source and destination points, are created. Each demand has a random capacity requirement of 1,2 or 3 unit capacities. Corresponding to each demand set, 20 additional demand sets, each having 20 random demands, are created. The average number of additional demands that can be carried is used as the performance measure. Optimization problems are solved using the CPLEX optimization software package for three different maximum range constraints and using the regeneration points obtained in Section 4.3. Same demand sets are used with each regenerator placement algorithm for comparison purposes.

		Method 1		Method 2		Method 3		Method 4	
Set	# demands	alg1	alg2	alg1	alg2	alg1	alg2	alg1	alg2
1	20	17.90	19.05	18.05	19.20	18.10	19.55	18.20	19.70
2	20	16.90	19.35	16.95	19.60	17.70	19.65	18.00	19.75
3	20	14.85	19.65	16.95	19.65	17.95	19.65	18.70	19.80
4	20	14.55	17.15	14.60	17.85	16.10	18.05	16.55	18.30
5	20	18.80	19.35	19.05	19.35	19.20	19.35	19.45	19.60
6	20	16.55	18.85	17.35	18.85	18.20	19.85	18.70	19.95
7	20	16.15	18.00	16.15	18.00	16.80	18.45	17.10	18.80
8	20	16.00	19.55	17.50	19.55	18.80	19.80	19.05	19.85
9	20	18.75	19.65	18.75	19.80	19.40	19.85	19.70	19.95
10	20	18.00	18.85	18.50	19.35	18.70	19.45	19.00	19.70

Table 4.2: Number of additional demands carried by each method for $R_{max} = 1500$.

		Method 1		Method 2		Method 3		Method 4	
Set	# demands	alg1	alg2	alg1	alg2	alg1	alg2	alg1	alg2
1	20	18.20	18.70	18.30	18.80	18.55	18.85	18.65	19.00
2	20	17.60	17.45	17.80	18.30	17.95	18.45	18.15	18.70
3	20	17.05	18.90	17.05	19.30	18.05	19.70	18.25	19.85
4	20	16.75	18.00	16.95	18.05	17.20	18.20	17.50	18.55
5	20	17.30	17.35	17.30	17.50	17.50	17.50	17.60	17.70
6	20	17.65	17.45	19.00	19.35	19.35	19.45	19.50	19.55
7	20	19.30	19.40	19.50	19.40	19.50	19.70	19.60	19.90
8	20	16.45	19.10	17.45	19.35	18.70	19.70	19.05	19.95
9	20	14.65	18.30	15.60	19.85	18.45	19.90	19.00	19.80
10	20	14.25	18.30	16.35	18.30	17.60	19.30	17.85	19.55

Table 4.3: Number of additional demands carried by each method for $R_{max} = 2000$.

The results obtained for $R_{max} = 1500$ is shown in Table 4.2. For each design method, number of additional demands that can be carried is tabulated for both regenerator placement algorithms. In a similar manner, Tables 4.3 and 4.4 shows the results obtained for $R_{max} = 2000$ and $R_{max} = 2500$, respectively.

Set	# demands	Method 1		Method 2		Method 3		Method 4	
		alg1	alg2	alg1	alg2	alg1	alg2	alg1	alg2
1	20	18.95	19.25	18.95	19.25	19.10	19.40	19.20	19.55
2	20	14.95	17.70	15.75	18.65	17.15	18.80	17.40	19.10
3	20	19.05	19.15	19.05	19.40	19.05	19.50	19.45	19.60
4	20	17.20	17.25	18.50	17.25	19.10	18.55	19.25	18.70
5	20	15.65	18.70	15.75	18.90	15.75	19.05	16.25	19.30
6	20	17.30	19.65	18.90	19.70	18.90	19.70	19.40	19.85
7	20	16.05	18.90	16.20	18.95	17.45	19.45	17.75	19.70
8	20	18.90	19.35	18.90	19.50	18.90	19.50	19.05	19.65
9	20	17.65	19.95	17.75	19.95	17.80	20.00	18.00	20.00
10	20	19.25	18.70	19.25	18.70	19.25	19.90	19.30	20.00

Table 4.4: Number of additional demands carried by each method for $R_{max} = 2500$.

In order to have a clear conclusion, the results are averaged for each method, and the rejection percentage is plotted in Figures 4.1, 4.2 and 4.3 for three different R_{max} values.

Relative performances of four methods for all R_{max} values are similar to the result demonstrated in Section 3.7. For $R_{max} = 1500$, the rejection ratio decreases from 15.775% to 7.775% going from method 1 to method 4 for the first regenerator placement algorithm, and from 5.275% to 2.3% for the second regenerator placement algorithm. For R_{max} values of 2000 and 2500, similar behavior can be observed from Figures 4.2 and 4.3. Hence, it is concluded that there is a significant enhancement in routing efficiency as we move from the first to the last design method, as in MPLS networks.

Using these results, efficiency of regenerator placement algorithms can be evaluated from a traffic engineering point of view. For $R_{max} = 1500$, the second algorithm results in one more regenerator than the first algorithm. But the results obtained in this section, show that the second algorithm is much better

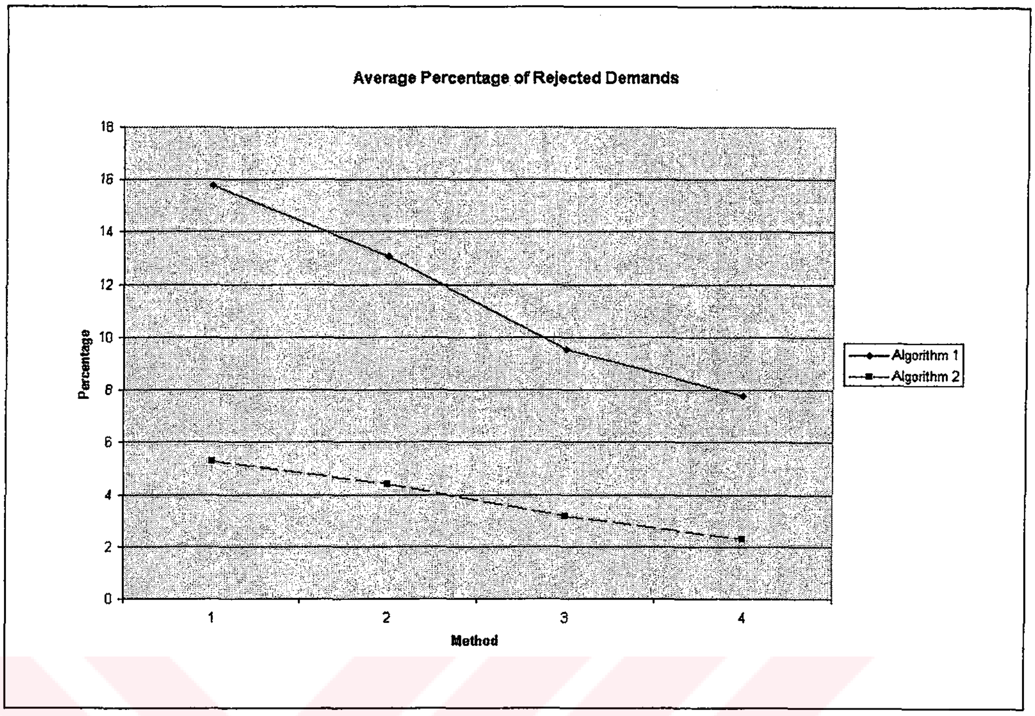

Figure 4.1: Percentage of rejection for $R_{max} = 1500$.

in terms of its robustness against traffic uncertainties. For each design method second regenerator placement algorithm have rejection percentages which are nearly one third of the percentages obtained for the first algorithm. Similarly, for $R_{max} = 2000$, the second algorithm uses one more regenerator than the first, but the rejection percentages are nearly halved for each path design method with the second heuristic approach. And finally for $R_{max} = 2500$, although both algorithms require two regeneration points, the second algorithm is more efficient from a traffic engineering point of view, since it decreases the rejection percentages nearly to one third of the percentages obtained by the first algorithm for each path design approach. In summary, the results show that the second regenerator placement algorithm is much more efficient from a traffic engineering perspective.

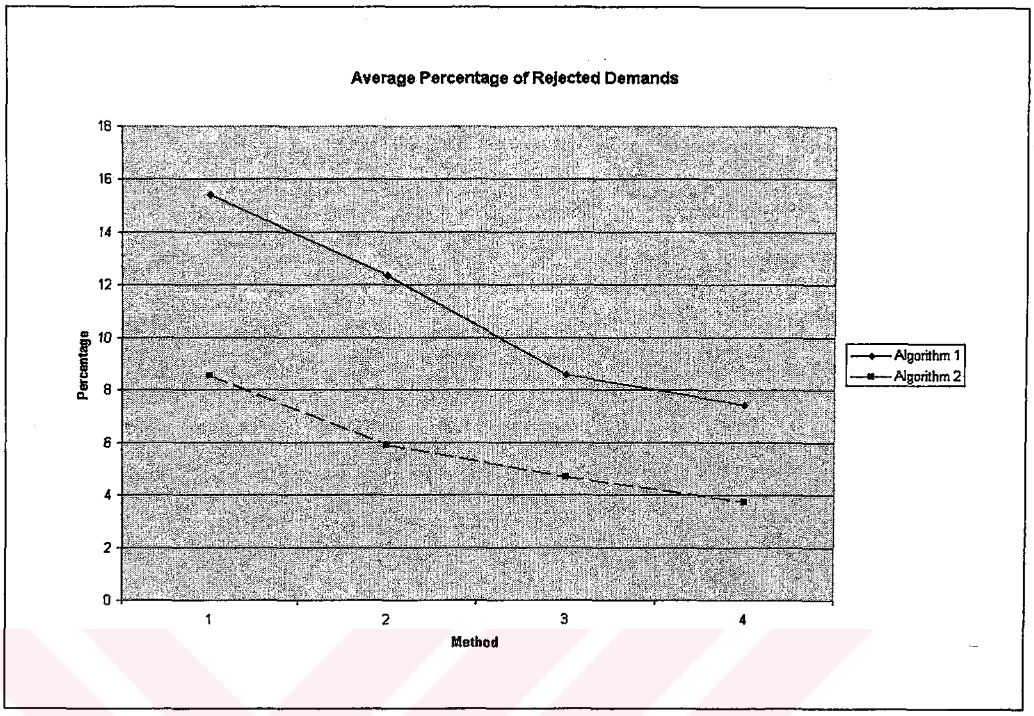

Figure 4.2: Percentage of rejection for $R_{max} = 2000$.

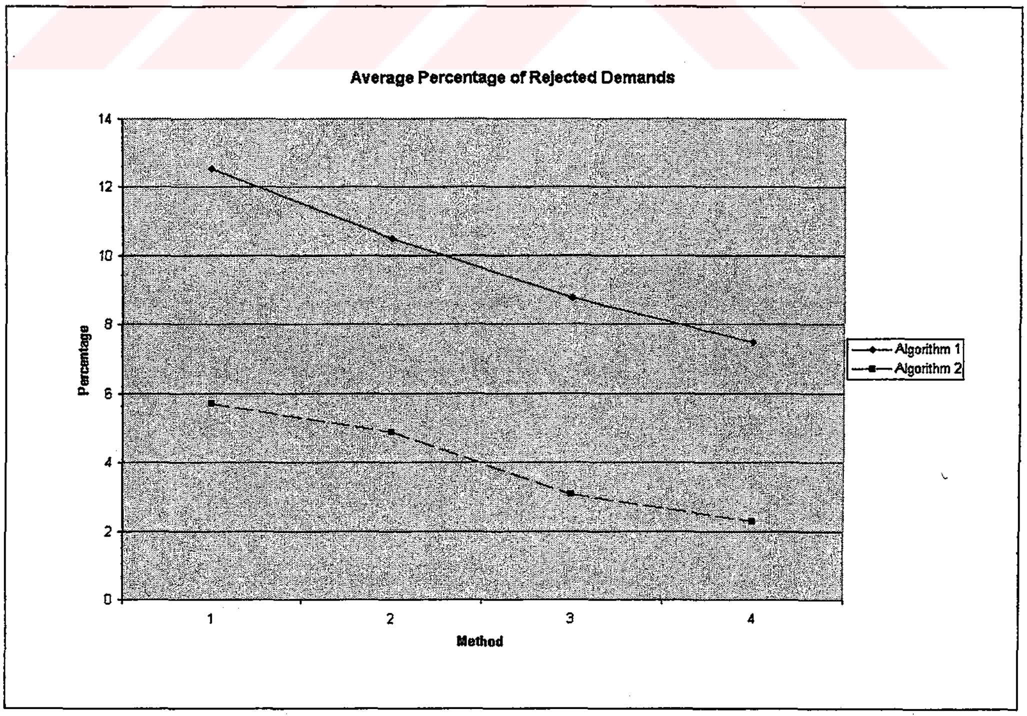

Figure 4.3: Percentage of rejection for $R_{max} = 2500$.

Chapter 5

CONCLUSION

The explosive growth in the number of users and the volume of traffic carried in the Internet put an ever increasing load on the backbones of networks. Besides, QoS and reliability become very critical issues, as Internet is used for carrying real-time and high-priority data. On the other hand, the success of IP protocol makes it the preferred solution at the network layer. But it is not capable of responding to the needs of QoS and reliability in a satisfactory manner. Practically, it supports only the best-effort traffic which is not suitable for most of the real-time applications. The slow response of the restoration mechanism is another problem for IP. As a result, a solution based on IP solving the performance, QoS and reliability problems is needed. At this point, label switching technologies that have been standardized by IETF under the name of MPLS emerged. MPLS has numerous advantages for QoS and reliable routing of data. The ability to support traffic engineering, which is an important issue in network management and planning, makes it a useful solution for core networks. On the other hand, the generalization of this approach to the optical networking provides a simpler and more manageable architecture. Using GMPLS it can be possible to have a network architecture which simply consists of an IP with MPLS layer interfacing with the Optical Transport Network (OTN) via an adaptation layer. Hence, MPLS approach is also valuable from the optical networking point of view.

Given the capabilities of MPLS, it is an important issue to develop traffic engineering methods and compare their efficiencies. In this thesis, approaches for traffic engineering with restoration for MPLS and GMPLS networks are developed. Besides, the regenerator placement problem in optical networks is analyzed, and two heuristic approaches are proposed.

For traffic engineering in MPLS networks, a method for creating candidate path sets for each demand is formulated as an ILP problem. Then, four different approaches are developed for selecting the best path pairs within this set. The first method uses a simple approach: First, the working paths are selected for each demand to minimize the total capacity usage, then the restoration paths are selected on the residual network to satisfy the same objective. The second method aims to evenly distribute the residual capacity over the network, as well as using the minimum capacity. The working and restoration paths are designed separately with this same objective. Last two methods employ a joint optimization approach. In the third method working and restoration paths are designed concurrently, with the objective of using minimum capacity while distributing the residual capacity over the network. The last method is similar to the third one, but it additionally takes into account the relative importance of each link in the network. All of these methods are formulated as ILP problems and numerical results are obtained on a sample network with different sets of demands. Results show that capacity usage efficiency increases going from the first to the last method. The typical capacity savings relative to the preceding method are 1%, 1.5% and 0.5% for the second, third and the last methods, respectively. The robustness of each network design method to uncertainties in the demand structure is studied using a traffic uncertainty modeling. The average number of additional demands that can be carried with each design method is taken as the performance measure. The numerical results show that the percentage of rejected demands decreases nearly 3% with the load balancing approach of the second method compared to the first one. Another 3% decrease is obtained with the joint optimization of the third method. The weighted load balancing of the last method further decreases the rejection percentage by nearly 1%. Hence it is concluded that, load balancing, joint optimization and weighted load balancing are important factors in traffic engineering.

Traffic engineering in GMPLS networks is a more involved process due to the physical layer impairments in the optical layer. Due to the maximum range constraint of optical signals, regeneration may be required in order to have feasible paths between some source-destination pairs. The placement of these regenerators is an important problem which has not been studied in the literature. The requirement is to have at least two feasible paths between each source and destination pair, one for working and the other for restoration purposes. To satisfy this criteria, regenerators are placed at some nodes in the network. First, an ILP formulation for the exact solution of this problem is developed. But the huge size of this problem necessitates the development of heuristic approaches. For this aim two algorithms are developed and numerical results are obtained for different maximum range constraints. It is observed that these algorithms select nearly the same nodes, although one is computationally much more efficient. The path set selection formulation is modified in order to take into account the maximum range of optical signals and location of regenerators. Traffic engineering methods are used to determine the suitable path pairs for each demand, and performances of these methods are compared using the traffic uncertainty model. The results are in parallel with the ones obtained for MPLS networks. The decrease in the rejected demand ratio is nearly the same with the 3%, 3%, 1% pattern of the previous analysis on MPLS. By using the same initial and additional demand sets with each value of R_{max} for both regenerator placement algorithms, relative efficiencies of these algorithms are compared in terms of traffic engineering. The second approach is computationally more efficient, and it has a significant performance advantage over the first algorithm from a traffic engineering point of view, as well. Simulation results show that the second approach has rejection percentages which are 50-65% lower than the rejection percentages obtained by the first algorithm.

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