School of Computer Science

Literature Review and Survey

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Heuristics for Traffic Grooming in WDM Optical Networks with Shared Path Protection

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Abstract

The emergence of wavelength division multiplexing (WDM) technology has significantly increased the transmission capacity of a link in today's optical networks. In WDM networks, the bandwidth request of a traffic stream is usually much lower than the capacity of a wavelength. Traffic grooming can aggregate low-rate connections onto high-capacity optical fibers to make an efficient use of the bandwidth and, also to increase the network throughput. In addition, since huge amount data can flow at a very high speed in a WDM optical network, survivability of such a network against any fault, especially, in the optical fiber link, is of prime concern. Survivable traffic grooming in WDM optical networks has become a topic that is gaining more and more research and commercial attention. In this paper we present a survey of recent research on traffic grooming in WDM optical networks. We have tried to review the research papers that are focused on survivable traffic grooming in WDM mesh networks with an emphasis on shared-path protection, which uses less network resources than dedicated-path protection.

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1. INTRODUCTION

The rapid growth of communication networks is driven by ever-increasing user demand for new applications as well as continuous advancements in the technologies involved. With the introduction of optical fibers as the communication medium, which can provide a huge bandwidth capacity, today's optical networks can easily handle the unprecedented demand for bandwidth capacity of modern day communications [Bandyopadhyay, 2006].

However, because of the limited speed of the electronic processing that must be done at the transmitting or receiving ends of a communication, it is unlikely that all of the bandwidth of an optical fiber will be exploited by using a single high-capacity optical channel or wavelength. For this reason, it is desirable to find an effective technology that can efficiently exploit the huge potential bandwidth capacity of optical fibers.

Figure 1: A bundle of optical fibres.

Theoretically, using advanced techniques such as DWDM (Dense WDM), the modest number of fibres seen here could have sufficient bandwidth to easily carry the sum of all types of current data transmission needs for the entire planet. (~100 terabits per second per fibre) [Courtesy:http://en.wikipedia.org]

The emergence of wavelength division multiplexing (WDM) technology has provided a practical solution to meeting this challenge. With WDM technology, multiple optical signals can be transmitted simultaneously and independently in different optical channels over a single fiber,

each at a rate of a few gigabits per second, which significantly increases the usable bandwidth of an optical fiber [Zheng and Mouftah, 2004]. Currently, Dense-WDM (DWDM) technology can already achieve up to 320 wavelengths per fiber, with each wavelength carrying 10Gb/s, for a total transmission capacity of up to 3.2 Terabits/sec [Xiang et al, 2003].

Furthermore, while each wavelength has a transmission capacity of gigabits per second, users may still require connections at a rate much lower than that of a full wavelength. Therefore, to make the network viable and more cost-effective, it must be able to offer sub-wavelength services and must be able to pack these services efficiently onto the full wavelength. These sub-wavelength services, or low-rate traffic streams, may vary in range from 51 .84 Mbps (or lower) up to the full wavelength capacity [Zhu and Mukherjee, 2003]. Such an act of multiplexing, de-multiplexing and switching of lower-rate traffic streams onto high capacity *lightpath*s is referred to as traffic grooming [Thiagarajan and Somani, 2001b]. Efficient traffic grooming improves the wavelength utilization and reduces equipment and hence the network costs. (A lightpath is an optical connection to carry encoded optical data from one end-node to another end-node, which may or may not pass through any set of intermediate nodes).

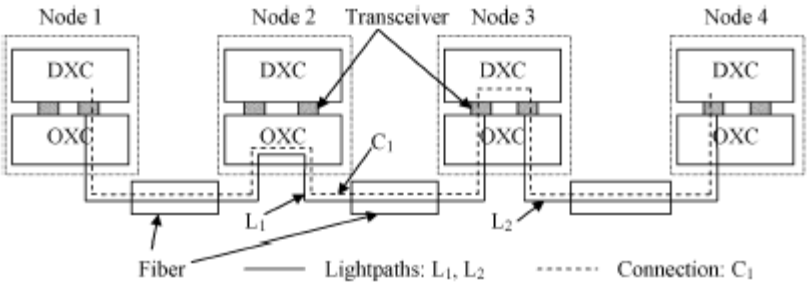

Figure 2: An illustration of lightpaths and connections in optical networks.
Lightpath $L1$ traverses fiber link (1, 2) and (2, 3), lightpath $L2$ traverses fiber link (3, 4), and connection $C1$ uses a two-hop path, including lightpaths $L1$ and $L2$.
[Yao and Ramamurthy, 2005, page 2847]

Due to efficient usage of WDM technology and proper grooming of traffic, a single fiber in today's optical network can carry a huge amount of data flowing at a tremendous speed. This fact gives rise to an ever-increasing demand for "survivable" networks, as even a momentary disruption of traffic flow can cause a loss of huge amount of data, thus making it a very serious matter.

There are two major architectures to ensure the survivability of an optical network. One is protection and the other is restoration [Bandyopadhyay, 2006]. Restoration may be efficient in terms of network resources, but it is time consuming, since new paths have to be found after a fault occurs to send the traffic affected by the fault. On the other hand, networks having protection architecture can respond to a fault much faster, since alternative paths are already reserved beforehand for any faulty situation. Traffic can be sent immediately using the reserved path after a fault occurs, though some resources may be under used due to the advanced reservations. Protection architectures are again divided into two schemes: dedicated-path protection and shared-path protection. In dedicated-path protection, every primary path has an alternative reserved path, whereas, in shared-path protection, reserved paths for different primary paths share the network resources. Obviously, shared-path protection scheme is more resource efficient than dedicated-path protection scheme.

In this paper we present a survey of research carried out on different aspects of optical networks, which includes traffic grooming in WDM optical networks, traffic grooming in WDM mesh networks, survivable traffic grooming in WDM mesh networks, survivable traffic grooming in WDM mesh networks with shared-path protection, and also some other aspects.

The rest of the paper is organized as follows: A general discussion is given in section 2. In section 3 the survey of research is presented, which includes main four topics. We present survey of traffic grooming in WDM ring networks in subsection 3.2, survey of traffic grooming in WDM mesh network in subsection 3.2, survey of survivable traffic grooming in WDM networks in subsection 3.3, and survey of survivable traffic grooming in WDM networks with shared-path protection in subsection 3.4. In section 4 a review of this survey is presented. We conclude this survey in section 5.

Annotations of the 20 important research papers are submitted as Appendix I, and the Bibliography is attached as Appendix II.

2. GENERAL DISCUSSION

2.1. An Overview of WDM Optical Networks

In an optical network, *optical fibers* are used as the main medium of communication, which are nothing but very thin glass cylinders carrying optical (light) signals. A single optical fiber has, at least theoretically, a potential bandwidth of nearly 50 terabits per second (Tbps), which is about four orders of magnitude higher than the currently achievable electronic processing speed of a few gigabits per second (Gbps) [Bandyopadhyay, 2006]. However, because of the limit of the electronic processing speed, it is unlikely that all the bandwidth of an optical fiber will be exploited by using a single high capacity optical channel or wavelength. For this reason, it is desirable to find an effective technology that can efficiently exploit the huge potential bandwidth capacity of optical fibers. The emergence of wavelength division multiplexing (WDM) technology has provided a practical solution to meeting this challenge. With WDM technology, multiple optical signals can be transmitted simultaneously and independently in different optical channels over a single fiber, each at a rate of a few gigabits per second, which significantly increases the usable bandwidth of an optical fiber [Zheng and Mouftah, 2004].

Besides the increased usable bandwidth of an optical fiber, WDM also has other advantages, such as, efficient failure handling, which means we can over come more efficiently the data communication interruption due to any failure of communication media or the related software, data transparency, means data are more reliable and flaws free, and also reduced electronic processing cost [Bandyopadhyay, 2006]. As a result, WDM has become the technology of choice to meet the tremendous bandwidth demand in current and future networks. Optical networks using WDM technology are being considered as the potential main network infrastructure for the next-generation of telecommunications networks and the Internet [Zheng and Mouftah, 2004].

2.2. WDM Technology

Wavelength division multiplexing (WDM) is an optical multiplexing technology to use the huge bandwidth capacity of the optical fibers. It is conceptually similar to frequency modulation (FM) that is being used in radio communication systems for over a century. The basic principle is to

divide the huge bandwidth of an optical fiber into a number of non-overlapping sub-bands or optical channels and transmit multiple optical signals simultaneously and independently in different optical channels over a single fiber.

The attenuation of an optical signal propagating through a fiber is acceptably low in the wavelength band of 1450 to 1650 nanometers (nm). This interval, which is called the *C-band,* is widely being used for optical communication in WDM networks. Most of the optical devices for this band are currently available in the market. Other bands such as the *L-band* from 1565 to 1625nm are expected be available in the near future.

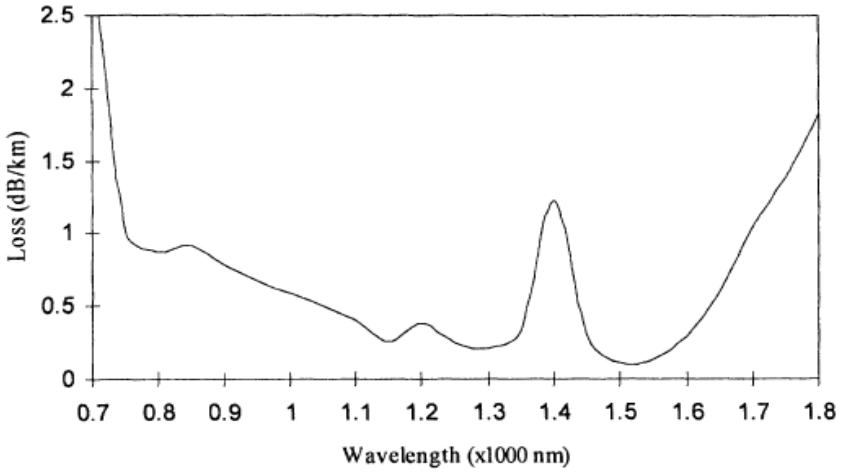

Figure 3: Transmission spectrums of optical fibers.

[Zheng and Mouftah, 2004, page 3]

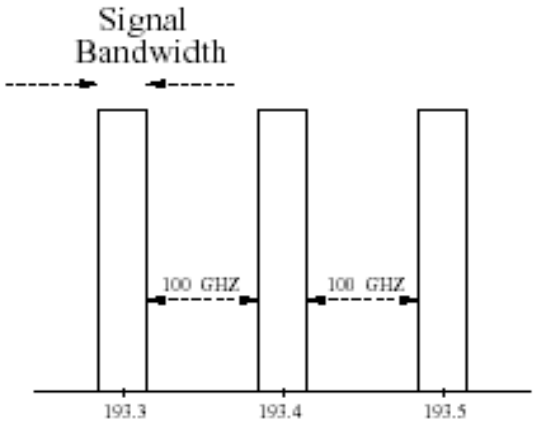

Figure 4: Signal bandwidth and channel spacing.

[Bandyopadhyay, 2006, page 15]

Generally, an optical fiber carries a number of optical signals in the band being used. These optical signals must obviously be at different carrier wavelengths. It is convenient to visualize the available bandwidth (which is currently the C-band) as a set of wavelengths bands, or *channels*, as they are usually called. Each signal is allotted a distinct channel such that each channel has a bandwidth to accommodate the modulated signal. In order to avoid interference between different signals, each channel is separated from every other channel by a certain minimum bandwidth called *channel spacing* [Figure 4]. Typically, a channel bandwidth of 10 GHz and a channel spacing of 100 GHz are currently being used. This means that the C-band can accommodate up to 80 channels, each having a bandwidth of 10 GHz. Shorter channel spacing (25 GHz) will lead to as many as 200 channels in the C-band alone.

2.3. Faults in WDM Networks

As WDM optical networks are becoming more and more popular for today's fast telecommunication networks and the Internet, the demand for a fault free or fully fault tolerant network system is also increasing. Since a huge amount of data can travel at a tremendous speed through the fiber of the optical network, even a momentary interruption of any component of the network system can cause the loss of a large amount of data.

As optical networks are being rapidly deployed on a global scale, which involves millions of kilometers of optical fibers and thousands of other network components, protecting a network from different types of faults and failures have become particularly important. One of the major challenges in design and maintenance of the today's large-scale optical networks is the survivability of the network.

In a WDM network, failure may occur in any component of the network. This includes link failures, node failures, channel failures and/or software failures. Link failure is the most common type of fault where the fiber constituting a link between two nodes in the network does not permit data transmission. Since a single fiber can carry 100 or more lightpaths, and each lightpath can carry data at the rate of 2.5 Gbps to 10 Gbps, even a brief disruption of this traffic is a serious matter [Bandyopadhyay, 2006].

2.4. Survivability of WDM Networks

There are two basic ways of fault recovery to ensure optical network survivability [Zhang and Mukheriee, 2004]. One is known as the *protection* scheme based on dedicated resources and the other is known as the dynamic *restoration* scheme. In the dedicated resource based-protection scheme, the network resources may be dedicated for each failure scenario, or the network resources may be shared among different failure scenarios. In the dynamic restoration scheme, the spare capacity available within the network is utilized for restoring services affected by a failure. Generally, dynamic restoration schemes are more efficient in utilizing the capacity of the network due to the multiplexing of the spare-capacity requirements and provide resilience against different kinds of failures, while dedicated-resource protection schemes have a faster restoration time and provide guarantees on the restoration ability. A categorization of fault management scheme for WDM optical network is depicted in the figure 5 below.

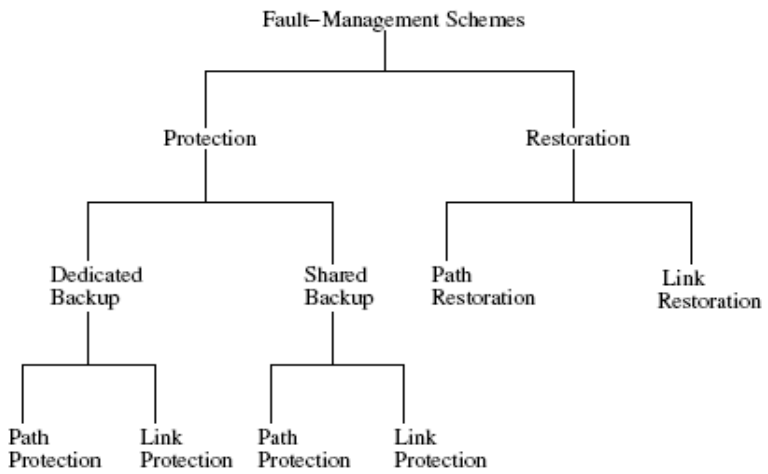

Figure 5: A categorization of fault management schemes.
[Bandyopadhyay, 2006, page 15]

2.4.1. Path Protection

In path protection, backup resources are reserved during connection setup. When a link fails [Figure 6(a)], the source node and the destination node of each lightpath that traverses the failed link are informed about the failure via messages from the nodes adjacent to the failed link, as illustrated in Figure 7.

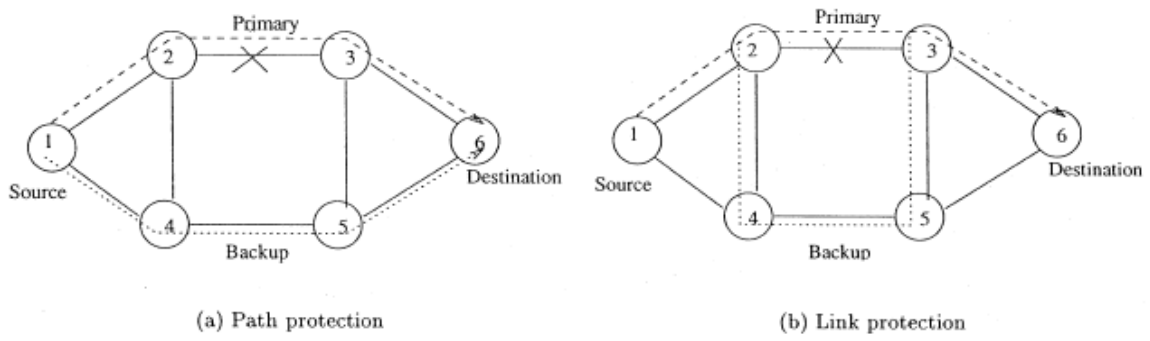

Figure 6: Protection Schemes

[Ramamurthy et al, 2003, page 3]

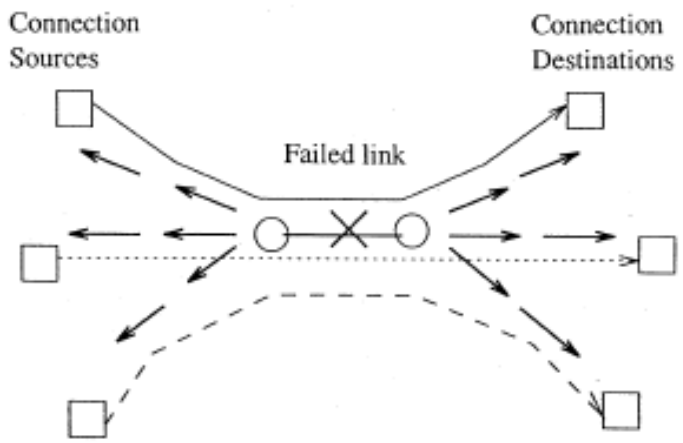

Figure 7: Link-fail messages.

Messages sent to all source and destination nodes of connections traversing a failed link
[Ramamurthy et al, 2003, page 3]

Path protection scheme is sub-divided into two categories:

1. Dedicated path protection: In dedicated-path protection, the resources along a backup path are dedicated for only one lightpath and are not shared with the backup paths for other lightpath. Dedicated protection scheme may be further classified as 1+1 or 1:1. In 1+1 protection scheme, the data is sent *simultaneously* using both the primary and the backup lightpaths. If there is a fault in the primary path, the destination simply continues to get the data from the backup path. The recovery of the network from faults in such a scheme is very fast since the destinations affected by a fault do not need to communicate with the

corresponding sources or have to wait for any corrective action. In 1:1 protection scheme, when the network is fault-free, the data is sent using only the primary lightpath. If there is a fault in the primary path, the destination node informs the corresponding source node, which then stops communicating using the primary path, sets up the backup lightpath using the backup path, and then continues data transmission using the lightpath. The recovery of the network from faults in 1:1 scheme is slower than the 1+1 scheme since the destinations affected by a fault need to communicate with the corresponding sources, wait for the source to set up the backup lightpath, and then to communicate over to the backup lightpath. There is one advantage of the 1:1 scheme over the 1+1 scheme. Since the backup lightpath is not set up until there is a fault and the probability of a fault is low, the resources for the backup lightpaths are not needed most of the time. These resources may be used for low priority traffic until there is a fault and there is a need to set up a backup lightpath.

2. Shared path protection: In dedicated protection approximately 50% of network resources are allotted to backup lightpaths. Since faults occur rarely, these resources are wasted, in the sense that they are not used most of the time. Shared path protection (also called *backup multiplexing* or *1:N protection*) reduces this wastage to some extent. The idea is that, if two primary lightpaths use edge-disjoint primary paths, then, under the single fault assumption, both the primary paths can never contain a faulty edge simultaneously. Therefore it is never necessary to use the respective backup lightpaths at the same time. In shared-path protection, the resources along a backup path may be shared with other backup paths. As a result, backup channels are multiplexed among different failure scenarios (which are not expected to occur simultaneously), and therefore, shared-path protection is more capacity efficient when compared with dedicated-path protection.

2.4.2. Path Restoration

In path restoration, the source and destination nodes of each connection traversing the failed link participate in a distributed algorithm to dynamically discover an end-to-end backup route. If no routes are available for a broken connection, then the connection is dropped. This scheme may be resource efficient, but at the same time it is time consuming. After a fault occurs, the system

has to search the entire network to find a suitable path (which, sometimes, may not be possible) to restart sending data. This scheme is not desirable for high priority data.

2.4.3. Link Protection

In link protection, backup resources are reserved around each link during connection setup. In link protection/restoration [Figure 6(b)], all the connections that traverse the failed link are rerouted around that link, and the source and destination nodes of the connections are oblivious to the link failure. Link protection scheme can also be sub-divided into two categories:

1. Dedicated link protection: In dedicated-link protection, at the time of connection setup, for each link of the primary path, a backup path and wavelength are reserved around that link and are dedicated to that connection. In practice, it may not be possible to allocate a dedicated backup path around each link of the primary connection and on the same wavelength as the primary path. It has been found that dedicated-link protection utilizes wavelengths very inefficiently, and therefore, is not much popular.

2. Shared link protection: In shared-link protection, the backup resources reserved along the backup path may be shared with other backup paths. As a result, backup channels are multiplexed among different failure scenarios (which are not expected to occur simultaneously), and therefore shared-link protection is more capacity-efficient when compared with dedicated-link protection.

2.4.4. Link Restoration

In link restoration, the end nodes of the failed link participate in a distributed algorithm to dynamically discover a route around the link. If no routes are available for a broken connection, then the connection is dropped.

As discussed above, though restoration schemes are more network capacity efficient, the uncertainty of recovering from a fault and, as well as, slow recovery has made this scheme unpopular. Similarly link protection/restoration schemes have also some drawbacks as mentioned above. All these facts have made path protection schemes more popular for making a

network survivable, which give a fast and guaranteed recovery from a fault, may be with some price tag. Most of the research works on survivable WDM network has been carried out considering path protection scheme.

2.5. Traffic Grooming in Optical Networks

As mentioned before, the transmission capacity of a fiber in today's optical networks has increased significantly due to wavelength-division multiplexing (WDM) technology. Each lightpath in a WDM network carries 10 Gbps or 2.5 Gbps depending on the technology used. The network performance is now mainly limited by the processing capability of the network elements, which are mainly electronic. Moreover, Individual requests for connection is typically for a much lower data communication rate, of the order of Mbps. By efficiently grooming low-speed traffic streams onto high-capacity optical channels, it is possible to minimize this electronic processing and eventually increase the network performance. Traffic Grooming in WDM can be defined as a family of techniques for combining a number of low-speed traffic streams from users so that the high capacity of each lightpath may be used as efficiently as possible. Traffic grooming minimizes the network cost in terms of transmitters and receivers and optical switches [Bandyopadhyay, 2006].

"Traffic grooming is composed of a rich set of problems, including network planner, topology design, and dynamic circuit provisioning" [Somani, 2006]. The traffic grooming problem based on static traffic demands is essentially an optimization problem. It can be seen as a dual problem from different perspectives. One perspective is that, for a given traffic demand, satisfy all traffic requests as well as minimize the total network cost. The other problem is that, for given resource limitation and traffic demands, maximize network throughput, i.e., the total amount of traffic that is successfully carried by the network [Zhang and Mukheriee, 2004]. In recent years, there has been an increasing amount of research activity on the traffic grooming problem, both in academe and in industry. Researchers are realizing that traffic grooming is a practical and important problem for WDM network design and implementation.

3. SURVEY OF RESEARCH

As mentioned before, with the introduction of WDM technology, the huge bandwidth of optical fibers in an optical network is being properly utilized. Further more, with proper traffic grooming, the network cost is greatly reduced and the throughput of today's optical networks is further improved. Numerous research works has been done on various aspects of optical networks. In this paper we have focused our survey on traffic grooming in WDM networks and survivable traffic grooming in WDM networks with the emphasis on shared path protection.

3.1. Traffic Grooming in WDM Ring Networks

As we have mentioned before, that with the introduction of wavelength-division multiplexing (WDM) technology the performance of today's optical network is mainly limited by the processing capability of the network elements, which are mainly electronic. It is possible to minimize this electronic processing and eventually increase the network performance by efficiently grooming low-speed traffic streams onto high-capacity optical channels. In this section we present a survey of some important research papers that deals with traffic grooming in WDM ring networks.

3.1.1. Traffic Grooming in WDM Networks to Reduce Network Costs.

There are some research papers where the authors propose different algorithms and/or heuristics for efficient traffic grooming in WDM networks in order to reduce the number of network resources, which ultimately reduces the overall network costs. In this chapter we discus three such papers.

1. The authors of the paper [Chiu and Modiano, 1998] address the problem of traffic grooming for unidirectional SONET/WDM ring networks and have developed algorithms for the purpose. They refer to the paper [Simmons et la, 1998], which considers traffic grooming for a bi-directional ring with uniform traffic, whereas the authors of this paper describe solutions for unidirectional rings

The authors claim that they have found a solution that minimizes the number of ADMs when the traffic from all the nodes is destined to a single node, and all traffic rates are the same. They also claim that in the more general case of all-to-all uniform traffic, they have obtained a lower bound on the number of ADMs required, and provide a heuristic algorithm that perform close to that bound. They consider the use of a hub node, where traffic can be switched between different wavelengths, and obtain an optimal algorithm which minimizes the number of ADMs by efficiently multiplexing and switching the traffic at the hub. Finally, with the help of some graphs and charts, they claim to prove that any solution not using a hub can be transformed into a solution with a hub using fewer or the same number of ADMs.

2. In the paper [Battiti and Brunato, 2001], the authors address the problem of minimizing the number of expensive Add-Drop multiplexers (ADMs) in a SONET/SDH optical ring network by proposing the Reactive Local Search (RLS) heuristic.

   The authors refer to the paper [Berry and Modiano, 2000], which proposes a combinatorial greedy algorithm to solve the problem of traffic grooming in WDM ring. In this paper the authors propose the Reactive Local Search (RLS) heuristic for the problem of minimizing the number of expensive ADMs, while respecting the constraints given by the overall number of fibers and the number of wavelengths that can carry separate information on a fiber.

   The authors claim to experiment their proposed algorithms with simulated networks and they claim that the results obtained by simulations of the all-to-all uniform traffic case showed that the proposed RLS technique is competitive with other greedy techniques that have been used in earlier papers. They provide some charts in support of their claims.

3. The authors of the paper [Konda and Chow, 2001] have studied of the problem of traffic grooming to reduce the number of transceivers in optical networks. They refer to the papers [Gerstel et al, 2000] and [Gerstel et al, 1998], where transceivers are considered as the cost of the networks for the first time.

Unlike decomposing the design of the WDM networks into two phases, first aggregating low speed traffic stream into lightpaths and then the lightpaths are assigned to the wavelength, as the previous authors suggest, the authors of this papers claim that they have considered only the first design phase and restricted themselves to minimizing transceiver costs which depend only on how the traffic streams are aggregated on to lightpaths.

The authors claim to perform some experiments with their algorithm and compare their results with result obtained from ILP formulation, but have failed to come up with an optimal solution. The authors state that they also have failed to understand the reason of such result. They also mention that they do not know whether the transceiver minimization problem is NP-hard.

3.1.2. Traffic Grooming and Topology Design in WDM Networks

Design of Topology for a WDM network needs substantial efforts. Finding the right topology is one of the major research topics. In this section study three papers that address the problem of traffic grooming as a part of topology design for WDM networks.

1. The authors of the paper [Dutta and Rouskas, 2002] address the problem of traffic grooming for wavelength-routed optical networks. They claim with the reference of [Zheng and Qiao, 1998] and other papers, that the full virtual topology design problem is NP-hard, and obtaining an exact solution requires a significant amount of computation, even for modest sized rings. They state that different authors, for obtaining good solutions for practical purpose, have proposed various heuristics. The authors refer to the paper [Chiu and Modiano, 1998] that present heuristic algorithms to minimize network cost by grooming for special traffic patterns such as uniform, certain cases of cross-traffic, and hub.

   They claim that what they have presented in this paper is a new framework for computing bounds for the problem of traffic grooming in ring topologies, which can be used to evaluate the performance of heuristics and which requires significantly less computation than evaluating the optimal solution.

To solve the problem, as they claim, the authors create a framework of both upper and lower bounds on the optimal value of the amount of traffic electronically routed in the network. They have divided the problem into a number of sub problems by decomposing the ring network a few nodes at a time. They claim that they have derived a result that shows that solving the decompositions is a considerably more tractable problem than solving the complete problem. They also claim to present a method of combining these partial solutions into a sequence of bounds, both upper and lower, in which every successive bound is at least as strong as the last one. They present various graphs and charts to support their claims.

2. The problem addressed by the authors of the paper [Mahalati and Dutta, 2004] is the reconfiguration of wavelength routed optical networks in the context of groomed sub-wavelength traffic. According to the authors, it is widely recognized that grooming of sub-wavelength traffic into the full-wavelength channels is an indispensable component of optical network design, but has received comparatively little attention. The authors refer to the some papers including [Berry and Modiano, 2000], [Gerstel et al, 2000] and [Zhu and Mukherjee, 2002], where works are done on traffic grooming to reduce the cost of the network through various algorithms and heuristics.

   In this paper the authors discuss a common basis to consider the grooming effectiveness and reconfiguration efficiency, and claim to develop a reconfiguration cost function. They formulate the joint problem of reconfiguration and grooming, and claim to offer a heuristic and an exact solution method to solve this problem.

   The authors claim to test their algorithm on simulated network and, with the support of various graph and charts, claim to make the important observation that a disjoint sequential consideration of the two problems leads to solutions that are very inefficient in the joint sense. They also claim to show through numerical results that their heuristic approach performs well with reasonable computational time demands.

3. The problem addressed by the author in his Ph. D. dissertation work [Yao, 2005] is to design cost effective and reliable next-generation optical WDM networks with traffic grooming

capability. The author refers to numerous papers that have worked with traffic grooming in SONET/WDM ring and mesh networks. Some of those papers are [Berry and Modiano, 2000] which presents a study the dynamic traffic grooming problem in SONET/WDM rings, [Chiu and Modiano, 2000], which proposes a heuristics to minimize the number of ADMs subject to the minimum number of wavelengths, and [Gerstel et al, 2000] where algorithms have been proposed for traffic grooming to reduce the network cost.

In order to address the challenge of traffic grooming in the next-generation WDM networks, the author in his dissertation investigates different topics of traffic grooming. For dynamic traffic grooming, the author proposes two rerouting schemes, rerouting at the lightpath label (RRAL) and rerouting at the connection label (RRAC). The author claims that simulation result showed that his algorithm improves the resource utilization efficiency.

For Survivable traffic grooming, along with two ILP formulations, the author proposes three heuristics, Separate Survivable Grooming Algorithm (SSGA), Integrated Survivable Grooming Algorithm (ISGA) and Tabu Search based Grooming Heuristic (TSGA), and claims with the support of simulation results, that ISGA is better than SSGA, and TSGA is even better than ISGA.

For performance analysis of traffic grooming the author proposes an analytical model based on multi-level decomposition approach and claims with the support of simulation results, that his model accurately characterizes the channel distribution within links, the wavelength continuity constrain within lightpaths and blocking correlation between alternate routes.

For sparse grooming networks, the author proposes two sparse grooming heuristics, Path-independent connect-through-node (PI-CTN) and Path-dependent connect-through-node (PD-CTN) heuristics and claims that numerical results showed that PD-CTN outperforms PI-CTN. The author suggests some topics that are open for further research, such as, Traffic Grooming Architecture, Traffic Grooming with Regeneration, Traffic Grooming and the Next-generation SONET/SDH, and General Framework for Constrained Traffic Grooming based on the LBAG Model.

3.1.3. Summary of Research Papers

We present a summary of research papers on traffic grooming in WDM ring networks.

Year	Authors	Major Contributions
1998	Chiu and Modiano	Developed heuristic algorithms for traffic grooming in unidirectional SONET/WDM ring networks.
2001	Battiti and Brunato	Proposed the Reactive Local Search (RLS) heuristic to minimizing the number of expensive Add-Drop multiplexers in a SONET/SDH optical ring network
2001	Konda and Chow	Developed algorithms and tried to reduce transceiver cost by traffic grooming WDM network
2002	Dutta and Rouskas	Presented a new framework for computing bounds for the problem of traffic grooming in WDM ring topologies
2004	Mahalati and Dutta	Presented a common basis to consider the traffic grooming effectiveness and reconfiguration efficiency, and develop a reconfiguration cost function for wavelength-routed networks
2005	Yao	Proposed various schemes and algorithm/heuristics to design cost effective and reliable next-generation optical WDM networks with traffic grooming capability

Table 1: Summary of research papers discussed in section 3.1.

3.2. Traffic Grooming in WDM Mesh Networks

Recently the academics and the industry are becoming more interested in WDM mesh network for some of its fundamental advantages over WDM ring network. The major advantage is the scalability. For large-scale, long-hauled, and wide-area networks, WDM mesh network is today's choice. Traffic grooming in WDM mesh network is getting more and more attention by the researchers. In this section we study some of the papers that deals with traffic grooming in WDM mesh networks.

3.2.1. Performance Issue of Traffic Grooming in WDM Mesh Networks

Analysis the performance of traffic grooming in WDM networks and finding means to improve the performance should be one of the interesting research topics. But few works have been done in this area. We discuss two papers, which address performance issues of traffic grooming in WDM networks.

1. The problem addressed by the authors of the paper [Thiagarajan and Somani, 2001a] is grooming traffic in WDM mesh network by proposing a new capacity correlation model to compute the blocking performance on a multi-hop single wavelength path. The author refer to their earlier work [Thiagarajan and Somani, 2000] where they address the same problem proposing a link independent model and they claim that their current approach is more accurate than their previous work. The authors also refer to numbers of other papers. Some of them are [Gerstel et al, 1998] and [Gerstel et al, 1999], where authors provide different network design scheme to reduce the overall network cost.

   The model proposed by the authors takes into account the capacity distribution on the wavelength, the arrival rates of the calls of varying capacity, and the load correlation on neighboring links to compute the blocking performance on a multi-hop single wavelength path. The authors claim that the correlation model could be used to compute the blocking performance of a network with arbitrary topology. They also argue that in the case of the mesh network example, their correlation model gives better estimates of the blocking probability than the independence model. They suggest that, since they have only analyzed their model for the simplest random wavelength assignment case, analytical models need to be developed for traffic grooming WDM networks for other wavelength assignment algorithms.

2. The authors of the paper [Xin and Qiao, 2003] present a study of the performance analysis of the multi-hop online traffic grooming algorithm in mesh WDM optical networks. The authors refer to some papers where, as they mention, some algorithms and heuristics have been developed for traffic grooming in optical mesh networks for single-hop and multi-hop traffic, but none of the works has carried out any performance analysis.

   The authors refer to the PhD dissertation paper [Xin, 2002] where the author proposed an analytical model for performance analysis of the SH algorithm. They claim that in this paper they further extend the earlier model to address performance analysis of traffic grooming using the MH algorithm.

The authors claim to develop the performance analysis model for the multi-hop traffic grooming in mesh WDM optical networks, using load sharing for traffic allocation in multi-hop paths that are limited to 2 hops. The claim to compare their analytical model with numerical results from the simulations test they have carried out, and claim that both results matched satisfactorily. They express their willingness is to address more sophisticated traffic grooming heuristics, and effect of having wavelength, as their future plan.

3.2.2. Use of Tools for Traffic Grooming in WDM Mesh Networks

Many researchers suggest different efficient algorithm, models, or tools to solve the problem of traffic grooming in WDM networks. Here we study two such papers where authors propose to use some modified versions of available tools.

1. The authors of the paper [Lee and Park, 2002] propose a new Genetic Algorithm (GA) – a search tool, to handle the traffic grooming problem in WDM optical network extending the classical GAs with heuristic approach to support network cost optimization for combining multiple traffic streams into a single lightpath.

   The authors refer to the papers [Konda and Chow, 2001], which attempts to solve general grooming problem mapped into a multi-commodity network flow problem, and [Zhu and Mukherjee, 2002], which maximized network throughput for given static traffic demands and network constrains using linear programming and heuristics.

   In this paper the authors claim that they have developed a set of new investigation including position-based bit matrix encoding, genetic heuristics operators, and fitness evaluation function using clustering method. Providing some experimental results, the authors claim that their GA model is superior to traditional heuristic approaches for small networks.

2. In the paper [Zhu et al, 2003], the authors propose a new generic graph model to solve the problem of traffic grooming in heterogeneous WDM mesh networks using various grooming policies and traffic-request-selection schemes.

The authors refer to a number of papers that contribute to various aspects of the traffic grooming in SONET/WDM ring/mesh networks. Few of them are [Berry and Modiano, 2000] which presents a study the dynamic traffic grooming problem in SONET/WDM rings and formulate it as a bipartite graph-matching problem, [Konda and Chow, 2001] where the authors formulate the static traffic grooming problem as an ILP and propose a heuristic to minimize the number of transceivers, and [Thiagarajan and Somani, 2001b] that compares two schemes to dynamically establish reliable low-speed traffic in WDM mesh networks with traffic grooming capability.

The authors of this paper claim that, based on the auxiliary graph, they have developed an integrated traffic grooming algorithm (IGABAG) and an integrated grooming procedure (INGPROC) which jointly solve several traffic grooming sub-problems by simply applying the shortest-path computation method. Among the three grooming policies they have proposed in this paper, they claim that, MinWL consumes the minimum wavelength-links and MinLP uses the minimum transceivers under non-blocking scenarios, while the traffic travels using the minimum number of hops on the virtual topology in non-blocking scenarios when MinTH is used, and MinTH achieves the maximum throughput under blocking scenarios. They also claim that for static traffic grooming, among their three proposed traffic-request-selection schemes, the LCF heuristic outperforms MUF and MAF when combined with the INGPROC procedure, while MUF and MAF scale better than LCF as the number of connection requests increases. They present various graphs and charts in support of their claims.

3.2.3. Dynamic Traffic Grooming in WDM Networks

Numbers of research works have been done for traffic grooming if WDM networks. Most of the earlier works deal with only static traffics. Recently problem of dynamic traffic grooming is getting much attention. We study two papers here, which deal with the problem of dynamic traffic grooming in WDM networks.

1. The authors of the paper [Huang and Dutta, 2004] identify the various problems that are being faced for grooming dynamic traffics in WDM optical networks to minimize the network cost, and indicate various flavors and dimensions of problems of this class.
   The authors refer to various papers that propose different algorithms and heuristics to solve this problem. Some of those papers are, [Chiu and Modiano, 2000], which proposes a heuristics to minimize the number of ADMs subject to the minimum number of wavelengths, [Dutta and Rouskas, 2002] that address the problem of traffic grooming in virtual topology design for wavelength-routed optical networks, [Zhu and Mukherjee, 2002], which propose different grooming policies and route-computation algorithms for different network states, and [Xin and Qiao, 2002], where a study on the performance analysis problem on the traffic grooming in single hop mesh networks is presented.

   The authors claim to identify the problems of dynamic traffic grooming in the context of the more traditional traffic grooming problem with discussions on different characteristics of traffic. The authors believe that they have described the different dimensions along with different flavors of problems. They suggest that while blocking probability computations are important analytical tools, network design problems to minimize Opto-Electro-Optic cost continues to be a significant problem in the context of dynamic traffic grooming. The authors claim to working on designing good grooming algorithms for such problems, and hope to come up with good results later.

2. In the paper [Xin et al, 2006], the authors address the problem of dynamic traffic grooming in WDM mesh networks by first designing a static logical topology a priori based on estimated traffic loads, and then routing each dynamically arriving client call on the established logical topology.

   The authors refer to a number of papers that propose various methods of traffic grooming in optical networks. Some of them are [Zhu and Mukherjee, 2002], which proposes different grooming policies and route-computation algorithms for different network states, [Ou et al, 2003], which compares PAL and PAC in the WDM mesh grooming networks, and [Zhu et al, 2003] that develops an algorithm for dynamically grooming based on a generic graph model

The authors claim to have studied two problems in this paper. One is to minimize the resource usage in the physical topology, constrained by traffic blocking probability, and the other is to maximize call accepting probability or grooming performance, constrained by the physical topology and resources such as the number of wavelengths or ports at each client node.

The authors provide ILP formulations and heuristics towards the solution of the problems. They claim that the results and analysis of simulation tests, that they have performed, indicate that the resource usage dramatically decreases when the blocking requirement is relaxed, and the grooming performance slowly increases when more resources are given. They also claim to find that the number of ports at client nodes have more profound impact on traffic grooming than the number of wavelengths.

3.2.4. Summary of Research Papers

We present a summary of research papers on traffic grooming in WDM mesh networks.

Year	Authors	Major Contributions
2001	Thiagarajan and Somani	Proposed a new capacity correlation model to compute the blocking performance on a multi-hop single wavelength path for grooming traffic in WDM mesh network
2002	Lee and Park	Proposed a new Genetic Algorithm (GA) – a search tool, to handle the traffic grooming problem in WDM mesh network extending the classical GAs
2003	Xin and Qiao	Presented a study of the performance analysis of the multi-hop online traffic-grooming algorithm in WDM mesh networks
2003	Zhu et al	Proposed a new generic graph model to solve the problem of traffic grooming in heterogeneous WDM mesh networks using various grooming policies and traffic-request-selection schemes
2004	Huang and Dutta	Identified various problems faced for grooming dynamic traffics in WDM optical networks to minimize the network cost
2006	Xin et al	Addressed the problem of dynamic traffic grooming in WDM mesh networks by first designing a static logical topology a priori based on estimated traffic loads, and then routing each dynamically arriving client call on the established logical topology

Table 2: Summary of research papers discussed in section 3.2.

3.3. Survivable Traffic Grooming in WDM Networks

As we have already discussed the efficient usage of WDM technology and properly grooming of traffics have enabled a single fiber of today's optical network to carry a huge amount of data flowing at a tremendous speed. This fact gives rise of the ever-increasing demand of survivable network, as even a momentary disruption of traffic flow can cause a loss of huge amount of data, thus making it a very serious matter. The problem of instantaneously recovering from a fault and grooming the traffic affected by the fault in the network has recently attracted much research and commercial attention. In this section we have presented a discussion of some of the important papers that mainly deals with the problem of survivable traffic grooming in WDM mesh networks.

3.3.1. Survivability and Traffic Grooming in WDM Mesh Networks

The introduction of fiber optic transmission systems and wavelength division multiplexing has led to a dramatic increase in the usable bandwidth of single fiber systems. We discuss here a book that covers different aspects of survivability and traffic grooming in WDM mesh networks.

1. The author of the book [Somani, 2006] provides detailed coverage of survivability and traffic grooming, both of which are key issues in modern optical networks. The author refers to numerous papers that have covered different aspects of survivability and traffic grooming in optical networks.

   As the author claims, this book is written for two main communities. One of them consists of professionals in the industry, research scientists, technology planners, network designers and also corporate laboratories. The peoples of second community are graduate teachers, researchers and students.

   The author claims that there are two most important contributions of his book. One of them is the attempt to provide a brief overview of different optical networking trends and technologies followed by different network design and restoration architectures in mesh-restorable optical networks. The author claims to study various protection and restoration

architectures, methods to model the problem, algorithms to design functionality and operational aspects, and the performance of various schemes.

Another most important contribution of his book, as stated by the author, is to address the problem of traffic grooming in optical networks. After studying different aspects of traffic grooming the author claims to present a new and powerful framework, which can support modeling of various traffic grooming mechanisms and analyze them.

3.3.2. Survivable Traffic Grooming in WDM Mesh Networks

Numbers of research papers are available, which discuss and propose different algorithms and heuristics for survivable traffic grooming in WDM mesh networks. We discuss here two papers that deal with this problem.

1. The authors of the paper [Thiagarajan and Somani, 2001b] address the problem of dynamically establishing dependable low-rate traffic stream connections in WDM mesh networks with traffic grooming capabilities. The authors refer to a number of papers for previous work done on various aspects of traffic grooming in WDM networks. Some of them are [Gerstel et al, 2000], which proposes solutions to improve the overall network cost, and [Zheng and Qiao, 1998] and [Chiu and Modiano, 1998] both propose algorithms for traffic grooming for assigning low rate connections to wavelength in WDM networks.

   In this paper the authors present methods to multiplex primary and backup traffic stream onto wavelength on a link. They propose two schemes for grooming traffic streams onto a wavelength: Mixed Primary-Backup Grooming (MGP) and Segregated Primary-Backup Grooming (SGP) and compared them for various topologies. They claim that using SGP provided better performance for topologies with good connectivity and good amount of traffic switching and mixing at the nodes, while using MGP provided better performance for the ring. They have produced various charts and graphs in support of their claims.

2. The authors of the paper [Fang and Somani, 2003] address the problem of enabling traffic grooming capability in the design of survivable WDM mesh networks. According to the

authors, this paper deals with lightpath protection schemes for sub-wavelength level traffic grooming networks, which are defined as shared-wavelength grooming networks with wavelength continuity constrained grooming nodes.

The authors refer to the paper [Thiagarajan and Somani, 2001b], which address the problem of dynamically establishing dependable low-rate traffic stream connections in WDM mesh networks with traffic grooming capabilities. They also refer to the paper [Assi et al, 2001] where a similar study in the context of IP/MPLS protection/restoration with dynamic traffic has been done.

The authors claim that they have provided two exact formulations for employing backup multiplexing and dedicated backup reservation with minimizing the total link-primary sharing. They have given some examples to show the improvement of wavelength utilization of the two schemes and different path selections. They claim that backup multiplexing helps to make reduce the amount of spare capacity, and with the significantly improved wavelength utilization brought by grooming, it is now affordable to use dedicated backup reservation to provide 100 % guaranteed restoration for single link failure.

3.3.3. Traffic Grooming in WDM Mesh in Multiple Faults Scenario

For survivable traffic grooming problem in WDM mesh network, most of the research works has been done with the consideration of single failure in the network at a time. But as the sizes of the optical networks are growing more and more, situations for multiple failures also should be considered. In this subsection we study one such paper.

1. The authors of the paper [Huo et al, 2005] propose protection for multi-granular optical networks against near-simultaneous dual-failures using capacity re-provisioning. They also present a study on the performance of re-provisioning under two different protection frameworks – lightpath level protection and connection level protection.

   The authors refer to the paper [Ou et al, 2003] where, based on the assumption of single failures, two approaches are proposed to groom connection requests with shared protection

capacity. One is Protection at Lightpath (PAL) Level and the other is Protection at Connection (PAC) Level. The authors also refer to the paper [Choi et al, 2002], which addresses the problem of routing high capacity connections (lightpaths) under dual failure assumptions. The authors also refer to the paper [Zhang et al, 2004], which proposes protection capacity reconfiguration after occurrence of the first failure. Protection capacity reconfiguration provides a mechanism by which one can find and allocate new protection capacities for these newly unprotected connections without a priori knowledge of the location of the second failure.

With different tests on simulated networks and with the support of test results and charts, the authors claim to find that the re-provisioning achieves good performance under different network conditions. They also claim that the results of their test confirmed the efficiency of their proposal on improving the restorability of multi-granular networks against dual failures.

3.3.4. Summary of Research Papers

We present a Summary of research papers on survivable traffic grooming in WDM networks.

Year	Authors	Major Contributions
2001	Thiagarajan and Somani	Presented methods to multiplex primary and backup traffic stream onto wavelength on a link for dependable dynamic traffic grooming in WDM mesh networks
2003	Fang and Somani	Provided two exact formulations for employing backup multiplexing and dedicated backup reservation with minimizing the total link-primary sharing for enabling traffic grooming capability in the design of survivable WDM mesh networks
2005	Huo et al	Proposed protection for multi-granular optical networks against near-simultaneous dual-failures using capacity re-provisioning
2006	Somani	Provided a detailed coverage of survivability and traffic grooming in WDM optical networks

Table 3: Summary of research papers discussed in section 3.3.

3.4. Survivable Traffic Grooming with Shared Path Protection

As the demand of survivable network is increasing, the studies of different protection schemes are also getting more and more attentions. Between two fault recovery schemes, restoration and

protection, protection schemes are more popular for making a network survivable, which give a fast and guaranteed recovery from a fault. Protection architecture is divided into two schemes, dedicated-path protection and shared-path protection. In dedicated-path protection every primary path has an alternative reserved path, whereas, in shared-path protections reserved paths for different primary paths share the network resources. Obviously, shared-path protection scheme is more resource efficient than dedicated-path protection scheme. In this section, we study some of the papers dealing with traffic grooming in survivable network with shared path protection.

3.4.1. Protection Schemes for Survivable Traffic Grooming in WDM Mesh Networks

Numbers of studies and research have been carried out on how to protect WDM mesh networks with traffic grooming capabilities. We study two papers in this subsection where the authors propose some heuristics and algorithms for different level of protections for survivable traffic grooming.

1. In the paper [Ou et al, 2003], the authors investigate the problem of survivable traffic grooming for optical mesh networks that employs wavelength division multiplexing. The authors refer to the paper [Thiagarajan and Somani, 2001a] that proposes a call-admission-control algorithm to address the capacity-fairness issue, and to the paper [Zhu and Mukherjee, 2002], which proposes different grooming policies and route-computation algorithms for different network states. The authors also refer to the paper [Zhu et al, 2003] that develops an algorithm for dynamically grooming based on a generic graph model.

   The authors propose three approaches for grooming a connection request with shared protection based on, as they have said, generic grooming node architecture. The approaches are: protection-at-lightpath (PAL) level, mixed protection-at-connection (MPAC) level, and separate protection-at-connection (SPAC) level. The authors claim that their work differs from previous work as they focus on route computation, the impact of different backup-sharing approaches, and the tradeoff between wavelength and grooming capacity.

The authors claim to come up with the following results after extensive experiment on simulated network. 1. Both MPAC and SPAC trade grooming ports for bandwidth efficiency. 2. PAL is not very sensitive to the changes in the number of grooming ports. 3. Both MPAC and SPAC utilize grooming ports more aggressively than PAL does. They present some numerical results in support of their claim. The authors suggest that further study was needed on residual connection-holding time, which has a significant impact on both backup sharing and grooming.

2. The authors of the paper [Yao and Ramamurthy, 2005] present a study of survivable traffic grooming problem in WDM mesh optical networks employing path protection at the connection level. The authors refer to the papers [Thiagarajan and Somani, 2001a], which focuses on the survivable grooming policies, [Ou et al, 2003], which compares PAL and PAC in the WDM mesh grooming networks, and [Fang and Somani, 2003] that presents an ILP formulation of the STG problem to minimize the total number of wavelength links in WDM optical networks with path protection.

   To solve the problem, the authors propose three efficient heuristic grooming algorithms: separated survivable grooming algorithm (SSGA), integrated survivable grooming algorithm (ISGA), and Tabu-search survivable grooming algorithm (TSGA) considering both dedicated and shared path protection at the connection level, in addition to the exact ILP-solution approach

   The authors claim to prove that shared protection is more resource efficient than dedicated protection. They also claim, with some numerical results, that integrated survivable grooming algorithm (ISGA) performs much better than separated survivable grooming algorithm (SSGA), with an average of 50% and 15% improvement in network throughput while using dedicated protection and shared protection, respectively. The authors further claim that Tabu-search survivable grooming algorithm (TSGA) further improves the grooming results from ISGA by an average of about 5%, with the cost of longer running time.

3.4.2. Shared Protection Traffic Grooming in WDM Mesh Networks

Among of different protection plans for survivable traffic grooming for WDM mesh networks, shared-path protection has become most popular due its certain advantages over other protection plans, most important of which is the reduced network resource cost. In this subsection we study two papers, which propose various useful heuristics and algorithms for efficient traffic grooming in WDM mesh networks with shared path protection.

1. In the paper [Xiang et al, 2003], the authors address the problem of dependable traffic grooming of low-rate connections in WDM mesh networks. They have presented a Shared Protection Traffic Grooming algorithm based on wavelength layered-graph (SPTG-LG).

   The authors refer to the paper [Zhu and Mukherjee, 2002] where an investigation has been done on the node architecture for a WDM mesh network with traffic grooming capability, to maximize the network throughput. They also refer to the paper [Thiagarajan and Somani, 2001b] that addresses the problem of dynamically establishing dependable low-rate traffic connections in WDM mesh networks with traffic grooming capabilities.

   The authors claim that their proposed SPTG-LC algorithm performs more efficiently than SP-Normal algorithm [Yuan and Jne, 2002] for more successful connection routes when the network connectivity is low. They also claim that their algorithm performs at par with SP-Normal algorithm when the network is fully connected. They present some numerical results and graphs from their experiments on simulated network, supporting their claims. The authors also draw a conclusion that their SITG-LG algorithm can provide better performance in terms of capacity efficiency, i.e., the algorithm can route more connections in a network with higher traffic grooming -to-wavelength ratio.

2. The authors of the paper [Xiang et al, 2004] address the problem of survivable traffic grooming in WDM mesh networks, by proposing a differentiated shared protection algorithm called, Partial Shared-path Protection algorithm supporting Traffic Grooming (PSPTG). The authors state that not much research has been done on survivable low rate connection traffic

grooming in WDM mesh networks. They refer to some of the research papers, such as, [Zhu and Mukherjee, 2002], which provide algorithms and heuristics to increase the network throughput in order to decrease the overall cost, and [Xiang et al, 2003] and [Thiagarajan and Somani, 2001b] both introduce shared path protection algorithm considering traffic grooming.

The authors have claim that their proposed algorithm (PSPTG) can provide different levels of protection with the single-hop or multi-hop lightpaths according to the bandwidth and reliability of low-rate connections. The authors claim to test their algorithm with simulated network in different situations, such as, full shared-path protection (FSP) and partial shared-path protection (PSP) both with traffic grooming and without traffic grooming. They also claim, based on their simulation test results, that their algorithm is efficient in terms of resources utilization while guarantying the reliability of connection.

3.4.3. Summary of Research Papers

We present here a Summary of research papers on survivable traffic grooming in WDM networks with shared path protection.

Year	Authors	Major Contributions
2003	Ou et al	Proposed three approaches for grooming a connection request with shared protection based on generic grooming node architecture for survivable traffic grooming
2003	Xiang et al	Presented a Shared Protection Traffic Grooming algorithm based on wavelength layered-graph (SPTG-LG) for dependable traffic grooming in WDM mesh networks
2004	Xiang et al	Proposed a differentiated shared protection algorithm called, Partial Shared-path Protection algorithm supporting Traffic Grooming (PSPTG) for survivable traffic grooming in WDM mesh networks
2005	Yao and Ramamurthy	Proposed three efficient heuristic grooming algorithms: separated survivable grooming algorithm (SSGA), integrated survivable grooming algorithm (ISGA), and Tabu-search survivable grooming algorithm (TSGA) considering both dedicated and shared path protection at the connection level

Table 4: Summary of research papers discussed in section 3.4.

4. REVIEW OF RESEARCH

There has been a growing number of research activities on traffic grooming in recent years both in the academic world and in the industry. Traffic grooming problem has emerged as a practical and important problem for WDM network design and implementation.

[Chiu and Modiano, 2000] prove that the general traffic grooming problem is NP-complete. There are some proposals to solve the ILP equations to obtain an optimal solution, when the network size is small. The limitation of the ILP approach is that the numbers of variables and equations increase explosively as the size of network increases. The ILP approach is hardly useful on networks that are practically large in size due to its computation complexity. It may be possible to get some results that are close to the optimal solution for medium size networks by relaxing some of the constraints in the ILP formulation. The results from the ILP may give some insight and intuition for the development of good heuristic algorithms to handle the problem in a large network. In most of the heuristic approaches, the traffic grooming problem is divided into several sub-problems and solved separately. Greedy approach, approximation approach, and simulated annealing approach are used in these heuristic algorithms [Zhu and Mukherjee, 2003].

As we have studied the research papers, most traffic grooming research in SONET/WDM ring networks have assumed a single ring network topology. Today's backbone networks are mainly constructed as a network of interconnected rings. Extending the traffic grooming study from a single ring topology to the interconnected-ring topology will be very useful for designing a large network and managing the network traffic.

Due to some limitations of the SONET ring network, which make it hard to accommodate the increasing Internet traffic, the next-generation optical network is expected to be an intelligent wavelength-routed WDM mesh network. This type of network is expected to provide fast and convenient automatic bandwidth provisioning and efficient protection mechanisms; and it will be based on an irregular mesh topology, which will make it much easier to scale. How to efficiently accommodate the incoming traffic requests, which may be static or dynamic, is a network-provisioning problem in such network.

The SONET/WDM ring networks have been proven to have reliable link protection schemes. There is no need to consider the protection issue separately for groomed traffic in such a network. But protection for groomed traffic in WDM mesh networks should be studied extensively as total reliable protection schemes are yet to be suggested.

Depending on the network preferences and the requirements, various protection schemes can be used in a WDM mesh network. WDM mesh networks may be protected using either link protection schemes or path protection schemes, and the protection resources may be either dedicated or shared by the protection paths/links. Protection with traffic grooming in WDM mesh network is an open research area and needs to be carefully addressed, although protection schemes without traffic grooming have been studied extensively.

Solution of traffic grooming is a very important issue that will enable us to fully develop a smart WDM optical communication network. Standardization of the unified control plane of such a network is developed, and is known as Generalized Multi-protocol Label Switching (GMPLS) [Zhu and Mukherjee, 2003], in the Internet Engineering Task Force (IETF) forum. This network control plane is supposed to provide an intelligent automatic end-to-end route provisioning/signaling scheme throughout the different network domains. There may be uses of different multiplexing techniques such as PDM, TDM, WDM, and SDM and good grooming schemes for such networks to efficiently allocate network resources.

5. CONCLUSION

Survivability is a prime concern of today's long-hauled and wide area optical networks. Reducing the network cost is also another prime concern. By intelligently grooming traffic on such a network having proper protection scheme these goals can be achieved [Somani, 2006]. In this survey we have studied some of the recent research papers that have studied the problem of traffic grooming in WDM ring networks, traffic grooming in WDM mesh networks, survivable traffic grooming in WDM mesh networks, and survivable traffic grooming in WDM mesh networks using shared path protections.

As it has been found that the general traffic grooming problem is an NP-complete problem [Chiu and Modiano, 2000], many heuristics have been proposed in different papers to find an optimum solution to the problem. The problem of survivable traffic grooming is still an open problem and need extensive research effort. As the size of the network is increasing the complexity of the problem is also increasing.

So far most of the research work on survivable traffic grooming is based on the assumption that there will be a single fault in the network at a time [Huo et al, 2005]. But with the increasing size of the networks, time has come to look into the problem with simultaneous or near simultaneous multiple faults.

6. ACKNOWLEDGEMENT

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7. DECLARATION

I declare that this survey is completely my own work.

(Quazi Rahman)

Appendix I

Annotation of 20 Important Papers

1. Battiti, R. and Brunato, M., 2001, Reactive search for traffic grooming in WDM networks, *In Evolutionary Trends of the Internet, Proceedings of 2001, Tyrrhenian International workshop on Digital Communications,* Italy, Springer-Verlag, September 2001, Page(s): 56 – 66.

   The authors of this paper address the problem of minimizing the number of expensive Add-Drop multiplexers (ADMs) in a SONET/SDH optical ring network by proposing the Reactive Local Search (RLS) heuristic.

   The authors refer to the paper [Berry and Modiano, 2000], which proposes a combinatorial greedy algorithm to solve the problem of traffic grooming in WDM ring. In this paper the authors propose the Reactive Local Search (RLS) heuristic for the problem of minimizing the number of expensive ADMs, while respecting the constraints given by the overall number of fibers and the number of wavelengths that can carry separate information on a fiber.

   The authors claim to experiment their proposed algorithms with simulated networks and they claim that the results obtained by simulations of the all-to-all uniform traffic case showed that the proposed RLS technique is competitive with other greedy techniques that have been used in earlier papers. They provide some charts in support of their claims.

2. Chiu, A. L. and Modiano, E. H., 1998, Reducing electronic multiplexing costs in unidirectional SONET/WDM ring networks via efficient traffic grooming, *Global Telecommunications Conference, 1998. GLOBECOM 98. The Bridge to Global Integration. IEEE,* Volume 1, November 1998, Page(s): 322 – 327.

   The authors of this paper address the problem of traffic grooming for unidirectional SONET/WDM ring networks and have developed algorithms for the purpose. They refer to the paper [Simmons et la, 1998], which considers traffic grooming for a bi-directional ring

with uniform traffic, whereas the authors of this paper describe solutions for unidirectional rings

The authors claim that they have found a solution that minimizes the number of ADMs when the traffic from all the nodes is destined to a single node, and all traffic rates are the same. They also claim that in the more general case of all-to-all uniform traffic, they have obtained a lower bound on the number of ADMs required, and provide a heuristic algorithm that perform close to that bound. They consider the use of a hub node, where traffic can be switched between different wavelengths, and obtain an optimal algorithm which minimizes the number of ADMs by efficiently multiplexing and switching the traffic at the hub. Finally, with the help of some graphs and charts, they claim to prove that any solution not using a hub can be transformed into a solution with a hub using fewer or the same number of ADMs.

3. Dutta, R. and Rouskas, G. N., 2002, On optimal traffic grooming in WDM rings, *Selected Areas in Communications, IEEE Journal on,* Volume 20, Issue 1, January 2002, Page(s): 110 – 121.

   The authors of this paper address the problem of traffic grooming for wavelength-routed optical networks. They claim with the reference of [Zheng and Qiao, 1998] and other papers, that the full virtual topology design problem is NP-hard, and obtaining an exact solution requires a significant amount of computation, even for modest sized rings. They state that different authors, for obtaining good solutions for practical purpose, have proposed various heuristics. The authors refer to the paper [Chiu and Modiano, 1998] that present heuristic algorithms to minimize network cost by grooming for special traffic patterns such as uniform, certain cases of cross-traffic, and hub.

   They claim that what they have presented in this paper is a new framework for computing bounds for the problem of traffic grooming in ring topologies, which can be used to evaluate the performance of heuristics and which requires significantly less computation than evaluating the optimal solution.

To solve the problem, as they claim, the authors create a framework of both upper and lower bounds on the optimal value of the amount of traffic electronically routed in the network. They have divided the problem into a number of sub problems by decomposing the ring network a few nodes at a time. They claim that they have derived a result that shows that solving the decompositions is a considerably more tractable problem than solving the complete problem. They also claim to present a method of combining these partial solutions into a sequence of bounds, both upper and lower, in which every successive bound is at least as strong as the last one. They present various graphs and charts to support their claims.

4. Fang, J. and Somani, A. K., 2003, Enabling subwavelength level traffic grooming in survivable WDM optical network design, *Global Telecommunications Conference, 2003. GLOBECOM '03. IEEE,* Volume 5, 2003, Page(s): 2761 – 2766.

   In this paper the authors have address the problem of enabling traffic grooming capability in the design of survivable WDM mesh networks. According to the authors, this paper deals with lightpath protection schemes for sub-wavelength level traffic grooming networks, which are defined as shared-wavelength grooming networks with wavelength continuity constrained grooming nodes.

   The authors refer to the paper [Thiagarajan and Somani, 2001b], which address the problem of dynamically establishing dependable low-rate traffic stream connections in WDM mesh networks with traffic grooming capabilities. They also refer to the paper [Assi et al, 2001] where a similar study in the context of IP/MPLS protection/restoration with dynamic traffic has been done.

   The authors claim that they have provided two exact formulations for employing backup multiplexing and dedicated backup reservation with minimizing the total link-primary sharing. They have given some examples to show the improvement of wavelength utilization of the two schemes and different path selections. They claim that backup multiplexing helps to make reduce the amount of spare capacity, and with the significantly improved wavelength

utilization brought by grooming, it is now affordable to use dedicated backup reservation to provide 100 % guaranteed restoration for single link failure.

5. Huang, S. and Dutta, R., 2004, Research problems in dynamic traffic grooming in optical networks. *In proceedings of First International Workshop on Traffic Grooming*, San Jose, October 2004.

   The authors of this paper identify the various problems that are being faced for grooming dynamic traffics in WDM optical networks to minimize the network cost, and indicate various flavors and dimensions of problems of this class.

   The authors refer to various papers that propose different algorithms and heuristics to solve this problem. Some of those papers are, [Chiu and Modiano, 2000], which proposes a heuristics to minimize the number of ADMs subject to the minimum number of wavelengths, [Dutta and Rouskas, 2002] that address the problem of traffic grooming in virtual topology design for wavelength-routed optical networks, [Zhu and Mukherjee, 2002], which propose different grooming policies and route-computation algorithms for different network states, and [Xin and Qiao, 2002], where a study on the performance analysis problem on the traffic grooming in single hop mesh networks is presented.

   The authors claim to identify the problems of dynamic traffic grooming in the context of the more traditional traffic grooming problem with discussions on different characteristics of traffic. The authors believe that they have described the different dimensions along with different flavors of problems. They suggest that while blocking probability computations are important analytical tools, network design problems to minimize Opto-Electro-Optic cost continues to be a significant problem in the context of dynamic traffic grooming. The authors claim to working on designing good grooming algorithms for such problems, and hope to come up with good results later.

6. Huo, W., Guang, L., Assi, C. and Shami, A., 2005, Survivable traffic grooming in optical networks with multiple failures, *Electrical and Computer Engineering, 2005. Canadian Conference on*, May 2005, Page(s): 1132 – 1135.

   For survivable traffic grooming problem in WDM mesh network, most of the research works has been done with the consideration of single failure in the network at a time. But as the sizes of the optical networks are growing more and more, situations for multiple failures also should be considered. The authors of this paper propose protection for multi-granular optical networks against near-simultaneous dual-failures using capacity re-provisioning. They also present a study on the performance of re-provisioning under two different protection frameworks – lightpath level protection and connection level protection.

   The authors refer to the paper [Ou et al, 2003] where, based on the assumption of single failures, two approaches are proposed to groom connection requests with shared protection capacity. One is Protection at Lightpath (PAL) Level and the other is Protection at Connection (PAC) Level. The authors also refer to the paper [Choi et al, 2002], which addresses the problem of routing high capacity connections (lightpaths) under dual failure assumptions. The authors also refer to the paper [Zhang et al, 2004], which proposes protection capacity reconfiguration after occurrence of the first failure. Protection capacity reconfiguration provides a mechanism by which one can find and allocate new protection capacities for these newly unprotected connections without a priori knowledge of the location of the second failure.

   With different tests on simulated networks and with the support of test results and charts, the authors claim to find that the re-provisioning achieves good performance under different network conditions. They also claim that the results of their test confirmed the efficiency of their proposal on improving the restorability of multi-granular networks against dual failures.

7. Konda, V. R. and Chow, T. Y., 2001, Algorithm for traffic grooming in optical networks to minimize the number of transceivers, *High Performance Switching and Routing, 2001 IEEE Workshop on,* May 2001, Page(s): 218 – 221.

The authors of this paper have studied of the problem of traffic grooming to reduce the number of transceivers in optical networks. They refer to the papers [Gerstel et al, 2000] and [Gerstel et al, 1998], where transceivers are considered as the cost of the networks for the first time.

Unlike decomposing the design of the WDM networks into two phases, first aggregating low speed traffic stream into lightpaths and then the lightpaths are assigned to the wavelength, as the previous authors suggest, the authors of this papers claim that they have considered only the first design phase and restricted themselves to minimizing transceiver costs which depend only on how the traffic streams are aggregated on to lightpaths.

The authors claim to perform some experiments with their algorithm and compare their results with result obtained from ILP formulation, but have failed to come up with an optimal solution. The authors state that they also have failed to understand the reason of such result. They also mention that they do not know whether the transceiver minimization problem is NP-hard.

The authors claim that they have provided two exact formulations for employing backup multiplexing and dedicated backup reservation with minimizing the total link-primary sharing. They have given some examples to show the improvement of wavelength utilization of the two schemes and different path selections. They have claimed that backup multiplexing helps to make reduce the amount of spare capacity, and with the significantly improved wavelength utilization brought by grooming, it is now affordable to use dedicated backup reservation to provide 100 % guaranteed restoration for single link failure.

8. Lee, C. and Park, E. K., 2002. A genetic algorithm for traffic grooming in all-optical mesh networks, *IEEE International Conference on Systems, Man and Cybernetics,* Volume 7, October 2002, Page(s): 6.

   In this paper the authors propose a new Genetic Algorithm (GA) – a search tool, to handle the traffic grooming problem in WDM optical network extending the classical GAs with

heuristic approach to support network cost optimization for combining multiple traffic streams into a single lightpath.

The authors refer to the papers [Konda and Chow, 2001], which attempts to solve general grooming problem mapped into a multi-commodity network flow problem, and [Zhu and Mukherjee, 2002], which maximized network throughput for given static traffic demands and network constrains using linear programming and heuristics.

In this paper the authors claim that they have developed a set of new investigation including position-based bit matrix encoding, genetic heuristics operators, and fitness evaluation function using clustering method. Providing some experimental results, the authors claim that their GA model is superior to traditional heuristic approaches for small networks.

9. Mahalati, R. and Dutta, R., 2004, Reconfiguration of traffic grooming optical networks, *Proceedings on First International Conference*, *Broadband Networks, BroadNets 2004* Page(s): 170 – 179.

The problem addressed by the authors of this paper is the reconfiguration of wavelength routed optical networks in the context of groomed sub-wavelength traffic. According to the authors, it is widely recognized that grooming of sub-wavelength traffic into the full-wavelength channels is an indispensable component of optical network design, but has received comparatively little attention. The authors refer to the some papers including [Berry and Modiano, 2000], [Gerstel et al, 2000] and [Zhu and Mukherjee, 2002], where works are done on traffic grooming to reduce the cost of the network through various algorithms and heuristics.

In this paper the authors discuss a common basis to consider the grooming effectiveness and reconfiguration efficiency, and claim to develop a reconfiguration cost function. They formulate the joint problem of reconfiguration and grooming, and claim to offer a heuristic and an exact solution method to solve this problem.

The authors claim to test their algorithm on simulated network and, with the support of various graph and charts, claim to make the important observation that a disjoint sequential consideration of the two problems leads to solutions that are very inefficient in the joint sense. They also claim to show through numerical results that their heuristic approach performs well with reasonable computational time demands.

10. Ou, C., Zhu, K., Zang, H., Sahasrabuddhe, L. H. and Mukherjee, B., 2003, Traffic grooming for survivable WDM networks - shared protection, *Selected Areas in Communications, IEEE Journal on,* Volume 21, Issue 9, November 2003, Page(s): 1367 – 1383.

    In this paper the authors investigate the problem of survivable traffic grooming for optical mesh networks that employs wavelength division multiplexing. The authors refer to the paper [Thiagarajan and Somani, 2001a] that proposes a call-admission-control algorithm to address the capacity-fairness issue, and to the paper [Zhu and Mukherjee, 2002], which proposes different grooming policies and route-computation algorithms for different network states. The authors also refer to the paper [Zhu et al, 2003] that develops an algorithm for dynamically grooming based on a generic graph model.

    The authors propose three approaches for grooming a connection request with shared protection based on, as they have said, generic grooming node architecture. The approaches are: protection-at-lightpath (PAL) level, mixed protection-at-connection (MPAC) level, and separate protection-at-connection (SPAC) level. The authors claim that their work differs from previous work as they focus on route computation, the impact of different backup-sharing approaches, and the tradeoff between wavelength and grooming capacity.

    The authors claim to come up with the following results after extensive experiment on simulated network. 1. Both MPAC and SPAC trade grooming ports for bandwidth efficiency. 2. PAL is not very sensitive to the changes in the number of grooming ports. 3. Both MPAC and SPAC utilize grooming ports more aggressively than PAL does. They present some numerical results in support of their claim. The authors suggest that further study was needed

on residual connection-holding time, which has a significant impact on both backup sharing and grooming.

11. Somani, A. K., 2006, Survivability and traffic grooming in WDM mesh networks, *Cambridge University Press, www.cambridge.org, 2006.*

The introduction of fiber optic transmission systems and wavelength division multiplexing has led to a dramatic increase in the usable bandwidth of single fiber systems. The author of this book provides detailed coverage of survivability and traffic grooming, both of which are key issues in modern optical networks. The author refers to numerous papers that have covered different aspects of survivability and traffic grooming in optical networks.

As the author claims, this book is written for two main communities. One of them consists of professionals in the industry, research scientists, technology planners, network designers and also corporate laboratories. The peoples of second community are graduate teachers, researchers and students.

The author claims that there are two most important contributions of his book. One of them is the attempt to provide a brief overview of different optical networking trends and technologies followed by different network design and restoration architectures in mesh-restorable optical networks. The author claims to study various protection and restoration architectures, methods to model the problem, algorithms to design functionality and operational aspects, and the performance of various schemes.

Another most important contribution of his book, as stated by the author, is to address the problem of traffic grooming in optical networks. After studying different aspects of traffic grooming the author claims to present a new and powerful framework, which can support modeling of various traffic grooming mechanisms and analyze them.

12. Thiagarajan, S. and Somani, A. K., 2001a. A capacity correlation model for WDM networks with constrained grooming capabilities, *IEEE International Conference on Communications, ICC 2001,* Volume 5, June 2001, Page(s): 1592 – 1596.

    The problem addressed by the authors of this paper is grooming traffic in WDM mesh network by proposing a new capacity correlation model to compute the blocking performance on a multi-hop single wavelength path. The author refer to their earlier work [Thiagarajan and Somani, 2000] where they address the same problem proposing a link independent model and they claim that their current approach is more accurate than their previous work. The authors also refer to numbers of other papers. Some of them are [Gerstel et al, 1998] and [Gerstel et al, 1999], where authors provide different network design scheme to reduce the overall network cost.

    The model proposed by the authors takes into account the capacity distribution on the wavelength, the arrival rates of the calls of varying capacity, and the load correlation on neighboring links to compute the blocking performance on a multi-hop single wavelength path. The authors claim that the correlation model could be used to compute the blocking performance of a network with arbitrary topology. They also argue that in the case of the mesh network example, their correlation model gives better estimates of the blocking probability than the independence model. They suggest that, since they have only analyzed their model for the simplest random wavelength assignment case, analytical models need to be developed for traffic grooming WDM networks for other wavelength assignment algorithms.

13. Thiagarajan, S., Somani, A. K., 2001b. Traffic grooming for survivable WDM mesh networks, *In proceedings of SPIE, Optical Networking and Communications*, *OptiComm 2001*, Volume 4599, August 2001, Page(s): 54 – 65.

    The authors of this paper address the problem of dynamically establishing dependable low-rate traffic stream connections in WDM mesh networks with traffic grooming capabilities. The authors refer to a number of papers for previous work done on various aspects of traffic

grooming in WDM networks. Some of them are [Gerstel et al, 2000], which proposes solutions to improve the overall network cost, and [Zheng and Qiao, 1998] and [Chiu and Modiano, 1998] both propose algorithms for traffic grooming for assigning low rate connections to wavelength in WDM networks.

In this paper the authors present methods to multiplex primary and backup traffic stream onto wavelength on a link. They propose two schemes for grooming traffic streams onto a wavelength: Mixed Primary-Backup Grooming (MGP) and Segregated Primary-Backup Grooming (SGP) and compared them for various topologies. They claim that using SGP provided better performance for topologies with good connectivity and good amount of traffic switching and mixing at the nodes, while using MGP provided better performance for the ring. They have produced various charts and graphs in support of their claims.

14. Xiang, B., Wang, S. and Li, L. 2003. A traffic grooming algorithm based on shared protection in WDM mesh networks. *In proceedings of the Fourth International Conference on Parallel and Distributed Computing, Applications and Technologies (PDCAT)*. August 2003, Page(s): 254 – 258.

    In this paper the authors address the problem of dependable traffic grooming of low-rate connections in WDM mesh networks. They have presented a Shared Protection Traffic Grooming algorithm based on wavelength layered-graph (SPTG-LG).

    The authors refer to the paper [Zhu and Mukherjee, 2002] where an investigation has been done on the node architecture for a WDM mesh network with traffic grooming capability, to maximize the network throughput. They also refer to the paper [Thiagarajan and Somani, 2001b] that addresses the problem of dynamically establishing dependable low-rate traffic connections in WDM mesh networks with traffic grooming capabilities.

    The authors claim that their proposed SPTG-LC algorithm performs more efficiently than SP-Normal algorithm [Yuan and Jne, 2002] for more successful connection routes when the network connectivity is low. They also claim that their algorithm performs at par with SP-

Normal algorithm when the network is fully connected. They present some numerical results and graphs from their experiments on simulated network, supporting their claims. The authors also draw a conclusion that their SITG-LG algorithm can provide better performance in terms of capacity efficiency, i.e., the algorithm can route more connections in a network with higher traffic grooming-to-wavelength ratio.

15. Xiang, B., Yu, H., Wang, S. and Li, L., 2004. A differentiated shared protection algorithm supporting traffic grooming in WDM mesh networks, *International Conference on Communications, Circuits and Systems, ICCCAS 2004,* Volume 1, June 2004, Page(s): 628 – 632

    The authors of this paper address the problem of survivable traffic grooming in WDM mesh networks, by proposing a differentiated shared protection algorithm called, Partial Shared-path Protection algorithm supporting Traffic Grooming (PSPTG). The authors state that not much research has been done on survivable low rate connection traffic grooming in WDM mesh networks. They refer to some of the research papers, such as, [Zhu and Mukherjee, 2002], which provide algorithms and heuristics to increase the network throughput in order to decrease the overall cost, and [Xiang et al, 2003] and [Thiagarajan and Somani, 2001b] both introduce shared path protection algorithm considering traffic grooming.

    The authors have claim that their proposed algorithm (PSPTG) can provide different levels of protection with the single-hop or multi-hop lightpaths according to the bandwidth and reliability of low-rate connections. The authors claim to test their algorithm with simulated network in different situations, such as, full shared-path protection (FSP) and partial shared-path protection (PSP) both with traffic grooming and without traffic grooming. They also claim, based on their simulation test results, that their algorithm is efficient in terms of resources utilization while guarantying the reliability of connection.

16. Xin, C. and Qiao, C., 2003, Performance analysis of multi-hop traffic grooming in mesh WDM optical networks, *Proceedings, The 12th International Conference on Computer Communications and Networks, ICCCN 2003*. October 2003, Page(s): 237 – 242

The authors of this paper present a study of the performance analysis of the multi-hop online traffic grooming algorithm in mesh WDM optical networks. The authors refer to some papers where, as they mention, some algorithms and heuristics have been developed for traffic grooming in optical mesh networks for single-hop and multi-hop traffic, but none of the works has carried out any performance analysis.

The authors refer to the PhD dissertation paper [Xin, 2002] where the author proposed an analytical model for performance analysis of the SH algorithm. They claim that in this paper they further extend the earlier model to address performance analysis of traffic grooming using the MH algorithm.

The authors claim to develop the performance analysis model for the multi-hop traffic grooming in mesh WDM optical networks, using load sharing for traffic allocation in multi-hop paths that are limited to 2 hops. The claim to compare their analytical model with numerical results from the simulations test they have carried out, and claim that both results matched satisfactorily. They express their willingness is to address more sophisticated traffic grooming heuristics, and effect of having wavelength, as their future plan.

17. Xin, C., Wang, B., Cao X. and Li, J., 2006, Logical topology designs for dynamic traffic grooming in *WDM* optical networks. *Journal of Lightwave Technology*, Volume.24, Issue 6, June 2006, Page(s): 2267 – 2275.

The authors of this paper address the problem of dynamic traffic grooming in WDM mesh networks by first designing a static logical topology a priori based on estimated traffic loads, and then routing each dynamically arriving client call on the established logical topology.

The authors refer to a number of papers that propose various methods of traffic grooming in optical networks. Some of them are [Zhu and Mukherjee, 2002], which proposes different grooming policies and route-computation algorithms for different network states, [Ou et al, 2003], which compares PAL and PAC in the WDM mesh grooming networks, and [Zhu et al, 2003] that develops an algorithm for dynamically grooming based on a generic graph model

The authors claimed to have studied two problems in this paper. One is to minimize the resource usage in the physical topology, constrained by traffic blocking probability, and the other is to maximize call accepting probability or grooming performance, constrained by the physical topology and resources such as the number of wavelengths or ports at each client node.

The authors provide ILP formulations and heuristics towards the solution of the problems. They claim that the results and analysis of simulation tests, that they have performed, indicate that the resource usage dramatically decreases when the blocking requirement is relaxed, and the grooming performance slowly increases when more resources are given. They also claim to find that the number of ports at client nodes have more profound impact on traffic grooming than the number of wavelengths.

18. Yao, W., 2005, Traffic grooming in next-generation optical WDM mesh networks, *Ph. D. dissertation,* 2005, *The Graduate College of the University of Nebraska, USA. https://wwwlib.umi.com,* 2005.

The problem addressed by the author in his Ph. D. dissertation work is to design cost effective and reliable next-generation optical WDM networks with traffic grooming capability. The author refers to numerous papers that have worked with traffic grooming in SONET/WDM ring and mesh networks. Some of those papers are [Berry and Modiano, 2000] which presents a study the dynamic traffic grooming problem in SONET/WDM rings, [Chiu and Modiano, 2000], which proposes a heuristics to minimize the number of ADMs subject to the minimum number of wavelengths, and [Gerstel et al, 2000] where algorithms have been proposed for traffic grooming to reduce the network cost.

In order to address the challenge of traffic grooming in the next-generation WDM networks, the author in his dissertation investigates different topics of traffic grooming. For dynamic traffic grooming, the author proposes two rerouting schemes, rerouting at the lightpath label (RRAL) and rerouting at the connection label (RRAC). The author claims that simulation result showed that his algorithm improves the resource utilization efficiency.

For Survivable traffic grooming, along with two ILP formulations, the author proposes three heuristics, Separate Survivable Grooming Algorithm (SSGA), Integrated Survivable Grooming Algorithm (ISGA) and Tabu Search based Grooming Heuristic (TSGA), and claims with the support of simulation results, that ISGA is better than SSGA, and TSGA is even better than ISGA.

For performance analysis of traffic grooming the author proposes an analytical model based on multi-level decomposition approach and claims with the support of simulation results, that his model accurately characterizes the channel distribution within links, the wavelength continuity constrain within lightpaths and blocking correlation between alternate routes.
For sparse grooming networks, the author proposes two sparse grooming heuristics, Path-independent connect-through-node (PI-CTN) and Path-dependent connect-through-node (PD-CTN) heuristics and claims that numerical results showed that PD-CTN outperforms PI-CTN.

The author suggests some topics that are open for further research, such as, Traffic Grooming Architecture, Traffic Grooming with Regeneration, Traffic Grooming and the Next-generation SONET/SDH, and General Framework for Constrained Traffic Grooming based on the LBAG Model.

19. Yao, W. and Ramamurthy, B., 2005. Survivable traffic grooming with path protection at the connection level in WDM mesh networks, *Journal of Lightwave Technology,* Volume 23, Issue 10, October 2005, Page(s): 2846 – 2853.

The authors of this paper present a study of survivable traffic grooming problem in WDM mesh optical networks employing path protection at the connection level. The authors refer to the papers [Thiagarajan and Somani, 2001a], which focuses on the survivable grooming policies, [Ou et al, 2003], which compares PAL and PAC in the WDM mesh grooming networks, and [Fang and Somani, 2003] that presents an ILP formulation of the STG problem to minimize the total number of wavelength links in WDM optical networks with path protection.

To solve the problem, the authors propose three efficient heuristic grooming algorithms: separated survivable grooming algorithm (SSGA), integrated survivable grooming algorithm (ISGA), and Tabu-search survivable grooming algorithm (TSGA) considering both dedicated and shared path protection at the connection level, in addition to the exact ILP-solution approach

The authors claim to prove that shared protection is more resource efficient than dedicated protection. They also claim, with some numerical results, that integrated survivable grooming algorithm (ISGA) performs much better than separated survivable grooming algorithm (SSGA), with an average of 50% and 15% improvement in network throughput while using dedicated protection and shared protection, respectively. The authors further claim that Tabu-search survivable grooming algorithm (TSGA) further improves the grooming results from ISGA by an average of about 5%, with the cost of longer running time.

20. Zhu, H., Zang, H., Zhu, K. and Mukherjee, B., 2003. A novel generic graph model for traffic grooming in heterogeneous WDM mesh networks, *IEEE/ACM Transactions on Networking,* Volume 11, Issue 2, April 2003, Page(s): 285 – 299.

    In this paper the authors propose a new generic graph model to solve the problem of traffic grooming in heterogeneous WDM mesh networks using various grooming policies and traffic-request-selection schemes.

    The authors refer to a number of papers that contribute to various aspects of the traffic grooming in SONET/WDM ring/mesh networks. Few of them are [Berry and Modiano, 2000] which presents a study the dynamic traffic grooming problem in SONET/WDM rings and formulate it as a bipartite graph-matching problem, [Konda and Chow, 2001] where the authors formulate the static traffic grooming problem as an ILP and propose a heuristic to minimize the number of transceivers, and [Thiagarajan and Somani, 2001b] that compares two schemes to dynamically establish reliable low-speed traffic in WDM mesh networks with traffic grooming capability.

The authors of this paper claim that, based on the auxiliary graph, they have developed an integrated traffic grooming algorithm (IGABAG) and an integrated grooming procedure (INGPROC) which jointly solve several traffic grooming sub-problems by simply applying the shortest-path computation method.

Among the three grooming policies they have proposed in this paper, they claim that, MinWL consumes the minimum wavelength-links and MinLP uses the minimum transceivers under non-blocking scenarios, while the traffic travels using the minimum number of hops on the virtual topology in non-blocking scenarios when MinTH is used, and MinTH achieves the maximum throughput under blocking scenarios. They also claim that for static traffic grooming, among their three proposed traffic-request-selection schemes, the LCF heuristic outperforms MUF and MAF when combined with the INGPROC procedure, while MUF and MAF scale better than LCF as the number of connection requests increases. They present various graphs and charts in support of their claims.

Appendix II

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