Project Final Report

Project Title: "Towards Scalable Cost-Effective Service and Survivability Provisioning in Ultra High Speed Networks"

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PROJECT SUMMARY

Optical transport networks based on wavelength division multiplexing (WDM) are considered to be the most appropriate choice for future Internet backbone. On the other hand, future DOE networks are expected to have the ability to dynamically provision on-demand survivable services to suit the needs of various high performance scientific applications and remote collaboration. Since a failure in a WDM network such as a cable cut may result in a tremendous amount of data loss, efficient protection of data transport in WDM networks is therefore essential. As the backbone network is moving towards GMPLS/WDM optical networks, the unique requirement to support DOE's science mission results in challenging issues that are not directly addressed by existing networking techniques and methodologies.

The objectives of this project were

- to develop cost effective protection and restoration mechanisms based on dedicated path, shared path, preconfigured cycle (p-cycle), and so on, to deal with single failure, dual failure, and shared risk link group (SRLG) failure, under different traffic and resource requirement models;
- to devise efficient service provisioning algorithms that deal with application specific network resource requirements for both unicast and multicast;
- to study various aspects of traffic grooming in WDM ring and mesh networks to derive cost effective solutions while meeting application resource and QoS requirements;
- to design various diverse routing and multi-constrained routing algorithms, considering different traffic models and failure models, for protection and restoration, as well as for service provisioning;
- to propose and study new optical burst switched architectures and mechanisms for effectively supporting dynamic services; and
- to integrate research with graduate and undergraduate education.

All objectives have been successfully met. This report summarizes the major accomplishments of this project. The impact of the project manifests in many aspects:

- First, the project addressed many essential problems that arisen in current and future WDM optical networks, and provided a host of innovative solutions though there was no invention or patent filing. This project resulted in more than 2 dozens publications in major journals and conferences (including papers in IEEE Transactions and journals, as well as a book chapter). Our publications have been cited by many peer researchers. In particular, one of our conference papers was nominated for the best paper award of IEEE/Create-Net Broadnets (International Conference on Broadband Communications, Networks, and Systems) 2006.

- Second, the results and solutions of this project were well received by DOE Labs where presentations were given by the PI. We hope to continue the collaboration with DOE Labs in the future.
- Third, the project was the first to propose and extensively study multicast traffic grooming, new traffic models such as sliding scheduled traffic model and scheduled traffic model. Our research has sparkled a flurry of recent studies and publications by the research community in these areas.
- Fourth, the project has benefited a diverse population of students by motivating, engaging, enhancing their learning and skills. The project has been conducted in a manner conducive to the training of students both at graduate and undergraduate levels. As a result, one Ph.D., Dr. Abdur Billah, was graduated. Another Ph.D. student, Tianjian Li, will graduate in January 2007. In addition, four MS students were graduated. One undergraduate student, Jeffrey Alan Shininger, completed his university honors project.
- Fifth, thanks to the support of this ECPI project, the PI has obtained additional funding from the National Science Foundation, the Air Force Research Lab, and other sources. A few other proposals are pending.
- Finally, this project has also significantly impacted the curricula and resulted in the enhancement of courses at the graduate and undergraduate levels, therefore strengthening the bond between research and education.

Summary of Technical Accomplishments

We summarize the major technical accomplishments of the project as follows, the details of which are given in the sections that follow.

- **A New Sliding Scheduled Traffic Model**

  Existing traffic models are not able to best capture the traffic characteristics of applications that require capacity during specific time intervals. Many DOE large-scale science applications (e.g., applications in high energy physics, climate data and computations, astrophysics, etc) that must deliver, at scheduled time durations, hundreds of Gbps throughput between two applications in near future and several Tbps within the next decade [66]. We proposed a general *sliding scheduled traffic model* [88] to suit the need for better service and survivability provisioning.

- **Holding-Time Aware Service Protection under the Scheduled Traffic Model**

  Based on the new traffic model, we have studied survivable service provisioning in wavelength convertible WDM optical mesh networks [47, 48, 51, 50]. We formulated the problem into joint integer linear programs that maximally exploit network resource reuse in both space and time. The objective is to minimize the total number of wavelength-links used by working paths and protection paths of all traffic demands while 100% restorability is guaranteed against any single failure. To solve large problems, the joint routing and wavelength assignment problems are divided to a routing subproblem and wavelength assignment subproblems which are then solved individually. Our simulation results indicate that the optimization of resource sharing in space and time enabled by our connection-holding-time-aware protection schemes can achieve significantly better resource utilization than schemes that are holding time unaware.

- **p-cycle Based Protection for Improving Network Survivability**

  We studied the optimal configuration of preconfigured cycle (p-cycles) in survivable wavelength division multiplexing (WDM) optical mesh networks with sparse or sparse-partial wavelength conversion while 100% restorability is guaranteed against any single failures [52, 49].

  Furthermore, we studied the protection performance of p-cycle configuration with partial wavelength conversion in networks with dual span failures [37]. Providing 100% restorability against both single and dual failures has been shown to be very costly in terms of additional spare protection capacity. In order to provide 100% protection against dual failures, the amount of additional spare capacity can be 2 to 3 times that required for 100% protection against single failures. However, the appropriate choice of solutions to providing 100% restorability to single failures can produce a configuration with impressive performance against dual failures. We applied this observation to develop a methodology in which the optimal cost (i.e., protection capacity and wavelength conversion cost) solutions for single failure protection are analyzed to determine the p-cycle configuration and spare capacity allocation which is likely to perform the best against dual failures as well.

- **Survivable Scheduled Service Provisioning**

  Survivable service provisioning design has emerged as one of the most important issues in communication networks in recent years. We studied survivable service provisioning with shared protection under a scheduled traffic model in wavelength convertible WDM optical mesh networks. In this model, a set of demands is given, and the setup time and teardown time of a demand are known in advance. Based on different protection schemes used, this problem has been formulated as integer linear programs with different optimization objectives and constraints in our work above [50, 51]. The problem is shown to be $\mathcal{NP}$-hard. We therefore studied time efficient approaches to *approximating* the optimal solution to the problem [53]. Our proposed approach was based on an iterative survivable routing (ISR) scheme that utilizes a capacity provision matrix and processes demands sequentially using different demand scheduling policies. The objective was to minimize the total network resources (e.g., number of wavelength-links) used by working paths and protection paths of a given set of demands while 100% restorability is guaranteed against any single failure. The proposed algorithm was evaluated against solutions obtained by integer linear programming. Our simulation results indicate that the proposed ISR algorithm is extremely time efficient while achieving excellent performance in terms of total network resources used. The impact of demand scheduling policies on the ISR algorithm was also studied.

- **Service Provisioning under the Sliding Scheduled Traffic Model**

  Under the sliding scheduled traffic model, we considered two problems [88] : (1) how to properly place a demand within its associated time window to reduce overlapping in time among a set of demands; and (2) route and assign wavelengths (RWA) to a set of demands under the proposed sliding scheduled traffic model in mesh reconfigurable WDM optical networks without wavelength conversion. In addition, we consider how to rearrange a demand by negotiating a new setup time that minimizes the demand schedule change in case that the demand is blocked. To maximize temporal resource reuse, we proposed a demand time conflict reduction algorithm to solve the first problem. Two algorithms, window based RWA algorithm and traffic matrix based RWA algorithm, are then proposed for the second problem. We compared the proposed RWA algorithms against a customized tabu search scheme and an RWA algorithm that sequentially routes and assigns wavelengths for a demand set. Simulation results showed that the proposed demand time conflict reduction algorithm can resolve well over 50% of time conflicts and the space-time RWA algorithms are effective in satisfying demand requirements and minimizing total network resources used.

- **Multicast Service Provisioning in WDM Optical Networks**

  We have studied the dynamic provisioning of multicast sessions in a wavelength-routed sparse splitting capable WDM network with an arbitrary mesh topology where the network consists of nodes with full, partial, or no wavelength conversion capabilities and a node can be a tap-and-continue (TaC) node or a splitting and delivery (SaD) node [91]. The objectives are to minimize the network resources in terms of wavelength-links used by each session and to reduce the multicast session blocking probability. The problem is to route the multicast session from each source to the members of every multicast session, and to assign an appropriate wavelength to each link used by the session. We proposed an efficient online algorithm for dynamic multicast session provisioning. To evaluate the proposed algorithm, we applied the integer linear programming (ILP) optimization tool on a per multicast session basis to solve off-line the optimal routing and wavelength assignment given a multicast session and the current network topology as well as its residual network resource information. We formulated the per session multicast routing and wavelength assignment problem as an integer linear program (ILP). With this ILP formulation, the multicast session blocking probability or success probability can then be estimated based on solving a series of ILPs off-line. We have evaluated the effectiveness of the proposed online algorithm via simulation in terms of session blocking probability and network resources used by a session. Simulation results indicate that our proposed computationally efficient online algorithm performs well even when a fraction of the nodes are SaD nodes.

- **Service Provisioning for Multicast Communication Under a Scheduled Traffic Model**

We have studied the multicast service provisioning problem under a scheduled traffic model [85, 87]. In this model, the starting time and ending time of a multicast session are scheduled. Two algorithms, resource-use based scheduling algorithm and session aggregation based scheduling algorithm, are proposed and compared. In addition, we considered in case that a multicast session is blocked, how to rearrange the session by negotiating a new starting time. Our performance evaluation shows that the proposed algorithms, by taking advantage of knowing the holding-time of sessions, are effective in satisfying the bandwidth and timing requirements of multicast sessions and reducing the total network resources used under the scheduled traffic model.

- **Multicast Traffic Grooming in WDM Optical Networks**

  We considered the grooming of multicast traffic in WDM optical mesh networks with sparse nodal light splitting capability [8]. Given multicast routing trees for individual multicast sessions, the multicast traffic grooming problem is $\mathcal{NP}$-hard. Moreover, constructing an optimal multicast routing tree in WDM optical mesh networks is also an $\mathcal{NP}$-hard problem. We formulated the problem of multicast traffic grooming in WDM optical mesh networks as an integer linear program. We proposed a heuristic algorithm for constructing multicast routing trees and a First-Fit algorithm for traffic grooming, assuming wavelength conversion capability in the network nodes. By intelligently grooming several multicast sessions with fractional wavelength bandwidth requirements onto a single wavelength, we demonstrated that our algorithms achieve a significant reduction in the maximum number of wavelengths required in a link as well as in the total number of wavelength links needed [8].

- **Effective Traffic Grooming for SONET/WDM Ring Networks**

  We studied traffic grooming in unidirectional ring (UPSR) networks with no switching capability under both uniform traffic and non-uniform traffic models to reduce electronic multiplexing costs [7]. Based on the clustering notion, we derived a *general and tighter* lower bound for the number of ADMs required in traffic grooming under the uniform all-to-all traffic model. This bound reduces to special cases obtained in previous work. We also derived *general, tighter, and closed form* lower bounds for the number of ADMs required under two non-uniform traffic models: the distance-dependent traffic model and the non-uniform symmetric traffic model. Cost-effective multi-phase algorithms that exploit traffic characteristics were then designed and studied to efficiently groom traffic streams under different traffic models. Our numerical and simulation results show that the proposed multi-phase algorithms outperform existing traffic grooming algorithms by using fewer number of ADMs. Our algorithms in several cases also achieve the lower bounds derived.

  For SONET/WDM BLSR networks, we studied traffic grooming under the uniform all-to-all traffic model with an objective to reduce total network costs (wavelength and electronic multiplexing costs), in particular, to minimize the number of ADMs while using the optimal number of wavelengths [9]. We derived a new tighter lower bound for the number of wavelengths when the number of nodes is a multiple of 4. We showed that this lower bound is achievable. All previous ADM lower bounds except perhaps that in [34] were derived under the assumption that the magnitude of the traffic streams (r) is *one* unit ($r = 1$) with respect to the wavelength capacity granularity g. We then derived new, more general and tighter lower bounds for the number of ADMs subject to the constraint that *the optimal number of wavelengths is used*, and proposed heuristic algorithms (circle construction algorithm and circle grooming algorithm) that try to minimize the number of ADMs while using the optimal number of wavelengths in BLSR networks. Both the bounds and algorithms are applicable to any value of r and for different wavelength granularity g. Performance evaluation showed that wherever applicable, our lower bounds are at least as good as existing bounds and are much tighter than existing ones in many cases. Our proposed heuristic grooming algorithms perform very well with traffic streams of larger magnitude. The resulting number of ADMs required is very close to the corresponding lower bounds derived.

- **Logical Topology Design for Dynamic Traffic Grooming with QoS Requirements**

  Traffic grooming in optical networks refers to consolidation of sub-wavelength client connections onto lightpaths. Depending on whether the client connections are given in advance or randomly arrive/depart, traffic grooming is classified as *static* and *dynamic*. Dynamic traffic grooming has been traditionally performed through dynamically establishing/releasing lightpaths. We have studied an approach that designs a static logical topology a priori and then routes randomly arriving client connections on it, to avoid frequent lightpaths setup/teardown [93, 94]. We considered two problems: (1) minimize resource usage constrained by traffic blocking requirements; (2) maximize performance constrained by given resources. We formulated them as integer linear programming (ILP) problems. The numerical results show that the resource usage dramatically decreases when the blocking requirement is relaxed, and the grooming performance slowly increases when given more resources. In addition, the ports of client nodes have more profound impact than wavelengths in traffic grooming.

- **All Hops Optimal Mechanisms for Dynamic Routing of Sliding Scheduled Traffic Demands**

  We considered dynamic routing of holding-time aware demands under a sliding scheduled traffic model to satisfy demands' bandwidth and timing requirements [84]. We proposed an all hops optimal routing algorithm that iteratively finds all feasible paths of at most h hops at the end of h-th iteration. We proved the correctness and analyze the time complexity of the algorithm.

- **Diverse Routing with Shared Risk Link Group (SRLG) Failures**

  We studied the diverse routing problem in WDM optical networks with SRLG failures [56]. We considered a more general case of SRLG failures than those considered in [17] and [18]. All the optical links in an SRLG share a common endpoint. In addition, a link can belong to arbitrary number of SRLG groups and an SRLG may include more than two links. We developed a polynomial time optimal algorithm to find a pair of least cost SRLG-disjoint paths between a source and a destination. We proved the correctness of the algorithm which is also shown to be more time efficient than the graph transformation based algorithm of [17].

- **Multi-Constrained Routing in Networks with SRLGs**

  We studied a *multi-constrained routing problem in networks with SRLGs* where a path between a source and a destination is determined such that both the path cost and the weight of SRLGs to which the links of the path belong are bounded [89]. The path cost is measured as the sum of cost of links on the path while the weight of SRLGs is calculated as the sum of the weight of individual SRLGs along the path. The solution to this problem can be used to find risk bounded and cost bounded path for a connection, or to design algorithms that find a pair of low cost SRLG-diverse paths between a source and a destination for survivable service provisioning. The multi-constrained routing problem was solved in two steps. First, an algorithm was devised that tries to find a least cost path in the network where the path cost is defined to be the combined cost of links and SRLG weights along the path. Second, an intelligent search algorithm that integrates the algorithm of the first step was designed to solve the multi-constrained routing problem to effectively find a path with the least total link cost while the total weight of the SRLGs along the path is bounded. The performances of the proposed algorithms were evaluated via extensive simulation and are compared with the solutions obtained by integer linear programming. Our simulation studies showed that the proposed algorithms produce excellent results.

- **Optical Burst Switching for Supporting Dynamic Service Provisioning**

  We proposed a new hybrid dynamic burst contention resolution scheme [45]. The proposed scheme is based on the notion of burst segmentation and judiciously uses optical buffering (i.e., FDLs) and partial wavelength conversion, and at the same time dynamically selects contention resolution policies in response to the network traffic load change. The Just-Enough-Time (JET) signaling protocol is used and switches only have limited number of full-range wavelength converters and some switches may not have FDLs or wavelength converters. The proposed hybrid scheme does not pre-reserve FDLs or wavelength converters. Instead it uses them on an as needed basis to reduce wavelength converters required. Extensive simulation was performed to evaluate the performance of the proposed scheme and to compare with other schemes. Results show that our hybrid scheme is effective.

  Burst grooming in OBS networks is to coalesce two or more sub-bursts to form a larger burst that will be switched as one unit in order to reduce resource waste and switching penalty. We studied the burst grooming problem where bursts originating from the same source and destined to different destinations may be groomed together [25]. Assuming burst grooming can only be realized at edge nodes, we explored the light splitting capability of core nodes and mainly deal with the case when bursts in the network is too small to satisfy the minimum burst length requirement. We proposed two effective burst grooming algorithms, (1) *no over-routing waste* approach (*NoORW*); and (2) *minimum relative total resource ratio* approach (*MinRTRR*). Our initial simulation results have shown that the proposed algorithms are effective in improving system performance in terms of burst blocking probability and average burst end-to-end delay.

  Existing optical burst switching (OBS) architecture has assumed the separated transfer of burst header packets and data bursts. To deal with burst contention and blocking, various approaches have been proposed such as using deflection routing, fiber delay line buffering, wavelength conversion, and burst segmentation. We investigated a shared channel architecture that allows the transfer of both burst header packets and data bursts on the same wavelength channel with some modifications on the current OBS architecture [12]. The new shared channel based OBS architecture is expected to have better flexibility in resource utilization and improved burst blocking performance. Based on the reduced load fixed point approximation, we provided an analytic model for burst blocking probability analysis under the proposed architecture which employs the just-enough-time signaling and fixed routing. The accuracy of the analytic model was validated via extensive simulation. Overall, our analysis and simulation showed that the proposed architecture achieves a significantly lower burst blocking probability than the conventional architecture.

DESCRIPTION OF ACCOMPLISHMENTS

1. Sliding Scheduled Traffic Model and Scheduled Traffic Model

As the DOE backbone network is moving towards WDM optical networks which will likely be integrated with existing networks under the MPLS/generalized MPLS framework [41, 22, 1, 24, 23], this project therefore studied service provisioning in this context.

Much previous work has considered several types of traffic models, e.g., static traffic model, dynamic random traffic model, admissible set model, and incremental traffic model. While these different traffic models are valid and useful in many circumstances, these models are not able to capture the traffic characteristics of applications that require capacity during specific time intervals. For instance, a client company may request some scheduled demands for bandwidth from a service provider to satisfy its communication requirements at a specific time, e.g., between headquarters and production centers during office hours or between data centers during the night when backup of databases is performed and so on. Other examples include many US Department of Energy large-scale science applications (e.g., applications in high energy physics, climate data and computations, astrophysics, etc) that must deliver, at scheduled time durations, guaranteed services between two applications. These applications require provisioning of scheduled dedicated channels or bandwidth pipes at a specific time with certain duration. These scheduled capacity demands are dynamic in nature. They are not static in the sense that the demands only last during the specified intervals. They are not entirely random either. We proposed a new traffic model that better captures the resource characteristics a class of applications. The traffic model is called the sliding scheduled traffic model and a special case of this model is called the scheduled traffic model [88].

1.1 Sliding Scheduled Traffic Model

Given a network topology $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ is the set of nodes and $\mathcal{E}$ is the set of links. Each link has W wavelengths. A set of capacity demands $\mathcal{M}$ is given, each of which is represented by a tuple (s, t, n, ℓ, r, τ) that satisfies $r - \ell \geq \tau > 0$ where s and t are the source and destination, n is the number of requested capacity units (e.g., number of wavelengths), ℓ and r are the starting time and ending time of a time window during which the demand that lasts for τ time units resides. In this model termed as the **sliding scheduled traffic model** (SSTM) (Fig. 1), the demand holding time τ is an interval within a larger time window $[\ell, r]$. Rather than fixing the starting time and ending time of the demand, we introduce a flexibility in the definition of the interval. As a result, the demand is allowed to slide within a larger time window $[\ell, r]$. This model allows an application to specify a larger time window during which the demand for communication capacity is movable and needs to be satisfied. Fixing the starting time and ending time of a demand may be too restrictive in practical scenarios. Furthermore, this model gives a service provider more flexibility in provisioning the requested demand and a better opportunity to optimize the network resources since a demand is considered accommodated as long as it is provisioned within the larger time window. Given a demand $d = (s, t, n, \ell, r, \tau)$, the actual starting time of the demand is variable relative to the left boundary ℓ of its associated time window. If the demand starts at a time units after ℓ, the demand is active during $[\ell + a, \ell + a + \tau]$.

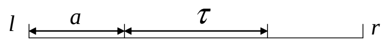


Figure 1: The sliding scheduled traffic model.

The sliding scheduled demand traffic model is different from the static and dynamic random traffic models generally assumed in the literature. Static traffic means that all the demands are known in advance and do not change over time, whereas dynamic random traffic assumes that the inter-arrival time and holding time of demands are random or conform to some probability distribution. The traffic model that is closest to ours is perhaps that of [44] where a scheduled light-path demand model was proposed. The routing and wavelength assignment problem is then solved using a branch and bound algorithm and a tabu search algorithm. Our sliding scheduled traffic model is more general and dynamic in nature since it takes into account the evolution of the traffic load in the network over time, i.e., the time dimension of demands is explicitly considered since many capacity demands in ultra high-speed networks will be short-lived in contrast to 7×24 operations. We believe that this model is more suitable to characterize the resource requirements of certain network applications. Note that the model may allow the applications to negotiate their starting time with a service provider. This flexibility introduces new problems that are solved for service provisioning, e.g., placement of demand intervals within time windows, resource conflict/reuse in the spatial and/or temporal domains, and so on. Finally, this model is also perfectly suitable for advance service provisioning (i.e., advance reservation) under the MPLS/GMPLS framework.

2. Holding-Time Aware Service Protection under the Scheduled Traffic Model

Given our sliding scheduled traffic model and our previous studies on service provisioning under this model, we understand that knowing the holding-time of demands enables service providers to more efficiently provision services through better temporal and spatial resource reuse as the time disjointness that could exist among scheduled demands reduces the amount of global resources required. Therefore, we propose to exploit the knowledge of demand holding-time to design resource efficient protection and restoration mechanisms for provisioning of dedicated-path-protected and shared-path-protected demands in GMPLS optical mesh networks. Most previous research work on network protection did not consider connection holding-time. We have proposed two approaches [47, 48, 51, 50].

2.1 Approach I: Optimization Formulations Based on Precomputed Candidate Routes

We have developed four integer linear program (ILP) formulations for dedicated and shared protection schemes in survivable WDM optical mesh networks with full wavelength conversion under the conventional static traffic model and the scheduled traffic model, respectively. Specifically, ILP1 and ILP2 are developed for dedicated and shared protection schemes, respectively, under the *static traffic model*, while ILP3 and ILP4 are developed for dedicated and shared protection schemes, respectively, under the scheduled traffic model. Hereinafter, we call the protection schemes given in ILP1, ILP2, ILP3, and ILP4, dedicated protection ($\mathbf{DP}$), shared protection ($\mathbf{SP}$), scheduled dedicated protection ($\mathbf{SDP}$) and scheduled shared protection ($\mathbf{SSP}$), respectively. ILP1 and ILP2 are used for comparison purpose. Their formulations are also different from previous work as explained below.

To obtain optimal solutions for the survivable service provisioning problems, routing and wavelength assignment for all the demands in a given traffic demand set $\mathcal{D}$ should be done jointly in the ILPs. To solve practical-sized problems, however, we found ILP2, ILP3 and ILP4 are too complex in terms of the number of variables and the size of search space. To reduce the computational complexity, we use a two-step optimization approach in all the protection schemes. Formulations for joint optimization can be similarly obtained. In the first step which is different from many previous work, we use Eppstein's k-shortest path algorithm [21] to

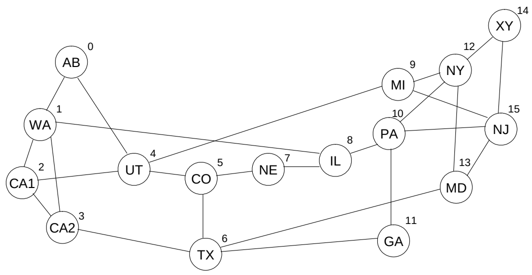


Figure 2: 14-node and 21-link NSFNET topology.

pre-compute a set of alternate routes, $\mathcal{I}$, for each of the demands in $\mathcal{D}$ as candidate working paths. For **each candidate working path of a demand**, we remove it from the network and use Eppstein's k-shortest path algorithm again to pre-compute a set of candidate protection paths, $\mathcal{J}$. Therefore, all the candidate protection paths are link-disjoint with respect to their corresponding candidate working paths, but routes in $\mathcal{I}$ or $\mathcal{J}$ are not necessarily link disjoint. In the second step, i.e., in the ILP formulation, for each demand r in the traffic demand set $\mathcal{D}$, a working path and its corresponding protection path will be selected and assigned wavelengths, such that the total network resources (i.e., number of wavelength-links) used in the network is minimized. We assume that network resources are sufficient to satisfy the entire traffic demand set, and the network has full wavelength conversion capability. The working paths and protection paths may use different wavelengths on the links they traverse, but we stipulate that the lightpaths used by the working path or the protection path of each demand must use the same physical route, i.e., bifurcated routing is not allowed in the ILPs. The detailed problem formulations are given in [51].

2.2 Performance Evaluation of Approach I

We have evaluated the performance of the optimization models described in the previous section. The objective of all the optimization models is to select a pair of working path and protection path, and assign wavelengths to them for each scheduled traffic demand in $\mathcal{D}$, so that the total number of wavelength-links used is minimized given that network resources are sufficient to accommodate all demands.

We use the 10-node network used in [97] and the 14-node NSFNET topology shown in Fig. 2 for performance evaluation and comparison. The source and destination of a demand are generated randomly, and the number of lightpath requests is drawn from a uniform distribution in [1,3]. In addition, the setup and teardown times of a demand are also generated randomly between 0 and 24 hours, and meet the demand time correlation requirements. We use the demand time correlation defined in [44] to characterize a set of demands. We consider three classes of demand set with a demand time correlation factor being weak (0.01), medium (0.5), and strong (0.8) to measure the extent of time overlapping among demands in a set. As described in the previous section, for each traffic demand, we pre-compute I candidate working paths and, for each working path, J candidate protection paths (i.e., in total, $I \times J$ candidate path combinations for each demand). The candidate working paths may traverse some common physical links, but each group of protection paths are link-disjoint with respect to their corresponding candidate working paths. In the simulation, we fix J to be 2 and let I take on 1, 2, and 3 to investigate the impact of the number of candidate working paths. The ILP optimization problems are solved using CPLEX 8.1 running on a 2.5 GHz Pentium IV processor with 2 GB RAM. Feasible sub-optimal solutions are recorded after 2 hours of execution if optimal solutions are not obtained before the time limit.

Table 1: Total number of wavelength-links needed (weak time correlation)

Case	Network	I	ILP1	ILP2	ILP3	ILP4
1	10-node	1	89	76	28	27
	$\|\mathcal{D}\| = 8$	2	89	74	28	27
	$\|\mathcal{K}\| = 16$	3	89	73	28	27
2	10-node	1	176	148	53	50
	$\|\mathcal{D}\| = 16$	2	176	136	52	48
	$\|\mathcal{K}\| = 32$	3	176	129	51	47
3	14-node	1	176	142	66	65
	$\|\mathcal{D}\| = 16$	2	176	138	65	62
	$\|\mathcal{K}\| = 32$	3	176	136	64	58
4	14-node	1	350	273	71	70
	$\|\mathcal{D}\| = 32$	2	350	248	70	68
	$\|\mathcal{K}\| = 64$	3	350	233	70	63

Tables 1, 2, and 3 show the total number of wavelength-links needed to satisfy different traffic demand sets in different optimization models with weak, medium, and strong demand time correlation, respectively. From the tables, we observe that $\mathbf{SDP}$ and $\mathbf{SSP}$ schemes use much less wavelength-links than $\mathbf{DP}$ and $\mathbf{SP}$ schemes in all scenarios, especially when the demand time correlation is weak. For example, in Case 2 with I=1, the performance improvement of $\mathbf{SDP}$ over $\mathbf{DP}$ is 70%, 61% and 35% when the demand time correlations are weak, medium and strong, respectively, while that of $\mathbf{SSP}$ over $\mathbf{SP}$ is 66%, 55% and 28%, respectively. This is because the protection schemes under scheduled traffic model fully exploit the time-disjointness among demands and reuse wavelength-links as much as possible.

From the percentages of performance improvement shown above, we observe that the improvement of $\mathbf{SDP}$ over $\mathbf{DP}$ is more significant than that of $\mathbf{SSP}$ over $\mathbf{SP}$. Moreover, we observe that the improvement of $\mathbf{SP}$ over $\mathbf{DP}$ under the static traffic model (i.e., holding time unaware) appears to be larger than that of $\mathbf{SSP}$ over $\mathbf{SDP}$ under the scheduled traffic model, e.g., 19% and 2%, respectively, in Case 3 with I=1 and weak demand time correlation. The reason may be that, in the static traffic model, the resource utilization can be im-

Table 2: Total number of wavelength-links needed (medium time correlation)

Case	Network	I	ILP1	ILP2	ILP3	ILP4
1	10-node	1	89	76	44	43
	$\|\mathcal{D}\| = 8$	2	89	74	44	43
	$\|\mathcal{K}\| = 16$	3	89	73	44	43
2	10-node	1	176	148	69	67
	$\|\mathcal{D}\| = 16$	2	176	136	68	61
	$\|\mathcal{K}\| = 32$	3	176	129	67	60
3	14-node	1	176	142	90	84
	$\|\mathcal{D}\| = 16$	2	176	138	89	82
	$\|\mathcal{K}\| = 32$	3	176	136	88	81
4	14-node	1	350	273	120	108
	$\|\mathcal{D}\| = 32$	2	350	248	119	104
	$\|\mathcal{K}\| = 64$	3	350	233	118	103

Table 3: Total number of wavelength-links needed (strong time correlation)

Case	Network	I	ILP1	ILP2	ILP3	ILP4
1	10-node	1	89	76	54	53
	$\|\mathcal{D}\| = 8$	2	89	74	54	52
	$\|\mathcal{K}\| = 16$	3	89	73	54	52
2	10-node	1	176	148	114	106
	$\|\mathcal{D}\| = 16$	2	176	136	113	101
	$\|\mathcal{K}\| = 32$	3	176	129	112	98
3	14-node	1	176	142	118	103
	$\|\mathcal{D}\| = 16$	2	176	138	117	100
	$\|\mathcal{K}\| = 32$	3	176	136	116	98
4	14-node	1	350	273	207	160
	$\|\mathcal{D}\| = 32$	2	350	248	203	152
	$\|\mathcal{K}\| = 64$	3	350	233	201	150

proved significantly through backup resource sharing, but the likelihood of finding sharable wavelength-links for time-disjoint protection paths is smaller in **SSP** scheme. Therefore, we observe less significant improvement of **SSP** over **SDP**, and a dedicated protection scheme can achieve greater improvement than a shared protection scheme under the scheduled traffic model. However, we also observe that as the demand time correlation gets stronger, the improvement of **SSP** over **SDP** increases as well, e.g., 1%, 10% and 23% in Case 4 with I=1 when demand time correlations are weak, medium and strong, respectively. This is because when the demand time correlation gets stronger, it is harder for **SDP** to reuse network resources among demands, and thus the advantage of **SSP** amplifies since it maximally exploits network resource reuse in both space and time domains.

It is also noteworthy that the increase of I from 1 to 2 leads to a larger savings in network resources than increasing I from 2 to 3. During the simulation, we also observed that much more computation time (over five times, roughly) is needed when I is 3 than that in the experiments in which I is 2. I taking on 2 appears to strike a good balance between performance and computational cost.

2.3 Approach II: Two-Step RWA Optimization Formulations

We have also developed two-step RWA integer linear program (ILP) formulations for dedicated and shared protection schemes in survivable WDM optical mesh networks under both *the conventional static traffic model* and *the scheduled traffic model*, respectively. The formulations under the former model are used for performance evaluation of the schemes under the latter model. Overall, four architectures are investigated and they are abbreviated as follows:

- **DP**: dedicated path protection under the conventional static traffic model (connection holding time unaware);
- **SP**: shared path protection under the conventional static traffic model (connection holding time unaware);
- **SDP**: dedicated path protection under the scheduled traffic model (connection holding time aware);

- $\mathbf{SSP}$: shared path protection under the scheduled traffic model (connection holding time aware).

To obtain the optimal solutions for the survivable service provisioning problems, routing and wavelength assignment (RWA) for all the demands in a given traffic demand set $\mathcal{D}$ should be done jointly in the ILPs. We first develop four joint RWA ILP formulations, $\mathbf{ILP1}, \mathbf{ILP2}, \mathbf{ILP3}$ and $\mathbf{ILP4}$, for each of the four architectures $\mathbf{DP}$, $\mathbf{SP}$, $\mathbf{SDP}$ and $\mathbf{SSP}$, respectively. The formulations under the first two architectures ($\mathbf{ILP1}$ and $\mathbf{ILP2}$, as well as $\mathbf{ILP6}$ and $\mathbf{ILP7}$ discussed below) serve as the references for performance evaluation of those under the other two architectures. The objective of all the ILPs is to minimize the total number of wavelength-links used.

To solve large problems, however, we found the joint formulations $\mathbf{ILP2}$, $\mathbf{ILP3}$ and $\mathbf{ILP4}$ are too complex in terms of the number of variables and the size of search space. To reduce the computational complexity, we propose a two-step optimization approach for each of the four architectures. Specifically, we partition the RWA problems into a routing subproblem and wavelength assignment subproblems, as did in [97]. For the routing subproblem, we use an ILP ($\mathbf{ILP5}$) to pre-compute a pair of link-disjoint routes for each of the demands in $\mathcal{D}$ as its working path and protection path. For the wavelength assignment subproblems, we present four ILPs ($\mathbf{ILP6}, \mathbf{ILP7}, \mathbf{ILP8}$ and $\mathbf{ILP9}$) for the four protection schemes $\mathbf{DP}$, $\mathbf{SP}$, $\mathbf{SDP}$ and $\mathbf{SSP}$, respectively. In the wavelength assignment subproblems, the pair of routes for each demand r in the traffic demand set $\mathcal{D}$ will be assigned proper wavelengths such that the total network resources (i.e., the number of wavelength-links) used by all the demands are minimized. We assume that network resources are sufficient to satisfy the entire traffic demand set, and that the network has full wavelength conversion capability. The details of these proposed approaches are given in [50].

2.4 Performance Evaluation of Approach II

We summarize the performance evaluation of the joint RWA ILP for $\mathbf{DP}$ architecture (i.e., $\mathbf{ILP1}$). Joint RWA ILPs for other architectures (i.e., $\mathbf{ILP2}$, $\mathbf{ILP3}$ and $\mathbf{ILP4}$) are too time consuming to solve. We also evaluate all optimization models that are based on the two-step approach described in the previous section (i.e., $\mathbf{ILP6}$, $\mathbf{ILP7}$, $\mathbf{ILP8}$, and $\mathbf{ILP9}$ after $\mathbf{ILP5}$ is performed). These different optimization models are denoted by $\mathbf{ILP1}$, $\mathbf{ILP6}$, $\mathbf{ILP7}$, $\mathbf{ILP8}$, $\mathbf{ILP9}$, respectively, in Tables 4, 5, and 6. The objective of all the optimization models is to determine a pair of working path and protection path, and assign wavelengths to them for each traffic demand, so that the total number of wavelength-links used is minimized given that network resources are sufficient to accommodate all demands.

We use the 10-node network used in [97] (Fig. 5(a) of [97]) and the 14-node NSFNET topology shown in Fig. 2 for performance evaluation and comparison. We assume that the links in the example networks are directed. Notice that the links are assumed bidirectional in our complementary work [51]. The source and destination of a demand are generated randomly, and the bandwidth requirements in terms of number of lightpaths is drawn from a uniform distribution in [1,3]. In addition, the setup and teardown times of a demand are also generated randomly between 0 and 24 hours, and meet the demand time correlation requirements. We use the demand time correlation defined in [44] to characterize the time overlapping behavior among a set of demands. We consider three classes of demand set with a demand time correlation factor being weak (0.01), medium (0.5), and strong (0.8) to measure the extent of time overlapping among demands in a set. The ILP optimization problems are solved using CPLEX 8.1 running on a 2.5 GHz Pentium IV processor with 2 GB RAM. Feasible sub-optimal solutions are recorded after 4 hours of execution if optimal solutions are not obtained before the time limit.

Tables 4, 5, and 6 show the total number of wavelength-links needed to satisfy different traffic demand

Table 4: Total number of wavelength-links needed (weak time correlation)

Case	Network	ILP1 (DP)	ILP6 (DP)	ILP7 (SP)	ILP8 (SDP)	ILP9 (SSP)
1	10-node $\lvert\mathcal{D}\rvert = 8$, $\lvert\mathcal{K}\rvert = 16$	89	89	80	45	44
2	10-node $\lvert\mathcal{D}\rvert = 16$, $\lvert\mathcal{K}\rvert = 32$	176	176	152	82	81
3	14-node $\lvert\mathcal{D}\rvert = 16$, $\lvert\mathcal{K}\rvert = 32$	176	176	146	91	90
4	14-node $\lvert\mathcal{D}\rvert = 32$, $\lvert\mathcal{K}\rvert = 64$	350	350	258	121	120

sets in different optimization models with weak, medium, and strong demand time correlation, respectively. From the tables, we observe that $\mathbf{ILP6}$ obtains the same results as $\mathbf{ILP1}$ which is the joint RWA optimization for $\mathbf{DP}$. This shows that the two-step approach can achieve good results. In addition, we observe that $\mathbf{SDP}$ and $\mathbf{SSP}$ schemes use much less wavelength-links than $\mathbf{DP}$ and $\mathbf{SP}$ schemes in all scenarios, especially when the demand time correlation is weak. For example, in Case 2, the performance improvement of $\mathbf{SDP}$ over $\mathbf{DP}$ is 53%, 45% and 25% when the demand time correlations are weak, medium and strong, respectively, while that of $\mathbf{SSP}$ over $\mathbf{SP}$ is 47%, 40% and 18%, respectively. This is because the protection schemes under the scheduled traffic model fully exploit the time-disjointness among demands and reuse wavelength-links as much as possible.

From the percentages of performance improvement shown above, we observe that the improvement of $\mathbf{SDP}$ over $\mathbf{DP}$ is more significant than that of $\mathbf{SSP}$ over $\mathbf{SP}$. Moreover, we observe that the improvement of $\mathbf{SP}$ over $\mathbf{DP}$ under the static traffic model (i.e., holding time unaware) appears to be larger than that of $\mathbf{SSP}$ over $\mathbf{SDP}$ under the scheduled traffic model, e.g., 17% and 1%, respectively, in Case 3 with weak demand time correlation. The reason may be that, in the conventional static traffic model, the resource utilization can be improved significantly through backup resource sharing, but the likelihood of finding sharable wavelength-links for time-disjoint protection paths is smaller in $\mathbf{SSP}$ scheme. Therefore, we observe less significant improvement of $\mathbf{SSP}$ over $\mathbf{SDP}$, and a dedicated protection scheme can achieve greater improvement than a shared protection scheme under the scheduled traffic model. However, we also observe that as the demand time correlation gets stronger, the improvement of $\mathbf{SSP}$ over $\mathbf{SDP}$ increases as well, e.g., 1%, 13% and 18% in Case 4

Table 5: Total number of wavelength-links needed (medium time correlation)

Case	Network	ILP1 (DP)	ILP6 (DP)	ILP7 (SP)	ILP8 (SDP)	ILP9 (SSP)
1	10-node $\lvert\mathcal{D}\rvert = 8$, $\lvert\mathcal{K}\rvert = 16$	89	89	80	54	53
2	10-node $\lvert\mathcal{D}\rvert = 16$, $\lvert\mathcal{K}\rvert = 32$	176	176	152	96	91
3	14-node $\lvert\mathcal{D}\rvert = 16$, $\lvert\mathcal{K}\rvert = 32$	176	176	146	116	112
4	14-node $\lvert\mathcal{D}\rvert = 32$, $\lvert\mathcal{K}\rvert = 64$	350	350	258	157	136

Table 6: Total number of wavelength-links needed (strong time correlation)

Case	Network	ILP1 (DP)	ILP6 (DP)	ILP7 (SP)	ILP8 (SDP)	ILP9 (SSP)
1	10-node $\|\mathcal{D}\| = 8$, $\|\mathcal{K}\| = 16$	89	89	80	67	66
2	10-node $\|\mathcal{D}\| = 16$, $\|\mathcal{K}\| = 32$	176	176	152	132	124
3	14-node $\|\mathcal{D}\| = 16$, $\|\mathcal{K}\| = 32$	176	176	146	132	124
4	14-node $\|\mathcal{D}\| = 32$, $\|\mathcal{K}\| = 64$	350	350	258	221	182

when demand time correlations are weak, medium and strong, respectively. This is because when the demand time correlation gets stronger, it is harder for $\mathbf{SDP}$ to reuse network resources among demands, and thus the advantage of $\mathbf{SSP}$ amplifies since it maximally exploits network resource reuse in both the space and time domains.

3. p-cycle Based Protection for Improving Network Survivability

The pre-configured protection cycle (p-cycle) based protection technique combines the benefits of both ring-based and path-based approaches in that it can achieve ring-like recovery speed while retaining the desired capacity efficiency of path-based protection approaches. We study a few fundamental p-cycle configuration problems in optical WDM networks with various constraints to deal with single and/or dual failures [52, 49, 37].

3.1 Minimizing Spare Capacity of p-Cycles in WDM Optical Networks with Sparse Wavelength Conversion

We studied the optimal configuration of pre-configured protection cycles (p-cycles) in survivable WDM optical mesh networks with sparse wavelength conversion while 100% restorability is guaranteed against any single failures. We formulate the problem as an integer linear program. In our optimization model, capacity of working paths are routed in advance. p-cycles, wavelength conversion sites, and wavelength converters are then optimally determined subject to the constraint that only a subset of nodes have wavelength conversion capability. The objective is to minimize the cost of link capacity used by all p-cycles to accommodate a set of traffic demands. In the proposed p-cycle configuration architecture, we take into account converter sharing: (a) when converters are used for accessing p-cycles and for wavelength conversion between two adjacent on-cycle spans; (b) when converters are used among disjoint straddling spans incident to the same node for accessing p-cycles. Converter sharing enables the network to require as few converters as possible to attain a satisfactory level of performance. Our simulation results indicate that the proposed approach significantly outperforms the approach for WP networks in terms of protection cost. Our approach can obtain the optimal performance as achieved by the approach for VWP networks, but requires fewer wavelength conversion sites and significantly fewer wavelength converters. The details are reported in [49].

3.2 Sparse-Partial Wavelength Conversion in Wavelength-Routed WDM Optical Networks with p-Cycle based Protection

We have studied the optimal configuration of p-cycles in survivable WDM optical mesh networks with sparse-partial wavelength conversion while 100% restorability is guaranteed against any single failures. We formulate the problem as two integer linear programs (Optimization Models I and II) which have the same constraints but different objective functions. In our optimization models, working paths are known before protection configuration is conducted. p-cycles and wavelength converters are then optimally determined subject to the constraint that only a given number of nodes have wavelength conversion capability and the maximum number of wavelength converters that can be placed at such nodes is limited. Such network architecture is referred to as *sparse-partial wavelength conversion*. Optimization Model I has a composite objective function: (**G1**) to minimize the cost of link capacity used by all p-cycles in order to accommodate a set of traffic demands; and (**G2**) to minimize the total number of wavelength converters used in the entire network. In Optimization Model II, on the other hand, the cost of one wavelength converter is measured as the cost of a deployed wavelength link with a length of α units; and the objective is to minimize the total cost of link capacity used by all p-cycles and the cost of wavelength converters required to accommodate a set of traffic demands. During the p-cycle configuration, we take into account converter sharing: (a) when converters are used for accessing p-cycles and for wavelength conversion between two adjacent on-cycle spans; (b) when converters are used among disjoint straddling spans incident to the same node for accessing p-cycles. Converter sharing enables the network to require as few converters as possible to attain a satisfactory level of performance. Our simulation results indicate that the performance of the proposed approach significantly outperforms the approach for WP networks in terms of protection cost. Our approach can obtain the optimal performance as achieved by the approach for VWP networks, but requires fewer wavelength conversion sites and fewer wavelength converters. In addition, our approach outperforms the approach in which wavelength converters can be used only for WP working paths to access WP p-cycles in terms of total cost of protection capacity and wavelength conversion. The details are reported in [52].

3.3 Improving Dual-Failure Performance in WDM Optical Networks using p-Cycle Based Protection with Minimized Wavelength Conversion Costs

We studied the configuration and dual-span failure performance of pre-configured protection cycles (p-cycles) in survivable WDM optical networks with partial wavelength conversion while 100 restorability is guaranteed against any single failures. We consider the general case in which a p-cycle is allowed to use converters partially on the path. We formulate the problem as an integer linear program using a non-joint optimization approach where working paths are known before protection configuration is processed. p-cycles and wavelength converters are then optimally determined. The objective is to minimize the total cost of link capacity used by working paths and p-cycles as well as the cost of wavelength converters required to accommodate a set of traffic demands, and additionally, to select from the set of optimal cost solutions, the solution which has the best performance in terms of the average loss due to dual failures, the average restorability in case of dual failure, and the efficiency of the protection capacity versus working capacity. The proposed p-cycle configuration architecture takes full advantage of converter sharing that reduces network cost by requiring as few converters as possible. Two different dual-failure performance improvement cost functions are applied as dual-failure protection performance predictors. Our numerical results indicate that the best solution in terms of dual failure performance can be obtained from the set of optimal solutions (in terms of capacity and wavelength conversion cost). The proposed approach outperforms the approach which does not consider dual-failure factors. The best prediction function depends on which of the metrics for dual failure performance is considered to be the most important. The details are reported in [37].

4. Survivable Scheduled Service Provisioning

Since a failure in a WDM network such as a cable cut may result in a tremendous amount of data loss, efficient protection of data transport in WDM networks is therefore essential. In a WDM optical mesh network with path based protection, each connection uses two link-disjoint paths: one working path and one protection path. A connection request is blocked if no sufficient resource is available to route either path. Efficient resource utilization can be achieved through backup resource sharing, a technique that allows multiple protection paths to share some common wavelength-links as long as their corresponding working paths are link disjoint while 100% restorability is still maintained. Shared path based protection outperforms, in terms of resource used, protection techniques based on the dedicated reservation of backup resources.

A great deal of research has been conducted on survivable service provisioning in WDM optical networks. Previous work has considered several types of traffic models, e.g., static traffic, dynamic random traffic, admissible set, and incremental traffic, where the connection holding time of demands is not explicitly taken into account for service provisioning. While different traffic models are valid and useful in many circumstances, these models are not able to capture the traffic characteristics of applications that require resources during specific time intervals, for instance, circuit leasing on a short term basis, where a client company may request certain amount of scheduled bandwidth from a service provider to satisfy its communication requirements at a specific time, e.g., between headquarters and production centers during office hours or between data centers during the night when backup of databases is performed, and so on. Many applications require provisioning of scheduled dedicated channels or bandwidth pipes at a specific time with certain duration. These scheduled bandwidth demands [44] are dynamic in nature. They are not static in the sense that the demands only last during the specified time intervals. They are not entirely random either.

We studied survivable service provisioning with shared protection under the scheduled traffic model [44] in wavelength convertible WDM optical mesh networks with single failures. We consider the static version of the problem where a set of demands is given, and the setup time and teardown time of a demand are known in advance. In practical scenarios, networks may expect a mix of static, dynamic, and scheduled traffic. The case studied in this work considers only scheduled traffic. Consideration of this case is justified because this allows to characterize the extent of survivable service provisioning performance gain under the scheduled traffic model. Based on different protection schemes used, this problem has been formulated as integer linear programs with different optimization objectives and constraints in our previous work [50, 51]. The problem is shown to be $\mathcal{NP}$-hard.

We therefore studied time efficient approaches to *approximating* the optimal solution to the problem [53]. Our proposed approach is based on an iterative survivable routing (ISR) scheme that utilizes a capacity provision matrix [53] and processes demands sequentially using different demand scheduling policies. The objective is to minimize the total network resources (e.g., number of wavelength-links) used by working paths and protection paths of a given set of demands while 100% restorability is guaranteed against any single failure. The additional information on connection holding time offers a service provider a better opportunity to optimize the network resources jointly in space (i.e., backup resource sharing) and in time (i.e., taking advantage of time-disjointness amongst demands). Since a demand is considered accommodated as long as it is provisioned during its holding time, time disjoint demands (working path and protection path alike) can therefore share network resources.

The proposed algorithm was evaluated against solutions obtained by integer linear programming [50].

Table 7: Scenario Information

Scenario	Network	D	K
1	3-node	3	6
2	6-node	4	6
3	10-node	8	16
4	10-node	16	32
5	14-node	16	32
6	14-node	32	64

We investigated 6 scenarios in the simulations. The settings of each scenario such as the network topology used, the number of demands (D), and the number of wavelengths on each link in the network (K) are given in Table 7. Table 8 shows the total number of wavelength-links required to accommodate different traffic demand sets in $\mathbf{ILP4}$, $\mathbf{ILP8}$ and the ISR algorithm with different demand scheduling polices when the demand time correlation are weak, medium, and strong, respectively. From the table, we observe that in the first two scenarios, the size of example networks is small; the set of traffic demands is small; and the number of wavelengths on each link is not large. In these scenarios, the optimization models $\mathbf{ILP4}$ and $\mathbf{ILP8}$ are solved with the optimal solutions. $\mathbf{ILP8}$ is also solved with the optimal solutions in Scenario 3. In larger networks with large demand sets, however, $\mathbf{ILP4}$ and $\mathbf{ILP8}$ cannot be solved with the optimal solutions within the time limit, even though $\mathbf{ILP8}$ employs two-step optimization approach, as shown in the last three scenarios in Table 8.

In the first three scenarios in Table 8, we observe that the ISR algorithm (with four different demand scheduling policies) achieves the same results in almost all cases; and the results are very close to that of $\mathbf{ILP4}$ and $\mathbf{ILP8}$, or even better than that of $\mathbf{ILP4}$ in Scenario 3 in which $\mathbf{ILP4}$ only obtains sub-optimal solutions within the time limit. As the network size, demand set size or wavelength set size increases, the computational complexity of $\mathbf{ILP4}$ and $\mathbf{ILP8}$ prevent them from achieving good solutions within the time limit. In contrast, the ISR algorithm achieves much better performance in much less time, as shown in Scenarios 4, 5 and 6. In addition, we observe that the performances of the ISR algorithm employing various scheduling policies do not differ significantly in all the scenarios investigated.

Table 9 shows the computational time of $\mathbf{ILP4}$, $\mathbf{ILP8}$ and the ISR algorithm when the demand time correlation are weak, medium, and strong, respectively, in the 6 scenarios investigated. A time range is given if different demand scheduling policies in the ISR algorithm result in different computational time. The results in the table indicate that the proposed ISR algorithm is extremely time efficient (several orders of magnitude less) while achieving excellent performance in terms of total network resources used, which has been shown in Table 8.

Our simulation results indicate that the proposed ISR algorithm is extremely time efficient while achieving excellent performance in terms of total network resources used. The impact of demand scheduling policies on the ISR algorithm is also studied. Our additional studies [53] showed that no significant difference exists among various demand scheduling policies for small demand sets and networks. For large networks and demand sets, the ISR algorithm employing the Most Conflicting Demand First (*MCDF*) policy achieves the best performance in most scenarios, and the one using the *LCDF* policy needs more wavelength-links than the three other policies.

Table 8: Total number of wavelength-links used. * indicates the optimal solution found and W, M, S represent weak, medium and strong time correlation, respectively. τ is the time correlation of a demand set.

Scenario	τ	ILP4	ILP8	ISR			
				ESDF	ETDF	MCDF	LCDF
1	W	11*	11*	12	12	12	12
	M	12*	12*	13	13	13	13
	S	13*	13*	14	14	14	14
2	W	24*	24*	25	25	25	25
	M	30*	30*	31	31	31	31
	S	33*	34*	35	35	35	35
3	W	43	44*	43	43	43	43
	M	54	53*	53	53	53	53
	S	68	66*	65	65	65	65
4	W	78	81	75	75	75	76
	M	91	91	85	86	86	88
	S	125	124	112	111	111	113
5	W	92	90	75	75	75	76
	M	104	112	85	86	86	85
	S	130	124	104	104	103	105
6	W	119	120	94	93	95	95
	M	152	136	119	121	119	123
	S	218	182	160	160	157	162

5. Service Provisioning under the Sliding Scheduled Traffic Model

A great deal of research has been conducted in the area of finding efficient algorithms for the RWA problem [98, 64]. Previous work has considered several types of traffic models, e.g., static traffic, dynamic random traffic, admissible set, and incremental traffic. In the static traffic model, all demands are known in advance and do not change over time. For instance, a client company may request virtual private connectivity among different company sites from a service provider. The objective is typically to minimize the network resources, e.g., the number of wavelengths, converters, etc, or to maximize throughput given a resource constraint [64]. This model does not allow dynamic call setup and tear-down. In the dynamic random traffic model, a demand is assumed to arrive at a random time and last for a random amount of time. Usually statistical models are used. These models assume certain arrival statistics (e.g., Poisson process) and holding time (e.g., exponential distribution) for demands, as well as a certain traffic distribution (e.g., uniform traffic). The design objective is typically to minimize the call blocking probability, or to analytically model the call blocking probability under various assumptions [10, 3, 42, 77, 103, 65, 70]. In the admissible set model, the objective is to design networks to accommodate any traffic matrix from an admissible set. The set of traffic matrices may be characterized by the maximum link load in the network [36], or by actual device limitations in the network [60, 69, 13], e.g., the numbers of tunable transmitters and tunable receivers at each end node (i.e., a node that sources and/or sinks traffic sessions). A new session is said to be allowable if its arrival results in a traffic matrix which is still in the set of admissible traffic. The goal is to minimize the number of wavelengths used. The work in [34, 60, 69, 13] mainly targeted at simple network topologies (i.e., ring and torus). The work reported in [67] considered time-variant offered traffic in the form of a set of traffic matrices at different instants for off-line configuration so as to accommodate such time-varying traffic. The work in [75] also used a set of traffic matrices to design and dimension a WDM mesh network to groom dynamically varying traffic. In the incremental model [71, 2], traffic demands arrive sequentially. Lightpaths are established for each demand, and remain in the network

Table 9: Computational time. $\times$ indicates the 4-hour time limit. h, m and s represent hour(s), minute(s) and second(s), respectively. τ is the time correlation of a demand set.

Scenario	τ	ILP4	ILP8	ISR
1	W	$1s$	$< 1s$	$(2.0 - 2.1) \times 10^{-4}s$
	M	$5s$	$< 1s$	$(2.3 - 2.4) \times 10^{-4}s$
	S	$10s$	$< 1s$	$(2.3 - 2.4) \times 10^{-4}s$
2	W	$4s$	$1s$	$(1.1 - 1.6) \times 10^{-3}s$
	M	$4m$	$5s$	$(2.7 - 2.8) \times 10^{-3}s$
	S	$2h10m$	$20s$	$(1.3 - 1.7) \times 10^{-3}s$
3	W	$\times$	$17s$	$2.3 \times 10^{-2}s$
	M	$\times$	$1h20m$	$3.0 \times 10^{-2}s$
	S	$\times$	$3h14m$	$4.1 \times 10^{-2}s$
4	W	$\times$	$\times$	$(0.10 - 0.11)s$
	M	$\times$	$\times$	$(0.12 - 0.13)s$
	S	$\times$	$\times$	$(0.13 - 0.14)s$
5	W	$\times$	$\times$	$(0.15 - 0.22)s$
	M	$\times$	$\times$	$(0.22 - 0.27)s$
	S	$\times$	$\times$	$(0.24 - 0.27)s$
6	W	$\times$	$\times$	$(0.95 - 1.23)s$
	M	$\times$	$\times$	$(1.33 - 1.80)s$
	S	$\times$	$\times$	$(1.40 - 1.68)s$

indefinitely. The work in [32] on multi-period network planning was based on an incremental traffic model and conducted network planning across several years to produce incrementally a network capable of carrying all traffic predicted up to the end of the planning horizon.

While these different traffic models are valid and useful in many circumstances, they are not able to capture the traffic characteristics of applications that require capacity during specific time intervals. A general *sliding scheduled traffic model* described in Section 1 is useful especially given that many applications exhibit the aforementioned capacity requirement characteristics and services need to be provided when fully dynamic speedy provisioning is still not available or deployed at least in the near future. We assume no wavelength conversion. Without optical wavelength conversion, routing of a session is subjected to the wavelength continuity constraint which dictates that lightpaths corresponding to a given session must travel on the same wavelength on all links from the source node to the destination node. Moreover, we assume that existing lightpaths cannot be disrupted in order to accommodate new sessions. We derive properties of the sliding scheduled traffic model and propose a demand time conflict reduction algorithm used to properly place demands within their respective time windows to minimize overlapping among demands in the time domain. We then propose efficient routing and wavelength assignment algorithms (window based algorithm and traffic matrix based algorithm). In addition, we consider how to rearrange a demand by negotiating a new setup time that minimizes the demand schedule change in case that the demand is blocked.

Our performance evaluation shows that the proposed RWA algorithms are effective in satisfying demand specifications and reducing total network resources used under the proposed traffic model [88].

6. Multicast Service Provisioning in WDM Optical Networks

To support multicast communications at the optical layer, we consider two problems: (1) the optical signal splitter placement problem or multicast capable node placement problem [91]; and (2) how to efficiently schedule a set of scheduled multicast traffic demands in wavelength reconfigurable optical networks [85].

6.1 Topology Based Multicast Capable Node Placement Algorithm

Many existing algorithms for the optical signal splitter placement problem or multicast capable node placement problem are based on the performance of multicast routing exhibited from attempting a large set of randomly generated sessions in the network. Experiments show that the selection of a node to be multicast capable based on its importance for routing one set of sessions may not be a right choice for another set of sessions. We propose placement algorithms that are based on network topology and the relative importance of a node in routing multicast sessions. Since network topology is fixed, the proposed algorithms will be mostly network traffic independent.

We propose several multicast capable node selection criteria, and multicast capable node placement algorithms. Instead of selecting nodes based on their importance for routing a random set of sessions, we emphasize the importance of network topology and the relative importance of a node's ability to efficiently reach other nodes (in terms of, e.g., cost) as the main basis for selecting a node to be multicast capable. Efficient routing of multicast sessions is often characterized by minimizing the cost of multicast trees. The two most used variations of such trees are either to minimize the cost from the source to individual destination or to construct a Steiner tree where the total cost of the tree is minimized. The rationale behind the proposed placement algorithms is to identify the nodes that may have more significant role than others in constructing multicast trees with the minimum cost regardless of traffic conditions. In order to evaluate this role, we propose the following node selection criteria that may be applied in the proposed placement algorithms:

1. *Node Degree*: a node with a larger degree of connectivity is likely to be used more frequently for reaching other nodes with less cost during multicast tree construction.
2. *Smallest Total Cost (STC)*: a node that has a smaller total cost to reach all other nodes in the network is more likely to be referenced in building minimum cost multicast trees.
3. *Largest Total Cost on Elimination (LTCE)*: For each node, the total cost to reach all other nodes in the network is calculated. Then the sum of the total costs for all the nodes are calculated.
4. *Multicast Capable Connectivity (MCC)*: This criterion essentially selects a node to be multicast capable on the basis of its connectivity to already selected MC nodes.
5. *Performance Based on a Random Set of Sessions*: This criterion is similar to what has been used by heuristic algorithms in previous work. It assigns some weight on the importance of a node based on routing a random set of sessions.
6. *Largest Minimum Cost from Nearest MC Node*: This criterion is a locality based criterion in which a tie among nodes can be resolved by first determining the minimum cost of nodes from the nearest MC node and selecting the node that has the largest minimum cost first.

We have developed several placement algorithms based on the node selection criteria presented above: (1) Placement Algorithm: Largest Degree with Smallest Cost (LDMC); (2) Placement Algorithm: Largest Total Cost on Elimination (LTCE); (3) Placement Algorithm: First Least MC Connectivity (FLMC); and (4) Placement Algorithm: First Smallest Cost MC Connectivity (FSCMC).

We have evaluated the proposed placement algorithms given static sets of multicast sessions as well as under dynamic traffic conditions. Our results show that the proposed algorithms perform well compared to existing algorithms. The details are given in [90, 6].

7. Service Provisioning for Multicast Communication Under a Scheduled Traffic Model

Problem Description We consider [85, 87] a WDM network with a topology represented by a directed graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ where $\mathcal{V}$ ($|\mathcal{V}| = n$) is the set of vertices and $\mathcal{E}$ ($|\mathcal{E}| = m$) is the set of links, each of which has W wavelengths (numbered from 0 to $W - 1$). We consider a network with and without wavelength conversion ability at any node, respectively. A set of scheduled multicast sessions $\mathcal{M} = \{d_1, d_2, \cdots, d_k\}$ is given. Each session d is represented by a tuple (s, D, n, t_s, t_e) where s is the source node, $D = \{t_1, t_2, \cdots, \}$ is the set of destination nodes of the session, t_s and t_e are the starting time and ending time of the multicast session, and n is the bandwidth requirement of the session. We assume $n = 1$, one wavelength.

The multicast session RWA problem under the scheduled traffic model is to route and assign a proper wavelength to each session $\in \mathcal{M}$ such that

- In the **non-blocking case** in which the network has enough resources to accommodate all the sessions in $\mathcal{M}$ to meet their specifications (i.e., bandwidth and schedule requirements), the goal is to minimize total network resources used in terms of, for example,
    1. the total number of wavelength-links used by all sessions; or
    2. the maximum number of wavelengths needed on a link.
- In the **blocking case** in which the network does not have enough resources to accommodate all the sessions as specified, in addition to minimization of total network resources used, the goal is, for example,
    1. to minimize the number of sessions to be rearranged (i.e., to minimize the subset of sessions that may have their starting time changed: postponed or moved forward) in order to have all the sessions in the set $\mathcal{M}$ accommodated by the network; or
    2. to minimize the total time from the time when the first sessions starts to the time when the last sessions ends (termed as the *schedule length*) it takes to satisfy all the sessions in $\mathcal{M}$.

Our primary objective is to minimize total wavelength-links used while trying to meet sessions' specifications. The hardness of the problem lies in the spatial and temporal constraints imposed on the set of sessions. In the spatial domain, sessions are routed through the mesh network topology and may share the same wavelength on the same link at different times. Routing of a lightpath may also be subjected to the wavelength continuity constraint when there is no wavelength conversion. In the time domain, sessions may overlap in time. In the performance evaluation, we use a demand time correlation factor [44] to characterize the extent of conflicts among sessions in the time domain. The problem is therefore termed as space-time multicast RWA problem. The problem can be shown to be $\mathcal{NP}$-hard from reduction of the multiprocessor-scheduling problem [29].

We have developed an efficient heuristic RWA algorithms that take advantage of resource reuse in both space and time–Resource-Usage Based Scheduling Algorithm [85, 87]. The basic idea of this algorithm is to accommodate multicast sessions, subject to the time correlation constraint, in the order of decreasing demand size which is defined as the product of multicast session holding time and the number of destination nodes involved in a multicast session. This demand size is a rough estimation of resources needed by a multicast session.

When scheduling a multicast session, the algorithm tries to allocate the lowest numbered wavelength available first. That is, wavelength 0 is tried first and then wavelength 1 if there is not enough resource on wavelength 0 to accommodate the session, and so on. While trying to schedule multicast session d on a wavelength (assume it to be i), an auxiliary graph $\mathcal{G}'_i$ is constructed to represent the available network resources on the wavelength plane i. The auxiliary graph is obtained by removing from $\mathcal{G}$ (the original network topology) all the links with wavelength i being assigned to the sessions that have time correlation with the multicast session d under consideration. Each link is assigned an initial weight of its physical length. In order to reuse the links that have been used previously (i.e., by multicast sessions that have been accommodated), the algorithm will scale down the weights of the links in $\mathcal{G}'_i$ that have been used by the sessions that have no time correlation with session d such that those links would have a much better chance of being selected when routing session d. Therefore, network resource reuse can be improved.

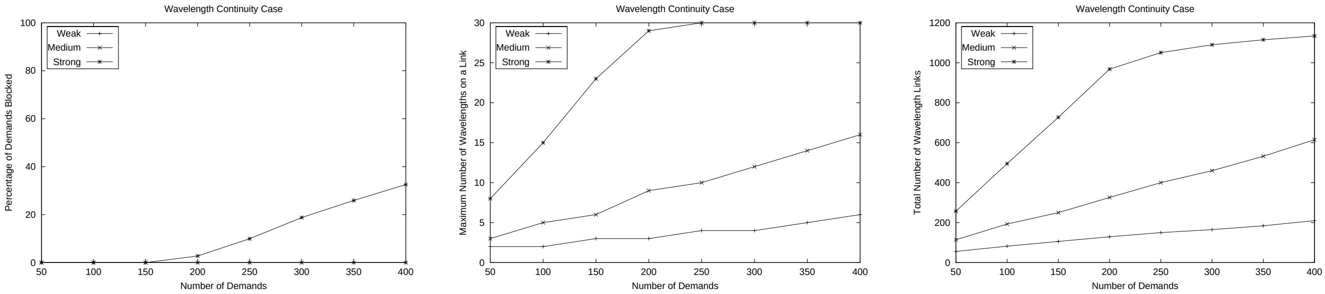
Our performance evaluation shows that the proposed algorithms, by taking advantage of knowing the holding-time of sessions, are effective in satisfying the bandwidth and timing requirements of multicast sessions and reducing the total network resources used under the scheduled traffic model.

Performance Evaluation We report the results using the NSFNET topology for performance evaluation and comparison [85, 87]. Simulations have also been run on other network topologies with similar observations. A weight that represents the physical length is associated with each link of the topology [44]. Different multicast session sets containing 50 to 400 multicast sessions with variable group sizes (drawn from [2, 8]) are used in the simulation. The source and destinations of a session are randomly generated. Each session requires one wavelength. We use the definition of demand time correlation in [44]. We consider three classes of session set with a demand time correlation factor being weak (0.01), medium (0.5), and strong (0.8) to characterize the conflicts among sessions in the time domain. We assume that each link has 30 wavelengths. Simulation was run to 95% confidence.

We are interested in the following performance metrics: (i) the total number of wavelength-links used in the entire network; (ii) the maximum of wavelengths used on a link; (iii) percentage of sessions rearranged. The primary objective of our algorithms is to schedule the set of multicast sessions so that the total number of wavelength-links used in the entire network is minimized when network resources are sufficient to meet multicast session specifications (i.e., schedule and bandwidth requirements). When network resources are not sufficient to accommodate all sessions in a set as specified, in addition to minimization of the number of sessions that need to be rearranged, the objective is to minimize the total number of wavelength-links used, including the wavelength-links used by the sessions rearranged.

Simulation Results Since network resources are limited, the number of sessions that cannot be satisfied in either the space domain or the time domain, or both grows as the number of sessions increases, i.e., as the traffic load of the network increases.

Fig. 3(a) shows the percentage of sessions that need to be rearranged using the resource-usage based algorithm under weak, medium, and strong demand time correlation, respectively. Demand time correlation



(a) (b) (c)

Figure 3: (a) Multicast session blocking rate; (b) The maximum number of wavelengths used on a link; (c) The total number of wavelength-links used; versus number of sessions in a session set with different time correlation, number of wavelengths = 30.

characterizes the extent at which sessions are correlated in time. Stronger time correlation indicates that sessions are more likely to overlap in time. From the figure, we observe that the percentage of sessions rearranged is essentially zero under weak and medium demand time correlation scenarios. This indicates that the proposed algorithm is effective in meeting the session specifications. The percentage of sessions rearranged increases as the session set size increases under the strong demand time correlation case. About 33% of multicast sessions need to be rearranged when the session set size is 400.

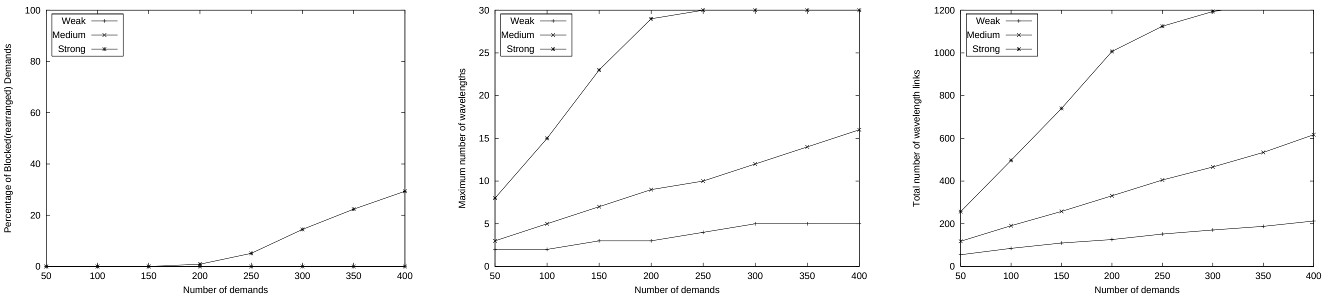
Fig. 3(c) shows the total number of wavelength-links used in the entire network versus the number of multicast sessions under different demand time correlation. We observe that the algorithm tries to minimize the number of wavelength-links used in the network by letting rearranged sessions reusing the wavelength-links that have been used by scheduled sessions as much as possible. In particular, time correlation among sessions has a huge impact on the amount of resources used. For example, when the session set size is 400, the weak time correlation case and medium time correlation case use only about 18% and 55%, respectively, of the resources in the strong time correlation case.

As the demand time correlation grows stronger, some sessions cannot be accommodated with their original specifications due to limited network resources and have to be rearranged to use residual resources that do not conflict in the time or space domain with scheduled sessions. For example, a session can be scheduled earlier or later in time with respect to its original schedule. In the later case, the schedule length may be prolonged.

These results show that the time correlation among the sessions in a set has a significant impact on the cost of a solution of an instance of the multicast session RWA problem under consideration. In fact, a set of sessions with significant time disjointness should help the reuse of wavelength-links and as a result, lead to a smaller number of required wavelength-links as shown in Fig. 3(c).

Fig. 3(b) depicts the maximum number of wavelengths used on a link versus the number of sessions in a set. Again, the maximum number of wavelength used on a link increases as demand time correlation grows stronger and the number of sessions increases. In the weak and medium time correlation cases, only about 7 and 17 wavelengths, respectively, are used when the session set size is 400. In the strong time correlation case, 30 wavelengths are used after the session set contains 250 or more sessions.

Fig. 4 shows the simulation results of the wavelength convertible case. Compared with the wavelength continuity case, the use of wavelength conversion slightly decreases the ratio of rearranged/blocked demands. The improvement appears to be not as much as we have expected. One explanation may be that our scheme tries to route demands in a greedy manner, which may require more network resources. When the available network resources become scarce, a demand that is not able to be routed in the wavelength continuity case may be routed in the wavelength convertible case. However, it may cause one or more demands to be rearranged later.



(a) (b) (c)

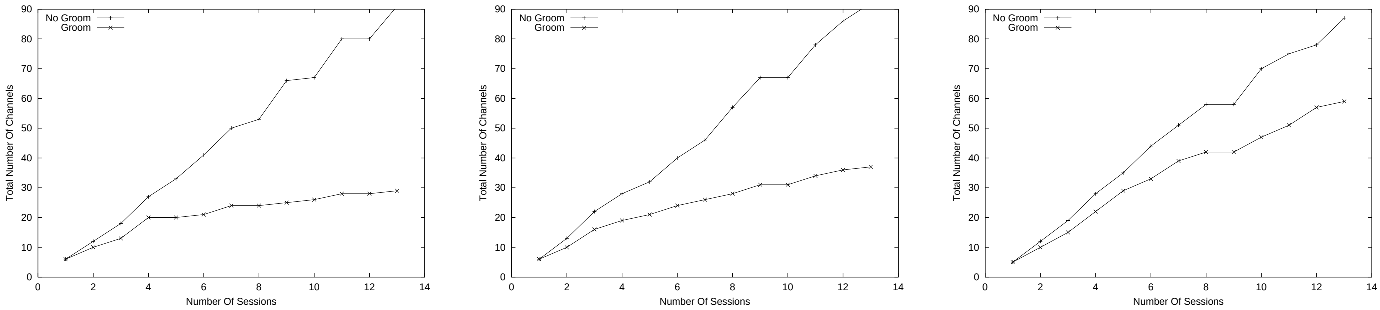
Figure 4: Simulation results for wavelength convertible case: each link has 30 wavelengths. (a) Multicast session blocking rate; (b) The maximum number of wavelengths used on a link; (c) The total number of wavelength-links used; versus number of sessions in a session set with different time correlation.

8. Multicast Traffic Grooming in WDM Optical Networks

Multicast has been used in a wide spectrum of applications as well as in many DOE science applications. These applications differ considerably in their bandwidth requirements. Many applications require much less bandwidth than a full wavelength can support. Occupying a full wavelength for a few megabytes of data results in very poor utilization of the available bandwidth. *Grooming of low-speed traffic streams onto a single wavelength turns out to be an inevitable means for efficient bandwidth utilization and higher network throughput.* Despite a tremendous amount of research work in WDM optical networks, multicast traffic grooming has remained an area to be explored with few recent studies.

The problem of multicast traffic grooming in WDM optical mesh networks may be expressed as routing multicast traffic streams from each source to the members of every multicast group, and assigning an appropriate wavelength to each multicast session. Traditionally, routing and wavelength assignment are considered as two separate problems. To derive an optimal solution, routing and wavelength assignment need to be considered simultaneously [8]. We formulate the problem of multicast traffic grooming as an integer linear program. We then propose a heuristic algorithm for constructing multicast routing trees and a First-Fit algorithm for traffic grooming, assuming wavelength conversion capability in the network nodes [8]. By intelligently grooming several multicast sessions with fractional wavelength bandwidth requirements onto a single wavelength, we demonstrate that our algorithms achieve a significant reduction in the maximum number of wavelengths required in a link as well as in the total number of wavelength links needed in the network.

We have considered a network with a few nodes that are multicast capable (i.e., supporting light splitting). We assume that every multicast incapable (MI) node is DaC capable. The number and location of the multicast capable (MC) nodes are pre-determined such that every MI node can reach an MC node in one hop.



(a) (b) (c)

Figure 5: (a) Impact of grooming on the total number of links used, $g = 16, r = 2.0$; (b) Impact of grooming on the total number of links used, $g = 16, r = 4.0$; (c) Impact of grooming on the total number of links used, $g = 16, r = 8.0$.

8.1 Multicast Tree Construction Algorithm

A multicast tree is constructed from the routing information maintained by each node. The route for a node may be generated by minimizing the cost metric from the node to every other node in the network. The route to individual destination node may be determined using the Dijkstra's algorithm for shortest paths. We consider the number of hops as the metric. Since we assume that the network has sparse splitting capability, an MI node can not have more than one child in the generated multicast tree. The Dijkstra's algorithm is applied to the network topology with sparse splitting capability by pruning network links leading out of the MI nodes. This means that we limit the connectivity of the MI nodes to two. Once the route for each node is determined, the multicast tree for a multicast session is generated by combining the individual route from the source to each destination member. The algorithm for constructing the routing table works as follow:

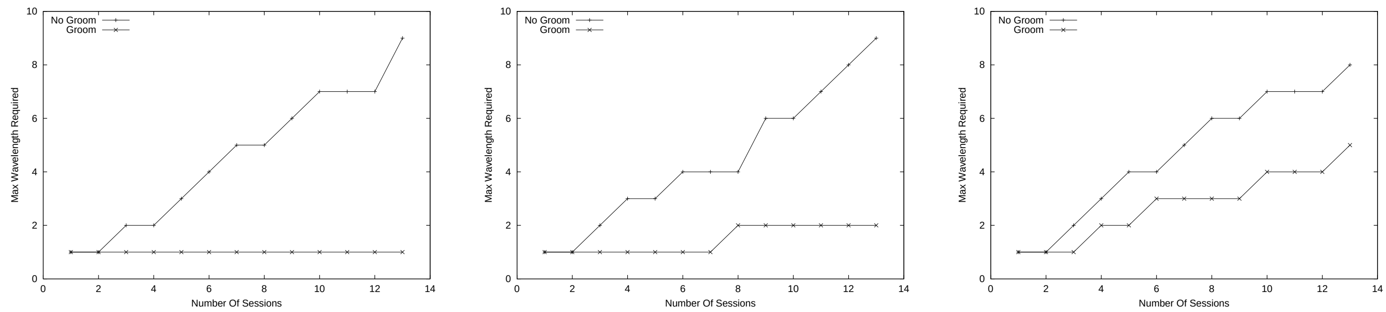
1. Step 1: For each MI node, limit the degree of connectivity to two. In our model, it must have at least one MC node as its neighbor. If an MI node has more than one MC node neighbors, take the two MC nodes with the highest node connectivity as the neighbors. Any tie is resolved arbitrarily. On the other hand, if the node has only one MC node and several MI nodes, then the MC node is taken as its first neighbor and the MI node with the highest node connectivity is taken as the second neighbor. Any tie between MI nodes having the same node connectivity is resolved arbitrarily.

2. Step 2: For each MC node, compute the routes by running Dijkstra's shortest path algorithm on the modified network to determine the shortest route between the MC node and all other nodes in the network.

3. Step 3: Sort the MC nodes in ascending order of the total number of links required in reaching all other nodes in the network, using the routes computed in Step 2.

4. Step 4: If an MI node has more than one MC node neighbors, select the MC node having fewer links required to reach all other nodes as determined in the Step 3, as the first neighbor, and similarly select the second neighbor.

5. Step 5: For each MI node, determine the routing table using the route of its first neighbor (which is an MC node) as obtained in earlier steps.



(a) (b) (c)

Figure 6: (a) Impact of grooming on the maximum number of wavelengths required, $g = 16, r = 2.0$; (b) Impact of grooming on the maximum number of wavelengths required, $g = 16, r = 4.0$; (c) Impact of grooming on the maximum number of wavelengths required, $g = 16, r = 8.0$.

8.2 First Fit Grooming Algorithm

We have designed a simple First-Fit algorithm for grooming the routed traffic from multiple multicast sessions. Let l be the number of multicast sessions, $|E|$ be the number of total links in the network, and w be the number of wavelengths on each link. The input to the algorithm is, therefore, l multicast trees. Every edge of each multicast tree is mapped onto its corresponding link. Let $t(i, j)$ be the traffic on link i by session j. Therefore, $t(i, j) = r_j$ if session j uses link i, otherwise, $t(i, j) = 0$, where r_j is the traffic requirement of multicast session j. The algorithm works as follow:

1. Step 1: Take a multicast tree and map traffic from the source (root) to all destinations onto appropriate links;
2. Step 2: Repeat Step 1 for all multicast trees;
3. Step 3: Take a link and get the list of traffic streams mapped onto this link if any (in Steps 1 and 2);
4. Step 4: Take a traffic stream from the list of streams in Step 3, and groom it onto the first channel that can carry it on this link;
5. Step 5: Repeat Step 4 to groom all the streams in the list for this link;
6. Step 6: Repeat Steps 3–5 for all the links in the network.

8.3 Performance Evaluation

For performance evaluation [8], we use the 14-node NSFNET topology with 5 MC nodes and 9 MI nodes. The MC nodes are selected based on the following criteria:

- All nodes having the largest node degree are MC capable;
- The number and location of MC nodes are such that each MI node can reach an MC node in a single hop;
- Any tie between nodes having the same degree is resolved arbitrarily.

The number of multicast sessions have been varied from 1 to 13. In each session, the source, the number of destination nodes, and the nodes in the destination set, are randomly generated.

We see from the simulation results (Fig. 5 and 6) that both the number of wavelength links used and the maximum number of wavelengths required to route all the sessions decrease dramatically if the traffic streams are groomed. The results show that grooming can substantially improve the wavelength bandwidth utilizations and reduce the maximum number of wavelength requirements in two aspects: (i) The savings in the number of wavelength links as well as in the maximum number of wavelength requirements increases as the number of sessions increases; (ii) The extent of savings in the number of wavelengths increases as the average amount of traffic for the given number of multicast sessions decreases. The latter is especially of practical significance. Specifically, Figs. 5(a), 5(b), and 5(c) illustrate that the extent of savings in total number of wavelength links decreases as the average amount of traffic per session increases from $\frac{g}{8}$ to $\frac{g}{2}$. In the case of average amount of traffic per session being $\frac{g}{2}$, the traffic streams can take values between 1 and g. Similarly, the traffic streams can take values between 1 and $\frac{g}{2}$ to have their average amount of traffic to be $\frac{g}{4}$ and so on. On the other hand, Figs. 6(a), 6(b), and 6(c) show that the maximum number of wavelengths required increases as the average amount of traffic per session increases from $\frac{g}{8}$ to $\frac{g}{2}$. Interestingly, the maximum number of wavelengths required remains at 1 in the case of average amount of traffic per session being 2.0 even up to 13 sessions if grooming is applied. Note that in this case, the multicast session traffic varies from 1 to $\frac{g}{4}$.

9. Effective Traffic Grooming for SONET/WDM Ring Networks

The number of traffic demands in WDM optical networks is likely to be much larger than the number of wavelengths available and that individual traffic demand is likely to require a smaller bandwidth than that of a full wavelength channel. Both factors call for multiplexing low-speed traffic requests onto a wavelength to efficiently utilize network resources. The multiplexing of lower rate traffic streams in current technologies employs time-division multiplexing (TDM) that requires electro-optic conversions. Synchronous Optical Network (SONET) rings are widely used in today's network infrastructure. Each SONET ring is constructed by using fibers to connect SONET add drop multiplexers (ADMs). An ADM can multiplex multiple lower rate traffic streams to form a higher rate stream. It has been recognized that the cost of electro-optic equipment such as SONET add-drop multiplexers (ADMs) is one of the dominant network cost metrics [101, 34]. These factors give rise to the concept of traffic grooming that is defined as the techniques of multiplexing lower speed traffic streams onto appropriate wavelength channels in order to minimize the cost metric and/or to optimize the throughput [101, 34].

Much work [33, 34, 74, 35, 58, 101, 4, 54, 83, 86, 15, 16, 20, 46, 38, 7] has focused on traffic grooming in SONET/WDM ring networks. Previous work has considered many aspects of traffic grooming, including minimizing the number of wavelengths, minimizing the number of ADMs, considering different traffic models, using different network architectures, incorporating switching capability, wavelength conversion, transceiver tunability and so on. Modiano et al. [58] and Wan et al. [83] have proved that the general traffic grooming problem is $\mathcal{NP}$-complete. The authors in [86, 38, 19, 20] formulate the traffic grooming problem as an integer linear programming (ILP) based optimization problem. The limitation of the ILP approach is that the numbers of variables and equations increase explosively as the size of the network increases. High computational complexity makes this approach unattractive in many practical cases.

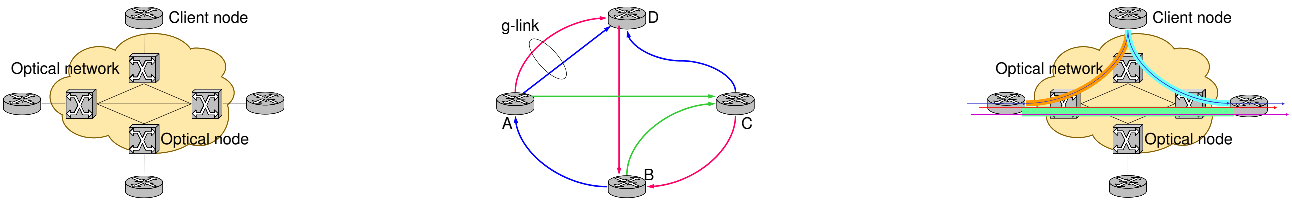
The bounds on the number of ADMs needed for traffic grooming in SONET/WDM ring networks have been addressed in previous work including [74, 34, 35, 58, 101, 4, 16, 7]. For uniform all-to-all traffic, lower bounds on the numbers of ADMs required for BLSR/2 rings with sub-wavelength traffic have been formulated in [34]. The bounds assume the availability of wavelength converters in the network and are rather loose. The work by Simmons et al. [74] considers all-to-all uniform and distance-dependent traffic models for BLSR networks. Expressions on approximate number (not necessarily lower bounds) of ADMs based on *super-node* approximation were derived for odd number of nodes only. No algorithms for grooming traffic streams were presented. Lower bounds on the number of ADMs have been calculated algorithmically for both unidirectional and bidirectional rings in [101] for all-to-all uniform traffic model. However, no lower bound expressions were given. Heuristic algorithms for grooming traffic have been presented. The grooming algorithm developed in [101] for all-to-all uniform traffic is based on traffic circles constructed using algorithms developed in [100]. To the best of our understanding, the circle construction algorithm of [100] for even number of nodes (N) **does not** include all traffic streams in one direction of the ring for all to-all uniform traffic model in BLSR networks, and therefore is not entirely correct for BLSR networks. Consequently, the number of circles constructed by that algorithm for even N is $\lceil \frac{N^2}{8} \rceil$ which is less than the lower bound on the number of circles we derived when $N = 4m, m \in Z^+$. Wan et al. [83] studied the grooming of arbitrary traffic in BLSR networks. General lower bounds that are claimed to be better than the bounds of [33] were derived for arbitrary traffic in BLSR networks. A second lower bound, more suited for all-to-all uniform traffic model has also been derived. Various approximation algorithms were proposed and their approximation ratio were analyzed. Modiano et al. [58] and Qiao et al. [101] have shown through examples that it is not always possible to minimize the number of wavelengths and the number of ADMs simultaneously. It has also been shown in [33] that minimizing the number of ADMs and the number of wavelengths are intrinsically different problems and that there exist cases where the two minima cannot be achieved simultaneously.

9.1 Traffic Grooming in UPSR Networks

We have studied traffic grooming in unidirectional ring networks [7] with no switching capability under both uniform traffic and non-uniform traffic models to reduce electronic multiplexing costs. Based on the clustering notion, we derive a *general and tighter* lower bound for the number of ADMs required in traffic grooming under the uniform all-to-all traffic model. This bound reduces to special cases obtained in previous work [58]. We also derive *general, tighter, and closed form* lower bounds for the number of ADMs required under two non-uniform traffic models: the distance-dependent traffic model and the non-uniform symmetric traffic model. Cost-effective algorithms that exploit traffic characteristics are then designed and studied to efficiently groom traffic streams under different traffic models. Our numerical and simulation results show that the proposed algorithms outperform existing traffic grooming algorithms by using fewer number of ADMs. Our algorithms in several cases also achieve the general lower bounds derived [7].

9.2 Traffic Grooming in BLSR Networks

We have studied traffic grooming in BLSR networks [9] under the uniform all-to-all traffic model with an objective to reduce total network costs (wavelength and electronic multiplexing costs), in particular, to minimize the number of ADMs *while using the optimal number of wavelengths*. All previous ADM lower bounds except perhaps that in [34] were derived under the assumption that the magnitude of the traffic streams (r) is *one* unit ($r = 1$) with respect to the wavelength capacity granularity g. We then derive new, more general and tighter lower bounds for the number of ADMs subject to the constraint that *the optimal number of wavelengths is used*, and propose heuristic algorithms (circle construction algorithm and circle grooming algorithm) that try to minimize the number of ADMs while using the optimal number of wavelengths in BLSR networks. Both the bounds and algorithms are applicable to any value of r and for different wavelength granularity g. Performance



(a) Physical topology (b) Logical topology (c) Traffic grooming

Figure 7: A mesh WDM optical network and traffic grooming illustration.

evaluation shows that wherever applicable, our lower bounds are at least as good as existing bounds and are much tighter than existing ones in many cases. Our proposed heuristic grooming algorithms perform very well with traffic streams of larger magnitude. The resulting number of ADMs required is very close to the corresponding lower bounds derived [9].

10. Logical Topology Design for Dynamic Traffic Grooming with QoS Requirements

Traffic grooming is an operation to consolidate client traffic onto lightpaths in the inter-networking of the optical network and client networks. Depending on whether the client traffic is static or dynamic, it can be classified into static and dynamic traffic grooming. We study how to design logical topology (using minimum network resource) for dynamic traffic grooming, to meet the given traffic blocking probability requirements [93, 94].

10.1 Single-Hop Dynamic Traffic Grooming

A lightpath is a logical link between a source and destination client nodes pair (*sd-pair*), and is set up along a physical route in the WDM optical network between the sd-pair, occupying one dedicated wavelength on each traversed link. Client traffic is transported over lightpaths between client nodes (e.g., IP routers and ATM switches) across the WDM optical network. The set of lightpaths among all client nodes forms a logical topology, and the set of lightpaths between an sd-pair is called a *grooming link* (g-link) in the logical topology. Fig. 7 illustrates a WDM optical network and a sample logical topology. Client traffic can be generically characterized as *calls* which can be IP traffic carried over MPLS label switched paths (LSPs) [68], or ATM virtual paths/channels. The data rates of calls are typically heterogeneous and significantly smaller than the lightpath capacity (which is at the granularity of one wavelength). To make the traffic transportation cost-effective, calls are consolidated onto lightpaths in the logical topology to be transported to destinations, an operation called *traffic grooming*, as illustrated in Fig. 7(c).

Traffic grooming in mesh WDM optical networks can be classified into *static* and *dynamic grooming*, depending on whether the client traffic is static or dynamic. With static traffic, the information of each call, e.g., source, destination, and data rate, is given in advance, and the fundamental problem is to design a logical topology and reserve dedicated bandwidth on lightpaths for each call [102]. For dynamic traffic grooming, although the client traffic is dynamic, the logical topology may be either configured on-demand by the arrival/departure of calls, or designed offline (based on estimated traffic demands). The former approach can dynamically respond to changing traffic load. Nevertheless, it needs the dynamic lightpath provisioning capability. Although the standards and technologies such as the Generalized Multi-Protocol Label Switching (GMPLS) [57] have been proposed for this purpose, it still takes a long time for service providers to widely deploy them, and thus the dynamic lightpath provisioning may not be available for a large number of WDM optical networks. Furthermore, even if a WDM optical network has this capability, the offline logical topology design may still be beneficial because online configuration causes large lightpath setup/teardown overhead, and delay for the first batch of packets carried in a call that invokes a new lightpath setup. (Note that unlike in the case of static traffic, the logical topology design for dynamic traffic cannot reserve bandwidth for client calls.)

There have been many efforts on logical topology design for WDM optical networks, such as [63, 59]. Nevertheless, these studies focused on packet traffic (although they can handle circuit traffic in the same manner, such handling is not sophisticated), and assumed that the traffic is carried without loss on paths from source to destination as long as the allocated paths capacities are larger than the traffic load. This is not realistic for dynamic traffic, because even though the stationary traffic load is fixed, the temporal traffic load randomly fluctuates from time to time, and some traffic gets blocked if the traffic load at a specific time is larger than the allocated capacity.

We study logical topology design for dynamic traffic grooming and formulates it into an integer linear programming (ILP) problem. We focus on dynamic *circuit traffic* because the predominant packet traffic is expected to be carried on LSPs with the MPLS deployed in IP networks [93]. We consider traffic blocking and minimize the used network resource (e.g., wavelengths) in the physical topology while meeting the traffic blocking probability requirements. We integrate wavelength assignment in the formulation, and consider sparse wavelength conversion. (Only the full wavelength conversion has been considered in a few previous studies on logical topology design.) In addition, we develop a heuristic to solve this problem in large networks.

Problem and Solution Approaches Similar to [63], we use the multi-commodity flow model to formulate logical topology design for dynamic traffic grooming. The problem is stated as follows: given the requirements for the end-to-end traffic blocking probabilities between sd-pairs, and the average traffic blocking probability (among all sd-pairs), compute the number of lightpaths that are needed by each sd-pair and assign wavelengths to each lightpath, such that the used network resource is minimized, and the requirements for traffic blocking probabilities are met. We address the average blocking probability for all classes of calls, instead of the blocking probability for each class of calls, and studies the *single-hop* (dynamic) grooming to avoid the nonlinear formulation (which is computationally expensive) in the path blocking probability computation. The single-hop grooming refers to the traffic grooming where the traffic between an sd-pair is carried over the lightpaths directly connecting this sd-pair [92]. It is primarily used in the case where the electronic forwarding (at intermediate client nodes) is more expensive than optical bypassing, and thus it is desirable to completely eliminate electronic forwarding so that a call only goes through one single hop in the logical topology to its destination.

We consider two types of network resource in the formulation: the ports (transmitters/receivers) at client nodes, and wavelengths. Each lightpath needs one outgoing port (transmitter) at the source client node and one incoming port (receiver) at the destination client node. We developed one formulation to minimize the total number of ports needed by the lightpaths in the logical topology, and three formulations to minimize the number of used wavelength-links, assuming no wavelength conversion, full wavelength conversion, and sparse wavelength conversion (where some optical nodes have full wavelength conversion [76]), respectively, for dynamic traffic grooming to meet the traffic blocking probabilities requirements. We have proposed a heuristic for very large networks. The formulations are found effective and efficient for small to medium-size networks, and the heuristic can obtain a good performance.

We have also addressed the general multi-hop dynamic traffic grooming problem, survivable traffic grooming, as well as modeling and computing loss probability for dynamic traffic grooming. The detailed results have been reported in [94].

11. All Hops Optimal Mechanisms for Dynamic Routing of Sliding Scheduled Traffic Demands

We considered the routing of holding-time aware demands under a *sliding scheduled traffic model* [88] to satisfy the bandwidth and timing requirements of dynamic demands (or demands that arrive sequentially) [84].

Given a network topology $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ is the set of nodes and $\mathcal{E}$ is the set of capacitated directed links. A demand in the sliding scheduled traffic model is represented by a tuple $d = (s, t, \ell, r, \tau, b)$ (Fig. 1) that satisfies $r - \ell \geq \tau > 0$ where s and t are the source and destination, b is the requested bandwidth units, ℓ and r are the starting time and ending time of a time window during which the demand with a holding-time of τ time units resides. An h-hop feasible path between s and t is a path that satisfies both the demand's bandwidth and timing requirements. An optimal path is a minimum-hop feasible path between s and t with respect to the current state of the network.

We have designed a Bellman-Ford flavored routing algorithm that given the network topology, current link state information, and a maximal hop count H ($H < |\mathcal{V}|$), finds, for each hop count value $h, 1 \leq h \leq H$, and destination node $t \in \mathcal{V}$, all h-hop feasible path between s and t under the sliding scheduled traffic model. The routing algorithm iteratively finds all feasible paths of at most h hops at the end of h-th iteration.

We proved the correctness of the algorithm with two theorems [84]:

Theorem 1 *The all hops optimal routing algorithm is cycle-free.*

Theorem 2 *The all hops optimal routing algorithm finds all feasible paths of at most h hops from the source to all other nodes at the end of h-th iteration.*

We have also analyzed the time complexity of the algorithm to be $\mathcal{O}(|\mathcal{E}| \cdot H \cdot \lfloor \frac{r-\ell}{\tau} \rfloor \log(N \lfloor \frac{r-\ell}{\tau} \rfloor))$ where N is the maximum node degree [84].

12. Diverse Routing with Shared Risk Link Group (SRLG) Failures

A bandwidth demand requires two paths in a network, one working path and one protection path, so that the service to the demand can be honored in case of a single network failure, such as a fiber cut. A basic requirement for the pair of working and protection paths is that they must be diversely routed. Optical networks have at least two layers: the physical layer and the optical layer. The physical layer consists of fiber spans and nodes that represent locations where fiber spans terminate. The optical layer consists of optical links (or lightpaths) and a subset of nodes contained in the physical layer. An optical link is a path connecting a pair of nodes via a set of fiber spans in the physical layer. Therefore, an optical link may traverse several fiber spans and nodes. In addition, several optical links may traverse a single fiber span or node. Therefore, a single failure in the physical layer can cause multiple failures at the optical layer.

The diverse routing problem in WDM optical networks is to find a pair of paths between a source and a destination at the optical layer such that no single failure in the physical layer may cause both paths to fail.

A shared risk link group (SRLG) is used to represent a set of optical links that are affected by a single failure in the physical layer. The diverse routing problem in networks with generally defined SRLG failures has been proved to be $\mathcal{NP}$-complete [39] where an SRLG may include an arbitrary group of links. We considered a special case of the diverse routing problem where all the optical links in an SRLG share a common endpoint [56]. An example of such a SRLG is a group of links that come out of a common node and share the same conduit.

Note that this problem can be reduced to some commonly known diverse routing problems. For example, if each SRLG includes all the links incident to a common node, the problem is transformed to the node-disjoint diverse routing problem. On the other hand, if each SRLG contains only a single link, this problem becomes the link-disjoint diverse routing problem. For the link/node disjoint diverse routing problem, Suurballe [78, 79] and Bhandari [5] have proposed polynomial time complexity solutions. For the diverse routing problem with SRLG failures, the work in [17] considered the problem subject to the constraint that a link cannot belong to more than one SRLG group except that a link incident to the two endpoints of a common link can belong to two SRLGs. The work in [18] also considered a similar problem in which a SRLG is defined as a *incident-SRLG* that has exactly two links incident to a common node. A link, however, is allowed to belong to more than one incident-SRLG group. This type of SRLG failures covers the dual-link failure scenario only.

The case studied by us is a more general case of SRLG failures[1] that allows a link to belong to arbitrary number of SRLG groups and an SRLG may include more than two links. We developed a polynomial time optimal algorithm to solve the diverse routing problem under this type of SRLG failures [56]. Our proposed algorithm is based on adapting the Bhandari's link disjoint routing algorithm [5] and the Bellman-Ford's algorithm to find an optimal pair of SRLG-disjoint paths in polynomial time.

We proved [56] that the proposed diverse routing algorithm produces the optimal solution: a pair of least cost SRLG-disjoint paths for a given source and a destination.

Theorem 3 *The two paths obtained by the diverse routing algorithm are SRLG-disjoint.*

Theorem 4 *The pair of paths obtained are optimal in terms of total link cost.*

The time complexity of the algorithm is given by the following theorem [56], which is also shown to be more time efficient than the graph transformation based algorithm of [17].

Theorem 5 *The time complexity of the proposed diverse routing algorithm is* $\mathcal{O}(|\mathcal{V}|log|\mathcal{V}| + |\mathcal{E}| \cdot |\mathcal{R}| + H \cdot (|\mathcal{E}| + |\mathcal{V}| \cdot \mathcal{D}^2))$ *where* $\mathcal{D}$ *is the maximum node degree.*

13. Multi-Constrained Routing in Networks with SRLGs

A shared risk link group (SRLG) is used to represent a set of links that are affected by a single failure (e.g., a failure in the physical layer like a cable cut). The failure of any SRLG that a connection traverses will disrupt the service provided to the connection. A cost is also incurred on a link when it is used to provide the service to the connection. The failure of an SRLG can be measured by a risk factor, e.g., the probability of failure. If the probability of failure of an SRLG i is p_i, the probability of no SRLG failure along a path can be calculated as (with standard independence assumptions) $\Pi_i(1-p_i)$ where i is any SRLG that the path traverses, which can be

[1]This definition of an SRLG is a generalization of those defined in [17] and [18].

expressed as a summation, $\sum_i ln(1-p_i)$, on logarithmic scale. For a service provider, it is important in some cases to make sure that the provisioning of a service for a client is both risk-bounded and cost-bounded (where the cost can be monetary cost, delay, etc), i.e., the accumulative risk and cost on the route of the connection is bounded according to the service level agreement (SLA). The problem is then to find a multi-constrained path in a network with SRLGs [89].

The solution to this problem can also be used in designing algorithms that find a pair of SRLG-diverse paths between a source and a destination for survivable service provisioning. In SRLG diverse routing, a demand requires two paths in the network, one working path and one protection path, so that the service to the demand can be honored in case of a single network failure, such as a fiber cut. The diverse routing problem in networks is to find a pair of paths between a source and a destination such that no single failure in the network may cause both paths to fail. The diverse routing problem in networks with generally defined SRLG failures has been proved to be $\mathcal{NP}$-complete [39] where an SRLG may include an arbitrary group of links. In addition, finding a pair of least cost SRLG-diverse routes is also $\mathcal{NP}$-complete [39]. This problem can be solved in polynomial time under some special definition of SRLGs [17, 56]. In many cases, it is desirable for service providers to make sure that both the working path and backup path are risk-bounded and cost bounded to provide certain degree of quality of service and protection.

Therefore, the multi-constrained routing problem we considered is to find in networks with SRLGs a path between a source and a destination such that both the path cost and the weight of SRLGs to which the links of the path belong are bounded. The path cost is measured as the sum of cost of links on the path while the weight of SRLGs is calculated as the sum of the weight of individual SRLGs along the path. The problem is proved to be $\mathcal{NP}$-complete by reducing from the Hitting-Set problem [43].

The multi-constrained routing problem is solved in two steps [89]. First, an algorithm is devised that tries to find a least cost path in the network where the path cost is defined to be the combined cost of links and SRLG weights along the path. Second, an intelligent search algorithm that integrates the algorithm of the first step is designed to solve the multi-constrained routing problem to effectively find a path between the source and the destination with the least total link cost while the total weight of the SRLGs along the path is bounded.

The performance of the search algorithm in finding multi-constrained paths is compared with that of an ILP solution [89]. A bound is imposed on the total weight of SRLGs along a path. In the simulation, if the bound is too tight, no feasible solution may be found. To test our algorithms, we set the bounds to be proportional to the number of SRLGs in the topology: $C_{SRLG} = 40 \cdot |\mathcal{R}|$. We have tested the algorithms using three topologies [56] with non-localized SRLGs as well as localized SRLGs, and the number of SRLGs ranges from 20 to 200. We record the total link cost of the paths returned by both the ILP and the search algorithm (columns 2 and 3 of Tables 10-13), and the number of instances that the algorithms fail to find feasible solutions (columns 4 and 5 of Tables 10-13). Table 10-13 show the results of the ILP and the search algorithm using Topology 1 and Topology 2 with localized and non-localized SRLGs. F_{ILP} and F_{Search} indicate the number of instances where no feasible path was found by the ILP and the search algorithm. From the tables, we can see that our search algorithm indeed demonstrates outstanding performance by obtaining paths with cost close to that of the optimal solution, and our algorithm appears to return feasible paths whenever they exist. In Table 10, when $|\mathcal{R}| = 40$, the solution of the our search algorithm is a little bit better than that of the ILP. This is because the search algorithm fails (in 15 cases) more than the ILP (in 13 cases). There are two cases in which solutions are found by the ILP but not by the search algorithm. And the two solutions (paths) have a higher cost than the average cost of paths. We also notice that in topology 2 although in most cases, there is a noticeable performance gap between our heuristic and the ILP approach in finding the optimal combined cost path, the search algorithm based on the heuristic performs very close to the ILP solution (Table 12). This is due to the fact that the path finding heuristic and the search algorithm have different goals, and by adaptively tuning the

$\|\mathcal{R}\|$	ILP	Search Algorithm	F_{ILP}	F_{Search}
20	229.778	240.267	10	10
40	269.563	268.071	13	15
60	196.556	196.556	46	46
80	140.684	140.684	62	62
100	185.154	185.154	61	61
120	142.389	142.389	82	82
140	132.477	132.477	56	56
160	101.571	101.571	65	65
180	98	98	88	88
200	100.357	100.357	72	72

Table 10: Comparison of ILP and Search Algorithm on Topology 1 with non-localized SRLGs.

parameters of the path finding algorithm the search algorithm can achieve good performance.

14. Optical Burst Switching for Supporting Dynamic Service Provisioning

14.1 Contention Resolution

Optical burst switching (OBS) has been conceived to more effectively support transporting bursty traffic in wavelength division multiplexing (WDM) optical networks. Optical burst switching is based on the separation of the control plane and the data plane. In optical burst switching, data packets are aggregated into much larger sized bursts before transmission. This allows amortization of the switching overhead across multiple packets. A data burst is preceded in time by a control packet which is sent on a separate control wavelength and requests resource allocation at switches. When the control packet arrives at a core OBS switch, resources are reserved for the burst. If the required resources can be reserved, the burst can pass through the switch after a prescribed offset time. The control packet may also specify the duration of the burst to allow the switch to reserve resources only for the duration of the burst that follows. The benefit of OBS over conventional wavelength switching is that there is no need to dedicate a wavelength for an end-to-end connection given a data burst. OBS may be more practical than optical packet switching because packet switched networks require per packet based processing and buffering. In addition, using small sized packets (or cells) increases control overheads and reduces bandwidth utilization.

In OBS networks, efficient contention resolution is a key issue that has attracted much recent research. A contention occurs at a switch whenever two or more bursts are trying to leave the switch from the same output port on the same wavelength. In electrical packet switched networks, contentions are usually resolved with the store-and-forward technique, which requires the packets in contention be stored in a memory bank and sent out at a later time when the desired output port is free. This has not been possible in all optical networks because of the unavailability of optical RAM. Many contention resolution schemes for OBS networks have been proposed. These schemes make use of deflection routing [81, 13], optical buffering [30, 55], and wavelength conversion [31, 99]. Vokkarane et al. [82] proposed a notion called the burst segmentation. Several mechanisms have been proposed on how to efficiently use the segmentation approach to achieve efficient contention resolution in optical burst switched networks, e.g., using burst segmentation combined with other approaches like the deflection routing [82]. In [40], Huang et al. introduced a segmentation feed back model with the use of

$\|\mathcal{R}\|$	ILP	Search Algorithm	F_{ILP}	F_{Search}
20	271.118	278.294	15	15
40	218.241	219.707	42	42
60	180.483	183	40	40
80	216.464	216.464	72	72
100	171.645	171.645	69	69
120	208.609	208.609	77	77
140	144.633	144.633	70	70
160	175.818	175.818	67	67
180	122.348	122.348	77	77
200	147.381	147.381	79	79

Table 11: Comparison of ILP and Search Algorithm on Topology 1 with localized SRLGs.

fiber delay lines. However, the model uses external dedicated output ports that are used only when there is a contention, which decreases the resource utilization. In this work, wavelength conversion is not considered. The work by Gauger et al. [30] considered the dimensioning of FDL buffers at a switch for OBS networks. The work in [30, 31] did not consider burst segmentation at all. The discussion about burst contentions is only limited to contentions that do not span more that two nodes. Vokkarane et al. [81] proposed an analytical model for burst segmentation with deflection routing and with full wavelength conversion. The study of dynamic selective use of burst contention resolution policies [82] indicates that schemes like the deflection drop policy do not do well at high traffic loads.

We proposed a new hybrid dynamic burst contention resolution scheme [45]. The proposed scheme is based on the notion of burst segmentation and judiciously uses optical buffering (i.e., FDLs) and partial wavelength conversion, and at the same time dynamically selects contention resolution policies in response to the network traffic load change. We assume that the Just-Enough-Time (JET) signaling protocol [96] is used and that the network has FDLs and/or wavelength converters. However, switches only have limited number of full-range wavelength converters. Some switches may not have FDLs or wavelength converters. The proposed hybrid scheme does not pre-reserve FDLs or wavelength converters. Instead it uses them on an as needed basis to reduce wavelength converters required. Extensive simulation was performed to evaluate the performance of the proposed scheme and to compare with other schemes. Results show that our hybrid scheme is effective compared with some existing contention resolution policies [45].

14.2 Burst Grooming

Optical burst switching (OBS) explores statistical multiplexing and is therefore more resource efficient than circuit switching in optical networks. In OBS networks, arriving data packets (e.g., IP packets) are assembled at the ingress OBS nodes to form a data burst. A burst header packet is sent on a control channel in advance of the data burst to reserve resources and configure the switches along the route traversed by the data burst. Burst assembly can be conducted in a number of ways using: (1) a timer-based approach in which all data packets that arrive before the timer expires are assembled as a data burst; (2) a length-based approach in which the burst assembler generates data bursts of certain size when enough bytes of packets arrive; or (3) a hybrid scheme that combines the timer-based approach and the length-based approach. The timer-based burst assembly may generate small data bursts while the length-based burst assembly may result in a large end-to-end burst delay.

$\lvert\mathcal{R}\rvert$	ILP	Search Algorithm	F_{ILP}	F_{Search}
20	48.61	48.63	0	0
40	56.1	56.15	0	0
60	54.07	54.1	0	0
80	52.06	52.11	0	0
100	55.7	55.76	0	0
120	55.63	55.63	0	0
140	56.46	56.51	0	0
160	57.33	57.36	0	0
180	57.99	58.03	0	0
200	52.57	52.62	0	0

Table 12: Comparison of ILP and Search Algorithm on Topology 2 with non-localized SRLGs.

An IP packet may have an end-to-end delay requirement due to, for example, TCP timer time-out requirements. Therefore, each data burst may have an end-to-end delay bound $\mathcal{D}$ determined by the IP packets in the data burst, i.e. the least tolerable end-to-end delay for the IP packets in the burst. In addition, a large switching time will negatively impact the resource efficiency, especially when the data burst size is small and comparable to the switching time [73]. To reduce the switching overhead, a *minimum burst length requirement*, L_{min}, is often imposed where bursts transmitted have to be at least L_{min} bytes. When the arrival rate of IP packets is low, a timer-based burst assembly may generate small bursts which cannot satisfy the minimum burst length requirement. In order to satisfy the minimum burst length requirement, small bursts have to be padded, which incurs resource waste, thus increasing burst blocking probability.

One approach to reducing resource waste is to groom small sub-bursts to form a large burst. Burst grooming in OBS networks is to coalesce two or more sub-bursts to form a larger burst that will be switched as one unit in order to reduce resource waste and switching penalty [73]. For example, sub-bursts with the same destination can be aggregated into a single burst to reduce the per burst switching overhead and to use the least number of switching operations possible. In addition, burst grooming may also reduce inter-burst gaps and recover some channel void capacity, leading to improved network utilization [72]. Burst grooming can be achieved at the ingress node if sub-bursts are available and destined to the same egress node [73, 72]. Sub-bursts with different destinations can also be groomed at the ingress node and transmitted as a single burst until they are separated at some egress node [26, 28, 27].

Assuming burst grooming can only be realized at edge nodes, we studied the burst grooming problem where sub-bursts with the same source may be groomed together regardless of their destinations under certain conditions, i.e., sub-bursts with different destinations may be aggregated together, and transmitted as a single burst [25]. Further assume that the path dependent end-to-end propagation delay experienced by a sub-burst is d_p which is less than the end-to-end delay bound $\mathcal{D}$. The *delay slack* of the sub-burst is $d_s = \mathcal{D} - d_p$. When the sub-burst times out at the end of the delay slack, it must be transmitted in order to meet its deadline. This sub-burst can be groomed with other sub-bursts currently at the edge node to form a large burst. Sub-bursts can be groomed subject to the *burst grooming criteria*: (1) the length of the groomed burst should not exceed the maximum burst length L_{max} since excessively long burst may increase the burst blocking probability; (2) the end-to-end delay bound of the sub-bursts is guaranteed; (3) the minimum length of a groomed burst should be at least L_{min} (padding will be applied if necessary).

To support the capability of grooming bursts destined to different destinations, previous work [26, 28,

$\|\mathcal{R}\|$	ILP	Search Algorithm	F_{ILP}	F_{Search}
20	51.52	51.53	0	0
40	53.88	53.91	0	0
60	54.63	54.65	0	0
80	54.26	54.27	0	0
100	56.43	56.45	0	0
120	58.58	58.59	0	0
140	54.54	54.62	0	0
160	55.12	55.17	0	0
180	57.9	58.02	0	0
200	57.62	57.73	0	0

Table 13: Comparison of ILP and Search Algorithm on Topology 2 with localized SRLGs.

27] adopted an approach that separates a burst into sub-bursts and drops sub-bursts only at a destination egress node. The advantage of this approach is its simplicity. The drawback is that bursts are likely to experience a long delay. We explore the capability that core nodes can split incoming light signals to support multicast for more efficient burst grooming. Therefore, core nodes can transmit the groomed burst to multiple downstream nodes if the sub-bursts in the groomed burst have different destinations. The groomed burst will traverse a tree which spans the source and all the destinations of the sub-bursts in the groomed burst. The destination egress nodes recognize, de-burstify, and drop the sub-bursts destined to these nodes, i.e., the sub-bursts destined to these egress nodes are removed from the groomed burst. At the same time, the remaining sub-bursts may be groomed with sub-bursts at these egress nodes subject to burst grooming criteria. We propose two effective burst grooming algorithms, (1) *no over-routing waste* approach (*NoORW*); and (2) *minimum relative total resource ratio* approach (*MinRTRR*). Our simulation results have shown that the proposed algorithms are effective in terms of burst blocking probability and average burst end-to-end delay [25].

14.3 Shared Channel Architecture for Better Throughput and Lower Burst Blocking Probability

Existing optical burst switching (OBS) architecture (or conventional OBS architecture) [62, 80, 95, 14, 61, 11] has assumed that data and control signals are transmitted separately on different channels or wavelengths, where a group of wavelengths usually called the data channel group (DCG) is established for the transfer of DBs and another group called the control channel group (CCG) is established for the transfer of BHPs. In such an architecture, costly O/E/O conversions are only required on a few control channels instead of a large number of data channels. However, burst contention and blocking are key issues that have attracted much recent research. A burst contention occurs at a switch whenever two or more bursts are trying to leave the switch from the same output port on the same wavelength. In electrical packet switched networks, contentions are usually resolved with the store-and-forward technique, which requires the packets in contention be stored in a memory bank and sent out at a later time when the desired output port is free. This has not been possible in all optical networks because of the unavailability of optical RAM. Many contention resolution schemes for OBS networks have been proposed. These schemes make use of deflection routing [81, 13], fiber delay line buffering [30, 55], wavelength conversion [31, 99], and burst segmentation [82, 81].

To deal with burst contention and blocking as well as to achieve greater resource utilization, we investigated a shared channel architecture that allows the transfer of both burst header packets and data bursts on the same wavelength channel with some modifications on the conventional OBS architecture [12]. The proposed OBS architecture is able to provide better flexibility in resource use and improved burst blocking performance. Based on the reduced load fixed point approximation, we provided an analytic model for burst blocking probability analysis under the proposed architecture that employs the just-enough-time signaling and fixed routing. The accuracy of the analytic model was validated via extensive simulation. Our analysis and simulation showed that the proposed architecture achieves a significantly lower burst blocking probability compared with the conventional architecture. We also showed that the best configuration of the conventional architecture depends on the load, average data burst size, and total number of channels [12]. Therefore, the proposed OBS architecture is easier to configure and achieves better overall performance.

Invention and Patent

None.

Broader Impact and Outreach

The impact of the project manifests in many aspects. First, the project addressed many essential problems that arisen in current and future WDM optical networks, and provided a host of innovative solutions. This project resulted in more than 2 dozens publications in major journals and conferences (including papers in IEEE Transactions and journals, as well as a book chapter). Our publications have been cited by many peer researchers. In particular, one of our conference papers was nominated for the best paper award of IEEE/Create-Net Broadnets 2006. Second, the results and solutions of this project were well received by DOE Labs where presentations were given by the PI. We hope to continue the collaboration with DOE Labs in the future. Third, the project was the first to propose and extensively study multicast traffic grooming, new traffic models such as sliding scheduled traffic model and scheduled traffic model. Our research has sparkled a flurry of recent studies and publications by the research community in these areas. Fourth, the project has benefited a diverse population of students by motivating, engaging, enhancing their learning and skills. The project has been conducted in a manner conducive to the training of students both at graduate and undergraduate levels. As a result, one Ph.D., Dr. Abdur Billah, was graduated. Another Ph.D. student, Tianjian Li, will graduate in January 2007. In addition, four MS students were graduated. One undergraduate student, Jeffrey Alan Shininger, completed his university honors project. Fifth, thanks to the support of this ECPI project, the PI has obtained additional funding from the National Science Foundation, the Air Force Research Lab, and other sources. A few other proposals are pending. Finally, this project has also significantly impacted the curricula and resulted in the enhancement of courses at the graduate and undergraduate levels, therefore strengthening the bond between research and education.

Interactions and Collaboration

The PI visited ORNL and UltraScience Net. The PI gave a presentation on the project accomplishments, scheduling algorithms for sliding scheduled traffic demand set, and had individual meetings with Dr. Nagi Rao and other staff members. Dr. Rao and Dr. Wing found that the proposed sliding scheduled traffic model appealing, practical, flexible and general, and the proposed scheduling algorithms practical and useful for UltraScience Net. The PI's work nicely complements work being carried out at UltraScience Net.

The PI has been in contact with Dr. Nagi Rao. In particular, we have exchanged research ideas and results on lookahead scheduling of traffic demands in UltraScience Net. The PI sent Dr. Nagi Rao a technical paper on dynamic routing of sliding scheduled traffic demands (which will appear in IEEE Communications Letters) and also had a brief discussion with Dr. Rao during ECPI panel review meetings.

The PI was invited by Dr. Dantong Yu and gave a talk on "Bandwidth Scheduling and Provisioning in Access and Wide Area Networks," to Dr. Dantong Yu's group at DOE Brookhaven National Laboratory (BNL). One of their interests (which overlaps the PI's work and interests) is to schedule traffic demands in access networks. We both found that some of the PI's work could be applicable to their needs. Some research issues still exist in, for example, point-to-point links or Ethernet over passive optical networks.

The PI attended BroadNet conference (International Conference on Broadband Communications, Networks, and Systems), IEEE International Workshop on Traffic Grooming, IEEE Globecom, IEEE INFOCOM, International Conference on Design of Reliable Communications Networks (DRCN), and IEEE ICC, and presented work on various topics including traffic grooming under the sliding scheduled traffic model, protection and restoration, and so forth, to disseminate our results. The presentations were well received. In fact, researchers have now started to look into how to exploit connection holding-time for better service provisioning. The PI had discussions on related research issues with Prof. Mukherjee (UC Davis) and Prof. Rouskas (NC State).

Relevant presentations and publications of this project are included as Appendix A at the end of this report. The publications have also been submitted via the DOE Energy Link System (E-Link) http://www.osti.gov/elink-2413.

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APPENDIX A

Project Publications (downloadable from http://www.cs.wright.edu/∼bwang/publications)

1. B. Wang, "Optical Communication." To appear in *Wiley Encyclopedia of Computer Science and Engineering*, Edited by Benjamin Wah, Wiley, 2006.

2. A. R. B. Billah, B. Wang, and A. A. S. Awwal, "Effective Traffic Grooming Algorithms for SONET/WDM Ring Networks." *Photonic Network Communications*, Vol. 6, No. 2, pp. 119-138, September 2003, Kluwer Academic Publishers.

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7. B. Wang and A. Deshmukh, "An All Hops Optimal Algorithm for Dynamic Routing of Sliding Scheduled Traffic Demands," *IEEE Communications Letters*, Vol. 9, No. 10, October 2005.

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12. T. Li and B. Wang, "Path-Protection Based Routing and Wavelength Assignment (RWA) in WDM Optical Networks under a Scheduled Traffic Model," *OSA Journal of Optical Networking*, 2006.

13. B. Wang and T. Li, "Approximating Optimal Survivable Scheduled Service Provisioning in WDM Optical Networks with Iterative Survivable Routing," *Proceedings of Broadnets'2006*, San Jose, CA. **Best paper nominee**.

14. B. Wang and X. Luo, "Multi-Constrained Routing in Networks with Shared Risk Link Groups," *Proceedings of Broadnets'2006*, San Jose, CA.

15. W. Chaffee, B. Wang, and H. Wang, “Modeling and Analysis of a Shared Channel Architecture for Performance Improvement in Optical Burst Switched Networks,” *Proceedings of Optical Burst/Packet Switching Workshop (Broadnets’2006)*, San Jose, CA.

16. Y. Fan and B. Wang, “Exploring Node Light-Splitting Capability for Burst Grooming in Optical Burst Switched Networks,” *Optical Burst/Packet Switching Workshop (Broadnets’2006) Poster Presentation*, San Jose, CA.

17. T. Li and B. Wang, “On Optimal Survivability Design under a Scheduled Traffic Model in Wavelength-Routed Optical Mesh Networks,” *Proceedings of Communication Networks and Service Research Conference (CNSR 2006)*, Canada, May 2006.

18. T. Li and B. Wang, “Approximating Optimal Survivable Routing in WDM Optical Networks under a Scheduled Traffic Model,” *Proceedings of 2006 IEEE Sarnoff Symposium*, Princeton, NJ, March 2006.

19. X. Luo and B. Wang, “Multi-constrained Routing in WDM Optical Networks with Shared Risk Link Groups,” *Proceedings of 2006 IEEE Sarnoff Symposium*, Princeton, NJ, March 2006.

20. C. Xin, B. Wang, X. Cao, and J. Li, “Logical Topology Design for Multi-Hop Dynamic Traffic Grooming in WDM Optical Networks,” *Proceedings of IEEE Workshop on Traffic Grooming in WDM Networks*, Boston, MA, October 3-7, 2005.

21. C. Xin, B. Wang, X. Cao, and J. Li, “Formulation of Multi-Hop Dynamic Traffic Grooming in WDM Optical Networks.” *Proceedings of IEEE Workshop on Traffic Grooming in WDM Networks*, Boston, MA, October 3-7, 2005.

22. T. Li and B. Wang, “On Survivable Service Provisioning in WDM Optical Networks under a Sliding Schedule Traffic Model,” Proceedings of *IEEE Globecom’05*, St. Louis, MO USA, November/December 2005.

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32. B. Wang and N. Lella, "Dynamic Contention Resolution in Optical Burst Switching Networks with Partial Wavelength Conversion and Fiber Delay Lines." Proceedings of *IEEE Globecom'04*, Dallas, TX USA, November/December 2004.

33. T. Li and B. Wang, "Optimal Configuration of p-Cycles in WDM Optical Networks with Sparse Wavelength Conversion." Proceedings of *IEEE Globecom'04*, Dallas TX, USA, November/December, 2004.

34. T. Li, B. Wang, and X. Zhang. "Dynamic Shared Path Protection in WDM Optical Networks." *7th INFORMS Telecommunications Conference*, Boca Raton, FL March 2004.

35. B. Wang and T. Mannan. "Dynamic Multicast Session Provisioning in WDM Optical Networks with Sparse Splitting Capability." *7th INFORMS Telecommunications Conference*, Boca Raton, FL March 2004.

36. A. R. B. Billah, B. Wang, and A. A. S. Awwal. "Multicast Traffic Grooming in WDM Optical Mesh Networks." *Proceedings of IEEE Globecom: Optical Networking Symposium*, San Francisco, CA USA December 2003, IEEE.

Project Presentations

1. B. Wang, "Towards Cost-Effective Provisioning and Survivability in Ultra High Speed Networks," DOE Brookhaven National Lab, PI Meeting, Upton, NY, October, 2005.

2. B. Wang, "Bandwidth Scheduling and Provisioning in Access and Wide Area Networks," presented to DOE Brookhaven National Laboratory (BNL), Upton, NY, November 15, 2004.

3. B. Wang, "Towards Cost-Effective Provisioning and Survivability in Ultra High Speed Networks," presented to DOE Oak Ridge National Lab, Oak Ridge, TN, September 9, 2004.

4. B. Wang, "Towards Cost-Effective Provisioning and Survivability in Ultra High Speed Networks," DOE Chicago Fermi Lab, PI Meeting, Chicago, IL, September 15, 2004.