CROSSLAYER SURVIVABILITY IN OVERLAY-IP-WDM NETWORKS

by

Peera Pacharintanakul

B.Eng. in EE, Chulalongkorn University, Thailand, 2000
M.S. in EE, Washington University, St. Louis, MO, 2004

Submitted to the Graduate Faculty of
the Graduate Telecommunications and Networking Program in
partial fulfillment
of the requirements for the degree of

Doctor of Philosophy

University of Pittsburgh

2010

UNIVERSITY OF PITTSBURGH

SCHOOL OF INFORMATION SCIENCES

This dissertation was presented

by

Peera Pacharintanakul

It was defended on

July 20, 2010

and approved by

Associate Professor David Tipper, Ph.D., University of Pittsburgh

Associate Professor Prashant Krishnamurthy, Ph.D., University of Pittsburgh

Professor Richard Thompson, Ph.D., University of Pittsburgh

Yu Liu, Ph.D., Juniper Networks

Associate Professor Eytan Modiano, Ph.D., Massachusetts Institute of Technology

Dissertation Director: Associate Professor David Tipper, Ph.D., University of Pittsburgh

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As the Internet moves towards a three-layer architecture consisting of overlay networks on top of the IP network layer on top of WDM-based physical networks, incorporating the interaction between and among network layers is crucial for efficient and effective implementation of survivability.

This dissertation has four major foci as follows: First, a first-of-its-kind analysis of the impact of overlay network dependency on the lower layer network unveils that backhaul, a link loop that occurs at any two or more lower layers below the layer where traffic is present, could happen. This prompts our proposal of a *crosslayer survivable mapping* to highlight such challenges and to offer survivability in an efficient backhaul-free way. The results demonstrate that the impact of layer dependency is more severe than initially anticipated making it clear that independent single layer network design is inadequate to assure service guarantees and efficient capacity allocation. Second, a *forbidden link matrix* is proposed masking part of the network for use in situations where some physical links are reserved exclusively for a designated service, mainly for the context of providing multiple levels of differentiation on the network use and service guarantee. The masking effect is evaluated on metrics using practical approaches in a sample real-world network, showing that both efficiency and practicality can be achieved. Third, matrix-based optimization problem formulations of several crosslayer survivable mappings are presented; examples on the link availability mapping are particularly illustrated. Fourth, survivability strategies for two-layer backbone networks where traffic originates at *each* layer are investigated. Optimization-based formulations of performing recovery mechanisms at each layer for both layers of traffic are also presented. Numerical results indicate that, in such a wavelength-based optical network, implementing survivability of all traffic at the bottom layer can be a viable solution with significant advantages.

This dissertation concludes by identifying a roadmap of potential future work for cross-layer survivability in layered network settings.

Keywords: Capacity allocation, Multilayer network, Multilayer traffic, Network survivability, Traffic survivability.

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ATM	Asynchronous transfer mode
CO	Capacity overbuilding
CSM	Crosslayer survivable mapping
FB	Flow blocking
FO	Flow overrouting
GMPLS	Generalized multi-protocol label switching
ILP	Integer linear programming
IP	Internet protocol
ISP	Internet service provider
JCA	Joint capacity allocation
JCA3L	Joint capacity allocation in three-layer networks
LO	Link overusing
OCh-S	Optical channel section
OMS	Optical multiplex section
RO	Resource overbuilding
SBPP	Shared-backup path protection
SCA	Spare capacity allocation
SDH	Synchronous digital hierarchy
SON	Service overlay network
SRLG	Shared risk link group
WDM	Wavelength-division multiplexing

PREFACE

I would like to acknowledge everyone whose path has crossed mine, whether our paths met and then diverged or merged into one. This completion would not have been possible without their assistance or efforts. Most importantly, I offer my deepest gratitude to my advisor, Dr. David Tipper, for his invaluable guidance, his moral and financial support, as well as for the specific direction provided in the course of developing this dissertation, all the while giving me the right amount of freedom to explore research issues and to find the one I am most passionate about. I have been very fortunate to have such a supportive and patient advisor.

I am also truly grateful to my dissertation committee members: Dr. Prashant Krishnamurthy, for giving me research advice in his project-based course and offering gracious and kind support throughout the whole course of study; Dr. Richard Thompson, for sharing his wisdom and cautious view on the current status of IP communications; Dr. Yu Liu, for spending hours discussing his past research experiences as well as current practical perspectives as part of the industry; and Dr. Eytan Modiano for diverting my thinking along new paths during the dissertation proposal ultimately allowing a more accurate and concise reporting of this research. The work of Drs. Liu and Modiano has been the primary inspirational source for this work; it is an honor for me that each agreed to serve as a member of my dissertation committee.

In addition to the members of my dissertation committee, I would like to take this opportunity to express my humble appreciation to Professor Mihaela van der Schaar for showing me the value of hard work and dedication, and Professor Chen-Nee Chuah for teaching me the importance of novelty and creativity.

I also gratefully acknowledge Dr. Poompat Saengudomlert for his constructive criticism and technical feedback as a dissertation reader; Janine Carlock for her terrific editing advice and sincere interest in helping me out on some earlier drafts that have become part of this dissertation; and Mark Steggert and Jace Schivins for their work in maintaining the computer servers and providing IT support promptly.

On the non-academic side, I am indebted to all my friends for making my time of graduate studies an unforgettable experience. Though I cannot list them all, I want to particularly thank Natthapong Liamcharoen, Worawan Arparatana, Phawit Putprasert, Suvimol Sangkatumvong, Aki Motohara, Nattapol Sitthimahachaikul, Siriwat Sakhonwasee, Fatos A. Peci, Pornsri Khlangwiset, and my office mate, Tae-Hoon Kim, for offering help and support.

This dissertation would not be possible without the full financial support of a TOT Graduate Fellowship, Royal Thai Government; a Predoctoral Fellowship, Office of the Provost, University of Pittsburgh; and various other teaching and research assistantships throughout my graduate years. In particular, I gratefully thank Dr. David Tipper, Dr. Martin B.H. Weiss, and the Center for Russian and East European Studies (REES) for offering me the research assistantship to work on a USAID-funded project.

Finally, I cannot express enough gratitude to my parents, Pornchai and Ninrat, and my sister, Pam. I thank them for their constant support and optimism in me. I also thank Patcharavipa Chaijuckam for being an endless source of moral support and patience, and thank the Chaijuckam family for their spiritual support and generosity.

1.0 INTRODUCTION

1.1 MOTIVATION

The phenomenal growth of the Internet is partly explained by the proliferation of underlying optical WDM technologies providing high bandwidth physical connectivity and the overlaying applications. The notion of a multi-layer technology system has long been used in telecommunication networks to describe the network architecture. Examples include an ATM-over-SDH [1], ATM-over-SDH-over-WDM [2], [3], IP-over-SDH [4], IP-over-ATM-over-SDH-over-WDM [4], IP-over-MPLS-over-WDM [5], IP-over-OTN network [6], a virtual lightpath network on a WDM-based network [7], [8], and the classic dial-up modem Internet access over a PSTN. Due to business considerations, sharing information, *e.g.,* topology, path performance, among Internet service providers (ISPs) is limited in practice. As a result, overlay networks have emerged as a means to connect a service and maintain its quality across multiple ISPs. Note that each overlay is normally administered under a single management group; the ease of operation and construction has encouraged a wide variety of overlay services to emerge. In this work, we consider a network of overlay services on top of the IP over WDM technologies as a layered network example; however, our work is also applicable to any layered networks in general. Many studies have examined the Internet architecture, but recent research has led us to consider a network of three layers, overlay-over-IP-over-WDM, as the likely future Internet architecture.

In this architecture, overlay nodes are attached to an IP router. IP routers are associated with an optical WDM switch; the switches are then interconnected by multi-wavelength fibers capable of carrying a number of transmission channels. Recognizing the lower two network layers, IP and WDM, each IP route is established by one or more lightpaths that span across

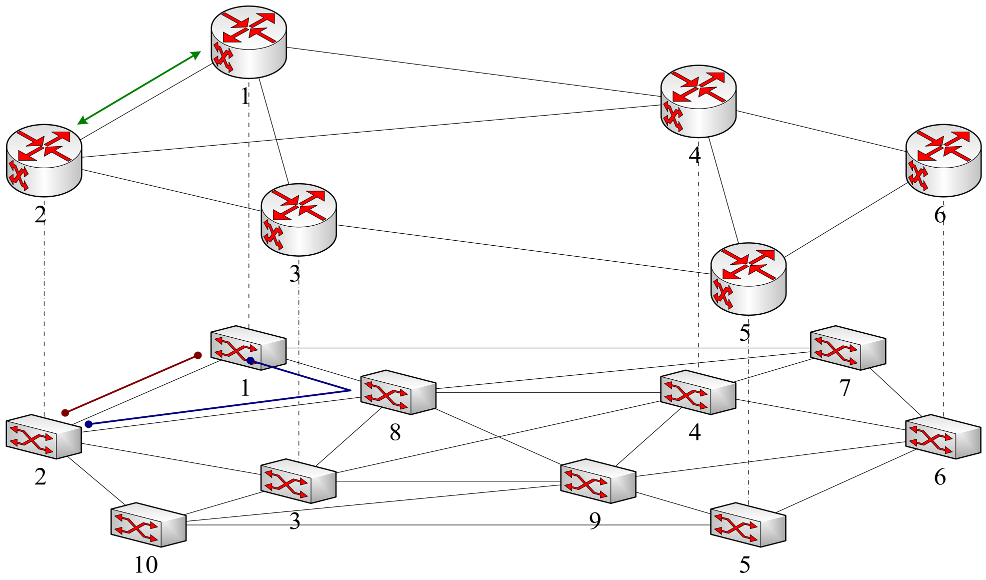


Figure 1.1: A sample two-layer sub-network of a layered network

fibers and occupies one or more wavelengths in each fiber. These two layers constitute the Internet backbone in the optical Internet. Interdependency of failures, routing, topology distribution, and signaling protocols between the two layers are still major concerns; however, thanks to the vertical integration of IP and WDM technologies in the backbone network, these two-layer networks can now be supported by GMPLS mechanisms acting as a glue layer for the two technology environments.

In general multiple layers present a number of survivability problems. First, failures at the bottom may tear down services at the top layer. This effect is called *failure propagation* and is at the forefront of problems in multilayer survivability. Survivable mapping, a map of a top-layer topology over a bottom-layer topology such that link failures at the bottom do not disconnect the top-layer topology, is a way to avoid failure propogation. Link mapping is almost always developed in anticipation of a single link failure [8]; however, reference [9] has recently developed a mapping for multiple link failures.

Failures at the IP layer may occur for several reasons. One of them is related to failures at the WDM optical layer such as node or link failures; an optical-related failure can result in many failures at the IP layer. This effect is again regarded as failure propagation, the severity of which is partly because of improper IP-to-WDM link mapping. Such a link mapping tells us on which of the lightpaths an IP path is routed. Reference [10] reveals that, in a highly-meshed operational IP network, this ill-chosen mapping contributes up to 9.12 percent of all unplanned failures that affect the IP traffic. The figure is likely to be higher in partial-meshed IP networks as it increases the chance of network partitioning or reduces the number of rerouting choices when a backup path is needed or failures happen. More interestingly, the authors also discover that, on average 8 WDM links and 7 nodes are shared by failed IP paths; these high numbers increase the chance of failures. In such circumstances, the need for good link mapping to mitigate the worst consequences of failures is obvious.

A second problem is, for a given mapping function, a top-layer path may require more or less bandwidth from the perspective of the top layer than that of the bottom, depending on which layer determines the capacity allocation and routing assignment. Depending on how the top-layer path (1,2) is mapped and routed in the bottom layer, it can have different capacity requirements. For example, as can be seen in Figure 1.1, if the path (1,2) needs one unit of capacity at layer 2 and it is routed at the bottom layer on the (1,2) link then only one unit of capacity at the bottom layer is required. However, if the layer 2 link (1,2) is routed along links (1,8) and (8,2) in the bottom layer, two units of capacity are consumed by the top-layer path (1,2).

Failure propagation also imposes difficulty in the network design phase as to deciding, for each top-layer path, which layer is responsible for failure recovery and under what conditions. This is because for a top-layer primary path, a backup path can be provided in either layer. Recovery mechanisms may also be redundant between two layers; however, this does not automatically imply that all of the mechanisms are used at both layers [2]. In addition, since the capacity of a bottom link can simultaneously be shared by many top paths, allocating capacity among their corresponding backup paths in two layers becomes a concern; the services provided by the top-layer network must be survivable under failures at the bottom. Capacity allocation ensures sufficient link capacity for rerouting traffic in the face of failures. Routing assignment guarantees that the end-to-end requirements are met, *e.g.,* availability, delay, etc. In practice, dynamic and efficient multilayer routing algorithms [11] may be needed.

Although overlay nodes are often referred to as end hosts, as our interest is core backbone networks, this dissertation considers more long-lived nodes, which are commonly called supernodes, gateways, or overlay servers, that tend to be more stable; for example, as in a content delivery overlay network or a service overlay network (SON). For these reasons, survivability by crosslayer mapping is a major concern for layered networks.

1.2 CONTRIBUTIONS

This dissertation attempts to address the following question:

> *Is it possible to design a survivable multilayer network which provides the capability to offer different resilient priorities for customer traffic without sacrificing capacity efficiency due to layer interactions?*

Key concepts include network and traffic survivability, capacity efficiency, resiliency, and availability. In this context, this dissertation makes the following contributions:

1. We reveal the backhaul routing problem in layered networks – backhaul is a routing loop at two or more layers below a layer of interest. Then we investigate the effects of conventional survivable mapping in layered networks with three layers or more and propose an efficient crosslayer survivable mapping (CSM). CSM is a mapping function which correlates links in one layer to those in the adjacent layer such that backhaul does not occur.
2. We examine the previous view of the networks from the perspective of service guarantee and network differentiation. First, we propose a modeling framework for differentiated crosslayer survivable mapping (DCSM) for each network service level according to a traffic priority or differentiation on the network use. Then, we consider a Graph reduction approach on the incidence matrix such that links that are hidden to some traffic are removed from consideration before the process of CSM is carried out. Finally, we develop a systematic approach to DCSM, with a unified optimization-based formulation for all multileveled service classes.

3. We build on our previous models, introducing new models that capture many possible metrics such as availability and delay, among others. These models include cases when we wish to maximize availability, to maximize the number of maximum concurrent failures, to put a constraint on delay bound, to put a constraint on maximum tolerable concurrent failures, and any combination therein. We show that in some cases the gain in availability comes at no cost to the number of lightpaths or wavelength use; this is equivalent to the opportunity cost in linear programming sensitivity analysis.
4. We dissect the core backbone, as an instance of two-layer networks, investigating the survivability of two-layer IP-over-WDM core networks when traffic is present at every layer. In this contribution, all four possible strategies featuring crosslayer capacity sharing and survivability at the bottom in such lightpath-based networks are examined and reported on. We provide a first study of the survivability of two-layer networks when traffic is present at each layer and present novel ILP formulations for performing recovery mechanisms at the bottom layer for both layers of traffic in two cases: (1) with crosslayer capacity sharing and (2) without crosslayer capacity sharing. Using the results, we develop guidelines for survivable multilayer network designs for an integrated network model by evaluating the effect of the amount of traffic at each layer against the spare capacity requirement of each strategy and investigating the impact of top-layer network connectivity on the spare capacity requirement.

Although this work explicitly considers an overlay-IP-WDM network as an instance of multilayer networks, the analyses presented in this dissertation are applicable to any layered network in general. The only requirement here is that bandwidth in each network layer has to be integral, or is reserved or allocated in integral units *e.g.,* SDH/SONET hierarchy.

1.3 DISSERTATION OVERVIEW

The remainder of this dissertation is organized as follows: Chapter 2 reviews work related to this dissertation and addresses some of the differences between previous work and our approach. We discuss choices in providing survivability in multilayered networks, some of

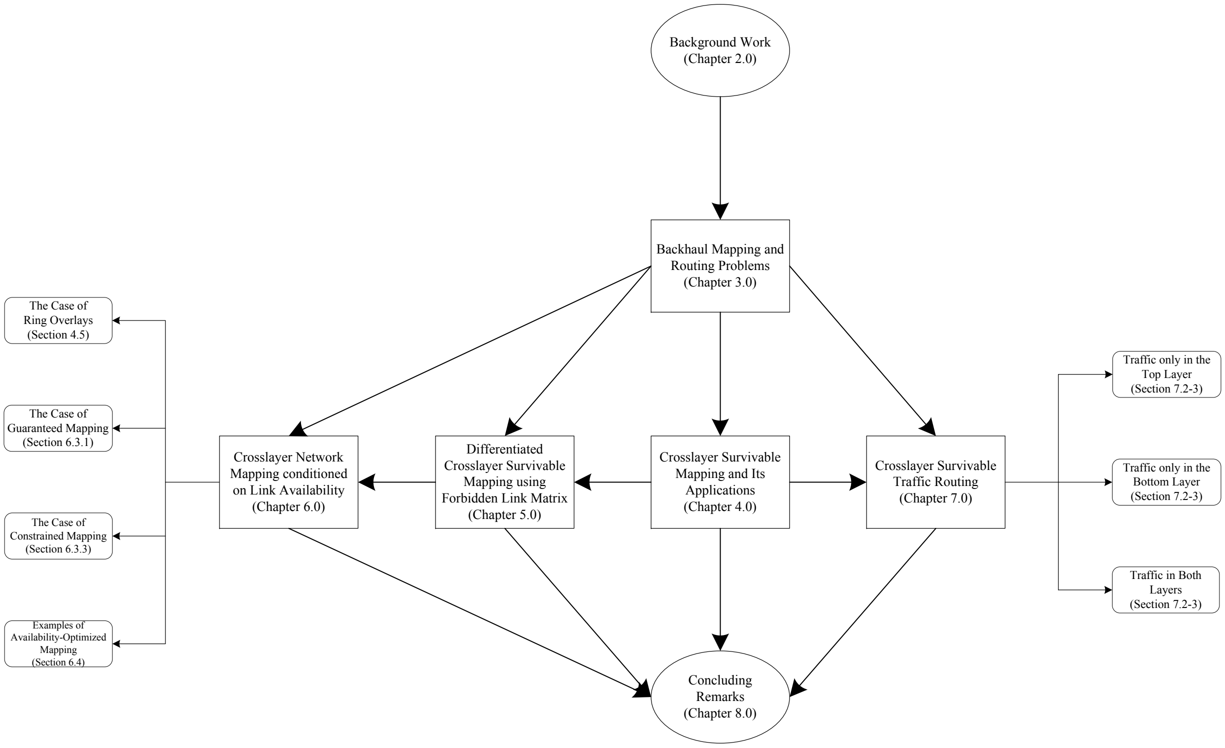


Figure 1.2: Dissertation roadmap and content dependency chart

the implications of potential trade-offs as well as survivability strategies typically deployed in each network layer. Figure 1.2 outlines a roadmap and shows dependency of the contents of the dissertation.

Chapter 3 presents some problems in resource-efficient multilayered network design; these problems constitute a basis for our research. We also explain and illustrate the situations in which the problems can be seen, from either the network architecture perspective, the customer traffic perspective, or both. This dissertation considers an overlay-IP-WDM layered network, but the concepts presented here can be applied in any layered network graphs or architectures.

Chapter 4 investigates some of the survivability issues in a greater depth and reveals an issue that is hidden in a traditional two-layer setting. This chapter primarily discusses primary paths and the role of their routes in each of the three network layers. We show the limitations of route selection resulting from network mapping. Other convex mapping schemes are also discussed.

Chapter 5 examines ways to offer multileveled service in a layered network. We describe network mapping through the view of network differentiation and at the same time extend it to include a case where both primary and backup paths are explicitly considered. We provide example uses of some real-work network scenarios and explain how they can be deployed. In addition to the cost-minimized or shortest path-based network mapping, we also begin exploring the cases of network mapping based on optimization and constraints on link-level metrics such as availability maximization, failure probability minimization, and delay bounds.

Chapter 6 presents our mathematical formulations for a number of convex network mappings, one of which is extensively discussed. We provide an illustration and explain how this mapping works when availability is considered as a metric to be optimized, and we discuss how it can be included in the crosslayer survivable mapping design.

Chapter 7 provides a study of survivability strategies in multilayer networks under a number of traffic scenarios. We discuss the benefits of each strategy as it relates to survivable traffic flows and provide an analytical framework through which the analysis and selection of deploying the best strategy can be achieved.

Chapter 8 concludes the dissertation and discusses directions for future work.

2.0 RELATED LITERATURE

There are some current planning approaches that mention networks with three layers, for example, ATM-over-SDH-over-WDM [2], [3] or IP/MPLS-over-WDM [5]; however, they either consider each pair of the sublayers two at a time or view them as a single super layer. In this dissertation, we explicitly consider an overlay-over-IP-over-WDM network as an instance of three-layer networks and address survivability from the viewpoint of the mapping and the multilayer traffic ratio in the core backbone network. To the best of our knowledge, this dissertation and our preliminary work presented in [12] is the first to formally study the multilayer survivability problem in the explicit context of overlay-IP over WDM-based networks. The following paragraphs review work related to this dissertation and address some of the differences between previous work and our approach.

There have been a number of survivability strategies proposed to recover from failures in a network of two layers. These strategies primarily lie in the choices of (1) in which layer the strategy is implemented (top (IP), bottom (WDM), both, none), (2) primary-backup paths disjointness (full, partial), (3) coordination of the two layers (coordinated, uncoordinated), (4) resources of failed paths, whether they can be reassigned to a newly calculated backup path or not (released, held), (5) when to compute a backup path (preplanned, dynamic upon failures), (6) shareability of the dedicated backup bandwidth (shareable, unshareable), (7) survivability techniques (link protection, path protection, p-cycles, etc.), among others. In the case of implementing a survivability strategy at both layers, two extended choices are also needed. First, which layer is to recover from failures first. It is called a bottom-up escalation strategy if the WDM layer is to take responsibility for failure recovery before the IP layer and a top-down strategy if they are reversed in order. Second, when a layer is to transfer its responsibility to the other layer. The decision can be based on either a timeout value or

Table 2.1: Survivability issues in layered networks

Problem	Cause	Solution
Topology Design	Failure propagation	Survivable mapping
Capacity Allocation	Insufficient hop-by-hop link capacity	Capacity planning
Flow Assignment	[constrained] End-to-end path	Constrained routing

a token; however, it is further required that both layers are notified when failures happen. References [2], [13], [14], [15], [16], [17], [18] provide discussion of the survivability strategies in two-layer networks in more detail. The major survivability issues in layered networks are summarized in Table 2.1 and explained in further detail in the subsequent sections.

2.1 GRAPH THEORETIC APPROACHES TO SURVIVABLE MAPPING

In this section we discuss two relevant heuristic graph theory based approaches to finding survivable mappings for the design of logical topologies.

2.1.1 Graph Contraction

Good mapping is important to enable the network to correctly recognize failure propagation between layers. One approach to crosslayer mapping is to consider subgraphs of an uncapacitated network which are survivable under any single physical failure and which gradually construct a full survivable mapping, if one exists [7]. In [7], both link failures and node failures are considered. In the case of link failure, it is intuitively follows that the first survivable subgraph would be a ring or cycle at both layers. This is because there are exactly two available paths between any demand pairs; one path in each direction. Then, the ring at the top layer can be contracted to a survivable point, and if it can be mapped onto a bottom-layer ring, then the top-layer ring is survivable. This technique is called graph contraction [19].

By recursively finding a way to map the contracted graph onto the bottom-layer topology, vulnerable links, if any, can be found and physical links installed so that the whole logical upper-layer topology is fully survivable. A similar concept can be applied in a case of node-failure where a physical node failure does not disconnect the contracted graph. This recursive graph contraction approach led to the development of a heuristic algorithm named survivable mapping algorithm by ring trimming (SMART). A case of a network with limited capacity is further considered in [20]. Here, a modified version of SMART, SMART-C, based on remaining capacity as a link cost, is proposed. However, logical links may take a long physical path with a significant number of hops. Therefore, physical resources may not be efficiently used.

2.1.2 Graph Coloring

An alternative approach to crosslayer mapping can be adapted from the wide applications of graph coloring techniques. Recently there has been work applying graph coloring techniques to improving network survivability [21], [22]. When a color is used to represent each SRLG from the bottom-layer view, a top-layer link can be defined by one color or more as the link may belong to more than one SRLG. By minimizing the number of colors in each path, failure risk, where each failure event is associated with a color, can be minimized. Reference [21] discusses a class of minimum-color path problems and develop two new subproblems. The authors first define the minimum-color single-path (MCSiP) problem as a single-shortest path problem such that the number of colors along the path is minimized. Then, the minimum total color disjoint-paths (MTCDiP) problem is developed. The MTCDiP considers two cases of finding a pair of link-disjoint and node-disjoint paths, each with a minimum number of colors on primary and backup paths. Based on this, a third problem, minimum overlapping color disjoint-paths (MOCDiP) is defined in such a way that the common colors are minimized. The MTCDiP finds use in practice in a case when paths passing fewer carriers or network operators are preferred because the operating cost is often less expensive. In this way, each color can represent a network carrier. Likewise, the MOCDiP may be used to represent each color for a submarine fiber and satellite link. Factors affecting the number of colors on a path include network size, the number of SRLGs, and node degree. While the first two factors have positive correlation with the number of colors, the last one shows negative correlation.

Finding paths with a minimum of colors is discussed, but in order to accomplish this feat, a transformation of multilayer networks into a colored graph is needed. Reference [22] proposes a mapping choice that maps SRLGs of the bottom layer to the top layer as a colored graph. In [22], a link contains more than one color and the colors on the link are connected by a dummy node; however, the order of colors is complicated and needs to be determined. By defining a span of a color as a number of connected components, which induce that color, the maximum span of all colors should be sought to be kept at a minimum so that the effect from a single failure can also be minimized. An example is given, but a more rigorous formalization and algorithm development is still open.

This dissertation complements the graph-based approaches by using matrix representations to formulate and formalize the survivable mapping problem.

2.2 RECOVERY TECHNIQUES

This section discusses how recovery techniques can be implemented in a multilayer framework by introducing recovery choices that have been proposed to date and discussing the computational requirements of the recovery reconfigurations. These options may include the choice of recovery on either a global or local scale. A global scheme performs reconfiguration for every route, regardless of their failure or success upon the emergence of a fault. In contrast, the local scheme reconfigures only the affected paths. Thus, a large part of the network is left undisturbed at the expense of suboptimum bandwidth utilization. In addition to bandwidth efficiency, performance can also be measured using recovery time and scalability [18], including the number of reroutes needed. For simplicity, all affected traffic could enter the recovery phase upon failure; however, a prioritized traffic restoration procedure may be preferred. For example, there may be dedicated protection at the physical layer for mission-critical applications, while there may be no protection at either or both layers

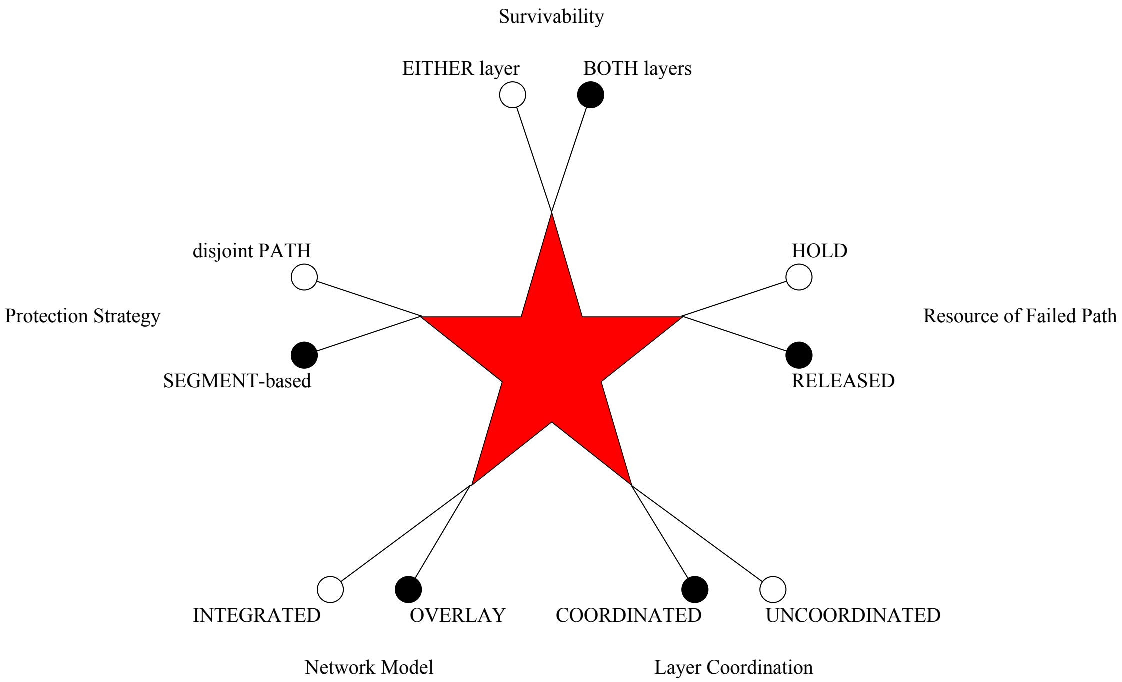


Figure 2.1: Recovery choices in layered networks

in the case of best-effort traffic. Alternatively, two protection strategies can simultaneously be implemented in the same network, one for high-priority traffic, the other for low-priority traffic [23]. These techniques can be used in any network regardless of the numbers of layers involved. Generally, performance metrics may include blocking probability, recovery time, recovery rate, and the amount of capacity needed.

2.2.1 Recovery Choices

Informative early work [3] from the protection across network layers (PANEL) project presents a general framework for multilayer survivability strategies based on single layer recovery options and a number of alternatives for network operators. This section readdresses the issue of recovery choices by incorporating views from some previous work; the choices are summarized in Figure 2.1.

2.2.1.1 Survivability at What Layers

While survivability mechanisms at the bottom layer provide simplicity and fast recovery time as well as possibly making the failure transparent to the top layer, survivability at the top layer has a better view and often requires fewer resources and is more flexible because only the affected paths needs to be recovered. Thus, one of the design goals is an answer to the following question: how to protect the network against any single failure with only moderate resource usage and within reasonable recovery time. In some cases, multiple failures may also be considered. In many cases, online protection is considered in the IP layer whereas offline protection is used in the WDM layer [7]; this is partly due to rapid rerouting in IP routers and fast protection service in optical switches.

2.2.1.2 Sequential vs. Integrated

Coordinated approaches depend heavily on the interconnection models [17] which specify the details of topology advertised across the layers and the control policies regarding the dynamic provisioning of all resources. With a sequential approach, the recovery function is handed over to the other layer when it is clear that the current layer is unable to perform the tasks. This approach can further be subdivided into two implementations: top-down and bottom-up. The difference between these two is clear from their names. The integrated approach supports the peer interconnection model as distinct from the overlay model in the sequential approach. In an integrated model, which receives more attention here, the recovery process is carried out in an integrative manner under a single instance of control plane and administrative domain across multiple layers.

2.2.1.3 Uncoordinated vs. Coordinated

In an uncoordinated approach, failures are recovered in multiple layers in parallel with no coordination [2]. While the coordinated approach requires coordination between the layers, its actual implementation cannot be accomplished without triggering mechanisms. Two kinds are commonly used. One is based on a timeout value; the other is token-based. These two approaches can be implemented in both bottom-up and top-down escalation strategies in a sequential network recovery model.

2.2.1.4 Resources Held vs. Released Whether to release the affected resource of the failure paths has to be determined in the design phase and the resource-freeing process may require signaling functions. A simpler approach in most literature is to recover failed traffic with the most recent network topology in mind, but without the failed links. Using this method, resource of the links that are not affected by the failed paths is still reserved, thus cannot be utilized in the reconfiguration phase; for instance, the capacity cannot be reallocated even though these links are no longer used by the failed paths.

2.2.1.5 Segment vs. Path-based This can be regarded as a generalization of link-based and path-based protection in a single-layer recovery framework. A path may be protected with segments which are subsets of links along the path. Segment-based protection provides for fast recovery time. In this case, trap paths can also be avoided. In contrast, path protection generally has better resource utilization. There are four possibilities in a two-layer scenario, each of the choices at each layer.

2.2.2 Computational Approaches

2.2.2.1 Offline vs. Online One choice towards recovery mechanisms is to decide between preplanned offline and dynamic online reconfiguration. Both options can be made towards any recovery choices in Section 2.2.1; however, the distinction between recovery times can differ greatly. The offline approach plans all backup paths in advance, thereby allowing fast recovery. However, while it may offer faster recovery than the online approach, the online approach is more flexible as it leaves room for unplanned failures that may happen in practice. In some cases, this choice between these two approaches is referred to as protection vs. restoration, pre-selected vs. on-demand, static vs. dynamic, or provisioning vs. restoration for offline and online reconfigurations, respectively.

2.2.2.2 Capacity Allocation vs. Reservation To bridge the gap between the offline and the online computations, capacity may be allocated but not reserved. The spare capacity allocation is invisible under normal working conditions; however, it can be seen after failure occurs. Obviously, this allocation-only approach requires signaling protocols, the presence of which results in increased complexity, but it is able to cope more flexibly with various failure scenarios and reconfiguration cases. This concept is also called the protected working capacity envelope [24].

2.2.2.3 Peak Demand vs. Multi-Hour Model A traditional design approach requires that all demand requests be accepted and be accommodated at any given time period. In this case, the network resource requirements are determined by total peak demands. However, because demand peaks may not occur at the same time for all traffic, the design could be handled in a more responsive manner and in a smaller time scale. For example, a nationwide network planning can be made for traffic spanned across time periods with different peak demands in each time zone. This is called multi-hour network planning.

2.2.3 Protection Strategies in Multilayer Networks

2.2.3.1 Escalation Strategies To achieve full survivability, a coordination strategy between recovery mechanisms is needed such that contention between the mechanisms can be avoided. As mentioned earlier in this chapter and further defined in Section 2.2.1.3, there are two well-known strategies which perform such a function, based on token and time-out value. Both of them can also be present in the same network when a time-out mechanism is called upon its preset value in the case of a corrupted token. Cooperative negotiation may also serve between affected nodes to form a quorum region, such that localized rerouting can be performed [25].

2.2.3.2 Disjointness Paradigms

Path-based protection is the simplest approach, requiring one or more backup paths for each primary path. In both cases, all paths are disjoint. When providing one backup path, it may be (1) assigned to a primary path (1:1), or (2) assigned to a number of primary paths (1:N). In these cases, a backup path is used only when the corresponding primary path fails. Demand-wise Shared Protection (DSP) [26] deploys the 1:N for each demand and requires that all multiple paths are disjoint. DSP considers an integral demand by evenly allocating it to the N paths, so the maximum split demand from the N paths is attained at its minimum. This allows the capacity requirement of the backup path to be minimum as well. DSP has been found to give the most benefit in highly dense networks, where a number of disjoint paths with likely equal length exist. Reference [27] offers an insight of the DSP on two network families: (1) three reference transport networks and (2) three random networks. They identify practical concerns that can affect the cost-saving aspect of the network designs. The identified limitations include the number of disjoint paths of each demand, the restriction on demand splitting due to integral value of the demands, and the diminishing of spare capacity as the number of multipaths increases. It is noteworthy that DSP mainly focuses on protection in the optical layer. However, in real networks, demands can be dynamic and may require more capacity than originally allocated. In this case, partially disjoint shared path protection (PDSP) [28] can be used. In [28], two formulation-based routing methods under dynamic demands have been proposed. In the first method, it requires two steps: First, it allocates all demands to the preset shared capacity. Second, if needed, it reroutes all affected paths that are still unsatisfied at a cost to the extra requested bandwidth. In the latter method, it considers rerouting in an integrated manner by jointly allocating all affected demands to both the preset shared capacity and the residual capacity in a link. This method gives routing favor to the shared capacity over the residual capacity with respect to the unit cost of link capacity.

Segment-based protection provides path protection with multiple backup paths that are not necessarily disjoint. Survivable Segment Protection (SSP) [29] presents the idea of overlapped segment protection to avoid the trap topology problem [30]. The protection provides different backup segments for different subpaths of a primary path. The proposed shortest path-based SSP algorithm considers link availability as link cost. This partially disjoint approach can achieve higher availability at a cost of a slight increase in resource utilization in terms of hop count. Alternatively, reference [31] proposes a partial path protection (PPP) scheme, which identifies a protection path for each specific failure that occurs on the primary path. For example, there could be at most L-protection paths for each primary path, where L is the number of links along the path. Since PPP is more flexible than the traditional end-to-end disjoint path protection, it follows that blocking probability is lower in PPP than in the traditional path protection. This is because some capacity resources can be shared among failure events. In [31], two PPP algorithms: greedy-based and shortest path-based, are also proposed. The first seeks to jointly optimize the capacity of both primary and backup paths by incrementally adding a capacity as small as possible. This leads to less capacity being required for path protection but may give a poorer blocking probability than the latter approach. Because the shortest path approach selects primary paths in a min-hop fashion and chooses the backup paths in which previously reserved capacity can be used at no cost, it has better bandwidth utilization than the greedy approach. This difference can be significant in highly-loaded networks. Reference [32] proposes a scheme that takes into account knowledge of protection strategies at the optical layer. By avoiding providing link protection where it is already protected at the bottom layer, a primary path at the top layer may be partially protected. This divided protection results in better resource utilization because some segments are protected at the logical layer while the other segments are protected at the physical layer. A method to find such protection is simple. A modified Dijkstra's algorithm calls upon a physical configuration and its backups to find a path for the demand. The link weights are assigned to be zero if optical protection already exists. Then a demand path is the path, which requires least spare capacity at the logical layer.

Scenarios involving both path and segment protections have been underexplored. The simplest, path-based protection at both layers, has been considered; however, the other three possible combinations still require more thorough analysis in order to providing efficient resource allocation in survivable networks.

2.3 SURVIVABILITY IN MULTILAYER IP-OVER-WDM NETWORKS

In the context of survivability in two-layer networks, several strategies have been proposed [2], [18], [33], [34]. Whether recovery can be initiated at either layer, both, or only at the bottom is based in part on the originating traffic layer. When the traffic originates at the top, recovery can be performed at either layer or both, but when the traffic originates at the bottom, it can only be recovered at the bottom layer.

2.3.1 Survivability at the Top Layer

Survivability at the top provides backup paths to top-layer traffic at the top layer. Survivability strategies at this layer can be used to give multiple availability guarantees to traffic with priorities. This approach can also resolve failures at both layers, *i.e.,* IP node, optical link, and WDM node failures. However, recovery time and rerouting states may be high due to the fact that each traffic flow needs to be recovered individually.

2.3.2 Survivability at the Bottom Layer

Survivability at the bottom provides backup paths to two-layer traffic at the bottom layer. Owning to fast failure detection and pre-reserved resources in WDM networks, recovery at this layer is usually faster [32]. However, it may not be able to provide survivability when a failure happens at the top layer, *e.g.,* IP line card failure. In some cases, this strategy is not aware of IP top-layer failures unless there is an appropriate signalling coordination like GMPLS. In most cases, recovery at the optical bottom layer has to be performed on an aggregate basis, meaning that all IP flows that share the same failed optical link are rerouted to the same backup optical link. In the case of lightpath (re-)establishments in WDM networks, the situation is a little different. Specifically, the IP flows that share that failed link can be rerouted to different lightpaths in optical links, giving more flexibility and better spare capacity utilization.

At the WDM layer, survivability is normally achieved through redundant paths – a number of backup paths and a primary path. Dedicated protection, 1+1, allows one backup path to protect the primary path by simultaneously sending the same traffic on both paths. Alternatively, shared protection, 1:N, allows the backup path to be shared by N primary paths. However, in this case, no more than one primary path can fail at any given time as the single backup path is shared. Shared-backup path protection (SBPP) allows the capacity of each backup path protecting a primary path to be shared; therefore, the survivability can be achieved with the least spare capacity requirement. These protection schemes can be applied either at a lightpath level or line level. In an optical transport network (OTN) [35], each optical channel (OCh) is assigned a wavelength; a number of channels can be grouped into an optical multiplex section (OMS). By protecting at a lightpath level – optical channel section (OCh-S) – each failed lightpath can be restored individually after a failure. Alternatively, the line level protection, OMS, restores an entire group of the lightpaths that belong to a failed link without allowing for individual recovery [36]. Because recovery time generally depends on the number of failed lightpaths and no single scheme is better for all possible failure scenarios, a hybrid implementation of both schemes is usually considered. Reference [37] considers a hybrid scheme of OCh-S/OMS which selects a protection scheme that requires less recovery time for a particular failure. They show that the two schemes can coexist while still being able to achieve 50 ms failure recovery requirement.

2.3.3 Survivability at Both Layers

Survivability at both layers provides backup paths to top-layer traffic at both layers. By providing each top flow with two backup paths, one path at each layer, this strategy guarantees full recovery upon failures at any layer. In such a case, protection selectivity [38] or spare unprotected [39] refer to the strategy where sharing space capacity of the two backup paths is not allowed. When the capacity can be shared, it is known as common pool survivability [2], [39]. Alternatively, the backup path at the top layer can also be provided with a backup path at the bottom. In such a case, spare capacity is used twice, resulting in an over-allocation of capacity.

2.4 SURVIVABILITY IN OVERLAY NETWORKS

In contrast to the IP-over-WDM architecture, an overlay network is normally formed without a knowledge of the underlying two layers. This can be a problem when failures happen. Survivability is usually attempted by constructing a number of redundant paths that are disjoint at the overlay layer; however, they may not be disjoint at the IP or physical WDM layers. Reference [40] proposes two survivability models for an overlay network. One permits node disjointness at the WDM layer in all redundant paths whereas the other permits only a guaranteed number of the paths that are node disjoint. Unfortunately, they both are NP-complete. Furthermore, these models require an overlay network to have topology knowledge of the underlying networks. One other direction is for the overlay to take complete responsibility for failures at the lower layers. Resilient overlay networks (RONs) [41] architecture, a well-known solution in this direction, aims at recovering from failures by forming a complete graph at the overlay layer over the IP layer; these networks can provide customized path selections specific to each application; however, they still need to be aware of the underlying IP network. Such networks can still suffer from physical layer fault propagation and duplicate transmissions in the physical link may occur due to improper mapping.

2.5 DIFFERENTIATED SURVIVABILITY

Survivability can also be provided to traffic with multiple availability guarantees. In many cases, combinations of the preceding strategies are considered. For example, in traffic with two priority classes, survivability at the bottom and at the top can be provided to high-priority and low-priority traffic, respectively. Inter-level sharing between the two classes [42] can also be allowed. Integrated shared pool [23] considers three traffic classes: Gold, Silver, and Bronze. Survivability at the bottom is provided to Gold whereas survivability at the top is provided to Silver while there is no survivability guarantee for Bronze classes of traffic. In this strategy, sharing capacity among Gold backup paths, Silver backup paths, and Bronze primary paths is allowed. As there is no backup path for Bronze traffic, some capacity savings can be achieved by allocating spare capacity only to the two most important traffic classes. Idle protection capacity reuse [43] retains the same bottom-layer strategy for all three classes of traffic but chooses to explore possibilities in capacity-limited networks, *i.e.*, whether some paths can be preempted by others with higher priority upon failures and whether backup paths are preplanned or computed upon failures. Alternatively, a notion of shared risk link groups (SRLGs) can also be used to provide multiple guarantees to different traffic classes [44], *e.g.,* when disjointness of the links that belong to an SRLG is not required.

Implementing a survivability strategy in practice may depend on whether a two-layer network is under a single administrative management. Under the overlay model [17], none of the network layers have a complete view of the other. In this case, from a global view, some care needs to be taken when allocating capacity or minimizing capacity costs because this can sometimes lead to different solutions from different perspectives of the top- and bottom-layer network providers.

3.0 THE BACKHAUL PROBLEM IN LAYERED NETWORK ARCHITECTURES

Designing a survivable network considering all involved layers that is also efficient presents numerous challenges. The most fundamental is the network graph design. Good design permits more routing options for a traffic request in each layer, especially at higher layers. Having more choices often leads to better capacity use, higher availability, or lower delay. In this chapter, we discuss core network structures and the degree to which we distinguish between network and traffic layers as separate, yet related entities, in the context of the interaction between and among layers. Here this interaction is investigated in terms of backhaul, a routing loop which occurs at two or more layers below a layer of interest. This chapter is organized as follows: Section 3.1 identifies the backhaul mapping problem. Section 3.2 explains the backhaul routing problem with traffic layers considered. Section 3.3 contains the chapter summary.

3.1 BACKHAUL MAPPING

3.1.1 Network Layer

Consider a graph $G = (\mathcal{N}^l, \mathcal{L}^l)$, where l denotes the network layer index starting from the lowest layer. Each node $n^l \in \mathcal{N}^l$ is associated with resources of a node *e.g.,* CPU or the number of ports. For example, this resource could be the number of available optical ports in a WDM optical switch or IP ports in an IP router. Each bidirectional link $e^l_{ij} \in \mathcal{L}^l$ between node i and j is associated with link capacity, defined as the number of available wavelengths in an optical link or available link bandwidth between IP routers. In the next section, we describe the relationship between and among links in different layers.

3.1.1.1 Network Link Mapping Given the node locations in all network layers, we define a link mapping H_i^j from $\mathcal{L}^j$ to $\mathcal{L}^i$, associating each element e^j of $\mathcal{L}^j$ with one or more corresponding element e^i of $\mathcal{L}^i$. In link mapping, (1) for every link $e^j \in \mathcal{L}^j$, there is exactly one path consisting of one or more $e^i \in \mathcal{L}^i$ such that the relationship between an upper layer link and a lower layer path is defined (unsplittable flow) and (2) not all $e^i \in \mathcal{L}^i$ may be included in the link mapping. In this dissertation, the association is done in a way that network layer j is still connected whenever some links in this network fail as a result of any single link failure in network layer i. This type of mapping is called *survivable* and is a major focus in this dissertation. The mapping can be constructed by enumerating all possible failure scenarios at the lower layer by means of the cut-set; therefore, this mapping is $\mathcal{NP}$-hard [45].

In order to understand how layers interact, in the following paragraph, we systematically present the property of two-connectedness and backhaul-free mapping which is critical in designing highly survivable overlay networks and services on top of the two-layer network infrastructure, IP-over-WDM.

Consider the sample network illustrated in Figure 3.1. Here, the overlay, IP, and WDM networks consist of 3 nodes, 3 links, 4 nodes, 6 links, and 5 nodes, 7 links, respectively. Without loss of generality, bidirectional links are assumed in the figure and throughout this section as well as the rest of the dissertation. The numbers on each link indicate the link index in that layer. In order to achieve routing that is survivable to any underlying single link failure in a lower-layer network, we need to ensure that each mapping is at least two-connected [8]. Let $H_i^j : \mathcal{L}^j \mapsto \mathcal{L}^i$ be a link mapping of Layer j onto Layer i where each j-th layer link is assigned to a subset of i-th layer links. When put in a matrix form, the mapping has rows corresponding to layer j links and columns corresponding to layer i links. Such mappings according to the figure can be given as

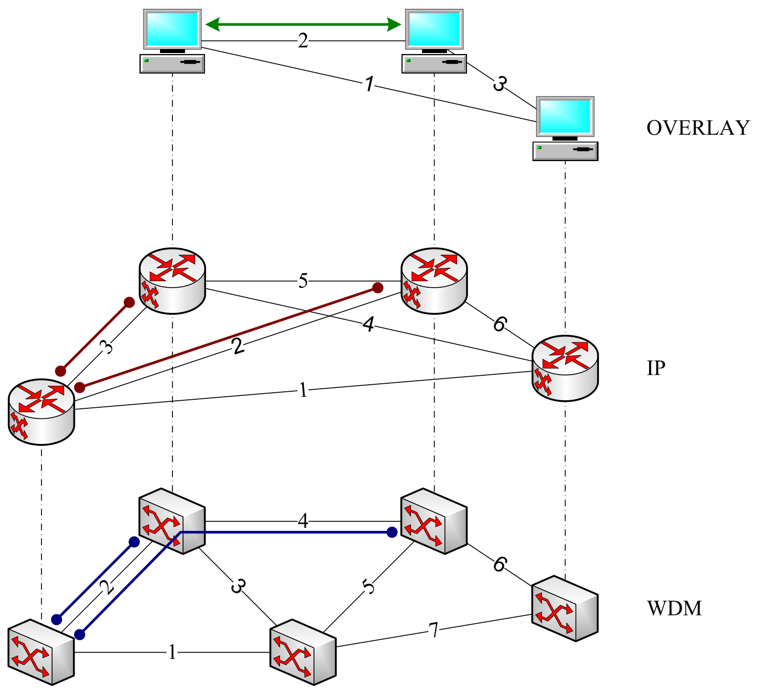


Figure 3.1: Backhaul mapping in a three-layer network

$$H_2^3 = \begin{array}{c|cccccc|} & 1 & 2 & 3 & 4 & 5 & 6 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 2 & 0 & 1 & 1 & 0 & 0 & 0 \\ 3 & 0 & 0 & 0 & 0 & 0 & 1 \end{array}$$

for the overlay-over-IP, *i.e.*, Layer 3 to Layer 2, network and

$$H_1^2 = \begin{array}{c|ccccccc|} & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\ 2 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 3 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 4 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 5 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 6 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{array}$$

for the IP-over-WDM network, *i.e.*, Layer 2 to Layer 1, network.

While this routing is survivable, it may not also be resource-efficient or loop-free. Consider link 2 at the overlay layer. This link is routed on links 2 and 3 at the IP layer. However, because these IP links 2 and 3 use links 2 and 4, and 2 at the WDM layer, respectively, the WDM link 2 is used twice. Thus, the solution reference [8] proposes to ensure survivability as well as other solutions in the current literature can be resource inefficient as backhaul can occur. In this dissertation work, we propose a survivable mapping that is backhaul-free.

3.1.1.2 Network Node Mapping In a more general case, node locations can also be planned. Nodes could be placed in such a way that all traffic requirements can be satisfied. Again, constraints at a node may be due to node resources such as the number of ports or computational capabilities of an IP router or an optical switch. In this case, let a node mapping from $\mathcal{N}^j$ to $\mathcal{N}^i$, denoted K_i^j, be a rule associating each element n^j of $\mathcal{N}^j$ with a corresponding element n^i of $\mathcal{N}^i$. We consider a node mapping such that: (1) for every node $n^j \in \mathcal{N}^j$, there is exactly one node $n^i \in \mathcal{N}^i$ such that the relationship between these two nodes is defined (unsplittable node) and (2) not all $n^i \in \mathcal{N}^i$ may be included in the node mapping.

In general cases, restrictions on the unsplittability conditions could be relaxed, thereby allowing two or more lower layer paths to support one upper layer link or two or more lower layer nodes to support one upper layer node *e.g.,* load sharing for a node.

3.2 BACKHAUL ROUTING

3.2.1 Traffic Layer

Traffic may be present in one or more layers of the network graph. Unlike other work in this area where traffic and network layers are considered as one layer, we explicitly consider them as two separate layers and present the backhaul routing problem. If this problem occures, the overlay topology may need to be redesigned if traffic in the overlay network changes dynamically or in a way that affects the optimality of the static design.

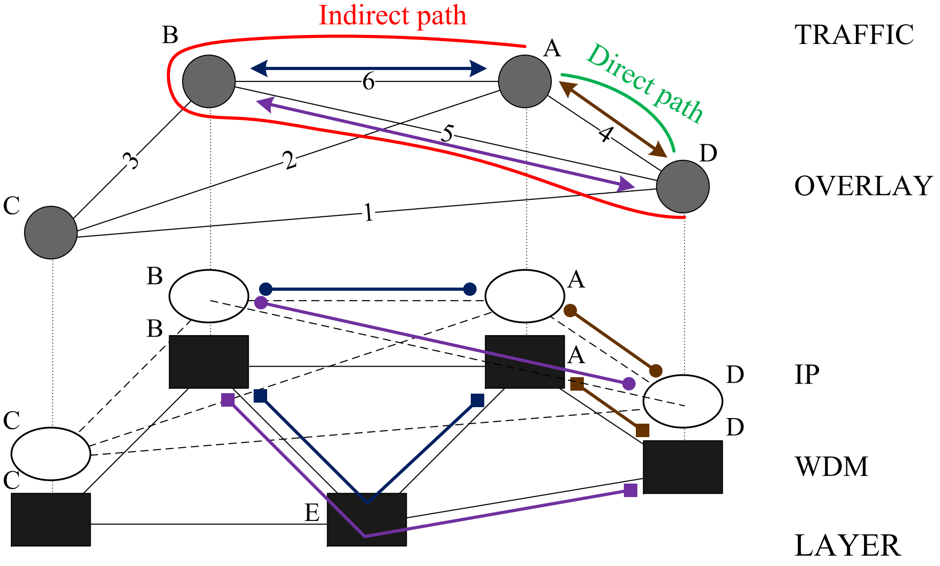


Figure 3.2: Backhaul example in a three-layer network

3.2.1.1 Direct/Primary Traffic Flow Routing In accordance with initial traffic requests, the original overlay topology is usually constructed such that primary traffic flow is supported by a direct path. Therefore, it is a one-to-one correspondence (bijective) mapping from overlay traffic layer to overlay network layer.

3.2.1.2 Indirect/Backup Traffic Flow Routing When an overlay topology has become disconnected due to failures, traffic reroutes through its backup path. A backup path typically needs one or more intermediary nodes for failed traffic to be rerouted through. This path is often called an indirect path and may be subject to the backhaul problem if the mapping is not properly designed.

In order to adequately contextualize this notion, we illustrate how the two paths, primary and backup, are distinctly defined. Consider the network example in Figure 3.2 where blue (darkest) and purple (lightest) lines constitute an indirect (backup) path and a brown (dark) line represents a direct (primary) path. Paths in different layers are differentiated through three different line-ends, namely arrow, circle, and square for overlay, IP, and WDM layers, respectively. Here, an indirect overlay path `A-B-D` is used as a backup after direct primary path `A-D` fails, which is a typical path protection scheme in the overlay network. However, a backhaul routing loop occurs at link `B-E` in the physical WDM layer, which is an undesirable property that is not directly addressed in [12] or any other existing literature. This backhaul problem may arise in a general case when an indirect backup path routes through an intermediary node [46], which is `B` in this case. In [12], only direct paths are explicitly considered; however, both direct and indirect paths are fully examined in this dissertation. Therefore, overlay link mapping alone is not sufficient when backup paths or any paths requiring more than a single hop are considered.

In this dissertation, we directly address the backhaul mapping and routing problems in the explicit pursuit of survivability in the context of overlay-IP-WDM networks.

3.3 SUMMARY

This chapter gives an overview of the problems under consideration and defines the survivability of a layered network in the context of network and traffic layers of the network. The next four chapters document our contributions, our perspectives, and major numerical results and findings.

4.0 CROSSLAYER SURVIVABLE MAPPING

4.1 INTRODUCTION

The lack of a well-studied survivability framework for a network of three layers or more has motivated our design of crosslayer survivable mapping as an initial look at layered networks. In some networks [47], overlay layer applications are believed to consume as much as 75 percent of the bandwidth of IP-over-WDM core backbone network infrastructures even though they make up only 5 percent of the users. This chapter focuses on link mapping in multilayer networks, including the interactions between and among layers and proposes an efficient survivable mapping when all layers are considered concurrently. Section 4.2 provides an overview of the design challenges. Section 4.3 defines the problem and proposes a mathematical model to provide minimum joint primary-backup capacity allocation for survivability of the traffic that originates at every network layer. Evaluation results and analysis are provided in Section 4.4. An example of the crosslayer mapping design for ring overlays is given in Section 4.5. Finally, our summary is given in Section 4.6.

4.2 MOTIVATION

The existing literature on survivable mapping, which is also known as survivable routing or survivable logical topology planning either explicitly considers a two-layer topology such as IP-over-WDM or deals with a logical topology constrained within a physical network such as WDM lightpaths in an optical fiber cable [8]. However, overlay networks are receiving more attention not only because they can offer new services, but also because they can overcome functionality limitations of the Internet without the need for modifications of the underlying network layers. Therefore, it is important that this overlay network layer also be included in the network design to complete the whole picture.

4.3 PROBLEM STATEMENT

In this chapter, we consider the survivability problem in three-layer networks such that no backhaul occurs and survivability is implemented using SBPP (please refer to Section 2.3.2 in Chapter 2 for the definition) under single-link failures.

4.3.1 Notation Used

The notation adopted in this chapter can be summarized as follows:

l	Network layer index, where $l = 1, 2, 3$ refers successively to higher layers, *i.e.,* the WDM, IP, and overlay layers, respectively
$\mathcal{N}^l$	l-th layer node set
$\mathcal{L}^l$	l-th layer link set
$\mathcal{F}^l$	l-th layer flow vector
M^l	Diagonal matrix of bandwidth of l-th layer flow index f^l with dimension $\lvert\mathcal{F}^l\rvert \times \lvert\mathcal{F}^l\rvert$
M_c^l	Diagonal matrix of bandwidth of l-th layer flow index f^l with dimension $\lvert\mathcal{F}^l\rvert \times \lvert\mathcal{F}^l\rvert$, when mapped to layer $l-1$
B^l	l-th layer incidence matrix with dimension $\lvert\mathcal{N}^l\rvert \times \lvert\mathcal{L}^l\rvert$
B_c^l	l-th layer incidence matrix with dimension $\lvert\mathcal{N}^{l-1}\rvert \times \lvert\mathcal{L}^{l-1}\rvert$, when mapped to layer $l-1$
D^l	l-th layer flow-node incidence matrix with dimension $\lvert\mathcal{F}^l\rvert \times \lvert\mathcal{N}^l\rvert$
D_c^l	l-th layer flow-node incidence matrix with dimension $\lvert\mathcal{F}^l\rvert \times \lvert\mathcal{N}^{l-1}\rvert$, when mapped to layer $l-1$
P^l	l-th layer primary path matrix with dimension $\lvert\mathcal{F}^l\rvert \times \lvert\mathcal{L}^l\rvert$

P_c^l	l-th layer primary path matrix with dimension $\|\mathcal{F}^l\| \times \|\mathcal{L}^{l-1}\|$, when mapped to layer $l-1$
Q^l	l-th layer backup path matrix with dimension $\|\mathcal{F}^l\| \times \|\mathcal{L}^l\|$
Q_c^l	l-th layer backup path matrix with dimension $\|\mathcal{F}^l\| \times \|\mathcal{L}^{l-1}\|$, when mapped to layer $l-1$
W^l	l-th layer primary-path link capacity vector with dimension $\|\mathcal{L}^l\| \times 1$
G^l	l-th layer spare capacity matrix with dimension $\|\mathcal{L}^l\| \times \|\mathcal{L}^l\|$
G_c^l	l-th layer spare capacity matrix with dimension $\|\mathcal{L}^{l-1}\| \times \|\mathcal{L}^{l-1}\|$, when mapped to layer $l-1$
S^l	l-th layer backup-path link capacity vector with dimension $\|\mathcal{L}^l\| \times 1$
S_c^l	l-th layer backup-path link capacity vector with dimension $\|\mathcal{L}^{l-1}\| \times 1$, when mapped to layer $l-1$
I	Identity matrix
H_i^j	Survivable mapping matrix between layers j and i ($H_0^1 = I$)
$\mathbf{e}$	The column vector of all ones in $\mathbb{R}^n$
$(.)_c$	The sucscript c stands for crosslayer by means of mapping or cost of the lower-layer link use

In particular, we consider the following mapping specific to the IP-over-WDM network in our considered three-layer networks.

$$B_c^2 = B^2 \tag{4.1}$$

$$D_c^2 = [D^2|0] \tag{4.2}$$

$$P_c^2 = P^2 H_1^2 \tag{4.3}$$

$$M_c^2 = M^2 \tag{4.4}$$

Because the incidence matrix is topology dependent, a layer 2 incidence matrix, when mapped to layer 1, is equivalent to that of layer 1. This is shown in equation (4.1) by the subscript c denoting crosslayer. Since a layer 2 network may not have the same number of nodes as the layer 1, *i.e.,* it could be more than or equal to that in layer 1 network, the flow-node incidence matrix in (4.2) is mapped to layer 1 by padding columns of zeros as necessary to D^2. Equation (4.3) computes the primary paths of layer 2 from the perspective of layer 1 given as P_c^2 using the link-mapping information in H_1^2. In (4.4), the bandwidth of the mapped layer 2 flow still holds the same value as that of layer 2 flow as it depends on flows only. We also note that the mapped layer 2 flow may include additional information such as grooming or framing overhead; however, these have not been considered in this work. The motivation behind these equations is briefly discussed in the next section; the details are given later in Chapter 7.

4.3.2 An Optimization-based Formulation

Layer l topology of an uncapacitated network consists of a set of nodes $\mathcal{N}^l$ and a set of directional links $\mathcal{L}^l$, each two of which are equivalent to two unidirectional links with an equal number of wavelengths, *i.e.,* same capacity, and the same failure state, *i.e.,* available or failed, in each link and have opposite direction. Then the incidence matrix B^l [48] of the network which has a row for each node and a column for each link where $B^l(n, e) = 1$ if and only if link e is connected to source node n and -1 if n is a sink node can be obtained.

Traffic originating at layer l can be formulated as follows: Let D^l denote a flow-node incidence matrix at layer l in which each row represents a source-sink pair of a flow index f^l where $1 \leq f^l \leq |\mathcal{F}^l|$ and $\mathcal{F}^l$ is a vector of flow at layer l. The matrix D^l has $+1$ in the row corresponding to a traffic source and -1 in the row corresponding to a traffic sink. Flow bandwidth is assumed integral based on a fixed bandwidth unit and is represented by $m^l(f^l)$ for each flow index f^l. The bandwidth matrix M^l puts $m^l(f^l)$ on the main diagonal; therefore, this matrix is a diagonal matrix with dimension $|\mathcal{F}^l|$ by $|\mathcal{F}^l|$. Identical source-sink pairs are here regarded as a single flow equivalent to the sum of all the flow bandwidths combined.

We aim at providing survivability using the SBPP scheme at layer l. Let P^l be the primary path matrix with dimension $|\mathcal{F}^l|$ by $|\mathcal{L}^l|$. For the element p^l_{fe} of P^l, $p^l_{fe} = 1$ if link e is in the primary path of flow index f^l, and 0 otherwise. Likewise, the backup path matrix Q^l with the same dimension as the primary path can be defined in a similar manner.

In order to route a link in layer $l+1$ on layer l properly, a good link mapping such that layer $l+1$ topology remains connected even after a single link failure in layer l is required. Such a mapping is given in [8] and is formulated as a mathematical optimization model in [49]. However, an additional requirement is needed in networks consisting of three layers or more to prevent backhaul. This requirement is given as follows:

Definition 4.1. *The condition $C_{\mathcal{L}}$ of the link mapping in three-layer networks such that no backhaul routing occurs is defined by $H_2^3 H_1^2 \preceq 1$, where the $\preceq$ symbol denotes element-wise comparison, i.e., each element of the product matrix is no more than* 1.

The following Lemma is motivated by the condition $C_{\mathcal{L}}$.

Lemma 4.1 (Crosslayer Mapping)**.** *No backhaul mapping occurs in a three-layer network if and only if a link mapping satisfies the condition $C_{\mathcal{L}}$.*

Proof. Given two survivable mappings, H_2^3 and H_1^2, in a three-layer network, it can be followed that an element (i, j) of the matrix product $H_2^3 H_1^2$ is nonzero if and only if a layer 1 link j is used by a layer 3 link i. This element determines the number of times layer 1 link j is used by layer 3 link i. Because in no backhaul routing there should be exactly one such use by any path in layer 3; therefore, the condition $C_{\mathcal{L}} : H_2^3 H_1^2 \preceq 1$ is required in routing with no backhaul. □

Clearly, the proof of Lemma 4.1 constructs efficient or backhaul-free mapping in three-layer networks. Next, we show that the situation is much more favorable when survivability is also considered.

Theorem 4.1 (Crosslayer Survivable Mapping)**.** *A mapping is survivable and produces no backhaul if and only if its corresponding link mapping is two-connected and satisfies the condition $C_{\mathcal{L}}$.*

Proof. Necessity and Sufficiency are a direct result of [8, Theorem 1] and Lemma 4.1 previously given. □

In addition, it can also be seen that the mapping can withstand multiple link failures if proper survivable mapping [9], [50] is employed.

The formulation of the Overlay-over-IP-over-WDM survivable networks employing SBPP can be summarized in a mathematical optimization model as follows: Denote $l = 1, 2, 3$ as the WDM, IP, and Overlay layer, respectively; this alpha numeric notation may be used interchangeably in this section as well as throughout the dissertation. The joint capacity allocation (JCA) problem in three-layer networks (`JCA3L`) can be formulated as follows:

Objective:

$$\min_{P^l, Q^l} \sum_{l=\{1,2,3\}} {W^l}^T \, (\prod_{k=1}^{l} H_{l-k}^{l-k+1}) \, \mathbf{e} + \sum_{l=\{1,3\}} {S^l}^T \mathbf{e} + \sum_{l=\{2\}} S_c^{l^T} \mathbf{e}, \tag{4.5}$$

subject to:

Primary Paths:

$$P^l {B^l}^T = D^l, \qquad l \in \{1, 2, 3\}, \tag{4.6}$$

$$W^l = (M^l P^l)^T \mathbf{e}, \qquad l \in \{1, 2, 3\}, \tag{4.7}$$

$$W^l \in \mathbb{R}^{|\mathcal{L}^l|}, \qquad l \in \{1, 2, 3\}, \tag{4.8}$$

$$P^l : \text{binary matrix}, \qquad l \in \{1, 2, 3\}. \tag{4.9}$$

Backup Paths:

$$Q^l {B^l}^T = D^l, \qquad l \in \{1, 3\}, \tag{4.10}$$

$$Q_c^l B_c^{l^T} = D_c^l, \qquad l \in \{2\}, \tag{4.11}$$

$$Q^l : \text{binary matrix}, \qquad l \in \{1, 3\}, \tag{4.12}$$

$$Q_c^l : \text{binary matrix}, \qquad l \in \{2\}. \tag{4.13}$$

Spare Capacity Requirements:

$$G^3 = {Q^3}^T M^3 (P^3 H_2^3 H_1^2), \tag{4.14}$$

$$G_c^2 = {Q_c^2}^T M_c^2 P_c^2, \tag{4.15}$$

$$G^1 = {Q^1}^T M^1 P^1, \tag{4.16}$$

$$S^l = \text{row-max } G^l, \qquad l \in \{1,3\}, \tag{4.17}$$

$$S_c^l = \text{row-max } G_c^l, \qquad l \in \{2\}, \tag{4.18}$$

$$S^l \in \mathbb{R}^{|\mathcal{L}^l|}, \qquad l \in \{1,3\}, \tag{4.19}$$

$$S_c^l \in \mathbb{R}^{|\mathcal{L}_c^l|}, \qquad l \in \{2\}. \tag{4.20}$$

Path Disjointness:

$$P^1 + Q^1 \preceq 1, \tag{4.21}$$

$$P_c^2 + Q_c^2 \preceq 1, \tag{4.22}$$

$$(P^3 + Q^3) H_2^3 H_1^2 \preceq 1. \tag{4.23}$$

The `JCA3L` problem has the objective to jointly minimize the total capacity requirement at the lowest (WDM) layer due to primary and backup flows at this and the other two layers. This is given in (4.5). Then there are four blocks of constraints. The first block deals with the basic requirements of the primary paths in each of the three layers. Constraint (4.6) is a flow conservation constraint, guaranteeing no traffic lost between two end-points. Constraint (4.7) calculates primary path capacity requirements from a perspective of layer l. Constraints (4.8) and (4.9) define variables with respect to the primary paths.

The second block of constraints deals with backup paths. Constraints (4.10) and (4.11) define the flow conservation constraints for the backup paths in layer l, where $l = 2$ here in constraint (4.11) refers to layer 2 traffic from the perspective of layer 1. In other words, this layer 2 traffic is mapped onto layer 1. For example, in this case, Q_c^2 is a backup path of layer 2 traffic provided at layer 1 which is denoted as $(.)_c^2$. Constraints (4.12) and (4.13) define variables with respect to this second block of constraints.

The third block of constraints considers the spare capacity requirements of the backup paths. Constraint (4.14) determines the amount of capacity units needed at the WDM layer in order to protect the primary overlay paths P^3 upon their failures. The last component in this constraint translates the capacity requirement to the view of the WDM layer using crosslayer mappings that conform with Theorem 4.1. At the IP layer, the situation is a little different. This is because while primary paths are calculated at this layer, the backup paths are provided at the WDM layer. We chose this survivability strategy for IP traffic by means of the best strategy as studied in Chapter 7 and [51]. Since traffic at the WDM layer is also provided backup paths at the WDM layer, this requires no translation. Therefore, whether traffic originates at the IP or the WDM layer, the amount of capacity units can be determined by constraints (4.15) and (4.16), respectively. The row-max (.) operation in (4.17) and (4.18) determines the maximum element in each row of the matrix G^l. These elements reflect the amount of capacity needed by their corresponding link in order to protect against a single link failure at the WDM layer. Like previously given, constraints (4.19) and (4.20) define a variable with respect to spare capacity of the backup paths. These spare capacity matrices are not allowed to share across layers; however, the capacity can be shared within a layer. It should be noted that mapping is not considered in the optimization of the backup-path link capacity vectors in objective (4.5) because we have already included the mapping in constraints (4.14) and (4.15), and equation (4.3) which is reflected in constraints (4.17) and (4.18).

The relationship between the primary and backup paths are provided in the fourth block of constraints. Constraint (4.21) guarantees that, at layer 1, each backup path is disjoint from the primary path. Constraint (4.22) guarantees paths disjointness of layer 2 traffic at layer 1. As the backup path to layer 2 traffic flows is provided at layer 1, this constraint guarantees such disjointness between this backup path and the mapped primary path. At layer 3, both primary and backup paths are computed at this layer; however, because the overlay network has no knowledge of the underlying layers, they are not necessarily disjoint from the perspective of layer 1. Constraint (4.23) guarantees such disjointness at layer 1. The `JCA3L` problem is $\mathcal{NP}$-hard as it can be reduced from some known $\mathcal{NP}$-hard problems [8], [45].

Before moving to the next section, which analyzes a large network, we have verified the optimization formulation manually on some small networks against the results obtained from an AMPL/CPLEX implementation to ensure its correctness.

4.4 NUMERICAL RESULTS AND ANALYSIS

In this section, we evaluate the efficiency and effectiveness of the crosslayer survivable mapping (CSM) in three-layer networks, we consider the NSFNet consisting of 14 nodes, 21 links, depicted in Figure 4.1, as a layer 1 (WDM) network. In the case of layer 2 (IP) network, links are added to the NSFNet such that the network is fully connected. Layer 3 (overlay) network is constructed as a partial, *i.e.,* half, mesh of the full mesh layer 2 topology, as shown in Figure 4.2. The overlay network is partially-connected. Here, the maximum number of overlay traffic flows in where each flow request is represented by an overlay link is 46. These particular links are employed as a means to overcome crosslayer survivable mapping limitation in this topology that not all disjoint paths in the overlay layer are also disjoint at the WDM layer. It should be noted here that the considered single-link flows can easily be extended into the case when the flows require two or more overlay links by concatenating the links. In addition, we consider a number of demand flows at the overlay layer and a fixed number of demand flows at the IP and WDM layer; the numbers of IP and WDM traffic flows do not affect capacity requirements of the overlay since sharing spare capacity across layers is not allowed. Following the setting of a three-layer network, we present some results, provide discussions, and evaluate the performance of crosslayer survivable mapping against three other mappings in terms of capacity overbuilding, flow overrouting, and link overusing due to both primary and backup paths.

To show efficiency and effectiveness of CSM, which conforms to Theorem 4.1. We first obtain CSM: (H_1^2, H_2^3). Then for comparison purpose, we also compute three other mappings, M1: $(\widetilde{H_1^2}, H_2^3)$, M2: $(H_1^2, \widetilde{H_2^3})$, and M3: $(\widetilde{H_1^2}, \widetilde{H_2^3})$. By using the integer linear programming (ILP) formulation of [8], we can calculate the two mapping matrices $\widetilde{H_2^3}$ and $\widetilde{H_1^2}$, each of which corresponds to the link mapping matrix of the overlay-over-IP and the IP-over-WDM networks, respectively. In this calculation, each mapping matrix is obtained independently without considering the effect from the other network layer. That is, $\widetilde{H_1^2}$ is computed as if

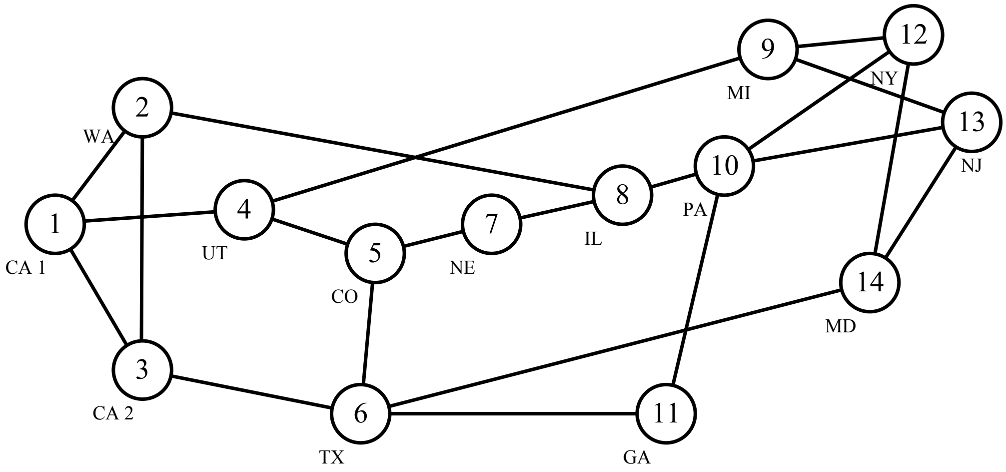


Figure 4.1: The 14-node, 21-link NSFNet

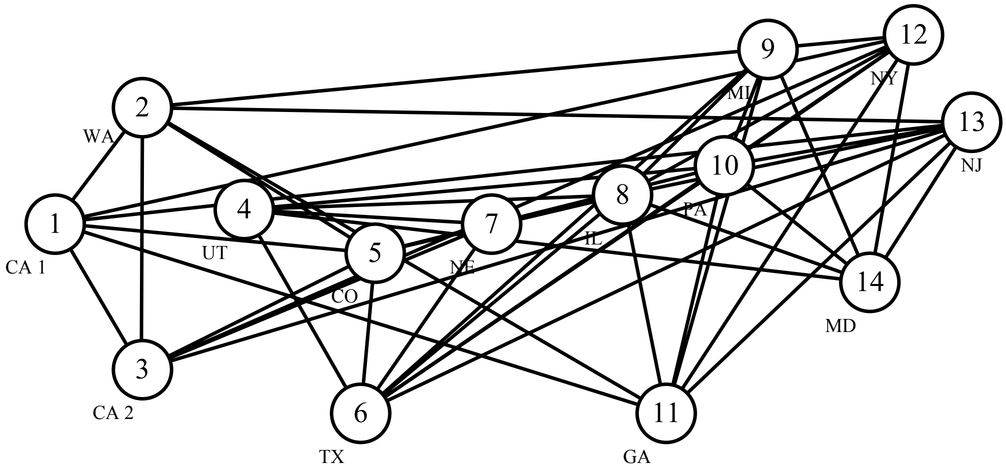


Figure 4.2: The 14-node, 46-link overlay network

the network had only two layers – IP and WDM. Similarly, $\widetilde{H_2^3}$ is obtained from the two layers 3 and 2 – overlay and IP. Therefore, CSM, M1, M2, and M3 are simply combinations of the four possible mapping matrices H_1^2, H_2^3, $\widetilde{H_1^2}$, and $\widetilde{H_2^3}$.

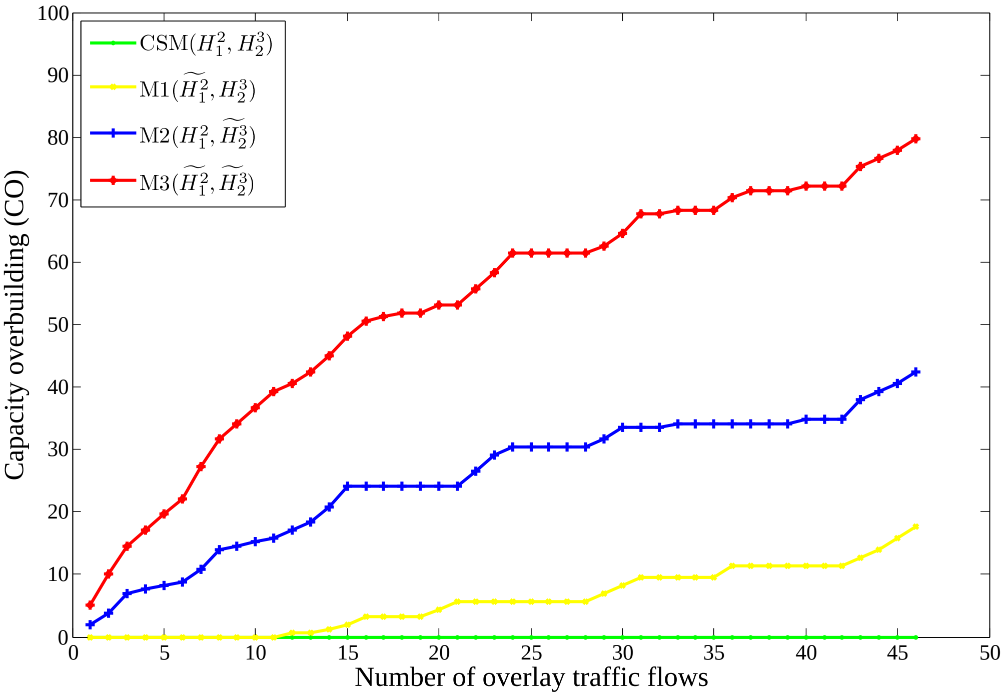


Figure 4.3: Capacity overbuilding of the overlay network

4.4.1 Metric 1: Capacity Overbuilding

Capacity overbuilding (CO), the percentage of the excess capacity requirement of the overlay traffic due to backhaul routing, is here used to evaluate the efficiency of the proposed CSM. The excess capacity occurs at the WDM layer whenever WDM links are unnecessarily used by overlay primary path, overlay backup path, or both. It should also be noted that CO is not the same as resource overbuilding (RO) [52], which refers to a capacity ratio of backup paths to primary paths.

Figure 4.3 shows CO under various network loads that our proposed CSM can effectively eliminate the redundant capacity reservation. This is because it takes into account all three layers together by addressing the problem of backhaul routing. In here, the CSM has best CO partly because the designs of the two mappings – Layers 3 and 2, and Layers 2 and 1 – in all M1, M2, and M3 are carried out independently.

In addition, both M1 and M2 have better CO than M3 because the alteration, discussed previously, has shown little change from the original mappings. This is partly due to the two-layer topology that has a limit on the number of mapping choices that a top-layer network has to be survivable under a single link failure at the lower layer. This limitation also happens in any two-layer network, but in the case of M1 versus M2 the situation is different. Their COs are dependent on topology, mapping, and order of flows. In this particular network M2 is outperformed by M1, in part for the two mapping matrices of the three-layer network and partly because full-mesh characteristics in Layer 2 (IP) network is said to provide much deviation in $\widetilde{H_2^3}$ from H_2^3 in terms of element-wise comparison of the two matrices. The COs of the four schemes become increasingly different under a higher number of overlay traffic flows because backhaul routes occur more often.

4.4.2 Metric 2: Flow Overrouting

Defined as the ratio of the number of overlay traffic flows that are routed on one or more backhaul links at the WDM layer to the total number of overlay flows, flow overrouting (FO) or fraction of backhaul flows is used to show the number of overlay flows that are affected by backhaul routing. In a manner similar to CO, Figure 4.4 shows that CSM can solve the problem while some flows in M1, M2, or M3 still suffer from it. In all M's, the flat FO at the beginning is understood to coincide with the flows ordering in our studied network; however, the average number of the affected flows is steady as the number of overlay traffic flows is increasing. In particular when the number of flows is 11 or fewer, M1 has no flow over routed, *i.e.,* 0% FO. This corresponds to its CO in Figure 4.3 where M1 also has no capacity overbuilt when there are 11 flows or fewer. In contrast to M1, M2 has a 100% FO when there are 15 flows or fewer. This is because either or both of the primary and backup paths are overrouted. This observation of the FO again corresponds to the CO in Figure 4.3 but with a different degree when the number of flows varies between 1 to 15.

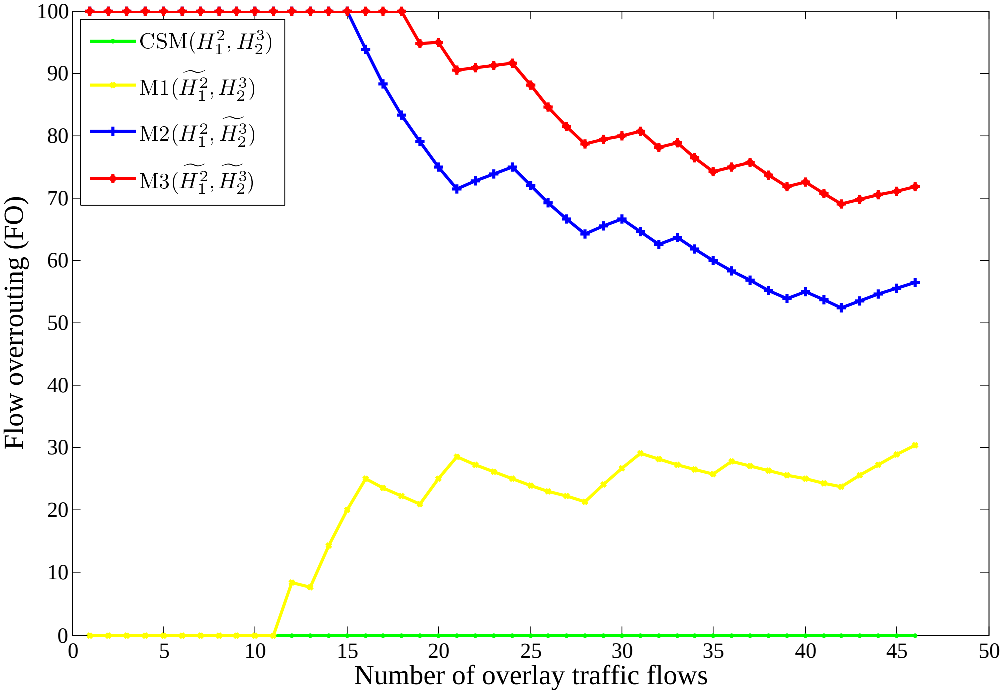


Figure 4.4: Flow overrouting of the overlay network

4.4.3 Metric 3: Link Overusing

Link overusing (LO) is a metric to show unnecessary use of WDM links. LO is defined as the ratio of backhaul routing at the WDM layer that affect overlay traffic flows to the total number of WDM links that are used by the overlay. This can be regarded as FO from the viewpoint of the WDM layer, instead of the overlay. In the cases of M2 and M3, it is shown in Figure 4.4 that at the beginning, *e.g.,* fewer than 10 flows, every overlay flow is affected by backhaul routing; but when we look at LO, Figure 4.5 shows that only some of the WDM links are unnecessarily used more than once. This is the same backhaul problem discussed earlier and shown in Figure 3.1 that capacity, or wavelength, saving in WDM links can be accomplished by letting an overlay flow use only some WDM links rather than these links and some other links more than once. A similar argument can also be applied to M1 with an interesting case at the beginning when the number of flows is 11 or fewer. We witness

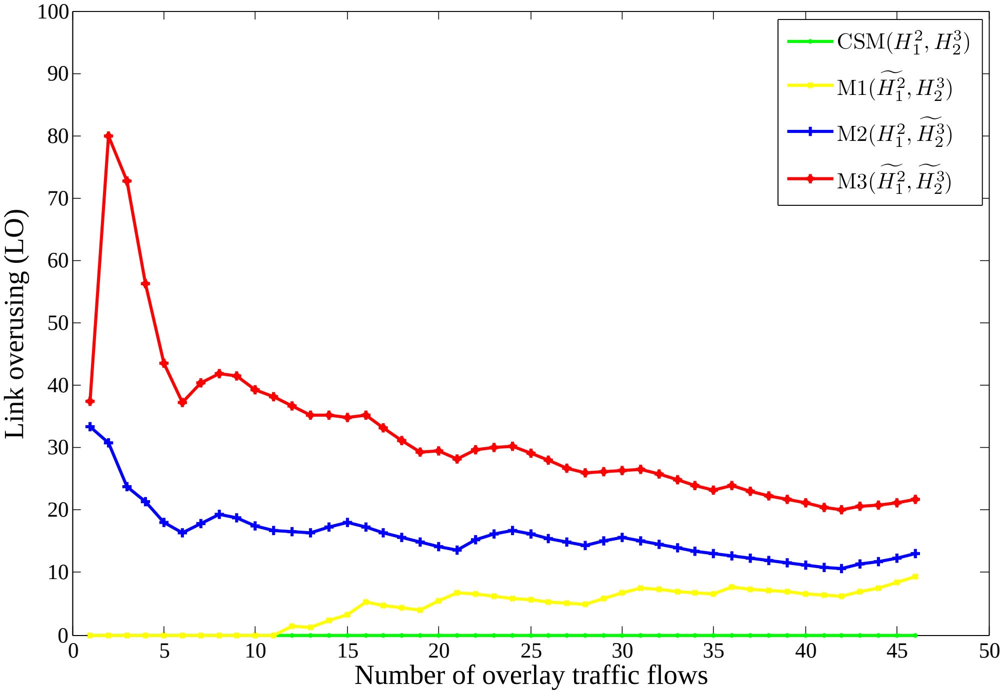


Figure 4.5: Link overusing of the overlay network

a unanimous correspondence among the LO, FO, and CO here in the sample network that backhaul routing does not occur for the first 11 flows in the case of M1; therefore, no capacity is overbuilt.

4.5 CASE STUDY: RING OVERLAY NETWORK

In this section, we evaluate the extent of the backhaul problem and the efficiency of CSM on a ring-type overlay. To evaluate the performance of CSM, we consider three-node ring overlay networks, where each overlay is chosen from $\binom{14}{3} = 364$ possible rings. An overlay is constructed on top of the IP-over-WDM network similar to the one considered in Section 4.4, which is based the network in Figure 4.1. Only overlays that do not see backhaul happens when CSM is deployed are considered; the number of overlays that corresponds to

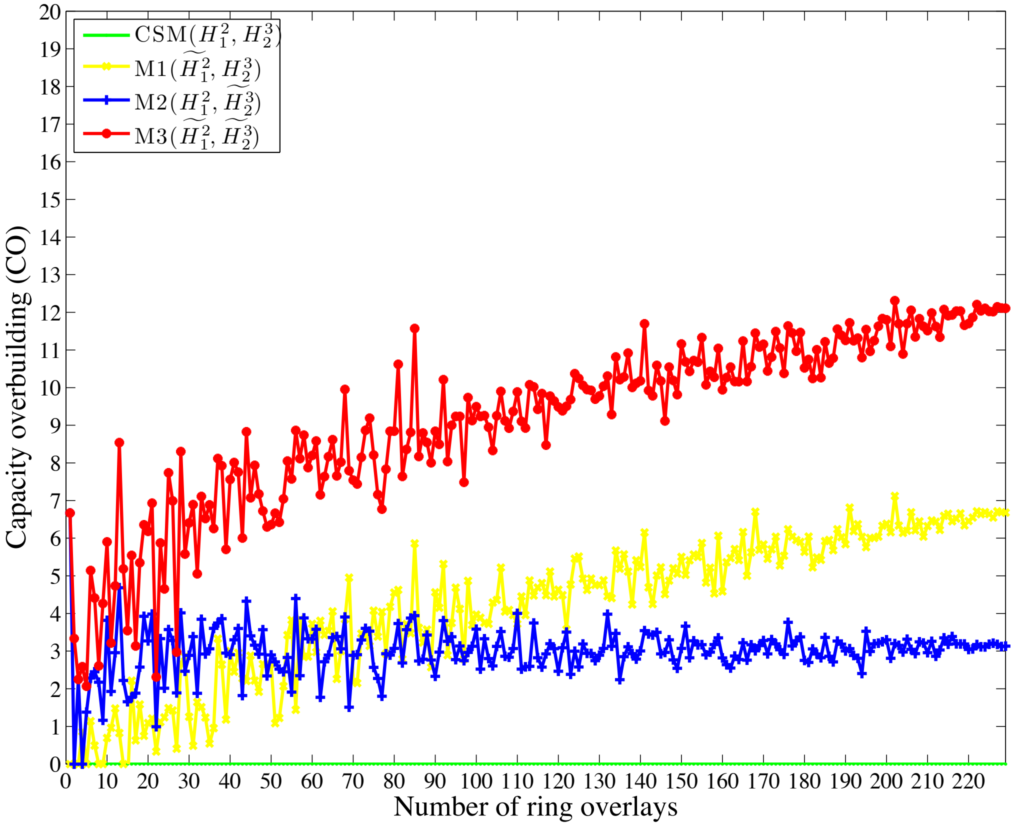


Figure 4.6: Capacity overbuilding of the ring overlays

this condition is 229.

As previously defined, the three metrics: CO, FO, and LO, are used to evaluate the performance of CSM against the three other mappings. In addition, resource overbuilding (RO) or redundancy, which is a ratio of backup path capacity to the primary path capacity, is also considered. Here the simulation is run 10 times and overlays are randomly chosen each time. We also observe that all plots tend to be stable, almost no fluctuation, beyond this number of simulation runs.

Figure 4.6 shows that in CSM, zero CO results. This corresponds to the previous findings and analysis. The remaining three mappings show some variation because of different network settings; however, the trends still continue. We observe in this figure that M3 performs worst most of the time, and M1 and M2 are competing during the first half of the maximum

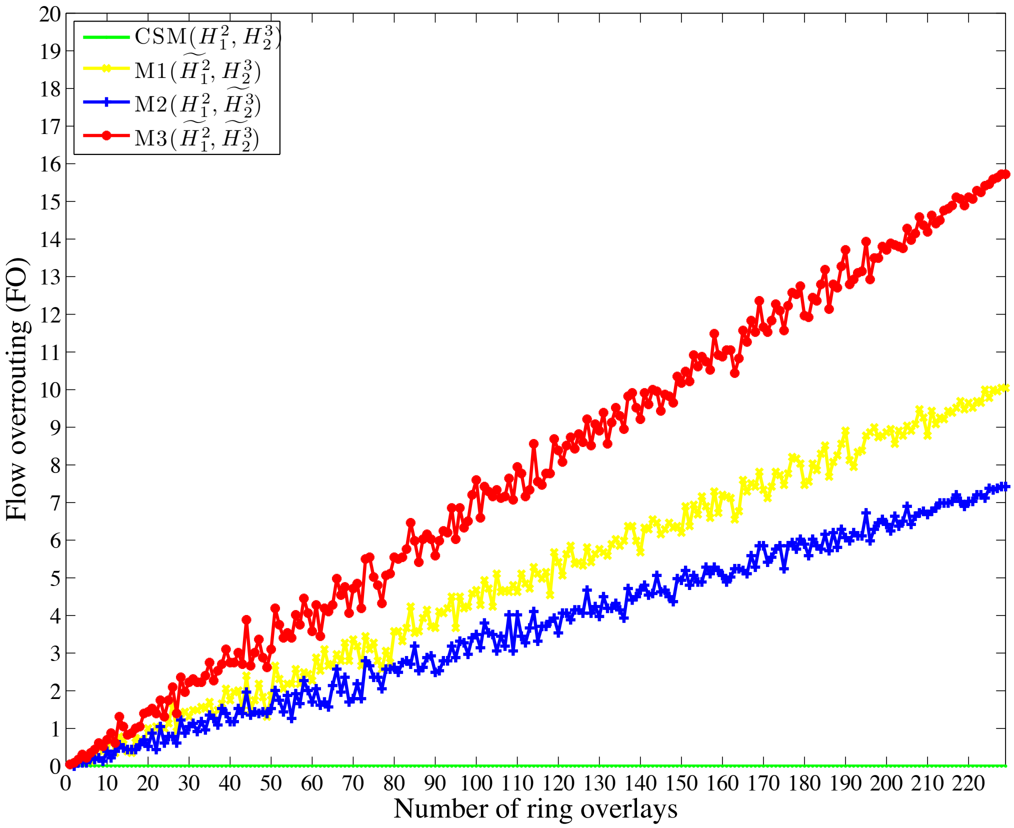


Figure 4.7: Flow overrouting of the ring overlays

number of rings whereas M1 tends to outperform towards the end.

The results are more predictable in the cases of FO and LO, which are shown in Figure 4.7 and Figure 4.8, respectively. Having flat FO and LO at zero, CSM behaves as expected. For the remaining three other mappings, both FO and LO increase as the number of overlay rings grow. The difference is more noticable in M3 when both of the two mapping matrices are altered. Comparing M1 and M2, M2 mostly performs better. The M2 performance is dependent on the two mapping matrices, which might happen to better suit the ring overlays than M1.

In addition, we also investigate on the performance of RO in all four mapping schemes. In Figure 4.9, we show that RO decreases as the number of ring overlays increases. This is predictable because spare capacity that is already dimensioned is likely to as well support

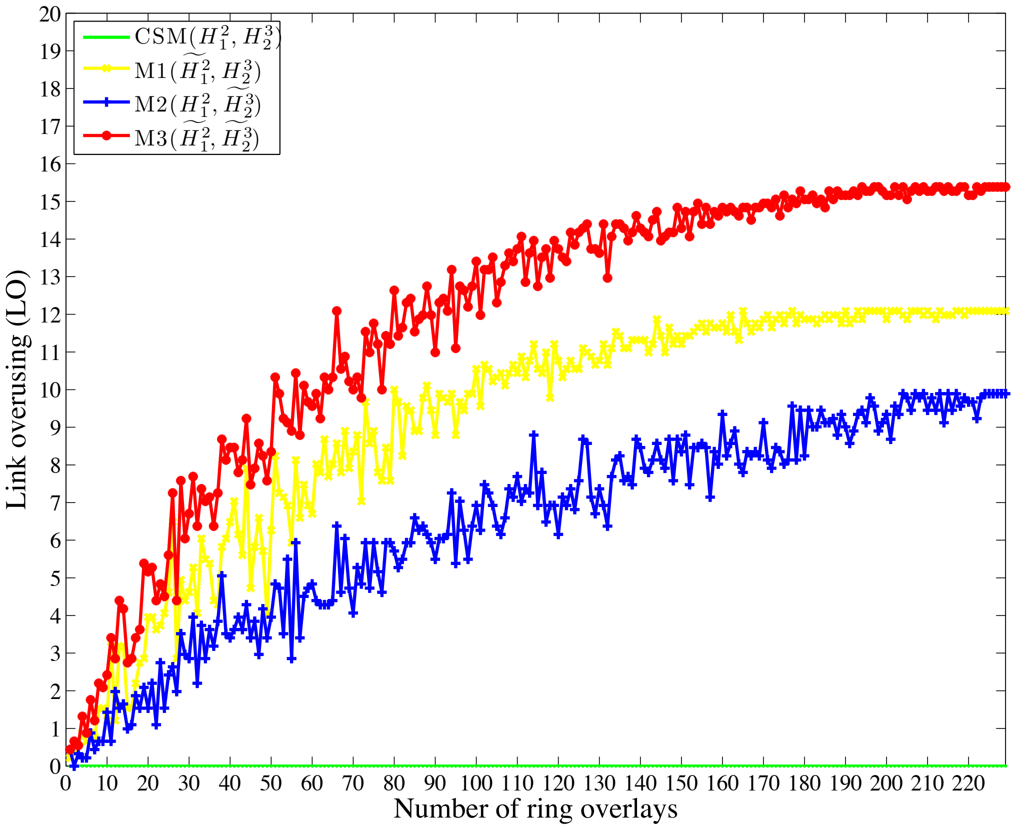


Figure 4.8: Link overusing of the ring overlays

the capacity need of other flows. It is also noteworthy that RO is always greater than unity here. This could be because each primary path always uses one link at the overlay layer while a backup path consistently routes on two links. As a result, the backup paths are more likely to require much more capacity when a ratio is taken and even when the capacity is shareable.

4.6 SUMMARY

This chapter presents the concept of crosslayer survivable mapping, which considers link mapping across all layers, introduced in this chapter is applicable to all multilayer net-

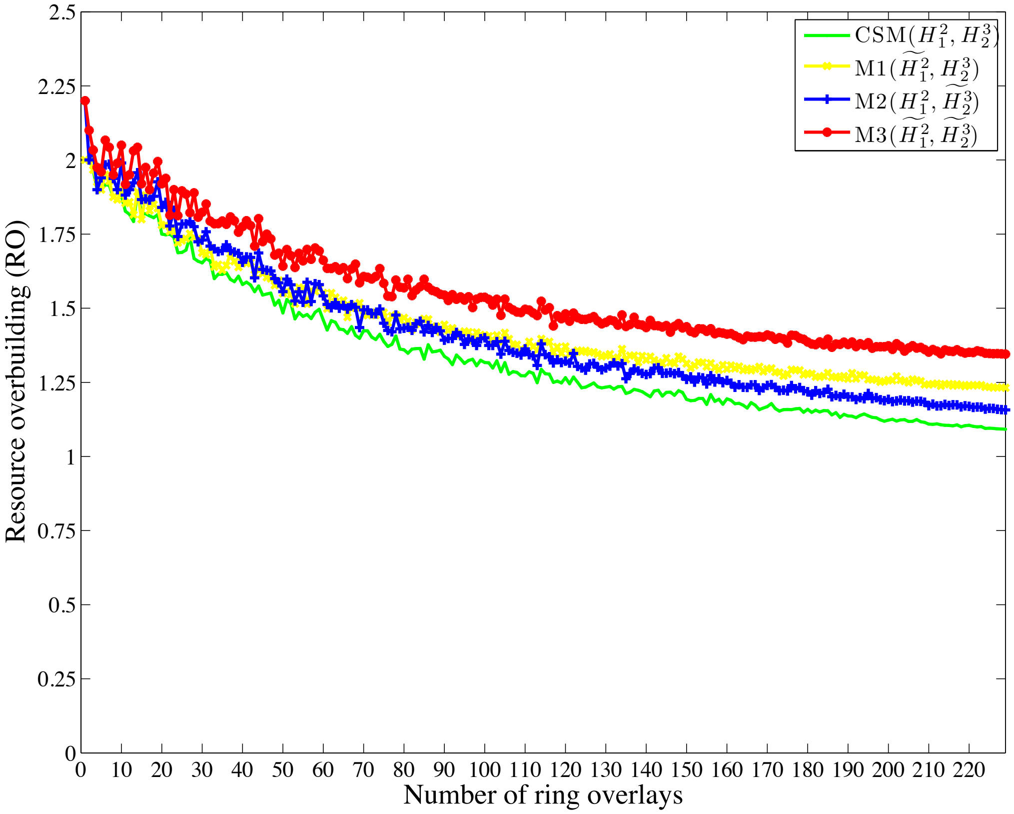


Figure 4.9: Resource overbuilding of the ring overlays

works and is highly useful and particularly necessary for a network of three layers or more. Numerical results confirm that our design approach can overcome the inefficiency of capacity allocation and at the same time can also guarantee an overlay that it be survivable under any single failure at the two layers below as compared to existing approaches of designing two mappings independently. Other mapping schemes can also be analyzed using the models presented in this chapter to compare availability, optical resource, and so forth.

5.0 DIFFERENTIATED CROSSLAYER NETWORK MAPPING

5.1 INTRODUCTION

Layered architecture constitutes one of the most fundamental structures of communications network design. This layering approach sees modern networks as being composed of overlay, IP, and WDM network layers with an emphasis on service, data forwarding, and bandwidth, respectively. With increasing needs, overlays provide a layer for the network which can take a role of processing and passing data between end-systems that arise to serve a range of diverse purposes and needs [41], [53], [54].

One of the principal areas of concern in overlay communications is service disruption. This, in part, occurs as a result of communications outages after failures or attacks. Recognizing common threats from electromagnetic pulse attacks (EMP) [55], earthquakes, or floods, to dragging anchors or shared failure risks, network infrastructure is a critical part of vulnerability mitigation to these threats. One way to avoid such a failure or human-based attack is to hide parts of the network information from unclassified or certain customers, *e.g.,* customers could see a network with different node degrees. Customers can be ranked based on their relationship with the network provider upon an established contract or procurement record. Alternatively, network information can be more open in some situations: Consider an ideal business model, in which a business is solely motivated by revenue generation. It is also important to recognize that in some cases, network information can be more open. In this case, service differentiation could be offered to customers according to their willingness to pay the price for a particular service. For example, customers with a limited budget might be more willing to tolerate a higher level of service disruption.

To meet these challenges, a number of studies have recognized the impact of underlay topology on the overlay topology [40], [56], [57], [58], [59], [60]. However, little attention has been paid to the problem of duplicate physical links that are shared by a virtual link [40], [58] in a multilayer network architecture.

In this chapter, we consider the problem of designing a differentiated communications network that is both efficient and survivable in the explicit context of overlay-IP-WDM. We consider the problem of link and flow path mapping in the entire three-layer network that avoids link duplication or backhaul at the WDM layer and at the same time be survivable under a single-link failure. We show that the introduction of *forbidden link matrix* is sufficient for differentiated network mapping and yet the proposed matrix is peculiar to the problem we are exploring.

The remainder of this chapter is organized as follows: In Section 5.2, we discuss prior related work as background for our discussion in this chapter. Then we describe the problem and formulate it as an integer linear programming (ILP) in Section 5.3. Next in Section 5.4, we present our analysis and provide some numerical results. Finally, we summarize the chapter in Section 5.5.

5.2 BACKGROUND

Nearly all existing literature focuses on topology use from service resilience or traffic engineering points of view. This section aims at providing background on the work from each of the two sub-layers in the layered network architecture.

5.2.1 Use of Topology Knowledge in Overlay Networks

At the overlay network layer, some initial effort has been made to examine the impact of underlying topology on the failure recovery ratio of overlay services [61]; unfortunately, how the link mapping was done is not fully explained in this work. A number of topology constructions of the overlay over a single physical network have been investigated; unfortunately, how the link mapping was done is not fully explained in this work. An effort that aims at building a generic overlay is SON [62]. A service overlay network (SON) can directly purchase bandwidth with a service guarantee from IP layer Internet service providers (ISPs) to build a logical end-to-end service overlay; end users can buy the service with some value added as provided by the SON. On one hand, by acting as a service broker, SON provides service guarantees on a much finer granularity to end customers, *i.e.,* per flow, than an ISP which is primarily concerned with provisioning bandwidth management on a per-SON basis. However, on the other hand, this construction requires two contracts: Users-SON and SON-ISPs. In addition, failure guarantee is not considered a part of the service guarantee in SON. Another similar effort that aims at offering Internet QoS using overlays is OverQoS [63]. OverQoS uses a controlled loss virtual link (CLVL) to provide a bound on the loss rate experienced by an aggregate traffic flow. This service option can be provided to customers without penalizing the existing best-effort background traffic. However, this work does not consider a subscription of dedicated bandwidth or failure guarantee as a part of QoS. QoSMap [46] aims at increasing resiliency against QoS failures while meeting QoS requirements of an overlay application. A backup path is provided for the resiliency and the considered QoS is based on the number of hops, *e.g.,* latency, loss rate. However, only heuristic solutions are sought. Another work aimed at provisioning end-to-end QoS across multiple autonomous systems (ASes) is presented in [60]. Here the authors formulate a network topology design problem for a service overlay network with bandwidth guarantees as a variant of the assignment problem. By connecting each end system to a provider node through an ISP at minimum cost, the problem can be divided into two sub-problems: end system-provider node and provider node-provider node. They show that, in a special case, this problem can be simplified and, thus is tractable. The same setting is further examined in a number of cases in [64]. Yet, an argument of offering QoS at the overlay is interestingly made in [65].

A key challenge in constructing a resilient overlay is to provide good routing services while maintaining QoS when failures happen. A heuristic-based is presented in [58]. Here the authors proposes a construction of a distributed overlay service using only passive measurements and static topology information of the underlay from PlanetLab [66]. A variant of the link-pruning algorithm is investigated on a sparse overlay, *e.g.,* a few hundred nodes.

Like RON, this approach may not scale well in a larger network. This is because the number of overlay links in the routing mesh is a limiting factor in the scalability of the overlay as it increases a chance of finding path duplication in the underlay network.

In fact, in order to better support overlay routing, some connectivity information at the underlay, *e.g.,* the IP routing table, needs to be exported to the overlay layer [57]. The benefit of sharing this information has also been discussed in [56], which explores several overlay constructions over a given IP underlay. This work also notes the correlation of failures between IP-layer links and overlay links, however, without much further insight. Reference [59] introduces some virtual network topology control mechanisms to overcome instability due to dynamic traffic demand. They attempt to reduce the number of virtual network topology reconfigurations, which occur when overlay traffic changes or switches its routes, and updates in available bandwidth of the underlay WDM layer occur.

5.2.2 Use of Topology Knowledge in IP-over-WDM Networks

A number of network models offering service differentiation have been discussed lately [67], [68]; however, only a handful of them recognize the effects of the interaction within a layered network. Considering traffic survivability, multi-topology routing (MTR) divides a network into multiple logical topologies and allows one or more of them for use as a backup topology when nodes in the primary topology fail to communicate to one another due to either node failure or link failure or both. Here the situation is analogous to the traditional way in which a backup path is deployed to protect each primary path. Therefore, it is conceivable that MTR would require far fewer topology images to be maintained than a backup path scheme. This is because each whole topology is maintained rather than individual paths; however, more spare capacity would be required or reserved. Reference [69] conducted experiments on two topologies of real networks and found that only two logical topologies are adequate to ensure single-link failure survivability, thereby requiring roughly only twice the required capacity of that of a path protection scheme. In addition, the logical topologies may share some links or any subset of physical topology with one another. When differentiation is concerned, each of the classes could be provided with a logical topology obtained from MTR. Together with a number of logical topologies, shared risk link groups (SRLGs), or constraints on the use of physical links, with link weights can also be taken to create a set of backup topologies when links belonging to the same group should not be grouped to the same logical topology [70]. Alternatively, imposing some constraints on the use of physical links, *e.g.,* same failure risk in SRLGs, or SRLG-disjoint, can also provide a number of routing topologies for different service classes. Work on multiple-link failure is presented in [71], [72]. However, it should be noted that although MTR provides some sort of routing isolation, it is not equivalent to VPN.

There is work that aims at providing frameworks for resilient services [68], [73]; for example, the Quality of Resilience (QoR) concept in [73]. This work, although mostly qualitative, sheds light on the need for the classification. Quantitatively, little work has been done, and the quantitative work that does exist has focused on operational aspects like availability or downtime rather than network differentiation point of view.

5.3 NETWORK MODEL AND PROBLEM DESCRIPTION

In this section, we present a technical description of the considered layered network and a mathematical model. The forbidden link matrix concept to enable levels of differentiation is also discussed. The notation used in this chapter is listed as follows:

l	Network layer index, where $l = 1, 2, 3$ refers successively to higher layers
r	Multileveled service class index
$\mathcal{N}^l$	Layer l node set
$\mathcal{L}^l$	Layer l link set
$\mathcal{F}_r^l$	Layer l flow vector of level r
M_r^l	Diagonal matrix of layer l flow f_r^l bandwidth requirements with dimension $\|\mathcal{F}_r^l\| \times \|\mathcal{F}_r^l\|$
B^l	Layer l incidence matrix with dimension $\|\mathcal{N}^l\| \times \|\mathcal{L}^l\|$
D_r^l	Layer l flow-node incidence matrix of level r with dimension $\|F^l\| \times \|\mathcal{N}^l\|$
P_r^l	Layer l primary path matrix of level r with dimension $\|\mathcal{F}_r^l\| \times \|\mathcal{L}^l\|$

Q^l_r	Layer l backup path matrix of level r with dimension $\vert\mathcal{F}^l_r\vert \times \vert\mathcal{L}^l\vert$
W^l_r	Layer l primary-path link capacity vector of level r with dimension $\vert\mathcal{L}^l\vert \times 1$
G^l_r	Layer l spare capacity matrix of level r with dimension $\vert\mathcal{L}^l\vert \times \vert\mathcal{L}^l\vert$
S^l_r	Layer l backup-path link capacity vector of level r with dimension $\vert\mathcal{L}^l\vert \times 1$
I	Identity matrix
H^j_i	Survivable link mapping matrix between layers j and i ($H^1_0 = I$)
$\texttt{FLM}(r)$	(diagonal) Forbidden link matrix of level r with dimension $\vert\mathcal{L}^1\vert \times \vert\mathcal{L}^1\vert$
$\mathbf{e}$	The column vector of all ones
$(.)_c$	The sucscript c stands for crosslayer by means of mapping or cost of the lower-layer link use

5.3.1 Forbidden Link Matrix

Before delving into details, we illustrate some scenarios when a forbidden link matrix affects the design. Figure 5.1 shows a three-layer network overlaid on the U.S. topology. There are a number of overlay link mapping across layers which are survivable under a single-link failure at the bottom WDM layer. However, this number is likely to be fewer if some WDM links cannot be used at all. In some cases, the overlay may also lack survivability. For example, when links originated from node 12, which might be situated near a nuclear plant, are unknown to a customer and forbidden for use, the overlay is not survivable but it is still connected. Another example is when a set of links are forbidden or a large-scale attack, which its design may be dependent on geographical location of the network. In some cases, node mapping, which is not directly considered in this chapter, may be needed.

We develop a topology-related mask in a matrix form that can be integrated into link mapping between and among network layers when multiple differentiation levels are required. In order to incorporate this proposed matrix into a layered network for service overlay support, we need to define two link mapping matrices: one for overlay-over-IP and one for IP-over-WDM networks. The link mapping matrix of layer i onto layer j is specified by an $(|\mathcal{L}^i|\text{x}|\mathcal{L}^j|)$-matrix $H^i_j = (h_{ij})$, where $h_{ij} = 1$ if and only if link $j \in \mathcal{L}^j$ is used by link $i \in \mathcal{L}^i$. However, we also must consider the backhaul problem presented earlier in this dissertation in which a routing loop may occur in a network of three layers or more (*see* Chapter 4).

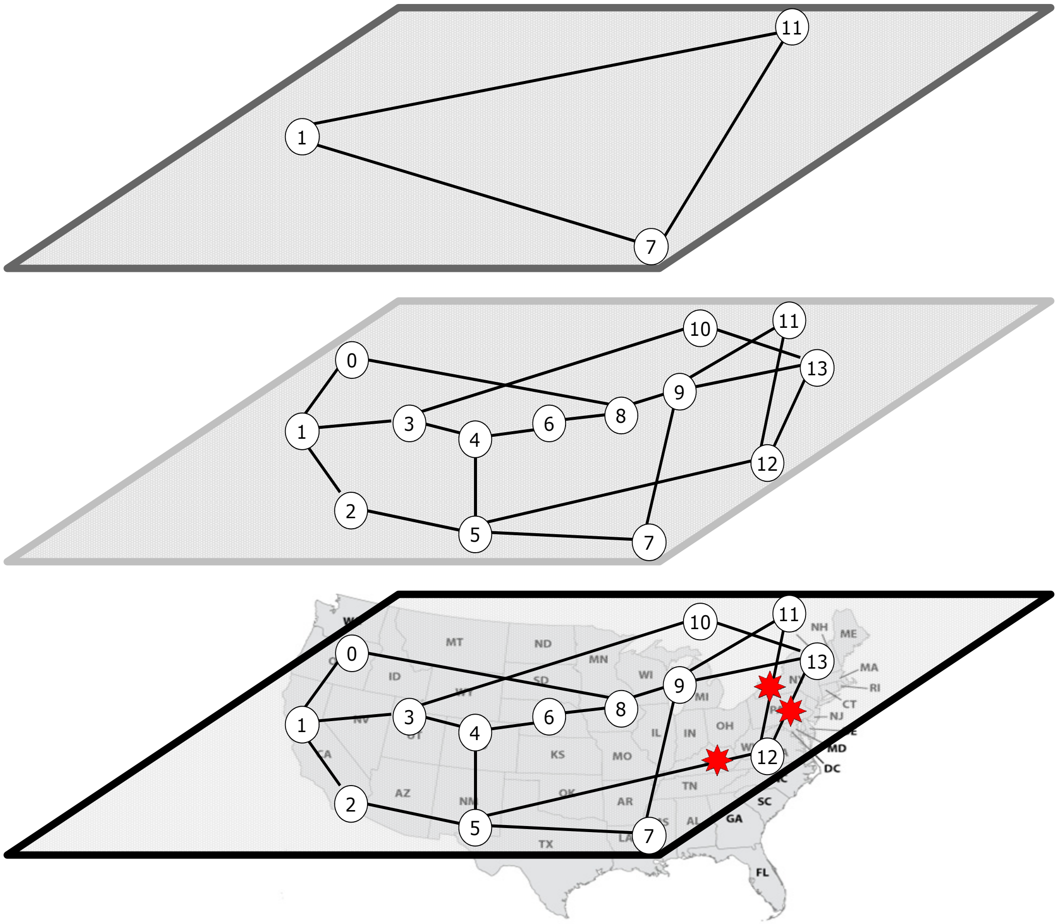
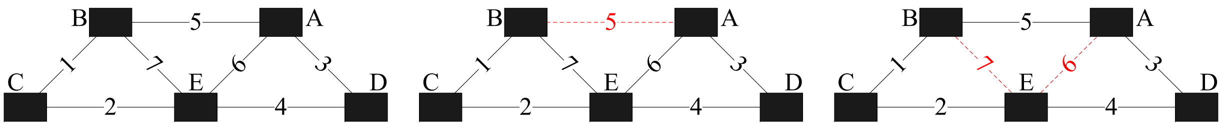


Figure 5.1: A use case example of forbidden link matrix in a layered network

Now let `FLM`($\mathbf{r}$) be the diagonal forbidden link matrix of a given level r. The diagonal entry (i, i) is one if and only if link i is allowed for flow routing and zero when it is forbidden, *i.e.,* taboo. In addition, it should also be noted that in a path-based protection, where the whole end-to-end path is calculated, backhaul routing could still occur and the link mapping matrices for survivability under any single-link failure can be obtained from the condition given in [74]. This, however, makes our problem one of the $\mathcal{NP}$-hard types.

We illustrate the use of our forbidden link matrix in Figures 5.2(a)-(c), which relates to the WDM network layer in Figure 3.2 given earlier in Chapter 3. Here we consider offering three differentiation levels, *i.e.,* $r = 1, 2, 3$, when no link is forbidden, link 5 is forbidden, and



(a) $r = 1$ (b) $r = 2$ (c) $r = 3$

$$\begin{array}{c|ccccccc} & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\ \hline 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 2 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 3 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 4 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 5 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\ 6 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{array}$$

(d) $r = 1$

$$\begin{array}{c|ccccccc} & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\ \hline 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 2 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 3 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 4 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 5 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\ 6 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \end{array}$$

(e) $r = 2$

$$\begin{array}{c|ccccccc} & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\ \hline 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 2 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 3 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 4 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 5 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 6 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{array}$$

(f) $r = 3$

Figure 5.2: Network and link mapping matrix H_1^2 of multileveled service class r

links 6 and 7 are forbidden or hidden from use, respectively. Link indices for the three network layers are given as shown in these figures and Figure 3.2, where those of the IP network are equivalent to the overlay. The corresponding forbidden link matrices and the link mapping matrices can be obtained as follows: $\texttt{FLM}(1)$ is equivalent to $I_{7\times7}$, $\texttt{FLM}(2) = \texttt{FLM}(1)$ except $\texttt{FLM}(2)(5,5) = 0$, and $\texttt{FLM}(3) = \texttt{FLM}(1)$ except $\texttt{FLM}(3)(6,6)$ and $\texttt{FLM}(3)(7,7)$ =0. In all levels, $H_2^3 = I_{6\times6}$; in each level, H_1^2 is given in Figures 5.2(d)-(f). Note in all levels that the overlay services are survivable under a single-link WDM failure and no backhaul occurs in the link mapping. For example, row 1 in Figure 5.2(d) indicates that two WDM links 2 and 4 are used by IP link 1.

Given the link mapping matrices and the forbidden link matrix, a necessary and sufficient condition for link mapping with no backhaul for level r is given next.

Lemma 5.1 (Differentiated Crosslayer Mapping)**.** *No backhaul mapping occurs in a three-layer network of service class r if and only if the two link mapping matrices satisfy the following condition ($C_{\mathcal{L}}^d$): $H_2^3 H_1^2 \texttt{FLM}(\texttt{r}) \preceq 1$, where the $\preceq$ symbol denotes element-wise comparison.*

Proof. First, consider a special case when $\texttt{FLM}(\texttt{r})$ is equivalent to the identity matrix. Given two survivable mapping matrices, H_2^3 and H_1^2, in a three-layer network, it can follow that an element (i, j) of the matrix product $H_2^3 H_1^2$ is nonzero if and only if a layer 1 link j is used by a layer 3 link i. This element determines the number of times layer 1 link j is used by layer 3 link i. In backhaul-free mapping there should be exactly one such use by any link in Layer 3; therefore, the condition $H_2^3 H_1^2 \texttt{FLM}(\mathtt{r}) \preceq 1$ is required. Now, it remains to show that this lemma also holds in a general case when $\texttt{FLM}(\mathtt{r})$ is not necessarily equivalent to the identity matrix. Because $\texttt{FLM}(\mathtt{r})$ is a $(0, 1)$-diagonal matrix, it is easy to see that $H_2^3 H_1^2 I \preceq 1$ implies $H_2^3 H_1^2 \texttt{FLM}(\mathtt{r}) \preceq 1$. □

Now the following theorem says that the differentiated crosslayer mapping can also be made survivable by adding an additional condition.

Theorem 5.1 (Differentiated Crosslayer Survivable Mapping)**.** *A mapping is survivable and is backhaul-free in a layered network if and only if the following conditions hold:*

(i) for each link mapping, no single lower layer link is shared by all upper layer links belonging to a cut-set of the upper layer topology;

(ii) the corresponding link mapping satisfies the condition $C_{\mathcal{L}}^d$ of Lemma 5.1.

Proof. This follows immediately from Theorem 4.1 in Chapter 4 and Lemma 5.1. □

5.3.2 Service Overlay Network

We model a service overlay network (SON) as an uncapacitated network and denote it by $G = (\mathcal{N}^l, \mathcal{L}^l)$, where $\mathcal{N}^l$ is a set of nodes and $\mathcal{L}^l$ is a set of links. In addition, let $l = 3$ here for SON to recognize its presence at a layer 3 in our network. Here each link is equivalent to two unidirectional links with equal capacity and the same failure state, *i.e.,* available or failed, in each link. Given all this information, the incidence matrix B^l [75] of a network graph G can then be obtained.

Traffic in a SON can be modeled as follows: Let $\mathcal{F}_r^l = (f_r^l)$ be a vector of traffic flows of multileveled service class r in SON. As an example, $f_r^l(n)$ represents the flow index n. When associated with the network, each traffic flow can further be put in a flow-node incidence matrix D_r^l, which provides that for each row corresponding to $f_r^l(n)$, an element equal to

1 corresponds to a traffic source, -1 corresponds to a traffic sink, and 0 otherwise. Flow bandwidth is non-negative and integral, which can be represented by each diagonal element of a ($|\mathcal{F}_r^l|$,$|\mathcal{F}_r^l|$)-diagonal bandwidth matrix M_r^l.

Using the preceding network and traffic information, survivability under a single-link failure employing a shared backup path protection (SBPP) scheme allowing the capacity of each backup path protecting a primary path to be shared can be obtained. Let P_r^l be the primary path matrix comprising a set of p_{fe}^l, where $p_{fe}^l = 1$ if link e is in the primary path of flow f_r^l and 0 otherwise. Therefore, the primary path matrix has a dimension of $|\mathcal{F}_r^l|$x$|\mathcal{L}^l|$. Similarly, the backup path matrix $Q_r^l = (q_{fe}^l)$ can also be formed. While primary paths alone can be calculated from a shortest path algorithm *e.g.,* Dijkstra's algorithm, mathematical models for both of the primary and the backup paths are given later in this chapter.

As a corollary to Theorem 5.1, we extend it to include traffic constituting a path matrix, or a path-link incidence matrix.

Corollary 5.1. *If T is a path matrix, then it has no backhaul if and only if* $T\prod_{k=1}^{l} H_{k-1}^{k}\,\mathtt{FLM}(\mathtt{r})$ $\preceq 1$*, where r is a multileveled service class index.*

Proof. The order in which the path matrix appears in the condition is important to ensure backhaul-free traffic routing. Lemma 5.1 allows us to extend it to a general case by multiplying a path matrix on the left hand side and when a network of k layers is considered. □

In our case, the matrix T can be a primary or backup path matrix. Throughout this chapter, and in fact the whole dissertation, we consider traffic flows with no backhaul; these include flows of both primary and backup paths. Here, the optimization-based model for the primary paths is presented as follows:

$$\min_{P_r^3} \; {W_r^3}^T \, H_2^3 \, H_1^2 \, \mathtt{FLM}(\mathtt{r})\mathbf{e} \tag{5.1}$$

$$P_r^3 \, {B^3}^T = D_r^3 \tag{5.2}$$

$$W_r^3 = (M_r^3 \, P_r^3)^T \mathbf{e} \tag{5.3}$$

$$P_r^3 : \text{binary matrix} \tag{5.4}$$

$$W_r^3 \in \mathbb{R}^{|\mathcal{L}^3|} \tag{5.5}$$

Objective (5.1) aims at minimizing the total capacity requirement of the primary paths in the network. Constraint (5.2) and constraint (5.3) define the flow conservation constraints and the capacity they need for each traffic flow in a multileveled service class. Equations (5.4) and (5.5) consider variables in the model.

Considering the spare capacity allocation (SCA) problem, in order to find shared backup paths and the capacity they need to ensure that each traffic flow be survivable under a single-link failure, we formulate the problem in a matrix-based formulation as follows:

$$\min_{Q_r^3} {S_r^3}^T \mathbf{e}, \tag{5.6}$$

$$(P_r^3 + Q_r^3) H_2^3 H_1^2 \texttt{FLM}(\texttt{r}) \preceq 1 \tag{5.7}$$

$$Q_r^3 (B^3)^T = D_r^3 \tag{5.8}$$

$$G_r^3 = {Q_r^3}^T M_r^3 P_r^3 H_2^3 H_1^2 \texttt{FLM}(\texttt{r}) \tag{5.9}$$

$$S_r^3 = \text{row-max } \; G_r^3 \tag{5.10}$$

$$Q_r^3 : \text{binary matrix} \tag{5.11}$$

$$S_r^3 \in \mathbb{R}^{|\mathcal{L}^3|} \tag{5.12}$$

Given the overlay traffic in the SON layer, the objective function (5.6) minimizes the total spare capacity requirement at the physical WDM layer. The rest of the model ensures that each backup path is properly calculated. At layer 3, both primary and backup paths are computed at this layer; however, because the overlay network has no knowledge of the underlying layers, they are not necessarily disjoint from the perspective of the WDM layer. Constraint (5.7) guarantees such disjointness at the WDM layer. Constraint (5.8) defines the flow conservation constraint for the backup paths of the overlay traffic in layer 3. The subsequent constraints deal with the spare capacity allocation of the backup paths: Constraint (5.9) calculates the spare capacity needed to ensure that each backup path is routable when its corresponding primary path fails as a result of a link failure at the WDM layer, and Constraint (5.10) determines the amount of capacity units each link needs to reserve by computing the minimum capacity that link needs when any one of the other links may fail. This can be realized by the row-max (.) operation. These elements reflect the amount of capacity needed by their corresponding link in order to protect against a single link failure at the WDM layer. Constraint (5.11) and Constraint (5.12) define variables associated with the preceding set of constraints.

5.3.3 Infrastructure Network

To relate an IP-over-WDM infrastructure network to the SON, we adapt the notation previously defined. However, we use the subscript c in $(.)^2_c$ to indicate a crosslayer mapping for a set of IP backup paths.

In fact, constraints relating to the differentiated crosslayer survivable mapping are the only adjustments we need when considering this infrastructure network. For an IP network when the traffic is protected at the WDM layer, some adjustments to the formulation are needed as follows: In objective (5.1), the product matrix $H^3_2 H^2_1 \texttt{FLM}(\texttt{r})$ is substituted by the product matrix $H^2_1 \texttt{FLM}(\texttt{r})$, in constraints (5.7) and (5.9), the product matrix $H^3_2 H^2_1 \texttt{FLM}(\texttt{r})$ are removed completely; however, some matrices need to be modified as follows:

$$B^2_c = B^2 \tag{5.13}$$

$$D^2_c = [D^2|0] \tag{5.14}$$

$$P^2_c = P^2 H^2_1 \texttt{FLM}(\texttt{r}) \tag{5.15}$$

$$M^2_c = M^2 \tag{5.16}$$

The suggested adjustments realize IP survivability at the WDM layer by mapping all necessary information to the lower layer, thereby recognizing IP-over-WDM as an integrated network. For brevity it is worth giving the optimization-based model for the IP primary paths which can be written as follows:

$$\min_{P^2_r} \; W^{2^T}_r \; H^2_1 \, \texttt{FLM}(\texttt{r})\mathbf{e} \tag{5.17}$$

$$P^2_r \, B^{2^T} = D^2_r \tag{5.18}$$

$$W^2_r = (M^2_r \, P^2_r)^T \mathbf{e} \tag{5.19}$$

$$P^2_r : \text{binary matrix} \tag{5.20}$$

$$W^2_r \in \mathbb{R}^{|\mathcal{L}^2|} \tag{5.21}$$

and the model for the IP backup paths can be written as follows:

$$\min_{Q^2_{c_r}} {S^2_{c_r}}^T \mathbf{e}, \tag{5.22}$$

$$(P^2_{c_r} + Q^2_{c_r}) \preceq 1 \tag{5.23}$$

$$Q^2_{c_r}(B^2_c)^T = D^2_{c_r} \tag{5.24}$$

$$G^2_{c_r} = {Q^2_{c_r}}^T M^2_{c_r} P^2_{c_r} \tag{5.25}$$

$$S^2_{c_r} = \text{row-max } \ G^2_{c_r} \tag{5.26}$$

$$Q^2_{c_r} : \text{binary matrix} \tag{5.27}$$

$$S^2_{c_r} \in \mathbb{R}^{|\mathcal{L}^2|} \tag{5.28}$$

When traffic is present in the WDM layer, objective (5.1), and constraints (5.7) and (5.9) can simply be adjusted by replacing the product matrix $H_2^3 H_1^2 \texttt{FLM}(\texttt{r})$ with the forbidden link matrix $\texttt{FLM}(\texttt{r})$ while the rest stays unchanged. The optimization-based model for the WDM primary paths and the WDM backup paths can be stated as follows:

$$\min_{P^1_r} {W^1_r}^T \ \texttt{FLM}(\texttt{r})\mathbf{e} \tag{5.29}$$

$$P^1_r \, {B^1}^T = D^1_r \tag{5.30}$$

$$W^1_r = (M^1_r \, P^1_r)^T \mathbf{e} \tag{5.31}$$

$$P^1_r : \text{binary matrix} \tag{5.32}$$

$$W^1_r \in \mathbb{R}^{|\mathcal{L}^1|} \tag{5.33}$$

and

$$\min_{Q^1_r} {S^1_r}^T \mathbf{e}, \tag{5.34}$$

$$(P^1_r + Q^1_r)\, \texttt{FLM}(\texttt{r}) \preceq 1 \tag{5.35}$$

$$Q^1_r {B^1}^T = D^1_r \tag{5.36}$$

$$G^1_r = {Q^1_r}^T M^1_r P^1_r \texttt{FLM}(\texttt{r}) \tag{5.37}$$

$$S^1_r = \text{row-max } \ G^1_r \tag{5.38}$$

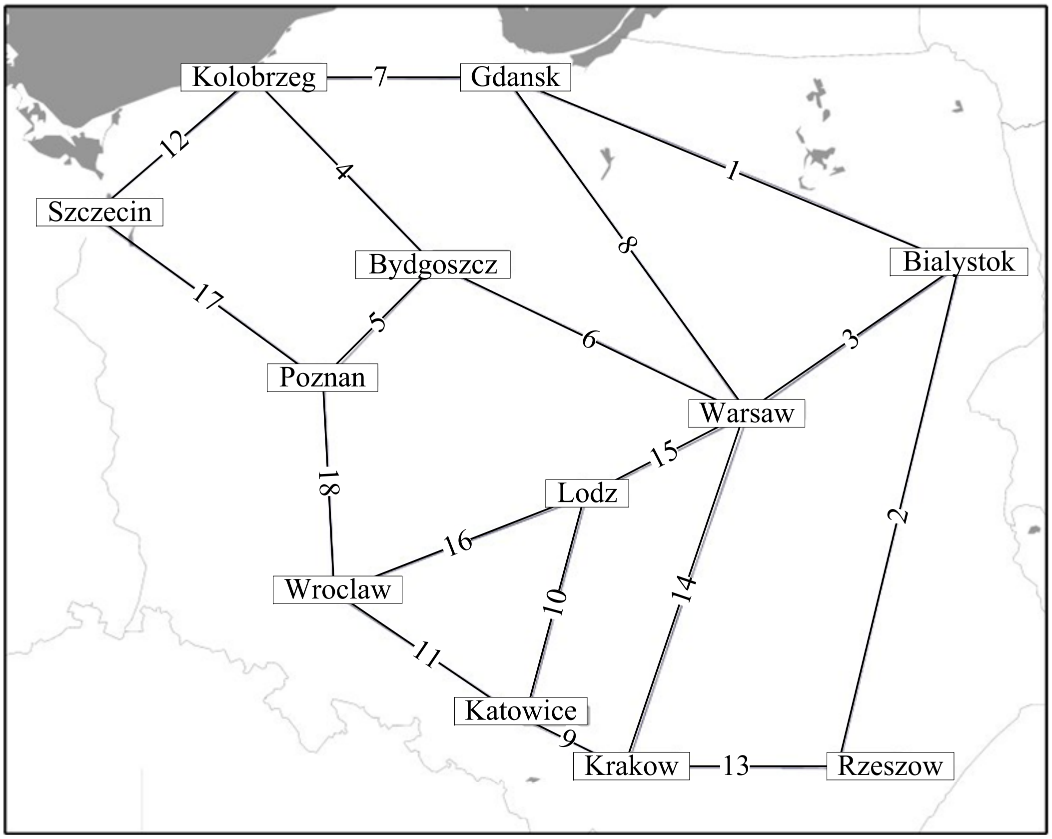


Figure 5.3: The 12-node, 18-link Polska network

$$Q_r^1 : \text{binary matrix} \tag{5.39}$$

$$S_r^1 \in \mathbb{R}^{|\mathcal{L}^1|} \tag{5.40}$$

5.4 NUMERICAL EVALUATION

Benefits and trade-offs of the two survivability strategies are here evaluated using numerical results. Following a standard way of looking at the problem, our first strategy determines a link mapping based on the original topology then computes routes of the two paths based on the forbidden links according to each differentiation level. The second strategy considers obtaining differentiated link mappings followed by computing the overlay routes.

Detailed simulations were conducted on the 12-node, 18-link Polska network [76], as shown in Figure 5.3. Before this network was chosen, the optimization formulation has been verified manually with some small networks against the results obtained from an AMPL/CPLEX solution that it works correctly. Here in the Polska network, the optimum results were obtained from AMPL/CPLEX 9.1 in the order of minutes, which may not be the case in larger networks where an efficient heuristic algorithm might be needed. The physical WDM network was taken as shown; however, our simulated IP network added more links to the network until it became fully meshed. Similarly, an equivalent network to the IP network was constructed for a SON. In addition, no manual intervention took place in the presence of trap paths [77], [78] and the survivable link mapping matrices were obtained by means of the cut-set in [74].

5.4.1 Mapping First Survivability

Link mapping without knowledge of the traffic demands could end up blocking some traffic flows. This may hurt one or both of the primary and backup paths. Consequently the questions of this section are largely those of flow blocking (FB) alone, which we define as the percentage of blocked flows regardless of whether only one or both primary and backup paths are not able to find routes. Figure 5.4 shows the average FB over repetitive runs of random flows for each number of flows in the network ranging from 1 to 43, which is the maximum number of flows that has no backhaul. At most 66 flows may exist. It is also informative to note that the difference appears because we do not modify H after it has been calculated.

We compare three classes here: (1) when the WDM link that supports the highest number of IP flows is forbidden; (2) when the WDM link that supports the lowest number of IP flows is forbidden; and (3) when no WDM links are forbidden. Simulations are run thrice and the results are averaged.

We discover that, as expected, for class (3) when no link is forbidden, zero FB results.

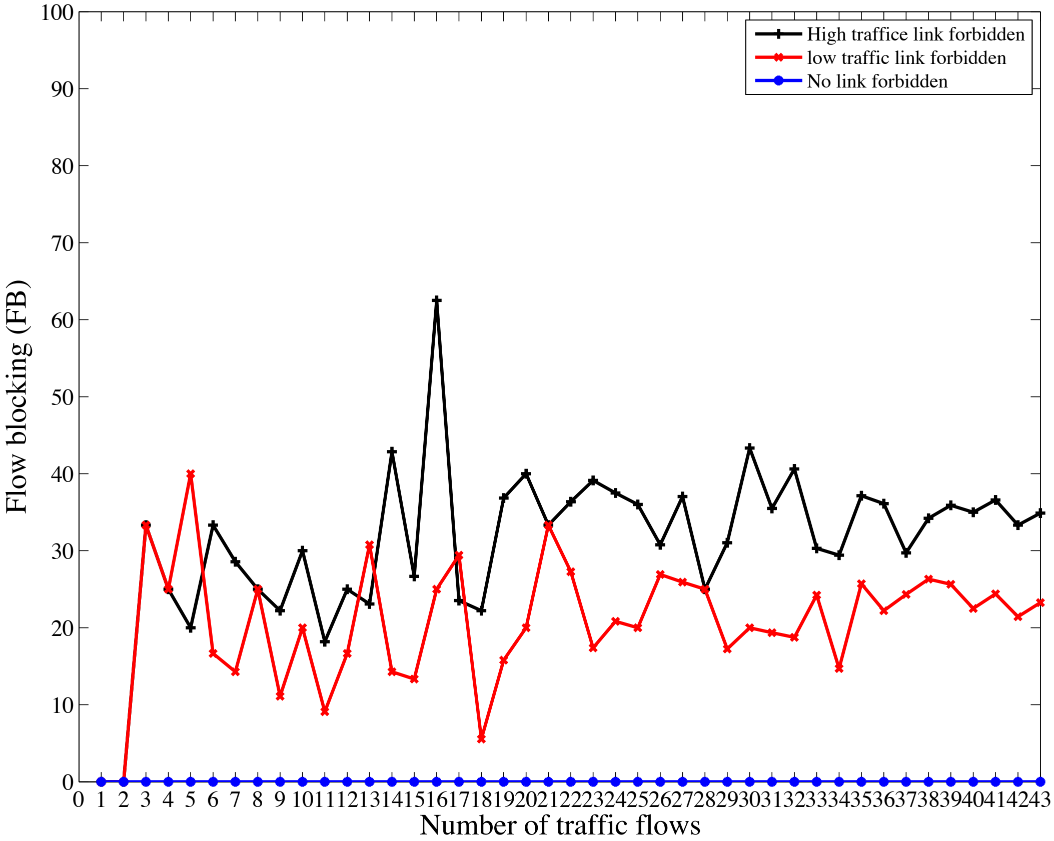


Figure 5.4: Flow blocking in mapping first survivability

No clear-cut difference exists between the other two. But there is a likelihood in these two classes, which also applies to other network topologies, that banning a link with high use, in this case link 7, is likely to block more traffic than banning a link with low use, in this case link 3. Although complicated in settings, this explanation is intuitive and understandable. However, we would also like to point out here that the difference in FBs among a number of forbidden links is not significant as compared to that when no link is forbidden; therefore, we identified a better strategy that involves simply reversing the order of computation.

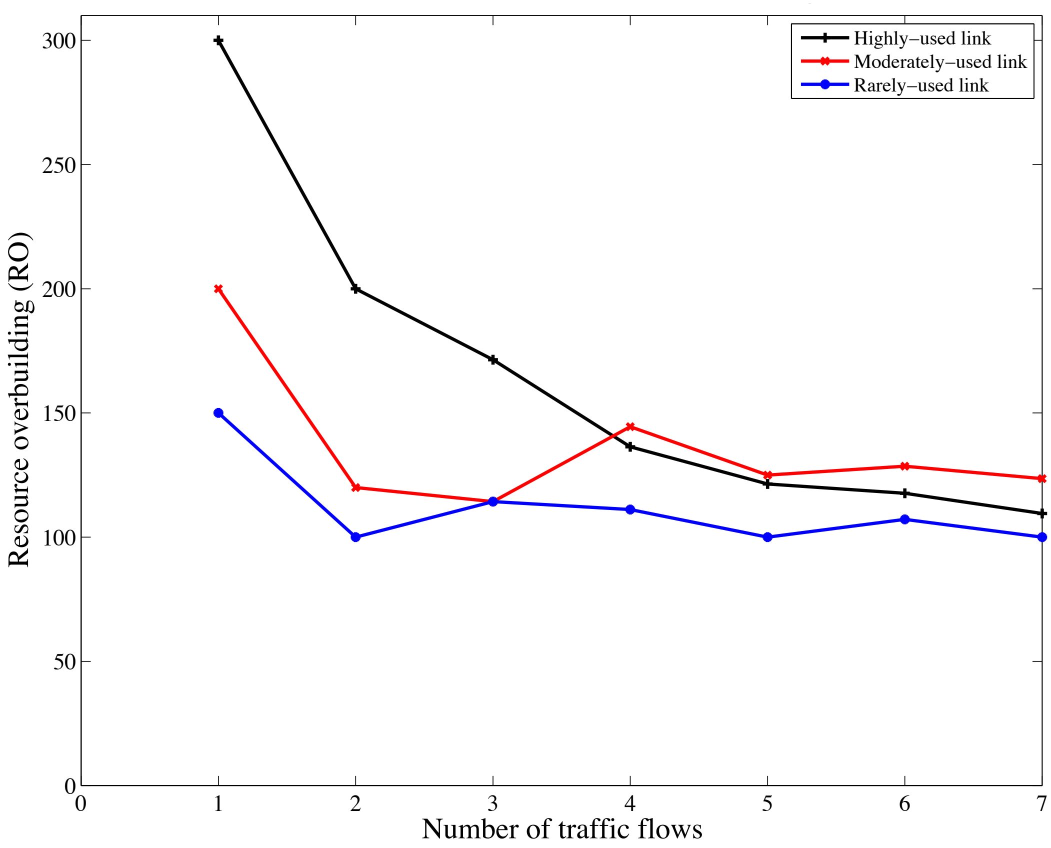


Figure 5.5: Resource overbuilding in routing first survivability

5.4.2 Routing First Survivability

In contrast to mapping first survivability (MFS), routing first survivability (RFS) considers a separate physical WDM topology, *i.e.,* subnetwork, for each forbidden-link multileveled service class.

A quantitative measure of the resource overbuilding (RO), which is defined as the capacity ratio of the backup paths to the primary paths, is captured in Figure 5.5. Here we examine RO in terms of the three levels of differentiation imposed upon and with specific reference to a particular forbidden link. Let us start with a base network where all links are still in place. We then compute a survivable link mapping based on the network information obtained from the base network. We denote the WDM link that has the highest number of IP traffic flows

– primary and backup paths – routed upon it as a "highly-used link". In the same manner, "moderately-used link" and "rarely-used link" can be found. In particular, the indexed links 9, 4, and 3 are classified as highly-, moderately-, and rarely-used links, respectively.

In order to fairly compare the ROs of the three classes, we show an average value over a random order of the same set of flows. We demonstrate the results in Figure 5.5. This figure, together with Figure 3 in [71], suggests that there is room for improvement if we could consider both mapping and routing jointly.

However, an intriguing part of the results shows how link protection can now play a role for RO. By looking closely at the number of flows each link carries, we observe that nearly all edge links, *i.e.,* 8 out of 9, carry more traffic than the rest. This is because traffic in an edge link tends to have fewer routing choices when it comes to failure; in fact, this link already provides the best routes in terms of RO when there is no link forbidden. This implies that links at the edge of a network may be of more importance when considering protection from failure.

5.4.3 Joint Mapping-Routing Survivability

Though we are primarily concerned in this dissertation work with differentiated mapping for survivability, it is important to point out here that some improvements over both FB and RO can be made if link mapping and flow routing are optimized jointly. Our work is different from [71] in that it considers differentiated link mapping in addition to joint mapping and routing survivability. This allows us to examine what benefits it can provide for different classes of services without compromising for performance.

5.5 SUMMARY

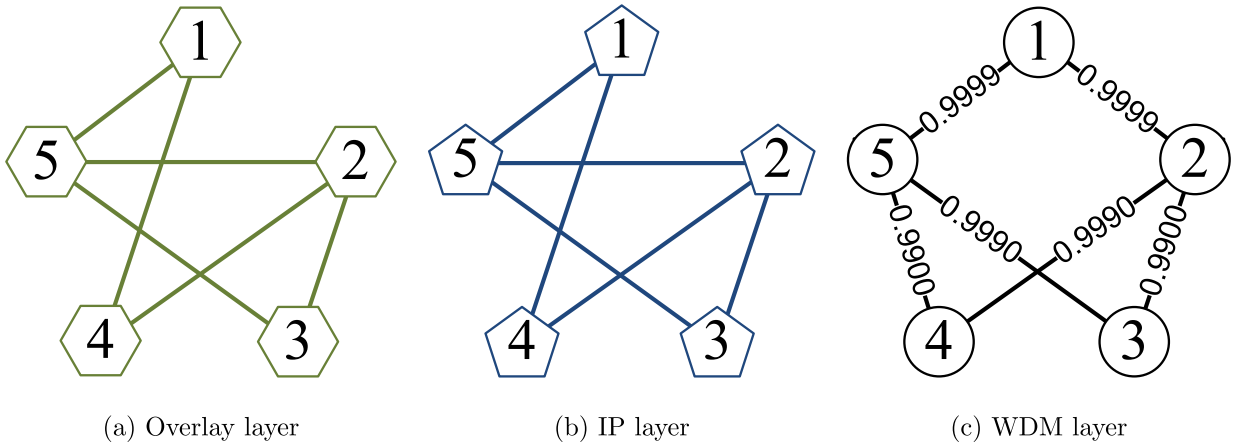
The profound benefits of any network include the ability to provide a variety of multileveled service classes to different customers. We identified a novel metric that can be included in the survivability design for multi-leveled differentiation in any layered network graphs and elaborate its use through an optimization-based network model. We also considered the logical link and the traffic layer separately that would otherwise be indistinguishable in traditional ways. Our study showed that the two solution approaches offer some trade-offs to consider when deciding whether flow blocking or resource overbuilding is of more importance. The findings are illustrated through numerical results.

6.0 LINK AVAILABILITY NETWORK MAPPING

Core networks are increasingly supporting overlay networks on top of an IP-WDM network. As network reliability is a growing concern, a major challenge in the survivable layered network design is the crosslayer survivable mapping problem that deals with QoS parameters such as availability as well as many others. This work directly studies this problem and proposes matrix formulations of the $\mathcal{NP}$-hard mapping problem, giving a detailed insight into the structure of the layered network as well as relationships between and among links and some potential mapping extensions. Numerical experiments show that intelligent crosslayer mapping can result in availability gains at little and occasionally no expense to the routing cost. The remainder of this chapter is arranged as follows: Section 6.2 gives our notation and definition of the problem. Section 6.3 provides the matrix formulations and presents them in different optimization goals. Section 6.4 presents the results of a detailed example of link availability mapping. Finally, we provide a summary of the work in this chapter in Section 6.5.

6.1 INTRODUCTION

As precursors to the future architecture of the Internet, overlays are not only adding one additional layer into the networks; but on a growing scale, they take a role of computing routes and delivering information among service points that arise to serve a range of diverse requirements upon the application [54]. In a general network environment, the overlay has to be supported by an infrastructure network, so that the full potential of high bandwidth can be realized; this network is typically IP-over-WDM technology.



(a) Overlay layer (b) IP layer (c) WDM layer

Figure 6.1: The three network layers, constituting an overlay-IP-WDM network

Overlay networks that can support applications with specific requirements are key elements to generating new sources of revenue. The needs are generally pressed by service requests with more granular level of performance guarantee or by scaling flaws in the original design of the Internet; particularly, when traffic runs across multiple Internet domains [79]. To meet these challenges, several commercial virtual network operators (VNOs) [53], [80], [81], [82], [83], [84], [85], [86] have managed to construct service overlay networks (SONs) that can provide secure and guaranteed application delivery to the customers.

Unfortunately, our understanding of the fundamental property of the layered network architecture, ranging from the effect and interaction among network layers, capacity allocation, and network and traffic survivability, is still in its infancy or waiting for more development. One known problem is *failure propagation* – a situation in which a failure in a lower-layer network can result in one or more failures in an upper-layer network. Chapter 4 has considered this problem in layered network in detail and developed *crosslayer survivable mapping* [12], which considered link mapping between network layers, such that the upper-layer network is still survivable, *i.e.,* connected, when any link in the lower-layer network fails.

In this chapter, we take a vertical look at the whole structure of the overlay-IP-WDM network architecture as an instance of a three-layer network by considering the relationship

Table 6.1: Optimum crosslayer survivable mapping of the three-layer network in Figure 6.1

		Traditional Mapping			**Link Availability Mapping**		
Overlay Link	IP Link	WDM Link	Cost	Availability	WDM Link	Cost	Availability
1-4	1-4	1-2-3-5-4	4	97.90%	1-2-4	2	99.89%
1-5	1-5	1-5	1	99.99%	1-5	1	99.99%
2-3	2-3	2-3	1	99.00%	2-3	1	99.00%
2-4	2-4	2-4	1	99.90%	2-1-5-4	3	98.98%
2-5	2-5	2-1-5	2	99.98%	2-1-5	2	99.98%
3-5	3-5	3-5	1	99.90%	3-5	1	99.90%
		Total	10	-	Total	10	-
		Mean	-	99.45%	Mean	-	99.62%

between and among network graphs in the different layers that also include link-level parameters such as availability, delay, among others. We are most interested in the link mapping problem that takes into account metrics associated with links and present a few novel mathematical models, which incorporate these metrics, in many different possible settings. These settings include cases when the goals are to maximize availability, minimize delay, or find traffic routes according to the delay constraint.

Consider the example in Figure 6.1 showing how availability-based crosslayer survivable link mapping can give better availability than the availability when the traditional link mapping model is considered. In this example, both availability-based link mapping and traditional mapping are survivable under single-WDM-link failure. It should also be noted that in some cases, multiple overlay or IP topologies may exist over a single WDM physical topology; however, we consider only one overlay topology request on an IP topology and a WDM topology here. A number on each link in Figure 6.1(c) indicates availability of the link, each of which is randomly chosen from $\{0.99, 0.999, 0.9999\}$. In Table 6.1, we show two survivable mappings when one aims at minimizing the number of WDM link use, denoted ‘cost’, and the other aims at maximizing the total availability of the IP network, which is mapped on the WDM network. The last two rows show total cost and mean availability of the two mapping schemes. In this particular example, we can see that the link availability mapping gives higher availability at no expense to the number of WDM links. It is noteworthy in the traditional mapping that IP link 1-4 is mapped to WDM links 1-2-3-5-4 because the survivability is required; otherwise, it would have taken WDM links 1-2-4, and because we aim at maximizing the average availability, it is possible that some links are higher in availability than the link availability mapping counterpart, *i.e.,* IP link 2-4. Clearly, we get a free ride to higher availability by taking advantage of the two degenerate solutions – the situation in which two distinct mappings have the same cost, *i.e.,* use the same number of WDM channels or wavelengths. We will show later in this paper that in general there is a tradeoff between the two criteria: availability and cost, or to sacrifice one for the other.

In this chapter, we introduce mathematical formulations that capture the link-level availability metric and the survivable link mapping problem in matrix models as well as other QoS metrics that could also be considered as link parameters. In the formulations, we derive for the first time the link mapping problem in a matrix form such that it can easily be integrated with the capacity allocation problem laying a path for future work to further explore the joint optimization of the two problems using the given formulation and model.

6.2 TERMINOLOGY AND PROBLEM DEFINITION

In this section we present the terminology and the problem considered in this chapter.

6.2.1 Terminology

We consider an uncapacitated network in each of the three network layers. Let a network be denoted by a set of nodes $\mathcal{N}^l$ and a set of links $\mathcal{L}^l$, where l is the layer index. Here we consider $l = 1, 2, 3$ as WDM, IP, and overlay layers, respectively. Each link is equivalent to two unidirectional links with an equal number of wavelengths and the same failure state, *i.e.,* available or failed, in each link and with the same failure probability. Furthermore, let B^k denote the incidence matrix, and let $H_i^j : \mathcal{L}^j \mapsto \mathcal{L}^i$ be a link mapping from network layer j to network layer i where each layer j link is assigned to a subset of layer i links [12]. The matrix H_i^j is called *link mapping* matrix.

6.2.2 Problem Definition

We now define the problem of interest regarding the link mapping matrix. We say a link mapping H_i^j is survivable under a single-link failure if layer j network remains connected after any layer i link fails. Generally, we call H_i^j a survivable mapping under n-link failures when it can withstand up to n concurrent link failures. The matrix can also be extended to include cases when link metrics are considered and when their summation is to be optimized or constrained.

6.3 MATRIX FORMULATIONS OF SURVIVABLE MAPPING

This section presents graph-based matrix-formulated optimization models for the survivable mapping problem in three categories: Guaranteed, optimized, and constrained mappings, each of which is discussed in each of the following sections, respectively.

6.3.1 Notation

This section provides a summary of the notation used in this chapter.

l	Network layer index, where $l = 1, 2, 3$ refers successively to higher layers
$\mathcal{N}^l$	Layer l node set
$\mathcal{L}^l$	Layer l link set
B^l	Layer l incidence matrix with dimension $\lvert\mathcal{N}^l\rvert \times \lvert\mathcal{L}^l\rvert$
C^l	Layer l segment-set matrix with dimension $\lvert 2^{\lvert\mathcal{N}^l\rvert-1} - 1\rvert \times \lvert\mathcal{L}^l\rvert$
$\mathtt{CNM}^l$	Layer l crosslayer node mapping matrix with dimension $\lvert\mathcal{N}^l\rvert \times \lvert\mathcal{N}^{l-1}\rvert$

H_i^j	Survivable link mapping matrix between layers j and i ($H_0^1 = I$)
$\mathbf{e}$	The column vector of all ones

6.3.2 Guaranteed Network Mapping

Nearly all the existing literature has assumed that a crosslayer survivable mapping that is resilient to a single-link failure, can be obtained from the likes of [74], [87], among others. In this section, we first derive an expression for the mapping in a matrix form and extend the model to include cases of a multiple-link failure in a layered network, we then modify the objective function to apply these extensions to the situation in which we wish to maximize the minimum number of physical-layer link failures that would disconnect the upper layer network topology.

6.3.2.1 Network Mapping for Single-Link Failures Given the notation previously defined, we formulate the survivable link mapping problem with an introduction of parameters C^k and $\mathtt{CNM^k}$, representing all possible segments of layer k network and crosslayer node mapping, respectively. Since an upper-layer network can be disconnected due to only some link failures in a lower-layer network even when the lower-layer network is still connected, we lose much of the original meaning of cut-set in a single-layer network when a multilayer network architecture is considered. Segment-set can simply be defined as a cut-set of the upper-layer network. The formulation for crosslayer survivable network mapping under a single-link failure can be expressed as follows:

$$\min_{H_2^3, H_1^2} \mathbf{e}^T H_2^3 H_1^2 \mathbf{e}, \tag{6.1}$$

$$H_k^{k+1} B^{k^T} \mathtt{CNM^{k+1}}^T = B^{k+1^T}, \qquad k = 1, 2, \tag{6.2}$$

$$[C^{k+1} \mathbf{e}] - C^{k+1} H_k^{k+1} \succeq 1, \qquad k = 1, 2, \tag{6.3}$$

$$H_2^3 H_1^2 \preceq 1. \tag{6.4}$$

Objective (6.1) defines the optimization goal, aimed at minimizing the number of links used in layer 1. Constraint (6.2) deals with the conservation of mapped links. Let $\mathtt{CNM^k}$ be a matrix of one-to-one crosslayer node mapping from network layer k to layer $k-1$ in which a diagonal entry (i, j) is one *if and only if* node i of layer k is associated to node j in layer $k-1$, zero otherwise. We consider node mapping from network layer k to $k-1$ such that a set of layer k node indices is a subset ($\subseteq$) of a set of layer $k-1$ node indices[1]. It is noteworthy here and throughout the paper that we assume the number of layer k nodes is no greater than that of layer $k-1$ nodes; if this is not the case then we further assume that all layer k nodes that are associated with the same $k-1$ node can be considered as a single super-node.

Survivability under a single-link failure is recognized in constraint (6.3), where C^k is a segment-set matrix in which the rows correspond to the segment-sets and the columns to the layer k links of the network. Reference [89] gives the total number of segment-sets in a network graph as $2^{|\mathcal{N}^k|-1} - 1$, where $\mathcal{N}^k$ is the number of nodes in layer k network; hence, the segment-set matrix has dimensions $(2^{|\mathcal{N}^k|-1} - 1, |\mathcal{L}^k|)$. In this constraint, there are two components on the left hand side: The first component refers to the number of links that belong to a segment-set, represented by each element of the column vector $C^{k+1}\,\mathbf{e}$. In the second component, each row refers to the number of links that would fail as a result of a failure in a layer 1 link, represented by each matrix column. The 1 on the right hand side of the constraint implies that two segments of layer $k+1$ network are still connected with at least one link when a single-link failure occurs. In other words, there is at least one surviving link when a failure occurs. The symbol $[u]$ on the left hand side defines a matrix comprising $|\mathcal{L}^k|$ column vector u's, that is $[u] = [u\,u \ldots u]$. In other words, $[u]$ defines a matrix constructed by augmenting a u column vector to the right-hand side $|\mathcal{L}^k| - 1$ times. The symbol $\succeq$ denotes vector-scalar inequality or componentwise inequality: $A \succeq 1$ means $A(i, j) \geq 1$ for all elements (i, j) of the matrix A. Constraint (6.4) defines mapping with no backhaul as previously discussed in [12]. Similar to constraint (6.3), the symbol $\preceq$ in constraint (6.4) implies that $A \preceq 1$ means $A(i, j) \leq 1$ for all elements (i, j) of the matrix A.

6.3.2.2 Network Mapping for n-Link Failures Here we present a generalization of the model presented in the preceding section by considering a multiple-link failure in the

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[1] Column switching, *i.e.*, node renumbering, may be required when the indices do not follow the assumption. This can be implemented by multiplying a corresponding $(0, 1)$-matrix to both sides of the constraint on the right-hand sides after column(s) of zeros is augmented [88], and $|\mathcal{N}^{(k)}| \leq |\mathcal{N}^{(k-1)}|$ still holds.

layered network. A model can be formulated as follows:

$$\min_{H_2^3, H_1^2} \mathbf{e}^T H_2^3 H_1^2 \mathbf{e}, \tag{6.5}$$

$$H_k^{k+1} B^{k^T} \mathtt{CNM}^{\mathtt{k+1}^T} = B^{k+1^T}, \qquad k = 1, 2, \tag{6.6}$$

$$[C^{k+1} \mathbf{e}] - C^{k+1} H_k^{k+1} \succeq n, \qquad k = 1, 2, \tag{6.7}$$

$$H_2^3 H_1^2 \preceq 1. \tag{6.8}$$

Objective (6.5), and constraints (6.6) and (6.8) have a similar description as given previously. Constraint (6.7) is a generalized version of constraint (6.3) when at most n links fail simultaneously, *e.g.,* dual-failure [90].

6.3.2.3 Max-Min Survivable Network Mapping

This formulation considers the network mapping problem with a goal of maximizing the minimum number of failures that would disconnect the network. The problem can be stated as follows:

$$\min_{H_2^3, H_1^2, n} \mathbf{e}^T H_2^3 H_1^2 \mathbf{e} - n, \tag{6.9}$$

$$H_k^{k+1} B^{k^T} \mathtt{CNM}^{\mathtt{k+1}^T} = B^{k+1^T}, \qquad k = 1, 2, \tag{6.10}$$

$$[C^{k+1} \mathbf{e}] - C^{k+1} H_k^{k+1} - n \succeq 0, \qquad k = 1, 2, \tag{6.11}$$

$$H_2^3 H_1^2 \preceq 1. \tag{6.12}$$

Here we consider n as an optimization variable that is in contrast to the one in constraint (6.7), which holds it to a fixed number of concurrent failures. In accordance with techniques in solving min-max or max-min optimization problems, we include our n in the objective function (6.9), which is to be maximized. This is equivalent to minimizing $-n$ because we consider n a strictly positive integer number. The similar idea has also been explored in [9]. Alternatively, the n can also be further defined at a more granular level, *i.e.,* per segment-set, where connectivity between two distinct segments of a network may be required to be stronger than the connectivity of the remaining two others. It can also be defined per physical-link failure when a particular link is more vulnerable to failures than others.

6.3.3 Optimized Network Mapping

We consider crosslayer survivable mapping aimed at optimizing a particular performance metric associated with links in this section. In order to accomplish so, the objective functions presented in Section 6.3.2 can be modified to embrace link-level metrics, so that they can be optimized. This section directly considers optimized network mapping under any single-link failure, but can be extended to cases of multiple failures and max-min failures upon taking into account the models presented in Sections 6.3.2.2 and 6.3.2.3, respectively.

In the area of QoS routing, the following cost function [91] has been widely used to study the feasibility problem and to design routing algorithms under multiple constraints:

$$g_\lambda(p) \triangleq (\frac{w_1(p)}{c_1})^\lambda + (\frac{w_2(p)}{c_2})^\lambda + \ldots + (\frac{w_e(p)}{c_e})^\lambda, \tag{6.13}$$

where $w_e(p) \leq c_e$ is a eth additive constraint for path p and λ is a positive nonlinear factor. A minimization of the function gives a range of solutions from generalized linear approximation (GLA) ($\lambda = 1$) to an asymptotically exact solution ($\lambda \to \infty$). Here we consider the special case of $\lambda = 1$. Without loss of generality, we also consider $c_e = 1$ for all e's and associate each $w_e(p)$ with a link-level metric for each link e, then we include the minimization of function $g_\lambda(p)$ in the following optimized network mapping model in which it is simply referred to as $\mathbf{g}$.

$$\min_{H_2^3, H_1^2} \mathbf{e}^T\, H_2^3\, H_1^2\, \mathbf{g}, \tag{6.14}$$

$$H_k^{k+1}\, B^{k^T}\, \texttt{CNM}^{\texttt{k+1}^T} = B^{k+1^T}, \qquad k = 1, 2, \tag{6.15}$$

$$[C^{k+1}\, \mathbf{e}] - C^{k+1}\, H_k^{k+1} \succeq 1, \qquad k = 1, 2, \tag{6.16}$$

$$H_2^3\, H_1^2 \preceq 1. \tag{6.17}$$

Objective (6.14) deals with aspects of the model of designing network mapping based on additive metrics such as delay, jitter, packet loss budget, linear link cost, WDM link distance, among others. The vector $\mathbf{g}$ consists of g_e's, where each g_e represents a cost associated with each link e in layer 1 network. The descriptions of constraints (6.15)-(6.17) have already been given in Section 6.3.2.1.

6.3.4 Constrained Network Mapping

While the preceding section considered optimizing the summation of the metrics, this section considers an upper bound of the summation. An example includes delay-bound mapping. An optimization-based formulation for constrained network mapping can be written as follows:

$$\min_{H_2^3, H_1^2} \mathbf{e}^T H_2^3 H_1^2 \mathbf{e}, \tag{6.18}$$

$$H_k^{k+1} B^{k^T} \mathtt{CNM}^{\mathtt{k+1}^T} = B^{k+1^T}, \qquad k = 1, 2, \tag{6.19}$$

$$[C^{k+1} \mathbf{e}] - C^{k+1} H_k^{k+1} \succeq 1, \qquad k = 1, 2, \tag{6.20}$$

$$H_2^3 H_1^2 \preceq 1, \tag{6.21}$$

$$H_2^3 H_1^2 \mathbf{b} \preceq b_c. \tag{6.22}$$

The formulation is similar to that presented in Section 6.3.2.1 but with constraint (6.22) added. This constraint puts a requirement on the summation of a metric in each layer 1 link that is used by a layer l link. In this constraint, the vector $\mathbf{b}$ consists of b_e's, where each b_e represents a cost associated with each link e in layer 1 network, and the scalar b_c is an upper bound for layer l links. Alternatively, this b_c can also be further defined per layer l link when a requirement is different for each layer l link. That is, constraint (6.22) can be replaced by constraint (6.23) expressed as follows:

$$H_2^3 H_1^2 \mathbf{b} \preceq \mathbf{b_c}, \tag{6.23}$$

where $\mathbf{b_c}$ consists of b_c's, where each b_c represents each upper bound for a layer l link.

6.3.5 Solving the Optimization Problems

In order to solve the presented matrix formulations, we first assume that network information in every network layer, *i.e.,* nodes, links, is known or given and then use CPLEX [92], which generally relies on a branch-and-bound algorithm to solve these problems. In general, solving time is exponential because our problems are $\mathcal{NP}$-hard; therefore, scalability is still an issue, pressing for efficient algorithms as part of future work. In the next section, we give a small example detailing the computational steps in obtaining optimum crosslayer survivable mapping in a layered network.

6.4 DETAILED SAMPLE RESULTS

In this section we give an example of availability-maximized mapping based on the presentation in Section 6.3.3 and provide some useful information from each computation step for appreciation of the models.

We consider a three-layer network in Figure 6.2, where $\mathtt{CNM}^2 = \mathtt{CNM}^3 = I$, and availability of each link is known or given. All link indices are shown, and the incidence matrices for layer 1, layer 2, and layer 3 networks, respectively, can be expressed as:

$$B^{(1)} = \begin{array}{c|ccccccc|} & 1^{(1)} & 2^{(1)} & 3^{(1)} & 4^{(1)} & 5^{(1)} & 6^{(1)} & 7^{(1)} \\ A^{(1)} & 0 & 0 & 0 & 1 & 0 & 1 & 1 \\ B^{(1)} & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ C^{(1)} & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ D^{(1)} & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ E^{(1)} & 1 & 0 & 1 & 0 & 1 & 1 & 0 \end{array},$$

$$\text{and } B^{(l)} = \begin{array}{c|cccccc|} & 1^{(l)} & 2^{(l)} & 3^{(l)} & 4^{(l)} & 5^{(l)} & 6^{(l)} \\ A^{(l)} & 0 & 1 & 0 & 1 & 0 & 1 \\ B^{(l)} & 0 & 0 & 1 & 0 & 1 & 1 \\ C^{(l)} & 1 & 1 & 1 & 0 & 0 & 0 \\ D^{(l)} & 1 & 0 & 0 & 1 & 1 & 0 \end{array},$$

for $l = 2$ and 3. The segment-set of network layer 3 in the considered network can be enumerated and represented in a matrix form as follows:

$$C^{(3)} = \begin{array}{c|cccccc|} & 1^{(3)} & 2^{(3)} & 3^{(3)} & 4^{(3)} & 5^{(3)} & 6^{(3)} \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 \\ 2 & 0 & 0 & 1 & 0 & 1 & 1 \\ 3 & 1 & 1 & 1 & 0 & 0 & 0 \\ 4 & 1 & 0 & 0 & 1 & 1 & 0 \\ 5 & 0 & 1 & 1 & 1 & 1 & 0 \\ 6 & 1 & 0 & 1 & 1 & 0 & 1 \\ 7 & 1 & 1 & 0 & 0 & 1 & 1 \end{array},$$

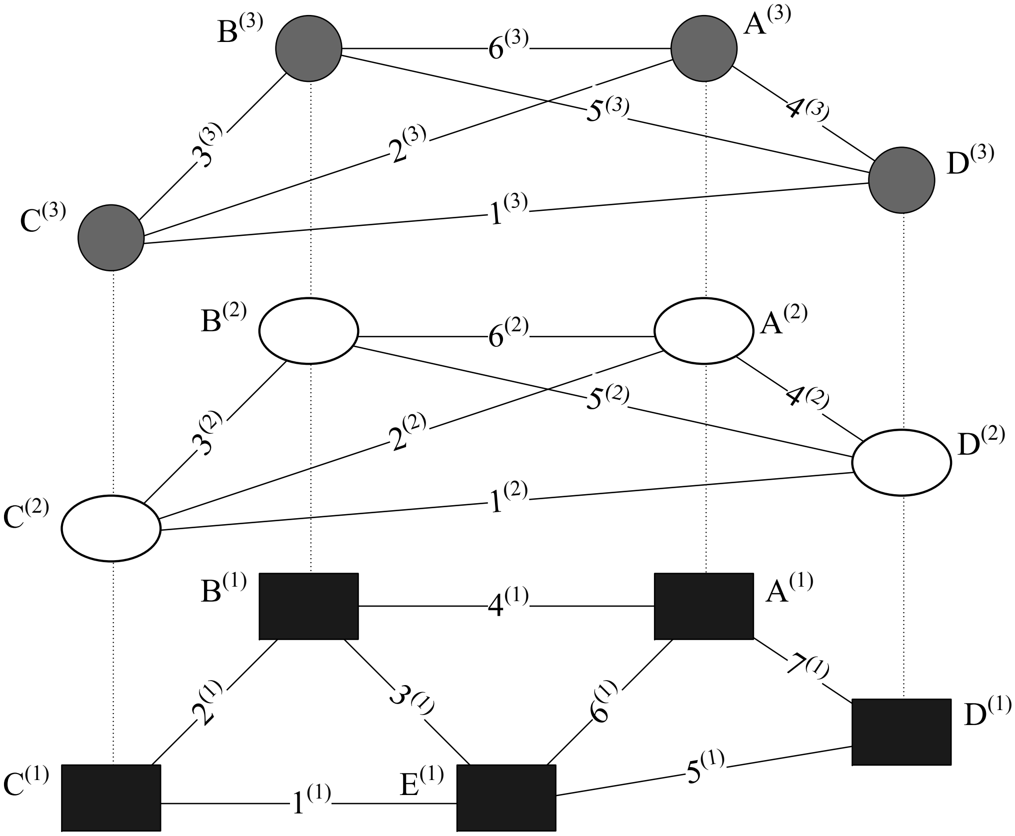

Figure 6.2: Availability-based network mapping in a layered network

where again each row corresponds to a segment-set index and each column corresponds to indices of the links that connect two independent sets.

In a similar way to the expression for crosslayer survivable mapping under a single-link failure previously given, we can consider the situation in which link availability is incorporated in the model. In this case the goal is to determine appropriate weights, representing availability of each link, for the optimum link mapping. In this example, we consider g_e as the availability of link e, where $g_e \in (0, 1]$. Although availability is a multiplicative metric, which follows the multiplicative rule, it can be transformed to an additive metric by using the logarithmic function [93]. Thus the link-level metric vector $\mathbf{g}$ can be represented as $\mathbf{g} = [-\log_b (g_e)]$; any change of base b will not affect the solution as it only represents a constant value. This logarithmic function is not linear; however, the objective is linear and convex, thereby allowing us to use the same model with only a modification in the objective function. It is noteworthy that we do not consider $g_e = 0$ simply because (1) $\log_b(0)$ is undefined, and (2) a link with zero availability is not part of a graph. In this example, we consider availability of a link randomly chosen from any one of 0.99, 0.999, and 0.9999. These numbers are used here for illustration purposes only, but the model is applicable to other values of link availability as well.

By solving the model given earlier in Section 6.3.3, we identify the two mapping matrices aimed at maximizing the total availability of the layer 3 network as a result of layer 1 link availabilities. The results named "Maximum availability" are as follows:

$$H_1^2 = \begin{array}{c|ccccccc|} & 1^{(1)} & 2^{(1)} & 3^{(1)} & 4^{(1)} & 5^{(1)} & 6^{(1)} & 7^{(1)} \\ 1^{(2)} & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 2^{(2)} & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 3^{(2)} & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 4^{(2)} & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 5^{(2)} & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 6^{(2)} & 0 & 0 & 1 & 0 & 0 & 1 & 0 \end{array},$$

$$\text{and } H_2^3 = I_6,$$

both of which are survivable under single-link failure and the multiplication of which, considering the two sub two-layer networks, has no backhaul.

Two other mapping schemes based on the model given in Section 6.3.2.1 aimed at minimizing the number of WDM links are presented for completeness of the example. The following matrices represent the first solution, denoted as "Minimum link #1":

$$H_1^2 = \begin{array}{c|ccccccc|} & 1^{(1)} & 2^{(1)} & 3^{(1)} & 4^{(1)} & 5^{(1)} & 6^{(1)} & 7^{(1)} \\ 1^{(2)} & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 2^{(2)} & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 3^{(2)} & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 4^{(2)} & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 5^{(2)} & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 6^{(2)} & 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{array},$$

Table 6.2: Availability and cost of mapping schemes

Mapping	Cost	Mean Availability (min∼max)
Maximum availability	10	99.41 (98.90∼99.90)
Minimum link #1	9	99.12 (98.01∼99.90)
Minimum link #2	9	98.95 (98.01∼99.90)

and $H_2^3 = I_6$.

The following matrices represent the second solution, denoted as “Minimum link #2”:

$$H_1^2 = \begin{array}{c|ccccccc} & 1^{(1)} & 2^{(1)} & 3^{(1)} & 4^{(1)} & 5^{(1)} & 6^{(1)} & 7^{(1)} \\ \hline 1^{(2)} & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 2^{(2)} & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 3^{(2)} & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 4^{(2)} & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 5^{(2)} & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\ 6^{(2)} & 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{array},$$

and $H_2^3 = I_6$.

By looking at the number of links used in each mapping scheme, we observe that these two mappings are degenerate, *i.e.,* have the same cost. The number of link use can be identified by the number of 1’s in each matrix. For example, in “Minimum link #2”, the number of link use is 9, which is identified by the number of 1’s in the product matrix $H_2^3\, H_1^2$.

Tabulated results are presented in Table 6.2, which shows that the average availability over all overlay paths is largest when availability is considered in the mapping design. The ‘cost’ column in the table is the number of links used. In the result, availability of each overlay link is calculated and recorded, the minimum and the maximum of which are taken from the record and shown by numbers in parentheses in the table. Then mean is also calculated and shown in the same column outside the parentheses. The table shows that the "Maximum availability" mapping gives the highest availability among all of the three considered mapping schemes. In particular, it is the best among all availability measures, including mean, min, and max availabilities. Nevertheless, this comes at an expense of cost, implying that we overly use the one more WDM link, compared to the two other mappings. Now we look at "Minimum link #1" and "Minimum link #2", we can see that both of which share the same cost, but with different availability. The first mapping gives slightly better availability, however, at the same cost as "Minimum link #2" unveiling the preference of equal cost mapping with more availability. After all, we may need more information related to capital expenditures (CapEx) or operational expenditures (OpEx) or both to decide whether 0.29% increased mean availability, which is 99.41% less 99.12%, is worth a WDM lightpath and revenue from reliability-focused customers.

6.5 SUMMARY

Common weaknesses of the work aimed at attacking the survivability problem in the layered communication systems include the lack of work that examines the problem from the perspective of the whole network architecture. In this chapter, we formulated several mathematical formulations of network mapping in a variety of settings and requirements, and specifically consider the availability-based link mapping in layered network graphs, considering both availability and survivability. A numerical example is given and presented in detail. Possible extensions include further investigation on the formulations in other network topologies; these may also include the explicit existence of traffic layers, and joint optimization of the mapping and routing problems.

7.0 SURVIVABILITY OF MULTILAYER TRAFFIC

The survivability of backbone networks to failures is an on-going concern. We put more focus on the lower two layers in this chapter, as they constitute a core backbone and examine capacity planning strategies and their tradeoffs in the network when traffic may be present in every layer. This chapter addresses the tradeoff between each pair of the four possible survivability strategies in a two-layer network setting under multilayer traffic ratios. We explicitly consider an IP-over-WDM scenario as an instance of the core backbone networks; we examine closely how each survivability strategy behaves in this network and report numerical results at the end of the chapter.

7.1 INTRODUCTION

7.1.1 Motivation

Revenue-generating IP and optical-switching WDM networks are moving toward an integrated high-speed backbone architecture with GMPLS as a common control plane. The ability of the network to survive link or node failures will be a required feature in future network infrastructure. However, multilayer planning is necessary to guarantee the survivability of traffic in a two-layer backbone network.

Survivability of the traffic at both layers is essential as bandwidth at the lightpath level is becoming more in demand by customers [94]. Such layer 1 customers purchase lightpaths connecting between end-points in the WDM layer for providing connectivity in a private network. However, providing survivability to both IP flows and lightpaths is challenging.

In most cases, these two-layer networks are under the same administrative ownership, but since the layers are formed by different technologies, interoperability between two layers of different technologies has become increasingly important.

7.1.2 The Proposed Evaluation Approach

Similar to much of the work in this area, we jointly consider capacity allocation and routing assignment problems as a spare capacity allocation (SCA) problem. This SCA problem has also been considered in the previous chapters. In this chapter, we examine several strategies for survivability in two-layer networks when traffic originates at *both* layers and grooming of the traffic, in each layer, is available at the edge. These strategies require traffic flows in both layers to be survivable under single link failure at the bottom. In particular, the following four survivability strategies are considered:

1. Strategy A: Backup paths are provided at the layer where traffic originates. Let BP_t^t be a set of top-layer backup paths to protect top-layer traffic, and BP_b^b be a set of bottom-layer backup paths to protect bottom-layer traffic. Sharing spare capacity between the two backup path sets is not allowed.
2. Strategy B: Similar to Strategy A but capacity between the two backup path sets BP_t^t and BP_b^b can be shared.
3. Strategy C: Backup paths of traffic at both layers are provided at the bottom layer. Let BP_b^t be a set of bottom-layer backup paths to protect top-layer traffic and BP_b^b as previously defined. Sharing capacity between the two backup path sets BP_b^t and BP_b^b is not allowed.
4. Strategy D: Similar to Strategy C but the capacity between the two backup path sets BP_b^t and BP_b^b can be shared.

For all strategies, spare capacity may be shared within a backup path set, *e.g.,* sharing capacity among backup paths in BP_b^b is allowed. Sharing is also allowed in BP_t^t as well as in BP_b^t.

This chapter is organized in the following manner. In relation to Section 4.3, we present a mathematical formulation of the two survivability strategies at the bottom, C and D in

Section 7.2. Performance evaluation of all strategies and numerical results are then given in Section 7.3. Finally, our summary is given in Section 7.4.

7.2 SURVIVABILITY OF TWO-LAYER TRAFFIC

In this section, we extend the SCA model in [49] to include survivability strategies when top-layer traffic is protected at the bottom layer. In this case, spare capacity due to the top BP_b^t and bottom BP_b^b layer traffic can either be unshared or shared. In addition, we consider a disjoint backup path from its primary path. For brevity, the notation is taken from the formulation presented in Section 4.3.1 and combined with superscripts denoting a two-layer network architecture. For clarity, we restate some of the definitions here. The notation used in this chapter is summarized as follows:

- *from* a {top, bottom}-layer perspective

$\mathcal{N}^{\{t,b\}}$	{Top, Bottom}-layer node set
$\mathcal{L}^{\{t,b\}}$	{Top, Bottom}-layer link set
$\mathcal{F}^{\{t,b\}}$	{Top, Bottom}-layer flow vector
$B^{\{t,b\}}$	{Top, Bottom}-layer incidence matrix with dimension $\lvert\mathcal{N}^{\{t,b\}}\rvert \times \lvert\mathcal{L}^{\{t,b\}}\rvert$
$M^{\{t,b\}}$	Diagonal matrix of bandwidth of {top, bottom}-layer flow $f^{\{t,b\}}$ with dimension $\lvert\mathcal{F}^{\{t,b\}}\rvert \times \lvert\mathcal{F}^{\{t,b\}}\rvert$
$D^{\{t,b\}}$	{Top, Bottom}-layer flow-node incidence matrix with dimension $\lvert\mathcal{F}^{\{t,b\}}\rvert \times \lvert\mathcal{N}^{\{t,b\}}\rvert$
$P^{\{t,b\}}$	Primary {top, bottom}-layer path matrix with dimension $\lvert\mathcal{F}^{\{t,b\}}\rvert \times \lvert\mathcal{L}^{\{t,b\}}\rvert$
$Q^{\{t,b\}}$	Backup {top, bottom}-layer path matrix with dimension $\lvert\mathcal{F}^{\{t,b\}}\rvert \times \lvert\mathcal{L}^{\{t,b\}}\rvert$

- *from* a bottom-layer perspective

$B^{t\to b}$	Top-layer incidence matrix with dimension $\lvert\mathcal{N}^b\rvert \times \lvert\mathcal{L}^b\rvert$
$M^{t\to b}$	Diagonal matrix of bandwidth of top-layer flow f^t with dimension $\lvert\mathcal{F}^t\rvert \times \lvert\mathcal{F}^t\rvert$
$D^{t\to b}$	Top-layer flow-node incidence matrix with dimension $\lvert\mathcal{F}^t\rvert \times \lvert\mathcal{N}^b\rvert$
$P^{t\to b}$	Primary top-layer path matrix with dimension $\lvert\mathcal{F}^t\rvert \times \lvert\mathcal{L}^b\rvert$
$Q^{t\to b}$	Backup top-layer path matrix with dimension $\lvert\mathcal{F}^t\rvert \times \lvert\mathcal{L}^b\rvert$

$G^{t\to b}$	Top-layer spare capacity matrix with dimension $\lvert\mathcal{L}^b\rvert \times \lvert\mathcal{L}^b\rvert$
$S^{t\to b}$	Backup top-layer link capacity vector with dimension $\lvert\mathcal{L}^b\rvert \times 1$
G^b	Bottom-layer spare capacity matrix with dimension $\lvert\mathcal{L}^b\rvert \times \lvert\mathcal{L}^b\rvert$
S^b	Backup bottom-layer link capacity vector with dimension $\lvert\mathcal{L}^b\rvert \times 1$

- General notation

H	Survivable mapping matrix
$\mathbf{e}$	The column vector of all ones

Our network of interest is defined as follows: Given a bottom-layer directed network with node set $\mathcal{N}^b$, link set $\mathcal{L}^b$, and incidence matrix B^b [48], a top-layer directed network with similar quantities in superscript t is constructed as follows: A node $n_k^t \in \mathcal{N}^t$, where $1 \leq k \leq |\mathcal{N}^t|$, exists only if its associative node $n_k^b \in \mathcal{N}^b$ at the bottom layer exists. That is, $\mathcal{N}^t \subseteq \mathcal{N}^b$. No more than one top-layer node is allowed to associate with a node at the bottom. Moreover, the presence of uncapacitated links at each layer is independent from each other.

Let H be a binary survivable mapping matrix, where $h_{ij} = 1$ if a top-layer link i is mapped onto a bottom-layer link j, and 0 otherwise. A survivable mapping matrix H can be derived from a necessary condition of a two-connected network, as presented in [8]. Now we have a topology construction including nodes, links, and link mapping. In the next two subsections, we will provide formulations of the SCA problem due to two-layer traffic.

7.2.1 Providing Backup Paths to Top-Layer Traffic at the Bottom Layer

At the top layer, primary and backup paths of flows f^t, where $1 \leq f^t \leq |\mathcal{F}^t|$ are represented by two $1 \times |\mathcal{L}^t|$ binary row vectors $p^t_{f^t l^t}$ and $q^t_{f^t l^t}$, respectively. The l^t-th element in one of the vectors equals one if and only if the corresponding path uses link l^t. The path matrices [95] P^t and Q^t are formed by a collection of $p^t_{f^t l^t}$ and $q^t_{f^t l^t}$, respectively. The primary paths: P^t, can be obtained from Dijkstra's shortest path algorithm. Let $M^t = \mathbf{diag}(\{m^t_{f^t}\}_{|\mathcal{F}^t| \times 1})$ be a matrix of top-layer integral flow bandwidth. The top-layer traffic flows are represented by a matrix D^t. An element $d^t_{f^t n^t}$ of the matrix D^t equals 1 if the flow f^t originates from node n^t and -1 if it terminates at node n^t. Flows having identical end points, if they exist, are treated as a single flow with flow bandwidth from those flow bandwidths combined.

In order to provide backup paths to top-layer traffic at the bottom, we need to map top-layer information to the bottom. Because the incidence matrix is topology dependent, a top-layer incidence matrix, when mapped to the bottom, is equivalent to that of the bottom. This is shown in (7.1). In (7.2), bandwidth of the mapped top-layer flow still holds the same value, *i.e.,* m^t_{ft}, as that of the top-layer flow as it depends on flows only. Since a top-layer network may not have the same number of nodes as the bottom, the flow-node incidence matrix in (7.3) is mapped to the bottom layer by padding columns of zeros as necessary to D^t. In (7.4), the link-mapping information in H is used to derive top-layer primary paths P^t from the perspective of the bottom layer, as $P^{t\to b}$. The $\odot$ symbol is a matrix multiplication operator, realizing the inclusive OR and AND operation, *e.g.,* 1+1=1. Using this operator, the logical relations among flows and links in a directed network can be simplified into one matrix operation. It is noteworthy that in backhaul-free traffic routing (*see* the definition in the Appendix), equation (7.4) is equivalent to the one where the $\odot$ symbol is replaced with the traditional matrix multiplication. Since binary flows are considered, we do not include a single-path routing constraint in our ILP formulation as it would be redundant.

A mapping function $f : t \to b$ can be described for each top-layer matrix as:

$$B^{t\to b} = B^b \tag{7.1}$$

$$M^{t\to b} = M^t \tag{7.2}$$

$$D^{t\to b} = [D^t|0] \tag{7.3}$$

$$P^{t\to b} = P^t \odot H \tag{7.4}$$

Using the notation and definitions given previously, the SCA problem of the top-layer traffic can be formulated as:

$$Q^{t\to b} B^{t\to b^T} = D^{t\to b} \tag{7.5}$$

$$P^{t\to b} + Q^{t\to b} \preceq 1 \tag{7.6}$$

$$G^{t\to b} = Q^{t\to b^T} M^{t\to b} P^{t\to b} \tag{7.7}$$

$$S^{t\to b} \in \mathbb{Z}_+^{|\mathcal{L}^b|} \tag{7.8}$$

$$Q^{t\to b} : \text{binary matrix} \tag{7.9}$$

Constraints (7.5) and (7.6) guarantee that a backup path matrix $Q^{t\to b}$ is feasible via flow conservation constraints and disjoint from the primary paths. A matrix $Q^{t\to b}$ has the same dimension as $P^{t\to b}$, which is $|\mathcal{F}^t|$ by $|\mathcal{L}^b|$. Constraint (7.7) determines the amount of spare capacity units needed in order to protect mapped top-layer primary paths which fail as the result of a single link failure at the bottom layer. This information is given in $G^{t\to b}$, which is a $(|\mathcal{L}^b|, |\mathcal{L}^b|)$ matrix. An element $g_{ij}^{t\to b}$ defines the spare capacity needed by bottom link i to reroute failed paths in the face of failure at bottom link j. Equation (7.8) defines integer variables, where $\mathbb{Z}_+^{|\mathcal{L}^b|}$ is the set of nonnegative integral $|\mathcal{L}^b|$-dimensional vectors; equation (7.9) defines a (0,1)-matrix variable, which will be explained further in the next section.

7.2.2 Providing Backup Paths to Bottom-Layer Traffic at the Bottom Layer

Since providing backup paths to bottom-layer traffic at the bottom layer requires no mapping, we now have all necessary information to find the backup paths of traffic in both layers. It is equivalent to finding a set of disjoint primary-backup path pairs in single-layer networks. A mathematical formulation for survivability of two-layer traffic at the bottom layer can be written as:

$$Q^b {B^b}^T = D^b \tag{7.10}$$

$$P^b + Q^b \preceq 1 \tag{7.11}$$

$$G^b = {Q^b}^T M^b P^b \tag{7.12}$$

$$S^b \in \mathbb{Z}_+^{|\mathcal{L}^b|} \tag{7.13}$$

$$Q^b : \text{binary matrix} \tag{7.14}$$

Similar to backup paths of top-layer traffic, a constraint set (7.10)-(7.14) defines backup paths $Q^b = \{q^b\}_{|F^b|\times|\mathcal{L}^b|}$ and the spare capacity $G^b = \{g^b\}_{|\mathcal{L}^b|\times|\mathcal{L}^b|}$ required to protect primary paths P^b of the bottom-layer traffic. As in Section 7.2.1, the primary paths P^b can be obtained from Dijkstra's algorithm.

The objectives of the two strategies C and D are defined as follows: Strategy C has an objective to minimize the spare capacity requirements of the two-layer traffic independently, and so can be described as:

$$\min\ ({S^{t\to b}}^T + {S^b}^T)\,\mathbf{e}, \tag{7.15}$$

where $S^{t\to b}$ = row-max $G^{t\to b}$, S^b = row-max G^b, and e is a column vector of ones. The row-max (x) operation determines the maximum element in each row of the matrix x. This min-max optimization of spare capacity requirements ensures the minimum capacity that must be allocated for each bottom-layer link under single link failure at any other links.

The objective function of Strategy D is expressed as:

$$\min\ (S^{t\to b,b})^T\,\mathbf{e}, \tag{7.16}$$

where $S^{t\to b,b}$ = row-max $(G^{t\to b} + G^b)$. This strategy merges the two spare capacity matrices and jointly consider them, allowing their spare capacity to be exchanged. The two survivability strategies at the bottom: C and D, and two strategies where traffic originates: A and B [49], presented in the next sections, construct a basis for our study in this chapter.

7.2.3 Providing Backup Paths to Top-Layer Traffic at the Top Layer

In Strategies A and B when each backup path is provided in the layer where a primary path is, we need to define the SCA problem of top-layer traffic at the top layer, which can be formulated as:

$$Q^t {B^t}^T = D^t \tag{7.17}$$

$$P^t + Q^t \preceq 1 \tag{7.18}$$

$$G^t = {Q^t}^T M^t P^t \tag{7.19}$$

$$S^t \in \mathbb{Z}_+^{|\mathcal{L}^t|} \tag{7.20}$$

$$Q^t : \text{binary matrix} \tag{7.21}$$

In a similar way to the definition given previously, Constraints (7.17) and (7.18) guarantee that a backup path matrix Q^t is feasible via flow conservation constraints and disjoint from the primary paths. A matrix Q^t has the same dimension as P^t, which is $|\mathcal{F}^t|$ by $|\mathcal{L}^t|$. Constraint (7.19) determines the amount of spare capacity units needed in order to protect mapped top-layer primary paths which fail as the result of a single link failure at the bottom layer. This information is given in G^t, which is a $(|\mathcal{L}^t|, |\mathcal{L}^b|)$ matrix. An element g^t_{ij} defines the spare capacity needed by bottom link i to reroute failed paths in the face of failure at bottom link j. Equation (7.20) defines integer variables, where $\mathbb{Z}_+^{|\mathcal{L}^t|}$ is the set of nonnegative integral $|\mathcal{L}^t|$-dimensional vectors; equation (7.21) defines a (0,1)-matrix variable.

Using the notation and constraints given previously in Section 7.2 and two constraint sets (7.10)-(7.14) and (7.17)-(7.21), the objectives of the two strategies A and B can be stated as follows: Strategy A has an objective to minimize the spare capacity requirements of the two-layer traffic independetly, and so can be stated as:

$$\min\,(S^t + S^b)^T\,\mathbf{e}, \tag{7.22}$$

where $S^t = \text{row-max}\ \ G^t$. This min-max optimization of spare capacity requirements ensures the minimum capacity that must be allocated for each link in their respective layer under single link failure at any other links.

The objective function of Strategy B is expressed as:

$$\min\,(S^{t,b})^T\,\mathbf{e}, \tag{7.23}$$

where $S^{t,b} = \text{row-max}\ (G^t + G^b)$. This strategy merges the two spare capacity matrices and jointly consider them, allowing their spare capacity to be exchanged.

In the following section, we study the four survivability strategies in an explicit context of the IP-over-WDM two-layer networks using the given four exact matrix-based optimization models. These optimization models have been manually verified on some small networks against the results obtained from an AMPL/CPLEX implementation to ensure its correctness.

7.3 NUMERICAL RESULTS AND ANALYSIS

In this section, we study the effects of the survivability strategies on spare capacity requirements of multilayer traffic in two-layer networks. First, we look at the impact of traffic ratios between top- and bottom-layer in fixed network topologies as well as the impact of capacity sharing between the two-layer traffic. Then, we look at the impact of top-layer network connectivity in terms of average node degrees. We use AMPL/CPLEX 9.1 on a Sun Fire V240, 2x1.2GHz UltraSPARC IIIi, 2GB to solve our models and the results are based on a zero integrality gap, meaning that they are optimal.

A two-layer network topology with a number of network scenarios is considered to determine the effects. The considered two-layer topology is Figure 1.1, which has been given earlier in Chapter 1, where the top has 6 nodes, 9 links and the bottom has 10 nodes, 22 links. Primary paths in both layers, when needed, are precomputed and unchanged over the course of simulations. A primary path is manually adjusted if the corresponding backup path cannot possibly be obtained, called a trap path. This is a counterexample to the existence of two disjoint paths in two-connected networks, when there are no parallel links. We are also aware that joint optimization of primary and backup paths often leads to better capacity utilization [96]; but since we want to focus on the spare capacity requirements of the survivability strategies, we let the primary paths be fixed. In addition, a number of wavelengths and wavelength converters are assumed to be available and unit-capacity flows are assumed.

7.3.1 Impacts of Traffic Ratios

In this section, the impacts of traffic ratios are discussed for the two possible settings: When the number of bottom-layer flows is fixed while varying the number of top-layer flows, and vice versa. With varying number of flows, f flows are chosen from the first f-th lexicographical element of the combinations of two elements out of the node set, *e.g.,* for 8 top-layer flows in Figure 1.1, the considered flows are $(\{1,2\},\{1,3\},\{1,4\},\{1,5\},\{1,6\},\{2,3\},\{2,4\},\{2,5\})$. Spare capacity requirements are measured in terms of redundancy, or resource overbuilding (RO), which is defined as a capacity ratio of backup paths to primary paths.

7.3.1.1 Varying Top-Layer Flows Over a fixed 45-flow bottom-layer network, Figure 7.1 shows by varying a number of top-layer flows that Strategy A and Strategy D perform worst and best, respectively. The reasoning can be given as follows: Let us put aside bottom-

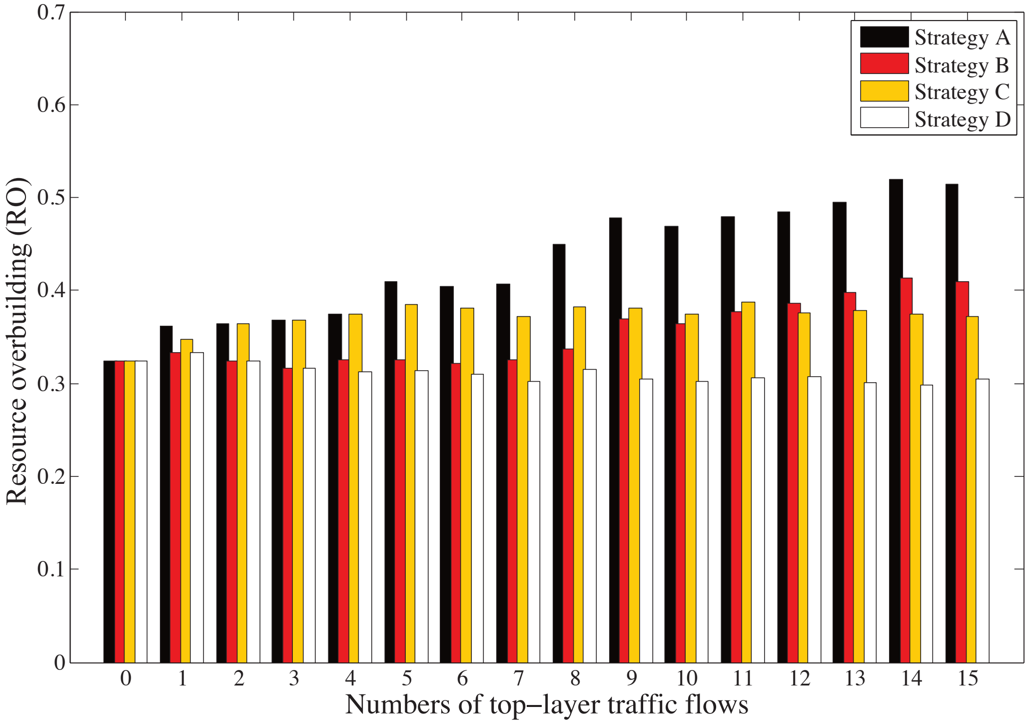

Figure 7.1: Top-layer flows vs. resource overbuilding ($|F^b| = 45$)

layer traffic to consider top-layer traffic only. There are two survivability strategies for the top-layer traffic: Providing backup paths at the top layer and at the bottom. We claim that the first strategy never requires fewer spare capacity units than the latter. The reasons are as follows: First, a survivable matrix limits the number of feasible backup paths of top-layer traffic at the bottom. This is because the matrix ties a top-layer link to bottom-layer links, and this link mapping is not allowed to change. Second, spare capacity is provided by the bottom layer; regardless of where backup paths are computed, their capacity requirements are constrained by bottom-layer topology. This is also true even if the survivable matrix can be changed because constraints will be at the bottom layer instead. In other words, if the number of top-layer links are significantly fewer than that of the bottom then the backup paths are limited by the top topology. But when the number of top-layer links are significantly more than that of the bottom, a bottom topology itself limits improvements on capacity sharing by its own topology. An example when these two strategies are equivalent is when the two-layer topologies are identical and a survivable mapping is link-to-link. Now let us put bottom-layer traffic back into consideration. We have shown that, for top-layer traffic, bottom-layer backup paths require no more capacity than the top-layer counterpart. This is also true when there is bottom-layer traffic and sharing spare capacity between BP_b^b and BP_t^t or BP_b^t is not allowed. Since capacity sharing usually reduces spare capacity requirements, Strategy D always outperforms or at least performs as well as Strategy A. This analysis supports other topologies as well.

The other two strategies, however, are competing. When a top-layer network has few traffic flows, Strategy B outperforms Strategy C. This is because these few flows may well be able to share capacity with the bottom flows. But when there are more flows at the top layer, the situation is reversed.

Consider a scenario of 1 primary top-layer flow and 45 primary bottom-layer flows in Figure 7.1. In this scenario, the bottom flows require 23 spare capacity units. Because of capacity sharing, Strategy B requires only 1 more capacity unit to provide a backup path to the top-layer flow. The total spare capacity required is now 24 units. However, in Strategy C, when sharing is not allowed, the backup path requires 2 capacity units. The spare capacity requirement of bottom-layer flows is never changed in Strategy C regardless of the number of top-layer flows because they do not allow capacity sharing with the top flows. In this scenario, primary paths require 1 and 71 capacity units for top- and bottom-layer flows, respectively.

When there are more flows, *i.e.,* more than 12 flows, in the top network, a higher number of flows in both layers are subject to failures. In this scenario, Strategy C reduces spare capacity requirements by giving more rerouting choices to the top flows. These choices offer an advantage over Strategy B. A similar trend is also observed for different numbers of top-layer flows, when bottom-layer flows are fixed, in Table 7.1.

7.3.1.2 Varying Bottom-Layer Flows

In this section, we continue to evaluate Strategy B and C, but instead, the number of top-layer flows is fixed, and we vary the number of flows at the bottom layer.

Consider a scenario of 8 top-layer flows when the number of bottom flows ranges from

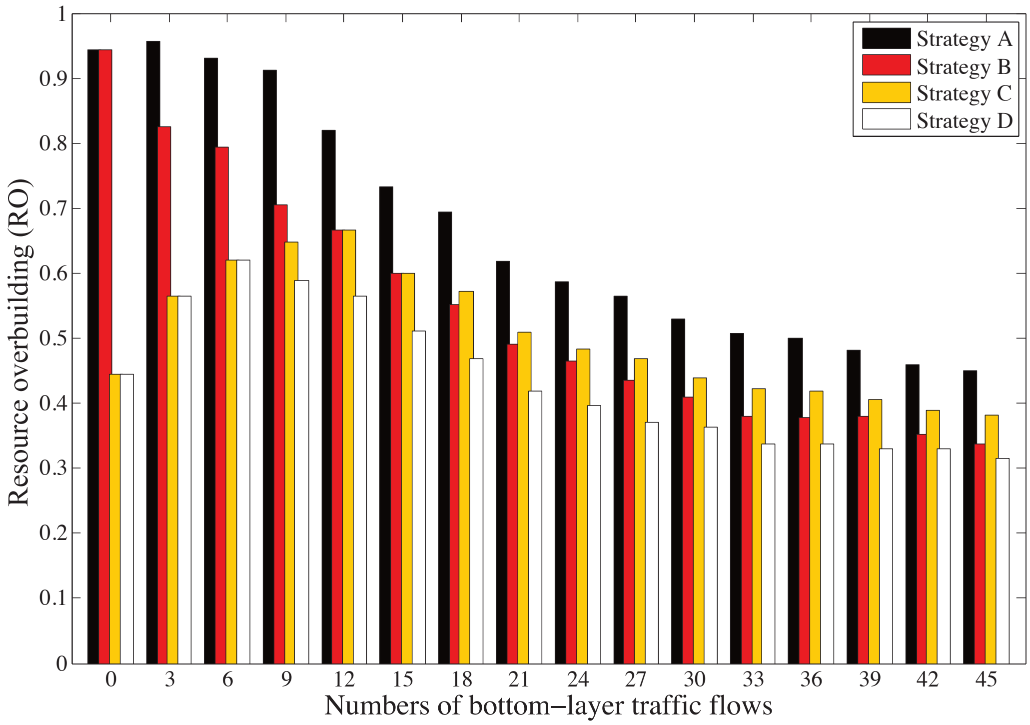

Figure 7.2: Bottom-layer flows vs. resource overbuilding ($|F^t| = 8$)

0 to 45, in multiples of 3. Unlike the setting in the previous section, this time Strategy C requires fewer capacity units than Strategy B when the number of bottom-layer flows is small. Figure 7.2 shows that Strategy B starts to outperform Strategy C when there are 15 flows in the bottom-layer network. These results conform with our previous discussions in Section 7.3.1.1 in terms of traffic ratios.

Observations in this section and Section 7.3.1.1 suggest that there should be a characteristic of the competing two survivability strategies, which could enable us to determine which strategy to implement to ensure better capacity utilization according to each network scenario. Due to its dependency on topology and mapping as well as backup path routing, we decide to omit the detailed discussion on the operating characteristics of the two survivability strategies.

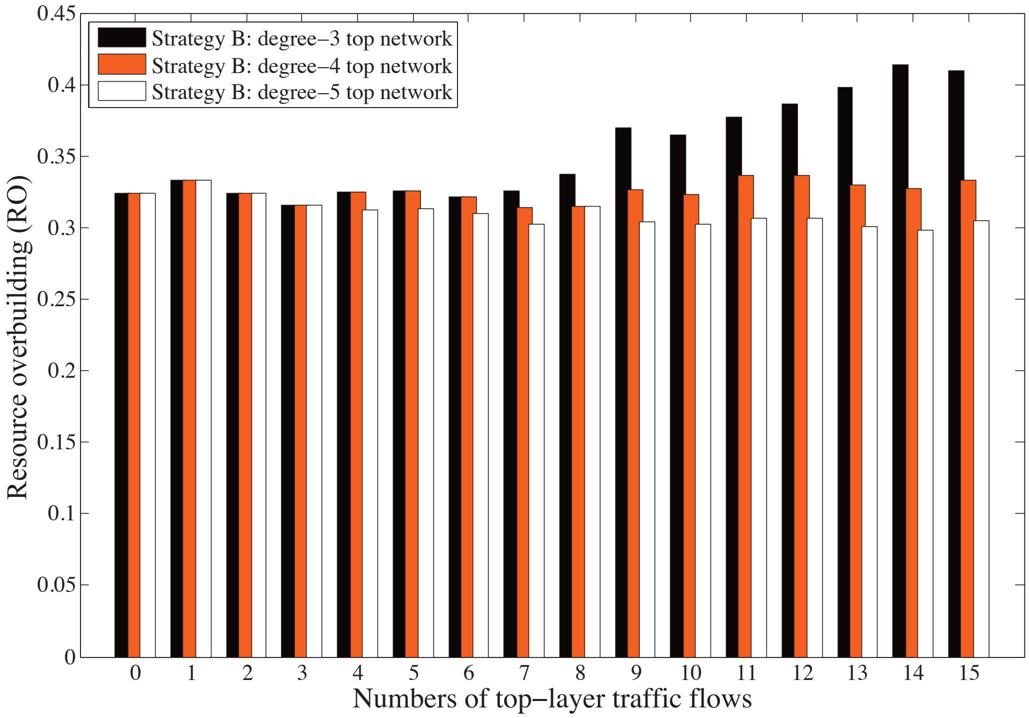

Figure 7.3: Resource overbuilding in networks with top-layer connectivities ($|F^b| = 45$)

7.3.2 Impacts of Network Connectivity

In this study, capacity requirements of top-layer networks with varying node degrees, 3, 4, and 5, over a bottom-layer network are compared. Networks in a family are related by link removals from a master network, while keeping nodes and demand flows fixed. The use of network families in simulations can resemble the results from many random networks while requiring much less simulation time. A more thorough analysis on the use of network families is provided in [97].

For a degree-3 top-layer network, we use the network shown in Figure 1.1. A degree-4 top network can be accomplished by adding links $(1, 5)$, $(2, 6)$, and $(3, 6)$ to the degree-3 network. A degree-5 top-layer network is set through its full mesh, *i.e.,* adding links $(1, 6)$, $(2, 5)$, and $(3, 4)$ to the degree-4 network.

Since top-layer topologies have effect on the spare capacity requirements of neither Strategy C nor D, we focus only on Strategy A and B. Figure 7.3 shows that reduction of spare capacity comes at an expense of a higher number of top-layer link installments in which a significant difference in capacity savings is observed when the number of top-layer flows is high. At 15 flows, which are the maximum number of distinct flows at the top, we observe a capacity saving of 9 units from a degree-3 to degree-5 network, compared to 2 when there are 8 flows at the top. One possible explanation is that an adding link can help reduce the capacity requirements by giving more routing choices to the backup paths. This link has little effect when there are few flows in the network, *i.e.,* 1 - 3 flows.

7.3.3 Deployment Issues

This section describes some issues relating to the implementation of the four survivability strategies in practice and discusses how they can be a key tool for the survivability in a layered network.

While all four strategies can be implemented in any layered network that follows the integrated network model, only two of them, *i.e.,* A and B, are applicable to the overlay network model. This is because the overlay model assumes a separate instance of the control plane for each network layer [17] or for each managed network. When a network provider owns and manages both of the technology layers, he will be able to choose the best survivability strategy among the four. However in a case when these two layers are administered by different entities; for example, an ISP who owns only IP equipment and an optical network provider who owns WDM switches, information sharing between these two network layers is limited. Theoretically when this case happens, only strategies A and B are possible. The actual implementation would also likely depend on how much and what kind of information is being shared between the two managed networks.

7.4 SUMMARY

This chapter examines the four possible survivability strategies in two-layer core backbone networks, where traffic is present at both layers. An optimization-based formulation is proposed to investigate the spare capacity requirements under various traffic ratios and network connectivities in the role of lightpath routing.

Numerical results show that the survivability of two-layer traffic at the bottom, when sharing spare capacity among all backup paths is allowed, performs best. However, two of the studied strategies are competing. Moreover, networks with higher average node degree can provide more capacity savings, but this comes at the expense of link installments. Our analysis and results provide important guidelines for the design of survivability strategies in networks and for understanding their tradeoffs.

Table 7.1: Resource Overbuilding of Optimal Spare Capacity in Multilayer Traffic Scenarios†

	Numbers of top-layer traffic flows							
Numbers of bottom-layer traffic flows	0	1	2	3	4	5	6	7
0	—	300,300,100,100	133,133,67,67	100,100,60,60	78,78,67,67	92,92,50,50	85,85,46,46	80,80,47,47
3	100,100,100,100	133,100,100,100	113,88,88,88	100,80,80,80	86,79,79,79	94,76,65,65	89,72,61,61	85,70,60,60
6	91,91,91,91	108,100,92,100	100,86,86,86	94,88,81,81	85,75,80,70	91,83,70,70	88,79,67,67	85,77,65,62
9	88,88,88,88	100,88,88,88	95,84,84,84	90,81,81,76	84,76,80,72	89,75,71,68	86,72,69,66	84,71,68,65
12	71,71,71,71	82,73,77,73	79,71,79,71	77,65,77,65	73,67,73,63	79,67,73,61	76,65,71,62	75,92,67,58
15	59,59,59,59	68,61,64,61	67,60,67,60	66,56,66,56	64,58,64,56	69,59,64,54	68,58,63,53	67,57,60,52
18	55,55,55,55	63,59,59,59	62,56,62,56	61,56,61,53	60,55,60,53	65,53,60,51	64,52,59,50	63,52,57,48
21	46,46,46,46	53,50,50,50	53,48,53,48	52,48,52,45	52,48,52,52	57,47,53,45	56,46,52,44	56,46,50,42
24	43,43,43,43	49,46,46,46	49,44,49,44	49,44,49,42	49,47,49,45	54,44,50,42	53,43,49,42	53,44,47,40
27	41,41,41,41	47,44,44,42	47,43,47,43	47,41,47,41	47,43,47,42	52,41,48,39	51,40,47,39	51,41,46,37
30	38,38,38,38	43,41,41,39	43,39,43,39	43,38,43,38	44,40,44,39	48,40,45,38	48,39,44,38	48,40,43,37
33	36,36,36,36	41,37,39,37	41,36,41,36	41,34,41,34	42,37,42,35	46,37,43,35	45,36,42,35	46,37,41,34
36	36,36,36,36	40,37,39,37	41,36,41,36	41,34,41,34	42,37,42,35	46,37,43,35	45,36,42,35	45,37,41,34
39	34,34,34,34	39,35,37,35	39,34,39,34	39,33,39,33	40,36,40,34	44,36,41,34	43,35,41,34	43,36,39,33
42	33,33,33,33	37,34,35,34	37,33,37,33	38,33,38,33	38,34,38,33	42,34,39,33	41,34,39,33	41,34,38,32
45	32,32,32,32	36,33,35,33	36,32,36,32	37,32,37,32	38,33,38,31	41,33,39,31	40,32,38,31	41,33,37,30

	Numbers of top-layer traffic flows							
Numbers of bottom-layer traffic flows	8	9	10	11	12	13	14	15
0	94,94,44,44	100,100,48,48	88,88,40,40	89,89,41,41	87,87,37,37	88,88,38,38	94,94,36,36	91,91,35,35
3	96,83,57,57	100,88,58,50	90,80,50,47	91,81,50,50	89,77,46,49	89,76,46,46	95,82,45,45	92,79,44,44
6	59,79,62,62	97,84,63,59	89,78,56,56	89,76,55,55	88,76,51,54	88,77,51,51	93,80,50,50	91,78,49,49
9	91,71,65,59	95,76,65,54	88,71,59,51	88,70,58,51	87,67,54,50	88,69,54,48	92,71,53,47	90,70,52,46
12	82,67,67,56	86,69,64,52	80,65,61,48	81,67,63,50	80,67,59,49	81,66,58,47	85,69,57,46	84,67,56,45
15	73,60,60,51	77,63,58,48	73,60,56,44	74,61,57,46	74,63,54,46	75,63,54,44	78,65,53,43	77,64,52,43
18	69,55,57,47	73,58,56,44	70,55,54,43	71,57,55,43	70,59,52,43	71,59,52,41	75,61,52,41	74,60,51,40
21	62,49,51,42	66,52,50,40	63,50,48,39	64,52,50,41	64,54,48,39	65,54,48,38	69,56,47,37	68,55,46,37
24	59,47,48,40	62,49,48,38	60,48,46,37	61,49,48,39	61,51,46,39	63,51,46,38	66,53,45,37	65,53,45,36
27	56,44,47,37	60,46,46,35	58,45,45,35	59,46,46,37	59,49,45,36	61,49,45,36	64,51,44,35	63,50,44,35
30	53,41,44,36	57,43,43,35	55,42,42,34	56,44,44,35	56,46,42,35	58,46,43,34	60,48,42,33	60,48,41,33
33	51,38,42,34	54,41,42,32	53,40,41,32	54,41,43,33	54,43,41,33	55,44,41,32	58,45,41,31	57,45,40,32
36	50,38,42,34	53,42,42,32	52,41,41,32	53,42,42,34	53,43,41,34	55,44,41,33	57,46,40,33	57,46,40,32
39	48,38,41,33	51,41,40,33	50,40,40,33	51,41,41,33	52,43,40,34	53,44,40,33	55,46,39,33	55,45,39,33
42	46,35,39,33	49,39,36,32	48,38,38,32	49,39,39,32	49,40,38,32	51,41,38,31	53,43,38,31	52,43,38,32
45	45,34,38,31	48,37,38,30	47,36,38,30	48,38,39,31	49,38,38,31	50,40,38,30	52,41,38,30	51,41,37,30

†format: Strategies A, B, C, D

8.0 CONCLUSIONS AND FUTURE WORK

This chapter provides a summary of the dissertation, and suggests some possible extensions and future work. The focus of this dissertation is to provide an analytical framework for survivability in layered networks. We considered a three-layer network in the explicit context of an overlay-over-IP-over-WDM and investigated the relationship between and among network layers. The major contributions and results of this dissertation have four core components, all of which address issues related to the fundamental design problems of survivability in multilayered networks as discussed below.

8.1 DISSERTATION SUMMARY

In this dissertation, we addressed a new issue related to the design of multilayer networks, namely backhaul, which is a routing loop that occurred due to improper link mapping. This backhaul can occur in any layered network graph of three or more layers, each of which could be a network or traffic layer. We examined the network by dissecting it into two different layers, which we called the network layer and the traffic layer. The first layer type is defined per nodes and links whereas the latter is defined per communications pair. This separate examination has allowed us to consider the two problems of network survivability and traffic survivability in more detail. Table 8.1 shows a summary of our contributions and Figure 8.1 illustrates the relationship between and among the major contributions presented in Chapters 4 - 7. Although we differentiate network survivability from traffic survivability, they are interconnected.

We first revealed the backhaul problem that may occur in a multilayer network and

Table 8.1: Summary of contributions

Crosslayer Survivability	**Network Survivability**			**Traffic Survivability**
Approach	Optimization			
Theory/Model	Crosslayer Survivable Mapping	Forbidden Link Matrix	Convex Mapping	Survivability Strategies
Examples	Backhaul-free mapping	Classified networks where some nodes/links are hidden to customers	Maximize availability/ guaranteed services	Ways to implement survivability for each traffic load scenario

proposed an efficient and effective implementation of crosslayer survivable mapping which can overcome this problem. We proposed an optimization model that considers both of the backhaul problem and the capacity allocation problem; this model is documented in Chapter 4.

Then we extended the idea of backhaul-free network mapping and routing and further considered ways to offer multi-leveled service in a multilayer network. We discussed two possible approaches. The first approach was based on network differentiation. Different customers could see different network topologies. The forbidden link matrix was introduced such that it could be included in the original mathematical formulation. We demonstrated that they can be integrated together well. We also made some observations that should be useful in a survivable network design *e.g.,* links at the edge of a network may be of more importance when considering protection from failure. This model is documented in Chapter 5.

The second approach was based on a link metric. We considered network mapping

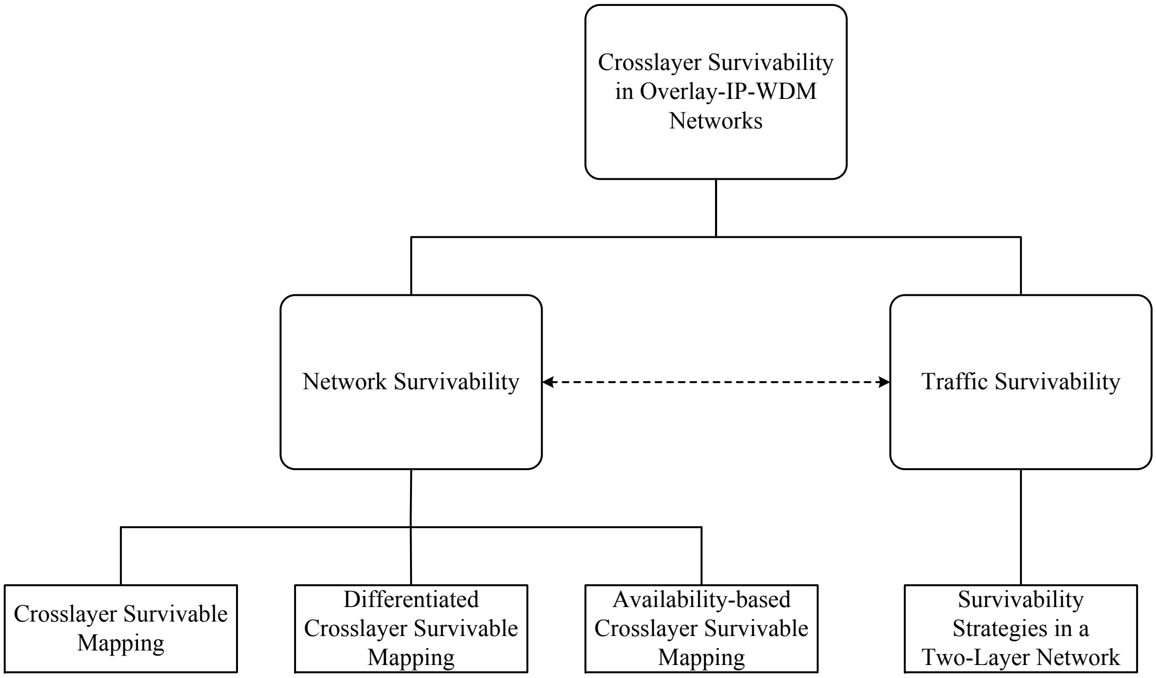

Figure 8.1: An illustration of the summary of contributions

and traffic routing in various convex network mappings. We examined the availability link mapping in detail. This is the subject of the third part of the dissertation. We provided an optimization model that included the availability metric in the original crosslayer survivable mapping formulation showing that in some cases there are equal cost mappings, but some have higher availability. This idea is very similar to that in Linear Programming sensitivity analysis. This model is documented in Chapter 6.

In the final part of the dissertation, we looked more closely at traffic survivability in a multilayer network. Because when there is no backhaul, a network of n layers can simply be reduced to a two-layer network, we considered a two-layer network in this part. We developed the matrix formulations of the four possible survivability strategies that can be implemented in any two-layer network. We discussed in detail benefits and drawbacks of each choice when traffic is present at each and every layer. This allows for the best implementation to be chosen from the four possible survivability strategies in each traffic load scenario. The strategies are documented in Chapter 7.

This research work is in the early stages of considering multilayer network design with efficient link use and capacity allocation. When an optical WDM network is considered, this link use refers to the efficiency of optical resources, channels or lightpaths. Although we used an overlay-IP-WDM network as an explicit example of multilayer networks, this work can be applied to any layered network graph. We further considered a case when traffic may be present in a network; in this case, we further differentiated the traffic layer from the network layer. This led us to a more thorough analysis of a survivable multilayer network design, which is discussed throughout the dissertation.

8.2 FUTURE WORK

The work presented here can be extended in several directions. First, the investigation of link mapping and traffic routing sheds some light on the relationship between and among links and traffic in different layers as well as links which are forbidden. However, these relationships could be further examined in the context of matrix algebra [98], [99]; some examples are given in Table 8.2. Second, joint optimization of the two approaches also deserves attention. We expect that it plays a role when taking the two criteria concurrently. These problems could be central to our future research.

Built upon the work in this dissertation, the immediate future work would include:

- Including additional numerical results for a various number of links, nodes, and layers. As described in Chapter 4, the crosslayer survivable mapping serves as a theoretical framework for backhaul-free mapping and routing in a multi-layer network. Together with the use of a forbidden link matrix in Chapter 5 and the inclusion of an availability metric in Chapter 6, possible directions of extension are given. For example,
    1. Multiple overlay networks, each of which represents a resilience or availability class. In practice, an overlay network could be constructed for each application. In this direction, further work would be to consider crosslayer survivable mapping and routing that has no backhaul for each overlay network over the same IP-over-WDM infrastructure network. The effect of the resource allocation, or resource sharing

Table 8.2: Crosslayer connectivity metrics for survivable layered networks

Single-layer network	Multi-layer network
Edge connectivity	Crosslayer link mapping[†]
Algebraic connectivity	Crosslayer algebraic connectivity
Betweenness centrality	Crosslayer betweenness centrality
Closeness centrality	Crosslayer closeness centrality
Degree centrality	Crosslayer degree centrality
Eigenvector centrality	Crosslayer eigenvector centrality

†has already been investigated

contention, on the survivability of each overlay would be worth a look.

2. A combination of forbidden link matrix and maximum availability mapping approaches. This combination would bridge the gap between network provider policies and customer needs by considering both approaches; it would also prevent the network provider from compromising its network differentiation policy for service availability.
3. The presence of traffic at every layer. As laid out in Chapters 4, 5, and 6, one potential further area of study involves including more numerical results when traffic is present at each and every layer simultaneously. The survivability and capacity allocation as a result of this consideration also deserves further investigation and analysis.

Furthermore, the dimensions of further work which would complement this dissertation include:

- Exploring further at a more detailed level the use of the mapping schemes presented in Chapter 6. Examples can be given on various networks and when traffic is present. By including requirements such as availability in the mapping and routing designs, we should efficiently yield better traffic routing, thereby requiring less capacity and, at the same time, having a higher chance of survivability.

- Examining the link relationship among layers in a layered network in the context of matrix algebra. This may include the new development of network mapping with good crosslayer connectivity, which could be measured by one or more of the following quantities: algebraic connectivity, betweenness, closeness, degree, and eigenvector centralities.
- Implementing good algorithms for dynamic overlay mapping to support dynamic changes in traffic patterns. These may include the development of efficient solution techniques to the optimization problems posed in this dissertation; for instance, through using heuristic algorithms, approximation algorithms, or both.
- Extending the general framework presented in this dissertation to include the case of multihop wireless networks. In wireless networks, interference between and among neighboring nodes is a major factor impacting data transmission. In this context, a conflict graph [100] could be used to recognize such a problem by including it in our proposed formulation. This direction of possible future work is expected to provide some valuable insights into the design of wireless core networks.

8.3 CONCLUSIONS

We are moving into a new era of multi-layer networks. Survivability network designing in the planning phase is sophisticated but from the information provided in this dissertation, it is clear that each layer should not be designed separately. We show that a complete picture of the network is essential for efficient capacity allocation and the survivability of services in each network layer. Ironically enough, the dependency of layers, which until now has largely been considered as an insignificant issue, is shown to be extremely important, even when a backup path is provided.

This dissertation advances our understanding of the structure of multilayer networks and establishes a mathematical framework for the survivability of such networks. This work can be extended in a number of promising directions for further research including multilayer routing, differentiated availability guarantees when some mapping choices are more robust than the others, and overlay topology design.

APPENDIX

A TAXONOMY OF CROSSLAYER SURVIVABILITY IN LAYERED NETWORKS

This appendix provides a summary of the taxonomy defined and used in this dissertation.

Backhaul: A mapping (routing) loop occurred due to improper link mapping (routing).

Backhaul Mapping: A mapping loop occurred due to improper link mapping.

Backhaul Routing: A routing loop occurred due to improper traffic routing.

Capacity Overbuilding: A ratio of excess capacity due to backhaul to the capacity requirement when there is no backhaul.

Crosslayer Survivable Link Mapping: A mapping function which correlates links in one layer to those in the adjacent layer such that the upper-layer network remains connected after a single-link failure in the lower-layer network, and no backhaul occurs.

Flow Overrouting: A ratio of the number of backhaul flows to the number of total flows.

Link Mapping: A mapping function which correlates links in one layer to those in the adjacent layer.

Link Overusing: A ratio of the number of backhaul links to the total number of links used by traffic.

Network Mapping: A mapping function which correlates links or nodes or both in one layer to those in the adjacent layer.

Network Redundancy: *see Resource Overbuilding.*

Network Survivability: The connectivity of an upper-layer network after a lower-layer link failure *e.g.,* two-connected networks.

Node Mapping: A mapping function which correlates nodes in one layer to those in the adjacent layer.

Redundancy: *see Resource Overbuilding.*

Resource Overbuilding: A ratio of backup path capacity to the primary path capacity, also known as Network Redundancy or Redundancy.

Traffic Routing: A way in which two disjoint paths can be found for each communications pair, preferably, with minimum capacity use.

Traffic Survivability: The ability to restore traffic *e.g.,* via two disjoint paths, primary and backup.

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