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Methods for Optimising Operation of Heterogeneous Networks

— D.Sc. Dissertation —

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*Gyermekeimnek,
Jolán Borbálának és Soma Zsoltnak,
akik az ihlet és a boldogság
kimeríthetetlen forrásai voltak
minden pillanatban...*

*Édesanyámnak és Édesapámnak,
negyvenegynéhány éves
bizalmukért, hitükért és
a biztos hátországért...*

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"Per aspera ad astra!"

„Az élet semmit sem ad a halandónak munka nélkül."

Seneca

"Nullus agenti dies longus est."

Seneca

„Mondottam, ember küzdj és bízva bízzál!"

Madách Imre: *Az ember tragédiája*

„Dolgozni csak pontosan, szépen,
ahogy a csillag megy az égen,
úgy érdemes."

József Attila

„Hass, alkoss, gyarapíts:
s a haza fényre derűl!"

Kölcsey Ferenc: *Huszt*

„Semmilyen szél nem kedvez annak,
aki nem tudja, melyik kikötőbe tart."

Seneca

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Preface

This dissertation was submitted to the Hungarian Academy of Sciences in partial fulfillment of the requirements for the title of the "Doctor of the Hungarian Academy of Sciences".

It summarises my results on routing, multicasting, traffic engineering and resilience in multi-layer and multidomain optical-beared modern transport networks achieved during my post-doctoral research. I have proposed models and algorithms for the above problems. The results are presented in Chapters 1, 2 and 3 in more details, they are summarised in Chapter 4 in 3 pages, while the booklet of theses lists the results with short explanation in roughly 6 pages in Hungarian.

Chapter 1 consists of results on resilience. It presents various approaches to reduce resource requirements while maintaining high level of availability.

Chapter 2 presents results related to grooming in two-layer networks. Models, ILP formulations and algorithms are presented.

Chapter 3 deals with methods for PICR, Physical Impairment Constrained Routing.

The results described in the dissertation can be efficiently used as a support tool for control or management of networks.

Chapter 1

Resilience of Networks

1.1 Introduction

In infocommunications networks there appear new applications all the time that face the network operators with new needs including the ever increasing requirement for higher availability.

Just to mention some examples. The electronic payment and the banking system must be always available, our VoIP systems as well as telephone systems must be always usable, our virtualised, often web based office applications, stored files, data centers and cloud computing facilities must be always accessible, not mentioning the high definition video contents where not only interrupts but also quality deteriorations are not tolerated by the users.

The problem is that the networks became rather heterogeneous, including the data plane, as well as the management and control planes. Under heterogeneity we mean multiple layers (MLN: Multi-Layer Network), multiple domains (MD), multiple networking technologies (MRN: Multi-Region Network) and protocols, multiple services and QoS requirements, multiple vendors, etc. In such heterogeneous, and therefore rather complex networks it is rather hard to satisfy the high availability expectations in a simple, scalable, cost-effective way.

1.1.1 On Availability

When guaranteeing availability of "four nines" (0.9999), "five nines" (0.99999) or "six nines" (0.999999) that are availability levels often required in practice the network is unavailable for up to 52.56 minutes, a bit over five minutes (5 min 15.36 sec) or a bit over half a minute (31.536 sec) respectively during a whole year! This can be not kept by repairing the failed network components upon a failure. The network must be equipped with mechanisms that "heal" the failed parts of the network by automatically bypassing failed components. The de facto standard for restoring network services upon a failure is 50 ms. This value was defined for SDH/SONET networks, however, it is now a requirement for all networks. The objective is to guarantee this value, in the most cost effective way. I.e., to use few resources to save CAPEX or to use very simple mechanisms to save the OPEX.

1.1.2 On Resilience

The term *Resilience* covers those schemes or mechanisms that make the network recover its services in short time upon a failure.

1.1.3 Protection or Restoration?

These mechanisms are traditionally classified into *Protection* and *Restoration* mechanisms. The difference is that while protection mechanisms have protection resources allocated in advance, and protection paths or segments of protection paths assigned to the resources the restoration schemes have typically no assigned protection paths, but they rather operate over instantly available free resources. The consequence of the operation is that protection works faster, however, requires

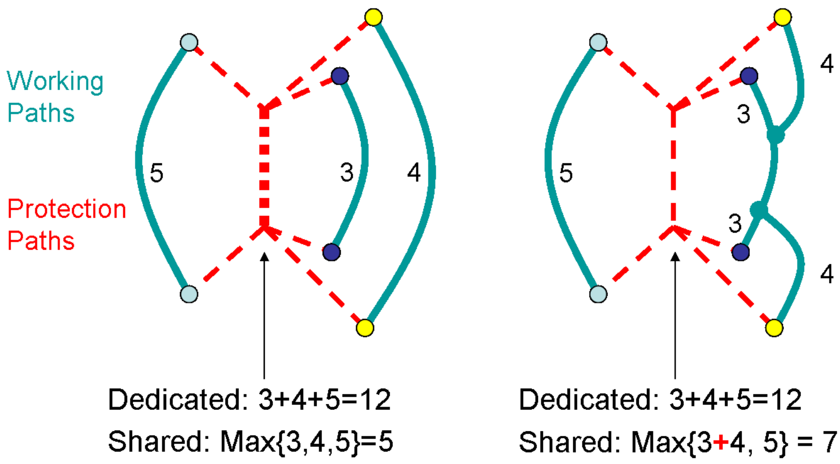

Figure 1.1: Illustration of the Shared vs. Dedicated Protection when some working paths share the risk of a single failure.

typically more resources. Restoration is typically slower, needs more complex control, however, it is more flexible, can restore typically multiple failures, and requires less data plane network resources. We will focus mostly onto protection schemes in this chapter.

1.1.4 Dedicated or Shared?

From the point of view of resource utilisation the protection schemes can be classified into *Shared* and *Dedicated*. In case of Dedicated each working path has a protection one, typically with the same capacity allocated along it. In case of 1+1 Dedicated Protection, sometimes referred to as "hot stand-by" the traffic is sent from the source along both paths, and the receiving end decides which signal to use. The 1:1 or "could stand-by" approach assumes that both, the sending and the receiving end have to switch to the protection path in any case the working path is affected. Here we will focus to the *Shared Protection* schemes, where we assume that a single failure can be present in the network at a time, and therefore any two working paths that have no element in common can share a protection path or a segment of a protection path, since either one or the other working path will need it, but never both of them, therefore, it is sufficient to allocate resources for the larger one only.

Figure 1.1 illustrates these cases. On the left hand side figure all three working paths having capacity requirements of 5, 3 and 4 respectively can share a protection path segment, since they have no element in common. Therefore 5 units of capacity instead of 12 are sufficient for shared protection in contrast to dedicated protection. However, if two paths have any element that can fail at the same time, then they belong to a Shared Risk Group (SRG) (in this case Shared Risk Link Group (SRLG)) and the sum of these two paths has to be considered in evaluating protection allocations as illustrated in the left hand side of Figure 1.1.

1.1.5 Path, Segment or Link?

Next we discuss the scope of protection. There are three cases.

First, when we protect each working path by a single protection end-to-end path that is completely disjoint from the working one (only the source and the target nodes are common) [97, 11]. In Figure 1.2 this protection scope is illustrated by a dashed-dotted thin line marked as "end-to-end / path". In this case the strong disjointness is illustrated when there is neither link (edge, arc), nor node (vertex) in common for the working-protection path pair. In weaker sense it is sufficient if no common links are present. Regardless which element of the working path will fail, the same protection path will be used. This is a failure independent scenario.

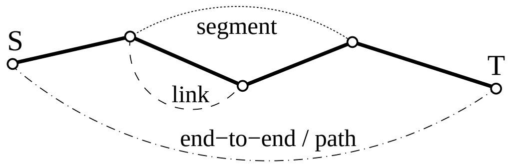

Figure 1.2: Link-, Segment-, and End-to-end Path Protection.

Second, when each link (or each element in general) of the working path has its own protecting bypass, typically one or more links, i.e., a segment. In Figure 1.2 this protection scope is illustrated by a dashed thin line marked as "link". Clearly, this is a failure dependent scenario. Ring protection and p-Cycle protection are typical examples of link protection. Local control is sufficient, the protection is very fast, however, it typically uses more network resources than path protection.

Third, when two or more links have a common protection path segment is the tradeoff between path and link protection. This is illustrated by a thin dotted line in Figure 1.2 marked as "segment". In this case not only the different working paths can share protection resources, but also the multiple segments or links of a single working path can mutually share protection resources, since these segments are mutually disjoint [43].

1.1.6 The Structure of the Chapter

This Chapter on Resilience is structured as follows. In Section 1.2 a lower bound on the cost (resource requirement) of any shared protection scheme is provided. In Section 1.3 a resilience method is proposed that reoptimises all the protection resources together with the working and protection paths of any new demand. Section 1.4 proposes two new schemes for routing elastic traffic with protection along with a new fairness definition referred to as relative fairness. Section 1.5 presents two different approaches for performing shared protection in a multi-domain environment, where no sufficient information is available for sharing resources.

1.2 GSP: Generalised Shared Protection

GSP gives the bound on the Best Single-Demand Generalised Shared Protection. It finds for each demand the best general shared protection, regardless weather it is link-, segment- or end-to-end path-protection. Therefore, we will refer to it as GSP, the Generalised Shared Protection. This is a very good reference method for routing and protecting a single demand in most cost efficient way. Since its ILP formulation is quite simple we provide it here.

1.2.1 ILP Formulation of the GSP

Let $\mathcal{N}(V, E, B^{free})$ be a network defined by vertices $v \in V$; edges $e(i, j) \in E$ where $i, j \in V$; and free bandwidths (or capacities) on edges e: $b(e) \in B^{free}$ where $e \in E$. B^{free} is the vector of currently available free capacities over all links e, i.e., if some demands are already routed over links e their bandwidth is subtracted from the capacity of that link.

Let (s, t, b) define the demands to be routed with GSP protection scheme. s is the source, t is the target (destination) of demands, while b is their bandwidth requirement. We assume routing a single demand at time.

Let $|B_{ij}^{kl}|$ be the matrix of extra bandwidth requirements for generalised shared protection of a demand having bandwidth requirement b as illustrated in Table 1.1. Each value of B_{ij}^{kl} in the matrix expresses how much additional bandwidth has to be allocated for protecting a demand over link ij that uses link kl in its working path by GSP. This conditional knowledge will help us to route simultaneously both, the working and the protection paths of a single demand.

Table 1.1: The illustration of the $|B_{ij}^{kl}|$ matrix.

	1	2	3	$\cdots$	kl	$\cdots$	$\vert E\vert$
1							
2							
3							
$\vdots$					$\vdots$		
ij				$\cdots$	B_{ij}^{kl}	$\cdots$	
$\vdots$					$\vdots$		
$\vert E\vert$							

Here we define the variables, the objective and the constraints of the ILP (Integer Linear Program) or more precisely of the MILP (Mixed Integer Linear Program).
Variables:

$x_{ij} \in \{0,1\}$ working flow over edge $ij \in E$

$y_{ij}^{kl} \in \{0,1\}$ protection flow over edge $ij \in E$ that corresponds to the working flow over edge $kl \in E$, i.e., $(ij,kl) \in E^2$

$B_{ij}^{max} \in R$ is a real variable that expresses the amount of protection capacity to be used over link ij in optimal case

Objective:

$$min\left\{b \sum_{\forall ij \in E} x_{ij} + \alpha \sum_{\forall ij \in E} B_{ij}^{max} + \beta \sum_{\forall ij \in E} \sum_{\forall kl \in E \setminus \{ij\}} y_{ij}^{kl}\right\} \tag{1.1}$$

The first term minimises the total bandwidth used by the working path, the second term minimises the total bandwidth allocated for GSP protection, while the third term expresses the total number of links used by protection segments and protection paths . Consequently these three terms have to be weighted adequately. We assume that the first term has weight of 1 assigned, the second term has a value of $0 < \alpha < 1$ typically $0.5 < \alpha < 0.9$ to slightly prioritise the working to protection paths, and the weight of the third term is $0 < \beta \ll 1$ where it should have an infinitesimal value just to avoid accidentally nonzero y variables. By increasing β we will force protection paths become shorter and fewer, that leads sooner or later to end-to-end path protection instead of link or segment protection. Setting the value of β to zero the third term will be neglected. Then the objective will minimise the total capacity only.
Subject to:

$$\sum_{\forall k \in E^{\to l}} x_{kl} - \sum_{\forall m \in E^{l \to}} x_{lm} = \begin{cases} -1 & \text{if } l = s \\ 0 & \text{otherwise} \\ 1 & \text{if } l = t \end{cases} \quad \forall l \in V \tag{1.2}$$

$$\sum_{\forall h \in E^{\to i}, hi \neq kl} y_{hi}^{kl} - \sum_{\forall j \in E^{i \to}, ij \neq kl} y_{ij}^{kl} = \begin{cases} -x_{kl} & \text{if } i = s \\ 0 & \text{otherwise} \\ x_{kl} & \text{if } i = t \end{cases} \quad \forall i \in V, \forall kl \in E \tag{1.3}$$

$$y_{ij}^{kl} B_{ij}^{kl} \leq B_{ij}^{max} \quad \forall kl \in E, kl \neq ij, \forall ij \in E \tag{1.4}$$

$$x_{ij} b + B_{ij}^{max} \leq B_{ij}^{free} \quad \forall ij \in E \tag{1.5}$$

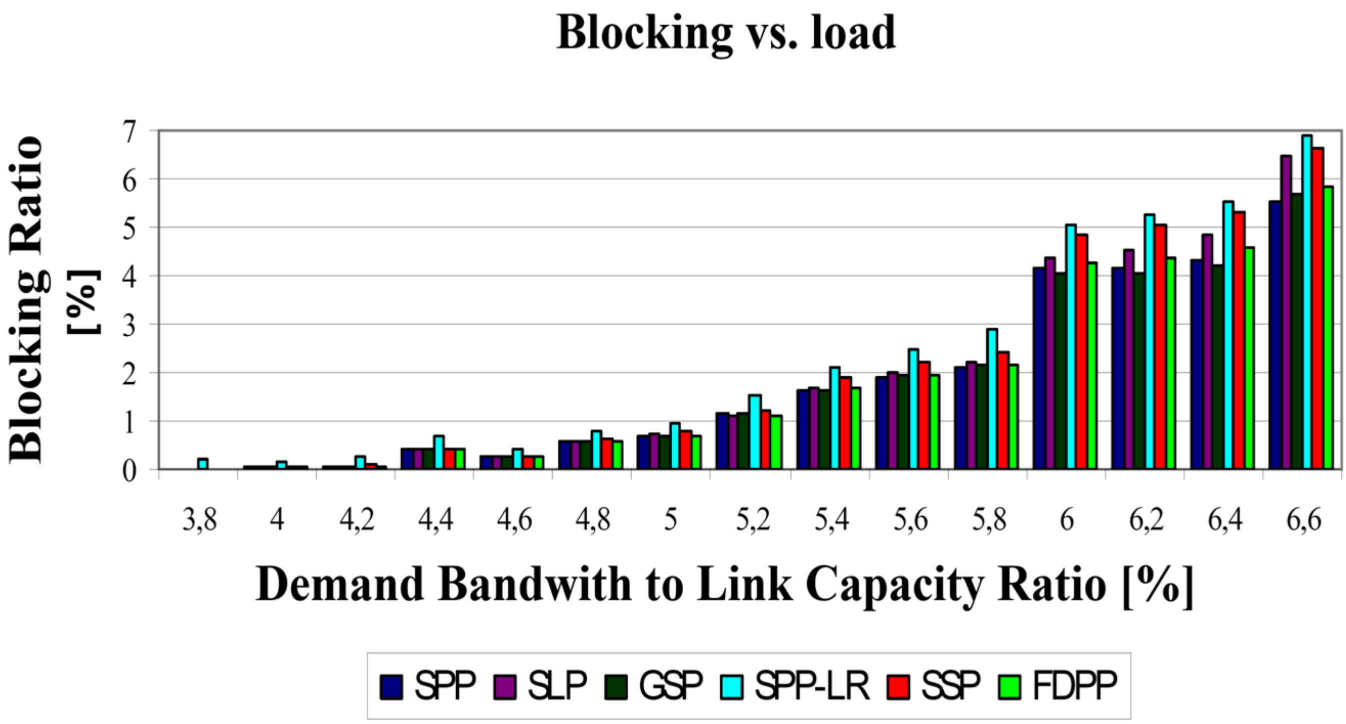

Figure 1.3: Comparing blocking ratios of five different protection methods to the GSP as the load increases in the network by scaling up the bandwidth b of demands.

1.2.2 Results

The results are shown in Figure 1.3. GSP is compared to five other protection methods:

- SPP: Shared Path Protection;
- SLP: Shared Link Protection;
- SPP-LR: SPP with LEMON Routing library [67] combinatorial solution;
- SSP: Shared Segment Protection;
- FDPP: Failure Dependent Path Protection.

It is interesting to note, that although GSP routes in any case the demand in most cost efficient way, in longer term in some cases it has suboptimal performance, since although all the protection paths are cheapest possible, they are often quite long, because they use those links for protection where no extra capacity is needed. In short term this thrifty scheme is advantageous, however, in longer term it uses to many resources and leads to blocking when the network is filled. All the numerical results were obtained running ILOG CPLEX [49] at our department computers and GNU GLPK [36] on supercomputers for solving the ILPs. The considered network was the COST266BT reference network, and the traffic was increased by increasing the ratio of its bandwidth to the link capacity from 3.8 to 6.6.

1.3 Adaptive Shared Protection Rearrangement

I propose a new approach with two algorithms for dynamic routing of guaranteed bandwidth pipes with shared protection that provide lower blocking through thrifty resource usage.

We assume that a single working path can be protected by one or multiple protection paths, which are partially or fully disjoint from the working path. This allows better capacity re-use (i.e., better capacity sharing among protection paths). Furthermore, the resources of a working path affected by a failure can be re-used by the protection paths.

The main feature of the proposed protection rearrangement framework is that since the protection paths do not carry any traffic until a failure they can be adaptively rerouted (rearranged) as the traffic and network conditions change. This steady re-optimisation of protection paths leads to lower usage of resources and therefore higher throughput and lower blocking.

The other novelty we propose in this paper is a modelling trick referred to as LD: Link Doubling that allows distinguishing the shareable part of the link capacity from the free capacity in case when multiple protection paths are being rerouted simultaneously. LD allows finding optimal routing of shared protection paths for the case of any single link failure!

The obtained results can be used for routing with protection in SDH/SONET, ngSDH/SONET, ATM, MPLS, MPLS-TP, OTN, Ethernet, WR-DWDM (including ASTN and GMPLS) and other networks.

This section is organised as follows. In Section 1.3.1 the problem is formulated, Section 1.3.2 presents the reference method used, while the idea of LD is presented in Section1.3.3. The two proposed methods are presented in Section1.3.4 and 1.3.5. Section 1.3.6 presents and evaluates the obtained numerical results.

1.3.1 Problem Formulation

The problem is how to optimally choose one working and one or more protection paths for a demand. Here we formulate the problem and in the next section we propose methods for solving it.

According to the above definitions, our protection methods

- are shared
- are adaptive
- operate on segments (sub-networks) that can be a single or multiple links long and are determined when the protection paths are sought
- use partially disjoint paths
- guarantee survival of any single failure, but work for some multiple failure patterns as well.

The probability of having two independent failures in the network at the same time is low, even lower for two failures along the same path. Therefore, it is justified to share protection resources (Figure 1.1).

The algorithm for determining the amount of capacity to be allocated for backup paths in thrifty way, is based on the idea explained on Figure 1.1 [C36] . The capacity C_l of each link l is divided into three parts (Figure 1.4):

1. C'_l allocated to working paths;
2. C''_l allocated for (shared) protection (i.e., spare capacity); and
3. $C_l - C'_l - C''_l$ the free, unallocated and unused capacity.

Given a network $N(V, E, C)$ with nodes (vertices) $v \in V$, links (edges) $e(v_1, v_2) \in E$ and link capacities C_l we want to satisfy all dynamically arriving (in advance unknown) traffic demands [C140] defined as a Traffic Pattern $T(o : o(s_o, d_o, b_o, \tau'_o, \tau''_o))$ where b_o stands for the bandwidth of traffic demand o between source node s_o and destination node d_o that has arrived at time τ'_o, and lasts until τ''_o.

The working path $P'(o) = (e'_1, e'_2, ...e'_{|P'|})$ should be the shortest path with available capacity b_o. Another "shortest" path $P''_{e'}(o) = (e''_1, e''_2, ...e''_{|P''_{e'}}|)$ is sought for each link e' of the working path $P'(o)$, that may fail, such that $e' \notin P''_{e'}$.

"Shortest" means the path that requires the lowest resource allocation from the $C - C' - C''$ capacities (i.e. the lowest increment of C'' capacities). The path is the shortest one in sense of the

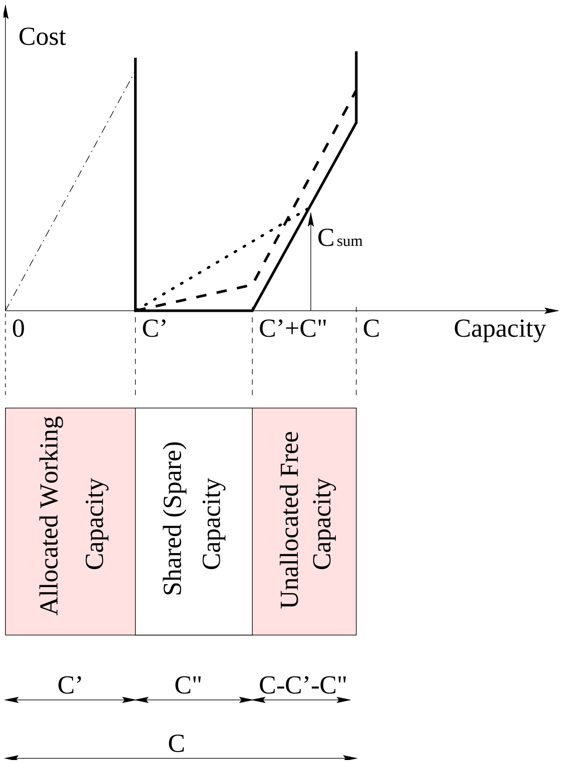

Figure 1.4: Three Capacity Cost Models for Protection Paths

capacity-cost functions shown in Figure 1.4. For routing the protection path for demand o that has bandwidth b_o we have to reserve on each link that amount of capacity only that exceeds the capacity that is shareable by the considered demand over the considered link. The sum of the costs of these non-shareable capacities for all the links along a path has to be minimal. This is the only metric we have used while routing. These paths $P''_{e'}(o)$ are referred to as partially disjoint, shared protection (PDSP) paths for path $P'(o)$.

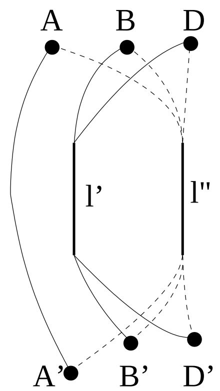

Figure 1.5: How to calculate the Capacity allocated for Shared Protection?

This problem can be formulated mathematically using graph theory and network flow theory. Due to the complexity of the problem, we apply heuristics with the aim of being close to the global optimum. These heuristics include decomposition, approximations and modeling tricks.

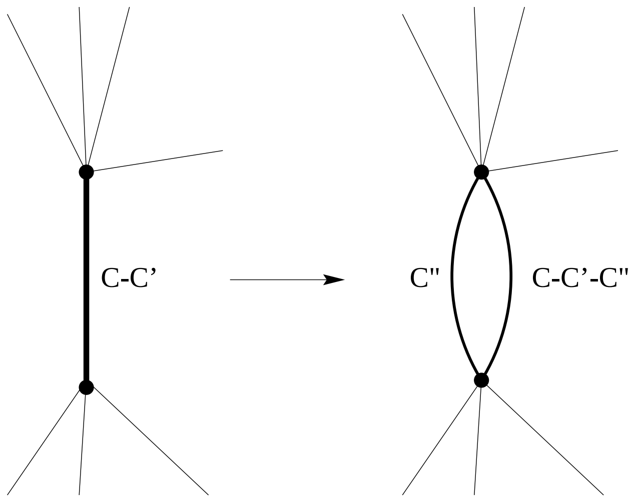

Figure 1.6: Illustration of the Link Duplication

1.3.2 The Reference Method: Shared Path Protection (SPP)

As the reference we use the well known Shared Path Protection, where after routing the working path, we search for an end-to-end disjoint protection path that requires the lowest cost in the sense of the capacity cost function 1.4. We have to note here, that to avoid loops and overlengthy paths the shareable capacity was not for free, however, its unit capacity costed only a fraction of the cost of a unit of free capacity to be allocated. The same principle was used for all the evaluations in this section: the cost ratio was 1:10.

Here we briefly describe the Shared Path Protection algorithm:

The algorithm works as follows:

- Step 1: For the new demand o_{new}:
  - Find the shortest working path.
  - Delete (hide) temporarily all the links of the working path.
- Step 2: For all links l' of the working path:
  - For all links l'' of potential protection paths:
    - Compute capacity $C_{l',l''}$ required on linkl'' when linkl' fails (Figure 1.5 and 1.1).
- Step 3: Find the largest value $C_{l''}$ of $C_{l',l''}$ for all l' found so far.
- Step 4: Calculate the cost increment required for routing the protection path of bandwidth requirement b_o of demand o_{new} according to figure 1.4 based on $C_{l''}$ along all the links l'' in the network.
- Step 5: Based on the cost increments obtained find the shortest protection path.
- Step 6: Store the new paths, deallocate resources for terminated connections, update the capacity allocations.
- Step 7: If more new demands arrive go to Step 1.

Shared Path Protection (SPP) is considered as a reference without the capability of rerouting (rearranging) the previously allocated protection paths. It is a really fast and easy solution for shared protection.

1.3.3 LD (Link Doubling)

In Section 1.3.2 we have presented the reference method, the SPP. Now we explain the idea of Link Doubling (LD) followed by the MILP formulation of Protection Re-arrangement and by our two proposed methods, namely Shared Path Protection with Link Doubling (SPP-LD) and Partially Disjoint Shared Path protection with Link Doubling (PDSP-LD).

Here we introduce LD, where LD stands for link doubling. LD is not an algorithm in itself but a modelling trick, however, it is the basis of the two proposed algorithms. First we explain why we need LD, then we explain how it works.

In a network that supports protection sharing, before routing the protection path of demand o with bandwidth requirement b_o, we simply calculate the amount of capacity it would need over the shareable link. This capacity depends on two things. First, the amount of capacity of the demand exceeding the shareable part depends on the bandwidth b_o of that demand. Second, the allocated spare capacity C'' is not fully shareable by any demand, but typically only a part of it. Remember, that if two demands have a common link l' in their working paths, then they may not share capacity on link l'' (Figure 1.1).

One of the basic principles of our proposed methods is that we rearrange the protection paths, i.e., re-route them simultaneously. When we want to route protection paths of more than one demand simultaneously we face the above described problem. The bandwidth requirements of different demands will be different, and it will often happen that two or more protection paths that would share a link have a common link in their working paths. LD solves this problem.

In LD we use a modeling trick to be able to represent the two-segment cost function as shown in Figure 1.4 by solid line, or by the dashed line, to avoid unnecessarily long paths. Since the two segment capacity-cost function is a non-linear one we can neither use it in an ILP (Integer Linear Program) formulation, nor by the Dijkstra's algorithm. Therefore, linearisation is needed.

The idea here is to use two parallel links (as shown in Figure 1.6) that both have linear capacity cost functions and represent the two segments of the cost function shown in Figure 1.4. The link representing the shared spare capacity will have capacity C'' and the same or lower cost than the other link, which represents the free capacity $C - C' - C''$.

The drawback is, that the number of links doubles in the worst case and therefore the runtime becomes longer, while the advantage is that we can get optimal result. Without LD an alternative would be to make a single segment linear approximation of the two segments, however, the result would be suboptimal.

For routing multiple shared protection paths an MILP (Mixed Integer Linear Programming) formulation is needed. Using LD the problem is linear and feasible.

MILP Formulation

In this section we present the MILP formulation of the problem of routing multiple shared protection paths simultaneously. The protection rearrangement means, that first we remove the considered protection paths from the network, recalculate all the free and shareable capacities and then we route all the removed paths and the new protection paths simultaneously as follows.
Objective:

$$\min \sum_{o \in T_e} \left\{ \sum_{l \in E^{free}} x_l^o w_l + \sum_{l \in E^{sh}} x_l^o \gamma_l \right\} \tag{1.6}$$

Where E^{sh} is the set of all added (doubled) edges, with capacity C'', representing the shareable part and E^{free} with capacity $C - C' - C''$ being the set of edges that represent the remaining free capacity of all edges. Now $E' = E^{sh} \cup E^{free}$. Note, that E' is the extended set of edges in contrast to E. Note, that the capacity used for working paths is not represented in this graph. If there is no shareable or no free capacity along a link, then the corresponding link can be left out from the *LD-graph*, the graph obtained by LD.
Here, γ_l represents the cost of a unit of capacity of the shareable spare capacity on link l. It can take

values $0 \leq \gamma_l \leq w_l$. If it is 0, then too long paths may appear. If it is equal to w_l then we do not prefer shareable to the free capacity at all. Extensive simulations have shown that the best results can be achieved by setting $\gamma_l/w_l \approx 0.1, \forall l \in E$. Note, that here x_l^o is not a binary indicator variable, but it represents the amount of flow of demand o over link l. T_e is the set of those demands o for which we route simultaneously the shared protection paths. This set typically depends on an edge e that is within the working path of the demand that has been routed just before the protection path rearrangement is started. We will discuss the composition and meaning of the set T_e in more details when discussing algorithms SPP-LD and PDSP-LD.
Constraints:

$$\sum_{o \in T_e} x_l^o \leq C_l - C_l' - C_l'' \text{ for all links } l \in E^{free} \tag{1.7}$$

$$\sum_{o \in T_e} x_l^o \leq C_l'' \text{ for all links } l \in E^{sh} \tag{1.8}$$

$$\sum_{\forall j \in V, j \neq i} x_{ij}^o - \sum_{\forall k \in V, k \neq i} x_{ki}^o = \begin{cases} 0 & \text{if } i \neq s_o \wedge i \neq d_o \\ b_o & \text{if } i = s_o \\ -b_o & \text{if } i = d_o \end{cases} \quad \text{for all nodes } i \in V \text{ and demands } o \in T_e \tag{1.9}$$

$$0 \leq x_l^o \leq b_o \quad \text{for all links } l \in E \text{ and demands } o \in T_e. \tag{1.10}$$

$$\sum_{\forall k \in V, k \neq i} x_{ki}^o = b_o \cdot z_i^o \quad \text{for all nodes } i \in V \text{ and demands } o \in T_e. \tag{1.11}$$

$$z_i^o \in \{0, 1\} \quad \text{for all nodes } i \in V \text{ and demands } o \in T_e. \tag{1.12}$$

z_i^o is an auxiliary binary variable (Eq.1.11). Its role is to avoid flow branching, while it allows flow splitting between the pairs of parallel edges of an adjacent pair of nodes (Eq.1.12), i.e., it models the LD. Equations (1.7) and (1.8) are the capacity constraints for free and shareable capacities, respectively. Equation (1.9) is the well known flow conservation constraint. Equation 1.10 is the non-negativity constraint and the upper bound of the flow.

Both SPP-LD and PDSP-LD use the MILP formulation of Link Doubling. The set T_e is the main difference between the SPP-LD and PDSP-LD.

1.3.4 SPP-LD: Shared Path Protection with Link Doubling

The basic idea of SPP-LD is that after routing the working path of demand o we do not route its protection path only, but also the protection paths of all the demands that have in their working paths any element (e.g., any link) in common with the working path of demand o. We do all this simultaneously.

The requirement is that there is a single end-to-end protection path for each demand o that is disjoint with the working path of that demand only, i.e., a protection path may use any link except those used by its corresponding working path. Protection paths can share resources except if they have any common link in their working paths.

However, routing all these demands simultaneously, and considering all constraints on disjointness of working and protection paths appeared to be extremely complex and not feasible in reasonable time.

Therefore, we have used an approximation of the above problem. We have decomposed the problem by relaxing the “all simultaneously” constraint, i.e., we consider the links of the working path one-by-one.

The algorithm works as follows:

- Step 1: For the new demand o_{new}:

  - Find the shortest working path.

- Step 2: For all the links e of the working path:
  - Delete temporarily link e.
  - Deallocate the protection paths of all the demands o that use e as a part of their working paths.
  - Set T_e to contain the new demand o_{new} and all the demands that used e as a part of their working paths.
  - Execute the MILP for demands T_e with added path diversity constraints.
- Step 3: If more links e go to Step 2.
  - Based on the knowledge of all working and protection paths currently present in the network calculate the capacity allocated for shared protection over all links.
- Step 4: If more new demands go to Step 1.

The path diversity constraint has not yet been discussed. It means, that a link e is either used by the working path of demand o or by its protection path or by non of them, but never by both, the working and the protection. To avoid introducing new variables or by making real (continuous) variables binary (discrete) the simplest way was to simply leave out some of the variables that further decreased the complexity: If the working path of demand o uses link l then we leave out variable x_l^o completely from the MILP formulation for edges representing both, the shareable and the free part of the link capacities. Note, this holds for the new demand o_{new} as well, to have its protection completely diverse.

If a working path has more than one link in common with the working path of the new demand it can happen that it will have more than one protection path. In that case any of them can be chosen. For simplicity reasons we choose the latter found one. Then the capacities allocated for shared protection are calculated accordingly.

1.3.5 PDSP-LD: Partially Disjoint Shared Protection with Link Doubling

The difference between SPP-LD and PDSP-LD is that while SPP-LD requires end-to-end disjoint protection paths, PDSP-LD will allow so-called partially disjoint paths as well. It means that we will allow protection paths to have common parts with the working one. However, to be able to protect the working path in case of failure of any of its links we must define more than one protection paths to cover all the failure cases.

As the numerical results show this leads to even better capacity sharing that results in better resource utilisation, while the complexity (and running time) of the algorithm is about the same as of SPP-LD.

The algorithm differs only in the last item of Step 2, i,e, MILP is executed without forcing path diversity, i.e., since link e is deleted all the protection paths will exclude it. In this case we define a protection scenario for each link of a protection path. Note, that it can happen that a path will be protected in the same way in the case of failures of its different links.

1.3.6 Numerical Results

The simulations were carried out on a Dual AMD Opteron 246 Linux server with 2 GBytes of memory. The code was written in *C++*, compiled by gcc 3.4.3 and the MILP solver was the ILOG CPLEX 9.030.

We have compared the performance of the three algorithms SPP, SPP-LD and PDSP-LD on three networks that consisted of 16, 22 and 30 nodes respectively. Table 1.2 shows the characteristics of the three networks and the characteristics of the traffic offered to these networks.

Table 1.2: The properties of the networks and of the offered traffic.

PROPERTIES:	'16'	'22'	'30'
number of nodes	16	22	30
density	0.59	0.49	0.47
number of demands	646	709	1320
number of simultaneous arrivals of demands	3.23	3.54	5.28
time unit	200	200	250
average holding time	15.55	25.06	19.89

To investigate different blocking ranges we have scaled the link capacities, not the traffic. Note, that increasing the capacity of every link uniformly is analogous to decreasing bandwidth of traffic offered to the network. We have investigated roughly the 0% to 90% blocking range. The number of demands that were routed was large enough to make the influence of the initial transient negligible.

Figure 1.7 shows the blocking ratios of demands of the three algorithms on three networks. The blocking drops as the capacities of all the links were scaled up. SPP-LD had typically performance slightly better than SPP. PDSP-LD had always the best performance except for the 30-node network in the 50-60 % blocking range. The enlarged figures within the figures show the range of practical interest.

Figure 1.8 shows that the running time of SPP was much lower than that of methods using protection repacking (rearrangement).

Figure 1.9 Shows the average network utilisation for the range, where the blocking of PDSP-LD was just below 1%. In all cases PDSP-LD used fewest resources. It is interesting to not, that although it has used typically slightly more resources for working paths it has used much less protection resources than the other two methods.

1.3.7 Remarks on PDSP-LD

In this section I have proposed re-arranging or re-packing protection paths to achieve better throughput. Re-arrangement makes no problem, since the protection paths do not carry any traffic. Second, we have introduced LD to linearise the two-segment capacity-cost functions.

The results show, that although the computational complexity has significantly increased it is still within boundaries of practical implementability for on-line routing. Both, the resource utilisation and the blocking ratios were better for PDSP-LD than for the SPP and for SPP-LD. The ratio of protection resources obtained by PDSP-LD was particularly low, while it achieved up to 5% lower blocking than the other two methods.

1.4 Protected Elastic Traffic without Extra Capacity?

In infocommunications networks the available bandwidth typically varies in time. The transmission rate of the *elastic traffic* can be tuned according to the actual network state. Assuming such elastic traffic there arises the problem how to allocate resources (bandwidth) to sources in a fair manner and how to protect connections against failures. In recent related works the paths of the demands are given in advance, consequently setting up elastic source rates in fair way leads to suboptimal solution. Better results can be achieved if we determine the bandwidth of elastic sources AND the routes used by these demands simultaneously. In several applications it is meaningful to define minimum and maximum rate for sources. For this case we propose the definition of Relative Fairness (RF).

In this section different resource allocation policies are formulated and algorithms proposed, supported by numerical results. Protection alternatives for elastic traffic are also discussed: two protection schemes are proposed and analyzed. The algorithms are compared assuming different

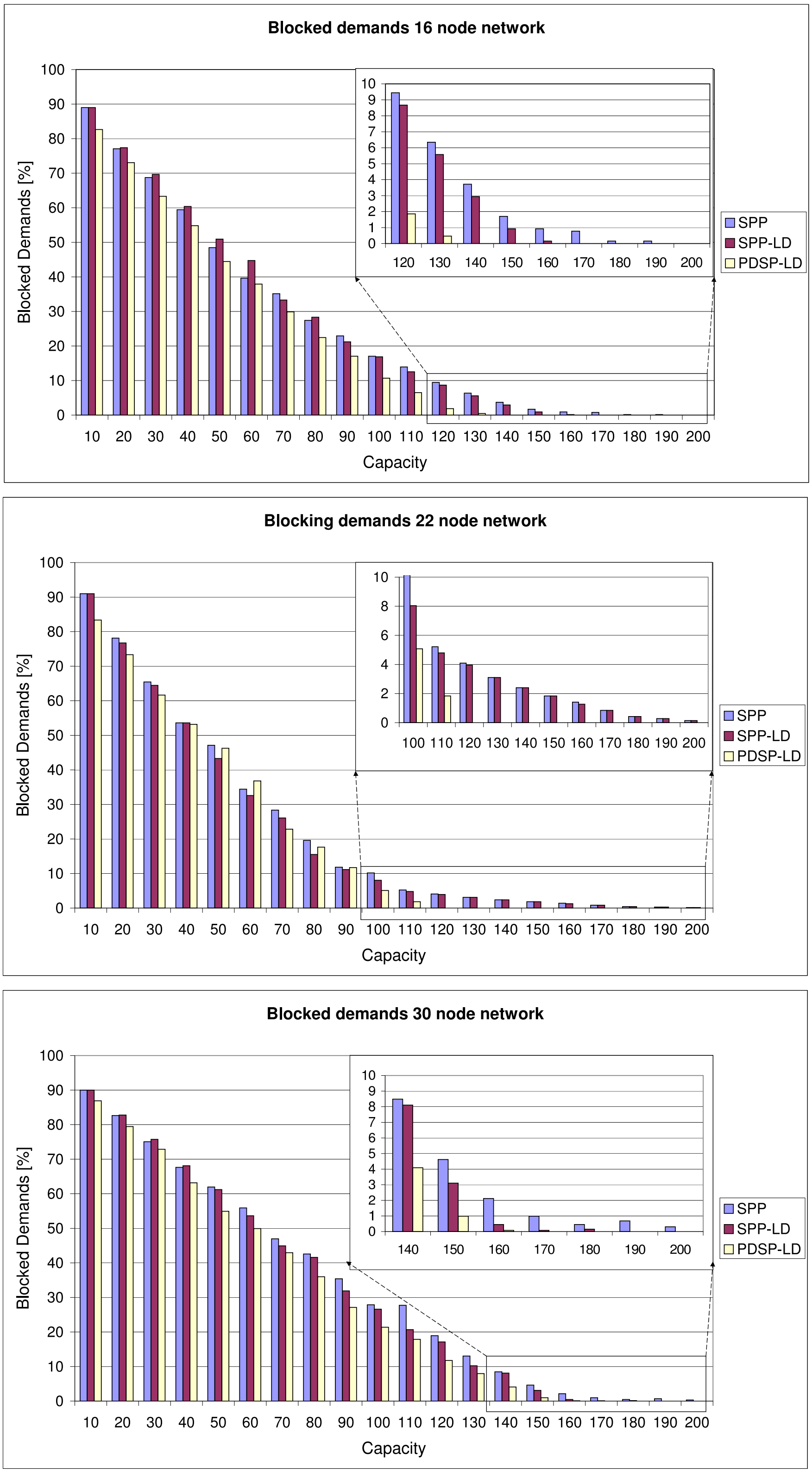

Figure 1.7: The blocking ratios of the three methods for three networks as the network capacity increases.

fairness definitions and different ways of handling protected elastic traffic. All the algorithms are a tradeoff (compromise) between network throughput, fairness and required computational time.

Nowadays, in infocommunications networks the rate of sources typically varies in time since

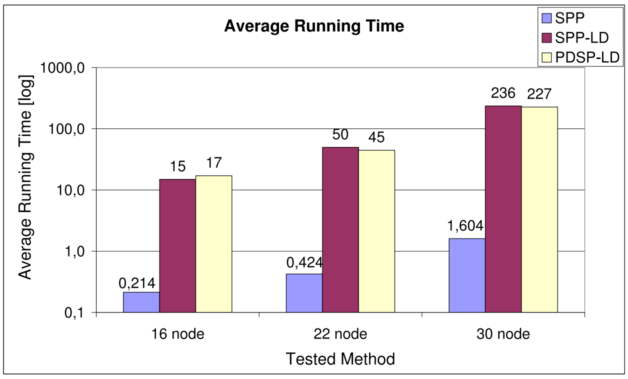

Figure 1.8: The running time average expressed in seconds on a logarithmic scale for the three methods for three networks.

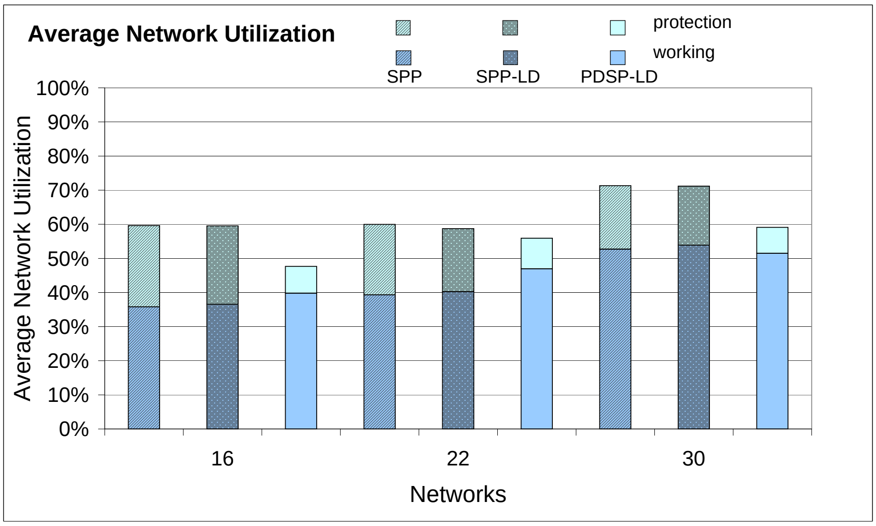

Figure 1.9: The average network utilisation by working and protection paths for the three methods for the three networks.

this guarantees higher throughput and better resource utilization. In non-real-time traffic of the Internet there is a growing interest in defining bandwidth sharing algorithms [87] which can cope with a high bandwidth utilization and at the same time maintain some notion of *fairness*, such as the Max-Min (MMF) [10, 15] or Proportional Rate (PRF) [60] fairness.

The most typical example of elastic traffic is the aggregate of TCP sessions in IP networks. The Available Bit Rate (ABR) Service Class in Asynchronous Transfer Mode (ATM) networks can be also mentioned. Label Switched Paths (LSPs) of Multiprotocol Label Switching (MPLS) networks are also easy to configure: their route and bandwidth can be adaptively changed. In all cases the source rates are influenced by the actual load of the network.

Three variants can be applied for determining the paths of elastic traffic : (1) *fixed paths*, (2) *pre-defined paths*, or (3) *free paths*. In the case of *fixed paths* there is a single path defined between each origin-destination (O-D) pair and the allocation task is to determine the bandwidth assigned to each demand. In the case of *pre-defined paths* we assume that between each O-D pair, there is a set of admissible paths that can be potentially used to realize the flow of the appropriate demand. In this case the allocation task does not only imply the determination of the bandwidth of the flow, but also the identification of the specific path that is used to realize the demands [34]. In the case of *free paths* there is no limitation on the paths, i.e., the task is to determine the bandwidth of the traffic AND the routes used by these demands simultaneously. This novel approach, the joint path and bandwidth allocation with protection is the main topic of this section.

Recent research results indicate that it is meaningful to associate a minimum and maximum bandwidth with elastic traffic [70]; therefore, it is important to develop models and algorithms for such future types of networks. For the bounded elastic environment a special weighted case of MMF notion: Relative Fairness (RF) is proposed that maximizes the minimum rates relative to the difference between upper and lower bounds for each demand.

Considering literature different aspects of the max-min fairness policy have been discussed in a number of papers, mostly in ATM ABR context, since the ATM Forum adopted the max-min fairness criterion to allocate network bandwidth for ABR connections, see e.g. [47, 48]. However, these papers do not consider the issue of path optimization in the bounded elastic environment. MMF routing is the topic of the paper [68], where the widest-shortest, shortest-widest and the shortest-dist algorithms are studied. These algorithms do not optimize the path allocation at all. A number of fairness notions are discussed and associated optimization tasks are presented in [70] for the case of unbounded flows and assuming fixed routes.

Proportional Rate Fairness (PRF) is proposed by Kelly [60] and also summarized by Massoulie and Roberts in [70]. The objective of PRF is to maximize the sum of logarithms of traffic bandwidths. While [60] does consider the path optimization problem, it does not focus on developing an efficient algorithm for path optimization when the flows are bounded.

Recent research activities focused on allocating the bandwidth of fixed paths. In [34] the approach has been extended in such a way that not only the bandwidth but also the paths are chosen from a set of pre-defined paths. The formulation of the pre-defined path optimization problem is advantageous, since it has significantly less variables than the free path optimization. However, its limitation is that the whole method relays on the set of pre-defined alternative paths. If the set of paths is given in advance, setting up elastic source rates in a fair way leads to suboptimal solution. Better results can be achieved if we determine the rate of elastic sources AND the routes used by these demands simultaneously. There arises the question how much resources should be reserved for each demand, and what path should be chosen for carrying that traffic in order to utilize resources efficiently while obeying fairness constraints as well.

The protection against failures is an important issue also in case of elastic traffic since one portion (e.g., half, or the lower bound) of the traffic should be "alive" even if a network component is affected by a failure. To our knowledge, protection issues of elastic traffic have not been studied in the literature. Accordingly, we propose and analyze two types of protection schemes in elastic environment:

1. Maximize both, working and protection paths (**MBP**). In this case the traffic is routed on two disjoint paths of half-half capacity. If one of the two paths is affected by a failure then the bandwidth of the connection will be degraded to the half of the original.

2. Maximize working paths (**MWP**) - find any protection paths. In this case we aim to maximize the bandwidth of each traffic according to the fairness definitions while ensuring (whenever it exists) a disjoint protection path such that the system of working and protection paths fits into the capacity constraints with their lower bounds.

In case of a failure at least one pre-defined path remains active ("alive") in case of either MBP or MWP. In case of MWP the bandwidths are set to the lower bounds, while with MBP will be halved, and augmented bandwidths can be calculated in a second phase of the recovery. Several questions arise: How fair are these protection schemes? How bandwidth-consuming they are? What amount of additional bandwidth do they need compared to the unprotected case?

In this section we investigate these questions and propose algorithms assuming three types of fairness definition: RF, MMF and PRF.

- *Relative Fairness (RF):* In this case the aim is, to increase the rates relative to the difference between upper and lower bounds for each demand.

- *Max-Min Fairness (MMF):* In this case we want to maximize the smallest demand bandwidth.
- *Proportional Rate Fairness (PRF):* In this notion the aim is to set the rates as a result of a convex nonlinear optimization prioritizing shorter paths to longer ones.

All these fairness definitions can be investigated in the bounded case (bounds on the minimal and maximal bandwidths for each O-D pair). In the unbounded case MMF and PRF can be optimized, while RF has no sense without bounds. All fairness definitions can be formalized with both unweighted and weighted fairness measures. We formulate the unweighted case, i.e., assume that all sources have the same priority and then extend the model for the weighted case, i.e., when the sources have different priorities.

In the following sections we deal with the proposed RF fairness notion only. In Section 1.4.1 the exact formulation of the problem is presented; in Section 1.4.2 ILP based and in 1.4.3 heuristic methods are proposed which solve the problem without, and in Section 1.4.4 with protection. Finally, in Section 1.4.5 numerical results are presented.

1.4.1 Relative Fairness (RF) Definition and Problem Formulation

Relative Fairness (RF) maximizes the minimum rates relative to the difference between upper and lower bounds for each demand. The formulation relays on the ILP (Integer Linear Programming) formulation of the unsplittable Minimal Cost Multi-Commodity Flow problem.

The network topology of N nodes and L links with link capacities C_l $(l = 1, 2, ..., L)$ are given. m_d and M_d are the lower and the upper bounds respectively for demands $d = 1, 2, ..., D$. Output is the capacity requirement (bandwidth) b_d of demand d: $m_d \leq b_d \leq M_d$, where b_d can be expressed as $b_d = m_d + \alpha_d(M_d - m_d)$ and where α_d (the parameter of RF) is a continuous variable which ensures fairness. It can take values $0 \leq \alpha_d \leq 1$. x_l^d is a 0-1 flow indicator variable on link l of demand d.

Objective:

$$\text{Maximise } min_d \ \alpha_d \tag{1.13}$$

Subject to constraints:

$$\sum_d x_l^d \cdot (m_d + \alpha_d(M_d - m_d)) \leq C_l \quad l = 1, 2, .., L, \quad \text{where} \quad 0 \leq \alpha_d \leq 1 \tag{1.14}$$

$$\sum_{j=1}^{N} x_{ij}^d - \sum_{k=1}^{N} x_{ki}^d = \begin{cases} 1 & \text{if } i \text{ is the source of } d \\ -1 & \text{if } i \text{ is the sink of } d \\ 0 & \text{otherwise} \end{cases} \quad i = 1, 2, ..., N, \quad d = 1, 2, ..., D$$

$$x_l^d \in \{0, 1\}, \quad l = 1, 2, ..., L, \quad d = 1, 2, ..., D \tag{1.15}$$

Equation (1.14) is the capacity constraint and Equations (1.15) is the well known flow-conservation constraint. It is to be noted that this formulation maximizes only the minimum of α_d, while it is reasonable to maximize the Objective for any subset of the demands (as done in Subsection 1.4.2). Unfortunately, this is a *nonlinear* formulation, since the Objective and Constraint (1.14) are not linear. In the following subsections it will be linearized by a simple method.

This was defined for RF. The MMF notion can be defined in a similar way, by simply omitting $(M_d - m_d)$ in Equation 1.14. To increase the throughput the fairness criteria should be redefined in manner to prioritize connections having less hops (i.e., using less resources) to those which are more distant. F. Kelly *et al.* have proposed the concept of Proportional Rate Fairness (PRF) [60] where the objective to be optimized is the sum of logarithms of the capacities used by the demands (max $\sum_d log b_d$), while the constraints are similar to the previous formulation: $\sum_d x_l^d b_d \leq C_l \quad l = 1, 2, ...L$ and (1.15) and (1.15).

For protected traffic the model is to be extended by equations described in subsection 1.4.4.

1.4.2 Algorithms Based on Integer Linear Programing (ILP)

For configuring networks which handle elastic traffic heuristic methods are preferred since nonlinearity is hard to handle. However, in this case the following simple deterministic algorithm guarantees the quality of the results.

The Unsplittable MultiCommodity Flow (UMCF) Subroutine

The algorithms are based on this subroutine that finds the optimal routing for fixed $\alpha = \alpha_d$, $d = 1, 2, ..., D$. This is the unsplittable multicommodity flow problem referred to as UMCF. It can be solved by an ILP solver, e.g., CPLEX.

Set:

$$b_d = (m_d + \alpha(M_d - m_d)) \quad d = 1, 2, ..., D \tag{1.16}$$

Objective:

$$\min \sum_d b_d \sum_l x_l^d \tag{1.17}$$

Subject to constraints (1.15), (1.15) and:

$$\sum_d b_d x_l^d \leq C_l \quad l = 1, 2, ..., L \tag{1.18}$$

Search Algorithms for minimal α (BSA&ASA)

The Binary Search Algorithm (BSA) algorithm is based on the idea of Binary Search for finding the optimal value of α between 0 and 1.

- *Step 1.* Check the feasibility by setting $\alpha = 0$. If satisfied, check the upper bounds by setting $\alpha = 1$. If satisfied, the solution is obtained, if not, set iteration counter $k = 1$, $\alpha = 0$, $\Delta = 1/2$ and proceed to Step 2.
- *Step 2.* Set $\alpha = \alpha + \Delta$ and run the Unsplittable MultiCommodity Flow (UMCF) subroutine (Section 1.4.2).
- *Step 3.* Increment k. If UMCF was feasible set $\Delta = 1/2^k$ else set $\Delta = -1/2^k$.
- *Step 4.* Go to Step 2 until required fairness is achieved.

This deterministic method guarantees the quality of the results, i.e., if the number of iterations is k, then the largest "unfairness" in sense of parameter α is upper bounded by $1/2^k$. In the 7^{th} iteration this unfairness will be less than 1% (0.0078125), while in the 10^{th} iteration less than 10^{-3}.

Instead of the BSA a faster method can be used for setting value of α. This is an extension of BSA referred to as ASA (Adaptive Search Algorithm). The idea is to increase α without changing the paths. After a feasible UMCF subroutine we find a new value of $\alpha^{(k+1)}$ to be used in the forthcoming ($(k+1)^{th}$) iteration based on the paths of the current (k^{th}) iteration. The new alpha is calculated by the following equation derived from constraint (1.14):

$$\alpha^{(k+1)} = min_l \left\{ \frac{C_l - \sum_d m_d x_l^{d,(k)}}{\sum_d x_l^{d,(k)}(M_d - m_d)} \right\} \; l = 1, 2, ..., L \tag{1.19}$$

This increase of parameter α is carried out after each feasible UMCF subroutine. Adaptive search speeds up the algorithm (or increases the precision of α within a given time interval).

Finding Different Values of α

Since all traffic rates are changed equally according to the definition of parameter α, the first saturated link will limit the value of α. Therefore, an iterative approach is needed, which increases the network throughput, however, it deteriorates the fairness slightly, by offering more resources to demands not using saturated links. The idea is to set a new, higher value of α_d $(d = 1, 2, ..., D)$ for some demands by using free resources of yet unsaturated links in each iteration k. Note, that there are two alternatives:

- *Case1.* The paths of demands are determined in the first iteration. They are not changed any more, only the bandwidths.
- *Case2.* Both, the paths and bandwidths are augmented in each iteration.

***Case1*: Increase Bandwidth** In this case the paths assigned to demands are determined in the first phase and are not changed any more. The allocations are changed only according to the following algorithm (Y_l^k represents the free capacity on link l after the k^{th} iteration):

- *Step 1.* Set $k = 0$, $b_d = m_d + \alpha(M_d - m_d)$, $Y_l^{(0)} = C_l - \sum_d b_d x_l^d$
- *Step 2.* Set k++.
- *Step 3.* Remove all saturated links and paths using these links. Set $\alpha_d = \alpha$ for each removed demand d.
- *Step 4.* If there is no more demand left or $\alpha = 1$ then *Stop*, otherwise continue.
- *Step 5.* $\alpha = min_l \left\{ \frac{Y_l^{(k-1)} - \sum_d m_d x_l^d}{\sum_d x_l^d (M_d - m_d)} \right\}$
- *Step 6.* $b_d = m_d + \alpha(M_d - m_d)$
- *Step 7.* $Y_l^{(k)} = Y_l^{(k-1)} - \sum_d b_d x_l^d$
- *Step 8.* Go to *Step 2*

The new value for α is calculated in *Step 5* that has analogous meaning to Equation (1.19). Note, that this iterative procedure has to be repeated up to L times, where L is the number of links in the considered network, since each iteration will saturate at least one link.

***Case2*: Increase Bandwidth by Rerouting** In this case both the routing of demands and allocations are changed. In each iteration (after BSA or ASA) saturated links are removed and all the paths using these links are de-allocated. The link capacities are decreased by the capacity allocation of removed demands (b_d). Now the whole algorithm (BSA or ASA) should be ran on the reduced graph until there is no more demand. This method has the longest running time, however, it gives the best resource utilization. It is to be noticed that even in this case the global optimum is not guaranteed. This is because the optimal solution of BSA or ASA is not unique and the choice of the optimal solution of BSA or ASA may influence the further course of the algorithm and its final result [34].

1.4.3 Heuristic Algorithms

Shortest Paths Algorithm (SPA)

A simple method called *Shortest Paths Algorithm* (SPA) has been implemented. It finds a shortest path for each demand and sets the bandwidth of the demand according to the appropriate fairness definition. This method is similar to those previous methods that assume fixed paths, i.e., it is not able to change the path, only the bandwidth of the demands.

Iterative Elastic Simulated Allocation (IESA)

The ILP based methods spend most of their time in the UMCF subroutine. The ILP formulation of them contains LD variables and $ND + L$ constraints. Several methods have been proposed in the literature that solve the unsplittable multicommodity flow problem much faster, e.g., SA++ or CA++ in [64]. We have applied SA++ in this study that is based on Simulated Allocation [35], speeding up the running significantly.

Using ILP in the UMCF subroutine is referred to as Elastic ILP (EILP) while replacing the UMCF subroutine by SA++ is referred to as Iterative Elastic Simulated Allocation (IESA).

Simulated Allocation can be used in a more sophisticated manner as well. The main point of this improvement is that after several iterations of allocations and de-allocations a special procedure called *bandwidth tuner* is called. The bandwidth tuner procedure tunes (changes) the bandwidth of each demand according to the appropriate fairness definition. In case of RF it decreases the value of α if any demand can not be allocated or increases the value of α if all demands can be allocated and more free space is available in the network.

1.4.4 Algorithms for Elastic Traffic Protected by MWP and MBP

In this section the traffic is protected by path protection, i.e., two node-disjoint paths are to be determined. As discussed in the introduction of Section 1.4, we propose two methods for bandwidth allocation. The first one is to maximize bandwidth for working paths and ensure a protection path of zero bandwidth (MWP). The second approach is to allocate the same bandwidth on the working and on the protection path (MBP). In this subsection extensions are described that are necessary to the MBP and MWP approaches.

Protection with ILP Based Methods

Integer Linear Programming (ILP) based algorithms have been proposed for unprotected traffic in Subsection **??**. In the MBP and MWP cases the UMCF subroutine is to be extended by adding some new constraints: flow conservation constraints for the protection paths, constraints to ensure that working and protection paths are disjoint, and constraints ensuring that working and protection paths with lower bounds (MWP), or with half capacity (MBP) fit into capacity constraints. Apart from these, the algorithms remain the same.

Protection with Heuristics

The extension of SPA is trivial: Route all demands with lower bounds (m_d) or half capacities ($b_d/2$) along a working and a protection path. Then set the bandwidth according to the protection scheme.

In case of IESA the UMCF subroutine is replaced by Simulated Allocation. Here the allocation of one commodity is done by Dijkstra's algorithm [28]. Assuming MBP, the extension to modified Dijkstra's algorithm proposed by Suurballe [97] is to be used to get two disjoint paths; while assuming MWP, to achieve a feasible solution the allocation of path-pairs is to be modified in the following way:

- *Step 1:* Delete all links that have free capacity less than b_d and find the working paths with a shortest path algorithm. If this step fails then STOP with no success, otherwise continue.
- *Step 2:* Restore all deleted links. Calculate the required capacities in case of a failure (sum of lower bounds of all working and all protection paths on each link) and delete those links that can not accommodate b_d in case of failure. Find the protection paths with a shortest path algorithm.
- *Step 3:* This Two-Step-Dijkstra algorithm may fail even if a solution exists, accordingly an Integer Programming based solution or Suurballe's algorithm based solution is required in this third step.

Comments

1. The proposed algorithms can be easily applied to the MMF fairness definition as well. For the solution of PRF, which is a convex problem, a piecewise linear approximation of the logarithmic function is proposed as described in [34].

2. If we want to prioritize some demands d then a weight factor w_d should be used. By setting, e.g., $w_1 = 2w_2$ the rate allocated to demand 2 will be increased by double of the increment of demand 1. In this case everything defined previously is valid except that in the UMCF subroutine we should add the weight factor w_d for each demand d to the Equation (1.16): $b_d = m_d + w_d\alpha^{(k)}(M_d - m_d)$, and in *Step 6* in Section 1.4.2 the same should be done, while in *Step 5* (and analogously Equation (1.19)) should be extended to $\alpha^{(k)} = min_l \left\{ \frac{Y_l^{(k-1)} - \sum_d m_d x_l^d}{\sum_d w_d x_l^d (M_d - m_d)} \right\}$.

   If we want to increase the network throughput we can prioritize those demands, which use shorter paths by setting w_d to be equal to the reciprocal value of the length of the demand, where the length is expressed in number of hops along the shortest possible path between the end-nodes of that demand. This leads to a fairness definition similar to PRF. In Section 1.4.5 we assume $w_d = 1$, $\forall d = 1, 2, ..., D$ that is equal to the unweighted case.

3. Although the problems have been defined here for unsplittable flows only, all the methods can be used for splittable flows as well. This even reduces the complexity, since Linear Programming can be used instead of Integer Linear Programming.

4. When both elastic and rigid traffics coexist in a network, the model has not to be changed, only m_d and M_d values are to be set to be equal ($m_d = M_d$) for all rigid demands. However, if the problem is being solved by an ILP (Integer Linear Programming) solver, it might be useful to introduce new variables instead. This will reduce the number of constraints and it will speed up solving the problem and allow problems of larger scale to be solved. In Section 1.4.5 we deal with elastic traffic only, not reducing the generality.

5. When MWP protection scheme is applied then shared protection can also be applied instead of dedicated protection. This yields the successful configuration even in tighter networks [C36].

6. We believe that the proposed approach ensures the highest fairness, i.e., RF is more fair than the plain MMF. Furthermore, the formulation of the joint path and bandwidth optimization guarantees throughput higher than (or at least equal to) that one with fixed or pre-defined paths.

1.4.5 Numerical Results

The tests have been carried out on six networks (see Table 1.3 for details). The bounds of traffic demands have been chosen randomly so that the task was not trivial, i.e., using m_d parameters the demands fit into capacities, while with M_d they do not.

	N5	N5A	N12	N15	N25	N35
Nodes	5	5	12	15	25	35
Links	5	6	18	15	31	51
Demands	10	10	66	105	300	595

Table 1.3: Details of the six test networks.

The methods have been compared according to 3 groups of criteria: computational time, network throughput and fairness parameters. The network throughput (TP) is expressed as the total of carried traffic for all demands. Fairness parameter is the objective value of the optimization, $\min_d(\alpha_d)$, denoted by $\min\alpha$.

In Figure 1.10 Relative Fairness (RF), Max-Min Fairness (MMF) and Proportional Rate Fairness (PRF) are considered; MMF and PRF both with and without bounds (denoted by B and NB); RF and MMF both with uniform (U) fairness parameters, $\alpha_d = \alpha$, and different (D) fairness parameters, α_d. The throughput is normalized to PRF/NB for each network. Trivially the unbounded (NB) cases always yield higher throughput than the bounded (B) case and the case allowing different (D) parameter yields higher throughput than the case with uniform (U) parameters. RF yields slightly more throughput than MMF, while PRF results in significantly higher throughput, especially in the unbounded case. The efficiency of PRF is very convincing in larger networks since in this case longer paths obtain significantly less bandwidth making space for many short paths. However, its fairness is more questionable.

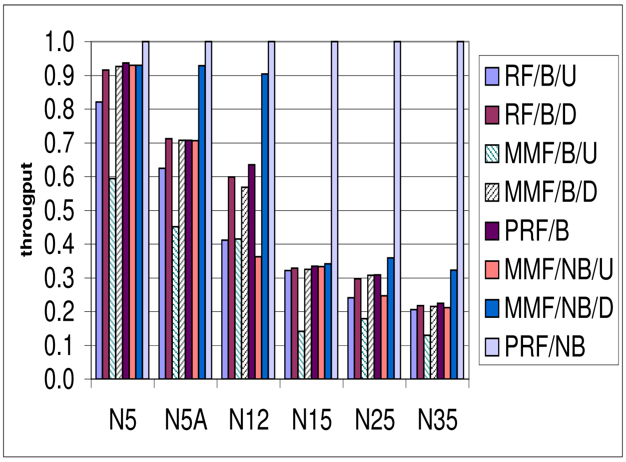

Figure 1.10: Throughput of six test networks assuming eight cases with three fairness definitions.

Numerical Results for Protected Traffic

The computational time (expressed in seconds) of EILP and IESA is compared in Table 1.4 without protection (NP) and with protection schemes Maximize Both Paths (MBP) and Maximize Working Paths (MWP). In case of EILP it was acceptable only in networks having up to 15 nodes with NP while up to 12 nodes with MBP and MWP. IESA is faster, it yields solution in acceptable time even for the 35-node network; however, in case of MWP further speed up is required.

EILP	N5	N5A	N12	N15	N25	N35
NP	0.18	0.65	39.4	8873	-	-
MBP	0.31	0.52	117732	-	-	-
MWP	0.37	1.04	705	-	-	-
IESA	N5	N5A	N12	N15	N25	N35
NP	0.03	0.02	0.53	0.95	9.15	30.6
MBP	0.03	0.02	0.85	1.51	28.5	92.8
MWP	0.08	0.06	9.57	50.6	386	4369

Table 1.4: Computational time [s] of ILP and IESA for six test networks and three protection schemes

The quality of the algorithms is demonstrated on network N12, a relevant part of the Polish backbone, and assuming fairness notion RF. The result of our simulations can be seen in Figure 1.11, where each point represents a simulation (in case of IESA 20 runs are considered) and shows the values for throughput and min α, representing the quality of the result.

The MWP approach yields higher throughput and higher min α values than the MBP. This is because MBP defines two disjoint paths where the second one is in general longer, reserving more resources. It is to note that values for MWP are almost the same as without protection. SPA methods (fixed shortest path with throughput maximised in fair way), that are the reference methods give poor results, especially in sense of fairness. IESA heuristic methods approach the optimal result, they sometimes even result better throughput, e.g., in case of MBP. The reason for this is that the objective of the EILP was to maximize the minimum of α, while with IESA we may get suboptimal min α with higher throughput.

Finally, we analyze how the performance of the algorithms depends on the tightness of the network. In other words: how min α decreases as the link capacities decrease and on how tight networks can the protection methods be applied? The answer can be seen in Figure 1.12. In case of MWP both dedicated and shared protection (DP and SP) can be applied for reserving backup resources, while for MBP dedicated protection is used since this scheme utilizes both paths even in a failureless network state.

It can be seen that curves of MWP are slightly below the one with no protection. Min α values of MBP are significantly lower. However, there is a lower bound (for the considered traffic and network it was between 85% and 90%) bellow which the problem can not be solved with MWP since the system of working and protection paths does not fit into capacity constraints even not with their lower bounds m_d. This limit can be decreased with shared protection (to 70-75% in this case). With MBP the protection can be solved in tighter networks as well (60% of the original link capacities). Consequently, for tighter networks MBP is proposed while for looser MWP.

1.4.6 Remarks on MWP and MBP

A wide range of algorithms has been proposed which are all a tradeoff (compromise) between network throughput, fairness and computational time. The obtained results were better for the proposed approach (in sense of both fairness and throughput) than in the case of fixed paths in both, protected and unprotected cases. Methods based on ILP are proposed for smaller (less than 12 node) networks, while iterative heuristics (IESA) for larger networks and for time-critical cases.

Two protection schemes have been proposed for elastic traffic: Maximize Working Paths that results fairness values close to the unprotected case, but fails in tight networks; and Maximize Both Paths that although deteriorates the fairness, it works even in tight networks.

These methods can be used in any centralized resource management system (similar to Diffserv Bandwidth Brokers) for configuration of ATM, TCP/IP and MPLS networks which will carry elastic traffic.

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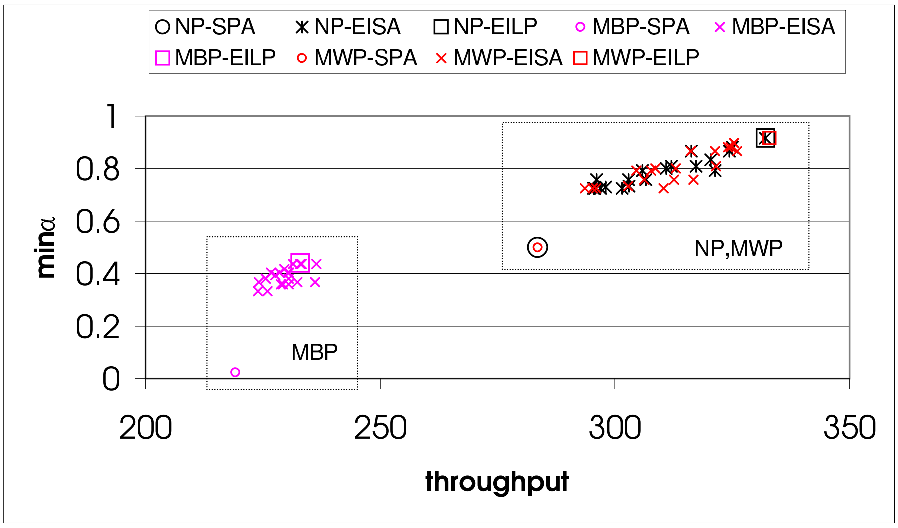


Figure 1.11: Values for throughput and minα resulted by methods SPA, EISA (IESA) and EILP assuming protection types MWP and MBP

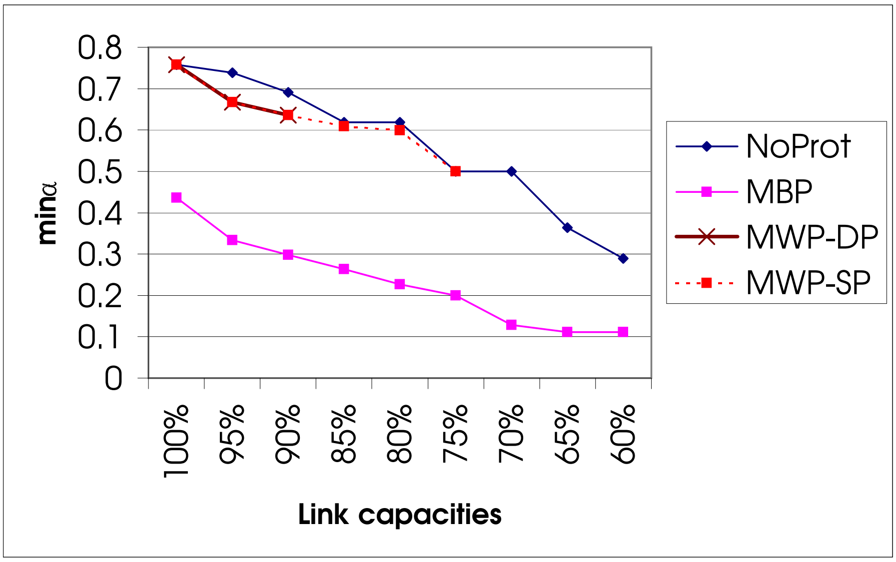


Figure 1.12: Values for minα while decreasing link capacities with the following protection types: without protection (NP), Maximize Working Path with dedicated protection (MWP-DP), Maximize Working Path with shared protection (MWP-SP) and Maximize Both Paths (MBP).

1.5 Can Multi-Domain Protection be Shared?

The Internet consists of a collection of tens of thousands of domains called Autonomous Systems (AS) operated mostly under different authorities (operators/providers) that although co-operate to a certain level over distinct geographic areas, they compete in a country or other common area.

Today BGP (BGP-4) is the de facto standard for exchanging reachability information over the domain boundaries and for inter-domain routing. The GMPLS controlled optical beared networks are expected to have similar architecture, however, more information has to be carried for TE (Traffic Engineering), resilience and QoS (Quality of Service) purposes. Therefore, extensions of

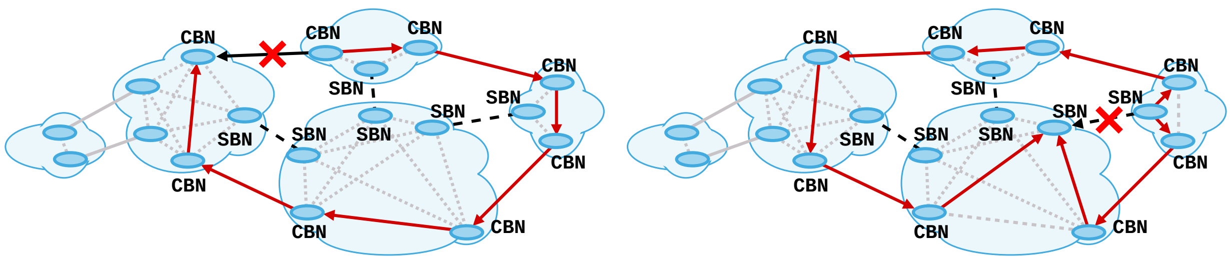
BGP and of PNNI (Private Network to Network Interface) as well as the PCE (Path Computation Element) have been proposed.

Still in all cases emerges the question of protection shareability. For dedicated protection it is enough to know the topology of the network to be able to calculate disjoint paths. However, to be able to perform sharing of protection resources (shared protection) it is not sufficient to know the topology, but it is mandatory to know the exact working and protection path pairs for all the demands, since protection paths can share a certain resource only if their working paths do not contain any common element or more generally they do not contain any element from the same Shared Risk Group (SRG). This can be checked within a domain where the full topology and link-state information is flooded, however, over the domain boundaries, on the one hand, for security reasons, on the other hand, for scalability reasons such information is not being spread.

In this Section we turn attention to the problem of sharing protection resources in a multi-domain environment and we propose using two techniques that do not require flooding the information on working and protection paths while they still allow sharing of resources. These two techniques are the Multi-Domain p-Cycles (MD-PC) and the Multi-Domain Multi-Path Routing with Protection (MD-MPP). After explaining the principles of these methods we give illustrative results.

1.5.1 Multi-Domain p-Cycles (MD-PC)

The use of p-cycles for multi-domain resilience is explained and evaluated in [C56]. In case of p-cycles we assume that only a single on-cycle link or a single straddling link can fail at time. This allows us sharing the resources allocated for protection without the knowledge on routing and protecting the other demands. p-cycles are pre-defined and while the network is operated we consider them unchanged.



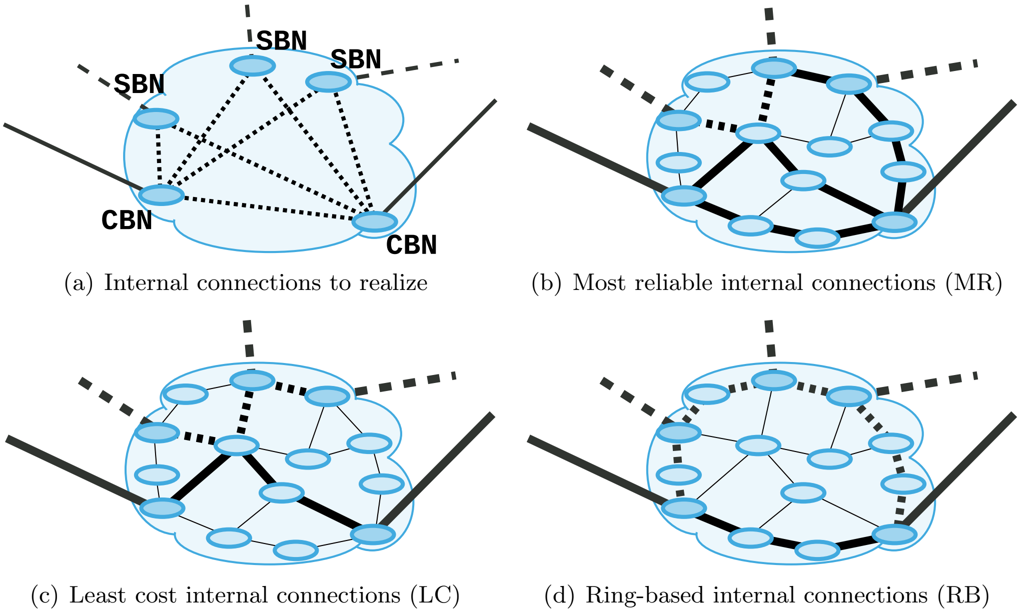
(a) On-cycle Inter-Domain Link Failure (b) Straddling Inter-Domain Link Failure

Figure 1.13: Handling Inter-Domain Link Failures

Figure 1.13(a) shows the case when we consider the aggregated (upper level) view of the network, and where each domain is represented by a simplified graph that defines only the relations between its own border nodes.

If an on-cycle inter-domain link fails the traffic is routed along the cycle in opposite direction. If a straddling inter-domain link fails (Figure 1.13(b)) then the traffic from that border node is routed to the closest on-cycle border node, and then the traffic can be carried in any or both directions along the p-cycle. We could see here, that only topology and link-state (only free capacity) information is needed to perform shared protection, i.e., to guarantee high availability with thrifty resource utilisation without requiring all the routing information. Evaluations of the trade-off between the availability and the amount of capacity used are presented in [C56].

While in Figures 1.13(a) and 1.13(b) we could see what happens at the upper layer, i.e., at the level of the inter-domain p-cycles in case of an inter-domain link failure, let us analyse now what happens *within* the domains in case of an *inter-domain* failure (Figures 1.14(a) - 1.14(d)). Figure 1.14(a) shows by solid line how the on-cycle border nodes (CBN) of neighbour domains are connected, and by dashed lines how the straddling border nodes (SBN) can be connected to the straddling border nodes (SBN) or on-cycle border nodes (CBN) of neighbour domains. Dotted lines



(a) Internal connections to realize (b) Most reliable internal connections (MR)

(c) Least cost internal connections (LC) (d) Ring-based internal connections (RB)

Figure 1.14: Logical internal p-cycle connections and alternate resolutions

between CBNs show how to set up the p-Cycle over the given domain, while the dotted lines from each SBN towards the two CBNs show how to set up a straddling segment over the p-Cycle using any of SBNs. Figures 1.14(b), 1.14(c) and 1.14(d) show the most reliable (MR), the least cost (LC) and the ring based (RB) internal interconnections respectively.

This was the case of *inter-domain* on-cycle and straddling link failures. Let us consider now the case when an *intra-domain* part of a working path fails. Regardless whether the failure is on on-cycle or straddling part, we consider three cases: *No Protection* at all; *CIDA*: p-cycle based connection between all the border nodes of a domain; and *CIDED*: dedicated protection of the segment between the considered border nodes.

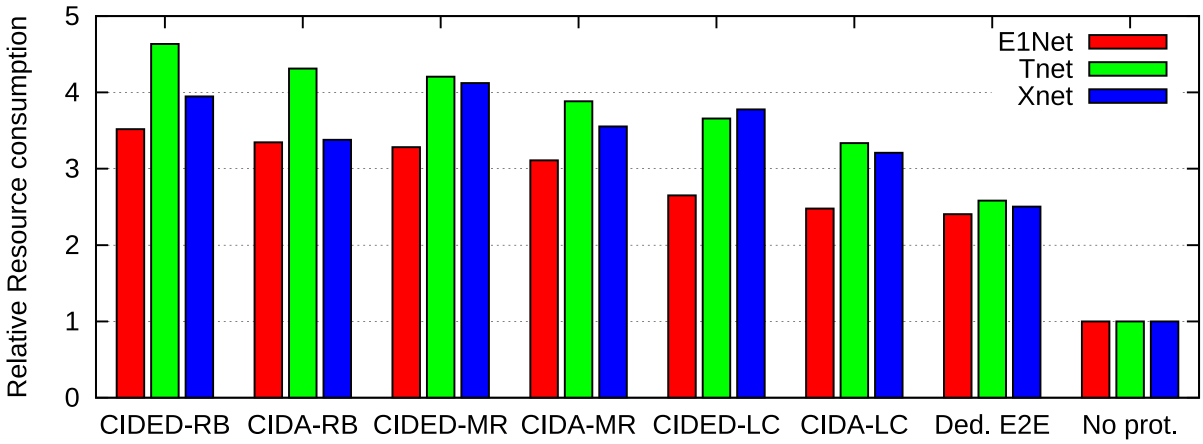


Figure 1.15: Resource requirement of protection schemes compared to the case of No Protection

As expected the strategies that result in higher availability require more additional resources. Figure 1.15 points out this behaviour for three different multi-domain reference networks. Connections with dedicated protection CIDED-LC, CIDED-MR and CIDED-RB require 2.5-4.5 times more capacity than connections without any protection (i.e., the backup paths are on average 1.5 times longer than the working paths). All cycle-based protection schemes have high capacity requirement, e.g., *CIDED-RB* roughly 4 times higher than the case with no protection. The intra-domain links employed by higher level p-cycles are wasted in sense that their resources are allocated, however, in contrast to the inter-domain links, the higher level p-cycle does not offer protection for their traffic. This explains the relative high resource consumption of MDPCs.

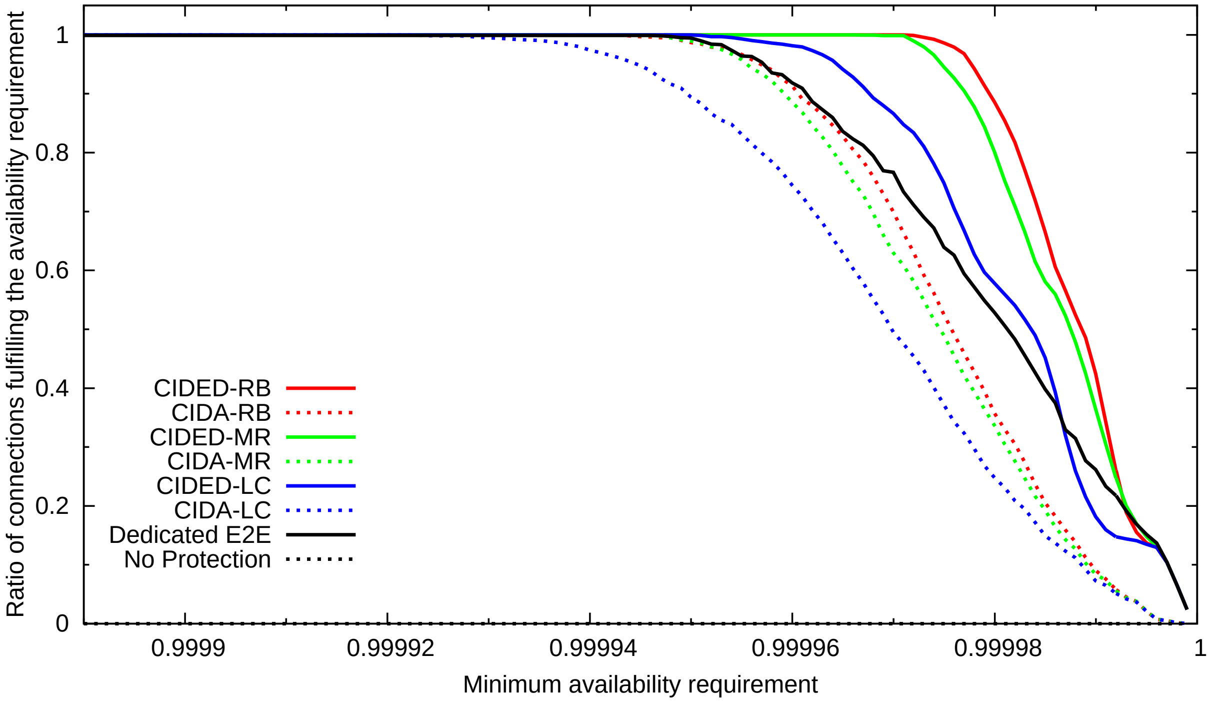


Figure 1.16: Tail behaviour of protection schemes in Tnet

Figure 1.16 shows what percentage of 3000 connections has higher availability than a given (x) threshold in the Tnet reference network. It is worth to look at the behaviour of the curve corresponding to the DP scheme. To a small ratio of connections it can provide high availability, as much as *CIDED-RB* - these are the short connections -, however, for most connections it offers a relatively low availability.

1.5.2 Multi-Domain Multi-Path Protection (MD-MPP)

Assuming that each domain is represented by a single node in the aggregated (upper level) graph we search for disjoint paths to be used for routing and simultaneously protecting a single demand along multiple paths. The idea has been first proposed in [62] for a single domain, referred to as DSP: Demand-Wise Shared Protection.

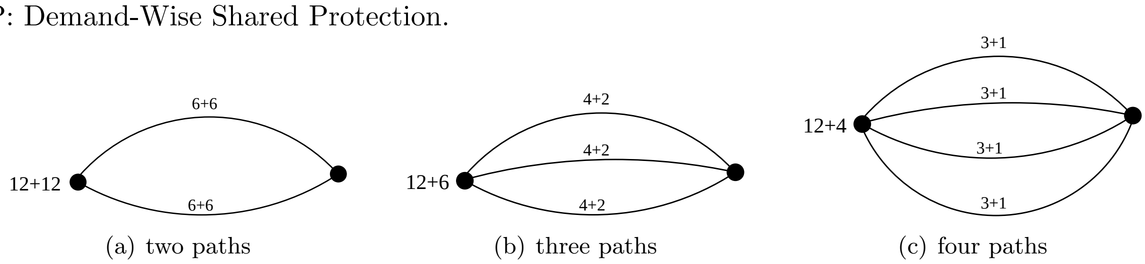


Figure 1.17: Illustration of the MPP problems: working + protection bandwidth allocations for certain two, three and four disjoint paths.

If we assume that two paths are available to route a demand of a bandwidth requirement of 12 units (Figure 1.17(a)) we do not gain at all, it requires as much resources (6+6 for working and

6+6 for protection, i.e., 12+12) as the dedicated protection. However, if we assume three paths (Figure 1.17(b)) then it requires less resources (4+4+4 for working and 2+2+2 for protection, i.e., 12+6) that is a significant reduction through internal sharing between these three paths. Internal (demand-wise) sharing means, that the different paths of a same demand can be considered as disjoint working paths, that can share capacity for their protection. Still, since they are all routed at the same time they can be forced to be disjoint. If we further increase the number of paths, e.g., to 4 (Figure 1.17(c)) we can further reduce the capacity requirements.

The ideal case is shown in Figure 1.18. The total capacity allocated for protection relative to the total working capacity drops steadily as the number of paths increases. The same scheme can be used to protect against multiple simultaneous failures as well.

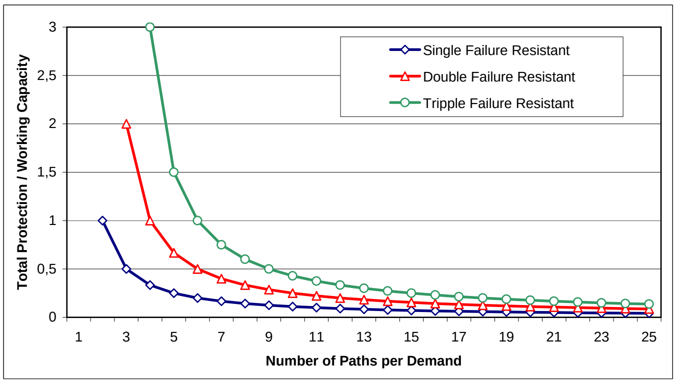


Figure 1.18: xy_{max} the required total protection capacity relative to the total working one as the number of disjoint paths grow: Theoretical result where all the paths are assumed to have the same length and the same allocation.

This was, however, the ideal case. As the number of paths used grows, they become increasingly longer and although less capacity per path is required, the total capacity requirement will first drop, and after a while start increasing. The other problem is that introducing multiple paths will use more links that are all prone to failures, i.e., by increasing the number of paths the availability will decrease.

LP (Linear Programming) Formulation

The network $\mathcal{N}(V, E, B)$ consists of vertices (network nodes) $i \in V$, of directed edges (directed links or arcs) $ij \in E$, where $i, j \in V$ and of the vector of link bandwidths (capacities) $B_{ij}, \forall ij \in E$. In Equations (1.21) and (1.22) $V^{\rightarrow j} \subset V$ and $V^{j\rightarrow} \subset V$ denote the set of nodes that have edges with destination (target, termination) and origin (source) in node j respectively, i.e., the nodes i and k of directed in and out links (arcs) ij and jk respectively adjacent to node j.

The demands $o \in O$ are defined as a traffic pattern O of length of $|O|$, characterised as $o(s, t, b, a, d)$ where s is the source, t is the target and b is the bandwidth requirement of the demand o, while a and d are the arrival time and the departure time of that demand, i.e., $d - a$ is the duration of the session/connection for demand o.

The objective is to route and protect all the demands along more than one path as they arrive one-by-one by using as few resources as possible. This is a trade-off between the number and the length of the paths with the aim to decrease the total capacity allocation. On the one hand, as we increase k the number of paths (Fig. 1.17), the protection will be increasingly more efficient, i.e., fewer resources will be allocated along the paths. On the other hand, as we increase the number of (disjoint) paths, first we exhaust shorter paths, then start with longer, therefore, the average path length will grow, and the total allocated capacity will again start to grow.

To illustrate the above problem we show in Figure 1.18 how the required protection capacity relative to the working one drops as the number of disjoint paths grow. We have assumed the ideal case, where all the paths carry equal share of the bandwidth. The curve for the Single Failure

Resistant case shows that for two disjoint paths the same amount of bandwidth is required as for dedicated protection (Figure 1.17.a), however, as the number of paths grows (Figure 1.17.b and 1.17.c), the bandwidth requirement drops steeply even below that typically needed for shared protection.

If we consider the other two curves in Figure 1.18 for double and triple failures we can see that they require more bandwidth, however, as the number of paths grows the bandwidth requirement drops faster. Over 10 paths (that is in practice a too large number) the absolute difference in bandwidth requirements of single, double and triple failure resistant cases is small.

The dependence of the amount of total protection capacity to be allocated along the different paths for a single demand over k paths and for up to f failures relative to the total working capacity can be expressed as $xy_{max} = f/(k-f)$.

We can conclude, that from the aspect of bandwidth requirement MPP performs increasingly better than the dedicated protection scheme as the number of paths and the number of failures to resist grows. It even outperforms shared protection in case of larger number of paths, although it does not require any knowledge on the working and protection paths of all the demands as the shared protection does.

The optimal MPP problem can be formulated as a Linear Program (LP). It is a special min-max flow problem.
Variables:

$x_{ij} \geq 0$	"working" flow over edge $ij \in E$
$y_{ij} \geq 0$	"protection" flow over edge $ij \in E$
xy_{max}	the maximum of $(x_{ij} + y_{ij})$ over $\forall ij \in E$

Objective:

$$min \sum_{\forall ij \in E} c_{ij} \left(x_{ij} + y_{ij} \right) \tag{1.20}$$

Subject to:

$$\sum_{\forall i \in E^{\to j}} x_{ij} - \sum_{\forall k \in E^{j \to}} x_{jk} = \begin{cases} -b & \text{if } j = s \\ 0 & \text{otherwise} \\ b & \text{if } j = t \end{cases} \quad \forall j \in V \tag{1.21}$$

$$\sum_{\forall i \in E^{\to j}} y_{ij} - \sum_{\forall k \in E^{j \to}} y_{jk} = \begin{cases} -xy_{max} & \text{if } j = s \\ 0 & \text{otherwise} \\ xy_{max} & \text{if } j = t \end{cases} \quad \forall j \in V \tag{1.22}$$

$$x_{ij} + y_{ij} \leq xy_{max} \quad \forall ij \in E \tag{1.23}$$

$$x_{ij} + y_{ij} \leq B'_{ij} \quad \forall ij \in E \tag{1.24}$$

The objective function (Equation 1.20) minimises the total allocation for both working and protection paths over all the links of the network. If the cost of allocation differs for different links then c_{ij} can be set to these values. Furthermore, c_{ij} can be used to perform Traffic Engineering by setting proper value to prefer or to try to avoid a certain link when routing. For simplicity reasons we have kept $c_{ij} = 1$ in all our evaluations.

The next two equations are the flow conservation constraints. Equation (1.21) is a conventional one, it states that whatever paths and whatever splittings the working flow chooses its total amount has to be equal to b, and whenever a flow enters a node it also has to leave it except for those nodes that are either the source or the target of the considered demand. x_{ij} denotes the working flow allocated to link ij.

Equation (1.22) is similar to (1.21), however, it is the flow conservation constraint for protection paths. The interesting and very important detail of this constraint is its right hand side. xy_{max} denotes the amount of traffic to be allocated for protection paths of the considered demand in total. Considering the worst case it is equal to the maximum flow over all the working paths (over all the links). However, if a working path fails the same path will not be able to carry any protection traffic, i.e., it also fails. Therefore, the amount of the traffic to be protected has to be increased by the amount of the protection traffic y_{ij} over the same link ij. Considering the worst case scenario for finding this maximum when the link carrying the largest total of working plus protection traffic fails, Equation (1.23) must hold for all links ij.

And finally the last constraint (1.24) is the capacity constraint, that states that the total flow may never exceed the amount of the available capacity of any link it uses. Since we use this program to allocate resources for the demands as they arrive one-by-one, B'_{ij} does not denote the real capacity B_{ij} of a certain link ij, but only its currently available, yet unused part $B'_{ij} \leq B_{ij}$.

Note, that constraints (1.23) and (1.24) can be also written as a single one: $x_{ij} + y_{ij} \leq xy_{max} \leq B_{ij} \quad \forall ij \in E$. This is a very simple ("four-line") yet very powerful formulation of the problem.

Two very interesting features of this formulation are as follows.

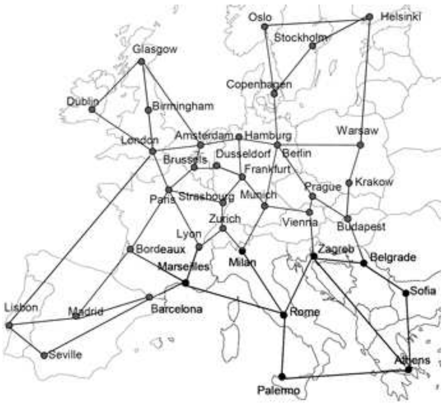
- **Low complexity:** This formulation uses LP, not ILP, and it still avoids branching of the paths in all nodes except the source and target nodes of the demand. LP can be solved in polynomial time, therefore, due to its low complexity the method can be implemented in source routers.

- **Even splitting:** When comparing the examples of Figure 1.17 we can clearly see that, sharing the load evenly (4+2 : 4+2 : 4+2) between the disjoint paths yields better result, i.e., fewer total allocation (18 units) (Fig. 1.17.c), than the hypothetical case with slightly different (3+2.5 : 4+2.5 : 5+2) allocations, where we need a total of 19 units. If we make the allocations even more distinct (2+3 : 4+3 : 6+2) then a total of 20 units will be needed. As the objective of our optimisation the **maximum** of the total working + protection allocation over all links should be **minimal**. I.e., instead of (3+2.5 : 4+2.5 : 5+2) allocation (3+3 : 4+2 : 5+1) is exactly as good as (4+2 : 4+2 : 4+2). In our evaluations it happened very rarely to have uneven allocations, however, the number of paths used varied significantly.

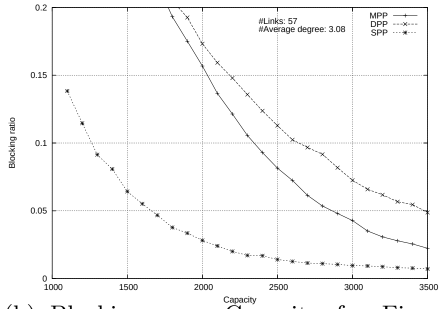
  This behaviour is resulted by constraints (1.22) and (1.23) and by the objective (1.20). Equations (1.22) and (1.23) together are a kind of a positive feedback: The smaller flows per links $(x_{ij} + y_{ij})$ we choose the smaller total flow (xy_{max}) we have to establish, that again results in smaller y_{ij} values. More precisely this is a min-max problem, where we try to minimise the largest $x_{ij} + y_{ij}$ value. This will lead to spreading the flow among multiple disjoint paths, whenever possible into equal parts. This will also lead to a trade off between having very many paths with very tiny bandwidths but very long paths on average or rather having fewer shorter paths, but larger per-link allocations. The objective of this trade-off is the total amount of used capacities according to the Objective (Eq. 1.20).

MD-MPP Numerical Results

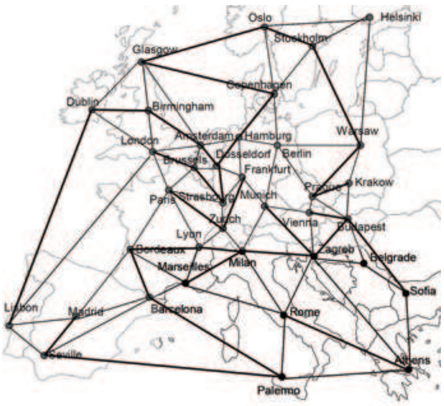
First, we have compared the blocking probabilities for DPP, SPP and MPP as the capacity of the network COST266 LT ([21, 50]) is being scaled up (Fig. 1.19). The three networks of different density (Fig. 1.19(a), 1.19(c), 1.19(e)) were considered. In all cases as the capacity grows, the blocking drops, and the performance of MPP is always in-between that of the DPP and that of the SPP. For sparser networks, MPP is closer to DPP, while for denser networks it approaches SPP (Fig. 1.19(b), 1.19(d), 1.19(f)). For very dense networks (figure not included) MPP outperforms SPP significantly.



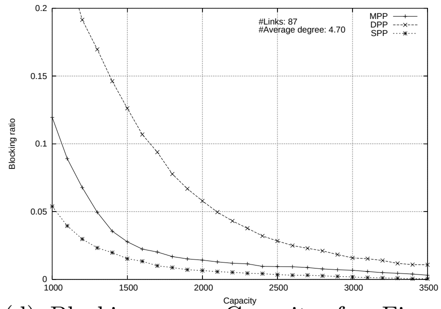
(a) The COST266 LT Reference Network (RN).



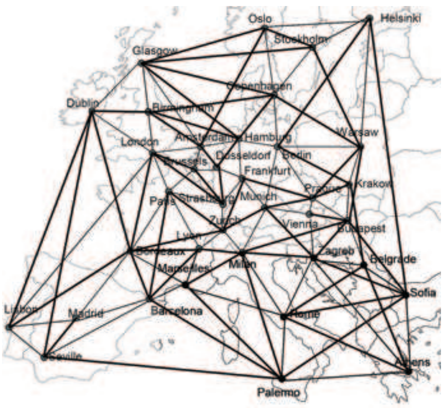
(b) Blocking vs. Capacity for Figure 1.19(a).



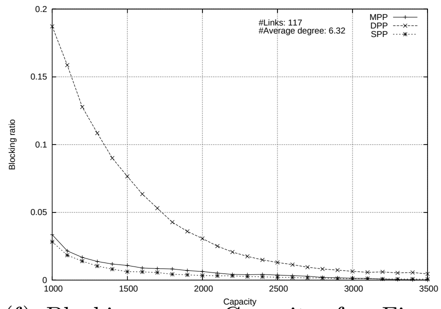
(c) The COST266 LT RN extended by 30 links.



(d) Blocking vs. Capacity for Figure 1.19(c).



(e) The COST266 LT RN extended by 60 links.



(f) Blocking vs. Capacity for Figure 1.19(e).

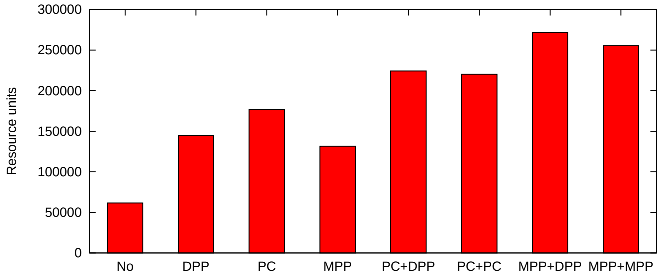
Figure 1.19: Comparing the blocking ratio of MPP to DPP and SPP for the COST 266 network as the capacity is scaled up of increasingly dense networks.

1.5.3 Comparing PC and MPP Strategies for MD Resilience

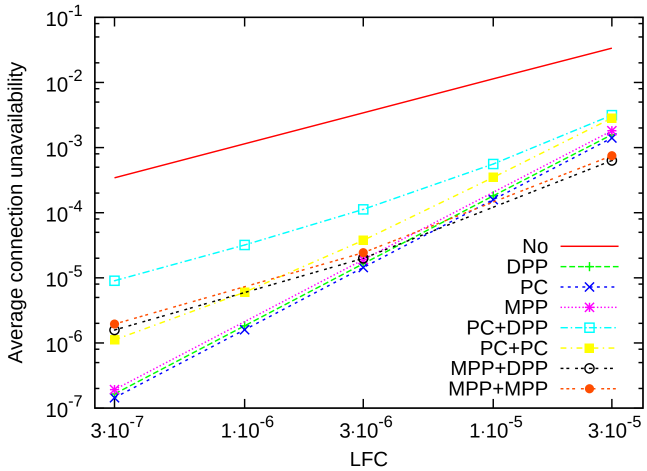
To illustrate the benefits of the proposed multi-domain resilience schemes compared to the case with no protection and to the case of dedicated protection we have used simulation.

The network considered was the e1net [C100] the Pan-European multi-domain optical reference network. The network consists of 205 nodes and 384 links in 17 domains.

Using this network we defined 3000 simultaneous traffic demands with a total of 9065 bandwidth units to deliver to end users.



(a) Resource requirements of different resilience strategies



(b) Average unavailability of connections

Figure 1.20: The trade-off between resource requirements and unavailability level.

Figure 1.20(a) shows the resource requirements of the different resilience strategies. Two things can be seen clearly.

First, when assumed that all the nodes are in a single domain (i.e., all the information is available) then all the methods (No, DPP, PC, MPP) require reasonably less capacity than for the case of multiple different domains (PC+DPP, PC+PC, MPP+DPP, MPP+MPP). The reason is that for all strategies over aggregated topologies the working path segments within the domains are protected by an additional method (either DPP, or the same method as the original interdomain method was: PC or MPP), that requires additional resources.

Second, whereas the single-domain p-Cycle scheme (**PC**) requires significantly more capacity than the **MPP**, in the multi-domain environment the **MPP** based strategies need more resources than the p-Cycle! The reason is that if full network information is available (no aggregation) there are much more branching opportunities than for the aggregated topology. This is particularly important for MPP since its quality depends on the number of relatively short paths found. For this reason for the MPP+DPP typically we can not route two disjoint paths over a single domain that was easily feasible for the MPP case. Therefore, fewer paths, with longer paths on average will be found.

However, the **MPP+DPP** that has the highest resource requirements will result in a solution with the highest connection availability – as will be discussed in the next subsection 1.5.4.

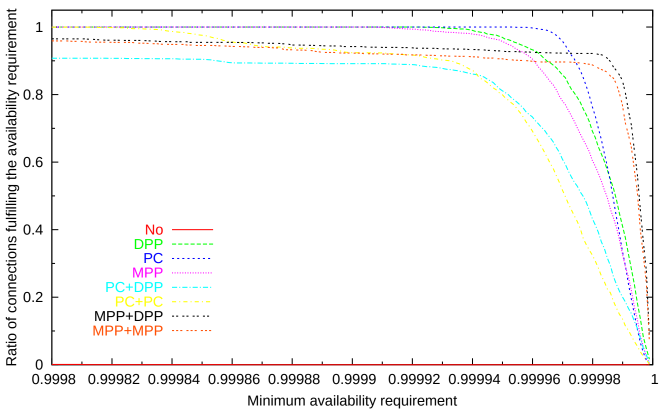
1.5.4 Availabilities Achieved by Different Strategies

For denoting the availability of a connection we use a simple probability metric A in the range $A \in [0, 1]$, where 1 means that the connection is always operational, whilst 0 means that it is always down. The connection availability can be derived from the link availability metrics along the path. However, the accurate availability of the connections cannot be calculated as a structure of serial and parallel switched components neither in case of p-Cycles nor in case of **MPP**.

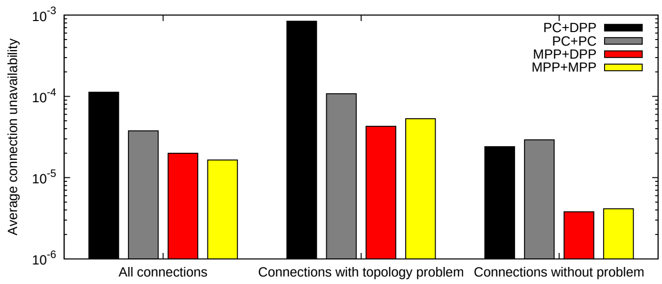
The link availability depends mostly on two things:

- How often do failures happen in a year per unit of length. In [38] a typical value is a single failure per year for an average cable length of 300 - 1000 km.
- How long does it take to recover after a failure (restoring services or if not available, repairing, e.g., the cut cables). Typical value is around 4-24 hours.

In our simulations we denote by LFC (*Link Failure Coefficient*) the probability of a 1 km long cable to be in down state (i.e., unavailable). This is the ratio of time when the link is in down state during a year to the one year period. The availability A_i of a link i of length l_i can be estimated as $A_i = 1 - LFC \cdot l_i$. In our simulations $3 \cdot 10^{-7} \leq LFC \leq 3 \cdot 10^{-5}$ according to [101], where $3 \cdot 10^{-7}$ is an optimistic, while $3 \cdot 10^{-5}$ is an pessimistic value.



(a) Tail behaviour of different resilience strategies



(b) Multi-domain resilience strategies decoupled by topological problems

Figure 1.21: What ratio of connections and why can satisfy a certain availability level?

Figure 1.20(b) shows the average unavailability for different resilience schemes. The lower is the value the better the scheme is. The case with no protection (No) has always the highest unavailability. The three "single-domain strategies" have roughly the same performance. One can see that having low LFCs (e.g., few failures or fast repairs) these strategies provide the lowest unavailability, i.e., the highest availability. However, in case of high LFC values the use of multi-domain methods is suggested, particularly of those based on **MPP**.

Our expectation was, as already discussed, that the MD (Multi-Domain) strategies are *always* better in sense of having higher availability than the single domain solutions, since each working path has additional protection for intra-domain segments. Why the simulations do not confirm this expectation?

The answer lies in the topology of the e1net. If we take a look at the tail behaviour of the strategies (Fig. 1.21(a)), we can observe the problem from another point of view. The figure shows how many connections (y-axis) have higher availability than minimally required (x-axis). These results were taken at $LFC = 3 \cdot 10^{-6}$. On the left hand side of the figure we can see how many connections have at least an availability of 0.9998. Note, that this is a relatively low requirement and all the protected connections fulfil it. Still we see that in case of **MPP+DPP** and **MPP+MPP** only the $\sim 95\%$ of the connections have higher availability than required. In case of **PC+DPP** the problem is even worse (and for **No** protection none of the connections has that high availability).

Those connections that do not allow a higher ratio of connections satisfying certain levels of availability are those that are not protected at all. Unfortunately, the e1net topology has some border nodes which are connected to the rest of their domain with a single link only! Whenever an inter-domain connection uses such a border node, within the domain neither **DPP** nor **MPP** can protect that segment!

Furthermore, the tail behaviour shows unambiguously the dominance of the **MPP** based inter-domain resilience schemes: the curves clearly demonstrate that these strategies provide the highest availability (close to "five nines") to the most (almost 90%) of the connections.

If we differentiate those connections that do not suffer from topological constraints from those that do, then we can see that the difference in the average availability is significant when we apply **MPP**.

Fig. 1.21(b) shows that the difference in the average availability is significant when we apply **MPP** at the inter-domain level (externally), or if we apply **DPP** at intra-domain level (internally).

If we do not consider those cases with topology problems, the "five nines" availability requirement (that corresponds to unavailability of 10^{-5}) would be easy to achieve using **MPP** (MPP+DPP and MPP+MPP). The figure also shows that the **PC+PC** strategy and generally all strategies that use p-Cycles internally, are more resistant to topological problems.

On Multi-Domain Resilience Issues

Coming back to the title of this Section (Sec. 1.5) we can state that even competitors can share resources for performing multi-domain protection even if only *aggregated topology and link-state information is available* but no information on working and protection paths of routed demands.

Although the operators will never want to share with their competitors their strategic and confidential information needed for shared path protection, based only on aggregated views of the topology and on the advertised free capacities of this aggregated topology we can still perform sharing of protection resources using the resource sharing between different on-cycle and straddling links of each p-Cycle or the internal resource-sharing between different paths of a single MPP demand at the inter-domain level.

Combining these inter-domain strategies with intra-domain protections, we can have connections with nearly the same availability as if the whole network was a single domain without domain boundaries. In the multi-domain environment the MPP based strategies provide even higher availability for those connections that are not hampered by topological constraints.

Chapter 2

Grooming in Multi-Layer Networks

Two multi-layer issues can be observed in the evolution of transport networks. First, there are multiple networking technologies layered one over the other. Second, it is required that not only the upper-most layer is dynamic, i.e., switched, but the upper two, or perhaps all the layers.

If the layers of this vertical structure are run by different operators or providers then they must communicate to each other to exchange information necessary for routing and other purposes. This vertical communication is referred to as Interconnection, and there are three defined Interconnection Models: (1) Overlay, (2) Augmented and (3) Peer model [29].

If all these layers are run by a single operator or provider then there is no need for communication interfaces between the layers. Therefore, a single unified integrated CP (Control Plane) can be used for all the layers and then we have instead of the interconnection the so called *Integrated Model*. The forwarding units of all the layers of the data plane are connected to a single control plane unit.

Similarly, if such a Multi-Layer network has layers or some parts of certain layers built of interconnected elements of a unique networking technology then the set of these elements is referred to as a *Region*. Having multiple different regions within a network is referred to as a *Multi-Region* network [29] [J31]. Often, it is referred to as MLN/MRN that stands for Multi-Layer Networks / Multi-Region Networks.

In switched multilayer transport networks (e.g. ASTN/GMPLS) the traffic demands have typically bandwidth by orders of magnitude lower than the capacity of λ-links. Therefore, it is not worth assigning exclusive end-to-end λ-paths to these demands, i.e., *sub-λ granularity* is required. Furthermore, the number of λs per fibre is limited and costy. To increase the throughput of a network with limited number of λs per fibre *traffic grooming* capability is required in certain nodes. There are many papers dealing with routing, traffic engineering and resilience in such multilayer networks, where grooming is one of the key issues [J31] [75] [C23] [C108].

Here we consider the case of Wavelength Routing Dense Wavelength Division Multiplexing (WR-DWDM) Networks and one layer built over it. In the WR-DWDM layer a wavelength path (λ-path) connects two physically adjacent or distant nodes. These two physical nodes will seem adjacent for the upper layer built over it via wavelength paths even if they are physically not adjacent.

This upper layer is an "electronic" one, i.e., it can perform multiplexing different traffic streams into a single λ-path via simultaneous time and space switching. Similarly it can demultiplex different traffic streams of a single λ-path. Furthermore, it can perform re-multiplexing as well: Some of the demands de-multiplexed can be again multiplexed into some λ-paths and handled together along it. This is referred to as *traffic grooming* [J4] [75]. Further on we will refer to it as *grooming*. This electronic layer is required for multiplexing packets coming from different ports (asynchronous time division multiplexing). It can be a classical or "next generation" SDH/SONET, MPLS, ATM, GbE, 10 GbE or it can be based on any other technology. However, in all cases the network carries mostly IP traffic. The only requirement is that it must be unique for all traffic streams that have to be de-multiplexed, and then multiplexed again, since we cannot multiplex e.g. ATM cells with Ethernet frames directly.

More generally, we can consider this two-layer approach as two layers of a 4-5 layer GM-

PLS/ASTN architecture [6] [83] [89]. However, not only the framing and layering structure is of interest, but also the control plane proposed in the GMPLS/ASTN framework.

Many excellent papers deal with design, configuration and optimisation of WDM Networks. Some of these methods can use the model we propose in this section and that way can be generalised for on-line routing in two-layer networks as well, using the models we propose in this Chapter.

There are also numerous papers dealing with on-line routing in WR-DWDM networks (see, e.g., Chapter 3 of [B4, B5]). There are multiple papers on grooming, mostly for the static case, i.e, when a two layer network is configured (see, e.g., Chapter 4 of [B4, B5]). Some papers consider the grooming capability in dynamic (on-line) routing [111]. There are also papers dealing with multilayer survivability, e.g., [24] and Chapter 5 of [B4, B5]).

However, there are only few papers, e.g., [C23] [109] [78], that take all these into account *simultaneously*, using the peer or the MRN model. To our knowledge there is no paper that proposes any method for adaptive, automated, on-line and distributed Multi-Layer Traffic Engineering (MLTE), Resilience and Multicast. The aim of our research was to fill this gap.

More precisely, our objective was to perform distributed on-line routing of the on-line arriving demands with estimated effective bandwidths as constant bandwidth pipes over the two network layers optimally in distributed way without separating these layers. The upper layer is assumed to support multiplexing (e.g., asynchronous TDM), while the lower layer is the λ-path system. Separating the two layers according to the overlay model decreases the complexity, however, it also deteriorates the routing.

The rest of the Chapter (Ch. 2) is organised as follows. In Section 2.1 we present the graph model used for simple grooming. In Section 2.2 we provide ILP formulation of routing, protection and multicast for grooming capable networks according to the graph model presented in Section 2.2. In Section 2.3 we propose a method for dimensioning grooming-capable networks in terms of O/E and E/O ports that allow grooming as well as in terms of required number of wavelengths. In Section 2.4 we extend the GG model of Section 2.1 to "Fragment-Graph" and introduce "Shadow-Links" to perform adaptive MLTE (λ-path fragmentation and defragmentation), and explain how our model works with available routing protocols. In Section 2.5 simulation results supporting our proposed method are shown and discussed. In Section 2.6 a state-dependent a'priori MLTE scheme is presented. In Section 2.7 an adaptive a'posteriori MLTE scheme is presented that ensures resilience in case of a failure of any SRG. Section 2.8 extends our results to setting up multi-layer multicast trees and performing restoration of these trees in case of any failure event.

2.1 GG: The Graph Model for Simple Grooming

The objective was to provide a general network model for routing in two layer networks with grooming, with different types of nodes and arbitrary topologies assuming peer/MRN-model, that allows optimal routing, using the resources of both layers jointly. The aim was to allow adaptive, automated, distributed MLTE (Multi-Layer Traffic Engineering) by the model used.

Although the most widespread topology is ring or interconnected rings, the model must be able to handle any regular or mesh topology. Furthermore, it must be able to handle any type of nodes of practical interest, e.g., OADM, OXC, EOXC, etc., all with or without grooming capability and with or without λ-conversion capability. Even limited grooming, and λ-conversion limited in number or range has to be supported. For this purpose we use our graph model, where the node is substituted by a sub-graph.

The simpler version of this model was first proposed in [C18]. ILP formulation of the static RWA problem with grooming and protection was given in [C7], using the wavelength graph, while in [C40] heuristics for solving the problem were proposed. [C62] explains the "WG" model and investigates the fairness issues of dynamic grooming with resilience.

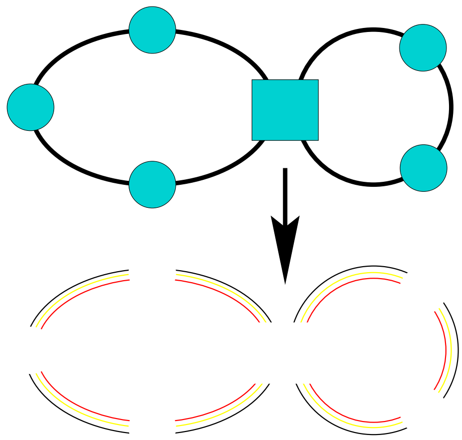


Figure 2.1: Modelling edges in the graph model.

2.1.1 Model of Links

A network consists of nodes, and links connecting the nodes. This can be modelled by a graph: a node is a vertex and a link is an edge. Having multiple λs (WL1-WL3) we will represent a λ of a link as an edge in the graph of wavelengths, according to Figure 2.1 for the network proposed in [56]. To prioritise filling up λs one-by-one we can assign slightly different weights to different λ-channels of one link. For example, edges representing WL1, WL2 and WL3 in Figure 2.1 will have weights (costs) 1,01, 1,02 and 1,03 respectively.

2.1.2 Model of Nodes

A node is modelled by a subgraph. The subgraph-nodes are the switch-ports for different wavelengths, while the weighted edges represent the costs of transitions, terminations, conversions, etc. There are different types of nodes. Models of nodes differ for these. Some examples will be shown here. In similar manner a model can be derived for any additional node-type.

Optical Add-and-Drop Multiplexer (OADM)

The OADM Nodes have in general two bi-directional ports (4 fibres). Their function is either to transmit a λ-path or to terminate it and usually they do not allow λ-conversion.

The weights assigned to edges representing termination (e.g., 50) are higher than weights of transition (e.g., 25), because transition is preferred to termination. According to the proposed model (Figure 2.2) the traffic streams can either enter or exit the OADM crossing vertex E or can be even re-multiplexed.

Cross-Connect with Electronic Core (EOXC)

In the model shown in Figure 2.3 each pair of nodes should be connected by an edge, representing potential Cross-Connection. All edges should have equal weights. Instead of connecting all pairs using nxn edges we use n edges and one node. This simplifies the model. Each incoming channel is converted to electronic domain switched by a space-switch and again converted to the optical domain to arbitrary λ. Each termination, transition or λ-change has the same cost (e.g., 25). Therefore all edges have the same weight (e.g., 25/2).

Optical Cross-Connect (OXC)

An optical Cross-Connect has more than two ports, e.g., four bi-directional ports according to Figure 2.1. In an OXC a λ-path can make transition to any output port which supports that λ ,

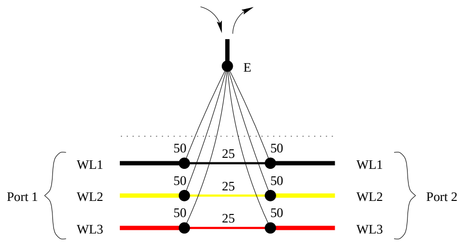


Figure 2.2: Model of OADM nodes.

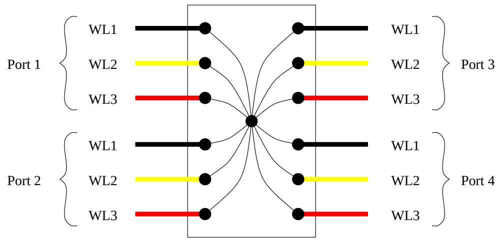


Figure 2.3: Model of EOXC nodes.

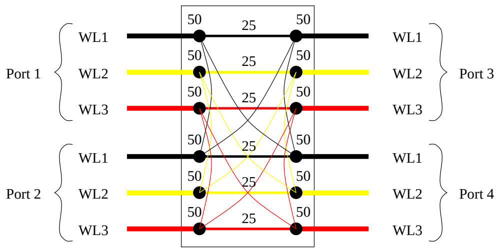


Figure 2.4: Simple OXC (no λ-conversion).

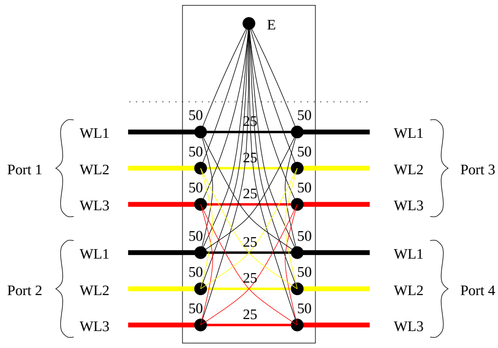


Figure 2.5: OXC with λ-conversion.

and that λ is not yet used. This OXC type (without λ-conversion capability) will be referred to as simple OXC (see Figure 2.4). In this case one incoming channel can exit at any of the remaining output ports where that λ is supported and not yet used.

In some cases the traffic stream termination is also among the functions of an OXC. In that case the model does not need any change. as shown in Figure 2.5. The only difference will be that there will be some traffic offered to that OXC node. This can be modelled by offering traffic to node E and considering it as an end-node. In this case, if sub-λ granularity is assumed, traffic-stream re-multiplexing capability is also required.

Modelling Grooming

Grooming can be modelled analogously to λ-conversion. The difference is that while in case of λ-conversion an incoming traffic stream will exit as a single outgoing stream at another λ, in case of grooming traffic streams can be multiplexed, i.e., instead of space switching space AND time switching/cross-connecting is performed.

These two functionalities can be combined as well within a single model.

Note, that λ-conversion is a special case of grooming. Therefore a node supporting only grooming can perform λ-conversion as well, while a λ-conversion node can not perform grooming.

The model we presented in Section 2.1 will be referred to as 'simple' grooming model and marked as OGS: Optical Grooming - Simple Method. To make this model better adapt to the traffic and network conditions we extend it in Section 2.4.

2.2 ILP Formulation of Routing, Protection and MultiCast

Here we provide the ILP formulation of the problem for two-layer Grooming-capable Multi-Hop Wavelength-Routing WDM networks modeled as GG (Grooming Graph) (Section 2.1). The upper layer is assumed electrical time-division multiplexing capable (or packet switching capable), while the lower layer is the WR-WDM layer.

We assume the network to be modeled as a wavelength graph as defined in Section 2.1 that consists of vertices V that correspond to the ports at different wavelengths of the switches that are interconnected within switches by edges from set E. The set of those edges that are used either in the electrical layer or to interconnect ports of the optical layer and of the electrical layer within a switch is referred to as E_E (Edges leading to the Electrical layer). Consequently the set of those edges that represent wavelength links, i.e., with both their ends in the optical layer are from the set $E \setminus E_E$.

2.2.1 ILP Formulation of Routing

Using the model of Section 2.1 we can formulate the problem of routing with grooming as follows [C7].

Constants:

- α, $0 < \alpha < 1$ is a tuning parameter that weights the optimisation objectives. It can prefer either the minimal routing cost (larger α) or the minimal total power used (smaller α).
- B is the bit/s capacity of wavelength channels, assuming for sake of simplicity that it has the same value over all the wavelength channels.
- s^o, t^o and b^o are the source, the target (destination) and the bandwidth requirement of demand $o \in O$, respectively.

Variables:

- $x_{ij}^o \in \{0,1\}, \forall (i,j) \in E, \forall o \in O$ denotes the flow of the commodity o on arc (directed edge) (i,j).
- $y_{ij} \in \{0,1\}, \forall (i,j) \in E$ is the binary indicator variable having value of 1 if wavelength channel between i and j is used or 0 if not.

Objective:

$$minimize \left\{ \alpha \sum_{\forall o \in O} \sum_{\forall (i,j) \in E_E} c_{ij} b^o x_{ij}^o + (1-\alpha) \sum_{\forall (i,j) \in E \setminus E_E} c_{ij} y_{ij} \right\} \tag{2.1}$$

Constraints:

$$\sum_{\forall j \in V^{\to i}} x_{ji}^o - \sum_{\forall k \in V^{i \to}} x_{ik}^o = \begin{cases} -1 & \text{if } i = s^o \\ \ \ 0 & \text{otherwise} \\ \ \ 1 & \text{if } i = t^o \end{cases} \quad \forall i \in V, \quad \forall o \in O \tag{2.2}$$

$$\sum_{\forall o \in O} b^o x_{ij}^o \leq B, \quad \forall (i,j) \in E \tag{2.3}$$

$$x_{ij}^o \leq y_{ij}, \quad \forall (i,j) \in E, \quad \forall o \in O \tag{2.4}$$

$$y_{ij} \leq \sum_{\forall o \in O} x_{ij}^o, \quad \forall (i,j) \in E \tag{2.5}$$

$$y_{ji} = \sum_{\forall k \in V^{i \to}} y_{ik} \quad \forall (i,j) \in E \setminus E_E \tag{2.6}$$

The objective 2.1 is to minimise the total number of hops for all traffic demands weighted by the required per-demand capacities b^o and by the costs c_{ij} of using certain wavelength links (edges).

Depending on the value of α the optimisation will prefer either the optical part of the network while routing (smaller α) or the electronic layer (larger α).

Equation 2.2 is the flow conservation constraint that ensures that the traffic streams are to be terminated at end nodes, while in all the other nodes where it enters it must leave as well, i.e., must be conserved.

Equation 2.3 is a classical capacity constraint stating that the total bandwidth requirement of demands using a certain wavelength link may not exceed its bandwidth B.

Equations 2.4 and 2.5 are to be considered jointly. They guarantee that that traffic streams may use available wavelength links only, and a wavelength path is established only if it is needed for carrying a traffic flow. If the value of α is strictly smaller than 1 then constraint 2.5 can be left out, since y_{ij} will be always minimised to 0 via the objective function whenever all corresponding x_{ij}^o values are 0.

Constraint 2.6 guarantees that no wavelength path may branch.

In [C7] the problem is formulated for undirected graphs as well.

2.2.2 ILP Formulation of Dedicated Protections

There are various types of protection, however, here we assume dedicated end-to-end disjoint path protection. It means, that the working and protection path have to be disjoint in sense of having no common link, no common node or no common SRG element at all. Whenever it is about a multi-layer network, we must distinguish between the protection at the upper layer, protection at the lower layer or protection using both the layers simultaneously. [C7] discusses most of these cases along with their ILP formulations. For brevity, here I provide only a single ILP formulation, that of the most complex case when the protection at both, the upper (electrical) and the lower (optical) layer can be performed and when it is SRLG disjoint. Handling shared protection by ILP [C36] tremendously increases the complexity, therefore, we omit it here for this two-layer architecture.

The formulation is similar to that for routing (Section 2.2.1). Here we add new variables for protection paths and corresponding new constraints and we introduce $SRLG$, the set of all shared risk link groups $srlg$, where each srlg contains one or more links (edges) $(i,j) \in E$ that are all affected at the same time by a single failure. This can be easily further generalised to SRGs that can contain not only the edges, but nodes, and other network elements as well.

Variables:

- $x1_{ij}^o \in \{0,1\}, \forall (i,j) \in E, \forall o \in O$ denotes the primary (working) flow of the commodity o on arc (directed edge) (i,j).

- $x2_{ij}^o \in \{0,1\}, \forall (i,j) \in E, \forall o \in O$ denotes the secondary (protection) flow of the commodity o on arc (directed edge) (i,j).

- $y1_{ij} \in \{0,1\}, \forall (i,j) \in E$ is the binary indicator variable having value of 1 if the primary (working) wavelength channel between i and j is used or 0 if not.

- $y2_{ij} \in \{0,1\}, \forall (i,j) \in E$ is the binary indicator variable having value of 1 if the secondary (protection) wavelength channel between i and j is used or 0 if not.

- $x_{ij}^o \in \{0,1\}, \forall (i,j) \in E, \forall o \in O$ indicates if either the primary (working) flow or the secondary (protection) flow or both flows of the commodity o use on arc (directed edge) (i,j).

- $y_{ij} \in \{0,1\}, \forall (i,j) \in E$ is the binary indicator variable having value of 1 if either the primary (working) or the secondary (protection) or both the primary and the secondary wavelength channels between i and j are used or 0 if not.

Objective:

$$minimize \left\{ \alpha \sum_{\forall o \in O} \sum_{\forall (i,j) \in E_E} c_{ij} b^o x^o_{ij} \quad + \quad (1-\alpha) \sum_{\forall (i,j) \in E \setminus E_E} c_{ij} y_{ij} \right\} \tag{2.7}$$

Constraints:

$$x1^o_{ij} + x2^o_{ij} \leq x^o_{ij}, \quad \forall (i,j) \in E, \quad \forall o \in O \tag{2.8}$$

$$y1_{ij} + y2_{ij} \leq y_{ij}, \quad \forall (i,j) \in E \setminus E_E \tag{2.9}$$

$$\sum_{\forall j \in V^{\to i}} x1^o_{ji} - \sum_{\forall k \in V^{i\to}} x1^o_{ik} = \begin{cases} -1 & \text{if } i = s^o \\ 0 & \text{otherwise} \\ 1 & \text{if } i = t^o \end{cases} \quad \forall i \in V, \quad \forall o \in O \tag{2.10}$$

$$\sum_{\forall j \in V^{\to i}} x2^o_{ji} - \sum_{\forall k \in V^{i\to}} x2^o_{ik} = \begin{cases} -1 & \text{if } i = s^o \\ 0 & \text{otherwise} \\ 1 & \text{if } i = t^o \end{cases} \quad \forall i \in V, \quad \forall o \in O \tag{2.11}$$

$$\sum_{\forall o \in O} b^o x^o_{ij} \leq B, \quad \forall (i,j) \in E \tag{2.12}$$

$$x^o_{ij} \leq y1_{ij}, \quad \forall (i,j) \in E, \quad \forall o \in O \tag{2.13}$$

$$y1_{ij} \leq \sum_{\forall o \in O} x^o_{ij}, \quad \forall (i,j) \in E \tag{2.14}$$

$$\sum_{\forall (i,j) \in srlg} (x1^o_{ij} + x2^o_{ij} + y1_{ij} + y2_{ij}) \leq 3, \quad \forall srlg \in SRLG, \quad \forall o \in O \tag{2.15}$$

$$y1_{ji} = \sum_{\forall k \in V^{i\to}} y1_{ik} \quad \forall (i,j) \in E \setminus E_E \tag{2.16}$$

$$y2_{ji} = \sum_{\forall k \in V^{i\to}} y2_{ik} \quad \forall (i,j) \in E \setminus E_E \tag{2.17}$$

In the Objective 2.7 the aim is to minimise the total cost of both the working and protection paths at both the layers (El. + Opt.), while we require each demand to be protected either at the optical or at the electrical layer, but never at both layers. That means that either at the E-layer or at the O-layer the protection and the working path of each demand share the same path. For this purpose we define the new variables x^o_{ij} and y_{ij} in 2.8 and 2.9, respectively, not to count resources twice.

Equations 2.10 and 2.11 are the flow conservation constraints for the working and for the protection traffic streams. 2.12 is the wavelength capacity constraint, while 2.13 and 2.14 are equivalent to Equations 2.4 and 2.5.

Constraint 2.15 is more interesting. It guarantees that either at the upper, or at the lower layer, but there must exist an SRLG-disjoint protection for each demand o. This sum can be 0, 1 or 3 but must be strictly less than 4, because all 4 flows must not use the same SRLG. In case of 0 none of them uses the considered SRLG. If it is 1, the lower layer protection uses it only. If it is 3 than the upper layer working and upper layer protection path use the same SRLG, however, at the optical layer they are protected by a wavelength path segment, that is disjoint. Because of the constraints and of the minimisation in the objective, the value of 2 will never appear in this constraint.

Constraints 2.16 guarantees that each working wavelength path segment is continuous between its electric terminations. Constraint 2.17 guarantees the same for each protection wavelength path segment.

2.2.3 ILP Formulation of MultiCast

In case of multi-cast demands t we assume that the traffic goes from one source s^t to more than one destinations $d^t \in D^t$. Instead of a path, here we have a tree that the traffic of bandwidth demand b^t follows. $D^t \subset V$ is the set of destinations of demand t, i.e., the leaves of the tree. Accordingly a demand t, $t \in T$ can be defined as $t(s^t, D^t, b^t)$. T is the set of all the multicast demands that has to be routed at the same time. We decompose this problem of routing a tree t from one source s^t to $|D^t|$ destinations to routing $|D^t|$ paths, from s^t to $d_1^t, d_2^t, ...d_{|D^t|}^t$, respectively. We will refer to these paths to be routed as sub-demands o of demand t, i.e., $o \in t \in T$. Set $V_E \in V$ is the set of vertices that are in the electrical domain. The objective is to use as few network resources as possible.

Variables:

- $x_{ij}^o \in \{0,1\}, \forall (i,j) \in E, \forall o \in t, \forall t \in T$ indicates whether sub-demand o of multicast tree t uses edge (i,j). Edge (i,j) corresponds to a wavelength link between nodes or within nodes according to the GG model presented in Section 2.1.
- $z_{ij}^t \in \{0,1\}, \forall (i,j) \in E, \forall t \in T$ indicates whether multicast tree t uses edge (i,j). It may happen that the multicast tree has a single leaf, i.e., then it is unicast. This way the mixture of unicast and multicast traffic can be optimised as well.
- $y_{ij} \in \{0,1\}, \forall (i,j) \in E$ is the binary indicator variable having value of 1 if wavelength channel between i and j is used by any of trees t or 0 if not.

Objective:

$$minimize \sum_{\forall (i,j) \in E_E} c_{ij} y_{ij} \tag{2.18}$$

Constraints:

$$\sum_{\forall j \in V^{\to i}} x_{ji}^o - \sum_{\forall k \in V^{i \to}} x_{ik}^o = \begin{cases} -1 & \text{if } i = s^t \\ 0 & \text{otherwise} \\ 1 & \text{if } i \in D^t \end{cases} \quad \forall i \in V, \quad \forall o \in t, \quad \forall t \in T \tag{2.19}$$

$$x_{ij}^o \le z_{ij}^t, \quad \forall (i,j) \in E, \quad \forall o \in t, \quad \forall t \in T \tag{2.20}$$

$$z_{ij}^t \le \sum_{\forall o \in t} x_{ij}^o, \quad \forall (i,j) \in E, \quad \forall t \in T \tag{2.21}$$

$$\sum_{\forall j \in V^{\to i}} z_{ji}^t \le \begin{cases} 0 & \text{if } i = s^t \\ 1 & \text{if } i \ne s^t \end{cases} \quad \forall i \in V_E, \quad \forall t \in T \tag{2.22}$$

$$\sum_{\forall j \in V^{\to i}} z_{ji}^t = \sum_{\forall k \in V^{i \to}} z_{ik}^t \le 1 \quad \forall i \in V \setminus V_E, \quad \forall t \in T \tag{2.23}$$

$$\sum_{\forall t \in T} b^t z_{ij}^t \le B, \quad \forall (i,j) \in E \tag{2.24}$$

$$z_{ij}^t \le y_{ij}, \quad \forall (i,j) \in E, \quad \forall t \in T \tag{2.25}$$

$$y_{ij} \le \sum_{\forall t \in T} z_{ij}^t, \quad \forall (i,j) \in E \tag{2.26}$$

$$\sum_{\forall j \in V^{\to i}} y_{ji} = \sum_{\forall k \in V^{i \to}} y_{ik} \le 1 \quad \forall i \in V \setminus V_E \tag{2.27}$$

The objective 2.18 minimizes the number of used wavelength links by all the trees. Implicitly this minimises the number of edges used by the trees, however, if we want to minimise the electric part we have to add with a smaller weight the weight of edges used by trees, defined by variables z.

The flow conservation 2.19 is defined for subdemands only, however for trees and wavelength path segments there is a similar rule defined to avoid branching in 2.23 and 2.27 respectively.

Constraint 2.20 ensures that if any subdemand o of tree t wants to use edge (i, j) ($x^o_{(i,j)} = 1$) then edge (i, j) must be allocated to tree t: $z^t_{(i,j)} = 1$. Constraint 2.21 ensures that edge (i, j) is not allocated to tree t if it is not used by any of sub-demands o of tree t. This can be completely left out if we add to the objective minimisation of variables z, at least with a very tinny weight.

Constraint 2.22 ensures that two branches of a multicast tree may not merge. I.e., the total of edges of a single tree t entering node i has to be o in the source of the tree and has to either 0 if not used by the tree or 1 if tree t uses node i. Constraint 2.23 is used if we want to forbid tree branching in electrical nodes. We used this constraint to define reference method where only optical branching is allowed. Otherwise it should be completely left out from the ILP formulation.

Capacity constraint 2.24 ensures that the total of tree capacities over a link may not exceed the link (wavelength channel) capacity. Here we have assumed, that multiple trees can use the same wavelength channel.

Constraints 2.25 and 2.26 are somewhat similar to 2.20 and 2.21 respectively, however, they defines the relation of the tree to the wavelength channel link. Constraint 2.25 ensures that a branch $z^t_{(i,j)} = 1$ can be assigned only to an existing and active wavelength link $y_{(i,j)} = 1$. Constraint 2.26 makes sure, that a wavelength link is activated only, if it will be really used.This constraint can be omitted, because it is implicitly included into the objective.

Constraint 2.27 will guarantee that the wavelength path segments can not branch in non-electrical nodes. This constraint is needed only, if we want to disable the optical tree-branching capability. If optical multicast is allowed we simply leave out this constraint from the formulation.

As discussed 4 of 9 constraints can be omitted. However, additional constraints can be introduced as well as discussed in [C126]. For example, the depth (longest sub-demand) or the breadth ($1 : n$ branching constraint for each node) of the tree can be simply constrained.

This method (Section 2.2.3) will be used in Section 2.8.

2.3 Dimensioning Grooming Capability

In switched multi-layer optical networks traffic grooming is the key of efficient bandwidth utilization. Without it a single traffic demand would occupy a full wavelength channel. However, it is not necessary to install grooming capability in all nodes of a network. Furthermore it is also unnecessary to equip all grooming nodes with full grooming capability. We can reduce the costs by deploying only the necessary grooming capacity. Here we introduce algorithms based on statistical utilization analysis which determine not only the necessary number of grooming ports, but also the necessary number of wavelengths in the network. We compare these dimensioning results for different protection techniques.

Setting up full exclusive wavelength paths for demands of tinny bandwidth is not economical. Therefore, a “digital” layer is set over the optical one that ensures the fine granularity that can be in general a ngSDH, MPLS or even IP or Ethernet switching capable one. The fine granularity and improved resource usage can be achieved by sharing the capacity of wavelength channels, i.e., by multiplexing the digital content in distributed way within the network. However, for this purpose a digital switch has to be added to each OXC (Optical Cross-Connect) that needs as many ports and as many O/E and E/O converters as many channels are going to be terminated or re-multiplexed in that node. This two-layer re-multiplexing that leads to better resource usage but significantly increases the complexity of routing, traffic engineering and protection is referred to as grooming [J4, J31].

In [C110] we introduced an algorithm with the following goals: first, it aims to decide, what number of wavelengths per fiber is needed in the network, i.e. what is the necessary number of ports of the digital equipment (e.g., cross-connect or switch). Second, it determines the required number of E/O and O/E converters in each network node, including the decision whether grooming capable equipment is needed at all in that node. The constraint is that the blocking rate may not exceed a certain predefined value. Consequently the algorithms carry out dimensioning of both, the optical layer and the electronic layer.

Our main goal here is to compare these dimensioning results for different kinds of *protection* schemes (i.e. no protection, dedicated or shared end-to-end path protection) [C109]. Our early results on this topic were presented in [C110].

2.3.1 Problem Formulation

We assume a two-layer network where the upper one is time switching capable while the lower one is wavelength (space) switching capable as explained in Section 2.1.

We suppose that the two layers are interconnected according to the peer interconnection model or vertically integrated model according to the multi-region network framework, i.e., while routing, the control plane has information on both layers and both layers take part in accommodating a demand. Note, that the result is applicable to overlay or augmented interconnection models as well.

The network topology and the number of fibers are assumed given as well as the estimated busy hour traffic. The capacity of wavelength channels, the cost of grooming capability and the cost of grooming ports can also be given in advance.

We assume dynamic traffic demands and three kinds of protection schemes: no protection, dedicated end-to-end path protection, and shared end-to-end path protection. The main goal of this section is to compare resource requirements for these protection schemes.

The simplest, but most expensive approach is to equip each node with full wavelength conversion capability, i.e., all wavelength links can be terminated in a node and switched via the electronic space-and-time switch. However this is a very expensive solution.

A wiser approach is to estimate the required number of grooming ports per node as well as to decide whether grooming capability is needed at all in a node. This strongly depends on the topology, on the number of fibers and wavelengths per link as well as on the traffic conditions.

The objective is to find the minimal (cheapest) configuration that can satisfy all the demands with an upper bound on the allowed blocking ratio.

The network and grooming models we use are described in details in [C26]. We have solved a similar but simpler problem in [C108], where the grooming facility location was the task without determining the number of ports or the number of wavelengths per fiber. A similar problem was discussed in [110]. There are numerous papers on sparse wavelength conversion capability dimensioning e.g., [95, 18, 13]), however, their model does not support grooming at all.

2.3.2 The Three Proposed Algorithms

In this section we present heuristic algorithms which use iterative simulations to determine the number of grooming ports necessary in each node and/or the number of wavelengths on each link. This means that we start from an initial network configuration and use simulations to measure different characteristics of the network. Then we automatically modify the network configuration based on the results, and iterate by starting a new simulation. The iteration is stopped when a network configuration is reached, which is the same as the previous one was, i.e., the algorithm cannot further improve it. We will refer to this configuration as a “balanced state” henceforth.

Optimizing the Number of Grooming Ports

The input of this algorithm is the network topology. For simplicity we suppose that the number of wavelengths on each link is the same (WL). However, the code can be extended easily to handle different number of wavelengths on each link. Let the number of fibers connected to node n be denoted by R_n.

We assume that the initial number of wavelengths on the links is relatively large, thus the blocking in the network is primarily caused not by the links, but by the nodes.

Initially the number of O/E and E/O converter ports was $WL \cdot R_n$ in all nodes. This is the theoretical maximum of the number of grooming ports needed, since this number of ports allows that every wavelength on each interface can be routed to the electronic layer of the switch at the same time. The number of O/E and E/O ports is the same. Each O/E conversion reduces the number of free O/E ports by one, and vice versa. This can happen in three cases:

- When routing a demand from the optical layer to the electric layer in a switch to perform wavelength conversion or traffic grooming.
- When routing a wavelength (which carries multiple traffic demands) to the electric layer. This only "consumes" a single O/E port too irrespectively of the number of demands groomed together in that wavelength.
- When the given node is the destination of a demand then also one O/E port is used up.

An E/O conversion reduces the number of available E/O ports by one. There are also three cases when this happens. These are analogous to the previous ones. During the simulations the number of available O/E and E/O ports in a switch change independently. However, due to the symmetry of the demands, their statistical properties are the same. We used unidirectional demands, but all nodes have the same chance to become the source or the destination, this explains the symmetry.

In each logical time step of the simulation the number of available O/E and E/O ports for each node are registered. From this data we construct two histograms for each node (Figure 2.6). The value (vertical axes) of the O/E histogram at n (horizontal axis) shows in what ratio of simulation time was the number of available O/E ports equal to n. The E/O histogram shows the same for the E/O port utilization.

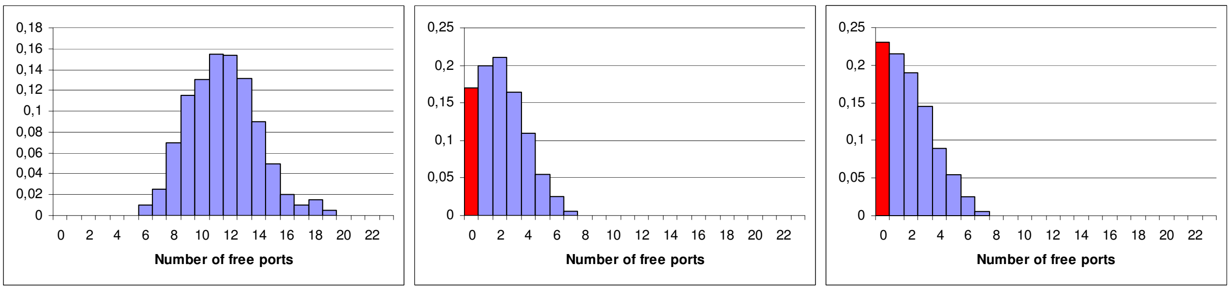


Figure 2.6: Relative frequency histogram of the number of free (unused) ports. Examples for under-utilised (left), optimally utilised (middle) and over-utilised (right) nodes.

The value of these histograms at zero is of great importance. This shows the ratio of time when the node was unable to perform further wavelength conversion or grooming because it had no free O/E or E/O ports. This value is not equal to the blocking rate of the node (B_N), because a demand passing through the node does not necessarily reach the electric layer. It may be handled only by the optical layer of the switch. Thus B_N is lower than the value of the histogram at zero, but there is a connection between them. The value of B_N determines the estimated average blocking rate of the network as follows (supposing that it is the same for every node): $\bar{B} = 1 - (1 - B_N)^i \approx i \cdot B_N$, for small values of B_N, where i denotes the number of nodes an average demand passes, which is the average distance of nodes plus one.

We modify (decrease) the number of grooming ports for overloaded nodes, until the resulting per node blocking rate drops below a predefined threshold T_N.

For this purpose we first determine the value of k as follows: $k := k_{max} - 1$ while $\sum_{i=0}^{i=k_{max}} p_i \leq T_N$, where p_i is the relative frequency of the event that the number of free ports is i (the i^{th} column of the histogram).

Then we decrease the number of the ports by k. The value of k is obtained by summing up the values from left to right of the histogram (the left tail of the distribution) until the sum reaches the threshold T_N. This means that we "shift" the whole histogram to the left. In the special case, when k_{max} is equal to 0, then k is set to -1. This means that we increase the number of ports by one.

Based on our experience for small values of T_N ($T_N < 0.03$) this procedure should be iterated, because the balanced state is not reached in one step. For larger values of T_N it takes only one step to reach the balanced state.

Optimizing the Number of Wavelengths

In this case we want to determine how many wavelengths are necessary on each link. We suppose that the number of grooming ports in the nodes is sufficiently large, so that the blocking of the network is caused solely by the link capacities. We follow a similar train of thought to the one in Section 2.3.2. In this case the result of the simulation is the used capacity on each link for each time step. The aim is to determine which links are under-utilized and which are over-utilized, and to decrease the number of wavelengths on under-utilized links, and to increase it on over utilized-ones accordingly.

If we denote the number of wavelengths on a link by WL, then the free capacity of the link may vary between 0 and $WL \cdot C_{WL}$, where C_{WL} is the capacity of a single wavelength. The capacity of all wavelengths of all links is assumed to be the same in our model.

From the used capacity we calculate the free capacity for each link, and then construct histograms from these as we did in the first algorithm (discussed in last subsection) for the grooming ports (Figure 2.7). Before constructing the histograms we quantify the values of free capacity. We do this to avoid having histograms with $WL \cdot C_{WL}$ number of columns. This is necessary because running simulations which produce such fine-grained results would take too much time. We divide the $WL \cdot C_{WL}$ range into N parts uniformly.

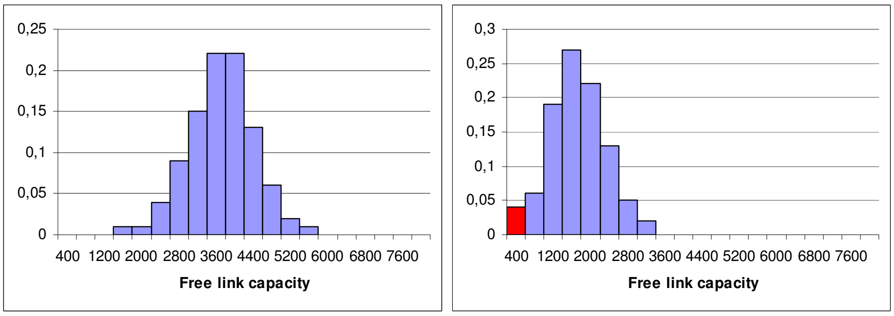


Figure 2.7: Relative frequency histogram of the free capacity of links. Example for a lightly (left) and for a heavily (right) utilised link.

We want to determine the blocking caused by one single link, which is not easy. Therefore, we make the following assumptions:

- A demand leaving a given network node on a given interface cannot pass the link, when there is no wavelength with free capacity larger than the bandwidth of the demand. In such a case the demand gets blocked by the link.

- The unused capacities on different wavelengths are independent.

A demand gets blocked by a link when the bandwidth of the demand is larger than the maximum of the free capacities (c^*) of the wavelengths on the link. For the sake of simplicity we will refer to this (c^*) as the "largest free block" on the link.

We modify the number of wavelengths similarly to the number of grooming ports in the first algorithm. We keep "shifting" the histogram to the left while B_L is smaller than the blocking rate threshold (T_L) of the link. Of course the histogram can not be shifted to the left by an arbitrary number, but just by the integer multiples of the wavelength capacity.

The number of wavelengths can be decreased by an arbitrary number, however, increased only by one.

In one step of the iteration we apply the above procedure to all links of the network. To reach a balanced state we may have to do more than one iteration. This depends on the value of T_L. In case when starting from a "lower state"(bottom-up approach) we surely need more steps, because the number of wavelengths can only be increased by one in each step.

Optimizing the Number of Grooming Ports and the Number of Wavelengths Jointly

Now we will combine the previous two algorithms. The combined algorithm optimizes the number of grooming ports and the number of wavelengths at the same time. We suppose that the cost of the wavelengths is greater than that of the grooming ports. Therefore, we primarily try to decrease the number of wavelengths.

This algorithm finds the balanced state through iterations by all means. In the starting configuration every link has only one wavelength, and the number of grooming ports is R_N in all nodes.

Just as in Sections 2.3.2 and 2.3.2, after every simulation we calculate the histograms, and do some modifications according them. After each step it is true that the number of grooming ports in all nodes is less than or equal to $\sum_{i=1}^{R_n} WL_{n,i}$, where $WL_{n,i}$ is the number of wavelengths used on the i^{th} interface (link) of node n, and R_n is the number of the links connected to node n. The algorithm uses the following heuristic rules:

1. Increase both the port number and the wavelength number: in case when the number of ports within a node exceeds the maximum, then we increase the number of wavelengths by one on each adjacent link, and increase the number of ports to the maximum.

2. Decrease the number of ports: this is the same as the rule used for decreasing the number of ports in the first algorithm. When using appropriate values for T_n (not too small) one step convergence is likely.

3. Modifying the number of wavelengths and the number of ports: this is the same as the rule used to modify the numbers of wavelengths in the second algorithm. With addition that in the case, when the number of wavelengths on some of the links changes, we set the number of ports in the adjacent nodes to the maximum.

The network reaches a balanced state, when the algorithm changes neither the number of ports, nor the number of wavelengths from one iteration to the next one. We can start the algorithm from two types of initial configurations. Starting from a "lower state" (bottom up) means that both the number of ports in all nodes and the number of wavelengths on all links is lower in the initial configuration than in the balanced state. Starting from an "upper state" (top down) means exactly the opposite.

The algorithm and the simulation are influenced by the topology of the network and the volume of the traffic in it. Other important parameters are T_N and T_L. The algorithm runs until these given threshold values are reached on every link and every node.

It may happen that the iteration does not reach a balanced state, but starts oscillating around it. The problem can be solved by changing the traffic pattern, that will hinder oscillation. We can also stop the iteration and consider one of the oscillation states as balanced state, because the amplitude of the oscillation is very low.

2.3.3 Simulation Results

The NSF-net (Figure 2.18) network topology was used during the simulations with uniform traffic demands between the nodes. We have chosen this medium-size network with 14 nodes and 21 links to shorten the simulation time. The traffic was generated by our own program. We set such a traffic load - by adjusting the mean inter-arrival time and the mean holding time of the traffic -, that the blocking ratio should be acceptable with all protection technique.

First we analyze the first algorithm used to determine the necessary number of ports. In the initial configuration there were 14 wavelengths on each link, and maximal number of grooming ports in all nodes. We adjusted the volume of the traffic so that the blocking rate of the network was less than 1 %, thus we started from an overdimensioned network and wanted to observe the effect of increasing T_N. This means that we allow more and more blocking for the nodes.

The left hand side of Figure 2.8 shows the growth of the network-level blocking rate as the per node blocking rate threshold (T_N) increases. The intensity of the growth is theoretically proportional to the average node distance in the network. The simulations resulted in similar curves in all protection scenarios. We know that the bandwidth requirement of shared protection - and especially dedicated protection - is higher than that of the unprotected case. This behavior slightly appears in the curves. Nonetheless, we can state that the network blocking ratio is mostly affected by the per-node blocking threshold, not by the protection technique.

However, it is more interesting to see how many grooming ports are necessary to provide a given network level blocking ratio in different protection scenarios (right hand side of Figure 2.8). In this sense there is significant difference between the protected and unprotected cases. In case of dedicated protection more than two times more grooming ports are necessary in the network compared to the unprotected case. Shared protection needs less than dedicated protection, but still over one and a half times more ports than the case with no protection.

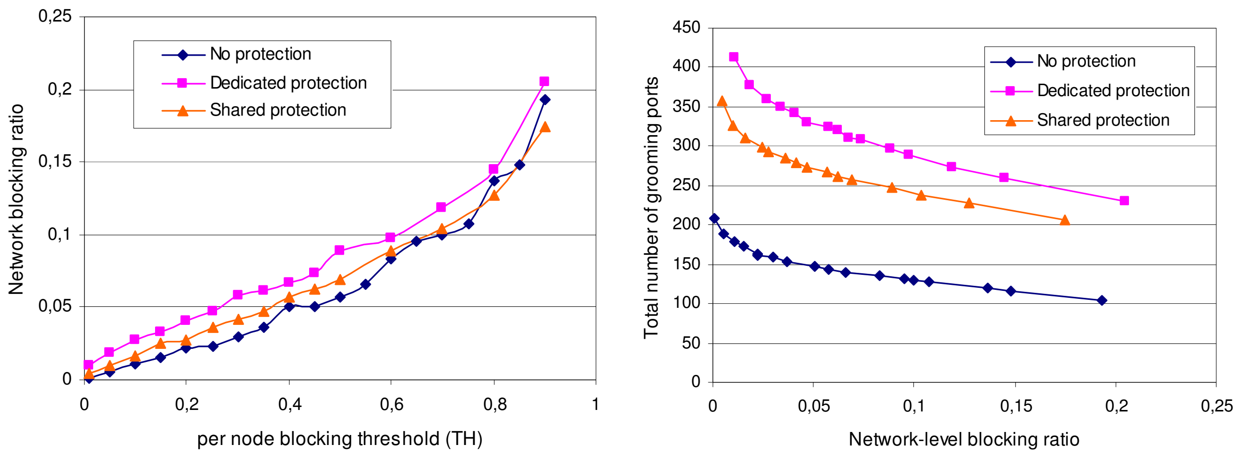


Figure 2.8: Network-level blocking ratio as a function of the per node blocking threshold T_N (left) and the required total number of grooming ports as a function of network-level blocking ratio (right).

The statement is true in all cases, that if we allow moderate network blocking ratio, we can reduce the number of grooming ports significantly. All curves are falling rapidly close to the zero-blocking region. For example if we allow a blocking ratio of 5% instead of 1% we can reduce the number of required grooming ports by 20%. We found that this gain is similar in all protection cases. Naturally this gain is inexpressively high if we compare the required number of grooming ports in this case to the number of grooming ports in a full grooming capable network. The results also suggest us that it is not wise to decrease the number of grooming ports after a certain point, because then the performance will deteriorate. Thus we cannot spare much more cost, however the network blocking ratio will raise.

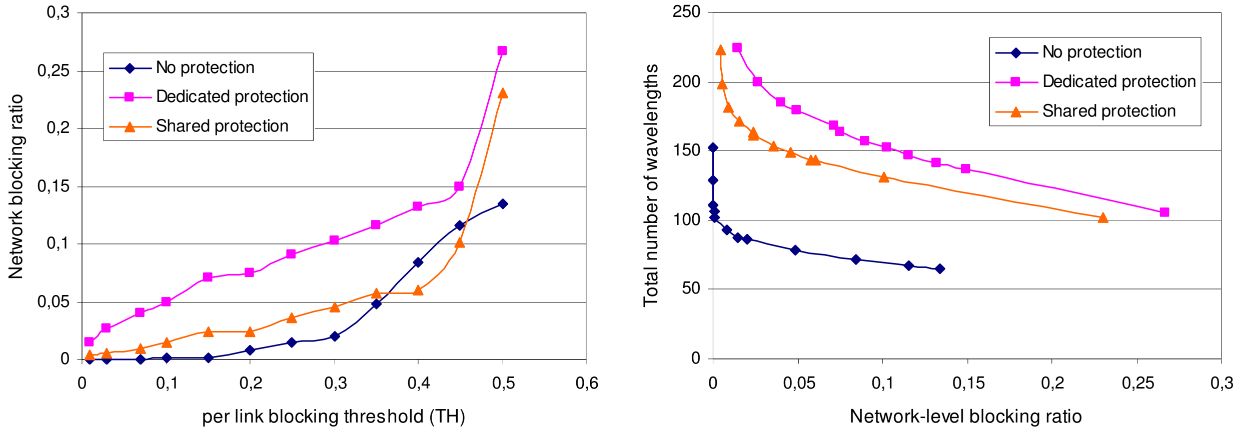


Figure 2.9: Network blocking ratio as a function of the per link blocking threshold (left) and the required total number of wavelengths as a function of network blocking ratio (right).

Now the results of the second algorithm, that is used to determine the number of wavelengths, will follow. In the initial configuration there were 14 wavelengths on all links, and the maximum number of grooming ports in all nodes, as in case of grooming port dimensioning. We again adjusted the volume of the traffic so that the blocking rate of the network was less than 1% in all protection scenarios. After that we started to increase the per link blocking rate threshold (T_L). We always set the number of grooming ports in all nodes to the maximum based on the current number of wavelengths, therefore, the bottleneck was the lack of wavelengths, not the lack of grooming ports.

The results are by some means similar to the grooming port dimensioning case. However in the left hand side of Figure 2.9 we can see huge differences between the blocking curves belonging to different protection scenarios. Especially the dedicated protection case shows higher network blocking ratio for the same value of per link blocking threshold. This phenomenon is due to the fact that capacity of a link (e.g. the number of wavelengths) cannot be adjusted with such a fine granularity as the number of grooming ports can. Thus a small difference in the per link blocking threshold can cause a large modification in the number of wavelengths. Consequently the network blocking ratio can raise or fall suddenly.

The necessary number of wavelengths as a function of the network blocking ratio (right hand side of Figure 2.9) shows a similar picture as in case of grooming port dimensioning. The curves are falling even more steeply close to the zero-blocking value, thus the sparing gain is higher than in the previous case. This sudden fall is also due to the rough granularity of the link capacities.

There is significant difference in the number of necessary wavelengths between the protected and unprotected cases. In case of dedicated protection more than two times more wavelengths are necessary in the network compared to the unprotected case. Shared protection needs over one and a half times more wavelengths. We realized that in protected networks the gain in the required number of grooming ports and the required number of wavelengths is similar.

Finally we analyze the third algorithm, which optimizes the number of grooming ports and the number of wavelengths at the same time. The value of T_N was 0.4, and the value of T_L was 0.1. The average inter-arrival time was 300, and the average holding time was 250. The volume of the traffic can be arbitrary of course, because the purpose of the algorithm is to find an appropriate network configuration for the given traffic.

Our objective was to compare the number of grooming ports, the number of wavelengths in the network in balanced state, and also the number of iterations to reach this balanced state.

We tried starting the algorithm both, from an “upper” and from a “lower” state. Starting from the “upper” state meant that, in the initial network configuration, there were 14 wavelengths on each link, and maximal number of grooming ports in each node. Starting from the "lower" state meant that there was only one wavelength on each link, and the maximal number of grooming ports was available in each node.

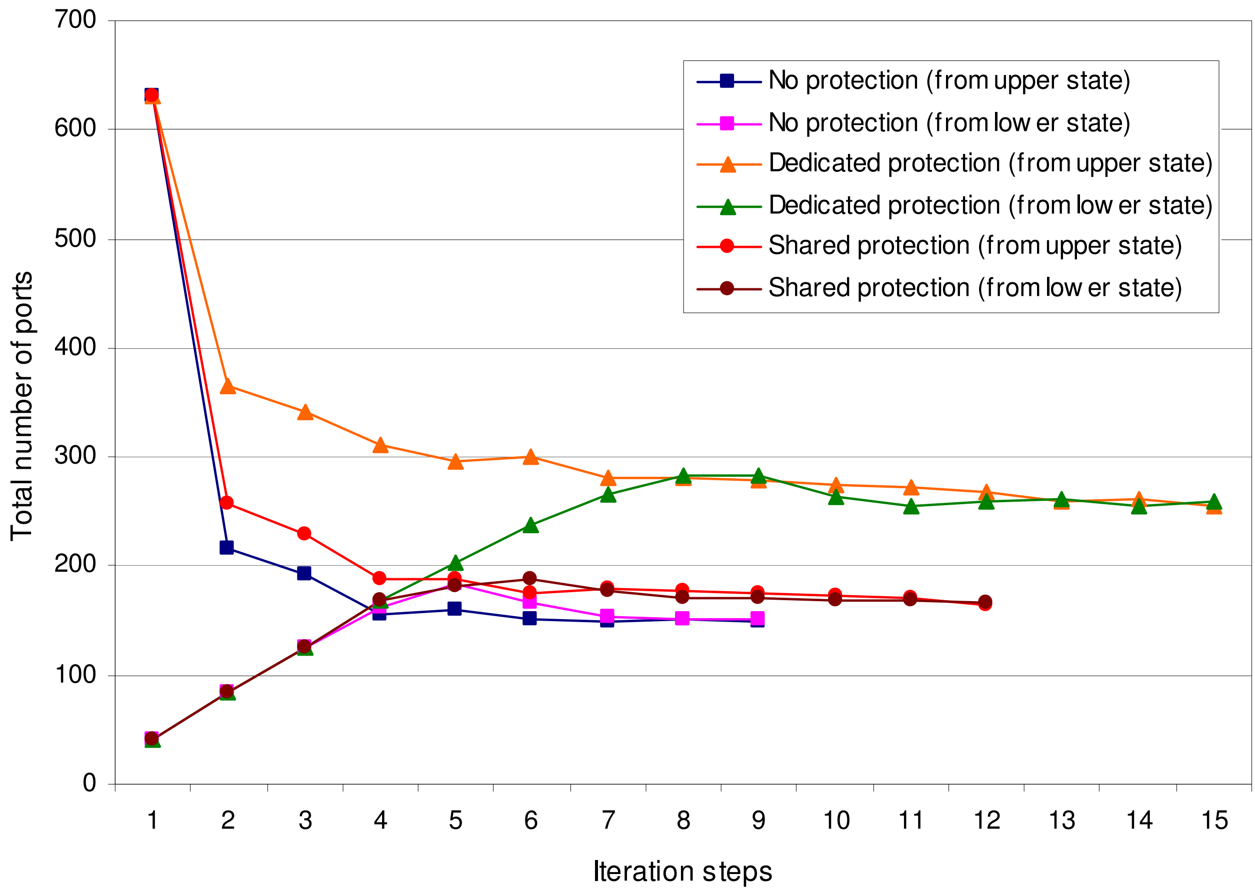


Figure 2.10: The total number of *ports* in the network vs. the iteration steps.

The algorithm found the appropriate balanced state in all protection scenarios (Figure 2.10); no matter whether from lower or upper state it was started. In case of shared protection and no protection there was negligible difference between the two appropriate balanced states reached from upper state and from lower state. Only the total number of grooming ports was slightly different. In case of dedicated protection the results were interesting. Neither the balanced state reached from the upper state, nor the balanced state reached from the lower state was stable. More interestingly both iterations ran into the same oscillation trajectory. Of course the amplitude of the oscillation was very low so we can consider one of the oscillation states as balanced state.

When we start our iterative algorithm from upper state, it reaches the balanced state faster - irrespectively of the protection scheme, or at least approaches the balanced state in a few steps. From lower state it takes more iteration steps to reach the balanced state. The number of required iteration steps slightly depends on the applied protection scheme too. In the case of protection the network needs more iteration steps to reach the balanced state. This fact is likely not only the consequence of the more complex routing, but also of the increased traffic load. Higher traffic load causes long iteration in itself.

In Figure 2.10 we can see the total number of grooming ports in the network during the iteration steps, while Figure 2.11 shows the total number of wavelengths. In the case of shared protection both, the number of wavelengths and the number of grooming ports is less than expected.

Note that the convergence is true not only for the total number of the wavelengths and for the total number of the ports, but also for the number of wavelengths on each link and for the number of ports in each node.

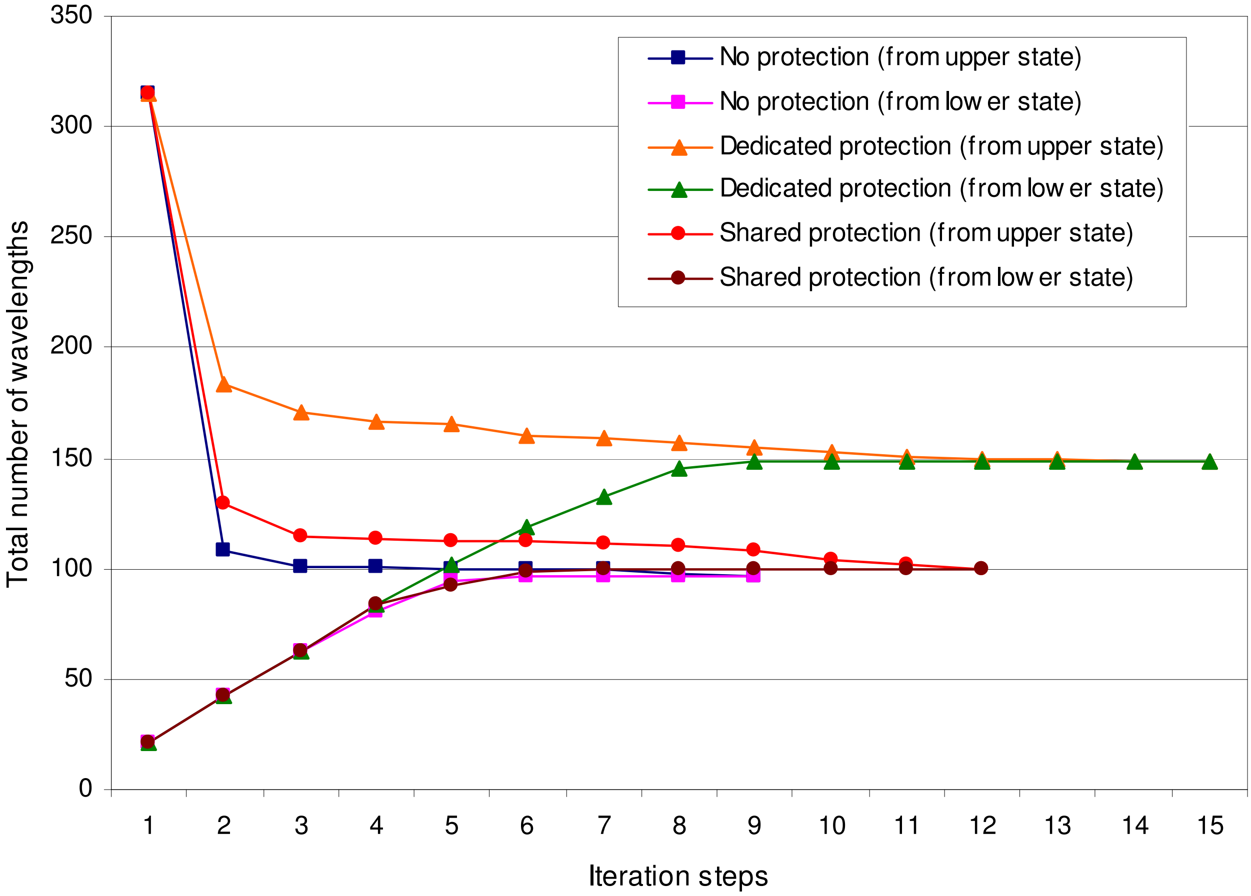


Figure 2.11: The total number of *wavelengths* as a function of iteration steps.

2.3.4 Conclusion

We introduced algorithms for optimizing the number of grooming ports in each node, and the number of wavelengths on each link in networks with partial grooming capability. These algorithms use statistical analysis and iterative simulation to dimension the network for a given traffic. Applying the algorithms we compared the resource requirement of different protection schemes and showed that significant amount of equipment can be saved by proper dimensioning.

2.4 FG: The Graph Model for Grooming with Fragmentation

In Multi-Layer networks, where more than one layer is dynamic, i.e., connections are set up using not only the upper, e.g., IP layer but the underlying wavelength layer as well leads often to suboptimal performance due to long wavelength paths, that do not allow routing the traffic along their shortest paths. The role of MLTE (Multi-Layer Traffic Engineering) is to cut these long wavelength-paths into parts (fragments) that allow better routing at the upper layer (fragmentation), or to concatenate two or more fragments into longer paths (defragmentation) when the network load is low and therefore less hops are preferred.

In this Section we present our new model, the Fragment Graph (FG) and an algorithm for this model that supports Fragmentation and De-Fragmentation of wavelength paths making the network always instantly adapt to changing traffic conditions. We introduce the notion of *shadow links* to model "λ-path tailoring". We implicitly assume that the wavelength paths carry such, e.g., IP traffic that can be interrupted for a few microseconds and that even allows minor packet reordering.

To show the superior performance of our approach in various network and traffic conditions we have carried out an intensive simulation study (Section 2.5) where we compare blocking ratios and path lengths as well as we analyse the dynamic behaviour and fairness of the proposed and of the reference methods.

We assume either the peer interconnection model or the vertically integrated multi-region network (MRN) node model for multi-layer networks [J31]. Then the resources of the network layers are set jointly, i.e., the control plane has knowledge of both the layers to best accommodate the arriving traffic demands.

This often leads to suboptimal performance, since the λ-paths will be routed depending on the arrival order of demands as well as on the load of the network. For instance in an empty network each arriving demand will be routed over an exclusive end-to-end λ-path. This will result in a set of long λ-paths that will hinder routing the new demands, i.e., the network will become de-fragmented. After the transients the λ-paths will be configured more or less adequately. However, if the level of traffic grows short λ-paths with plenty of grooming are needed to accommodate it, i.e., λ-paths have to be fragmented into shorter parts.

To have always optimal performance the λ-path system has to adapt to the changing traffic conditions. Unfortunately, in the simple model (Section 2.1) the virtual topology offered by the wavelength system may not be changed until there is any traffic within the considered λ-paths.

2.4.1 An Example for Fragmentation and Defragmentation

To better understand the advantages of this distributed adaptive on-line Multi-Layer Traffic Engineering that is performed by fragmenting and defragmenting λ-paths we show an example (Figure 2.12).

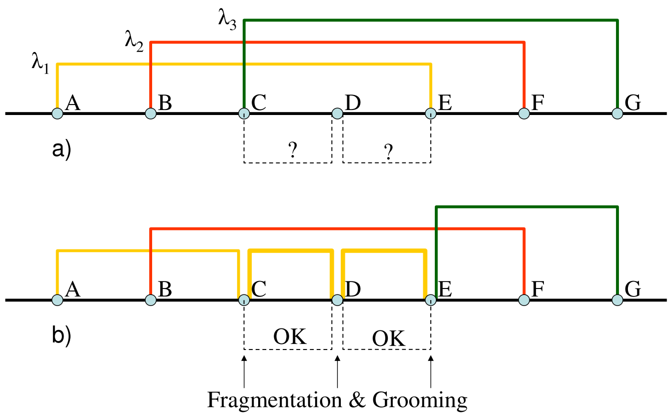


Figure 2.12: An example for fragmentation of λ-paths when new demands arrive that would be otherwise blocked in case with no fragmentation.

Assume that there is a part of a network that consists of seven nodes (A-G) and where each physical link supports the same set of three different wavelengths. If we build three at least partially overlapping connections (λ-paths), e.g., between nodes A-E, B-F and C-G, then we will not be able to accommodate any further λ-path over the link where these three paths overlap (links C-D and D-E in Figure 2.12).

Now if we have no support for fragmentation we will not be able to set up λ-paths between nodes C-D or D-E or C-E or between any par of nodes that need to use any of these segments.

However, if we have support for fragmentation, then we can cut any existing λ-path and groom its traffic with the new connections that allow admission of numerous new connections to the extent of the free capacity of considered λ-paths. Figure 2.12.b shows that the lightest λ-path (A-E) is first fragmented into three parts and then used to carry traffic of new connections groomed with the traffic of λ-paths A-E and C-G while λ-path B-F remains untouched.

We see, that as the number of connection requests grows the λ-paths become shorter (more fragmented) while the blocking becomes lower compared to the case with no fragmentation allowed. Simulation results support well this behaviour as discussed in Section 2.5.2.

2.4.2 Algorithm for Routing with Adaptive Fragmentation and Defragmentation over Shadow Links (OGT)

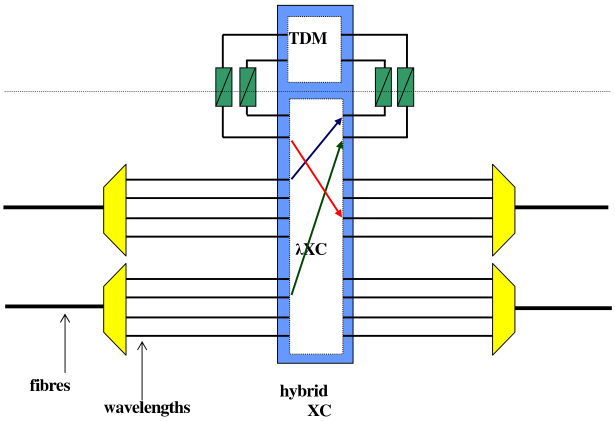


Figure 2.13: A grooming capable node to be modelled as a FG.

Figures 2.13 - 2.17 explain the use of shadow links and shadow capacities. Let us consider an example. Figure 2.13 shows a peer/MRN node that has two incoming and two outgoing fibres each carrying three λs. The bottom part is a wavelength cross-connect, that has two E/O and two O/E converters that connect to the electronic part of the node. In the upper part (marked as 'TDM') the signals can be groomed (or added, or dropped). The figure shows, that the content of two λ-paths is groomed into a single one.

Now, let us see the model of this node. Figure 2.15.a shows an example for setting up the internal link weights to be used for routing. Wavelength transition is cheaper (25 cost units) than using the electronic layer, that will cost at least $50 + 50 = 100$ cost units.

Based on these weights set for all the internal and external links in the network model we search for a shortest path between certain nodes. In Figure 2.15.b we have chosen a transition, while Figure 2.14 shows a grooming. Routing is always followed by re-setting the link weights. Figure 2.15.b shows the approach used for the simple grooming model, while Figures 2.16 and 2.17 introduce the shadow links.

Figure 2.16 shows that after routing a demand of bandwidth b_1 using any of the shortest path algorithms (e.g., Dijkstra's [28]) over the model shown in Figure 2.16.a (and 2.14.a), the internal links connected to those internal nodes that are used by the considered demand will neither be deleted, nor will be their costs increased to infinity (as done in Figure 2.14.b), but increased enough to avoid using those links until other wavelengths or other paths exist. In Figure 2.16.b we have multiplied the weights of these links by parameter $\alpha \gg 1$. It means that the model allows not only the already used internal link, but introduces more expensive alternative links, the so called *shadow links* that have as much shadow capacity as the free capacity of the internal link used by the considered demand is. For simplicity reasons we assume that all the λ-links have the same capacity marked as B in figures. This does not mean that the optical signal may branch (split), but it gives the opportunity to choose instead of using the internal optical link as in the OGS model to cut (fragment) the λ-path and to go to the upper, electronic grooming layer.

Figure 2.17 shows routing another demand of bandwidth of b_2. Here we assume that there was no cheap alternative wavelength or path, and a more expensive shadow link of the FG had to be chosen while searching for the shortest path. If the shadow path is chosen it results in cutting the λ-path that has "branched" (Figure 2.17.a). After routing a demand the FG has to be updated as shown in Figure 2.17.b. Now the two traffic streams are demultiplexed (de-groomed) in the electronic time-switching capable part of the switch, and the yet lightened link will be turned into an expensive shadow link with new shadow capacity (dotted thick line). We delete the traffic over this link that has status changed from "lightened" to "shadow". It can again turn from shadow to lightened link when, e.g., the second demand first terminates, and the first demand will be the only user of the considered λ-path and therefore no grooming will be needed any more.

Until there is any free capacity in the λ-paths, they will have shadow links of shadow capacities equal to the free capacity.

In the upper example, we have shown how a λ-path can be cut for grooming purposes. Similarly, if a λ-path does not carry any traffic, it will be cut into λ-links, and the capacity and weight values of these links will be set to their initial values. We refer to these actions as *λ-path fragmentation*.

Similarly, two λ-paths can be concatenated if they use the same wavelength AND they are connected to the same grooming node, but there is no third traffic that has to be added or dropped. Although it happens rarely, it is very useful in case when the number of grooming ports is the scarce resource. We refer to this action as *λ-path defragmentation*.

In Section 2.5 based on results of simulations we show what parameters influence and how do they influence the performance and dynamic behaviour of the network. The blocking was in all cases the lowest for this proposed adaptive grooming approach with λ-path fragmentation and de-fragmentation for most parameter settings as will be discussed in Section 2.5.

2.5 Performance Evaluation of Routing with Grooming

The code was written in C++ under Linux and Windows operating systems, while the simulations were carried out on a Linux MSI K8Dual AMD Opteron 246 MP workstation with 4 GBytes of RAM. We have applied DES (Discrete Event Simulation) where we route the demands in the given order, however, to speed up the simulation we do not wait between two demands as the time stamps determine, but route the next demand as soon as the last demand is routed.

The test networks were the COST 266 European reference Network [21] consisting of 28 nodes and 41 physical links shown in Figure 2.36(a) and the NSFnet consisting of 14 nodes and 21 links shown in Figure 2.18. We have used OADMs in all nodes of degree 2 and OXCs with grooming capability in all other nodes.
We have compared the behaviour of three network node models:

- OXC: Optical cross-connect with no wavelength-conversion capability and no grooming capability.
- OGS: OXC with grooming capability. This is the *simple* grooming node model that we proposed earlier.
- OGT: OXC with grooming capability with support for *"tailoring"* λ-paths, i.e., adaptive, distributed fragmentation and de-fragmentation of λ-paths. This is our new method proposed in this Section [C26, C24, F3, J8].

2.5.1 Blocking as a Function of Capacity and Traffic Parameters

We investigate how the blocking ratio depends on three parameters, namely the bandwidth of demands, the holding time of sessions and the number of λs per link.

We have assumed 6 wavelengths per link, 1000 units of capacity for all wavelengths, 100 units of bandwidth on average and 8 units of holding time for the demands as the default values, for both, COST266 and NSF networks. Session arrival rate was 0.025 for the COST266 while it was 0.08 for the NSF network.

As a reference the OXC case was used, i.e., all nodes were OXCs without λ-conversion capability. In this case all the traffic demands have used exclusive λ-paths.

Bandwidth of Demands

First we tune the ratio of the average bandwidth of the demands to the capacity of λ-links (Figure 2.19). While the bandwidth ratio is significant, there is a huge difference in blocking. Adaptive grooming is superior to simple grooming. However, as the bandwidth ratio approaches 0,1 the blocking grows for both grooming approaches and they become comparable.

It is interesting to note, that blocking of both grooming approaches is larger than that of the approach with no grooming (OXC) as the bandwidth of the demands approaches the capacity of the λ-links. It is probably resulted by the long λ-paths that hinder routing demands over shorter paths. Note, that in our adaptive grooming framework we do not allow rerouting existing connections to other paths, but just cutting or concatenating the λ-path fragments they use, for three reasons. Namely, to simplify the operation, keep the adaptive and automatic traffic engineering local, and to keep the interruption time very short.

However, in practice the typical operational region of networks falls out of this critical region, i.e., the typical bandwidth of demands is lower at least by one to two orders of magnitude than the capacity of λ-links.

Holding Time of Demands

Figure 2.20 shows that when increasing the holding time of connections the blocking grows. Our adaptive grooming approach (OGT) has significantly lower blocking than the other two methods, particularly for the NSF network (Figure 2.20). It is very interesting that simple grooming (OGS) has higher blocking for short holding times than in the case with no grooming at all (OXC)!

Number of Wavelengths

Figure 2.21 shows, that increasing the number of λs per link the blocking smoothly drops for the case with no grooming (OXC). The adaptive grooming model (OGT) has always better performance than the other two methods. Both grooming models have roughly the same blocking when the number of λs grow, while the performance of the model with no grooming improves. For large number of λs the simple grooming approach (OGS) has higher blocking than that with no grooming at all! The proposed grooming method has always the best performance. The curves for OXC are very smooth, while for grooming they fluctuate. This supports that grooming inherently introduces numerous anomalies.

2.5.2 Performance as a Function of Dynamicity

The Two Scenarios Investigated: 'CP/CP' and 'CP/MP'

The question we try to answer in this section is whether all (both) the layers should be dynamic, or the uppermost one only? For example in traditional PCM/PDH based PSTN networks the uppermost layer is switched only, while the underlying SDH/SONET is a provisioned, statically configured one. We compare two scenarios, both assuming two layers, a WDM layer and an IP/MPLS layer on top of it:

- **CP/CP:** First, both the layers are handled by the CP (Control Plane). We assume either the Peer Interconnection or the Vertically Integrated Unified MRN Model. If a demand arrives it is routed either at the upper layer, or at the lower layer, or by involving both the layers, depending on the network conditions. For example, if a demand can not fit into the free capacity of the virtual topology built of wavelength paths (i.e., into the upper layer), then new λ-paths are built via the CP of the lower layer. We will refer to this scenario as CP/CP.

- **CP/MP:** Second, the upper layer is assumed to be handled by the CP, while we assume that the lower layer is handled by the MP and therefore rarely reconfigured. This allows the Network Resource Management to take actions to better accommodate the traffic of the upper layer. Here the lower layer, the WDM layer is statically configured in an optimal way, however, it does not adapt to the changing traffic conditions. If a demand can not be accommodated by the upper layer it is blocked. If needed, the lower layer can be re-configured, to better satisfy the changed conditions of the upper layer, however, as said, this is done through the MP and it is performed rarely. We will refer to this scenario as CP/MP.

Modelling the Two Scenarios

To emulate these two scenarios we have performed simulations as follows.

For the "CP/CP" scenario we have developed a novel graph model (explained in Section 2.4) that supports adaptation of the two layers to intensively changing traffic conditions. Here the λ-path system is being adaptively fragmented and de-fragmented according to the traffic and network conditions. It models the peer interconnection or the vertically integrated MRN model, where the two layers perform routing jointly.

For the evaluation of the "CP/MP" scenario we have used a simplification. We have optimised the wavelength-path system (the lower layer) by using the CP/CP model while simulating incoming traffic with steady parameters. Then we have "frozen" the lower layer, i.e., we did not allow any change in the wavelength path system any longer, and then after a while we have changed the traffic parameters: changed the territorial distribution of the traffic as well as the level of traffic. The performance of the CP/MP scenario was worse than that of the CP/CP scenario. After a while we "melted" again the lower layer, and then it started adapting to the traffic conditions again. Then we have "frozen" it again, and so on. "Melting" and keeping the melted state for a while emulates the optimal re-configuration of the lower layer via the MP. "Freezing" and keeping the frozen state emulates the steadily configured lower layer. We refer to this method as OGF: Optical Grooming with Freezing (See Figures 2.23,2.24, 2.25).

Evaluation of the Results

We have carried out the simulations on the COST266BT European reference network that consists of 28 nodes and 41 links, the number of wavelengths was 10 on all links, and the capacity of each wavelength link was 9953 capacity units (e.g., MBytes/s as in STM-64). There were 250 grooming ports (O/E and E/O ports) between the two network layers in all nodes in all cases.

Different traffic patterns were created and the same set of patterns was used for different cases to have as objective comparison as possible. The bandwidth of demands was 622 capacity units (e.g., MBytes/s as in STM-4), with binomial distribution of variance of 100 units. The holding time of the demands had exponential distribution with mean of 225 time units, while the intensity was 0.01 per unit of time.

These are the default settings, it will be noted when different values are used.

"Simple Grooming" versus "Teardown Grooming" for Altering Levels of Traffic

First, we compare the blocking behaviour of the simple grooming with that of the proposed adaptive grooming with tear-down (i.e., fragmentation). Figure 2.22 shows a simulation interval of 4000 time units where 33000 demands were routed. At time unit 1000 we have increased the traffic by 20% by increasing the intensity from 0.01 to 0.012, then dropping to the original value at 2000 time units, and again increasing by 20% at 3000 time units to compare the two grooming approaches when the level of traffic changes. Figure 2.22 shows an average of 50 simulations with traffic patterns that differ but are generated with the same parameters, and then smoothed by a sliding window of length of 50 time units.

It can be well seen that simple grooming (lighter curve: OGS) has always higher blocking than the proposed Adaptive Grooming approach (OGT). The difference is most significant when the traffic is being routed in a yet empty network, because the simple grooming approach builds too long λ-paths that can not be cut into smaller parts. After this initial transient the blocking of the two methods approaches, however, when the load increases the proposed method is significantly better again.

"CP/CP" versus "CP/MP" for Altering Levels of Traffic

Second, we compare methods "CP/CP"("not frozen": OGT) and "CP/MP"("frozen": OGF) how they adapt to changing traffic conditions. For this purpose we have carried out a three times longer simulation (12000 time units) with roughly three times more (97000) demands routed.

To emulate the CP/MP scenario as described in Section 2.5.2 we have frozen the system of λ-paths at 2000 time units, then melted it at 6000 time units and frozen it again at 10000 time units. The traffic levels were changed analogously to that described in Section 2.5.2. For the interval of 4000-8000 time units we increase the traffic by 20%.

Figure 2.23 shows the average of 20 simulations smoothed with a sliding window of 100 time units. It can be seen well that the blocking of the CP/MP (OGF) approach is significantly larger than that of the CP/CP (OGT) approach (intervals of 2000-6000 and 10000-12000). The reason is that the existing λ-paths can not be fragmented and they hinder routing new demands until they are terminated. The difference is particularly large when the level of traffic is increased by 20%! Note, that when the system is in melted state (0-2000 and 6000-10000) system of λ-paths adapts in very short time to changed traffic conditions by fragmenting the existing long λ-paths and system of λ-paths is adaptively optimised. However, if freezing the system of λ-paths again at 10000 time units, the same significant difference will appear again.

We can conclude that using our adaptive MLTE method with the FG it is advantageous to have both the layers switched, i.e., to allow the network always to instantly adapt to changing traffic and network conditions.

Path Length Distribution for the Different Methods for Different Levels of Traffic

Figures 2.24 and 2.25 show the histogram of path lengths for three different methods with arrival intensity of 0.01 and 0.012 respectively. All 6 simulations were carried out for time interval of 2000 units with 15000 demands routed. When freezing, the simulation is first run for 500 time units for "melted" network to overcome the transients, and then it is frozen for the next 1500 time units.

It can be well seen, that the paths are the shortest for the case of CP/CP with the new proposed adaptive grooming approach, followed by the case of CP/MP with the same adaptive grooming model, while the paths are the longest for the case of the simple grooming model that cannot fragment the λ-paths.

When the load is increased (Figure 2.25), the length of paths grows negligibly only (that was surprising) for all three methods, however, do not forget that due to the blocking that has tremendously increased (Figure 2.23) there are much fewer demands in the network, i.e., the total load of the network is kept at about the same level!

Having longer paths means that there might be loops and that the total load of λ-paths is higher that leads to higher blocking.

2.5.3 Bandwidth Fairness and Distance Fairness

So far we have seen how blocking depends on different parameters (Section 2.5.1) and how the proposed method adapts to dynamically changing conditions in time (Section 2.5.2), now we will investigate the fairness issues.

We compare performance of OGT to OGS. We assume that the capacity of λ-links is 1000 bandwidth units, the demands have bandwidth of uniform distribution between 0 and 1000 units of bandwidth, and the arrival intensity of demands is 0.0333 (1/30).

We have first compared the blocking in case of OGS and of OGT. As we have increased the traffic by increasing the mean holding time of connections from 2 to 18 the blocking has grown faster for the OGS model than for the OGT model as shown in Figure 2.26. Figure 2.27 shows the relative gain of OGT over OGS.

Now a "working point" has been chosen, where the two methods have roughly the same blocking (roughly 0.12), where the mean holding time is 15 time units for the OGS while 18 for the OGT.

Bandwidth Fairness

It is known in general that demands having larger bandwidth have worse chances to be accommodated by a network. Since we have tuned blocking to roughly the same level, it is about the same for both, OGS and OGT for all bandwidth values (Figure 2.29). Note, that both grow steeply after half of the capacity is achieved.

When making statistics on the dependence of hop-counts on the bandwidth, the results are interesting (Figure 2.28). For the OGT model the hop-count of both physical links and λ-paths does not significantly depend on the bandwidth, i.e., the network adapts well to changing conditions. However in case of OGS, for smaller bandwidths we have less, but longer λ-paths and hop-count of both, physical links and λ-paths grows as the bandwidth of demands grows.

Distance Fairness

Another fairness issue is that more distant nodes have worse chances to be connected than, e.g., neighbour nodes. To compare OGS and OGT from this aspect we have made statistics according to the length of shortest paths between certain demands (Figures 2.30 and 2.31).

While the blocking of OGT is lower for shorter distances it exceeds blocking of OGS for demands of larger distances. The hop-count of both physical links and λ-paths of both OGS and OGT is similar to that obtained for Bandwidth Fairness (last subsection), however, even more remarkable (Figures 2.28 and 2.29).

It must be mentioned again, that for both, bandwidth and distance fairness evaluations OGT was loaded by 20 % more traffic then OGS!

2.5.4 Remarks on the OGS Model and on its Performance

In Section 2.4 we have proposed a new model, the Fragment Graph (FG), that supports distributed, automatic, adaptive and on-line multi-layer traffic engineering performed through adaptive grooming using the *shadow links*. As demonstrated in Section 2.5 this approach allows the network to adapt well to changing traffic conditions. The λ-paths are *fragmented* and *de-fragmented* as the network and traffic conditions require in a fully automated, adaptive and distributed way without any centralised action or initialisation while simply using the available routing protocols!

The results show, that our approach yields the lowest blocking ratio in all cases for all scenarios studied for almost all parameter settings. In some cases the blocking of our proposed method is by orders of magnitude lower than that achieved by known methods. Applying the proposed method in networks the throughput can be significantly increased and therefore the revenue as well, while minor investments are needed to upgrade to using this method: The nodes have to calculate and flood regularly the new costs assigned to links.

The only limitation of the proposed approach is that separate wavelengths should be allocated for traffic that is sensitive even to these very short interrupts and delay variations needed for λ-path fragmentation and de-fragmentation.

2.6 SD-MLTE: State-Dependent Multi-Layer Traffic Engineering

In modern optical transport networks multiple networking technologies are layered one over the other. In our model we assume an IP/MPLS layer upon a DWDM layer, which are both controlled by a vertically integrated GMPLS control plane. The traffic streams of the upper layer are multiplexed into the λ-paths of the DWDM layer in a distributed manner to improve the bandwidth utilization. This is referred to as grooming.

In order to adapt routing to the changing network conditions we propose the State-Dependent Multi-Layer Traffic Engineering (SD-MLTE), which modifies the edge weights based on the actual state of a node. We compare this new method to the earlier static weighting for two different grooming scenarios.

The modern networks are rather heterogeneous, however, the common is that they are all based on optical, typically wavelength division multiplexing based transmission.

Studying traffic engineering in such a complex network structure is a challenge, addressed in this section.

The simplest definition of TE is to put the traffic where enough resources are available. It is typically being done by assigning higher weights to more critical links to decrease the number of paths routed over them. The most well known such algorithm is the MIRA (Minimum Interference Routing Algorithm) that works for single-layer networks [61].

In Multi-Layer networks there are two TE (MLTE) approaches. First, to set weights assigned to links analogously to that for single-layer networks [C58]. Second, to "tailor" λ-paths, i.e., to fragment and de-fragment them as the traffic and network conditions require [C26].

2.6.1 State-Dependent Multi-Layer Traffic Engineering

SD-MLTE uses the fragment-graph model described in Subsection 2.4 but with different edge weights. Instead of using static weights it changes the weight of the internal edges of a node based on its state. It takes into account how many λ-paths cross the node (in the optical layer), and the utilization of these λ-paths.

The SD-MLTE works by identifying certain states and modifying the edge weights according to these. If many λ-paths cross the node but their utilization is low, then it modifies the weights to aid cutting, i.e. fragmenting these. When the number of λ-paths crossing the node is low, but they are highly utilized, then it promotes creating new ones.

When a demand arrives to a node it can encounter three different node states.

The first one is when the incoming port is not used by any other demand. In this case the demand can cross the node in the optical layer with a cost of $a * 20$ units, or in the electronic layer with cost of 40 units (Figure 2.32(a)). The value of parameter a is at best 1, so the optical path is cheaper.

The second case is when the demand arrives to an incoming port which is already used by another demand, and this demand crosses the node in the optical layer (Figure 2.32(b)). In this case the demand can choose the optical path with cost of 10 units, or it can go to the electronic layer of the switch by tearing the λ path (with cost of $b * 50$ units).

The third possibility is that the demand arrives to an incoming node which is used by another demand which uses the electronic layer of the switch (Figure 2.32(c)). In this case the only possibility for the new demand is to use the electronic layer with cost of $b * 25$ units.

The values of parameters a and b depend on the number of λ-paths passing through the node. There are at most that many of these as many incoming ports the node has (8 on Figure 2.32). The default value of both parameters is 1.

The value of parameter a changes when the λ-paths crossing the node is small and they are highly loaded. More precisely when the number of λ-paths crossing the node is less than the half of the possible maximum and their average utilization is higher than 60%. In this case the value of

a increases from 0 to 1 linearly in proportion with the number of λ-paths (Figure 2.33). This aids creating new λ-paths.

This also means that the λ-paths get filled up by demands gradually. Let us assume an empty node. Let us also assume that the first demand passes through the node in the optical layer. After this the path of the first demand can be chosen with a cost of 10, while the other (not yet used) optical paths with a cost of $a * 20$, where a is 1. So the already used path is cheaper, until its utilization reaches 60%. At this point a takes a value near 0, so a not yet used optical path gets cheaper than the already used one. When the next demand opens a new λ-path through the node, the average utilization drops below 60%, and the already used paths get cheaper again.

The value of parameter b changes when the number of λ-paths crossing the node is high and they are under utilized. More precisely when the number of λ-paths crossing the node is more than the half of the possible maximum and their average utilization is lower than 40%. In this case the value of b decreases from 1 to 0 linearly in proportion with the number of λ-paths (Figure 2.34). This aids tearing existing λ-paths.

2.6.2 Evaluation of the Simulation Results

We compared SD-MLTE to the static weighting method described in Subsection 2.4 using simulations. We tested them using both the so called teardown grooming model and simple grooming model. The teardown grooming was introduced in Subsection 2.4. The simple grooming model is a simplification of this: it works in the same way as the teardown model, but does not allow tearing an already established λ-path (as explained in Section 2.1).

We used two network topologies in our simulations. The first one was the NSFnet [103] (Figure 2.18), which has 14 nodes and 21 edges. The second one was the COST 266 Basic Reference Topology [21] (Figure 2.36(a)). This one has 28 nodes and 41 edges. We run the simulation with 6, 11 and 16 wavelengths per fiber. The capacities of all the wavelengths were set to 5000, 2500 and 2000 units respectively in order to get about the same level of blocking in all cases. The results are only shown for the larger topology (COST 266 BT), because they were similar in both cases.

The traffic demands were generated the following way. The arrival process of the demands is a Poisson process with λ parameter ($\lambda = 0.01$). More precisely for each point pair a Poisson process ($n(n-1)$ together). The holding time is exponentially distributed with $\frac{1}{\mu}$ expected value. The bandwidth of the demands is binomially distributed with bw_{mean} expected value and bw_{var} variance ($bw_{mean} = 622$, $bw_{var} = 100$). The length of the traffic samples was 1000 units.

On the following figures the x-axis shows the expected value of the holding time. We used this parameter to increase the load of the network.

The first row of Figure 2.35 shows the blocking, i.e. the ratio of failed and all demands when the number wavelengths per fiber is 6, 11 and 16 respectively. The SD-MLTE method in case of teardown grooming blocks less demands than the other two methods. The highest blocking can be observed when using the static method with simple grooming. The other two are between them. This is true except for the last measurement point (in case of 6 or 11 λs), where in case of simple grooming SD-MLTE blocks more than the static method.

The second row of Figure 2.35 shows the average lambda hop number (hop count) when the number of wavelengths per fiber is 6, 11 and 16 respectively. The lambda hop number means how many times a given demand uses the electronic layer of some switch. Considering only the teardown grooming cases the SD-MLTE method uses the electronic layer much less often than the static method. This is true for the simple grooming case as well. The SD-MLTE method in case of 6 λs per fiber and simple grooming model uses the electronic layer even less than in case of the teardown model, at the cost of longer physical paths, as we will see. The static methods use the electronic layer approximately independently from the network load, while in case of SD-MLTE the number of lambda hops increases linearly with the network load.

The third row of Figure 2.35 shows the average physical hop number when the number of wavelengths per fiber is 6, 11 and 16 respectively. The physical hop number means the number of physical links the path of a given demand uses. Considering the teardown grooming cases SD-MLTE produces shorter physical paths. This is the case for the simple grooming model too, except for the last point of evaluation (holding time of 550) in case of 6 or 11 λs per fiber. This is presumably caused by the high blocking ratio at these points. The difference in terms of physical path lengths between the teardown and the simple grooming model is worth the note. As we can see in case of the teardown model the resulting average path length is roughly independent from the network load, while in case of the simple grooming model it increases with the network load. This is because in case of the simple grooming model new λ-paths need to follow the older ones when it is not possible to create new ones. Contrarily the teardown grooming model can cut the older λ-paths.

The forth row of Figure 2.35 shows the number of cuts, i.e. how many λ-paths were torn down when the number of wavelengths per fiber was 6, 11 and 16, respectively. Only the teardown grooming model can cut existing λ-paths, this is why these figures have only two curves. As we can see, the adaptive method causes more λ-path cuts, but this number decreases with the increasing network load in case of 6 or 11 λs per fiber. We can also see that the difference between the two methods decreases with the number of λs per fiber increasing.

The fifth row of Figure 2.35 shows the the number of cut demands, i.e. how many demands were affected by the cuts altogether when the number wavelengths per fiber is 6, 11 and 16 respectively. The curves are similar to the ones in the cut number figures, but the difference is larger between them.

2.6.3 Remarks on SD-MLTE

In this paper we presented the State-Dependent Multi-Layer Traffic Engineering scheme, and we have investigated its performance using simulations.

As the results show using SD-MLTE significantly lowers the load of the electronic layer, and thus requires less powerful (less ports and slower back-plane) switching equipment in this layer. It also uses shorter physical paths and yields less blocking than the static method. In case of the teardown model SD-MLTE causes more λ-path fragmentation, but in case of simple grooming it does not amount to this drawback.

2.7 Adaptive Multi-Layer Traffic Engineering with Shared Risk Group Protection

In this section we propose a new *traffic engineering* scheme to be used jointly with *protection* in multi-layer, grooming-capable, optical-beared networks. To make the working and protection paths of demands better adapt to changing traffic and network conditions we propose the Adaptive Multi-Layer Traffic Engineering (AMLTE) scheme that "tailors" i.e., fragments and de-fragments wavelength paths in a fully automatic distributed way.

The majority of networks, particularly in the metro and core parts consist of multiple network layers stacked one over the other. This is referred to as the vertical structure. The certain layers are typically based on different network technologies and are often operated by different operators or service providers. To make such a network operational control information has to be interchanged between the layers. In our work we assume either the so called Peer Interconnection model, where the full information can be exchanged between the layers or the Vertically Integrated model, where a single operator is assumed to operate these layers, again, having access to all the information of all the layers [J31].

2.7.1 Protection Alternatives Considered for the AMLTE

In this section we compare the shared protection to the dedicated protection and to no protection at all.

Having no protection at all means simply to route the demand in the FG, i.e., AMLTE is performed as explained in Section 2.5, however, without any resilience scheme implemented.

The simplest case is when we implement "dedicated end-to-end disjoint path protection" that we will refer to as Dedicated Protection or 'DP' for brevity. In this case the protection path is routed as a working one from the point of view of the FG. However, the SRLGs (Shared Risk Link Groups), or in general SRGs (Shared Risk Groups) are to be taken into account. In Subsection 2.7.2 we will discuss the alternatives for path-pair calculation.

Next we discuss the "shared end-to-end disjoint path protection" that we will refer to as Shared Protection or 'SP'. This is much more complex, i.e., not only the disjointness is to be obeyed, but also the sharing of lightpaths. A similar problem, but without TE has been addressed in [78].

Sharing λ-paths that are used for protection works analogously to that for working paths as explained in Section 2.4.2.

The difference is that since the protection is shared the used capacities are shared among many paths, i.e., more protection paths (PP) can share a single λ-path than working paths (WP). This will result in very fragmented λ-paths, i.e., these fragments become shorter through shared protection. This also causes that the transponders between the optical and the grooming-capable (time and space switching capable) electronic part are the scarce resource.

This will make our FG model more complex, since for shared protection paths it will seem like branching λ-paths, that is normally not allowed.

We can conclude, that although SP saves the capacity it does not save the O/E and E/O ports (transponders) at all.

2.7.2 Path-Pair Calculation Alternatives for the AMLTE

We have implemented two Path Calculation scenarios.

First, we use the Dijkstra's algorithm [28] to determine the shortest path that has enough resources to accommodate the considered demand. Then we temporarily delete (hide or increase its cost to a very large value) all the links along the path including all those that share a common risk (i.e., those belonging to the same SRG). After we search again for the shortest path in the yet reduced topology.

This seems advantageous, since the working path will be the very shortest path, while the protection one – that uses its resources rarely, and the allocated capacities are shared – can be longer.

The drawback of this scenario is that it may get stuck if a so called trap topology is formed, i.e., where deleting the found working path cuts the graph, i.e., it hinders routing the disjoint protection path.

Second, since the previous path calculation scenario can get stuck, we use Suurballe's algorithm [97, 11], where we determine the shortest pair of paths simultaneously, not in two phases as for the first scenario. From the pair of shortest paths we consider the shorter one to be the working one, while the longer one will be the protection path. Whenever a pair of disjoint paths exists it will be found, although the working path may be considerably longer than that found by Dijkstra's algorithm.

To avoid (or at least minimise) the effects of the trap topology we improve the first scenario, by applying the Suurballe's algorithm only for those demands for which the two-phase Dijkstra's algorithm failed. We will refer to this scenario as "Dijkstra+Suurballe", while to the scenario where Suurballe's algorithm is used for routing and protecting all the demands we will refer to as "Suurballe". We will also use abbreviations 'D+S' and 'S', respectively.

2.7.3 Evaluation of the Simulation Results

We have carried out the simulations on the COST266BT European reference network (Figure 2.36(a)) that consists of 28 nodes and 41 links, the number of wavelengths was initially 4 on all links, and the default value of the capacity of each wavelength link was 1000 bandwidth units. There were

250 grooming ports (O/E and E/O ports) between the two network layers in all nodes in all cases. All the simulations have been carried out for the NSFnet as well, however, these results were very similar to those obtained for the COST266BT network, therefore we do not present them.

The traffic was as follows. We have generated for 16 different traffic levels (16 average mean inter-arrival times) 2 random traffic patterns with identical traffic parameters (bandwidth distribution, holding time distribution and arrival rate distribution) with equal probability for all the node pairs. The length of the traffic pattern, that determines the length of the simulation as well, was 20000 time units in all cases. The inter-arrival time between connection requests had geometrical distribution with expected mean value of 1, 2, 3, ..., 16 time units. The expected mean holding time was 1000 time units, while the bandwidth had uniform distribution from interval 50-150 bandwidth units.

Here we compare three protection alternatives: No Protection (NP), Dedicated Protection (DP), and Shared Protection (SP). For both, DP and SP we have implemented two path calculation scenarios: Suurballe (S), and Dijkstra+Suurballe (D+S).

Blocking Performance

First, we compare the performance of these strategies as the traffic level decreases in the network. Figure 2.36(b) shows, that the case with no protection (NP) has always the lowest blocking as expected, followed by the shared (SP) and then by the dedicated protection (DP). It is interesting, that for both DP and SP the pure Suurballe-based path calculation strategy yields lower blocking than the Dijkstra + Suurballe one. The reason is that using Dijkstra's algorithm we allocate more resources since it does not minimise for the pair of paths but it finds the shortest and the second disjoint shortest path. Furthermore, the fragmentation for protection paths deteriorates the shareability of resources for shared protection. It is interesting to note that in our earlier studies on *design* of one-layer simple networks in case of Shared Protection Dijkstra's algorithm proved to have better performance than the Suurballe's one [C46].

Resource Utilisation

Figure 2.36(c) shows how the utilisation of resources depends on the level of traffic. As the traffic level decreases the resource usage decreases as well. These results are averages during the total length of each simulation.

The relevant part of the figure is where the blocking is negligible, i.e., that over the mean arrival time of 10 time units. There the order of curves is roughly the same as in Figure 2.36(b), i.e., the method with highest resource utilisation has the largest blocking as well and the method with smallest blocking has the smallest resource utilisation. It is interesting, that in the high-blocking region (left hand part of the figure) the curves for S and D+S interchange their positions.

Distance Fairness

Figure 2.36(d) is very interesting from the fairness point of view. It shows the average distance of the end-points of connections for different methods and for different loads. It is to be studied together with Figure 2.36(b).

While for lower loads, where there is hardly any blocking, all the methods have roughly the same average distances around 3,55 hops. When we move to the left hand side of Figure 2.36(d), where the blockings are rather high, the curve referred to as "Total offered" shows the average distance of end points of *offered* demands, while the other curves the average distance of the *successfully routed* demands.

It can be well seen that all the methods with protection perform similarly, in all cases the average distance becomes much shorter, that means that the more distant demands have much worse chances (unfairness) to set up connections and protection than those that are close. This is referred to as distance fairness.

Protection Weighting Strategy	Protection				Capacity for Protection
	Wavelength Path		Path Length	O/E & E/O Number	
	Average Length	Segments / Demand			
Capacity-Shared	1.235 1.072–1.399	8.266 6.536–9.996	9.349 8.469–10.229	588 165–1010	8.05% 2.345–13.76%
Port- & λ-Shared	1.662 1.447-1.877	4.464 4.003–4.925	7.192 6.942–7.442	113 74–152	8.885% 2.775–14.995%

Table 2.1: Advantages of the Port- & λ-Shared Protection over the Capacity-Shared Protection.

Average Physical Hop-Counts

In this section we compare the lengths of paths counted in physical hops for both, working and protection paths for the different methods.

Figure 2.36(e) shows the average path lengths when Suurballe's algorithm is used only, while Figure 2.36(f) when Dijkstra + Suurballe is used. Since the curve marked as "No protection" is at the same level in both figures, we can see well, that all the protection methods for the 'D+S' case require longer paths than those for the 'S' case, particularly when the load is lower. Furthermore, there is a significant difference in the length of working paths for 'D+S' (Figure 2.36(f)), while they are roughly the same for 'S' (Figure 2.36(e)).

2.7.4 Remarks on AMLTE with Resilience

In this section we have implemented Dedicated (DP) and Shared (SP) Path Protection in our Adaptive Multi-Layer Traffic Engineering (AMLTE) framework and we have investigated their performance for two path-pair calculation strategies 'S' and 'D+S'.

As the simulation results show, SP performs always better (uses less resources and has lower blocking) than DP, although not as much better as in case of simple single-layer networks. It is interesting, that the protection paths of DP and SP have the same hop-counts, while their working paths differ only. It can also be seen very well, that when the blocking increases, it affects first those demands that have more distant end-nodes. When comparing the two path-pair calculation strategies 'Suurballe' (S) has better performance even for shared protection than 'Dijkstra+Suurballe' (D+S).

2.7.5 Port- and λ-Shared Protection

In contrast to the protection case discussed so far where the capacity of protection paths was shared only and we assumed that all the protection paths have to be set up in advance, here we propose a new approach. The idea of Port- and λ-Shared Protection is that the protection paths are not set up at all, even not preconfigured. The resources (ports and wavelength links) are only reserved as a common pool to be used in case of any failure for all precalculated failure scenarios. This reserved common pool has to contain enough resources to accommodate protection of all demands that can be affected by any single failure. When a failure happens, then protection paths of all affected working paths will be set up and allocated. Although this will result slightly longer setup time, all the protection paths will consist of less hops (less segments). Therefore, there will be less enterings into the electirc nodes and therefore they will use much less O/E and E/O ports, that are the most expensive part of the nodes.

Discussion of Results on Port- & λ-Shared Protection

The simulations were carried out for the COST266 network, with demands of mean bandwidth of 500 Mbit/s. The blocking was 0% in all cases to avoid impact of blocked demands onto the result. We neglected the start and end part of simulations to avoid the effects of transients. In Table 2.7.5

the cells show the average values as well as the centered mid 95% intervals. All the details of these methods and related assumptions are explained in **??**.

In case of Capacity-Shared Protection the weight of edges was proportional to the additional capacity that has to be reserved over them in case they are used as a protection path of a certain working one.

In case of Port- & λ-Shared Protection the weights of edges were independent of their requirement for additional capacity for accommodating protection paths, while the weights of edges within the switches that correspond to the optical part were set to low values to encourage sharing the wavelength paths as much as possible.

Table 2.7.5 shows that using the proposed Port- & λ-Shared Protection makes the segments of the wavelength path longer on average by almost 35% (1.662 instead of 1.235). The reason is, that there are less wavelength path fragmentations due to the wavelength path sharing. This will result longer, but fewer wavelength path segments resulting in shorter paths than for the Capacity-Shared case (See the 'Path Length' column of Table 2.7.5). The most significant advantage of the proposed method can be seen in terms of O/E and E/O converters. Their number has dropped from 588 to 113, less than fifth. However, the drawback of the proposed method is, that the ratio of the capacity reserved in the network for protection will be larger by more than 10% (8.885% instead of 8.885%).

2.8 Multi-Cast Tree Routing and Resilience

In this Section we consider dynamically changing multicast trees (light-trees) in two-layer optical-beared grooming-capable networks. The continuous changing of the tree "leaves" causes the degradation of the tree in time. Therefore, a huge amount of network resources can be spared by reconfigurations performed periodically or upon failures and reparations.

In this section we focus onto restoration of trees if a link (or any other network element) fails. The failures are more critical if they affect the tree closer to its root, while less critical if closer to a leave. We propose and evaluate four simple restoration strategies and investigate their performance for different multicast routing algorithms.

2.8.1 On Multicast and Broadcast

Multicasting and broadcasting TV programs over the networks is one of the key services offered by most telecom operators nowadays. This service requires high network availability since a failure can affect a very large number of users. These connections should be able to survive even multiple simultaneous link failures.

There are similar services that require setting up multicast trees. These include caching for VoD, and particularly for streaming video services, peer-casting the decoded and transcoded content, VPLS (Virtual Private LAN Services), anycast for GRID services, etc.

Currently, there exist multiple transport alternatives for multicasting video distribution in metro and core networks. Operators can choose among layer 1 (ngSDH [51] [52] [53], OTH (OTN)) [55] [54], layer 2 (PBB, PBB-TE, T-MPLS, RPR) and layer 3 (IP/MPLS) transport solutions. While most of these technologies already include protection mechanisms, the development of restoration mechanisms for multi-cast services is still an open issue. This section proposes four simple restoration schemes and provides a performance analysis for multicast TV services in metro and core networks.

Broadcast TV traffic volume does not depend on the number of customers but on the number, definition and encoding of TV channels. So, TV traffic volume would be similar in the metro access and metro core segments. For example, 100 HDTV channels, with MPEG 4 encoding, will need 1 Gbps from the TV Head-End to the rest of Service PoPs (points of presence) in the metro core, and from the Service PoP to the access nodes in the metro access.

2.8.2 Multicast/Broadcast Solutions for Core Networks

In core networks the video content is distributed (multi-casted) in bundles of tens to hundreds of programs to the metro networks. Depending on the resolution and encoding of certain program channels this requires a capacity from 100 Mbps to a few Gbps. Therefore, some multi-casts having smaller bandwidth requirement can share a single wavelength path, while others that exhaust the capacity of a wavelength channel may even require multiple wavelength channels bundled together.

We assume a two-layer network architecture, where the upper layer is an asynchronous time switched one, e.g., IP transport over Ethernet and/or MPLS while the lower layer is a circuit switched one, based on wavelength division multiplexing (typically DWDM eventually with OTN framing).

In such a two-layer architecture we assume multi-casting capability at both layers. At the upper, IP/MPLS/Ethernet layer multi-cast is supported, by sending the same packets to two or more outgoing ports. This increases the load of the backplane of the switch. At the lower, optical layer the multi-cast is done physically, i.e., the signal, as well as its power is divided among two or multiple outgoing ports. This approach requires splitters in the optical switches that although not yet supported by many manufacturers can be done by a simple and cheap splitter.

We also assume grooming in our approach as follows. If there are two or more sub-lambda traffic streams that use the same path in a part of the network, they can be groomed together into a single wavelength channel by any grooming capable node as well as they can be separated (de-multiplexed) again by any other grooming capable node. This leads to much better resource utilisation.

This two-layer network is represented as a single graph, with as many parallel edges between certain nodes as many wavelengths are supported over that link and using sub-graphs connecting these parallel edges in nodes to model different functionality including cross-connecting, grooming, etc. The model of this network is discussed in our earlier papers, including [C126] and [C111].

2.8.3 Optical (O) or Electronic (E) Multicasting?

Assuming two network layers,

- an upper, electronic, packet switching capable one and
- a lower, optical, circuit switching capable one,

multicast can be performed by any of them. However, while in the electronic domain an incoming packet is forwarded to two or more output ports, in the optical domain the whole optical signal (e.g., a wavelength) is physically split (e.g., by a directional coupler) to two or more parts without access to sub-lambda granularity multiplexing or switching capability.

Clearly, a compound of multiple channels that fills the capacity of a wavelength path, the 'O' multicast seems more efficient, while for smaller granularity 'E' multicasting is preferred.

2.8.4 Methods for Multicast Routing

We have assumed that a single source (the root of the tree) supplies a few sinks, (destinations, leaves of the tree). This is a special Steiner tree, where the idea is to carry the information in a single exemplar (copy) as long as possible and to multiply at the farthest node to use as few capacity as possible for the whole multi-cast connection (tree). However, there are two constraints. Both upper (electronic) and lower (optical) layer multi-cast capabilities have breadth limitations, i.e., each node has limitation to how many output ports can it copy the same content. Furthermore, the depth of the tree, i.e., the largest source-destination distance has to be limited as well.

Here we have evaluated the following three multi-cast routing methods that we proposed earlier in [C126] and [C111]: ASP, MPH and ILP.

- **ASP**: Accumulative Shortest Path (Dijkstra)

This method is the fastest and simplest one however the results it provides are suboptimal. The root-to-leave demands are not routed at once simultaneously, but in a sequence one after the other using Dijkstra's algorithm. The idea is that the cost of elements (links in the wavelength graph) already used by a root-to-leave demand of the same tree is set to zero, that means it can be used for free for all future root-to-leave demands of the same tree. Of course the chosen sequence significantly influences the result.

- **MPH**: Minimal Path Heuristic

  We have adapted [3] to our wavelength graph model. The idea is that we calculate the shortest path in our wavelength graph model between all leaves and between the leaves and the route. This results in a complete graph where the number of vertices equals to the number of leaves plus one for the root. In this simpler graph Prim's algorithm [20] is used to find the least cost spanning tree. This minimum spanning tree is then traced back to the wavelength graph. Analogously to the ASP, where a new demand joins the tree, here while reconnecting the cut leaves the costs of all already used edges are set to zero.

- **ILP**: Integer Linear Programming

  Since this method provides always the global optimum in terms of the objective function this was the reference method to compare other methods to. The time requirements for ILP were the largest among the three methods ranging from a few to a few hundred seconds in our case. The ILP formulation was proposed and explained in our earlier paper [C126].

2.8.5 Methods for MultiCast Restoration (MCR)

If a link or a node fails in the network it will affect all the multi-cast connections that use that element. However, if this element is just a leave (a single user) its failure will affect only that user, however if an element close to the source (to the root of the tree) fails, than typically many leaves (end users) will be cut from the source. We propose methods for all the cases that reconnect the cut leaves (users) or whole branches (groups of users) to the healthy part of the tree or directly to the source.

Here we propose and discuss the different methods for restoring the multicast trees upon failures. The four methods we propose for restoration(ASP, ASP partial, ILP and ILP partial) are based on methods for routing as follows.

- **ASP**

  ASP restoration can be applied to any tree that was set up by any algorithm. Its idea is that if a link fails it can cut a single, or multiple, or even all the leaves from the root. We use here Dijkstra's algorithm to find a new path from each cut leave to the root, where the costs of already used links are set to zero as explained for the ASP routing.

- **ASP Partial**

  ASP partial restoration is a kind of link restoration, i.e., if a branch of the tree is cut, then the whole branch as it is will be reconnected to the closest point of the tree.

- **ILP**

  The whole tree is configured from scratch in optimal way. Instead of the original graph we use the graph without the elements that failed. This is the optimal new tree. However, it can be very different from the original one. This is a drawback, since many connections will have to be interrupted for reconfiguration purposes.

- **ILP Partial**

  This is very similar to the ILP restoration approach with the difference, that the part of the tree that is not affected by the failure is kept, i.e., all unaffected links will have zero cost.

Our earlier results [C57] show that while there are few failures at time restoration is fast enough not to affect the understandability and enjoyability of the video content. However, if there are multiple failures at time, and instead of protection restoration has to be used that can last even for seconds the users will not be satisfied with the quality. The probabilities of having such a failure pattern that will interrupt the streaming for more than half a second is very rare. In case of interrupts longer than a few tens of milli-seconds the content should be cached and streamed again as soon as the network, or the cut branches of the tree have recovered.

2.8.6 MC Resilience Simulation Results

The simulations have been carried out on the COST 266 BT European reference network that consists of 28 nodes and 41 links. Each tree consisted of one 'root' and 5-27 'leaves' all randomly chosen with uniform distribution.

First, we have optimally configured the multi-cast trees using 'ASP', 'MPH' and 'ILP' as explained in Section 2.8.4 and shown as the leftmost triplet of bars in Figures 2.37(a)-2.37(f).

Then, we have simulated link failures one-by-one for all links used by the considered tree, and for each such failure scenario we have restored the tree using the four methods 'ASP', 'ASP partial', 'ILP', 'ILP partial' as explained in Section 2.8.5.

The evaluation criteria were as follows.

First we have evaluated the cost of the obtained tree as shown in Figure 2.37(a). The failureless tree was always the 'cheapest' particularly that obtained by 'ILP'. After the failure, the 'ILP' has best restored the tree, regardless what was the initial tree set up method. For other restoration methods 'MPH' had roughly the same performance as 'ILP', while 'ASP' was the worst.

Second, the time required to calculate the multi-cast tree as well as to recalculate the restoration of the tree was evaluated as shown in Figure 2.37(b). Here we see the drawback of the 'ILP' method for both routing and restoring the tree. However, it gives the global optimum in terms of its cost-based objective function. 'ILP' has the most significant time requirement, while 'ASP' and 'ASP partial' are the fastest.

The amount of used capacity shown in Figure 2.37(c) has similar character to that of the cost (Figure 2.37(a)).

Figure 2.37(d) shows how many wavelengths are used by the different methods to set up and restore the trees. For both, ILP is followed by ASP. For restoration the partial methods have better performance than the simple full ASP.

Figure 2.37(e) shows how many E/O ports are required to perform multi-cast in the electronic (upper) layer. This is slightly related to the number of wavelengths used (Figure 2.37(d)). If more wavelengths are used, slightly less E/O and O/E conversions are requested, since in some cases 'E' (electronic) multi-casting can be substituted by the 'O' (optical) multi-casting. Any failure will cause significant growth in using O/E and E/O ports.

In Figure 2.37(f) it is interesting to note that the size of the network relative to the failureless case can be somewhat smaller, particularly for the ASP tree set-up with ILP tree-restoration! The explanation of this behaviour is, that in the failureless case ASP did not find a good tree, so relative to it ILP resets the whole tree from scratch, resulting a much better tree even if a link is unavailable due to its failure!

Finally, Figures 2.37(g) and 2.37(h) show how the tree set-up method and the restoration strategy upon a failure impact the users. For this purpose we have defined two metrics, the Relative Impact (Figures 2.37(g)), and its variant (Figure 2.37(h)) weighted by the relative change of the number of wavelengths used, i.e., by the ratio of the number of wavelengths in the failureless case to that in the case of failures.

We have defined the relative impact of failures as the average of the following products for all failure scenarios:

- The ratio of leaves cut from the root of the tree by the considered failure to all the leaves of the tree.

- The time of restoring the tree, i.e., calculating and setting up the new tree.
- The length of the link, the failure of which is being considered (the longer the link is the more prone to failures it is, i.e., has lower availability and will fail more often, therefore, it is taken with higher weight into the average).

In Figures 2.37(g) and 2.37(h) it is to be noted that regardless of the tree set-up methods, the faster 'ASP' and 'ASP partial' methods should be used for restoration upon the failure, since although they provide slightly cheaper trees, their calculation times are unacceptably long!

2.8.7 Concluding Remarks on Multi-Cast Resilience Issues

In this section we have analysed what are the resilience requirements of IPTV based video streaming (multi-cast, broadcast) services, and also compared a wide range of resilience mechanisms and evaluated their capabilities and performance for metro and core networks.

The results clearly show, that the speed of calculating the restoration is crucial, while the method how the tree was set up and how good the resulting tree will be is less significant. I.e., the length of the service interrupt is more important than the quality of certain trees before and after the failure.

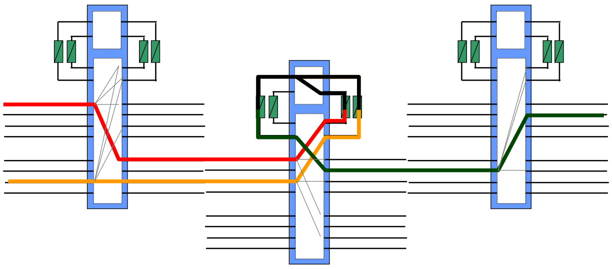


Figure 2.14: Routing with grooming in the FG that models 3 nodes.

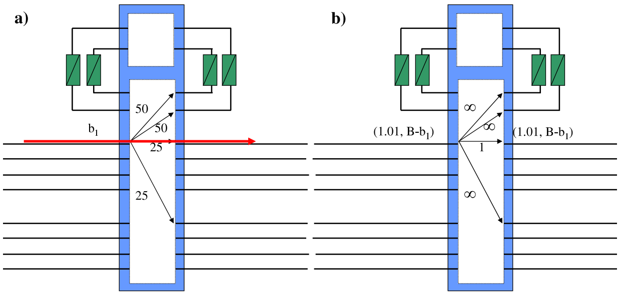


Figure 2.15: FG when simple grooming is assumed: a) A demand of bandwidth b_1 is routed using the shown edge costs; b) after routing a demand the costs and capacities are set - all alternative links are disabled except one.

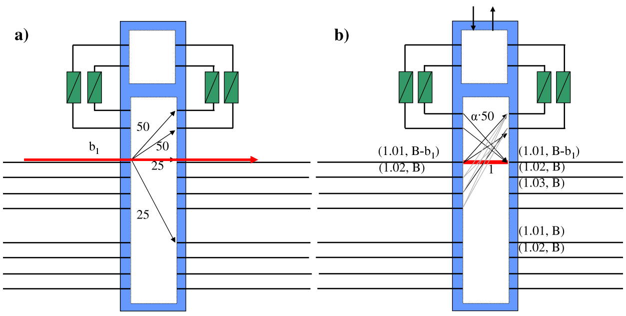


Figure 2.16: FG when the proposed method is used: b) After routing a demand all alternative links are allowed ("shadow links"), but their costs include cost of fragmentation as well.

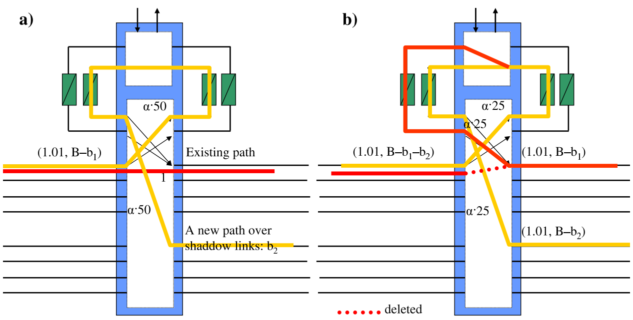


Figure 2.17: If routing a new demand of bandwidth b_2 over the shadow links in the FG the λ-paths will be cut (fragmented) by temporarily disabling (deleting) the internal optical link.

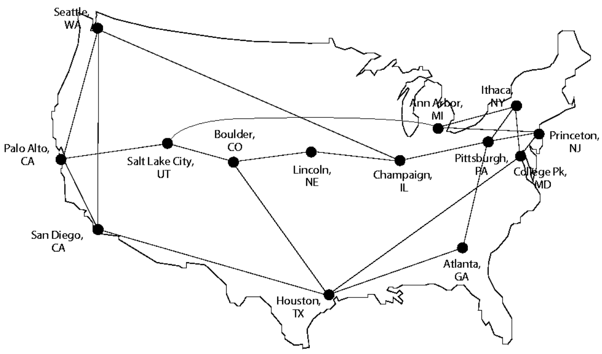


Figure 2.18: The NSFnet topology.

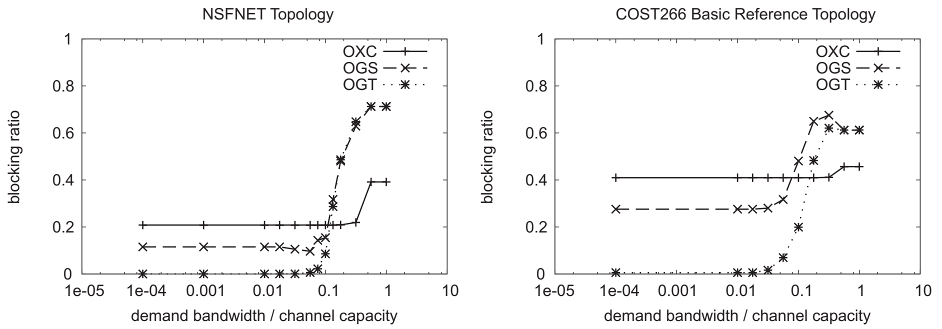


Figure 2.19: Blocking ratio against the ratio of the demand bandwidth to the channel capacity for the NSFnet and for the COST266BT networks.

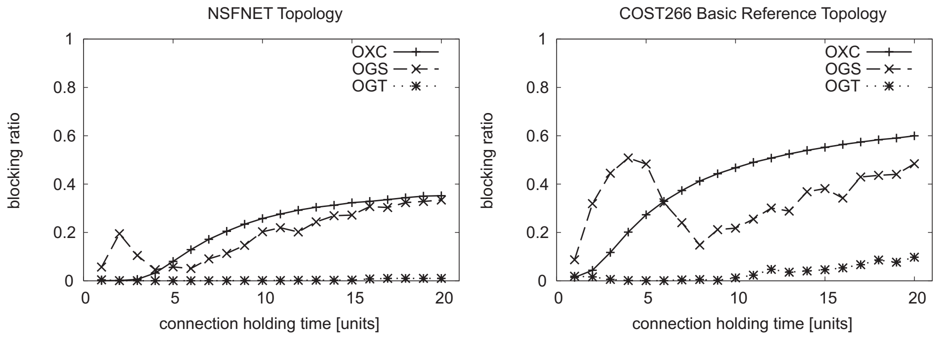


Figure 2.20: Blocking ratio against the average connection holding time for the NSFnet and for the COST266BT networks.

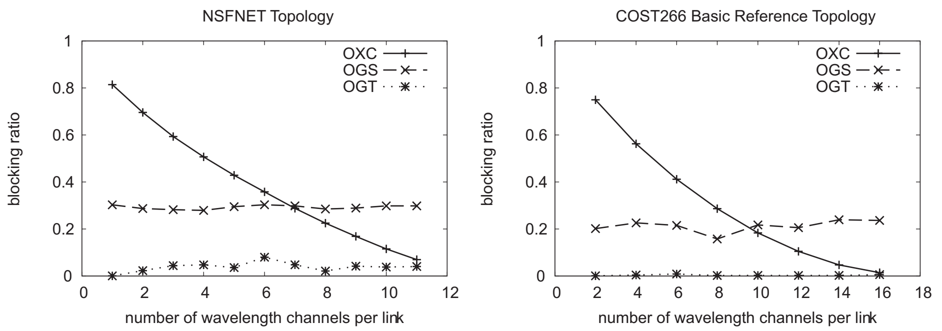


Figure 2.21: Blocking ratio against the number of wavelengths for the NSFnet and for the COST266BT networks.

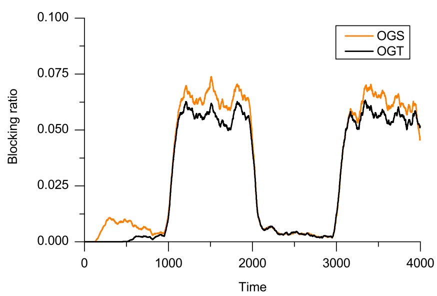


Figure 2.22: Comparing blocking performance of the simple grooming and of the proposed adaptive grooming as the level of traffic changes.

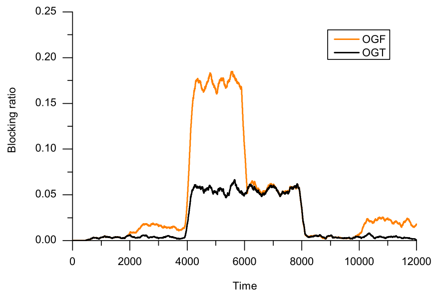


Figure 2.23: Comparing blocking performance of the CP/CP to the CP/MP model as the level of traffic changes ('freeze' at 2000; increase traffic at 4000; 'melt' at 6000, decrease the traffic at 8000; 'freeze' at 10000).

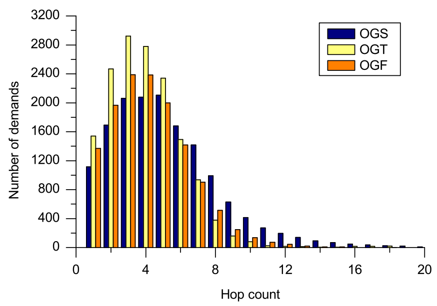


Figure 2.24: Hop-count histogram for the case of connection arrival intensity of 0.01 for the three methods (simple, CP/CP and CP/MP).

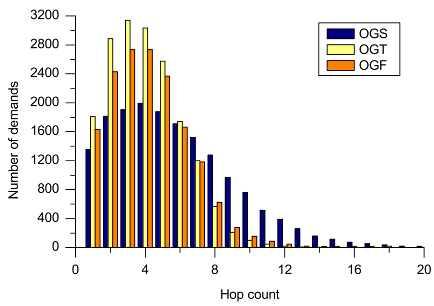


Figure 2.25: Hop-count histogram for the case of connection arrival intensity increased by 20% (0.012) for the three methods (simple, CP/CP and CP/MP).

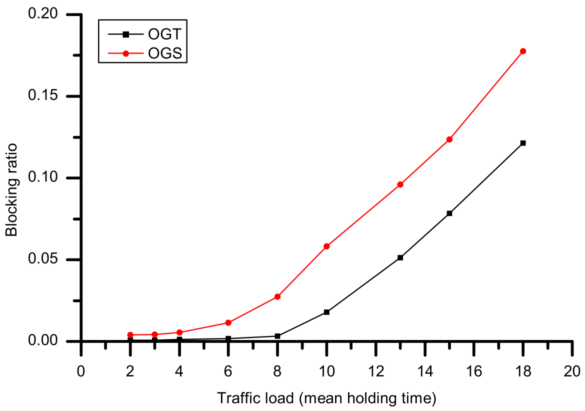


Figure 2.26: Blocking ratio for OGS vs. the λ-path tailoring OGT model.

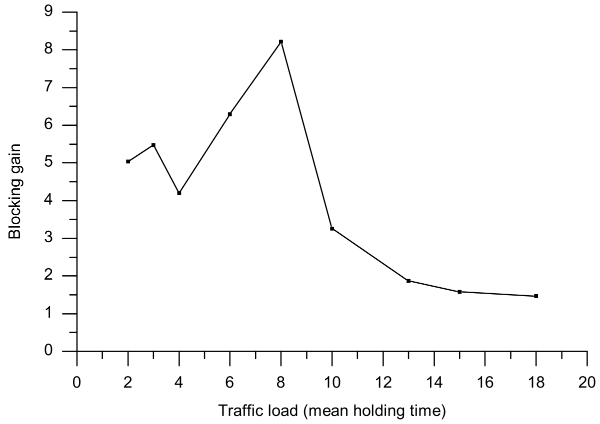


Figure 2.27: Relative gain of OGT over OGS.

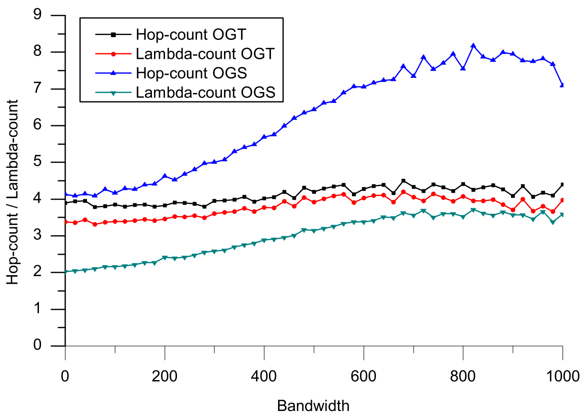


Figure 2.28: Physical and λ Hop-Count as a function of bandwidth.

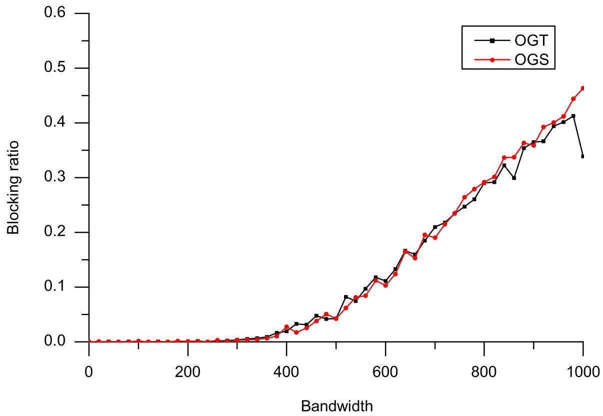


Figure 2.29: Blocking ratio as a function of bandwidth.

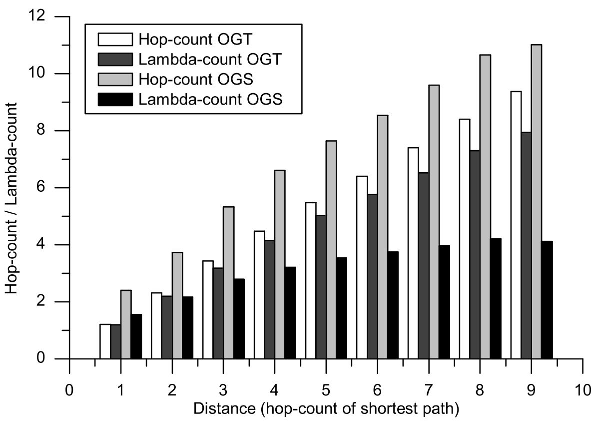


Figure 2.30: Physical and λ Hop-Count as a function of the distance.

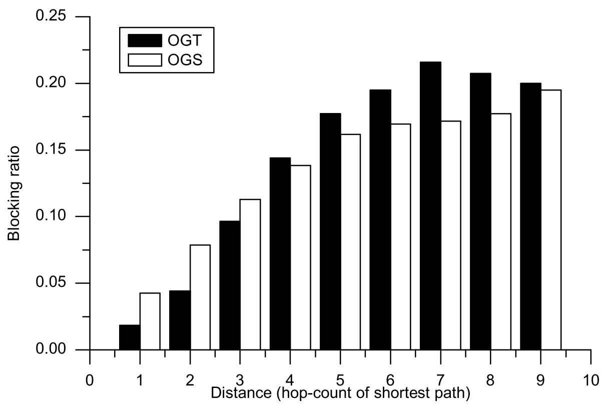
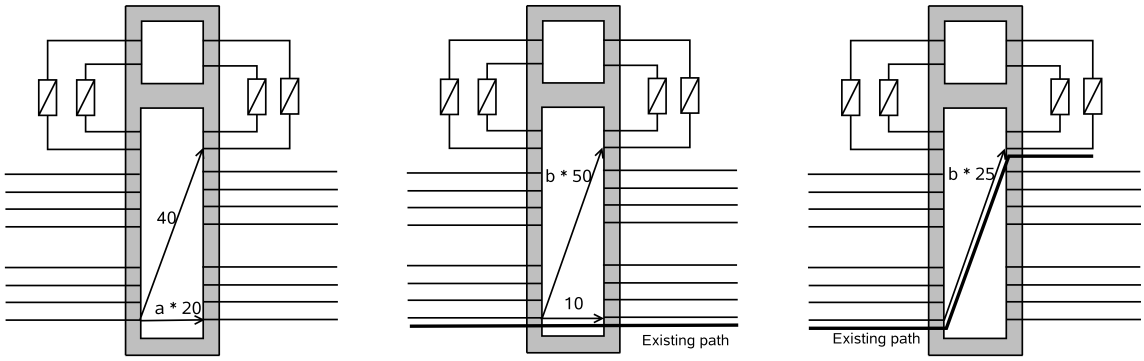


Figure 2.31: Blocking ratio as a function of the distance.



(a) Edge weights in case of a not yet used port.

(b) Edge weights in case of a demand already using the optical path.

(c) Edge weights in case of a demand already using the electronic layer.

Figure 2.32: Edge weights

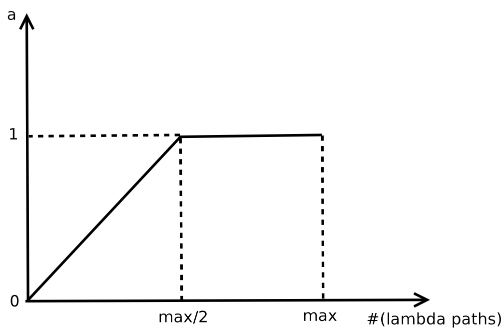


Figure 2.33: The value of parameter a.

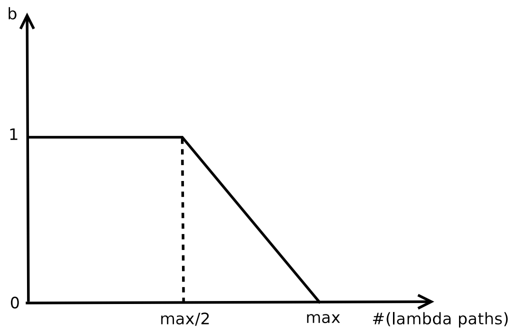


Figure 2.34: The value of parameter b.

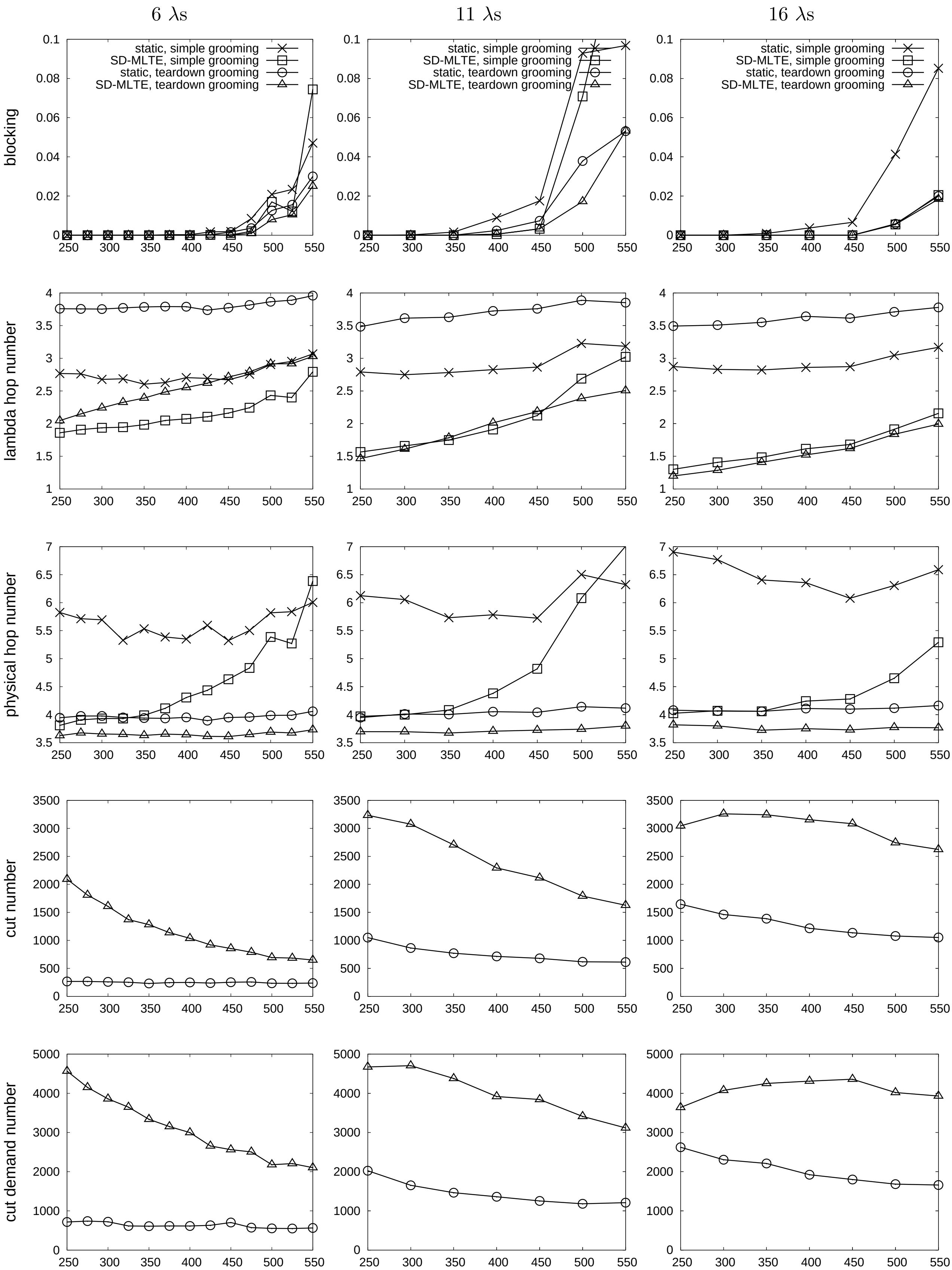
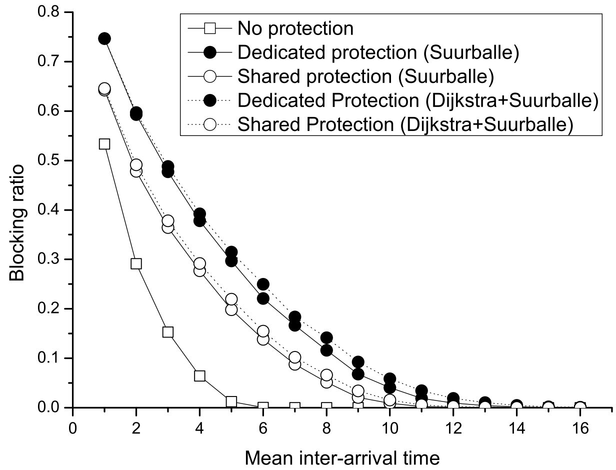
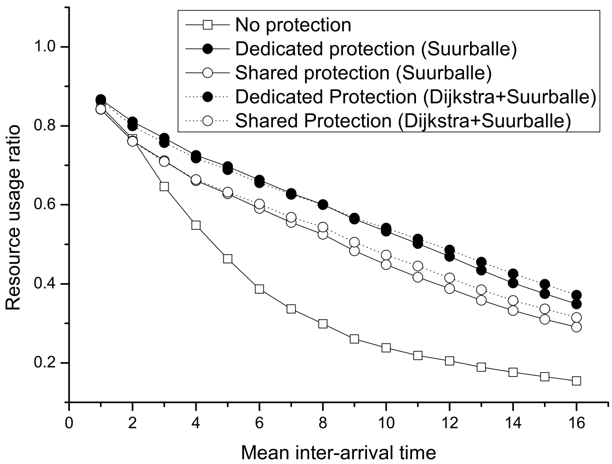


Figure 2.35: The results. The x-axis shows the expected value of the holding time (i.e. the network load). The legend is only shown in the first row, but applies to the rest too.

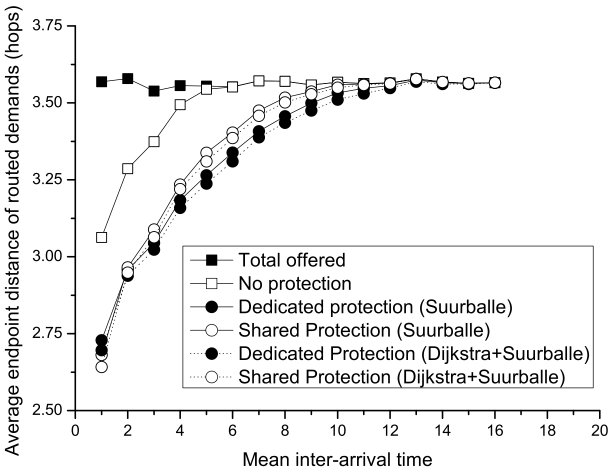
(a) The COST266BT Reference Network.



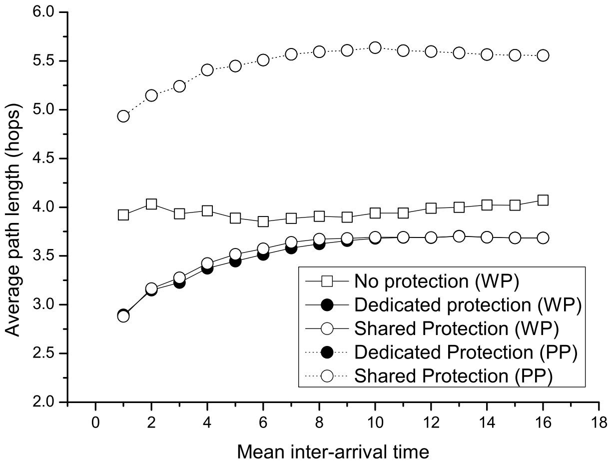
(b) Blocking ratio vs. the decreasing traffic.



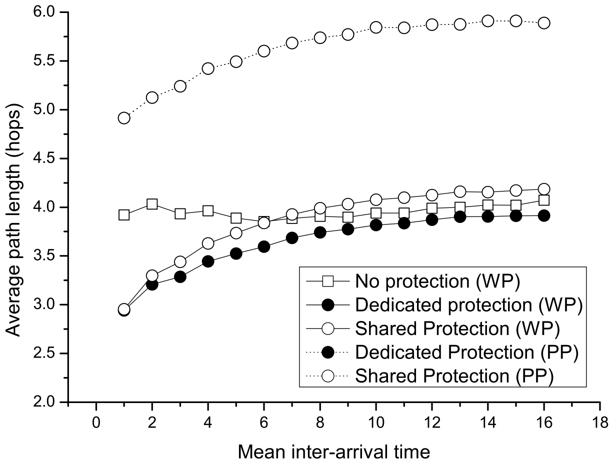
(c) Capacity usage ratio vs. the decreasing traffic.



(d) Average distance of the end-nodes vs. the traffic.

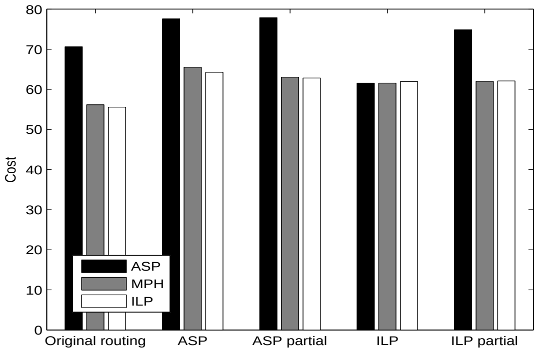


(e) Physical-hop-count vs. the traffic (Suurballe only).

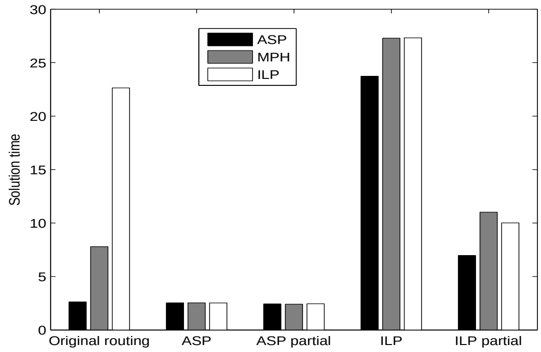


(f) Physical-hop-count vs. the traffic (Dijkstra + Suurballe).

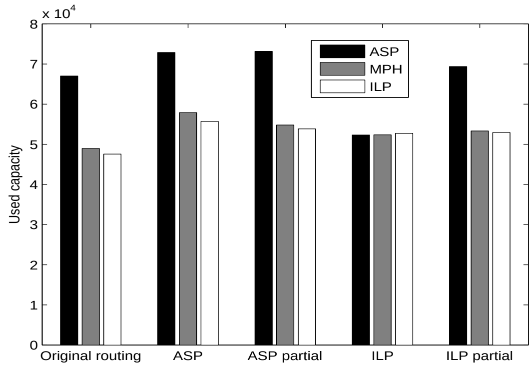
Figure 2.36: The COST 266 reference network and various simulation results, all shown as the offered traffic decreases (horizontal axis). The results for protection paths of Dedicated and Shared Protection overlap in Figures 2.36(e) and 2.36(f).



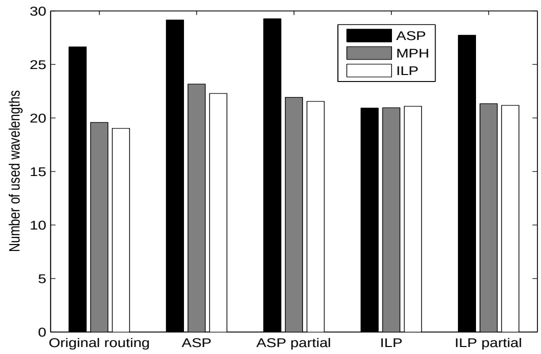
(a) The tree costs.



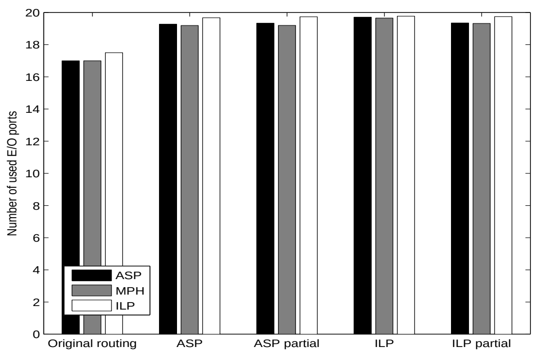
(b) Calculation times.



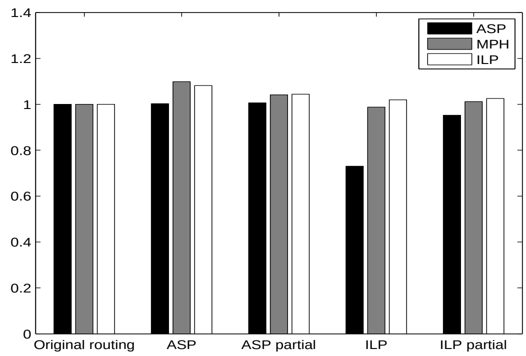
(c) Capacity requirements.



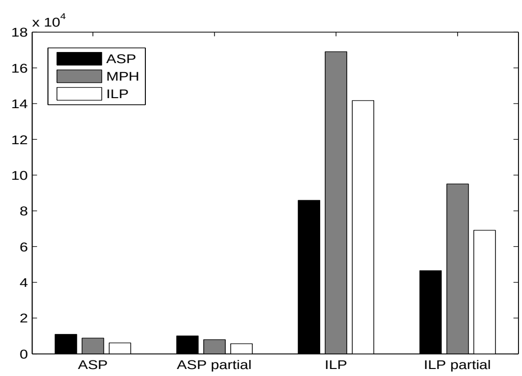
(d) Number of used wavelengths.



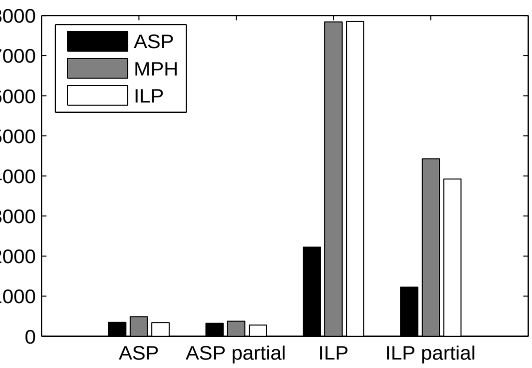
(e) Number of used E/O ports.



(f) Number of links used after restoration, relative to the case without any failure.



(g) Relative Impact of Failures (Service Unavailability)



(h) As in Fig. 2.37(g), weighted with the relative change of wavelengths used.

Figure 2.37: The results of simulating failures and recovering after them using four methods: ASP, ASP partial, ILP, ILP partial. The triple columns show the three methods ASP, MPH and ILP for setting up trees initially. The left-most triplet of columns is the failureless reference case in Figures 2.37(a)-2.37(f).

Chapter 3

Phyisical Impairment Constrained Operation

In both, metropolitan optical networks (MON) and long haul optical networks (LHON) the signal quality is often influenced by the physical impairments, therefore proper impairment constrained routing decisions are needed.

In this chapter we propose two new approaches that jointly perform, on the one hand, routing and wavelength assignment (RWA) and, on the other hand, either tuning the signal power of certain Wavelength Division Multiplexed (WDM) channels or grooming the traffic of some WDM channels in nodes that are grooming capable.

We evaluate the proposed optimization methods for both, single and multilayer networks. For single layer networks we assume that no full signal regeneration is allowed along the path, only optical re-amplification, while in the more complex two-layer case we assume grooming in the electronic layer that implicitly performs 3R signal regeneration and wavelength conversion as well.

The idea to completely separate services from the transport appears for long time in numerous recommendations and papers. Similarly, when considering the services of optical networks it is expected that the signal is regenerated in the optical layer and there is no need to consider it at all while routing or configuring the connections. However, while the all-optical signal re-amplification has been solved by the fiber amplifiers (e.g., EDFA), there is still no commercially available solution for all-optical 3R regeneration, including re-shaping and re-timing of pulses impaired by the physical effects during the transmission along the optical fibers and nodes.

Therefore, in current, particularly metro and core networks the physical impairments are to be considered. One of the first papers dealing with the effects of transmission impairments onto the routing was [84] followed by many others, including [4], [5] and [99]. Recently a European project has been completed on this topic [27].

In this chapter we propose solutions to moderate the limiting effect of physical/transmission impairments

- either by performing electronic signal re-generation via O/E/O conversion while the signal quality is still sufficient to achieve low bit error rates (BER) (Section 3.1),
- or by tuning the power level of certain signals (Section 3.2),

both combined and used jointly with taking proper routing decisions.

3.1 Joint *Traffic Grooming* and *Routing*

First, let us illustrate the problem. Figure 3.1 shows a part of a network, where three demands were already routed from s_1, s_2 and s_3 to d_1, d_2 and d_3 respectively, all using the fiber between nodes a

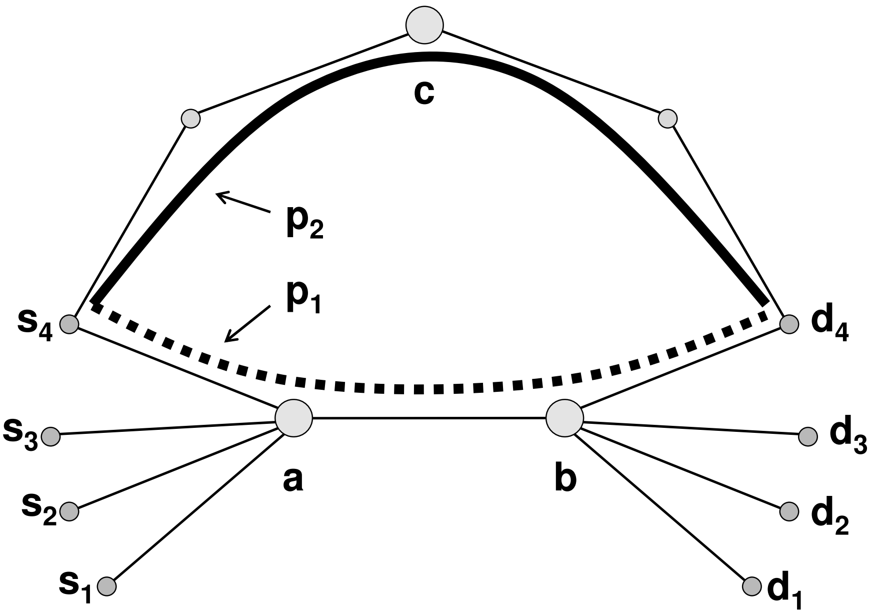


Figure 3.1: Illustration of the two PICR (Physical Impairment Constrained Routing) problems considered.

and b. When we want to route a fourth demand between nodes s_4 and d_4, the shortest path will lead through the same link a-b.

Let us consider the following cases:

- *Case 1:* If the distance between s_4 and d_4 is short enough, the demand can be routed using a new wavelength-path and no 3R re-generation is needed.
- *Case 2:* The distance between s_4 and d_4 is too long therefore no direct wavelength-path can be set up. However, nodes a and/or b have traffic-grooming capability so that the signal can be implicitly re-generated either in a or in b (or even in both, a and b).
- *Case 3:* If nodes a and b do not have grooming capability or all their grooming ports are already occupied by other connections we will not be able to route the demand between s_4 and d_4 along the shorter path (marked as dotted). In this case a longer path (marked as solid) will be chosen, that has enough grooming capable (e.g., c) nodes (and ports within these nodes) to maintain the good signal quality via implicit O/E/O conversion of grooming. (Grooming ports, or simply ports are the O/E and E/O converter pairs between the optical switch/cross-connect that lead to the upper layer, i.e., to the electronic switching device.)
- *Case 4:* Otherwise, the demand cannot be routed and is considered blocked.

3.1.1 Heuristic Methods

The idea of the heuristic algorithm we used is explained in [C151] for Case 2 and in [J33] for Case 3. Its steps are as follows. We try to route all incoming traffic demands one-by-one, in the two-layer wavelength graph model that was discussed in Chapter 2, however, here the physical impairments are considered as well.

- *Step 0:* Model the considered network as a wavelength graph. Initialize it. Set the source of the path to be the ‘considered node‘ from which we try to find the shortest path towards the destination node.

- *Step 1:* Route the demand in the wavelength graph along its shortest path from the ‘considered node‘ towards its destination node. Check the BER (Bit Error Rate) at the end node.

  If satisfactory (above a predefined threshold), the demand is successfully routed. Save the status ‘routed‘ for this path. Allocate and store the path. Update all the weight and capacity values in the wavelength graph. Exit.

  Else, if BER was not satisfactory, proceed to *Step 2*.

- *Step 2:* Find the farthest node along this path from the considered node towards the destination node in the wavelength graph that can be reached and has either free or available grooming capability. Further on, this will be the ‘considered node‘. If a new segment of this path was found in this Step (*Step 2*). Go to *Step 1* to find the next segment.

  Else, if no grooming capability is present or if it was already exhausted by other demands proceed to *Step 3*.

- *Step 3:* Crank back towards the considered node to try alternative segments. Choose the first one feasible (the farthest from the ‘considered node‘ that has sufficient grooming capability and the BER is above the given threshold). If a new segment of this path was found in this Step (*Step 3*). Go to *Step 1* to find the next segment. If not yet, keep cranking back.

  Else, if none succeeds (no segment found while cranking back) the demand is considered blocked. Restore the graph, save the status ‘blocked‘ for this path and Exit.

3.1.2 Results

We have carried out all the evaluations for the COST 266 reference network shown in Figure 2.36(a).

Figure 3.2 shows the achieved simulation results. We have evaluated the ratio of demands blocked to the ratio of the total of offered demands as we scale the network. Compared to the initial scale of 1 we have scaled down to 0.4 and up to 2.7, i.e. proportionally decreased and increased all the physical distances that has decreased and increased the transmission impairments, respectively. For network scale of 1 having 40, 80 or 1000 O/E/O add-and-drop ports between the optical and electronic grooming-capable layer yields roughly the same results. However, if we further decrease the number of ports to 20 or 10 the blocking will significantly increase for two reasons. First, the number of different wavelengths is not sufficient; therefore, to accommodate all the demands grooming is needed. Second, as the distances grow (i.e., the scale factor increases - horizontal axis), first the number of grooming actions will remain the same, however, their position will start to change, then after a while the number of grooming actions will be dominated by physical impairments, not by the traffic conditions anymore. It can be seen, that the sections of the blocking characteristic around the scale factor of 1 become steeper as the number of ports decreases. This is caused only by the increased impact of impairments induced by increased distances.

If we further decrease the scale factor of the network the blocking remains constant, i.e., the physical impairments are negligible - they do not influence the routing anymore. On the other hand if we further increase the scale factor, the distances will be so large, that hardly any demand can be routed without regenerations that rapidly exhausts all the grooming ports and causes extreme blocking.

3.1.3 Free Regeneration via Compulsory Grooming?

We present some more simulation results to better support our statement on the mutual impact of grooming and physical impairments. In each physical link we have used 16 wavelengths, 10 Gbit/s capacity per wavelength and demands of average bandwidth of 1 Gbit/s. Each simulation routed 200000 demands. The holding time of demands was set to achieve and maintain the network load at level of 60 %.

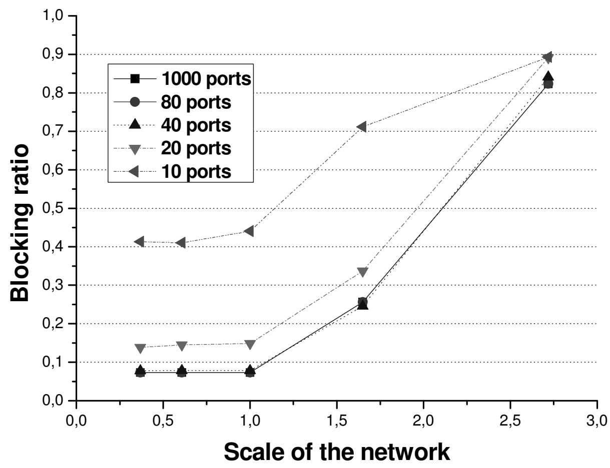


Figure 3.2: Dependence of the blocking on the network scale and grooming capacity (number of ports).

There were two parameters we tuned. First, the network was scaled between 25 % and 65 % of its original size. Second, the number of O/E and E/O ports between the optical and electronic layer was tuned from 20 to 80. This parameter limits the grooming capability of the node. I.e., if set to 20 just a few demands can be groomed, while if set to 80 all demands can be groomed at the same time. We have used the 72-processor, 164 GByte RAM supercomputer.

Figure 3.3 shows that as long as the network scale is small and the grooming capacity sufficient there is practically no blocking (front part of the Figure). As we start scaling the network up, i.e., all the links become longer, the physical impairments start to grow and the blocking will slightly increase for larger networks. Similarly if we start decreasing the number of ports that make the grooming possible, the blocking will also start to grow. However, if we tune both the parameters at the same time for the scale of 0.65 of the network the blocking will strongly depend on the grooming capability. This demonstrates that at scale of 0.65 the blocking can be reduced by almost one order of magnitude by increasing the grooming capacity.

Figure 3.4 shows how many consequent physical links are used by a single wavelength path on average. It is counted for established connections only, i.e., blocked requests do not count. It can be seen that for larger scales the average length (hop-count) of the wavelength paths decreases. One of the reasons is that more regenerations are needed, and therefore there are fewer long wavelength paths. The other reason is that longer paths are blocked, and they do not contribute to the average.

The optical signal is routed to the electronic layer and back via O/E and E/O conversions for any of the following three reasons:

- First just to 3R regenerate it electronically, to improve the signal quality.
- Second, to perform wavelength conversion if the wavelength continuity cannot be maintained if it is already used.
- Third to perform traffic grooming for the reason of more efficient resource utilisation.

Figure 3.5 shows only the first one, i.e., the use of the electronic layer for regeneration only.

While the network size is small (small scale), there is no regeneration need at all. When we start expanding the network the demand for regeneration will start to grow, however, even for a network scale of 65% it will affect less than 1 % of demands! This clearly supports, that the grooming capacity can handle the regeneration as well, practically, for no extra cost! I.e., although the point where the demand enters the electronic layer may change, the number of these enterings remains almost the same.

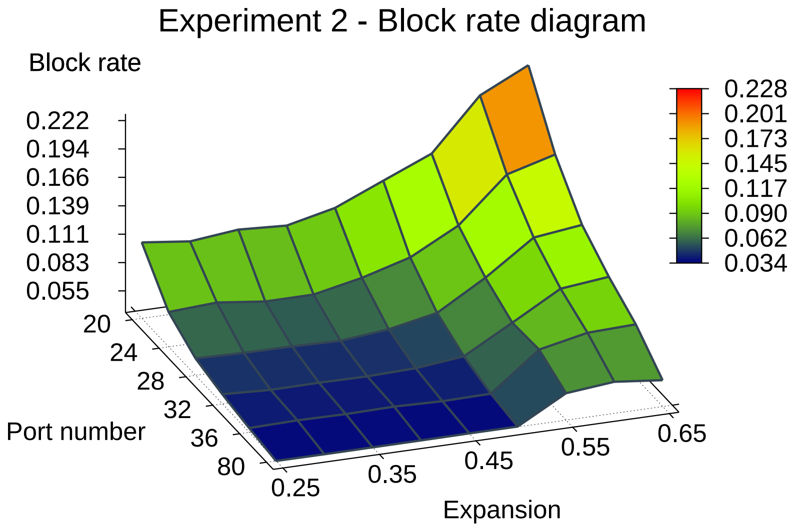


Figure 3.3: Blocking: Dependence on the network scale ('Expansion') and grooming capacity ('Port number').

3.2 Joint *Power Level Tuning* and *Routing*

Let us consider the second scenario, where we try to fight against impairments by increasing the power level of certain signals. In this case the BER drops as the level of the signal grows, however, only until a certain threshold. When the total of channel powers in a certain link achieves a threshold, the transmission impairments will rapidly escalate due to non-linear effects!

To better explain the problem, let us consider Figure 3.1 again, however, this time assuming no grooming capability at all. Considering that link a-b is used by the largest number of demands it will have the highest total power level. If we want to improve the quality of the signal between any of the s-d node-pairs, we have to increase the power. However, as we increase the power of certain channels, the total power grows as well, that leads to risen nonlinear impairments. To avoid this problem we propose two solutions.

First, routing some of the demands to longer paths (solid instead of dashed path in Figure 3.1) decreases the total power of critical links. This will need higher power for that wavelength-path, however, as long as it does not use any critical link it is no problem, it may have higher power level.

Second, we propose using different power levels for different wavelength channels even within a single link. Although the optical equipment allows this uneven tuning, to our knowledge it has not been used so far. Nowadays in nearly all reconfigurable optical add-drop multiplexers (ROADM) the signal power can be tuned this way by the control plane via variable optical attenuators (VOA). The proposed methods can be used in existing WDM optical networks wherever the nodes support signal power tuning.

3.2.1 Technology Background of PICR

New technologies aim to reduce operational expenditure (*OPEX*). Reconfigurable optical add/drop multiplexers (*ROADM*) provide remote configuration capability, including capacity and power tuning without manual intervention for a wide range of wavelengths.

Most of the operators, to optimise the performance of their networks require monitoring and wavelength control. Thus, additional management functions, that allow power measurement and other per wavelength settings are included in most of the commercial products [19], [69].

Nowadays in nearly all types of *ROADM*s signal power can be tuned with variable optical

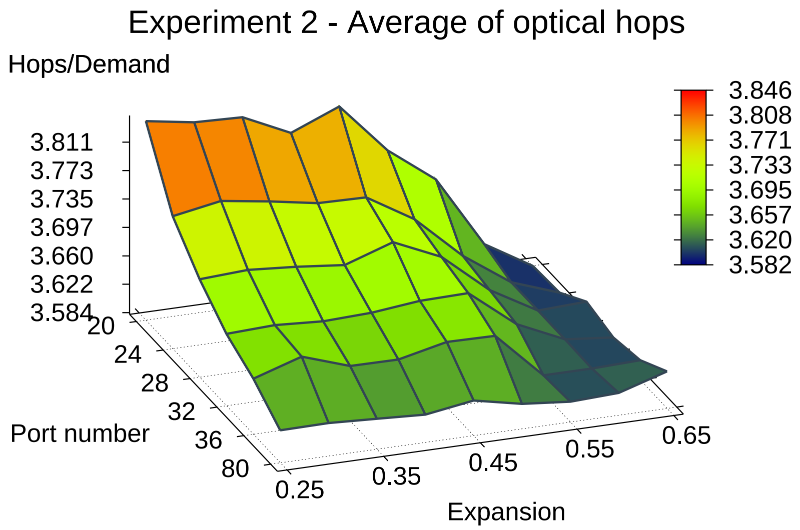


Figure 3.4: Average per-demand hopcount: Dependence on the network scale ('Expansion') and grooming capacity('Port number').

attenuators (*VOA*) through the management system. This, along with the Routing and Wavelength Assignment (*RWA*), enables fully reconfigurable networks.

The details of the configuration, design, and optimization of optical networks have been intensively investigated so far, see e.g. [86]. However, only few papers focused on the physical parameters of *RWA* in case of fully reconfigurable optical networks [40], [C124]. To our knowledge, none of these examined the idea of handling physical impairments by joint power level tuning and routing.

In metro *WDM* networks signal power of optical channels is determined by Cross-Phase Modulation (*XPM*) and Raman scattering and not by the Brillouin threshold. This means that the maximum of total power inserted into a fiber is limited, not the power used to transfer single demands. Thus, it is suitable to increase the power of some channels up to the Brillouin threshold while other channel powers are tuned down to fulfill the *XPM* and Raman scattering constraints. This idea allows the use of Physical Impairment Constrained Routing (*PICR*) for lightpath configuration [C112].

In Fig. 3.7 we have two wavelengths: ϕ_1 and ϕ_2. In *Case A* we do not apply *PICR*. Here, due to physical constraints, node A can only reach node C in all-optical way. If there is a demand between node A and D its path can only be established with electric signal regeneration either in node B or in node C. *Case B* shows the same situation when the proposed *PICR* approach is used. Here the signal power of ϕ_2 is increased to fulfill the Optical Signal-To-Noise Ratio (*OSNR*) requirement at node D. This can be done only, if the total power load is affordable on each link. Therefore, the power level of ϕ_1 has to be decreased. This way it is possible to establish an all-optical connection between A and D.

3.2.2 The MILP Formulation of the Problem

In [P4] and [C112] we propose a new method for finding the global optimum of the wavelength-path system configuration by simultaneously tuning the power levels for each wavelength path and routing these wavelength paths in order to minimize the effects of non-linear impairments while maintaining the sufficient signal level for required end-to-end signal quality in terms of BER. This method also minimizes the use of network resources within the constraints of end-to-end BER for each wavelength path. These approaches are based on ILP (Integer Linear Programming) and on heuristics. If there exists a global optimum the ILP algorithm will find it, for any network

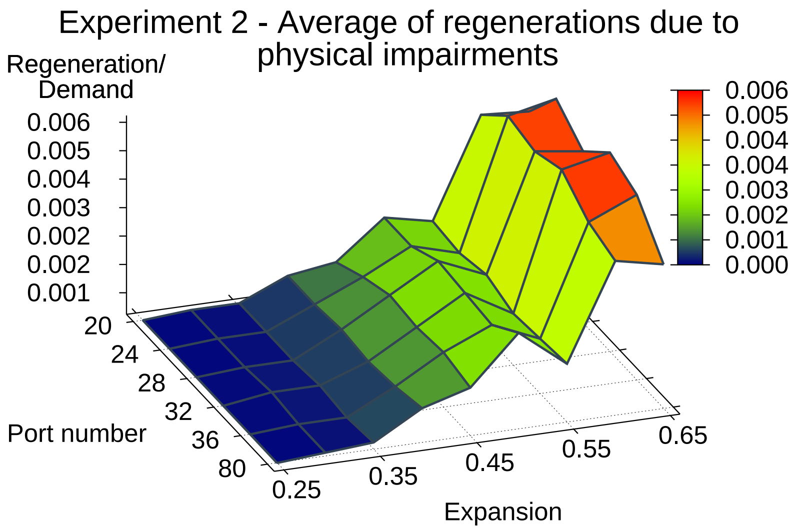


Figure 3.5: Average per-demand number of those regenerations that were required explicitly because of physical impairments: Dependence on the network scale ('Expansion') and grooming capacity ('Port number').

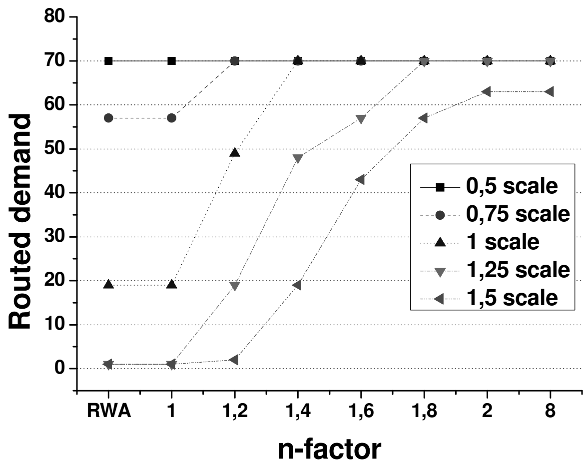


Figure 3.6: Maximum number of routed demands versus the n-factor for different scale parameters.

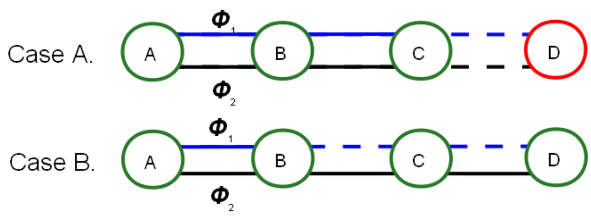


Figure 3.7: Base idea of *PICR*

topology, physical constraint and demand set. In [C112] we generalize the results for two-layer grooming-capable networks as well.

Here we provide the ILP (or rather the MILP: Mixed Integer Linear Programming) formulation of the problem for single layer wavelength routed single-hop networks.

We assume the network to be modeled as a wavelength graph that consists of vertices V that correspond to the ports at different wavelengths of the switches that are interconnected within switches by edges from set E_{sw}. The edges that are used to interconnect ports of different switches are from set $E \setminus E_{sw}$. These edges from the set E_{sw} belong to different physical links (fibers) pl. All the pls make the set of physical links PL. Considering all the edges (i, j) belonging to $\forall pl \in PL$ we will have the set $E \setminus E_{sw}$.

The set of demands o is denoted as O. A single demand o will be routed using a single, end-to-end wavelength channel. The signal will be amplified all optically to maintain its power level, however, no 3R regeneration is assumed.

Constants:

- $P^{max}_{pl[mW]}$ is the upper limit of total power in physical link (fiber) pl expressed in mW. ($P_{[dBm]} = 10\log_{10} P_{[mW]}$, i.e., 1 mW corresponds to 0 dBm.) The total power level in a SMF fiber must never exceed $100mW$ ($P^{max}_{pl[mW]} < 100mW$, $P^{max}_{pl[dBm]} < 20dBm$) and has typical value of over 3 mW (4.77 dBm). Depending on the network parameters (including the number of wavelengths used) the value of $P^{max}_{pl[mW]}$ is set between these limits.

- l_{ij} is the length of a physical link between nodes i and j expressed in [km]. If we want to model physical impairments induced by a node, we assume that the impairments induced by the switch are equivalent to that experienced while sending the signal along a certain length of a fiber, (e.g., 90 km). The simplest way to include physical impairments induced by a node is to add this length to fibers.

- L_c is a linear factor between the distance the signal has to reach and the input power required for reaching that distance with acceptable BER. It is expressed in [km/mW]. As the input power level is increased, the signal quality will improve, however, after a certain level the nonlinear impairments will significantly deteriorate the signal quality. Here we have assumed $L_c = 1000$ km/mW for a single λ.

- α, $0 < \alpha < 1$ is a tuning parameter that weights the optimisation objectives. It can prefer either the minimal routing cost (larger α) or the minimal total power used (smaller α).

- n-factor is the value of maximal relative deviation from average per channel power level for a single λ (wavelength). If there are $|\lambda|$ wavelengths per channel the average per channel power level will be $P^{max}_{pl[mW]}/|\lambda|$. If the n-factor has value of 1 all the channels must have this equal power level. If it has value of e.g. 1.5 it means that a channel can have power level by 50 % higher, however, then it may happen that the other λ (wavelength) channels must decrease their power level in order not to exceed the total per fiber power level.

- s^o and t^o are the source and the target (destination) respectively of demand $o \in O$.

Variables:

- $p^0, 0 \leq p^0 \leq n/|\lambda|, \forall o \in O$ is the input power of demand o expressed in mW and then normalised by $P^{max}_{pl[mW]}$

- $p^0_{ij}, 0 \leq p^o_{ij} \leq p^o, \forall (i, j) \in E, \forall o \in O$ is the power of demand o on link (edge) (i, j) normalised by $P^{max}_{pl[mW]}$

- $y_{ij}^0 \in \{0,1\}, \forall (i,j) \in E, \forall o \in O$ is the binary indicator variable having value of 1 if demand o uses edge (i,j), or 0 if not.

Objective:

$$minimize \left\{ \alpha \sum_{\forall o \in O} \sum_{\forall (i,j) \in E \setminus E_{sw}} y_{ij}^o + (1-\alpha) \sum_{\forall o \in O} p^o \right\} \tag{3.1}$$

Constraints:

$$\sum_{\forall j \in V^{\to i}} p_{ji}^o - \sum_{\forall k \in V^{i \to}} p_{ik}^o = \begin{cases} -p^o & \text{if } i = s^o \\ 0 & \text{otherwise} \\ p^o & \text{if } i = t^o \end{cases} \quad \forall i \in V, \quad \forall o \in O \tag{3.2}$$

$$\sum_{\forall j \in V^{\to i}} y_{ji}^o - \sum_{\forall k \in V^{i \to}} y_{ik}^o = \begin{cases} -1 & \text{if } i = s^o \\ 0 & \text{otherwise} \\ 1 & \text{if } i = t^o \end{cases} \quad \forall i \in V, \quad \forall o \in O \tag{3.3}$$

$$p_{ij}^o \le y_{ij}^o, \quad \forall (i,j) \in E, \quad \forall o \in O \tag{3.4}$$

$$\sum_{\forall o \in O} \sum_{\forall (i,j) \in pl} p_{ij}^o \le P_{pl}^{max}, \quad \forall pl \in PL \tag{3.5}$$

$$\sum_{\forall o \in O} y_{ij}^o \le 1, \quad \forall (i,j) \in E \tag{3.6}$$

$$\sum_{\forall (i,j) \in E} y_{ij}^o \cdot l_{ij} \le L_c \cdot p^o, \quad \forall o \in O \tag{3.7}$$

Explanation of the MILP Formulation

- Constraints 3.2 and 3.3 are the flow conservation (real) variables for the power and for the flow indicator (0-1) respectively.
- Constraint 3.4 ensures, that whenever the power of demand o on edge (i,j) exceeds 0, than edge is considered used via the 0-1 indicator variable y_{ij}^o.
- Constraint 3.5 guarantees, that the total power limit of a physical link (fiber) is not exceeded.
- Constraint 3.6 ensures that a single wavelength of a fiber can be either not used or used by a single demand only.
- Constraint 3.7 ensures that the reach of demand o cannot exceed the distance determined by its input power. Violating this constraint would lead to signal quality deterioration expressed as BER or Q-factor.

3.2.3 Results

We have evaluated the proposed ILP based approach for the same network, shown in Figure 2.36(a). The results are presented in Figures 3.6 and 3.8. In both figures we evaluate the number of demands that can be simultaneously routed for certain n-factors. n=1 means, that all channels have the same power level, i.e., the maximum power allowed in a fiber is divided by the number of wavelength channels.

Figure 3.6 shows, that as we allow more and more diverse power levels, the amount of demands that can be routed grows significantly, e.g., from 18 to 70 for scale factor 1 while the n-factor grows

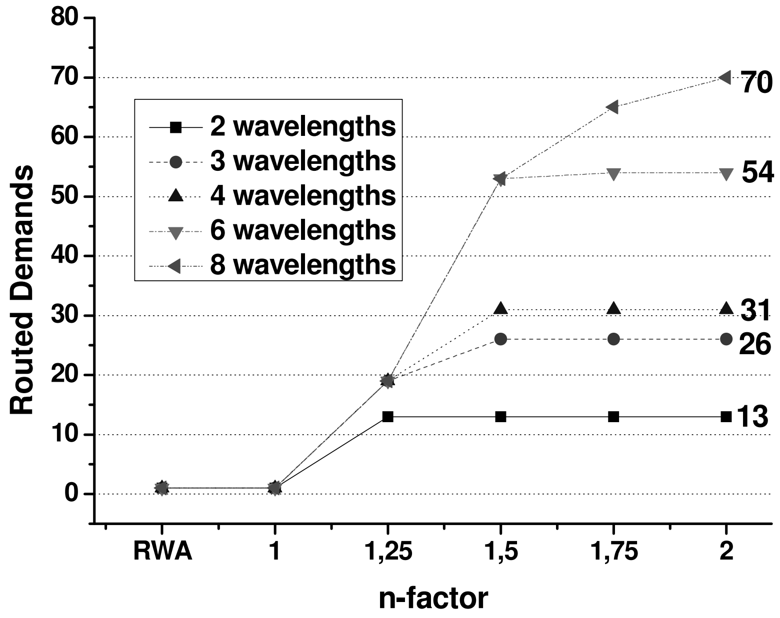


Figure 3.8: Maximum number of routed demands versus the n-factor for different number of wavelengths.

from 1 to 1.4. This shows the great performance of allowing this minor difference in power levels! If we consider the scale factors, it can be seen that for value of 0.5 where physical impairments do not impact the number of routed demands at all, there is no difference - no need to use different power levels. However, for scale factors larger than 1, where the physical impairments become significant allowing different power levels results a tremendous growth in the number of routed demands. The first value on the horizontal axis marked as RWA is the reference method, where all the power levels are exactly the same.

Figure 3.8 shows the dependence of the number of routed demands on the n-factor as the number of wavelength channels is increased in the links of the WDM network. It can be seen that as the number of wavelengths grows, the proposed approach of allowing different power levels has an incredible positive impact: Instead of a single demand, up to 70 demands can be routed in a system with 8 wavelengths as the n-factor grows from 1 to 2!

3.2.4 Increased Throughput through Proposed PICR-Aware Methods

In Section 3.1 and in Section 3.2 we have proposed two scenarios for Physical Impairment Constrained Routing (PICR). First, in Section 3.1, using the grooming capability present in certain nodes of the network to perform O/E/O signal regeneration. Second, in Section 3.2, to tune the signal power of certain wavelength-paths to different levels depending on the destination of that wavelength path, as well as on the current power budget of the links along that path. Both schemes were used simultaneously with routing over optical C/D WDM networks. Our simulations have shown that using the proposed schemes presented in Sections 3.1 and 3.2 the ratio of demands routed can be significantly increased compared to the cases when all demands are blocked that could have been routed by conventional methods, however, their signal quality was poor due to the physical impairments.

3.3 Why TE does not Work for PICR?

For networks where a plenty of bandwidth is available, however, the total per link free power is the scarce resource due to the size of the network (large distances), we have defined the Power

Engineering (PE) framework that is complementary to the TE framework.

As we already discussed in 2.6 TE always tries to move the traffic from highly loaded parts of the network to parts with lower load. As the total power over a link can be handled analogously to the total load of a link we will base our TE metrics on the power (PE) instead of the bandwidth load of a link.

We also explain why the classical traffic engineering (TE) approach does not work for physical impairment constrained routing (PICR).

3.3.1 Problem Formulation

We assume here the network model as defined in Section 3.2. The difference is that there (Section 3.2) we have assumed the static case where we configure the network for all the demands simultaneously, while here we assume the dynamic case, when all the demands arrive one-by-one in order and with timing that is unknown in advance. For these demands we try to set the power level and find the appropriate route simultaneously. According to the TE principles, we try to adaptively prioritise paths over links with lower total power to save some power budget for future demands.

A two-layer network is assumed, where the upper, electronic layer is time switching capable, while the lower, optical layer is a wavelength (space) switching capable one. The two layers are assumed to be interconnected, i.e., the control plane has information on both layers and both layers take part in accommodating a demand.

We assume dynamic traffic consisting of unicast demands. The objective is to accommodate all demands while obeying all routing and technology constraints with the lowest possible power usage. According to [C112] the function between the reach (the distance that can be overbridged with no O/E conversion, i.e., in a single hop) and the needed power of that signal is linear.

3.3.2 The PE (Power Engineering) Heuristics

Routing demands in optical networks without power constraints is a well investigated problem, both for the static and for the dynamic cases. There exist various heuristics, a significant ratio of them based upon Dijkstra's algorithm [28]. These methods can be applied to our problem with an additional search loop.

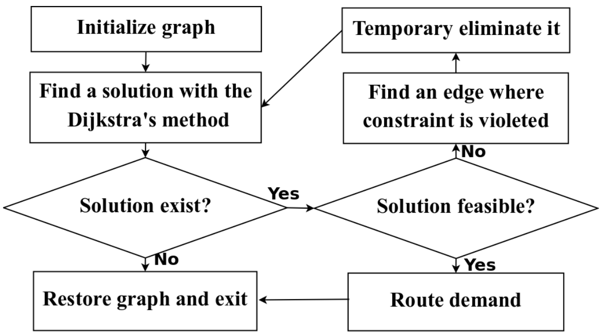


Figure 3.9: PICR (Physical Impairment Constrained Routing) of a single demand.

The algorithm to route a single demand according to pre-set edge weights in the graph model of the network is illustrated in Figure 3.9. The main steps are as follows:

SINGLE-DEMAND PICR ALGORITHM

- *Step 1:* Try to find a weighted shortest path from the source to the destination of the considered demand according to the edge weights using the given routing method (Typically Dijkstra's Shortest Path Algorithm [28]).
- *Step 2:* If solution does not exist: exit. Otherwise check the constraints on every affected link.

- *Step 3:* If no power constraint is violated, route along this path.
- *Step 4:* If one or more power constraints are violated, find the edge (or an edge) with the highest total power level and temporarily remove it.
- *Step 5:* Go to *Step 1* to search for another path in the modified graph, i.e., repeat until path is found or the loop exits (*Step 2*).

3.3.3 Alternative PE Weights

The path along which a new demand is routed depends on the weights that were assigned to certain edges of the graph. These metrics can be various. In case of classical TE as the number of the demands that are routed over a link grows, i.e., as the expected amount of free link capacity drops, that link will have higher TE metric assigned. As the power requirement of a demand is a commodity similar to capacity we have applied weight functions that are power-level dependent (PE) instead of utilisation-level dependence (TE). We have evaluated six different weight functions as follows:

- **Dijkstra:** The weight w_{pl} of a physical link pl depends only on the physical *length* l_{pl} of that link. $w_{pl} = l_{pl}$. The dependence is linear.
- **Linear:** The weight of a link is proportional to the total p_{pl} of powers p^o_{ij} of all demands o that use an edge $ij \in pl$. $w_{pl} = p_{pl} = \sum_{\forall o \in O} \sum_{\forall ij \in pl} p^o_{ij}$.
- **Logarithmic:** The weight of a link is the logarithm of the total power over that link plus one. Adding one to the value of power guarantees that the weight will be non-negative ($log_a x \geq 0$ if $x \geq 1$). $w_{pl} = \log\{1 + p_{pl}\}$.
- **Exponential:** The weight of a link is the exponential function of the total power, i.e., $w_{ij} = e^{p_{pl}}$.
- **Square:** The weight of a link is equal to the square of the power: $w_{ij} = p^2_{pl}$.
- **Breakline:** The weight of a link is equal to 0 if the power is lower than a certain value (80 % in our case) of the maximum power ($w_{ij} = 0$ if $p_{pl} < 0.8 \cdot P^{max}_{pl}$). Otherwise (if $p_{pl} \geq 0.8 \cdot P^{max}_{pl}$) the weight is equal to the total power $w_{pl} = p_{pl}$ (as in case of 'Linear TE').

3.3.4 Results

To confirm our observations we carried out simulations with different routing modes. The results are presented in Figure 3.10. During our simulations we assumed that a demand cannot be transported further than 1000 km, the maximum power over a link is 10 dBm, the coefficient is $L_c = 1000\ km/mW$. We supposed that the holding time of a demand is given with exponential distribution, the arriving of demands during a given time period is uniformly distributed. The average number of demands was set to 50, the number of wavelengths per link to 10.

Figure 3.10(a) shows the ratio of routed demands as the scale of the network decreases. When the network is larger, i.e. the needed power to transport data is greater and even the smallest detour is insupportable, PE methods behave quite the same, however, those that give less penalty for higher load perform better. Dijkstra's algorithm gives the best solution. When the network is of small scale the difference between the solutions vanishes, or even Dijkstra's algorithm becomes the worst.

Figures 3.10(b) and 3.10(c) show the average power of a routed demand and the average load of an used link respectively. The average power of a routed demand decreases with the network size because the distance that should be spanned also decreases (Figure 3.10(b)). This is close to linear dependence. The growth of the average power load of a link is sublinear (Figure 3.10(c)). This can be explained by higher blocking rate (lower routing rate: Fig 3.10(a)) in case of higher power levels, i.e., larger network scales.

3.3.5 TE (Traffic Engineering) vs. PE (Power Engineering)

The main idea of TE is to choose from the potential solutions the one that interferes less with the future demands [C117], i.e. the load of the network should be balanced. This means that the probability of using an edge during the routing is inversely proportional to its current load. However, to balance the traffic these methods use longer paths which can be a drawback when the resource requirement depends on the length of the path, just like in case of the investigated (PE) problem. I.e., in case of PE as the length of paths increases the required power level has to be increased that increases the total power level, that was not the case with the capacity in case of TE. This is the reason why PE cannot be applied; Therefore, the shortest path routing that leads simply to minimal total power is preferred, particularly for for higher power loads, i.e., for larger networks (with larger distances).

We have shown that the idea of TE cannot be used for those problems where the resource need is not independent of the distance. PE tries to balance resource utilization, i.e., to shift a part of the traffic to longer paths, thus it wastes resources. This forces demands that arrive later to take even longer detour. This leads to a positive feedback, thus in such cases it is better to use Dijkstra's shortest path algorithm with weights proportional to the distance and independent of power levels.

3.4 Physical Impairment aware Resilince?

In this section we investigate the idea of Shared Protection applied to sharing power budgets of links. When defining protection paths not as a "hot stand-by" but rather as a "cold stand-by" the power needed for protection will be lower; therefore, the routeable distance of certain connections will be longer, according to the idea explained in Section 3.2, that increases the number of routeable demands. In this section we present simulation results to show that in reality with the introduction of Power-Shared protection for Physical Impairment Constrained Routing (*PICR*) in large or saturated networks the number of routeable demands is lowered.

3.4.1 Problem Formulation

We assume the optical network given with its topology, number of fibers per cable, number of wavelength channels per fiber, wavelength channel capacity, physical length of fiber links and the physical effects that lead to signal deterioration.

We assume dynamic unicast-only (point-to-point) traffic, i.e., a traffic pattern, that defines the scheduling of demands with given traffic parameters.

The objective is to reach destination node with at least a primary (working) and if possible a backup (protection) path from the source without any common link, for each demand, while obeying all the given constraints and minimizing the power usage. In our model having no common link means SRLG-disjointness (SRLG: Shared Risk Link Group), i.e., that if the primary path uses an edge of the given WG then the backup path has to avoid all the edges that belong to the same link. I.e., if a working path uses a wavelength of a fiber, then its protection path has to avoid all the wavelengths of that fiber and that cable, although in the wavelength graph they seem disjoint. More generally SRRG (Shared Resource Risk Group) is assumed [23] where the above assumption holds not only for edges but for any other resources as well.

We use a simplified version of our Wavelength Graph (WG) model introduced in Chapter 2, where only OXC nodes (Optical Cross-Connects) were used. Therefore, neither wavelength conversion nor grooming capability is supported. This reduces our WG model to somewhat similar to those presented in [16], [108].

Handling Physical Impairments

The proposed approach (*PICR*) injects different channel powers into the same optical fiber according to the distance the ligthpath has to take. With the modification of power allocation schema new problems have to be solved. Most of these are mentioned and solved in [C112].

To investigate the relation between signal power and maximum allowed distance we consider a noise limited system where other physical effects can be taken into account as power-penalties. It is possible to prove by analytical calculations that there is a linear relationship between the channel power and the maximum allowed distance of a lightpath [58]: $L = L_c * P_{mW}$, where P_{mW} is the input power in mW, L is the maximum allowable distance, and L_c is the linear factor between them. L_c is between 500 and 2000. The effect of a node onto the signal quality is equivalent to that of a certain length of a fiber. Thus it is modeled by an addition to the edge length: $len_{PhyNode}$.

Handling the Protection

There are solutions for routing static demands in optimal or quasi-optimal way with protection, see, e.g. [C7], [C123]. All these methods can be extended to fit *PICR*. However, their time requirement makes it hard to use them for dynamic routing.

Calculating primary and back-up paths between a given source and destination with heuristic methods is well investigated as well. The two most common ideas are Shortest Pair of Link Disjoint Paths (SPLP) [41] and k-Disjoint Paths Method (KDPM) [11].

In most cases the backup paths are not used, they serve only as a standby against unpredictable events occurring quite rarely. Resource sharing between back-up paths can only be done if they provide protection against different events, i.e. their primary paths have no element in common.

The idea of sharing resources (typically bandwidth) of the backup paths was well studied, e.g. [42]. In our case the main resource is power instead; thus we will concentrate onto shared protection as the mean of power sharing.

3.4.2 P-PICR: The PICR Algorithm for Dedicated and for Shared Protection

Here we define the method for physical impairment constrained routing of the working path and its either dedicated or shared protection path. As we mentioned in Section 3.3 the power budget is a commodity similar to capacity, therefore, we handle it analogously. We differentiate power-dedicated protection as a hot stand-by, and a power-shared protection as a could stand-by. For the seak of simplicity we will refer to these as *dedicated* and *shared* respectively.

We also investigated a special case where we prefer to route a demand with no protection to the case of not routing the demand at all. We will refer to this approach as 'partial' (partially protected) route, while the regular one, where a working (primary) path cannot exist without a protection (back-up) path, will be referred to as 'full' (fully protected) route.

The workflow of the Protected PICR method is defined in Figure 3.11.

Both, the primary path (the working one) and the secondary path (the protection one) are searched by the *SINGLE-DEMAND PICR ALGORITHM* as defined in Section 3.3.2, i.e., this algorithm is called as a subroutine *Step 1* and in *Step 4* of the following algorithm.

P-PICR: THE PICR ALGORITHM FOR DEDICATED AND SHARED PROTECTION

- *Step 0:* Initialize the graph that models the network with all free wavelength and free power parameters.

- *Step 1:* Try to find the shortest path for the considered demand using the PICR algorithm. If a path is found proceede to *Step 2*. Else, if not found, conider the demand blocked and go to *Step 7*.

- *Step 2:* Modify the graph temporarily as follows: Remove all the edges (links) from all the SRRGs of the graph that were used by the working path found in *Step 1*.

- *Step 3:* If dedicated protection (input parameter) is assumed proceede to *Step 4*. Else, if shared protection (input parameter) is assumed select all the edges of the graph where power budget can be shared among protection paths. For these selected edges update the free (including sharable) power budget.

- *Step 4:* Try to find the shortest path for the considered demand using the PICR algorithm. If a path is found allocate the protection path and go to *Step 6*. Else, if not found, proceede to *Step 5*.
- *Step 5:* If partially protected demands (input parameter) are not allowed, consider the demand blocked and go to *Step 7*. Else, if partially protected demands (input parameter) are allowed, consider the demand routed with partial protection and proceede to *Step 6*.
- *Step 6:* Allocate the working path of the demand.
- *Step 7:* Restore the graph, update all power and capacity measures and exit.

3.4.3 Results

To evaluate the benefits of our approach we have carried out simulations where the demands were randomly generated according to predefined parameters. First, dedicated and shared protection were compared. Second, the case the case of the partial routing was allowed, not only the full routing.

During our simulations we assumed that a demand cannot be transported further than 1000 km, maximum power over a link is 10 dBm, coefficient is 1000 km/mW. We supposed that holding time of a demand is given with exponential distribution, arrival of demands during a given time interval is uniformly distributed. Average number of demands if other data is not given was set to 50, the wavelength number per link to 30. To simulate the metro network size we scaled down the *COST266BT* [50] network to 0.5 and to 0.03125 of its original size. We supposed that demands arrive with Poisson distribution, while their holding time follows exponential distribution. Simulations were run on an Intel Core2 Quad Q6600 processor with 2 GBytes of memory. In the figures with confidence level of 95% the confidence interval was at most 5% of the shown average.

Comparing the four routing scenarios: full or partial / dedicated or shared

Figure 3.12 shows the ratio of demands routed, against the scale of the network for the four methods used. Figure 3.12(a) shows the ratio of those demands only that could be routed with backup paths. Here the strictest approach, the dedicated protection with full routing has the best performance. However, in Figure 3.12(b) where the ratio of demands with at least the primary path routed is shown, the most permissive approach, the shared protection with 'partial' route is the most profitable.

According to these the 'partial' route is the one that maximizes the number of demands routed if we allow not only protected routes but also routes with no protection. To understand this behavior at first we checked the number of routed demands as the function of time (Fig. 3.13). Here we show how the investigated methods performed during one of our simulations. 'Time' denotes the moments when we took samples from the network. As it is shown, difference between routing methods increases when the number of routed demands grows. While the routing methods using 'full' route saturate, the 'partial' routes raise the ratio of partially routed demands and decrease the number of the fully routed ones. The same behavior can be observed when the ratio (number) of demands routed is shown against the number of demands inserted (Figure 3.14). Here we increased the average number of demands inserted, and measured the ratio (number) of demands routed.

This behavior can be explained by the abandon of the protection paths. Since there is no constraint to have backup paths, when network distances are large or the number of demands routed is high the newly arrived demands will be routed without protection. This leads to the slow drop of the number of protection paths. This phenomenon is enhanced by allowing shared protection, in such cases the most of the link power can be used by the primary paths. Thus an operator supposing that the charge for routing a demand without protection is not significantly smaller than with protection it will prefer 'partial' route to maximize the profit.

When Power-Dedicated Outperforms Power-Shared

Another interesting result is the poor show of the shared protection in sense of the ratio of demands routed with protection ('full' route) observed on any of Figures 3.12-3.14. According to Figure 3.14 the performance of shared protection compared to dedicated protection further deteriorates as the number of inserted demands grow, while Figure 3.12 shows the same behavior with decreasing distances (network size). These lead to the recognition that more demands of larger distances can be routed when allowing shared protection. Thus, while resources are saved on a group of edges a greater amount is used to route longer demands. On the hole this mechanism results in higher total resource utilization. According to these simulations in case of *PICR* the good solution is not to use shared protection if protection must be provided.

Routing time

The average routing time for a demand is shown in Fig. 3.15. Routing time is significantly higher in case of methods using shared protection. It increases as the the network size decreases. Both phenomena can be explained by the properties of our search algorithm, introduced in Section 3.3.2. This method executes path searches as long as the demand is either routed or no route exists. Thus, if more potential but infeasible paths exist the search will take longer. All the observed factors (network size, shared protection, etc.) have such effect.

Power requirements

We also evaluated the power requirement to route primary and back up paths. If dedicated protection was used the average power needed to route primary and back-up paths behaved as expected: the power requirement for routing the back-up was higher than that of the primary path. However, this phenomenon changed in case of shared protection: the difference between average power needs for primary and back-up paths was lower. Even for a given demand the power requirement for a back-up path could be smaller than for the primary one. Such case is shown in Figure 3.16. This can happen when the back-up path uses segments of previously established back-up paths while the given path is prohibited to be used as primary path by the power constraints.

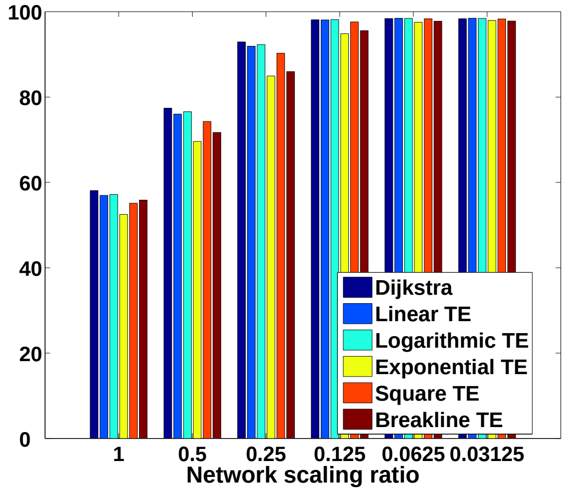
This phenomena enhances the observations described in Section 3.4.3, as it allows even longer demands to be routed.

3.4.4 Impact of PICR onto Resilience

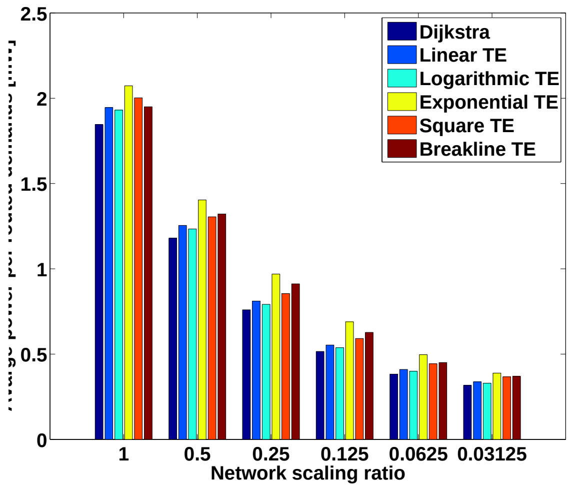
We have investigated different strategies for routing with protection in case of *PICR*. This included the option of shared protection as well as 'partial' (partially protected) routes.

Based on simulations we have shown that when the routing decision is based on physical constraints (case of *PICR*) operators should not use power-shared protection if the system is near to saturation (power budget of some links close to exhausted). If the system is quite large (large distances) or the number of demands is significant (higher gain of sharing) 'partial' route can be a solution for operators to maximize their profit and optimize resource utilization.

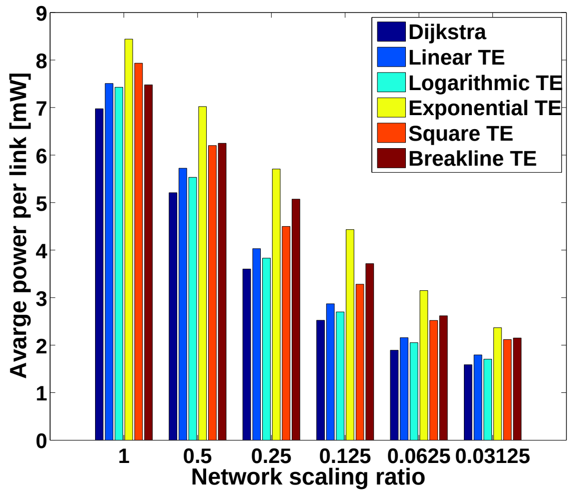
We have shown, that if physical impairments are to be considered while routing, the physical limitations (particularly power) can be handled similarly to bandwidt limitations (capacities). However, when it comes to power-shared protection, it is often outperformed by power-dedicated protection due to significantly increased length of protection paths.



(a) Routed ratio of demands



(b) Average power of a routed demand



(c) Average power load of an edge

Figure 3.10: Simulation results for *Cost266BT* (diameter 5051 km). Link weight models: *Linear*: the cost of a link is equal to its power load, *Logarithmic*: the cost is the natural logarithm of the load, *Exponential*: the cost is e raised to the load, *Square*: the cost is the square of the load, *Breakline*: the cost is the maximum of zero and the load minus maximum power multiplied by 0.8, *Dijkstra*: the cost is the link length.

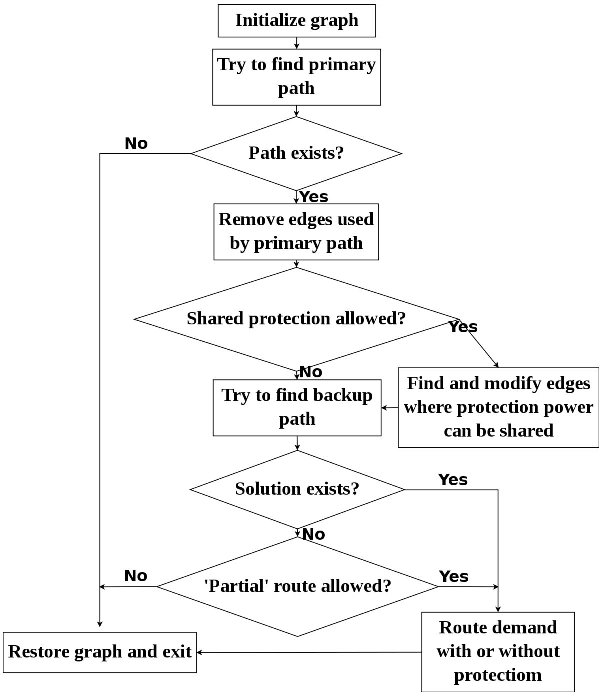
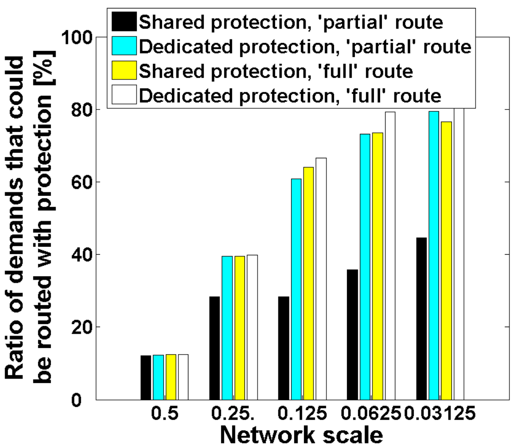
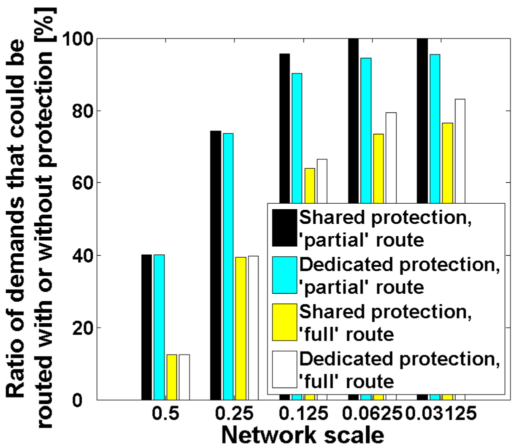


Figure 3.11: Work-flow for Protected PICR (P-PICR).

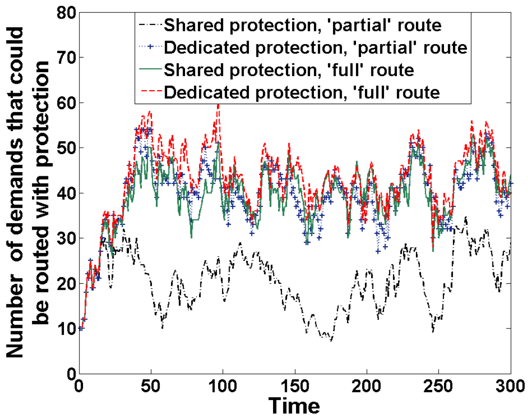


(a) Ratio of demands routed with protection

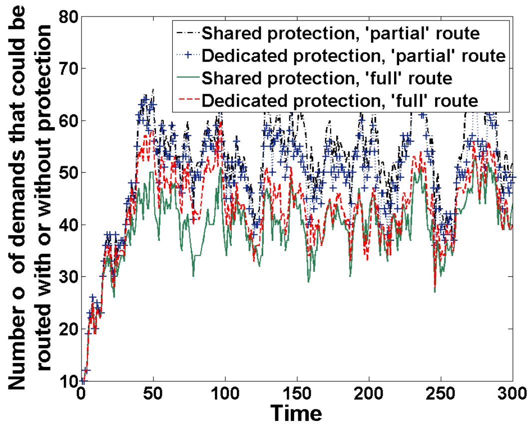


(b) Ratio of demands routed with at least primary path

Figure 3.12: Routing ratio of demands

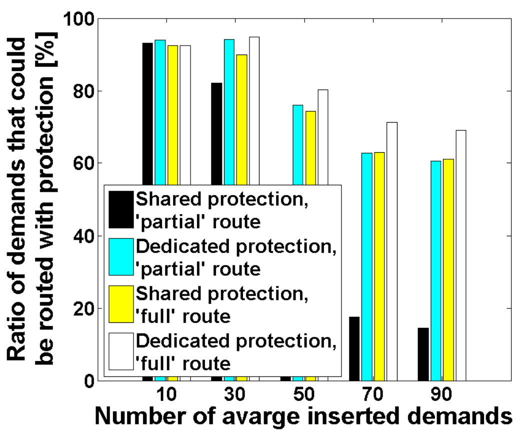


(a) Number of demands routed with protection

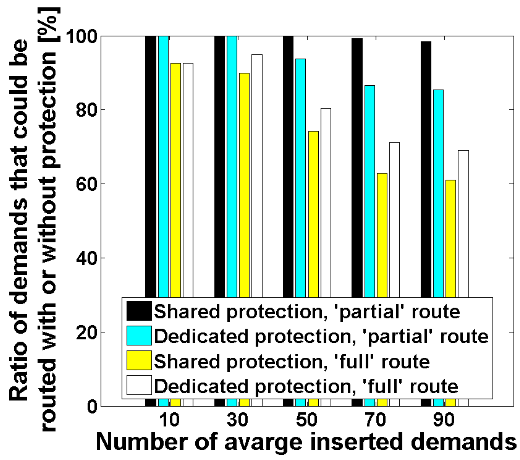


(b) Number of demands routed with at least primary path

Figure 3.13: Number of routed demands as a function of time step



(a) Ratio of demands routed with protection



(b) Ratio of demands routed with at least primary path

Figure 3.14: Ratio of routed demands as a function of inserted demand number

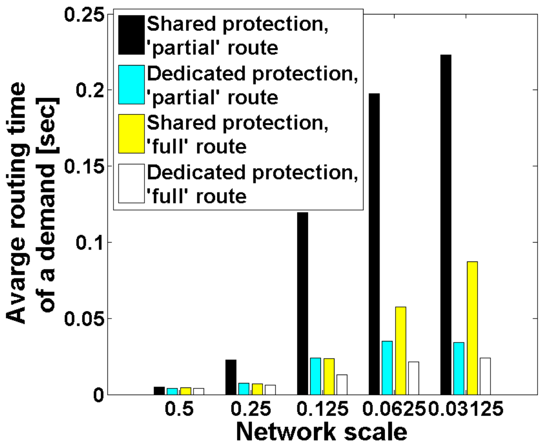
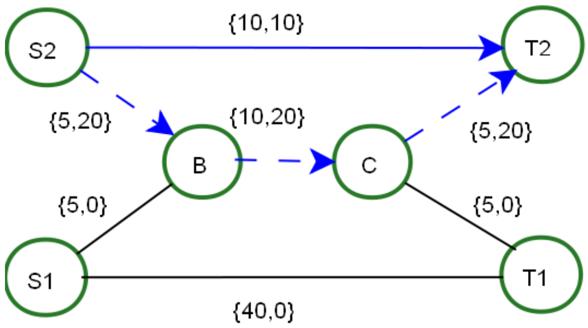
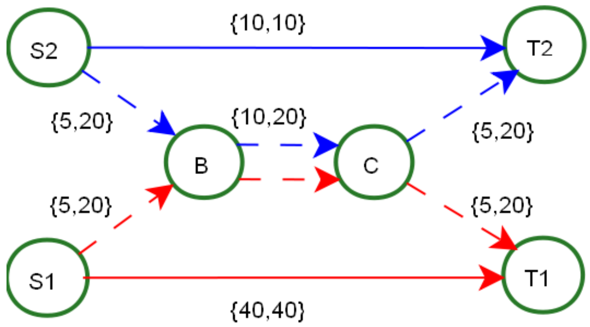


Figure 3.15: Average routing time



(a) A demand from $S2$ to $T2$ is routed. Dashed line represents the back-up path.



(b) Routing demand from $S1$ to $T1$. Primary path could not be routed via $S1 - B - C - T1$ because of the power limit. Therefore the primary one was routed with larger power (40), while power level of 20 was sufficient for the power-shared protection.

Figure 3.16: Routing of two demands between $S2 - T2$ and $S1 - T1$ respectively. The length and reserved power load is shown in curly brackets. We supposed linear dependence between the distance and power with 1 as factor, the maximum link power load is set to 40 units.

Chapter 4

Summary of New Results

4.1 Resilience

I.1. *GSP (Generalised Shared Protection)*: I have proposed a method that finds the optimal working path with its best shared protection for a single demand regardless weather it will be an end-to-end path protection, a segment protection or a link protection.
Section 1.2 — [J6] — [J10] [J7] [J14]

I.2. *Routing with Resilience Reoptimisation* via PDSP-LD (Partially Disjoint Shared Protection with Link Doubling): I have proposed a method that finds the optimal working path with one or more protection paths that can partially overlap with the working one, however, the working path must be protected for every single failure. The novelty of this method is that all the protection paths can be rearranged to better accommodate the new demand with its protection. The protection paths can be reoptimised at any time, and they can be rearranged whenever they do not carry any traffic, e.g., in any failureless case.
Section 1.3 — [H4, C41, C42, C98, C99] — [J14] [J29]

I.3. *Fair Routing and Protection of Elastic Traffic*: I have proposed a method for routing elastic traffic with two protection schemes and the definition of Relative Fairness that allocates bandwidth to demands simultaneously with the routes for these demands. The importance of elastically protecting elastic traffic is that in case of a failure the rate (and therefore the throughput as well) is negligibly decreased, however, the fairness is still maintained.
Section 1.4 — [J9, C35, C37] — [C83] [P2]

I.4. *Sharing Protection in Multi-Domain Resilience* (MDR): I have proposed two different methods MDPC (Multi-Domain P-Cycle) and MPP (Multi-Path Protection) for shared protection where no information is available on routing of working and protection paths of the other, already routed demands. This is the typical case for a multi-domain environment. The idea is the self-sharing (demand-wise sharing) in case of MPP, i.e., the branches of the demand share the protection among these branches, while MDPC is shared for protection among all working paths that use any part of the p-cycle.
Section 1.5 — [J25, C48, C25, C56, C64] — [C89, C90] [J12] [C100] e[J24] [J26] [C88, C49]

4.2 Grooming

II.1. *ILP Formulation of Resilience and Multicast Problems*: I have provided (Section 2.2) ILP formulation for finding global optimum of resilience and multicast problems in grooming-capable two-layer WDM-beared networks modeled as GG (Grooming Graph) (Section 2.1). These problems I solved include:

- Routing with grooming of multiple demands simultaneously.
  [C38] — [J32] [P3]
- Routing with grooming and protection of multiple demands simultaneously. The protection alternatives include on the one hand: link-, node-, SRLG- and SRG-disjoint cases. While on the other hand protection at the upper layer, protection at the lower layer and protection at both the layers at the same time. For brevity only the most complex case is provided in the dissertation: the SRLG/SRG-disjoint protection using both the layers. This formulation can be simply reduced to all the listed cases.
  [B1] [J16]
- Routing multiple multicast demands with grooming that allows branching (1) at the upper layer only; (2) at the lower layer only; or (3) at both the layers in most cost efficient optimal way.
  [C126]

II.2. *Dimensioning Resources for Grooming*: I have proposed methods for dimensioning the resources of a given network under given traffic conditions. The method is based on statistical evaluation of load measures and on feeding these data back iteratively into simulation. The output is the number of required wavelengths per fiber as well as the number of ports between the optical and electronic layer in nodes that allow grooming.
Section 2.3 — [C108, C109, C110] — [C40] [J1] [J4]

II.3. *FG, the Wavelengthpath Fragmenting and Defragmenting Graph Model*: I have proposed a graph model to allow routing the demands with grooming using both the layers simultaneously. The FG (Fragment Graph) allows cutting existing wavelength paths if no free wavelengths exist, or if cutting (fragmenting) has lower total cost than setting up a new wavelength path. The advantage of this method is (1) its high adaptability to traffic and network conditions; (2) the complex operation of routing over two layers is performed with simple shortest path routing algorithms (e.g., Dijsktra's one) using the proposed graph model. If the add and drop functions are not needed anymore in a node, the two wavelength path fragments can be concatenated (defragmemted).
Section 2.4) — [J8] — [C18] [P1] [B6] [J23]

II.4. *Routing with Fragmentation and Grooming*: I have demonstrated applicability of proposed graph models for routing using Dijkstra's shortest path algorithm and FG modifications. I have evaluated the performance of dynamic routing over GG and FG for the overlay and for the integrated model, for the case of dynamic and of static optical layer and evaluated fairness aspects. I have demonstrated that FG performs better than GG in case of significant traffic changes.
Section 2.5 — [J8, C24, C26, C27, C28, C29, C69] — [C23] [J3]

II.5. *State-Dependent TE (Traffic Engineering) with Grooming* (SD-MLTE): I have proposed a state-dependent a'priori TE scheme that leads to lower load of the electronic layer, shorter paths, lower blocking and lower total network resource requirement.
Section 2.6 — [C86, C13] — [J31] [C71] [J11] [J21] [J20] [J19]

II.6. *Shared Protection with Grooming*: I have proposed dedicated and *shared* protection schemes for two-layer networks optimising both the layers as well as the working and protection paths all simultaneously using the FG model and two different schemes for finding disjoint paths. I have proposed not setting up the protection paths, just reserving resources for them that although causes slightly longer protection time, it saves significant number of O/E and E/O converters.
Section 2.7 — [C30, C31, C60, C62, C63] — [J16, C82]

II.7. Multi-Layer *Multi-Cast with Restoration*: I have proposed four methods for routing and restoring the multicast sessions/connections in a two-layer network. The branching of the content can be performed at both optical and electronic layer, and there were the same alternatives considered for both, setting up the tree and restoring the tree. However, the speed of the restoration is more important than the excessive optimality.
Section 2.8 — [C126, C57, C44] — [C77] [H5] [C111] [H6] [J22] [J13] [J5] [J15] [J2] [J18] [J28]

4.3 PICR

III.1. *Routing with Regeneration via Grooming*: I have proposed to use the already deployed traffic grooming capability as a means of implicit O/E/O regeneration of optical signals. I have provided simple methods for joint routing and regeneration via grooming nodes. Even limited grooming capacity can significantly improve the throughput of a network where the signal is affected by physical impairments. Using grooming not only for traffic optimisation, but also for regenerating physical impairments increases the number of groomings negligibly.
Section 3.1 — [C151, J33] — [J30]

III.2. *Routing with Tuning Channel Powers*: I have proposed tuning the power level of wavelength channels within a fiber to different levels to increase the reach of certain signals. I have proposed global optimisation method for routing the demand and setting its input power level simultaneously. I have illustrated the significant gain in throughput of the proposed method.
Section 3.2 — [C112, C51, C150] [H7] [P4] — [C95, J17] [J27] [C50]

III.3. *Power Engineering*: I have proposed a Power Engineering (PE) framework that is analogous to Traffic Engineering (TE), however, instead of traffic loads, the link weights are a function of power loads of links. I have demonstrated that the classical TE approaches, that are based on spreading traffic evenly over the network to increase the network throughput, deteriorate the throughput when used as PE schemes.
Section 3.3 — [C124]

III.4. *Power-Shared Protection*: I have proposed Power-Shared protection schemes for optical networks that analogously to sharing capacity share the power for protection in systems where the power budget of links is the scarce resource. However, in contrast to capacity sharing, in case of power-sharing the power-shared approach is often outperformed by power-dedicated approach, particularly for smaller network scales and for the case of larger number of demands inserted.
Section 3.4 — [C47]

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