Minimizing Installation Costs of Survivable DWDM-Mesh Networks: A Heuristic Approach

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***Abstract*—The cost function for the capacity of optical links follows a step function. That means, the support of one more lightpath might require a costly upgrade of an optical cross connect (OXC), but then additional lightpaths can be supported at almost no further cost. This should be considered when lightpaths are routed through an optical network. In this paper we optimize the routing of the lightpaths to minimize the costs for the required optical equipment. We consider this problem for the failure-free case only and for survivable networks using dedicated path protection. We formulate the problems by integer linear programs (ILPs). In addition, we propose heuristics to solve the problem since solving ILPs is computationally expensive and not feasible for large problem instances. We show that our heuristics lead to good results within a fraction of time compared to ILP solvers.**

I. Introduction

Optical transmission technologies like wavelength division multiplex (WDM) or dense WDM (DWDM) provide abundant bandwidth for the future such that it is often said "bandwidth will be for free". This is not quite true as dark fiber requires costly optical equipment to be operated, i.e. optical cross connects (OXCs), line cards, repeaters, or optical protection switches (OPSs). This technology has the nice property that it is gradually extensible in the sense that network operators can install base initial equipment with low capacity and upgrading it only later to higher capacity when needed. Upgrade modules are costly but increase the capacity of an OXC considerably. Therefore, the equipment costs to support an increasing number of lightpaths follows a step-function. Furthermore, the cost structure of optical equipment allows cheaper transport by larger OXCs. On the one hand, this makes transportation of highly aggregated traffic more cost-efficient which is good, but on the other hand it requires that networks are installed and configured in such a way that they make use of this economy of scale. The routing of the lightpaths has an impact on the network costs. For instance, it is cheaper to carry new lightpaths over longer paths when their OXCs have free capacity than to upgrade the equipment on the shortest paths. Moreover, constraining aspects like the maximum number of wavelengths on a fiber also need to be considered.

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In this work, we optimize the routing of the lightpaths to minimize the installation costs of a (survivable) optical network. It helps operators to plan networks from scratch, recommends where to place which optical equipment and where to route the lightpaths. We explain the cost model we use in detail. We formulate an integer linear program (ILP) including all technical constraints to calculate the routing of lightpaths in such a way that the installation costs of a new network are minimized. Then, we look at survivable DWDM mesh networks that require link-disjoint primary and backup paths for dedicated protection and integrate these additional conditions in the optimization problem making it more complex. Solving ILPs yields exact results, but it is an $\mathcal{NP}$-hard problem. Therefore, this strategy is very time-consuming and limited to small problem instances.

We propose several heuristic optimization algorithms of different complexity to solve the above problem. We compare the quality of their results with those of the powerful ILP solver CPLEX on various problem instances. As the runtime of the ILP solvers is very long, we terminate them after 6 hours while we terminate our heuristics after 2 minutes of computation time, i.e. we compare the results of both approaches for limited computation time. It turns out that our heuristic results are rather good although they use only a fraction of the computation time of CPLEX.

This work is structured as follows. In Section II, we explain the technological background of the optimization used and present related work. In Section III, we introduce the cost model and ILPs to optimize the routing of the lightpaths to minimize the network costs with and without resilience requirements. In Section IV, we develop four heuristics for that purpose. Section V compares the quality of the results obtained from the ILPs and the heuristics. In Section VI, we conclude this paper and give an outlook on future work.

II. Technological Background and Related Work

In this section, we make the reader familiar with the basic concepts of optical networking technology, minimization of installation costs for survivable DWDM mesh networks, and give an overview of related work.

A. Optical Technology

In optical networks, data are transmitted via *fibers* using light pulses. These light pulses are generated and received

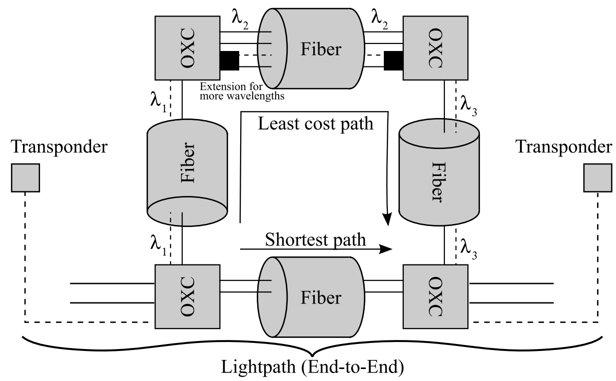


Fig. 1. MODEL OF OPTICAL TRANSMISSION AND OPTICAL COMPONENTS

by *transponders* at both ends of a *lightpath*. Transponders have lasers that are able to send such light pulses at a certain wavelength through a fiber. Data can be transmitted simultaneously on different wavelengths on a single fiber which is called *wavelength division multiplex* (WDM). If the number of different wavelengths is large, we need to consider *dense WDM* (DWDM) which is able to handle more wavelengths on a single fiber than mere WDM. Additionally, the usual time multiplex and code division multiplex techniques from the electrical domain can be applied on each wavelength. Optical networks use *optical cross connects* (OXCs) which receive many incoming light pulses from one fiber and forward them onto other fibers, possibly with wavelength conversion. *DWDM multiplexers* have reduced functionality and just multiplex several signals onto one fiber. Optical signals attenuate over distance and by the processing in switching nodes such that they might have to be refreshed by *repeaters*. Thus, a lightpath often traverses several OXCs, DWDM multiplexers, and repeaters as depicted in Figure 1.

With further optical know-how (e.g., polarization), the data rate per fiber can be even increased. But there also are several restrictions which result from the fact that computers handle electrical signals. Many manipulations to a data flow, like packet switching, can be done only in the electrical domain. Thus, an opto-electrical conversion has to be performed. There are several ways to distinguish optical networks.

On the one hand, optical networks can be declared as *transparent*, *opaque*, or *hybrid*. In this paper, we consider opaque networks, i.e., optical signals are converted to the electrical domain at each OXC and can be arbitrarily manipulated, e.g., via wavelength conversion. This is different to transparent networks where lightpaths are never interrupted by electrical conversion and hybrid networks which are a mixture of opaque and transparent. On the other hand, we have to distinguish the principle of optical *ring* and *mesh* networks. Formerly, optical networks were only used for long haul backbone transport based on SONET/SDH and were realized by a ring topology. Nowadays, optical networks also can be built more flexible and are more meshed. We consider mesh networks. An overview of optical technology and physical principles is given in [1].

Another important aspect in optical networks is *survivability* (or *resilience*), i.e., a network's ability to keep up a certain service level even in the case of failed network components. A detailed explanation and an overview of resilience mechanisms can be found in [2]. In this paper, we consider the hardware requirements for the failure-free case and all single link failures with *end-to-end* (e2e) protection switching. We use *dedicated path protection* which means that each primary path is protected by its own backup path. With 1:1 protection, traffic is redirected from the primary path to the backup path only in case of a failure such that the backup path can be used to carry other low priority traffic under failure-free conditions. With 1+1 protection, signals are simultaneously carried over primary and backup paths such that the failover time is very short in case of a failure. End-to-end protection requires additional components for managing primary and backup paths. We subsume this functionality in *optical protection switches* (OPS) that are installed at both ends of a lightpath to double and merge the signals in case of 1+1 protection. Alternatively, we could monitor the primary path and only send data on the backup path in case of a failure, but this would need additional signalling functionality.

B. Approaching Optimization Problems

The considered optimization problem is combinatorial, i.e. the solution space can be represented as a vector whose elements are positive integrals and we can find the optimal solution by combining the right integers. Usually, such problems are modeled as *integer linear programs* (ILP) which are a special case of *linear programs* with a purely integral domain. A decent introduction to ILPs can be found in [3]. In such ILPs, an objective function is to be optimized and a set of constraints is given to whom the optimization is subject to. While real number solutions of ILPs can be efficiently found, e.g. using the Simplex algorithm [4], integral solutions are hard to find because such problems are $\mathcal{NP}$-hard [5]. ILP solvers like CPLEX [6] make use of sophisticated approaches to solve ILPs efficiently by shrinking the valid domain and number of constraints of a problem. Such approaches are described in [7]. Albeit, these approaches improve the performance of the ILP solution, they still suffer from the complexity and cannot efficiently handle large problem instances, i.e. networks with a large number of nodes in our case.

To overcome this scalability issue, we use *heuristics*. A heuristic is an approximative approach and does not explore the complete solution space. Hence, it is able to get a (feasible) solution even for large problems within acceptable time, but cannot guarantee to find the optimum. In literature, the most common heuristics are randomized, i.e., their solution depends on a random seed and runs can be repeated to possibly improve already obtained solutions. Examples of such randomized approaches are simulated annealing (e.g., [8]) and genetic algorithms (e.g., [9]). In contrast, the heuristics developed in this papers are deterministic.

C. Related Work

Protection in multi-layer networks was considered in [10]. [11] gives an overview of different wavelength routing algorithms, and disjoint path protection in optical mesh networks was considered in [12]. However, the objective of these algorithms is to optimize the routing of the lightpaths in a network in such a way that the number of required wavelengths is minimized.

Currently, there are only a few papers that consider installation costs of survivable DWDM mesh networks. In [13], the effect of protection mechanisms on transparent optical networks is investigated. The authors of [14] derived their cost model from an extensive study of normalized costs for optical components [15] within an European context. This cost model was also used in [8] whose authors investigated the installation costs with dedicated path protection by using simulated annealing. We used this cost model as a basis for our own cost model, too.

In this paper, we develop efficient heuristics that are much faster than an exact ILP solver. In contrast to a fast approach, e.g., based on simulated annealing [8], the presented heuristics are not randomized, but deterministic. To the best of our knowledge, this is the first paper that tackles the problem of installation costs in survivable DWDM mesh networks with enhanced deterministic heuristics.

III. Modelling and Problem Formulation

First, we present our simplified cost model for an optical network explaining what components are required including their capacity. Then, we set up *integer linear programs* (ILP) to optimize the routing of lightpaths to minimize the installation costs of a network which is the sum of the costs for the required components. We consider networks with and without dedicated path protection.

A. Cost Model

We review a simplified cost model used in [14] which is based on [15]. We have assumed that the topology of the network is given, i.e. the network operator owns dark fiber. To make a fiber usable, an OXC base unit is required at both ends. Furthermore, the OXC base unit must be equipped with one or more OXC upgrade units which can support N^λ wavelengths each. In our study, we use $N^\lambda = 10$. A simple fiber can accommodate at most W wavelengths. In our study, we mainly use $W = 40$. To set up a lightpath, a transponder at the source and at the destination is needed, and if the lightpath extends over several hops, all nodes in between require sufficiently many OXC base and upgrade units for the used fiber links. We assume that all nodes can either convert wavelengths or that W is large enough such that suitable wavelength assignment is possible. To facilitate 1+1 protection, a demand requires two link-disjoint lightpaths, each equipped with separate transponders at their sources and destinations, and it requires an optical protection switch (OPS) at both sides of each such pair. Normalized cost of these devices are compiled in Table I.

TABLE I
NORMALIZED COSTS OF THE CONSIDERED COMPONENTS

Component	Costs (normalized)	ILP identifier
fiber	0	c^{fib}
10G transponder	50	c^{tp}
OXC base unit	480	$c^{\text{oxc}}_{\text{base}}$
OXC upgrade unit	105	$c^{\text{oxc}}_{\text{upgrade}}$
OPS	42	c^{ops}

B. Mathematical Problem Formulation

We describe the problem of minimizing the network costs by optimizing the routing of the lightpaths by an integer linear program (ILP) which is based on the ILPs used in [14]. Our ILP calculates optimal paths while the ILP in [14] reduces its solution space to the k shortest paths for each demand. We first explain the notation used in this paper. We then present the ILP for the case without protection and then for the case with dedicated path protection.

1) Notation: We represent the structure of the network by a directed graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ with $\mathcal{V}$ being the set of nodes and $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ being the set of links. We assume *unit demands* between all nodes, i.e. all demands have the same size. To speed up the computations, we only consider bi-directional demands which was also done in [14]. Consequently, there are $\sum_{i=1}^{|\mathcal{V}|}(i-1) = |\mathcal{V}| \cdot (|\mathcal{V}|-1)/2$ demands in a network[1] instead of $|\mathcal{V}| \cdot (|\mathcal{V}|-1)$. We assume that a single lightpath (10G) satisfies the bit rate requirements of each demand such that each demand requires only a single lightpath from source to destination, i.e., our study is bit rate agnostic.

We need the following notation for the ILPs.

- $i, j, s, t \in \mathcal{V}$: specific nodes
- $(i, j) \in \mathcal{E}$: a specific link
- d_{st}: binary value; it is 1 if there is a demand from node s to node t, otherwise it is 0.
- u_{ij}: binary variable; it is 1 if link (i, j) is used by any lightpath, otherwise it is 0.
- F_{ij}^{st}: binary variable; it is 1 if a lightpath from s to t is routed over link (i, j), otherwise it is 0.
- n_{ij}^{λ}: variable indicating the number of wavelengths used on link (i, j)
- n_{ij}^{oxc}: variable indicating the number of OXC upgrade units on link (i, j)

The names and the values for component costs are listed in Table I.

2) Unprotected Case: Without protection, the network consists of the transponders required to activate the lightpaths and the OXC base and upgrade units that are necessary to support

[1] $|\mathcal{X}|$ denotes the cardinality of set $\mathcal{X}$.

the links. We calculate the costs for the unprotected case by

$$C_0 = 2 \cdot c^{\text{tp}} \cdot \sum_{d_{st} \in \mathcal{D}} d_{st} + 2 \cdot \sum_{(i,j)\in\mathcal{E}: i<j} \left(\left(c^{\text{fib}} + c^{\text{oxc}}_{\text{base}} \right) \cdot u_{ij} + c^{\text{oxc}}_{\text{upgrade}} \cdot n^{\text{oxc}}_{ij} \right). \quad (1)$$

This cost function needs to be minimized while meeting the constrains (2) – (4c) that are explained in the following.

a) Flow Conservation: We consider a particular node i and look at the difference of inflowing and outflowing traffic induced by a specific demand from s to t. If i is the source of the demand, the outflow is d_{st}, if i is the destination of the demand, the inflow is $-d_{st}$; otherwise the difference between in- and outflowing traffic at node i is zero. This holds for any node i and demand between any nodes s and t. This is captured by the following equation.

$$\forall i,s,t \in \mathcal{V}: \sum_{(i,j)\in\mathcal{E}} F^{st}_{ij} - \sum_{(j,i)\in\mathcal{E}} F^{st}_{ji} = \begin{cases} d_{st}, & i = s \\ -d_{st}, & i = t \\ 0 & \text{otherwise.} \end{cases} \quad (2)$$

b) Minimum Number of Lightpaths per Link: The number of lightpaths n^{λ}_{ij} on a unidirectional link (i,j) is at least the sum of all demands carried over link (i,j):

$$\forall (i,j) \in \mathcal{E}: \sum_{(s,t)\in\mathcal{V}\times\mathcal{V}} F^{st}_{ij} \le n^{\lambda}_{ij} \quad (3)$$

c) Maximum Number of Lightpaths per Link: The number of lightpaths carried over a bidirectional link $n^{\lambda}_{ij} + n^{\lambda}_{ji}$ is limited by the number of OXC upgrade units n^{oxc}_{ij} and by the maximum number W of wavelengths on a fiber. It also requires that the link is upgraded by an OXC base unit, i.e. $u_{ij} = 1$. This holds for both directions of the link.

$$\forall (i,j) \in \mathcal{E}: \quad n^{\lambda}_{ij} + n^{\lambda}_{ji} \le W \cdot u_{ij} \quad (4a)$$

$$\forall (i,j) \in \mathcal{E}: \quad n^{\lambda}_{ij} + n^{\lambda}_{ji} \le n^{\text{oxc}}_{ij} \cdot N^{\lambda} \quad (4b)$$

$$\forall (i,j) \in \mathcal{E}: \quad u_{ij} = u_{ji} \quad (4c)$$

3) Dedicated Path Protection: Dedicated path protection sets up a primary and a backup lightpath for a demand from s to t and these links must not share any common links. Therefore, two transponders for each protection path are required and another two optical protection switches per lightpath to facilitate the failover function. The costs for the additional protection hardware have to be added to the costs of the unprotected case. Hence, the network costs are

$$C_1 = C_0 + 2 \cdot \left(c^{\text{tp}} + c^{\text{ops}} \right) \cdot \sum_{d_{st}\in\mathcal{D}} d_{st}. \quad (5)$$

This cost function needs to be minimized while meeting the Constraints (6), (2), (7), (8), and Inequalities (4a) – (4c). The missing constraints are explained in the following.

a) Primary and Backup Paths: Like above, we use the binary variable F^{st}_{ij} to indicate whether the primary path for a demand from s to t uses link (i,j). We introduce another binary variable G^{st}_{ij} to indicate whether the backup path for a demand from s to t uses link (i,j). Each link can be used at most once by the primary and backup path for a demand from s to t, otherwise primary and backup paths are not link-disjoint. This can be expressed by

$$\forall s,t \in \mathcal{V}, (i,j) \in \mathcal{E}: F^{st}_{ij} + F^{st}_{ji} + G^{st}_{ij} + G^{st}_{ji} \le 1. \quad (6)$$

We consider both directions of a link to avoid that primary and backup path use the same link in opposite direction.

b) Flow Conservation for Backup Paths: Flow conservation also holds for backup paths. In analogy to Equation (2), the following equation must be respected.

$$\forall i,s,t \in \mathcal{V}: \sum_{(i,j)\in\mathcal{E}} G^{st}_{ij} - \sum_{(j,i)\in\mathcal{E}} G^{st}_{ji} = \begin{cases} d_{st}, & i = s \\ -d_{st}, & i = t \\ 0 & \text{otherwise.} \end{cases} \quad (7)$$

c) Minimum Number of Lightpaths per Link: The minimum number of lightpaths n^{λ}_{ij} carried over link (i,j) now consists of the number of primary and backup paths. In analogy to Equation (3), we get

$$\forall (i,j) \in \mathcal{E}: \sum_{(s,t)\in\mathcal{V}\times\mathcal{V}} F^{st}_{ij} + G^{st}_{ij} \le n^{\lambda}_{ij}. \quad (8)$$

IV. Heuristics

In this section, we introduce four heuristics that optimize the routing of the lightpaths to minimize the installation costs of optical networks. We start with a very simple and intuitive heuristic and iteratively refine it towards a sophisticated heuristic using a look-ahead mechanism in combination with a k-shortest path algorithm. We first consider the unprotected case and then explain how to add resilience constraints to the basic algorithms to route link-disjoint primary and backup paths when resilience is required.

A. Min-Hop Heuristic

The *Min-Hop* heuristic is based on Dijkstra's shortest path algorithm [16]. We use the hop-count metric to realize shortest path routing, i.e., the weights of all links are 1 such that the shortest path is the one with the least number of hops. All lightpaths are routed in the order of their generation by the program. When all demands are routed, the required equipment is installed. The Min-Hop heuristic is very simple and does not respect the installation costs of the DWDM mesh network. It just serves as a simple reference.

B. Greedy Heuristic

With the *Greedy* heuristic, the lightpaths are also routed in the order of their generation. In contrast to the Min-Hop heuristic, the Greedy heuristic respects equipment costs. The routing of a lightpath consists of two steps. In the first step, we calculate a link cost function $c(i,j)$ for each link

Input: Graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, set of unplanned demands $\mathcal{D}$

```
while D ≠ ∅ do
  c^best ← +∞
  for all d ∈ D do    {look-ahead steps}
    perform Greedy heuristic starting with d on shortest path p
    c ← network costs
    if c < c^best then
      c^best ← c, d^best ← d, p^best ← p
    end if
  end for
  D ← D \ {d^best}
  fix p^best for lightpath of demand d^best
end while
```

Output: Routes for all lightpaths

Algorithm 1: GLA HEURISTIC

$(i, j) \in \mathcal{E}$ reflecting its required upgrade cost to support another lightpath. In the second step of the heuristic, the path of the new lightpath is determined by Dijkstra's shortest path algorithm based on this link cost function. These two steps are repeated for all remaining demands. If there are several least-cost paths w.r.t. this metric, the path which was the first in the path generation process is chosen.

1) Link Cost Function: The link cost function is based on the cost model defined in Section III-A.

$$c(i,j) = \begin{cases} 2 \cdot (c^{\text{oxc}}_{\text{base}} + c^{\text{oxc}}_{\text{upgrade}}), & \text{if } n^{\lambda}_{ij} = 0 \\ 2 \cdot c^{\text{oxc}}_{\text{upgrade}}, & \text{if } n^{\lambda}_{ij} \neq 0 \wedge \\ & n^{\lambda}_{ij} = 0 \pmod{N^{\lambda}} \\ 1 & \text{otherwise.} \end{cases} \tag{9}$$

If a link $(i, j) \in \mathcal{E}$ was not used for routing so far, i.e., $n^{\lambda}_{ij} = 0$, an OXC base unit and the first unit for managing N^{λ} wavelengths must be installed on both sides of a link. Therefore, the link cost function returns the sum of their costs $c^{\text{oxc}}_{\text{base}} + c^{\text{oxc}}_{\text{upgrade}}$. If another lightpath increases the number of lightpaths n^{λ}_{ij} on the link (i, j) in such a way that another OXC upgrade unit is required for managing further N^{λ} wavelengths, the link cost function yields the cost $c^{\text{oxc}}_{\text{upgrade}}$ of this OXC upgrade unit. Otherwise, no further node components have to be installed to support a further lightpath over the considered link. Nevertheless, we set the link cost function to 1 to minimize the resources used by the new lightpath when its path is determined by the shortest path algorithm using this link cost function.

2) Improvement of the Cost Function: We found that the Greedy heuristic tends to exceed the maximum number of wavelengths W on "popular" links. As this prevents the routing of some demands, we introduced a penalty term $p(i, j)$ which is added to the normal link cost function $c(i, j)$. Such a penalty term must respect the ratio of the number of lightpaths (n^{λ}_{ij}) currently routed over the link (i, j) and the maximum number of wavelengths W on a fiber. We found that

Input: Graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, set of unplanned demands $\mathcal{D}$, maximum number of shortest paths k

```
while D ≠ ∅ do
  c^best ← +∞
  for all d ∈ D do    {look-ahead steps}
    create set of up to k-shortest paths P for demand d
    for all p ∈ P do
      perform Greedy heuristic starting with d on path p
      c ← network costs
      if c < c^best then
        c^best ← c, d^best ← d, p^best ← p
      end if
    end for
  end for
  D ← D \ {d^best}
  fix p^best for lightpath of demand d^best
end while
```

Output: Routes for all lightpaths

Algorithm 2: k-SHORTEST PATH GLA HEURISTIC

$p(i, j) = \lceil 20 \cdot |\mathcal{V}| \cdot n^{\lambda}_{ij} / W \rceil$ effectively solves the problem. It also improves the results of the Greedy heuristic.

C. Greedy Look-Ahead Heuristic

The *Greedy Look-Ahead* (GLA) heuristic is an extension of the Greedy heuristic. While the normal Greedy heuristic routes the demands in the order of their generation, the GLA heuristic changes this order to improve the routing of the lightpaths and to minimize the required network costs.

The GLA heuristic looks one step ahead into the planning process before fixing the route of a lightpath. To that end, GLA considers every demand $d \in \mathcal{D}$ for which the route of its lightpath is not yet determined. It applies the normal Greedy heuristic to route all unplanned demands starting with the considered demand d. Then, the network costs are calculated and the demand d leading to the least network costs is the next for which the route of its lightpath is fixed according to the normal Greedy heuristic. A formal description of the GLA heuristic is given in Algorithm 1.

D. k-Shortest Path GLA Heuristic

The GLA heuristic considers only one shortest path w.r.t. the link cost function for each demand. We extend the GLA heuristic by offering the k shortest paths w.r.t. the link cost function when a demand d is tested as a next candidate in a look-ahead step and call this the k-shortest path GLA heuristic. We use Yen's algorithm to find k-shortest paths, which was presented among other algorithms for this task in [17]. A formal description of the k-shortest path GLA heuristic is given in Algorithm 2. The GLA heuristic is the special case $k = 1$ of the k-shortest path GLA heuristic. The k-shortest path GLA heuristic explores more paths and can yield better results. However, it also performs more look-ahead steps leading to longer computation time.

E. Heuristic Algorithms for Survivable Networks

Resilience requires a primary and a backup path for each demand. Therefore, the heuristics calculate two lightpaths for each demand that need to be link-disjoint. We realize that by first determining the primary path for a demand and removing its links from the network for choosing the path of its backup path. This concept is rather simple and can be improved by k-*disjoint* shortest paths algorithms [18].

V. Numerical Results

We first illustrate the networks used for the comparison. We then compare the installation costs obtained for the routing of the lightpaths which was optimized by CPLEX as well as by our four heuristics, and explain special cases. We discuss how the maximum number of considered shortest paths k should be set to efficiently use the k-shortest path GLA heuristic and the impact of the maximum number of wavelengths W per fiber. Finally, we discuss the relative cost structure of optimized networks with and without resilience requirements.

A. Network Topologies

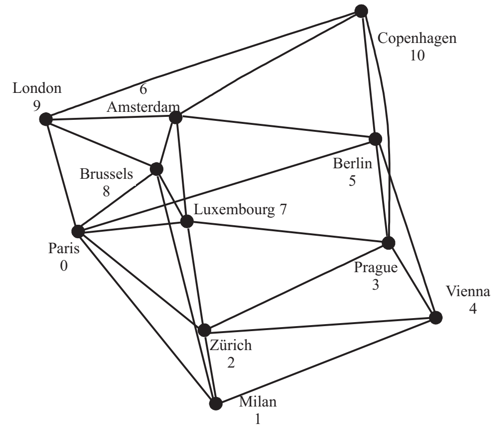
We consider four network topologies that are often used in academic studies: COST239, GÉANT, Labnet03, and Nobel. They are depicted in Figure 2 indicating their size in terms of links and nodes.

B. Comparison of Network Costs Gained by the ILP Solver and Heuristics

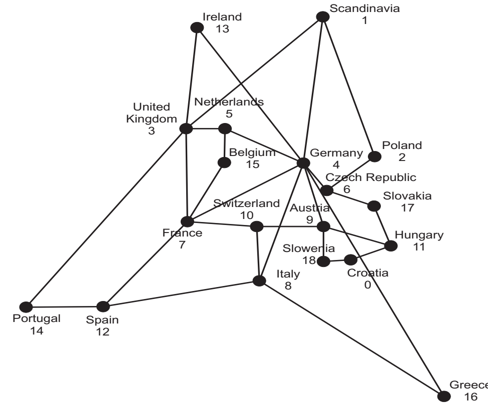
For each of the above networks, we compare the minimal network costs gained by the heuristics with those gained by CPLEX, which is a powerful ILP solver. To that end, we allow 2 minutes of computation time for the heuristics and 6 hours of computation time for CPLEX before stopping the calculations. Table II shows the network costs for optimized lightpath routing with and without protection.

In general, CPLEX gradually approaches the best solution. It keeps track of an upper bound for which it has already found a solution, i.e. a lightpath routing, and estimates the gap towards the lower bound. When upper and lower bound have converged CPLEX has finalized the optimization. That means, CPLEX may have found already the optimal solution, but requires still a lot of time to prove that it is really the best one. The table shows the upper bound calculated by CPLEX and the gap towards the lower bound in percent. None of the CPLEX runs was able to prove the optimality of the best solution found within 6 hours, which is noted by a positive gap. Nevertheless, we can assume that these solutions are near the optimum for all networks since our experience shows that the ILP solvers quickly find very good solutions and need a lot of time to decrease the gap.

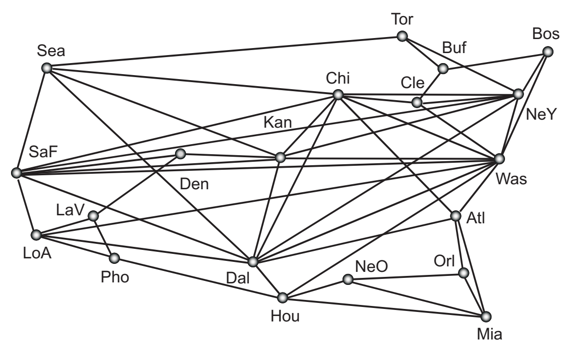
The table shows that the lightpath routing optimized by the heuristics leads to network costs that are only a few percent more expensive than the one optimized with CPLEX. More



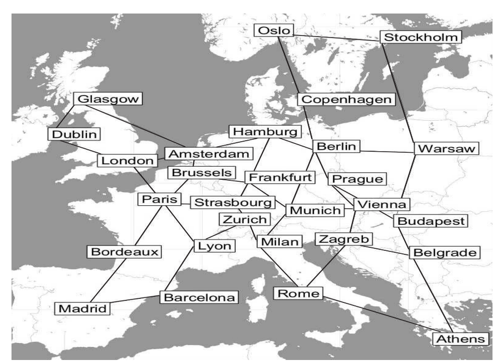
(a) COST239: 11 nodes and 26 bi-directional links [19].



(b) GÉANT: 19 nodes and 30 bi-directional links [20].



(c) Labnet03: 20 nodes and 53 bi-directional links [21].



(d) Nobel: 25 nodes and 41 bi-directional links [22].

Fig. 2. The considered network instances

TABLE II
NETWORK COSTS FOR OPTIMIZED LIGHTPATH ROUTING WITH AND WITHOUT PROTECTION.

	Parameter		Heuristics				ILP Solver	
	Network	W	Min-Hop	Greedy	GLA	k-shortest GLA	Upper bound	Gap (%)
No protection (C_0)	COST239	40	35920	18040	17830	17620	17620	4.81
	GÉANT	40	57450	52740	49440	48270	47010	3.16
	Labnet03	40	84370	58660	54940	51550	52930	22.15
	Nobel	160	109710	108900	104760	104760	100740	9.69
Dedicated Path Protection (C_1)	COST239	40	46880	39290	38120	36290	35360	1.37
	GÉANT	80	102354	104754	102354	102624	99264	0.10
	Labnet03	40	129620	–	120800	122600	114050	7.70
	Nobel	160	222102	–	221892	221892	218832	0.59

complex heuristics mostly generate better results than simple heuristics. In particular, both GLA heuristics lead to very good results within a fraction of time (2 min vs. 6 hrs) compared to CPLEX. Therefore, they are a powerful and handy means for network planners of survivable DWDM mesh networks.

C. Special Cases

For Labnet03 without protection, CPLEX leads to a more expensive network design after 6 hours (52930) than the k-shortest GLA heuristic after 2 minutes (51550). Even after 12 hours, the CPLEX's best solution costs 52930 with a gap of 22.15%.

For Labnet03 and GÉANT with protection, the normal GLA leads to a cheaper network design than the actually enhanced k-shortest path GLA variant. The k-shortest path GLA spends a lot of time in the look-ahead steps for only a few demands. As it is stopped after 2 minutes, it cannot show its superiority. If it is given four minutes computation time, it leads to network designs with a cost of only 119960 for Labnet03. By reducing the parameter k, the k-shortest path GLA is able to find a cost value of 102354 within two minutes for the GÉANT network. Thus, the enhanced GLA does lead to better results than the simple GLA when the computation time is long enough or if the parameter k is small enough. Hence, k is an important tuning knob: larger k leads to better solutions but only after longer computation time.

D. Configuration of the Maximum Number k of Shortest Paths for the k-Shortest Path GLA Heuristic

The k-shortest path GLA heuristic requires a suitable k that limits the maximum number of shortest paths in the optimization. It has a significant impact on the run time of this heuristic. As we are interested in heuristics that are fast and good, we make a trade-off. Without protection, $k = \lceil 500/4^{(|\mathcal{V}|/10-1)} \rceil$ yields good results for the tested networks. With dedicated path protection, we choose half the value of k as we have to route twice as many lightpaths.

E. Impact of the Maximum Number of Wavelengths per Fiber

The maximum number of wavelengths per link W significantly impacts the solvability of the problem and the quality of the results. It is a very sensitive parameter w.r.t. possible improvements of the heuristics. To face the challenge, we doubled the parameter W only if CPLEX could not find a solution within 6 hours. This parameter W is also listed in Table II. With protection, twice as many lightpaths are needed as without protection, therefore, protection requires a larger W for GÉANT than without protection.

While the simple Greedy heuristic is not able to find a solution for Labnet03 and Nobel, the GLA variants find solutions as they reorder the demands. This again shows the superiority of both GLA variants over the normal Greedy heuristic.

F. Comparison of Relative Installation Costs for Survivable and Non-Survivable Networks

Figure 3 shows the relative installation costs for all four test networks. The reported costs are based on lightpath routing with and without protection optimized with CPLEX. For each network the costs are normalized by the costs without protection. The compilation shows that most of the costs are due to equipment for optical cross connects (OXCs), followed by transponders (TPs), while optical protection switches (OPSs) only cause a minor portion of the overall installation costs. The installation costs with protection are about twice the ones without protection. This is surprisingly little. Protection requires more than twice the transmission capacity compared to no protection because backup paths are often longer than primary paths, and OPSs are also required. However, the OXC and TP costs for the installed primary and backup capacity are less than double compared to the mere primary capacity. The

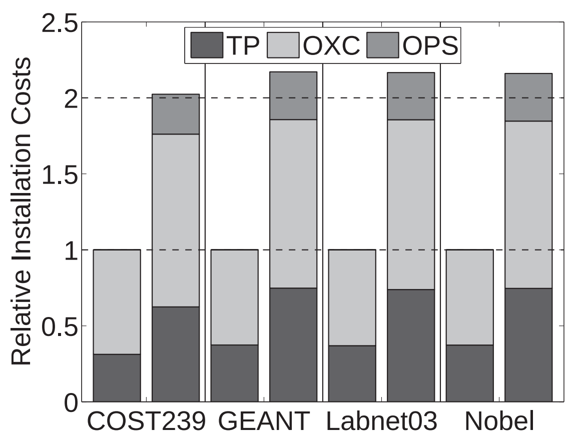


Fig. 3. INSTALLATION COSTS SPLIT BY THE CONSIDERED COMPONENTS IN THE NETWORK INSTANCES

reason for that is that optical base units are costly and required only once per link. As a consequence, the costs of a link do not scale linearly with its capacity when more OXC upgrade units are installed. Therefore, the costs for networks with protection can be even less than twice the costs for the same networks without protection.

VI. Conclusion

In this paper, we optimized lightpath routing to obtain cost-minimal DWDM networks with and without protection. We explained our technological assumptions and the cost model. We formulated the technical constraints by setting up an integer linear program (ILP) to minimize the equipment costs for a new network with a given topology and demand matrix by optimizing the routing of the lightpaths. The solution of ILPs guarantees optimal results, but it is time-consuming and applicable only to small problem instances.

We proposed four heuristics with increasing complexity: shortest-paths routing (Min-Hop), a simple greedy heuristic, a simple greedy heuristic with look-ahead (GLA), and a complex GLA. More complex heuristics lead to more cost-efficient networks. To assess the performance of our algorithms, we compared them with solutions found by the powerful ILP solver CPLEX. Within a limited computation time of two minutes, the heuristics produced good results that were close to those that CPLEX achieved within 6 hours. This gives justification for the use of good heuristic optimization methods on large problem instances where ILP solvers do not produce reasonable results within acceptable time.

Comparing the costs for non-survivable and survivable DWDM mesh networks using dedicated path protection, we observed that survivable networks are only about twice as expensive as non-survivable networks which is surprisingly cheap.

This paper is only an initial step towards the design of cost-minimal survivable optical networks. In future work, we intend to consider grooming to benefit from cheaper transmission at higher bit rates and we want to study more detailed cost models. We would like to take into account routing and protection or restoration mechanisms on higher layers such as IP, MPLS, or Carrier Ethernet and design cost optimal solutions for survivable optical multi-layer networks.

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