# Design Strategies for Meeting Unavailability Targets Using Dedicated Protection in DWDM Networks

Giray Birkan, Jeff Kennington, Eli Olinick, Augustyn Ortynski, and Gheorghe Spiride

***Abstract*—Service providers operating DWDM networks are often faced with the problem of designing their networks such that a certain level of service availability can be delivered to their customers. This investigation introduces optimization-based algorithms that address this problem efficiently and effectively. For a given network topology specified by existing dark fiber links, our algorithms determine a cost effective solution consisting of the size and location of equipment needed to satisfy the desired amount of point-to-point traffic demands. In addition, the solution approach discussed in this investigation delivers estimates for the service unavailability probability of each traffic demand pair, and enables the service provider to programmatically determine which and how many supplemental node-disjoint protection paths are required in order to attain a pre-specified demand pair unavailability target. To the best of our knowledge, these algorithms provide the user with the most detailed design created by any optimization-based design tool to date. The efficiency and effectiveness of the proposed network design algorithms is studied using an empirical analysis.**

***Index Terms*— Integer Programming Applications; Network Provisioning; DWDM Network Design; Polarization Mode Dispersion; Dedicated Protection; Unavailability**

## I. INTRODUCTION

CONTINOUS advances in optical switching and transmission technologies promise significant cost savings in network provisioning, while effectively addressing the technological restrictions of long-haul DWDM networks. Signal-to-noise ratio restrictions call for costly equipment that can recover the original electrical signal from an optical signal, and convert it again into the optical domain. Long-reach optical amplifiers extend the reach and increase the range over which optical-electrical-optical (O/E/O) conversions need to be performed. An all-optical network keeps the signal in the optical domain until one of the technological restrictions mandate an O/E/O conversion. This design principle makes all-optical design more cost efficient than the traditional opaque network design, where a conversion takes place at every terminal node. The benefits of reduced costs through elimination of O/E/O conversion come at a cost of increased complexity in handling traffic demand changes in the network. A change in the traffic demand pairs may result in either redundant equipment in the network or the need for additional equipment to be deployed, with potential changes to the overall network engineering, though such changes are unlikely to occur too frequently. In contrast, an opaque network design can tolerate traffic demand churn more cost effectively, since changes are isolated to point-to-point links between terminal nodes. In recognition of these facts, we address both opaque and all-optical network design strategies.

Service providers and network operators continuously monitor the availability of their networks, since reliability is a key marketing and product differentiation topic and an important service level agreement metric. Failures may render one or more demand pairs out of service for several hours or halt transmission on one or more fibers. There are many approaches used for providing additional network capacity to mitigate the effects of failures upon network availability. A detailed overview and discussion of their benefits and approaches goes beyond the scope of this presentation. This investigation focuses on using dedicated protection (1+1) as an effective means to protect DWDM networks against such disruptions.

This investigation proposes a family of optimization-based algorithms that determine cost-effective equipment provisioning for opaque and all-optical networks that use dedicated protection, while taking into account detailed technological restrictions. Given equipment reliability information, an algorithm determines the routing and unavailability for each *(o,d)* demand pair and attempts to bind estimated *(o,d)* demand pair unavailability to a target value by increasing the number of protection paths. Several test cases used in an empirical analysis verify the practical application of the design algorithms. For a given set of *(o,d)* demand pairs with their corresponding traffic, a design tool based on the algorithms for opaque networks with dedicated protection requires less than two minutes of CPU time for large practical

Manuscript received October 9, 2001. (Write the date on which you submitted your paper for review.) This investigation was partially supported by a grant from the Office of Naval Research under Award Number N00014-03-1-0053.

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test problems on a DEC Alpha 21164 machine. Similar problems employing the all-optical design strategy require at most an hour for the largest test case. In cases where the underlying network topology was sufficiently dense to provide enough node-disjoint paths, the design tool was successful in meeting the target unavailability of five minutes/year by adding node-disjoint protection paths. Otherwise, the design tool opted for leasing links to meet the target unavailability.

### A. *Survey of Literature*

This investigation addresses protection and unavailability in opaque and all-optical networks using the same basic design principles introduced in [1]. A method to assess the impact of failures and the time required for restoration on high speed DWDM networks employing optical shared protection rings may be found in [2]. A comparison of availability performance for various protection schemes based on dedicated and shared protection methods appears in [3]. This work, closely related to the investigation in [4], uses Monte-Carlo simulation to verify the accuracy of their unavailability calculations. They also present an excellent discussion on availability and reliability theory. Various schemes for provisioning ring-based networks based on cost and unavailability are compared in [5]. The availability of two ring protocols for transoceanic networks is discussed in [6]. Integer programming models introduced in [7] consider the DWDM routing and provisioning problem under demand uncertainty. The follow-up study discussed in [8] adds models for various protection schemes including p-cycle protection. Widely accepted assumptions for determining unavailability of systems with numerous elements are outlined in [9], which finds that the critical factor for unavailability reduction is network connectivity. Their study concludes that span restorable mesh networks are superior to ring architectures in case of dual failure situations in networks carrying priority services. Our investigation adopts the assumptions listed in [9].

Opaque and all-optical network architectures are compared in [10], along with a discussion of challenges awaiting all-optical networks and optical switching. [11] discusses optical switching, where the signal remains in the optical domain from input to output. The study [12] describes capabilities and possible implementation problems for the Differentiated Optical Services model for metropolitan DWDM networks. The advantages of DWDM as a short- and long-haul multi-service platform for a pan-European network are analyzed in[13]. The multi-path routing and local failure reaction methods introduced in [14] are meant to improve network availability and to provide uninterrupted QoS to bandwidth demanding real-time applications. The Sprint network architecture analysis in [15] aims to improve network reliability. Several redundancy options for the SuperPON access network design are compared in [16] with traditional access network designs.

Dynamic traffic restoration in DWDM networks is addressed in [17]: reserved protection paths for every connection are necessary due to the rarity of faults in DWDM networks. The algorithms presented for dynamically assigning suitable protection paths to failed working paths assume that wavelength translators are used at intermediate nodes along a path. Integer linear programs presented in [18] compare using wavelength translators at every switch or only at certain switches with the case where no wavelength translation is permitted. A profit maximization model described in [19] computes node-disjoint working and protection paths in all-optical and opaque DWDM networks based on a profit maximization model for optimal routing of user selected sessions when single link failures affect multicast sessions. A starting point for our study is given in [20]: a heuristic method to improve network reliability by adding additional capacity. If possible, redundant links are added to increase bandwidth for node-disjoint protection paths. The optimization-based algorithms introduced in this investigation provide greater insight into the proposed network architecture by providing the user with a detailed plan with the equipment sizes and locations while considering the technological restrictions, such as polarization mode dispersion (PMD), and transmission link budget constraints. The advantages are that in-depth cost calculations can be performed once equipment requirements are determined and that more accurate unavailability calculation are possible when equipment reliability metrics are used to determine *(o,d)* demand pair unavailability.

### B. *Contributions*

The first contribution of this investigation is a design tool for DWDM networks employing dedicated (1+1) protection. Given *(o,d)* demand pairs and the corresponding traffic, the tool generates candidate routes for each demand pair and provides detailed output on equipment needs for those point-to-point demands. O/E/O conversion is allowed at nodes where additional equipment (optical amplifiers and multiplexers) is already present or at intermediate points between nodes. The second contribution is an empirical analysis for cost savings for primarily performing O/E/O conversions at nodes rather than at intermediate points between nodes. The third contribution is the development and empirical evaluation of a DWDM network design tool that attempts to satisfy a user provided unavailability target. Based on the empirical evidence in this investigation, the proposed algorithms are computationally solvable and worthy of practical consideration for resolving realistic problem sets. Finally, the run files and test data used in this investigation can be obtained from the study web site (http://engr.smu.edu/~jlk/publications.htm) for verification and comparison purposes.

## II. THE DWDM DESIGN PROBLEM

Dense wavelength division multiplexing (DWDM) networks consist of fiber and optical equipment of various types: optical amplifiers (As), regenerators (Rs), multiplexers (MUXs), demultiplexers (DMUXs), and optical cross connects (OXCs). Optical amplifiers boost multiple weakening signals multiplexed onto the same fiber directly, without conversion to the electrical domain. Noise build-up as the optical signals traverse fiber spans and optical equipment is mitigated by regenerating the original signal retrieved from the optical domain into the electrical domain, and then converted back to the optical domain. Regeneration is a costly process which employs optical amplifiers, regenerators, multiplexers, and demultiplexers.

Long-haul optical transport networks contain nodes corresponding to locations where traffic originates and terminates. Equipment needed for amplification and/or regeneration can be placed in huts located between nodes along the fiber. The term *span* refers to fiber between two locations (huts or nodes) where optical amplification occurs. The signal data rate, the type of optical fiber and other factors determine the maximum length of a span (optical reach or link budget) that can be traversed before amplification is required. For a given combination of such factors associated with a particular link budget, there is a limit on the number of spans that can be traversed before regeneration is needed. A sample combination of maximum number of spans with corresponding link budgets is illustrated in Table 1. For example, for a link budget of 100, (optical amplifiers are no more than 100km apart) a signal can traverse 23 optical amplifiers (24 spans) before regeneration is required.

TABLE 1: LINK BUDGET VALUES

| LINK BUDGET | MAXIMUM SPANS | LINK BUDGET | MAXIMUM SPANS | LINK BUDGET | MAXIMUM SPANS |
|---|---|---|---|---|---|
| 162 | 1 | 130 | 9 | 114 | 17 |
| 158 | 2 | 128 | 10 | 112 | 18 |
| 154 | 3 | 126 | 11 | 110 | 19 |
| 150 | 4 | 124 | 12 | 108 | 20 |
| 146 | 5 | 122 | 13 | 106 | 21 |
| 142 | 6 | 120 | 14 | 104 | 22 |
| 138 | 7 | 118 | 15 | 102 | 23 |
| 134 | 8 | 116 | 16 | 100 | 24 |

*Polarization mode dispersion* (PMD) is another technological restriction that needs to be considered for high data rate optical systems. Signal dispersion is a function of the optical characteristics of the fiber and can cause serious signal quality degradation at long distances. Signal regeneration before the negative effects of PMD materialize is one method to mitigate its effects.

Given dark fiber, a traffic demand matrix, and hut locations, the DWDM design problem consists of determining the size and location of equipment needed to light the fiber while satisfying the traffic demand requirement and technological restrictions. DWDM optical networks that perform O/E/O conversion at each end of a fiber link are called *opaque networks*. More cost effective designs can be attained through an *all-optical* design methodology where O/E/O conversions occur only when required by technological restrictions.

In previous work (Birkan et al., 2005), an opaque network design approach consists of an optimal hut selection procedure for every link and each possible link budget using a greedy algorithm. The selection process minimizes the number of huts that are used and thus the overall link cost. The link budget selected for least cost design for a given link is called the *best link budget* for that link. Using the best link designs, a routing and provisioning model determines the routing and the traffic on each link. This optimization-based model minimizes the equipment cost for a given set of demands by assigning traffic to candidate paths provided by the user, or determined by the design tool. The output from this model is the opaque design with the location and size of DWDM equipment required.

A similar approach can be used for an all-optical design: each *(o,d)* demand pair is examined in turn and may be routed across several links. Such a routing path can be viewed as a long “link” where regeneration is not required at every intermediate node. The proposed all-optical method uses the paths determined by the previous routing and provisioning model to determine the equipment configuration starting from origin node *o* with the best link budget for the current link. The design is complete when destination node *d* on the path has been reached. Since different paths may traverse the same links, the use of best link budgets aids the design process when merging the individual path designs. In addition, the algorithm determines which hut locations are needed for installing regeneration equipment, in order to satisfy PMD and signal-to-noise ratio restrictions. Once all equipment needs are determined for the all-optical design, overall costs can be calculated using the same relative equipment pricing model as in the case of the opaque network design strategy.

## III. DWDM DESIGN WITH DEDICATED PROTECTION

From amongst the multitude of protection schemes that have been investigated in the literature (see [21]), dedicated protection using 1+1 dedicated alternate paths is the least complicated operationally: recovery in the event of a failure is quick with small downtime. One or more copies of the working traffic are sent along node-disjoint path(s) between the origin and the destination nodes. These distinct paths are called *protection* or *back-up* paths. The optical equipment provisioned at the receiver constantly compares the working signal with its copies on the protection path(s) and determines if a switch needs to take place. (see [3] and [8]).

The opaque and all-optical design algorithms used in [1] have been enhanced to incorporate dedicated protection: the design process begins with finding a solution to the *path generator* binary program which finds *k* shortest distinct cycles for each *(o,d)* demand pair. For a given *(o,d)* demand pair, each cycle may be split into two node disjoint paths that originate at node *o* and terminate at node *d*. The underlying network topology is known and modeled by a connected graph $G = (N, E)$, where $N$ is the set of nodes where terminal equipment may be placed, and $E$ corresponds to the fiber links between them. Binary variables $z_{ij}$ will be 1 if arc *(i,j)* is selected to be part of the cycle; and 0, otherwise. For demand pair *(o,d)* let $b_o = 2$, $b_d = -2$, and $b_i = 0$ for all $i \in N \setminus \{o, d\}$. The flow conservation constraints are

$$\sum_{(i,j)\in E} z_{ij} - \sum_{(j,i)\in E} z_{ji} = b_i, \qquad \forall i \in N \tag{1}$$

Two paths that form a cycle are node-disjoint:

$$\sum_{(i,j)\in E} z_{ij} \le 1, \quad \forall j \in N \setminus \{o,d\} \tag{2}$$

If $\overline{L}_{ij}$ is the length of arc *(i,j)* in kilometers, then the objective function is:

$$\text{minimize} \quad \sum_{(i,j)\in E} \overline{L}_{ij} z_{ij} \tag{3}$$

Let $\overline{A}_1$ denote the arcs in the first cycle. Then the second cycle is obtained by solving (1)-(3) plus the constraint

$$\sum_{(i,j)\in \overline{A}_1} z_{ij} \le \left|\overline{A}_1\right| - 1 \tag{4}$$

Let $\overline{A}_2$ denote the arcs in the second cycle. The third cycle is obtained by solving (1)-(4) plus the constraint

$$\sum_{(i,j)\in \overline{A}_2} z_{ij} \le \left|\overline{A}_2\right| - 1 \tag{5}$$

This process continues until *k* distinct shortest cycles have been discovered. The choice of *k* influences the amount of path diversity that the final solution is likely to have. Alternatively the branching strategy proposed by Lawler (1972) may be used to compute k-shortest cycles.

The design process continues with the greedy hut selection algorithm. For each combination of link and link budget, the minimum number of huts is determined where amplification occurs. Next, regenerator placement at huts is determined so that the link budget and PMD restrictions are satisfied. For each link, the link budget value that results in the least number of As and Rs is recorded as the best link budget for that link. With the best link designs, an enhanced routing and provisioning model determines which candidate cycles are used as well as the location and size of equipment required for an opaque network with dedicated protection. Solving the cycle generator and hut selection problems can be done in parallel, as there are no dependencies between the two.

In the hut selection model, N denotes the set of nodes, F denotes the set of links, and D denotes the set of demand pairs. Let $r_{od}$ denote the total demand in wavelengths for demand pair *(o,d)*. Let $H_{od}$ denote the set of cycles for demand pair *(o,d)*. The binary variable $\overline{P}_{od}^{p}$ will be 1 if cycle $p \in H_{od}$ is selected for demand pair *(o,d)*; and 0 otherwise. The following constraints force the selection of exactly one cycle for each demand pair.

$$\sum_{p\in H_{od}} \overline{P}_{od}^{p} = 1, \quad \forall (o,d) \in D \tag{6}$$

In this arc-cycle model, each link is represented by two directed arcs in the set E. The variable $t_{ij}$ denotes the total number of wavelengths assigned to arc *(i,j)* and $W_{ij}$ ($B_{ij}$) denotes the set of working (protection) paths that use arc *(i,j)*. We assume that paths are directed from *o* to *d* for a given *(o,d)* pair, but since demands are symmetrical, the capacity of arcs *(i,j)* and *(j,i)* will be identical. The number of wavelengths assigned to arc *(i,j)* is given by

$$\sum_{p\in W_{ij}} \sum_{(o,d)\in D, p\in H_{od}} (r_{od} \overline{P}_{od}^{p}) + \sum_{p\in B_{ij}} \sum_{(o,d)\in D, p\in H_{od}} (r_{od} \overline{P}_{od}^{p}) = t_{ij}, \forall (i,j) \in E \tag{7}$$

Amplifiers and multiplexers are available with discrete fixed capacity and our model used three sizes for each (small, medium and large). Let S, M, and L denote the number of wavelengths that can be processed by each of the three sizes. Note that this approach can be expanded to any number of fixed equipment capacities. Let $A_{ij}^{S}$, $A_{ij}^{M}$, and $A_{ij}^{L}$ be the integer variables that denote the number and size of amplifiers on link *(i,j)*. If the best link budget for a given link requires amplification at a hut or a node on that link then the following set of constraints determine the size and number of amplifiers for that location:

$$t_{ij} + t_{ji} \le S\, A_{ij}^{S} + M\, A_{ij}^{M} + L\, A_{ij}^{L}, \qquad \forall (i,j) \in F \tag{8}$$

Let $T_i$ be the number of TEs needed at node *i* and let $R'_{ij}$ denote the number of Rs required at a hut on link *(i,j)*. Note that TEs and Rs are installed on a per-wavelength basis and an intermediate node on a path requires twice the number of TEs as the origin and destination nodes. The number of TEs at the nodes is given by

$$\sum_{(i,j)\in E} (t_{ij} + t_{ji}) = T_i, \qquad \forall i \in N \tag{9}$$

The following set of constraints determines the number of Rs at a hut on a given link:

$$t_{ij} + t_{ji} = R'_{ij}, \qquad \forall (i,j) \in F \tag{10}$$

The number of amplifier, regenerator, and multiplexer or demultiplexers (MUX/DMUX) locations determined by the best link budget on link *(i,j)* are stored in constants $B_{ij}^{A}$, $B_{ij}^{R}$, and $B_{ij}^{M}$ ,respectively. Let $C_{A^S}$, $C_{A^M}$, $C_{A^L}$ be constants denoting the cost of small, medium, and large amplifiers, and $C_{M^S}$, $C_{M^M}$, $C_{M^L}$ be constants denoting the cost of small, medium, and large MUX/DMUX equipment. $C_T$ denotes the cost of TE equipment, and finally $C_R$ denotes the cost of an R. Then the objective function is to minimize the cost of provisioning the opaque network and is given by

$$\begin{aligned} \text{minimize} \sum_{(i,j)\in F} (C_{A^S} A_{ij}^{S} + C_{A^M} A_{ij}^{M} + C_{A^L} A_{ij}^{L}) B_{ij}^{A} + \sum_{i\in N} C_T T_i + \sum_{(i,j)\in F} C_R R'_{ij} B_{ij}^{R} \\ + \sum_{(i,j)\in F} (C_{M^S} A_{ij}^{S} + C_{M^M} A_{ij}^{M} + C_{M^L} A_{ij}^{L}) B_{ij}^{M} \end{aligned} \tag{11}$$

A solution to this model consists of the demand routings and the number and size of equipment needed to light the fiber and satisfy demands.

Using the cycles determined by the routing and provisioning model, the all-optical design algorithm starts by examining the working path then the protection path(s) for each *(o,d)* pair successively. Starting from node *o*, the wavelengths carried on each path are translated to equipment needs while considering PMD and signal-to-noise ratio restrictions. The design for this demand is complete when the equipment at node *d* has been provisioned.

The opaque and all-optical design procedures are augmented by unavailability estimates which are compared to user specified target unavailability values. Demand pairs with unacceptable unavailability are candidates for additional protection paths. For each candidate *(o,d)* demand pair in the list, the supply at node *o* and demand at node *d* are incremented by 1 and the path generator model is run again. The newly determined routings may differ from the previously created paths, so a re-run of the routing and provisioning procedures is required. The process continues until either the unavailability drops below the threshold value, or it is impossible to decrease the unavailability with additional back-up paths. The AMPL code corresponding to the algorithm pseudo-code presented in Figure 1, is available at http://engr.smu.edu/~jlk/publications.htm.

```
procedure Opaque Design $(D,t,\alpha,U)$;
  Inputs: $D,t,\alpha$
    /* $D$ denotes the set of demand pairs */
    /* $t$ denotes the target unavailability value */
    /* $\alpha$ denotes the maximum number of candidate paths for each demand*/
  Output: $U$
    /* $U(o,d)$ denotes the unavailability for demand pair $(o,d)$ */
  begin
    for each link use the Greedy Algorithm to obtain the best link budget and the
      locations for the As and the Rs;
    $\forall(o,d)\in D \; n(o,d)\leftarrow 1$;
    repeat
      $\forall(o,d)\in D$ do
        $P(o,d)\leftarrow\varnothing$;
        Solve the Path Generator Model in an attempt to obtain $\alpha$ sets of
          working and $n(o,d)$ node-disjoint protection paths;
        Let $\beta$ denote the number of sets obtained;
        if $\beta=0$ then display "Target unavailability cannot be met"; stop;
        else add $\beta$ sets to the set $P(o,d)$;
      end do
      Solve the Routing and Provisioning Model to determine the paths to be used,
        the traffic on each link, and the equipment needed for the opaque design;
      (For All-Optical Design: Find the all-optical design for each path in P using
        the paths and the traffic determined by the Routing and Provisioning Model;)
      Calculate the unavailability $U(o,d)$ for all $(o,d)\in D$;
      $T\leftarrow\varnothing$;
      $\forall(o,d)\in D$ do
        if $U(o,d) > t$ then $T\leftarrow T\cup\{(o,d)\}$ and $n(o,d)\leftarrow n(o,d)+1$;
      end do
    until $|T|=0$;
    return $U(o,d)\;\forall(o,d)\in D$ and the current design;
  end
```

Figure 1: The Pseudo-Code for the Opaque (All-Optical) Design

## IV. DWDM NETWORKS UNAVAILABILITY

*Unavailability* is the probability of finding a system in a non-functional state at any given time. Unavailability estimates are widely used by telecommunication service providers to differentiate their product as well as to measure their adherence to the requirements of a service level agreement. In this study, unavailability is estimated as the percentage of time that the total service requirement between a pair of demand nodes cannot be fully satisfied. Unavailability is frequently expressed in units of minutes per year as opposed to a percentage value. For example, an unavailability of 60 minutes/year is approximately 0.01%.

For a given *(o,d)* demand, fiber cuts and equipment failures may render the service unavailable. The simplified calculation of unavailability of a component requires knowledge of the failure rate *(r)* and the mean time to repair *(MTTR)* for that component. Mean time to failure *(MTTF)* is also widely used in place of *1/r*. There is an industry wide adopted assumption that the failure rates for fiber and DWDM equipment do not vary with time. In other words, there is no wear out period or increased failure rate for fiber and equipment as a result of aging and/or deterioration. Failures are assumed to occur independently of each other and each component is repaired and returned to full functional state after an expected duration of time (*MTTR*). The following formulas provide a close approximation for the unavailability ($U$) of a single DWDM network component (see [22], [4], and [9]).

$$U=\frac{Downtime}{Uptime+Downtime}=\frac{MTTR}{MTTF+MTTR}=\frac{(r)(MTTR)}{1+(r)(MTTR)} \tag{8}$$

$A'$ denotes availability, the complement of unavailability:

$$A'=1-U=\frac{MTTF}{MTTF+MTTR} \tag{9}$$

The path unavailability estimate in a telecommunication network requires computing the unavailability estimates of each element in the path. If the path is composed of elements in series, then a failure of any component results in a failure for the path. Suppose there are $K$ elements in series in a system with unavailability of $U_k$, $k=1\ldots K$, then the unavailability for the system is given by

$$U_{system}=1-\prod_{k=1}^{k=K}A'_k=1-\prod_{k=1}^{k=K}(1-U_k) \tag{10}$$

Unavailability of a system in series can be fairly accurately approximated by adding the unavailability (see To and Neusy 1994, Grover 2004).

$$U_{system}\approx\sum_{k=1}^{k=K}U_k \tag{11}$$

In a system composed of $K$ redundant units working in parallel the exact unavailability for the system is given by

$$U_{system}=\prod_{k=1}^{k=K}U_k \tag{12}$$

The unavailability calculation for an *(o,d)* demand pair with dedicated protection involves several groups of components in series and parallel. A system decomposition is needed to identify these groups of elements. Once the unavailability of each group is calculated, relations (series or parallel) among those groups are determined so the unavailability of the whole system can be calculated. For this investigation, it is assumed that customers require the full bandwidth for their time critical applications, so a single TE failure on a path that carries a demand of $d > 1$ wavelengths is viewed as a path failure even though some of the traffic can be transmitted. Failure of a fiber duct can be viewed as a failure of all fiber cables sharing the same duct and therefore a duct and the fiber inside have a single unavailability value associated with them.

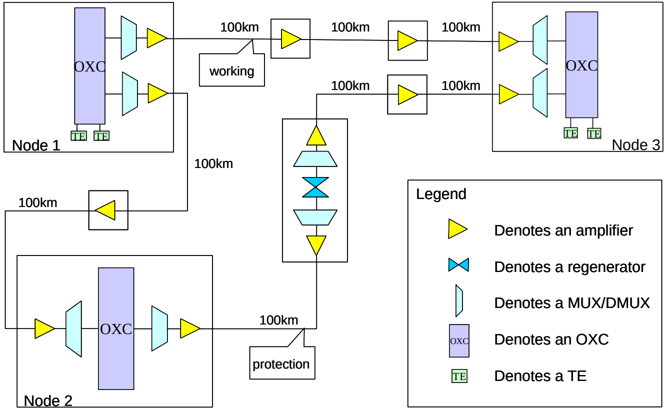

Figure 2: Example Network

OXCs at the demand nodes are shared among working and protection paths in dedicated protection, so that if the OXC at node 1 or node 3 in Figure 2 fails, a transmission disruption is inevitable. However, in long-haul networks with numerous elements in series, the intermediate elements, and especially fiber, contribute more to the system unavailability than the OXCs at the terminal nodes. Test cases considered in the empirical analysis assume that the largest demand is 80 wavelengths, and each wavelength carries signals at data rates up to 40 Gbps. Larger traffic demands can be accommodated by modifying the formulation to consider multiple links in series for both working and protection paths.

## V. Empirical Analysis

The different test network topologies described in Table 2 are used to evaluate the all-optical design with dedicated protection. Average node degree is a good overall indication of path diversity. All the *(o,d)* demand pairs are randomly generated and the wavelengths assigned to these demand pairs are uniformly distributed over [10,80]. For each test case described in Table 3, a maximum of 6 candidate paths per demand pair are used.

Table 2: Test Network Topology Descriptions

| | \|N\| | \|E\| | D | *(o,d)* | Dem. | DPMD | H | Dist |
|---|---|---|---|---|---|---|---|---|
| EU | 18 | 35 | 3.89 | [50,125] | U[10,80] | [0.1,1.0] | 438 | [5,90] |
| EB | 18 | 49 | 5.44 | [50,125] | U[10,80] | [0.1,1.0] | 773 | [5,117] |
| US | 28 | 42 | 3.15 | [50,250] | U[10,80] | [0.1,1.5] | 423 | [3,134] |
| NA | 36 | 67 | 3.69 | [50,250] | U[10,80] | [0.1,1.0] | 705 | [5,100] |

The all-optical design with dedicated protection is implemented using the AMPL modeling language (Fourer et al. 2003) and is solved using the branch-and-bound optimizer in CPLEX http://www.cplex.com. The relative equipment costs that are used to calculate overall design costs are given in Table 4.

Table 3: Test Problem Characteristics

| Problems | Number of Demand Pairs | Avg. Number of Hops | Total Demand (λs) |
|---|---|---|---|
| EU110 | 50 | 2.94 | 2197 |
| EU160 | 75 | 2.91 | 3029 |
| EU210 | 100 | 2.86 | 4662 |
| EU260 | 125 | 2.85 | 5362 |
| US310 | 100 | 4.70 | 4028 |
| US360 | 150 | 4.92 | 6291 |
| US410 | 200 | 4.80 | 8751 |
| US460 | 250 | 4.85 | 10997 |
| NA510 | 100 | 3.88 | 4544 |
| NA560 | 150 | 3.93 | 6986 |
| NA610 | 200 | 3.99 | 9243 |
| NA660 | 250 | 4.06 | 11408 |
| EB710 | 50 | 2.12 | 2054 |
| EB760 | 75 | 2.27 | 3242 |
| EB810 | 100 | 2.35 | 4540 |
| EB820 | 125 | 2.28 | 5547 |

O/E/O conversion at a hut requires amplifiers, multiplexers, demultiplexers, and regenerators. Regeneration at a node only requires the addition of Rs for each wavelength. A test was conducted to determine if cost savings are possible by moving regeneration from a hut to a previous non-demand node thus exploiting existing As and MUX/DMUXs.

Table 4: Relative Equipment Cost

| Equipment | Wavelengths | Cost/Unit | Leasing Cost/Unit |
|---|---|---|---|
| TE | 1 | 75 | 93.75 |
| R | 1 | 130 | 162.5 |
| A | 1 – 20 | 100 | 125 |
| A | 21 – 40 | 150 | 187.5 |
| A | 41 – 80 | 200 | 250 |
| MUX/DMUX | 1 – 20 | 120 | 150 |
| MUX/DMUX | 21 – 40 | 180 | 225 |
| MUX/DMUX | 41 - 80 | 240 | 300 |

The EU, US, and NA test networks with various values for the total number of *(o,d)* demand pairs are used in this empirical analysis. Failure rates and MTTR values for the various equipment types are listed in Table 5. With the relocation feature enabled, fewer As and MUX/DMUXs were used, but the provisioning costs were 2% to 7% higher for the EU, US, and NA test networks. This is due to the fact that placing regenerators earlier on a long-haul route may result in an additional regeneration. See the discussion in [24] for a detailed presentation of the results.

Table 5: Failure Rates and Mean Repair Times

| Module | Failure Rate (r) | MTTR |
|---|---|---|
| Fiber | 2.12566E-07 | 12 |
| Regen | 3.35521E-06 | 2 |
| TE | 3.35521E-06 | 2 |
| MUX | 4.98153E-07 | 2 |
| OXC | 1.96685E-06 | 2 |
| AMP | 4.22508E-06 | 2 |

Both opaque and all-optical designs try to add protection paths for demand pairs which exceed target unavailability.

| Problem Name | As | Rs | TEs | Cost (M) | CPLEX Time | Total Time | Max Unavail. (Min/Yr) | New Paths Added | Total Time | Final Max Unavail. (Min/Yr) | Final Cost (M) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EU110 | 1709 | 2017 | 25570 | 2.61 | 00:01 | 00:07 | 121 | 0 | 00:07 | 121 | 2.61 |
| EU160 | 2445 | 2571 | 34860 | 3.55 | 00:01 | 00:10 | 201 | 0 | 00:10 | 201 | 3.55 |
| EU210 | 3513 | 4088 | 53436 | 5.42 | 00:01 | 00:13 | 153 | 0 | 00:13 | 153 | 5.42 |
| EU260 | 3988 | 4357 | 61500 | 6.18 | 00:01 | 00:17 | 172 | 0 | 00:17 | 172 | 6.18 |
| US310 | 3040 | 2135 | 72826 | 6.58 | 00:01 | 00:15 | 238 | 0 | 00:15 | 238 | 6.58 |
| US360 | 4924 | 3363 | 119520 | 10.77 | 00:01 | 00:27 | 225 | 0 | 00:27 | 225 | 10.77 |
| US410 | 6642 | 4598 | 164920 | 14.82 | 00:01 | 00:44 | 225 | 0 | 00:44 | 225 | 14.82 |
| US460 | 8679 | 6533 | 211448 | 19.12 | 00:01 | 01:04 | 237 | 0 | 01:04 | 237 | 19.12 |
| NA510 | 5421 | 6375 | 72342 | 7.58 | 00:01 | 00:24 | 279 | 0 | 00:24 | 279 | 7.58 |
| NA560 | 8440 | 10226 | 111900 | 11.79 | 00:01 | 00:37 | 297 | 0 | 00:37 | 297 | 11.79 |
| NA610 | 11059 | 14603 | 148454 | 15.77 | 00:01 | 00:52 | 297 | 0 | 00:52 | 297 | 15.77 |
| NA660 | 13629 | 16557 | 184648 | 19.36 | 00:01 | 01:09 | 332 | 0 | 01:09 | 332 | 19.36 |
| EB710 | 1510 | 1264 | 17284 | 1.81 | 00:01 | 00:15 | 83 | 50 | 00:18 | 4.90 | 2.71 |
| EB760 | 2498 | 1882 | 30266 | 3.10 | 00:01 | 00:17 | 122 | 78 | 00:32 | 4.90 | 4.81 |
| EB810 | 3310 | 2449 | 42268 | 4.27 | 00:01 | 00:21 | 127 | 104 | 00:46 | 4.91 | 6.58 |
| EB860 | 3846 | 3368 | 51150 | 5.21 | 00:01 | 00:25 | 122 | 130 | 01:03 | 4.95 | 8.14 |

TABLE 6: OPAQUE DESIGN WITH DEDICATED PROTECTION (TARGET UNAVAILABILITY IS 5 MIN/YEAR)

Table 6 summarizes an empirical analysis that was conducted to test this feature of the opaque network design tool. The EU, EB, US, and NA test networks with various numbers of *(o,d)* demand pairs are used in this test.

| Problem Name | As | Rs | TEs | Cost (M) | CPLEX Time | Total Time | Max Unavail. (Min/Yr) | New Paths Added | Total Time | Final Max Unavail. (Min/Yr) | Final Cost (M) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EU110 | 1780 | 6789 | 8788 | 2.02 | 00:01 | 01:34 | 91 | 0 | 01:34 | 91 | 2.02 |
| EU160 | 2540 | 8909 | 12116 | 2.73 | 00:01 | 02:41 | 149 | 0 | 02:41 | 149 | 2.73 |
| EU210 | 3639 | 14236 | 18648 | 4.22 | 00:01 | 03:58 | 129 | 0 | 03:58 | 129 | 4.21 |
| EU260 | 4143 | 16090 | 21448 | 4.81 | 00:01 | 05:35 | 136 | 0 | 05:35 | 136 | 4.81 |
| US310 | 3222 | 19598 | 16112 | 4.71 | 00:01 | 06:48 | 129 | 0 | 06:48 | 129 | 4.71 |
| US360 | 5208 | 32658 | 25164 | 7.69 | 00:01 | 14:00 | 130 | 0 | 14:00 | 130 | 7.69 |
| US410 | 7005 | 44420 | 35004 | 10.49 | 00:01 | 22:37 | 130 | 0 | 22:37 | 130 | 10.49 |
| US460 | 9139 | 58335 | 9139 | 13.60 | 00:01 | 36:39 | 139 | 0 | 36:39 | 139 | 13.60 |
| NA510 | 5625 | 20395 | 18176 | 5.48 | 00:01 | 22:07 | 208 | 0 | 22:07 | 208 | 5.48 |
| NA560 | 8742 | 32840 | 27944 | 8.64 | 00:01 | 34:42 | 208 | 0 | 34:42 | 208 | 8.64 |
| NA610 | 11444 | 44194 | 36972 | 11.51 | 00:01 | 49:56 | 214 | 0 | 49:56 | 214 | 11.51 |
| NA660 | 14095 | 54251 | 45632 | 14.15 | 00:01 | 1:05:12 | 233 | 0 | 1:05:12 | 233 | 14.15 |
| EB710 | 1559 | 4425 | 8216 | 1.58 | 00:01 | 03:32 | 81 | 50 | 09:22 | 4.79 | 2.34 |
| EB760 | 2586 | 7739 | 12968 | 2.63 | 00:01 | 05:27 | 106 | 78 | 23:37 | 4.78 | 3.97 |
| EB810 | 3415 | 10389 | 18160 | 3.56 | 00:01 | 07:44 | 95 | 104 | 33:58 | 4.85 | 5.50 |
| EB860 | 3981 | 13229 | 22188 | 4.41 | 00:01 | 10:15 | 106 | 130 | 46:15 | 4.92 | 6.89 |

TABLE 7: ALL-OPTICAL DESIGN WITH DEDICATED PROTECTION (TARGET UNAVAILABILITY IS 5 MIN/YEAR)

The maximum unavailability calculated exceeds the specified target for the EU, US, and NA networks. Due to the low node degree of these networks, it is not possible to find additional backup paths to decrease network unavailability. According to the FCC, a 1000 mile fiber experiences an average of 3 cuts per year or approximately 1.863 cuts per 1000 kilometers (see [21]).

The EB network is used to test whether the 5 minute target can be reached by assigning more than one dedicated protection path per *(o,d)*. For all 8 test problems using this network, the design tool successfully lowers maximum unavailability to less than 5 minutes per year. For the EB810 problem with one hundred *(o,d)* demand pairs, the maximum unavailability decreased from 127 minutes/year to 4.91 minutes/year with 104 additional protection paths. Since there are 100 *(o,d)* pairs, on average each demand pair required approximately two protection paths.

Additional equipment needed to accommodate this traffic caused an increase in cost from 4.27 million to 6.58 million. The addition of new protection paths required two more runs of the model, increasing the processing time from 21 seconds to 46 seconds. Table 7 summarizes the test runs using the all-optical design tool. For the same test problem the all-optical design was substantially lower in cost (3.56 million). The addition of 104 new paths decreased the maximum unavailability to less than 5 minutes while increasing the design cost by 1.94 million to 5.50 million. This EB810 test problem for the all-optical design required approximately 34 minutes of processing time.

If no additional node-disjoint paths can be found in the existing network, new links must be appended to obtain additional backup paths. The service provider has an option to build new links, or lease them from another provider. The remainder of this section explores the effect of adding leased links has on the overall solution parameters. The results summarized in Table 8 describe the number of new leased links that were selected in order to allow the test network (based on the EU network topology) to meet the specified network unavailability target. Leased links are appended to EU to form a complete graph called EL.

Both opaque and all-optical designs were examined for the same test network. The original cost function has to be modified to incorporate the cost of leasing which translates into paying a 25% premium in addition to what the owned equipment would cost (see Table 4). All leased links are assumed that use 100km hut spacing, with the possible exception of the last hut, and good quality fiber with small PMD values. Switching between the operator's network and the leased link network may require additional TEs as well as other nodal equipment such as OXCs and MUX/DMUXs.

| | Problem Name | Cost (M) | CPLEX Time | Total Time | Max Unavail. (Min/Yr) | New Paths Added | Total Time | Final Max Unavail. (Min/Yr) | Number of Links Leased | Leased Cost (M) | Final Cost (M) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Opaque | EL110 | 2.61 | 00:01 | 00:09 | 121 | 52 | 00:20 | 4.97 | 23 | 0.40 | 3.56 |
| | EL160 | 3.55 | 00:01 | 00:13 | 201 | 79 | 00:33 | 4.98 | 32 | 0.70 | 4.91 |
| | EL210 | 5.42 | 00:01 | 00:17 | 153 | 110 | 00:50 | 4.99 | 43 | 1.12 | 7.60 |
| | EL260 | 6.18 | 00:01 | 00:22 | 172 | 135 | 01:07 | 4.85 | 49 | 1.28 | 8.54 |
| All-Optical | EL110 | 2.02 | 00:01 | 04:12 | 91 | 50 | 10:40 | 4.92 | 21 | 0.26 | 2.85 |
| | EL160 | 2.73 | 00:01 | 06:50 | 149 | 78 | 27:07 | 4.77 | 32 | 0.51 | 3.89 |
| | EL210 | 4.22 | 00:01 | 08:46 | 129 | 105 | 38:51 | 4.98 | 39 | 0.72 | 6.07 |
| | EL260 | 4.81 | 00:01 | 12:31 | 137 | 130 | 50:46 | 4.98 | 46 | 0.84 | 6.74 |

Table 8: Leased Line Designs with Dedicated Protection (Target Unavailability is 5 min/yr)

For example, the EL210 problem which carries 100 demand pairs using the opaque (all-optical) design a cost increase from 5.42 (4.22) million to 7.60 (6.07) million was needed for 110 (105) new protection paths to meet the target unavailability of 5 minutes/year. Results are consistent with the previous tests, showing that the all-optical design requires fewer components than the opaque network design.

## VI. Summary and Conclusions

In this investigation, design tools capable of provisioning opaque and all-optical networks with dedicated protection are introduced. All-optical networks employ an O/E/O conversion only when it is imposed by the PMD and signal-to-noise ratio restrictions. Since there is generally less conversion equipment needed, all-optical networks enable network operators to reduce design costs. Dedicated protection requires two node-disjoint paths per *(o,d)* demand pair, a working path and a protection path. While both paths are active all the time, the wavelengths along a protection path are committed to carry only the back-up traffic for a specific *(o,d)* demand pair. The described tools for both designs finds two node-disjoint paths for each *(o,d)* demand pair using the path generator model (an integer linear program). A greedy algorithm is used to determine the huts where amplification is needed. This hut selection algorithm is solved for each link with each feasible link budget value to determine the best link budget for a given link. Finally, an optimization-based routing and provisioning procedure is run to determine the traffic and equipment on each link. The output from this procedure is the opaque design for a given test case. A reduction in the overall number of O/E/O conversions can be obtained by further analysis of the opaque design. The optimized all-optical network design thus obtained results in additional cost savings.

For a network design identified by the routing and provisioning procedure, the design tool calculates the unavailability probability estimate for each *(o,d)* demand pair. These estimates are then compared to a user-set target unavailability. Demand pairs with unavailability higher than the target value are considered as candidates for using additional protection paths. The results of the empirical analysis conducted by the authors argues in favor of the fact that a network design for realistically sized DWDM network employing dedicated protection can be produced in a reasonable amount of time using the approach outlined in this paper. The analysis also illustrates the fact that sufficiently dense networks may be used to provide reliable designs that can attain the desired unavailability targets through adding new protection paths. This investigation considered the option of leasing links for networks limited by their low average node degree: for example, the EU test network topology with an original average node degree of 3.89, does not allow for the unavailability goal to be met via using additional protection paths unless the leasing option is enabled.

The design tools presented in this investigation facilitate the relocating of O/E/O conversion equipment which allows the user to exploit existing As and MUX/DMUXs already provisioned in the network. The empirical analysis shows that with the relocation feature enabled, fewer As and MUX/DMUXs are used, but the total number of Rs needed increased for the EU, US, and NA test networks thus increasing equipment costs.

The wide set of additional facilities summarized argue convincingly for the practicality of the design approaches considered. Practical concerns like these which are likely to address real problems faced by service providers represent another contribution of this work. Future work is planned to expand and extend the current network approaches to allow for additional protection methods to be considered, such as shared or ring protection, in order to reduce protection costs while providing an adequate level of redundancy.

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