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Design and Restoration Strategies for Opaque and All-Optical DWDM Networks with Dedicated Protection

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Design and Restoration Strategies for Opaque and All-Optical DWDM Networks with Dedicated Protection

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This investigation presents a set of optimization based algorithms for designing opaque and all-optical DWDM networks with dedicated protection. Given the network topology and dark fiber links, these algorithms determine the size and location of equipment needed to light this fiber to satisfy point-to-point demands. Service level agreements offered to telecommunication customers by service providers promise certain levels of service reliability. A common feature of the algorithms presented in this investigation is that given the failure rate and mean time required for repair for each equipment type, these algorithms determine the unavailability of service for every demand pair. One algorithm also attempts to reduce the unavailabilities for each demand pair to a target value by increasing the number of node-disjoint protection paths. To the best of our knowledge, these algorithms provide the user with the most detailed design created by any optimization based design tool. Our empirical analysis demonstrates the practicality of using our optimization based design tools.

(*Integer Programming Applications; Network Provisioning; DWDM Network Design; Polarization Mode Dispersion; Dedicated Protection; Unavailability*)

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1. Introduction

Continuous advances in optical switch and transmission technologies promise significant cost savings in network provisioning. However, on long-haul DWDM networks, there are still some technological restrictions that need to be addressed. For example, the signal-to-noise ratio restriction calls for expensive optical/electrical/optical (O/E/O) conversions that involve equipment of various types. While the latest optical cross connects offer low power consumption and small footprints, long-reach optical amplifiers also extend the distance between O/E/O conversions. All-optical networks provide a means for network operators to reduce costs by exploiting the capabilities of this new hardware. All-optical networks keep the signal in the optical domain until one of the technological restrictions mandate an O/E/O conversion. This design principal makes all-optical design more cost efficient than the traditional opaque network design, where a conversion takes place at every terminal node. However there are still issues surrounding upgrades to all-optical networks. Although it rarely happens in transport networks, a change in the demand pairs can result in redundant equipment in the network. To accommodate potential changes in demand over time, a more traditional method of designing DWDM networks, opaque design is also considered and evaluated.

Reliability is a key marketing issue for network operators. A single fiber cut, one of the main causes of data loss, can put one or more demand pairs out of service for several hours. Similarly, equipment failures can halt transmission on one or more fibers. Dedicated protection is an effective way to protect DWDM networks against these types of disruptions.

This investigation presents a family of optimization based algorithms capable of provisioning opaque and all-optical networks with dedicated protection, while taking into account the technological restrictions. One algorithm not only determines the routing and unavailability for each *(o,d)* demand pair but it also attempts to reduce unavailability for a given *(o,d)* demand pair to a target value by increasing the number of protection paths. Several test cases were used in an empirical analysis to verify the practical application of the design algorithms. Given *(o,d)* demand pairs and the corresponding traffic, the design tools based on these algorithms for opaque networks with dedicated protection, requires less than two minutes of CPU time for large practical test problems. The all-optical designed required at most an hour for the largest test case. For the test cases where the node degree was sufficiently large, the design tool was successful in meeting the target unavailability of five minutes/year by adding node-disjoint protection paths. In other cases, the design tool opted for leasing links to meet the target unavailability.

1.1 Survey of Literature

This investigation addresses protection and unavailability issues in opaque and all-optical networks using the same basic design principles introduced in Birkan et al. (2005). Aguirre-Torres et al. (2000) present a method to assess the impact of failures and the time required for restoration on high speed DWDM networks employing optical shared protection rings. Arci et al. (2003) compare availability performance of various protection schemes based on dedicated and shared protection methods. Their work, closely related to the investigation by To and Neusy (1994), includes Monte-Carlo simulation to verify the accuracy of their unavailability calculations. They also present an excellent discussion on availability and reliability theory. A similar discussion on service unavailability can be found in Grover (1999). Grover introduces various schemes for provisioning ring based networks and provides comparisons based on cost and unavailability. Taking a similar approach for availability modeling, El-Torky and Lafleur (2000) compare availability of two ring protocols for transoceanic networks. Kennington et al. (2003) introduced integer programming models that address the DWDM routing and provisioning problem when there is uncertainty involved in demand forecasts. A follow up to this study, Birkan et al. (2002), introduced models that use various protection schemes including p-cycle protection. Clouqueur and Grover (2002) outline the assumptions that are widely accepted for determining unavailability of systems with numerous elements. These assumptions are also adopted in this investigation. Their study also yields the advantages of span restorable mesh networks over ring architectures in case of dual failure situations on networks carrying priority services. Network connectivity is the critical factor that determines the possible reduction in unavailability.

Ellinas et al. (2004) compare opaque and all-optical network architectures and discuss the challenges awaiting all-optical networks and optical switching. Morris (2001) provides insight into the future of optical switching where the signal stays in the optical domain from input to output. Golmie et al. (2000) propose a QoS model for metropolitan DWDM networks called the Differentiated Optical Services Model and describe capabilities and possible implementation issues of their model. Struyve et al. (2000) present the reasoning behind the choice of DWDM technology for the Pan-European network. They provide an overview of the advantages of DWDM as a multi-service platform in long and short haul setups. Schollmeier et al. (2003) introduce multi-path routing and local failure reaction methods to improve network availability and to provide uninterrupted QoS to bandwidth demanding real-time applications. Jones et al. (1999) present Sprint's network architecture to improve reliability and the reasoning behind the choices that were made. Philips et al. (2001) introduce and evaluate several redundancy options for an access network design (called SuperPON) that can perform efficiently with fewer switching nodes than more costly traditional access network designs.

The problem of dynamic traffic restoration in DWDM networks is addressed in Mohan and Somani (2000). They argue the necessity of having reserved protection paths for every connection due to the rarity of faults in DWDM networks and present algorithms for dynamically assigning suitable protection paths to failed working paths. Wavelength translators used at intermediate nodes along a path allow a traffic signal to use a different set of wavelengths than those assigned to the origin node. Integer linear programs presented by Kennington and Olinick (2004) compare the networks that employ wavelength translators at every switch with ones that do not permit any wavelength translation. For the cases where translation is only allowed at certain switches an algorithm based on a tabu search heuristic is proposed. Singhal and Mukherjee (2003) introduce algorithms that determine node-disjoint working and protection paths in DWDM networks to address single link failures that could affect multicast sessions. A profit maximization model for optimal routing of user selected sessions is also given. They tested their model with both all-optical and opaque switching technologies. The investigation by Laborczi et al. (2000) provides a starting point for our research investigation. They propose a heuristic method to improve the reliability of a given network by adding additional capacity; and, if possible, redundant links to increase bandwidth for node-disjoint protection paths. Our optimization based algorithms 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. Our approach provides two advantages. First, in depth cost calculations can be performed once the equipment requirements are known; and second, it leads to a more accurate unavailability calculation where reliability and mean time to repair of all the equipment determine the unavailability for each *(o,d)* demand pair.

1.2 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, this design tool generates several candidate routes for each demand pair and provides the user with detailed output on equipment needed to satisfy these point-to-point demands. An O/E/O conversion can occur at nodes where additional equipment (optical amplifiers and multiplexers) is already present or at intermediate points between nodes. The second contribution is an empirical evaluation of potential 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 set unavailability target. The empirical evidence presented in this investigation demonstrate that the proposed algorithms are computationally solvable. 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.

2. The DWDM Design Problem

Dense wavelength division multiplexing networks are composed of fiber and optical equipment of various types including optical amplifiers (As), regenerators (Rs), multiplexers (MUXs), demultiplexers (DMUXs), and optical cross connects (OXCs). Optical amplifiers boost a weakening signal directly, without converting it to an electrical signal. As the signal travels along fiber spans and passes through optical equipment, a noise build up occurs. Retrieving the original signal can be accomplished by an O/E/O conversion (regeneration). This expensive process employs optical amplifiers, regenerators, multiplexers, and demultiplexers.

In long-haul optical networks, the *nodes* are the locations where traffic originates and terminates. Between nodes and along the fiber are *huts*, where equipment needed for amplification and/or regeneration can be placed. The term *span* refers to fiber between two locations (can be huts or nodes) where amplification occurs. The *link budget* term can be viewed as the maximum length of a span that can be traversed before an amplification is required. With a selected link budget, there is a limit on the number of spans that can be traversed before a regeneration is needed. These maximum number of spans (*max spans*) and the corresponding link budgets are listed in Table 1. For example, given a link budget of 100, (meaning we amplify in at most 100 kilometers) a signal can pass through 23 optical amplifiers or 24 spans before a regeneration is required.

Table 1 About Here

Another technological restriction that needs to be considered in high bandwidth optical systems is *polarization mode dispersion* (PMD). The signal dispersion is a function of the optical characteristics of the fiber and can cause serious signal quality degradation at long distances. Performing a 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 is to determine the size and location of equipment to light the fiber while satisfying the demands and technological restrictions. DWDM optical networks that perform O/E/O conversion at each end of a fiber link are called *opaque networks*. Today, network operators are in search of more efficient design strategies that eliminate these expensive O/E/O conversions. One method of reducing these conversions is through use of an *all-optical* design methodology that allows O/E/O conversions only when it is required by technological restrictions.

In Birkan et al. (2005), a method for opaque network design begins with a hut selection procedure for every link with each possible link budget. A greedy algorithm which has been shown to find the optimal configuration is used for this procedure. The purpose of this selection process is to minimize the number of huts that are used, thus decreasing the overall link cost. The link budget used for the least cost design for a given link is called the *best link budget* for that link. Next, using these best link designs the routing and the traffic on each link are determined by a routing and provisioning model. This optimization based model minimizes the equipment cost for a given set of demands by assigning traffic to candidate paths provided by the user (if not provided the design tool can determine the candidate paths). The output from this model is the opaque design with the location and size of DWDM equipment required.

In Birkan et al. (2005) an all-optical design is determined by examining each *(o,d)* demand pair successively. In DWDM networks, a given *(o,d)* demand pair may traverse several links. Such a path can be viewed as a long link where regeneration is not required at every intermediate node. The proposed all-optical method uses the same paths determined by the routing and provisioning model for the opaque design and determines the equipment configuration starting from node *o* using the best link budget for the current link. The design is complete when node *d* on the path has been provisioned. Since different paths may traverse the same links, the use of best link budgets aids the design process when merging the individual path designs. Also during this process, in order to satisfy the PMD and the signal-to-noise ratio restrictions, the appropriate huts for installation of regeneration equipment are determined. Once the equipment requirements are determined for the all-optical design, overall costs can be calculated using the (relative) equipment prices.

3. Design Methodologies using Dedicated Protection

In dedicated protection, in addition to the traffic on the working path, one or more copies of this traffic are also sent along node-disjoint path(s) between the origin and the destination. These distinct paths are called *protection* or *back-up* paths. In case of an equipment failure or a fiber cut, one of these protection paths assumes the role of the working path. It should be noted that the wavelengths assigned to paths carry traffic only for a specific *(o,d)* demand pair. However, the equipment and fiber on these paths may be multiplexed with traffic from other *(o,d)* demand pairs (see Arci et al. 2000, Birkan et al. 2002).

The opaque and all-optical design algorithms used in Birkan et al. (2005) have been enhanced to incorporate dedicated protection. The design process begins with a binary linear program called the *path generator model* that finds k shortest distinct cycles for each *(o,d)* demand pair. Each one of these cycles for a given *(o,d)* demand pair can be split into two node disjoint paths that originate at node *o* and terminate at node *d*. The formal statement of this model is now presented. The binary variable 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

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

The following constraints ensure that the two paths that form the cycle are node-disjoint.

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

Let $\bar{L}_{ij}$ be the length of arc *(i,j)* in units of km, then the objective function is

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

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

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

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

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

This continues until k distinct shortest cycles have been discovered.

Once the cycles are determined, the design process proceeds with the hut selection (greedy) algorithm. For each (link, link budget) combination this algorithm yields the minimum number of huts where amplification must occur. Next, the huts that require regeneration to satisfy the link budget and the PMD restrictions are determined. 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. Using these best link designs, an enhanced routing and provisioning model determines the cycles to be used as well as the location and size of equipment required for an opaque network with dedicated protection.

In this enhanced model, the demand and flow constraints from the original model are replaced by two new constraints. Let D denote the set of demand pairs *(o,d)* and let H_{od} denote the paths for demand pair *(o,d)*. The binary variable $\bar{P}_{od}^{p}$ will be 1 if path p is selected to carry the traffic for demand pair *(o,d)*; and 0, otherwise. Then the constraints that force the selection of some path for each *(o,d)* pair are as follows:

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

Let E denote the set of arcs in the network and let t_{ij} denote the total flow on arc *(i,j)*. Let W_{ij} denote the working paths that use arc *(i,j)* and B_{ij} denote the protection paths that use arc *(i,j)*. *Let* r_{od} denote the total demand in wavelengths for demand pair *(o,d)*. The new flow constraints are as follows:

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

Using the cycles determined by the routing and provisioning model, the all-optical design algorithm examines each *(o,d)* pair successively, first the working path then the protection path(s). Next, starting from node o, the wavelengths carried on each path are translated into equipment requirements while considering PMD and signal-to-noise ratio restrictions. Design of a path ends when node *d* has been provisioned. The outputs from these two algorithms provide extensive detail on the individual node and hut designs.

Another new extension to the opaque and all-optical design procedure is the unavailability calculations. Once the design is complete, unavailability for each *(o,d)* demand pair is calculated. These unavailabilities are then compared to a user set minimum value. Demand pairs with unacceptable unavailabilities are then listed as candidates for receiving additional protection paths. For each *(o,d)* demand pair in the list, supply at node *o* and demand at node *d* are incremented by 1 and the path generator model is run again. Note that for the demand pairs on the list, these newly determined routings may be completely different from the previously created paths, which then requires a rerun of the routing and provisioning procedures. This process continues until either the highest unavailability lower than the threshold value is reached or it is impossible to decrease the unavailability with additional back-up paths. The pseudo-code for this dedicated protection procedure can be found in Figure 1 and the AMPL run file can be obtained from the study web site http://engr.smu.edu/~jlk/publications.htm.

Figure 1 About Here

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4. Unavailability of DWDM Networks

Unavailability is the probability of finding a system in a non-functional state at any given time. Unavailability values are widely used by telecommunication service providers to promote the reliability of their product. As used in this study, unavailability is simply 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 0.01% (approximately).

Fiber cuts and equipment failures result in a service disruption between a given *(o,d)* demand pair. The calculation of unavailability of a component requires 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. It is also assumed that these failures occur independently of each other and each component is repaired and returned to full functional state after an expected average duration of time (*MTTR*). The following unavailability formulation provides a close approximation for such random failures when unavailability (*U*) of a single DWDM network component is in question (see Lewis 1987, To and Neusy 1994, Clouqueur and Grover 2002).

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

$$\text{if } MTTF \gg MTTR, \text{ then } U \approx (r)(MTTR) \tag{9}$$

Let A' denote availability, the complement of unavailability, then

$$A' = 1 - U = \frac{MTTF}{MTTF + MTTR} \tag{10}$$

The calculation of the unavailability of a path in a telecommunication network requires finding the unavailability 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 unavailabilities of U_k, $k=1, \ldots, K$, then the unavailability for the system is given by

$$U_{system} = 1 - \prod_{k=1}^{k=K} A'_k = 1 - \prod_{k=1}^{k=K} (1 - U_k) \tag{11}$$

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

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

If a system is composed of K redundant units working in parallel (at least one of the units must be operational in order for the system to work), then the exact unavailability for the system is given by

$$U_{system} = \prod_{k=1}^{k=K} U_k \tag{13}$$

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 will be determined and then the unavailability of the whole system can be calculated. Figure 2 illustrates an example with a working path and a node disjoint protection path linking nodes 1 and 3. It is assumed that n wavelengths ($1 \leq n \leq 80$) are simultaneously transmitted on both paths. For this investigation, it is assumed that customers require the full bandwidth for their time critical applications. Hence, single failure scenarios that may only affect part of the traffic on a path are regarded as path failures. 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. In terms of the unavailability calculations, we assume that failure of a single cable has the same effect on the traffic between a pair of demand pairs as a multiple cable failure and time required for replacing a single cable is identical to that of replacing multiple cables in a duct. In this study, a duct and the fiber inside have a single unavailability value associated with them.

Figure 2 About Here

In dedicated protection, OXCs at the demand nodes are shared among working and protection paths. In case of a failure of an OXC at node 1 or node 3 in Figure 2, a transmission disruption is inevitable. However, in long-haul networks with numerous elements in series, these intermediate elements (especially the fiber) contribute more to the system unavailability than the OXCs at the terminal nodes.

In the example network the working path is composed of 4 As, 300km of fiber and fiber duct, 2 MUX/DMUXs, 2*n* TEs and the protection path is composed of 8 As, 500km of fiber and fiber duct, 6 MUX/DMUXs, *n* Rs, 2*n* TEs, and an OXC. Since the equipment in each path forms a group that work in series the unavailabilities for the two paths can be calculated as follows:

$$U_{working} \approx 4\, U_A + 300\,(U_{Fiber/Duct}) + 2\, U_{MUX} + 2n\, U_{TE} \qquad (14)$$

$$U_{protection} \approx 8\, U_A + 500\,(U_{Fiber/Duct}) + 6\, U_{MUX} + n\, U_R + 2n\, U_{TE} + U_{OXC} \qquad (15)$$

Working and protection paths work in parallel and the group that is formed by these two paths work in series with the 2 OXCs at the demand nodes. Unavailability of the complete system is then

$$U_{system} \approx 2\ U_{OXC} + (U_{working})(U_{protection}) \tag{16}$$

Unavailability of DWDM networks can be reduced by provisioning additional protection paths for *(o,d)* demand pairs. Extension of this unavailability formulation to *m* node-disjoint protection paths can be easily accomplished by using the following formula

$$U_{system} \approx 2\ U_{OXC} + (U_{working})\prod_{j=1}^{m}(U_{protection\ j}) \tag{17}$$

Our unavailability formulations are based on the assumption that a traffic demand of n wavelengths ($1 \leq n \leq 80$) is carried on a single fiber. That is, if a traffic demand is less than the capacity of the fiber, it is assumed that it uses a single fiber. Spreading a traffic demand over several fiber links would increase the unavailability due to fiber, amplifier, and MUX/DMUX related failures. In all our test cases we assume the largest demand to be 80 wavelengths and each wavelength carries at most 40 Gbps data. If larger traffic demands are expected then the formulation should be modified to account for multiple links that are working in series for both working and protection paths. If we assume r wavelengths ($r \geq 1$) of traffic on the example network then let b be an integer that represents the number of fibers that are required. Then $b = \left\lceil \frac{r}{80} \right\rceil$ and the unavailability for the working and protection paths are

$$U_{working} = 4b\ U_A + 300\ U_{Fiber/Duct} + 2b\ U_{MUX} + 2r\ U_{TE} \tag{18}$$

$$U_{protection} = 8b\ U_A + 500\ U_{Fiber/Duct} + 6b\ U_{MUX} + r\ U_R + 2rU_{TE} + U_{OXC} \tag{19}$$

5. Empirical Analysis

To help evaluate the various aspects of the all-optical design with dedicated protection, four different test networks are used. The European test network (EU) consists of 18 nodes, 35 links and has an average node degree of 3.89. To increase the number of node-disjoint paths that can be provisioned for a demand pair, 14 new links were added to the original European network to form test network EB. This expanded version has an average node degree of 5.44. These networks are illustrated in Figure 3. The US network (US) has 24 nodes and 42 links. The North American test network (NA) has 36 nodes, 67 links and is based on a real network operated by a well-known company. These networks are illustrated in Birkan et al. (2005). All the *(o,d)* demand pairs are randomly generated and the wavelengths assigned to these demand pairs are uniformly distributed over [10,80]. The PMD values and hut locations are specified in the data file for the corresponding test network. Details on these test networks can be found in Table 2. For each test case described in Table 3, a maximum of 6 candidate paths per demand pair are used.

Figure 3 and Tables 2 and 3 About Here

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 4 About Here

An O/E/O conversion that takes place at a hut requires amplifiers, multiplexers, demultiplexers, and regenerators. Since As, MUX/DMUXs are already present at all nodes, regeneration at a node only requires the addition of Rs for each wavelength. A test was conducted to determine if savings in cost is possible by moving regeneration from a hut to a previous non-demand node thus exploiting existing As and MUX/DMUXs. 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. Table 5 presents a comparison of the two regeneration location policies. The numbers associated with a problem name correspond to the seed used in the random number generation for this test case. Total demand on the test networks varied from 887 to 11,321 wavelengths. The time required to solve the routing and provisioning models is listed under columns B and F (CPLEX Time). Even for the largest test network, NA, solving the routing and provisioning model took no more than 1 second. Note that a 5% optimality gap is used when obtaining these results. An optimality gap of 0% resulted in solution times exceeding an hour on some test cases. The unavailability of the *(o,d)* demand pair with the maximum unavailability on a given network (in terms of min/year) is also provided under columns D and H . The failure rates and MTTR values for the various equipment types can be found in Table 6. When the relocation feature was 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 fact that on long haul networks a regeneration that happens earlier than required may result in an additional regeneration.

Tables 5 and 6 About Here

The design tools for the opaque and all-optical designs with dedicated protection use a target unavailability value and attempt to add protection paths to the demand pairs that exceed this target to reduce the overall unavailability. Table 7 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. Even though the maximum unavailability exceeded the target for the EU, US, and NA networks, due to the low node degree of these networks, it was not possible to add additional backup paths. 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 Grover 2004). At the same time, network providers claim unavailabilities of less than 5 minutes annually for their transport networks. We have found some of these claims for standard long-haul networks with simple dedicated protection to be conflicting both with our observations and with the data provided by the FCC. Additional investigation of this issue is provided in Appendix A. A network with higher connectivity, EB, 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 was successful in lowering maximum unavailabilities to less than 5 minutes per year. For the EB810 problem with one hundred *(o,d)* demand pairs, the maximum unavailability is decreased from 127 minutes/year to 4.91 minutes/year by 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 4.91 million. The addition of new protection paths required two more runs of the model, increasing the processing time from 21 seconds to 46 seconds. Similarly Table 8 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.

Tables 7 and 8 About Here

If the existing network has no additional node-disjoint paths, then new links must be appended to obtain additional backup paths. For this investigation, it is assumed that additional links can be appended via a leasing arrangement. An empirical analysis is performed to test the various aspects of leasing and is summarized in Table 9. The EU test network is used in this test. Leased links are appended to EU to form a complete graph called EL. Using the same test cases both opaque and all-optical design tools were run. However, the cost function used in the original model has to be modified to incorporate the cost of leasing. Leased equipment costs 25% more than an owned counterpart (see Table 3). For the links that are leased, it is assumed that huts are 100km apart (except for the last hut) and the fiber is of good quality with small PMD values. Switching between networks requires additional TEs as well as other nodal equipment such as OXCs and MUX/DMUXs. For the EL210 problem with one hundred *(o,d)* 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.

Table 9 About Here

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6. 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 times, 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. Using this output and analyzing each *(o,d)* demand pair, all-optical design determines possible savings in cost by reducing the number of O/E/O conversions.

Unavailability of a system is the ratio of downtime to total time and is also expressed in terms of minutes per year. Once one of the designs are complete, the design tool calculates the unavailability for each *(o,d)* demand pair. These unavailabilities are then compared to a user set minimum value. Demand pairs with unavailabilities higher than this threshold value are then listed as candidates for receiving additional protection paths. The empirical analysis presented in this study demonstrated that a moderately sized DWDM network with dedicated protection can be designed in a reasonable amount of time using the proposed methods. For test networks with sufficient node degree, the design tool also proved that it can lower the unavailabilities by the addition of new protection paths. The option of leasing links for networks limited by low node degree is also considered. For the EU test network with an average node degree of 3.89, the unavailability goal was achieved by additional protection paths only when the leasing option was enabled. Relocating O/E/O conversion equipment thus exploiting existing As and MUX/DMUXs is also considered in this study. When the relocation feature was enabled, fewer As and MUX/DMUXs were used, but the total number of Rs needed increased for the EU, US, and NA test networks thus increasing equipment costs. These design tools for opaque and all-optical networks with dedicated protection can be further extended to consider other network restoration strategies, such as shared protection, to reduce the protection costs while providing an adequate level of redundancy.

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Appendix A Unavailability Analysis

Consider the example network in Figure A.1 where only the fiber links are of concern to us. There are two paths in this network from node 1 to node 2. We assume that n wavelengths (1≤ n ≤80) are simultaneously transmitted on both paths. The working path is 1500 km (932 miles) and the protection path is 2000 km (1242 miles) in length. The average link lengths for our test networks are 543 km for the US, 799 km for the NA, and 845 km for the EU; the average hop counts for the paths on our test networks are approximately 3.7 for the US, 3.3 for the NA, and 2.2 for the EU; and the average path lengths for our test networks are approximately 2800 km for the US, 3300 km for the NA, and 2200 for the EU.

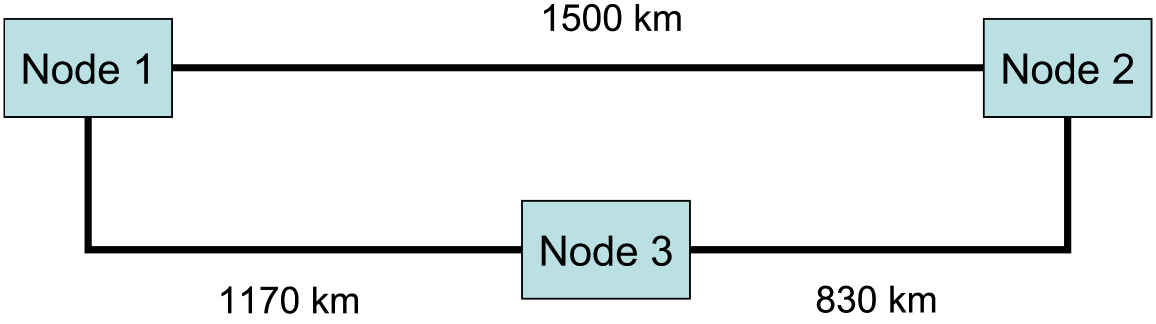

Figure A.1 Example Network

Mean time required for fiber link repair (or replacement) is 12 hours which is generally in the range of 12 to 14 hours in the literature (see El-Torky and Lafleur 2000, Grover 2004, and To and Neusy 1994). Then the unavailability of the working path is 0.003826 or 33.5 hours annually. If we consider both paths in a dedicated protection arrangement, then the unavailability drops down to 0.0000195 or 10 minutes annually. Even without considering the other crucial equipment on the paths, we are well over the advertised unavailability. For example, with 40 wavelenghts of traffic and the supporting equipment (see Figure A.2) we obtain an unavailability of 18.46 minutes for this example network. For this analysis it is assumed that any component failure results in a path failure. The detailed calculations for the network in Figure A.2 are given in Table A.1. Even for this small test network, unavailability is almost four times the value claimed by many service providers.

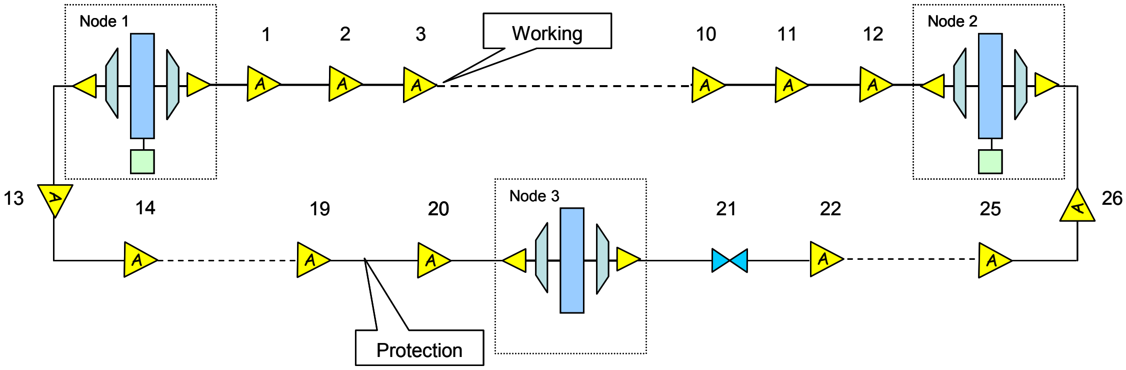

Figure A.2 Example Network

Table A.1 Unavailability Calculations for the example network in Figure A.2

Equipment	Failure Rate	MTTF(yrs)	MTTF(hrs)	MTTR(hrs)	Avail	Unavail
A	4.22508E-06	27.0	236,682	2.0	0.999992	8.45E-06
Fiber	2.12566E-07	536.7	4,704,420	12.0	0.999997	2.55E-06
MUX	4.98153E-07	229.0	2,007,414	2.0	0.999999	9.96E-07
OXC	1.96685E-06	58.0	508,428	2.0	0.999996	3.93E-06
R	3.35521E-06	34.0	298,044	2.0	0.999993	6.71E-06
TE	3.35521E-06	34.0	298,044	2.0	0.999993	6.71E-06

	Working Path		
	Quantity	**Avail**	**Unavail**
As	14	0.999881705	0.0001183
Fiber	1500	0.996181126	0.0038262
MUXs	2	0.999998007	1.993E-06
TEs	80	0.999463312	0.0005368
Total		0.995516697	0.0044833

	Protection Path		
	Quantity	**Avail**	**Unavail**
As	19	0.999839461	0.0001606
Fiber	2000	0.994911412	0.0051016
MUXs	6	0.999994022	5.978E-06
OXCs	1	0.999996066	3.934E-06
Rs	40	0.99973162	0.0002684
TEs	80	0.999463312	0.0005368
Total		0.99392272	0.0060773

Working & Protection Path Unavailability (parallel)	2.72463E-05
Working & Protection Path Availability (parallel)	0.999972754
Include OXCs at the demand nodes	0.999964887
Total Unavail	3.51134E-05
hrs/yr	0.307804195
mins/yr	18.4682517

As discussed in Section 4, some failure scenarios do not necessarily cause path failures. In order to model this kind of behavior, we need to compute the unavailability of components where only *K* out of *M* of them are sufficient for the path to be considered operational. The following formulations (see Malek 2004) can be used to model *K* out of *M* components assuming they are identical in terms of MTTR and MTTF.

$$MTTR_{SYSTEM} = \frac{MTTR}{M-K+1}$$

$$MTTF_{SYSTEM} = MMTF\left(\frac{MTTF}{MTTR}\right)^{M-K}\left(K\binom{M}{K}\right)^{-1}$$

$$= MMTF\left(\frac{MTTF}{MTTR}\right)^{M-K}\left(\frac{(M-K)!(K-1)!}{M!}\right)$$

The unavailability of the system is then:

$$U = \frac{MTTR_{SYSTEM}}{MTTF_{SYSTEM} + MTTR_{SYSTEM}}$$

The formulation above can be used in systems where there is redundant equipment in place (such as redundant TEs that replace the failed ones). Such arrangements help reduce and even eliminate the effects of that equipment type on overall unavailability of the path. In order to calculate unavailability when partial failures are permitted, some assumptions are required. Suppose the traffic requirement on a path is $m > 1$ wavelengths, then there are at least *m* pairs of TEs at the demand nodes. If there is a hut or a node where regeneration is required, then there are also *m* Rs. The first assumption is related to TEs and Rs. If a TE or an R for a specific wavelength fails, then this is a partial failure affecting only a single wavelength. Using the example network in Figure A.2, we define the subsystems composed of TEs and Rs on each path, where K out of M working are sufficient for the path to be considered operational. In the case shown below, if more than 25% of these subsystems (TEs and Rs) fail then the path is considered down for repair. From Table A.2 , we see that TEs and Rs have almost no effect on overall system unavailability.

Table A.2 Unavailability Calculations for the 2 subsystems in Figure A.2

	Subsystems	
	2TEs (Working Path)	2TEs&R (Protection Path)
MTTF(hrs)	149022	99348
Avail	0.999986579	0.999979869
MTTR(hrs)	2.00000671	2.000013421
Unavail	1.34207E-05	2.0131E-05
	K out of M Calculations	
M	40	40
K	30	30
MTTR(hrs)	0.181818792	0.181819402
MTTF(hrs)	3.09098E+43	3.57337E+41
Avail(approx)	1	1
Unavail	0	0

A single amplifier failure acts as a glass-through and we lose some of the traffic but not all, is the second assumption. The following table summarizes the unavailability calculations for the amplifiers in the working and protection paths.

Table A.3 Unavailability Calculations for the Amplifiers in Figure A.2

	As in the Working Path	As in the Protection Path
M	14	19
K	13	18
MTTR	1	1
MTTF	153896618.5	81898200.47
Avail	0.999999994	0.999999988
Unavail	6.49787E-09	1.22103E-08

Finally, the detailed calculations for the network in Figure A.2 with partial failures are given in Table A.4. Note that when the two scenarios are adopted the overall unavailability dropped from 18.46 minutes to 14.38 minutes per year. Even with these liberal assumptions on partial failures, the unavailability is substantially more than the 5 minutes/year.

Table A.4 Unavailability Calculations for the Network in Figure A.2

		Working Path		
	Total	**Required**	**Avail**	**Unavail**
As	14	13	0.999999994	6.49787E-09
Fiber	1500	1500	0.996181126	0.003818874
MUXs	2	2	0.999998007	1.99261E-06
TEs	40	30	1	0
Total			0.996179135	0.003820865

		Protection Path		
	Total	**Required**	**Avail**	**Unavail**
As	19	18	0.999999988	1.22103E-08
Fiber	2000	2000	0.994911412	0.005088588
MUXs	6	6	0.999994022	5.97782E-06
OXCs	1	1	0.999996066	3.93368E-06
TEs + Rs	40	30	1	0
Total			0.994901539	0.005098461

Working & Protection Path Unavailability (parallel)	1.94805E-05
Working & Protection Path Availability (parallel)	0.999980519
Include OXCs at the demand nodes	0.999972652
Total Unavail	2.73477E-05
hrs/yr	0.239730108
mins/yr	14.38380646

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

Table 2: Test Network Descriptions

Name	Nodes	Links	Node Degree	*(o,d)* Pairs	Demand	DPMD	Total Huts	Distance Between Huts
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]

Table 3: Test Problem Characteristics

Problems	Number of Demand Pairs	Average 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

Table 4: 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

Table 5: Empirical Analysis for Test Problems Using Dedicated Protection with and without Regeneration Relocation

	Dedicated Protection without Regeneration Relocation				Dedicated Protection with Regeneration Relocation				$\frac{[E]-[A]}{[A]}$
Problem Name	[A] Cost (000,000)	[B] CPLEX Time	[C] Total Time	[D] Max Unavail. (Min/Yr)	[E] Cost (000,000)	[F] CPLEX Time	[G] Total Time	[H] Max Unavail. (Min/Yr)	Cost Difference
EU110	2.02	00:00:01	00:01:34	91	2.09	00:00:01	00:01:44	97	3.47%
EU160	2.73	00:00:01	00:02:41	149	2.80	00:00:01	00:02:55	152	2.56%
EU210	4.21	00:00:01	00:03:58	129	4.34	00:00:01	00:04:00	130	3.09%
EU260	4.81	00:00:01	00:05:35	136	4.92	00:00:01	00:05:36	138	2.29%
US310	4.71	00:00:01	00:06:48	129	5.05	00:00:01	00:06:57	142	7.22%
US360	7.69	00:00:01	00:14:00	130	8.19	00:00:01	00:14:03	137	6.50%
US410	10.49	00:00:01	00:22:37	130	11.20	00:00:01	00:22:48	137	6.77%
US460	13.60	00:00:01	00:36:39	139	14.52	00:00:01	00:35:09	147	6.76%
NA510	5.48	00:00:01	00:22:07	208	5.80	00:00:01	00:21:17	212	5.84%
NA560	8.64	00:00:01	00:34:42	208	9.07	00:00:01	00:34:06	213	4.98%
NA610	11.51	00:00:01	00:49:56	214	12.18	00:00:01	00:49:27	219	5.82%
NA660	14.15	00:00:01	01:05:12	233	14.86	00:00:01	01:04:15	232	5.02%

Table 6: Failure Rates and 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

Table 7: Empirical Analysis for Test Problems Using Opaque Design and Dedicated Protection with Target Unavailability of 5 Min/Year

Problem Name	[A] As	[B] Rs	[C] TEs	[D] Cost (000,000)	[E] CPLEX Time	[F] Total Time	[G] Max Unavail. (Min/Yr)	[H] New Paths Added	[I] Total Time	[J] Final Max Unavail. (Min/Yr)	[K] Final Cost (000,000)
EU110	1709	2017	25570	2.61	00:00:01	00:00:07	121	0	00:00:07	121	2.61
EU160	2445	2571	34860	3.55	00:00:01	00:00:10	201	0	00:00:10	201	3.55
EU210	3513	4088	53436	5.42	00:00:01	00:00:13	153	0	00:00:13	153	5.42
EU260	3988	4357	61500	6.18	00:00:01	00:00:17	172	0	00:00:17	172	6.18
US310	3040	2135	72826	6.58	00:00:01	00:00:15	238	0	00:00:15	238	6.58
US360	4924	3363	119520	10.77	00:00:01	00:00:27	225	0	00:00:27	225	10.77
US410	6642	4598	164920	14.82	00:00:01	00:00:44	225	0	00:00:44	225	14.82
US460	8679	6533	211448	19.12	00:00:01	00:01:04	237	0	00:01:04	237	19.12
NA510	5421	6375	72342	7.58	00:00:01	00:00:24	279	0	00:00:24	279	7.58
NA560	8440	10226	111900	11.79	00:00:01	00:00:37	297	0	00:00:37	297	11.79
NA610	11059	14603	148454	15.77	00:00:01	00:00:52	297	0	00:00:52	297	15.77
NA660	13629	16557	184648	19.36	00:00:01	00:01:09	332	0	00:01:09	332	19.36
EB710	1510	1264	17284	1.81	00:00:01	00:00:15	83	50	00:00:18	4.90	2.71
EB760	2498	1882	30266	3.10	00:00:01	00:00:17	122	78	00:00:32	4.90	4.81
EB810	3310	2449	42268	4.27	00:00:01	00:00:21	127	104	00:00:46	4.91	6.58
EB860	3846	3368	51150	5.21	00:00:01	00:00:25	122	130	00:01:03	4.95	8.14

Table 8: Empirical Analysis for Test Problems Using All-Optical Design and Dedicated Protection with Target Unavailability of 5 Min/Year

Problem Name	[A] As	[B] Rs	[C] TEs	[D] Cost (000,000)	[E] CPLEX Time	[F] Total Time	[G] Max Unavail. (Min/Yr)	[H] New Paths Added	[I] Total Time	[J] Final Max Unavail. (Min/Yr)	[K] Final Cost (000,000)
EU110	1780	6789	8788	2.02	00:00:01	00:01:34	91	0	00:01:34	91	2.02
EU160	2540	8909	12116	2.73	00:00:01	00:02:41	149	0	00:02:41	149	2.73
EU210	3639	14236	18648	4.22	00:00:01	00:03:58	129	0	00:03:58	129	4.21
EU260	4143	16090	21448	4.81	00:00:01	00:05:35	136	0	00:05:35	136	4.81
US310	3222	19598	16112	4.71	00:00:01	00:06:48	129	0	00:06:48	129	4.71
US360	5208	32658	25164	7.69	00:00:01	00:14:00	130	0	00:14:00	130	7.69
US410	7005	44420	35004	10.49	00:00:01	00:22:37	130	0	00:22:37	130	10.49
US460	9139	58335	9139	13.60	00:00:01	00:36:39	139	0	00:36:39	139	13.60
NA510	5625	20395	18176	5.48	00:00:01	00:22:07	208	0	00:22:07	208	5.48
NA560	8742	32840	27944	8.64	00:00:01	00:34:42	208	0	00:34:42	208	8.64
NA610	11444	44194	36972	11.51	00:00:01	00:49:56	214	0	00:49:56	214	11.51
NA660	14095	54251	45632	14.15	00:00:01	01:05:12	233	0	01:05:12	233	14.15
EB710	1559	4425	8216	1.58	00:00:01	00:03:32	81	50	00:09:22	4.79	2.34
EB760	2586	7739	12968	2.63	00:00:01	00:05:27	106	78	00:23:37	4.78	3.97
EB810	3415	10389	18160	3.56	00:00:01	00:07:44	95	104	00:33:58	4.85	5.50
EB860	3981	13229	22188	4.41	00:00:01	00:10:15	106	130	00:46:15	4.92	6.89

Table 9: Empirical Analysis for Test Problems Using Dedicated Protection with Target Unavailability of 5 Min/Year

	Problem Name	[A] Cost (000,000)	[B] CPLEX Time	[C] Total Time	[D] Max Unavail. (Min/Yr)	[E] New Paths Added	[F] Total Time	[G] Final Max Unavail. (Min/Yr)	[H] Number of Links Leased	[I] Leased Cost (000,000)	[J] Final Cost (000,000)
Opaque	EL110	2.61	00:00:01	00:00:09	121	52	00:00:20	4.97	23	0.40	3.56
	EL160	3.55	00:00:01	00:00:13	201	79	00:00:33	4.98	32	0.70	4.91
	EL210	5.42	00:00:01	00:00:17	153	110	00:00:50	4.99	43	1.12	7.60
	EL260	6.18	00:00:01	00:00:22	172	135	00:01:07	4.85	49	1.28	8.54
All-Optical	EL110	2.02	00:00:01	00:04:12	91	50	00:10:40	4.92	21	0.26	2.85
	EL160	2.73	00:00:01	00:06:50	149	78	00:27:07	4.77	32	0.51	3.89
	EL210	4.22	00:00:01	00:08:46	129	105	00:38:51	4.98	39	0.72	6.07
	EL260	4.81	00:00:01	00:12:31	137	130	00:50:46	4.98	46	0.84	6.74

```
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
        $P(o,d) \leftarrow \emptyset$;
        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 $(o,d) \in D$;
      $T \leftarrow \emptyset$;
      $\forall (o,d) \in D$ 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

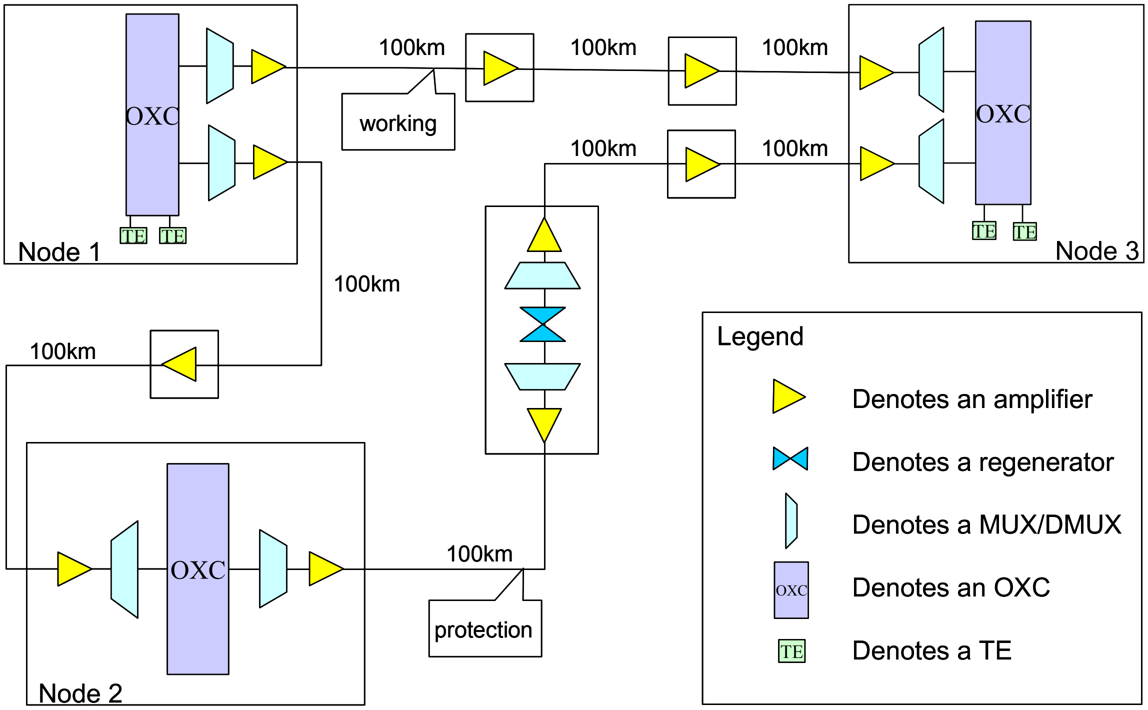

Figure 2: Example Network

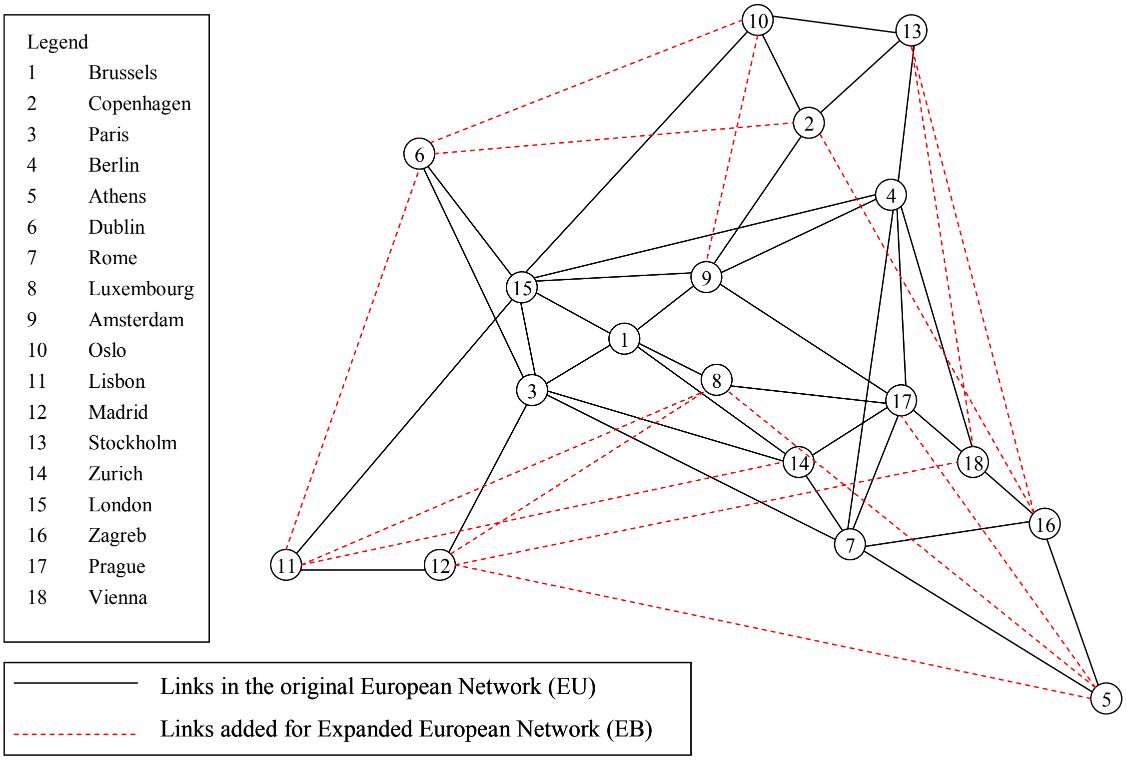

Figure 3: European Test Network