

## **Technical Report 03-EMIS-01**

# **Practical Integrated Design Strategies for Opaque and All-Optical DWDM Networks: Optimization Models and Solution Procedures**

Giray A. Birkan<sup>1</sup>, Jeffery L. Kennington<sup>1,\*</sup>, Eli V. Olinick<sup>1</sup>,  
Augustyn Ortynski<sup>2</sup>, Gheorghe Spiride<sup>3</sup>

<sup>1</sup>*EMIS Department, School of Engineering, Southern Methodist University, Dallas, TX 75275, USA*

<sup>2</sup>*Amazon.Com, Seattle, WA 98101, USA*

<sup>3</sup>*Nortel Networks, Richardson, TX 75081, USA*

**EMIS Department**  
**School of Engineering**  
**Southern Methodist University**  
**Dallas, TX 75275**

**Revised March 3, 2005**

---

\* Corresponding author. Fax: +1-214-768-1122  
Email address: [jlk@engr.smu.edu](mailto:jlk@engr.smu.edu) (J. L. Kennington) 02/20/05

# Practical Integrated Design Strategies for Opaque and All-Optical DWDM Networks: Optimization Models and Solution Procedures

Giray A. Birkan<sup>1</sup>, Jeffery L. Kennington<sup>1,\*</sup>, Eli V. Olinick<sup>1</sup>,  
Augustyn Ortynski<sup>2</sup>, Gheorghe Spiride<sup>3</sup>

<sup>1</sup>*EMIS Department, School of Engineering, Southern Methodist University, Dallas, TX 75275, USA*

<sup>2</sup>*Amazon.Com, Seattle, WA 98101, USA*

<sup>3</sup>*Nortel Networks, Richardson, TX 75081, USA*

---

## Abstract

Dense wavelength division multiplexing (DWDM) networks that use expensive optical/electrical/optical (O/E/O) conversion at each end of a fiber link are called *opaque networks*. In an attempt to reduce the O/E/O conversion cost component, a combination of technological advances has been used. Improved optical amplifiers using distributed Raman amplification allow signals to traverse longer distances without amplification and/or regeneration. Optical switches are also available so that most of the processing at nodes can be accomplished in the optical domain. Networks that use this equipment to eliminate some of the O/E/O conversions are called *transparent* or *all-optical networks*. Capital costs for these types of networks are less expensive, however operational costs and complexity increases in order to handle adjustments in traffic demand. In this investigation we develop optimization-based algorithms to route traffic and design DWDM links for both opaque and all-optical networks. We compare the performance of AMPL/CPLEX implementations of both algorithms on realistically sized networks with up to 36 nodes and 67 links. In all test cases the all-optical network design is substantially less expensive than the traditional opaque network design with cost reductions in the range of 12% to 26%.

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

---

\* Corresponding author. Fax: +1-214-768-1122

Email address: [jlk@engr.smu.edu](mailto:jlk@engr.smu.edu) (J. L. Kennington) 02/20/05

## 1. Introduction

DWDM networks are composed of optical fiber, optical amplifiers and multiplexers/demultiplexers, regenerators, terminal equipment, and optical switches. Both fiber quality and amplifiers and nodal equipment sizes may be different in a network. Optical amplification performed at certain intervals along a fiber span is used to compensate for the inherent signal deterioration caused by propagation through the fiber. However, optical amplifiers boost not only the signal but also noise. Consequently, the original signal must be recovered and regenerated after a certain number of amplifications. Regeneration traditionally involves an expensive optical/electrical/optical (O/E/O) conversion requiring a combination of regenerators, multiplexers, demultiplexers, and optical amplifiers.

The DWDM design problem is to determine the routing of specified point-to-point traffic demands and the corresponding placement and provisioning of optical equipment components that satisfy these demands. The optimal solution to this problem results in a specification for a least-cost network that can be used to satisfy the demand forecasts and that meets technological restrictions for signal regeneration. Depending upon the quality of the fiber, expensive O/E/O conversion must occur at specified intervals. The technological restrictions that determine these distances are complicated, involve nonlinear loss functions, and do not lend themselves to straightforward optimization modeling. Creating an optimal design for a DWDM transport network is an extremely difficult combinatorial optimization problem and is very dependent upon the characteristics of the optical amplifiers used. The key parameters for these amplifiers are the maximum distance that a signal can traverse without amplification, called the *optical*

*reach*, and the maximum number of amplified spans above which signal regeneration is required, called the *max spans*. For example, in a system characterized by optical reach of 130 km and a max spans value of 9, the maximum distance between amplifiers is 130 km and regeneration is required after at most 8 amplifications.

Recall the definition of an opaque network as one where O/E/O conversion equipment is present at each node in the network: this simplifies the design process because it allows the problem to be decomposed on the links of the network (Ramaswami and Sivarajan, 2002). Hence, an optimal design is simply the combination of optimal link designs. Until recently, optical amplifiers had relatively small values for both the optical reach and max spans parameters. Hence, this design strategy and the resulting opaque networks made the most efficient use of the equipment. However, recent advances in the commercial production of long-reach optical amplifiers and optical switches resulted in significant increases for the optical reach and max spans parameters. Lower-cost designs can now be constructed by installing O/E/O conversion equipment along the path for a traffic demand only where required by technological restrictions. These ideas drive the emergence of *all-optical networks* that employ a path-based design strategy, in contrast to the link-based approach used traditionally.

For this investigation, we developed procedures and software for constructing both an opaque and all-optical network design in an integrated system. Given a network topology, a set of potential hut locations and a set of traffic demand requirements, the system employs an arc-path optimization model to determine traffic demand routings in an attempt to minimize overall capital costs. We also developed test cases and evaluated both design strategies in an empirical analysis. In all test cases considered in this study,

the all-optical network designs confirm the expectation of a substantially lower cost than the corresponding opaque network designs, while the additional computational effort needed to obtain an all-optical network design is remarkably modest (less than 4.5 minutes) even in the most difficult test cases. However, the costs savings come at the expense of potentially additional operational costs due to new demands and/or some demands being terminated. Changes to the traffic demand set for an opaque network may require re-optimization on a per link basis, whereas changes to the all-optical network design may call for the simultaneous consideration of multiple links.

### *1.1 Survey of the Literature*

Much of the published research in the area of DWDM network design addresses some version of the routing and wavelength assignment (RWA) problem. We only give a brief overview of the RWA literature here; for a comprehensive survey see Zang et al. (2000). Most investigations develop designs for mesh networks, but the literature also includes procedures for the special cases of ring and star topologies. Assumptions about the nature of the demand pattern that will be placed on the network, static or dynamic, give rise to other variants of the problem. Some versions of the RWA problem permit the use of wavelength converters while others impose the so-called continuity constraint that prohibits wavelength conversion. Another source of variation in RWA problems comes from the choice of protection scheme that the network will use to restore service in the event of link and/or node failures. Protection is usually provided for single link and/or single node failures, and uses one of three strategies: dedicated protection, p-cycle protection, or shared protection. Birkan et al. (2002) give an overview of these protection schemes.

The largest number of variations of the RWA problem is related to the objective being optimized. Many of the versions of the RWA problem for the case of static demands can be modeled as integer linear programs (ILPs). They are rather complicated multicommodity routing models and most investigations present a specialized heuristic procedure to obtain a feasible design. Zhang and Acampora (1995) present a heuristic procedure based upon simulated annealing that seeks to minimize average propagation delay. Ramaswami and Sivarajan (1995) introduce an ILP model whose objective is to maximize the number of connections that are successfully routed. The linear programming relaxation of their model is used to provide an upper bound on an optimal solution. The upper bound provides a metric against which the performance of different heuristics can be measured. Subramaniam et al. (1999) investigate the problem of converter location on a path such that blocking probability is minimized. An ILP for minimizing congestion in a DWDM network without wavelength conversion is given by Krishnaswamy and Sivarajan (2001). Using IBM's Optimization Subroutine Library, they were able to use this model to find an optimal design for a 14-node network.

Mukherjee et al. (1996) develop a very sophisticated and difficult-to-solve nonlinear integer program aimed at upgrading the NSFNET. A pair of heuristics was developed to obtain feasible designs. This is one of the first investigations in which upgradeability issues are addressed. A revision of this model involving only linear functions may be found in Banerjee and Mukherjee (2000). Several simplifying assumptions are used to engineer the model into one for which problem instances are computationally tractable. The basic idea is for the network designers to seek a balance between the time required to obtain a solution and the quality of the solution. They also found that early termination

of the branch-and-bound procedure in CPLEX provided quite good solutions for their test cases.

As noted by Gerstel and Ramaswami (2000) amongst others, and at least implied throughout the literature, customers in the telecommunications industry demand high reliability from their networks and will generally accept a maximum downtime of six minutes per year on average. This requirement prompts network providers to typically build spare capacity, in the form of redundant optical fibers and node equipment into their designs to guard against service disruptions caused by link and/or node failures. The equipment used during normal conditions is referred to as the *working network* and the spare capacity is referred to as the *protection network*.

Alanyali and Ayanoglu (1999) describe models and heuristic procedures for both the working network and the protection network. The objective was to minimize total fiber miles in the resulting network and they tested their procedures on a problem instance with 32 nodes and 50 links. Designing fault-tolerant networks is also the subject of the investigation by Miyao and Saito (1998). Their cost model assumes that the transmission, multiplexing, and cross-connection costs are proportional to the total fiber length, the total number of fibers, and the total number of optical cross connects needed. Computational results are reported on a 14-node problem. An ILP model and three-step heuristic method for a fault-tolerant network using dedicated protection paths can be found in Kennington et al. (2003b). Wavelengths are assigned in blocks and translation is not permitted. The cost structure involves complete subnetworks and photonic switches. An extension of this study that considers wavelength translation is presented in Kennington and Olinick (2004).

The work most closely related to our investigation is described in Yang et al. (2003). Their translucent network is identical to our all-optical network. They apply dynamic programming to determine optimal regenerator placement while our algorithms use integer linear programming. Our algorithms also determine the placement of MUX/DMUX equipment and incorporate more detailed technological restrictions. Ramamurthy et al. (1999) compared blocking probabilities of transparent, opaque, and translucent networks on interconnected-rings using simulation techniques. In their study, transparent networks do not allow O/E/O conversion to take place at intermediate locations.

The notion of traffic demand uncertainty has been addressed in Birkan et al. (2002) and Kennington et al. (2003a). The robust optimization methodology as described in Mulvey et al. (1995) has been adapted for the DWDM routing and provisioning problem. Empirical comparisons with a stochastic programming model, a mean value model, and a worst-case model are given. In all cases, problem instances that used the robust optimization model produced superior designs.

Since ring network topologies may be used to provide automatic protection, there is great interest in designs that meet point-to-point demands over a network composed entirely of rings. Ring versions of the RWA problem are investigated by Berry and Modiano (2000), Lee et al. (2000), and Calinescu et al. (2002). Design issues for optical star networks are discussed by Dasylva and Srikant (1999).

Issues related to the operation, administration, and maintenance of DWDM transmission networks may be found in Tada et al. (1996) and Maeda (1998). An

excellent discussion of the economic issues related to the design of a long-haul system appears in Dowdell et al. (2003).

### *1.2 Contributions*

Three contributions are claimed. First, this manuscript presents the most comprehensive version of the DWDM design problem that has been published to date in the technical literature. For the first time, polarization mode dispersion restrictions and uneven hut spacing are considered in the problem statement. In addition, the cost function to be optimized involves specific equipment needed for provisioning an actual optimal design and specifies the actual routing of traffic demands throughout the given network topology. Second, an integrated network design strategy is presented. It involves solving a special shortest path algorithm at each evaluation point in a search over the design space, followed by an optimization-based routing and provisioning algorithm. The shortest path problems are different for each link and are used to determine optimal equipment placement in the huts. The integrated network design approach results in solutions for both an opaque and an all-optical network design, and provides the opportunity to compare the two strategies. Using an empirical evaluation across realistically sized network topologies and traffic demand sets not only the two design strategies but also the practicality of the proposed solution approaches are compared. In every test case considered, the new all-optical strategy resulted in substantial cost savings.

## 2. The DWDM Design Problem

A DWDM transport network is composed of fiber, terminal equipment (TEs), optical amplifiers (As), regenerators (Rs), multiplexers (MUXs), demultiplexers (DMUXs), and switches called optical cross connects (OXC). The TEs and the Rs operate on a single wavelength ( $\lambda$ ) and perform O/E/O conversion. For this design problem, it is assumed that dark fiber is available for use at no additional cost and that it can be lit by the installation of TEs, As, Rs, MUXs, DMUXs, and OXC located at appropriate points in the network. In long haul networks such as DWDM transport networks, demands originate and terminate in large metropolitan areas/cities which are referred to as nodes in this study. A simple link with TEs at the end nodes and As and Rs at the appropriate positions between the nodes is illustrated in Figure 1. The TEs and Rs must be accompanied by MUX/DMUX equipment and the equipment at the intermediate positions along the link must be placed in equipment-storage locations, *huts*. In this figure there are 40 TEs, 20 Rs, 7 As, 2 MUXs, 2 DMUXs, and 2 OXC. As a matter of terminology, amplifiers co-located with optical switches or regenerators are referred to as pre-amplifiers or post-amplifiers in some studies. In this study, there is no distinction made between pre-amplifiers, post-amplifiers, and optical amplifiers with respect to either cost or capabilities. Although WDM links are bi-directional in general, for clarity Figure 1 only shows equipment required for signals traveling in one direction, while assuming that fiber type and quality on both directions for the same link is identical. Not all physical hut locations present on a link need be used, depending on the specific combination of link length, link budget, amount of traffic carried, etc.

-----  
Figure 1 About Here  
-----

### *2.1 Amplification and Regeneration*

Optical amplifiers boost the entire signal in a given fiber. Due to transmission impairments on the signal quality after a signal travels through several optical components, regeneration will be required at certain places along a link or path. The *link budget* values (also referred to as optical reach) and *max span* values given in Table 1, provide the parameters for one of the rules used to determine the maximum allowable distance that can be traversed before O/E/O conversion is needed. For example, a link budget of 150 implies that max span is 4, which means that the maximum distance between amplification sites is 150 km with at most three amplifications between O/E/O conversions. For a link budget of 116, amplification must occur within 116 km and O/E/O conversion must occur after at most 15 amplifications. A 900 km link using a link budget of 150 is illustrated in Figure 2. Note that in this study, the term *span* refers to the fiber between amplifiers while a *segment* refers to the spans between two O/E/O conversions. In Figure 2 one segment is composed of four spans while the other only has two. While hut locations in this example are equally spaced, that is not necessarily the case in general.

-----  
Table 1 and Figure 2 About Here  
-----

### *2.2 Polarization Mode Dispersion*

Amplification and regeneration restrictions in high data rate (40 Gbps) transmission systems are further complicated by the quality of the fiber. Light traveling along a single

mode fiber has a pair of polarization modes that move toward the receiver at right angles to each other. When the core of the fiber is not perfectly symmetrical, light traveling along the two axes moves at slightly different speeds. After a sufficiently long distance, this effect can change the shape of the pulses enough so that interference between pulses occurs. This phenomenon is called *polarization mode dispersion* (PMD), Ramaswami and Sivarajan (2002). One way to mitigate the effect of PMD is by the installation of regenerators at distances that may be shorter than those required for satisfaction of the link budget. Hence, PMD restrictions provide a second rule for determining the maximum distance between O/E/O conversions.

Let DPMD denote the *polarization mode dispersion parameter* associated with a given fiber. These constants are generally in the range of 0.1 to 2.0 and are measured in units of (picoseconds/km)<sup>1/2</sup>, with larger values implying poorer quality fiber. Proper operation of poor quality fiber at high data rates requires short distances between O/E/O conversions. For this investigation, PMD restrictions for a single fiber force regeneration to occur within at most  $K / DPMD^2$  km, where the constant K is equipment dependent. For this investigation K is set to 900. Hence, for fiber with a DPMD of 1.1, regeneration must occur within 743 km. It is possible that different fiber types of various qualities are used to link some origin node to some destination node with intermediate nodes. Let  $d_i$  denote the length of fiber  $i$  and  $DPMD_i$  denote the polarization mode dispersion parameter for fiber  $i$  in a path, then the following inequality must be satisfied.

$$\sum_{i=1}^n (DPMD_i)^2 (d_i) \leq K$$

If this inequality does not hold, then O/E/O conversion must occur at some intermediate point along the segment. Figure 3 illustrates an example of this case, where a path/segment extends across multiple links.

-----  
Figure 3 About Here  
-----

### 2.3 Hut Spacing

Technological restrictions on the maximum distance between amplification and O/E/O conversion sites are determined by the link budget and PMD considerations noted previously. A further complicating feature is that the equipment placed along a link (As, Rs, MUXs, DMUXs) must be installed in existing huts on this link. Due to differences in the terrain as well as previously installed equipment, the huts may not be evenly spaced along a link. For the example illustrated in Figure 4, a link budget of 120 could be satisfied by using amplification only at huts 1 and 3. The equipment in a hut that does not contain any active amplification or regeneration equipment is referred to as a *glassthrough* in this study. Hut 2 from Figure 4 contains a *glassthrough*. A design that uses a link budget of 118 will require amplification at all three huts, since the span between hut 1 and 3 is 119km long, and therefore exceeds the link budget.

-----  
Figure 4 About Here  
-----

### 2.4 The DWDM Design Problem

In simplest terms, the *DWDM design problem* may be stated as follows:

*Given the network topology with known hut locations, the point-to-point demands with candidate paths, and DPMD values associated with each link, determine the*

*choice of an optimal link budget for each link and least cost routing to satisfy the point-to-point demands and polarization mode dispersion restrictions.*

The first challenge for this design problem is to determine where O/E/O conversion will take place. Conversion can be accomplished via the installation of TEs at nodes and the installation of regenerators at nodes and in huts along a link. Since extra O/E/O conversion equipment can always be installed to meet the link budget and PMD restrictions, it is easy to obtain a feasible design. The second challenge is to determine the least cost routing using the optimal link designs.

### **3. Opaque and All-Optical Network Designs**

Traditionally, the DWDM design problem has been solved by decomposing the problem into a set of individual link design problems. That is, the point-to-point demands can be accumulated so that the total traffic on each link is known. By inserting O/E/O equipment (TEs) at each node, an optimal opaque network design is simply a combination of the optimal link designs. Hence, O/E/O conversion will occur at every node and may also be required at some of the huts along a link. In this investigation, an all-optical design strategy is proposed which does not require O/E/O conversion at every node. Therefore, fewer TEs will be required at the expense of additional Rs. Our empirical analysis is designed to help evaluate these two designs.

#### *3.1 Hut Selection Algorithm*

The first step in the design process involves the selection of huts for placement of optical amplifiers. This can be accomplished by solving a greedy algorithm for each (link, link budget) combination. Let  $B$  denote a given link budget from Table 1. Suppose

a link has  $n$  huts. Then the origin node corresponds to hut 0 and the destination node corresponds to hut  $n+1$ , for a total of  $n+2$  huts. Huts 0 and  $n+1$  always have amplification. The objective is to select a minimum number of huts from the remaining huts  $(1, \dots, n)$  for amplification, such that the distance between the huts with amplification does not exceed  $B$ . Starting from hut 0, the next amplification occurs at the hut ( $H_1$ ) that is furthest away from hut 0, such that the total distance between the huts is no more than  $B$ . The next amplification occurs at the hut ( $H_2$ ) that is furthest from  $H_1$  such that the total distance between  $H_1$  and  $H_2$  is no more than  $B$ . This continues until hut  $n+1$  is reached. It can be shown that this greedy procedure which will be called the *hut selection algorithm*, yields the minimum number of amplifiers required for a given (link, link budget) combination.

In order to validate this claim a directed shortest path formulation of this problem is now presented. Let  $V = \{0, \dots, n+1\}$  and  $\bar{d}_h > 0$  denote the distance from hut  $h-1$  to hut  $h$ ,  $1 \leq h \leq n$ . Let  $A = \{(i, j) : i, j \in V, i < j, \sum_{h=i+1}^{h=j} \bar{d}_h \leq B\}$ . The selection of the minimum number of huts for amplification can be determined by finding the shortest directed path from node 0 to node  $n+1$  on the graph  $G = [V, A]$  where the length of each arc is one. Clearly  $G$  is acyclic. Finding a shortest path in an acyclic network with unit arc lengths can be achieved using a breadth-first search (see Ahuja et al. 1993). The length of the directed shortest path from node 0 to node  $n+1$  in  $G$  indicates the number of huts chosen for amplification, and the amplifiers will be placed at each node (hut) in the shortest path.

**Proposition:** Suppose  $i$ ,  $j$ , and  $k$  are nodes in graph  $G$  such that  $i < j < k$ . If  $(i, k) \in A$ , then  $(j, k) \in A$ .

**Proof:** If  $(i, k) \in A$  then  $\sum_{h=i+1}^{h=k} \bar{d}_h \leq B$ . Since  $\sum_{h=j+1}^{h=k} \bar{d}_h < \sum_{h=i+1}^{h=k} \bar{d}_h$ ,  $\sum_{h=j+1}^{h=k} \bar{d}_h \leq B$ .

Hence,  $(j, k) \in A$ .

This proposition implies that the nodes (huts) further along the link that can be reached from node (hut)  $i$  with a single hop, such as  $k$ , can also be reached from node  $j$  with a single hop. Due to this property, the bread-first search need not visit every node to determine the shortest path from 0 to  $n+1$ . At each iteration, the bread-first search determines a set of nodes to be added to the search tree. Appending only the node with largest value (index) and ignoring the other elements in the set results in a shortest path from 0 to  $n+1$  in the least amount of steps.

### 3.2 The Opaque Network Design

Suppose the design problem has  $L'$  links. For each link, the best link budget will correspond to one of the 24 values from Table 1, without loss of generality. To obtain this value, the hut selection model is solved for each link budget in Table 1. The solution indicates the huts that require amplification to satisfy the given link budget. Starting with hut 0 and proceeding toward hut  $n+1$ , the appropriate huts for regeneration are determined such that both the max span for this link budget and the PMD restrictions are satisfied. A merit function (related to the number of As and Rs needed) is used to compute the best link budget for a given link. The (link, link budget) combination with the smallest function value is selected as the best link budget for that link. Hence, this step in the opaque network design algorithm involves solving at most  $24L'$  hut selection problems. Underlying this approach is the assumption that the same link budget choice must be consistently used along a link, but may vary across links and is a direct consequence of the optimal solution decomposing across links.

The next step in the opaque network design algorithm is to determine the traffic on each link. Once the traffic is known, the size of the As, MUXs, DMUXs, and number of Rs can be easily determined. The routing and provisioning model described in the following computes the traffic on each candidate path while minimizing the opaque network equipment cost. This model uses an *arc-path* formulation where a maximum of  $m$  ( $m \geq 1$ ) candidate paths for each  $(o,d)$  demand pair are provided as input from which an optimal set is selected. For the test problems discussed in this study, the paths are generated by a special  $k$ -shortest path model. The routing and provisioning model allows a point-to-point demand to be routed on multiple paths in order to minimize costs. Multiple paths allow the exploitation of the modular sizes of hardware (such as 20, 40, or 80 wavelengths).

Let  $N$  denote the set of nodes in the network and  $F$  denote the set of links in the network. Let  $D$  denote the set of demand pairs  $(o,d)$  and  $r_{od}$  denote the total demand in wavelengths for demand pair  $(o,d)$ . Let  $W_{od}$  denote the paths that are used for demand pair  $(o,d)$  and the integer variable  $f_p$  denote the traffic assigned to path  $p$ . Then the demand constraints are as follows:

$$\sum_{p \in W_{od}} f_p = r_{od}, \quad \forall (o,d) \in D \quad (1)$$

For the arc-path model, each link in the network is represented by two directed arcs in set  $E$ . Let  $t_{ij}$  denote the total flow on arc  $(i,j)$  and  $P_{ij}$  denote the paths that use arc  $(i,j)$ . Then the flow constraints are as follows:

$$\sum_{p \in P_{ij}} f_p = t_{ij}, \quad \forall (i,j) \in E \quad (2)$$

Amplifiers and multiplexers come in fixed capacities and in the models presented in this study 3 different sizes of this equipment. Let  $A_{ij}^S$ ,  $A_{ij}^M$ , and  $A_{ij}^L$  be the integer variables that denote the number of small, medium and large amplifiers needed at each utilized hut on link  $(i,j)$ , respectively. This approach could be expanded to an arbitrary number of fixed equipment capacities instead of just three different sizes. If the best link budget for a given link imposes amplification at a hut on that link then the following set of constraints determine the size and number of amplifiers needed at that hut:

$$t_{ij} + t_{ji} \leq S A_{ij}^S + M A_{ij}^M + L A_{ij}^L, \quad \forall (i, j) \in F \quad (3)$$

where  $S$ ,  $M$ , and  $L$  are constants denoting the number of wavelengths that can be processed by a small, medium, and large amplifier. Note that (3) also determines the number and size of MUX/DMUX equipment at a hut or a node. Let  $T_i$  be the number of TEs needed at node  $i$ . The following set of constraints determines the required number of TEs at the nodes:

$$\sum_{(i,j) \in E} (t_{ij} + t_{ji}) = T_i, \quad \forall i \in N \quad (4)$$

Note that an intermediate node on a path requires twice the number of TEs as the origin and destination nodes. Let  $R'_{ij}$  denote the number of Rs required at a hut on link  $(i,j)$ .

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

$$t_{ij} + t_{ji} = R'_{ij}, \quad \forall (i, j) \in F \quad (5)$$

Let  $B_{ij}^A$ ,  $B_{ij}^R$ , and  $B_{ij}^M$  are constants denoting the number of amplifier, regenerator and multiplexer/demultiplexer locations determined by the best link budget on link  $(i,j)$ , respectively. Then the objective function is to minimize the cost of provisioning the opaque network and is given by

$$\begin{aligned}
\text{minimize } & \sum_{(i,j) \in F} (C_{A^S} A_{ij}^S + C_{A^M} A_{ij}^M + C_{A^L} A_{ij}^L) B_{ij}^A + \sum_{i \in N} C_T T_i + \sum_{(i,j) \in F} C_R R'_{ij} B_{ij}^R \\
& + \sum_{(i,j) \in F} (C_{M^S} A_{ij}^S + C_{M^M} A_{ij}^M + C_{M^L} A_{ij}^L) B_{ij}^M
\end{aligned} \tag{6}$$

where  $C_{A^S}$ ,  $C_{A^M}$ ,  $C_{A^L}$  are constants denoting the cost of small, medium, and large amplifiers,  $C_{M^S}$ ,  $C_{M^M}$ ,  $C_{M^L}$  are 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. The main output from this model is the demand routings and equipment needed for implementation.

### 3.3 The All-Optical Network Design

In this portion of the investigation, a design strategy is proposed that uses the  $(o,d)$  demand pairs to determine where O/E/O conversion should occur. The proposed all-optical design strategy uses the same paths as the opaque design (determined by the routing and provisioning model). The opaque network design requires O/E/O conversion at every node whereas the all-optical network design attempts to minimize the number of O/E/O conversions. A given  $(o,d)$  pair may traverse several links each with a different best link budget as determined by application of the hut selection model. Such a path can be viewed as a long link with certain huts that require amplification. The intermediate nodes in a path are treated as huts for which amplification is required. Starting at the hut corresponding to node  $o$  and proceeding toward the hut corresponding to node  $d$ , regeneration is installed at the appropriate huts such that both the max span for the link budgets and the PMD restrictions are satisfied. The rule given in Subsection 2.2 is applied when DPMD values are different for different links in a path.

Since different paths may use some of the same links, the number of wavelengths that require amplification and the number of wavelengths that require regeneration in a hut are summed. Once the total demand for amplification and regeneration at a hut is known, then the equipment requirements can be determined. The sum of the costs for all equipment at all nodes and all huts gives the all-optical network design cost.

### *3.4 An Example of the Two Designs*

The basic topology for the example network is illustrated in Figure 5. This network has 6 nodes, 7 links, and 23 huts positioned at various locations along the links. Each node contains an optical cross connect (OXC) and the associated MUX/DMUX equipment. This is typical for DWDM networks and simplifies the work required to make changes as well as the initial cable layout. Each fiber with inbound or terminating traffic has a pre-amplifier (A) followed by a DMUX. Output from the DMUX can either pass through a regenerator or proceed directly to the OXC. Each fiber with outbound or originating traffic has a similar configuration with a MUX and a post-amplifier. The basic node architecture as well as regeneration at a hut is illustrated in Figure 1.

-----  
Figure 5 About Here  
-----

For this investigation, it is assumed that a fiber can carry at most 80 wavelengths. Hence, 90λs of traffic that require amplification at a given hut will use a pair of amplifiers, one for 80λs and a second for 10λs. In this study, it is assumed that amplifiers and multiplexer/demultiplexer equipment come in three sizes, depending upon the maximum number of wavelengths that can be handled. The sizes and corresponding relative costs can be found in Table 2. The equipment costs used are not specific to any actual equipment vendor costs, but instead are selected so that the ratios are

approximately correct. The demands are given in units of  $\lambda$ s and 4 demand pairs are considered, each with 3 candidate paths as described in Table 3. The wavelengths assigned to each path by the routing and provisioning model are also listed in Table 3.

---

Tables 2 and 3 About Here

---

The opaque network design is illustrated in Figure 6. All O/E/O conversion occurs at the nodes and all huts only contain As. Two fibers are required between nodes 1 and 3 and nodes 2 and 4. The total cost for this design is 109,500.

---

Figure 6 About Here

---

The all-optical network design is illustrated in Figure 7. Note that there is no O/E/O conversion at node 6 and conversion is required between nodes 5 and 6. The details of the equipment placed in node 3 may be found in Figure 8 where  $\lambda_j^{(o,d)} - \lambda_k^{(o,d)}$  denote the range of wavelengths ( $j$  through  $k$ ) for demand pair  $(o,d)$  that are assigned to a fiber and/or equipment. For node 3, regeneration only occurs for the  $62\lambda$ s that are assigned to path 4-3-5 which partially satisfies the demand between nodes 4 and 5. The total cost for the all-optical design is only 93,390 compared to 109,500 for the opaque network design resulting in a savings of 14.7%. The saving is attributed to the reduction in TEs from 1306 down to 836. The addition of 142 Rs was more than offset by the TE reduction.

---

Figures 7 & 8 About Here

---

#### 4. Empirical Analysis

To help evaluate the opaque and all-optical design strategies, both procedures are implemented using the AMPL modeling language Fourer et al. (2003) with a direct link to the solver in CPLEX <http://www.cplex.com>. All test runs are made on a Compaq AlphaServer DS20E with dual EV 6.7(21264A) 667 MHz processors and 4096 MB of RAM. The details on the three test networks used can be found in Table 4. The European transport network (EU) in Figure 9 consists of 18 nodes, 35 links and has an average node degree of 3.89. The US transport network (US) has 24 nodes, 42 links and is illustrated in Figure 10. The North American transport network (NA) illustrated in Figure 11 is based on a real network operated by a well-known company. This network has 36 nodes and 67 links. The hut spacing varies with the number of huts on a link being related to the length of the link. For example, for the US network, the link (DA, EP) has 19 huts while the link (DA, KA) has 29 huts. The DPMD values vary from a low of 0.1 to a high of 1.5. Hence, PMD restrictions call for regeneration between 400km and 90,000km. All the  $(o,d)$  demand pairs are randomly generated and the wavelengths assigned to these demand pairs are uniformly distributed over [10,80].

-----  
Table 4 & Figures 9, 10, and 11 About Here  
-----

We developed an algorithm to obtain the k-shortest distinct paths  $W_{od}$  for each  $(o,d) \in D$ . A binary linear program is solved at each step to obtain one new path. The binary variable  $z_{ij}$  will be 1 if arc  $(i,j)$  is selected to be part of the path j and 0, otherwise. For paths for demand pair  $(o,d)$  let  $b_o=1$ ,  $b_d = -1$ , and  $b_i = 0$  for all  $i \in N \setminus \{o,d\}$ . The flow conservation constraints are

$$\sum_{(i,j) \in E} z_{ij} - \sum_{(j,i) \in E} z_{ji} = b_i, \quad \forall i \in N \quad (7)$$

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

$$\text{minimize} \quad \sum_{(i,j) \in E} \bar{L}_{ij} z_{ij} \quad (8)$$

Let  $\bar{A}_1$  denote the arcs in the first path. Then the second path is obtained by solving (7)

and (8) plus the constraint

$$\sum_{(i,j) \in \bar{A}_1} z_{ij} \leq |\bar{A}_1| - 1 \quad (9)$$

Let  $\bar{A}_2$  denote the arcs in the second path. The third path is obtained by solving (7)-(9)

plus the constraint

$$\sum_{(i,j) \in \bar{A}_2} z_{ij} \leq |\bar{A}_2| - 1 \quad (10)$$

This continues until k distinct shortest paths have been discovered.

In order to determine the impact of the number of candidate paths on cost and processing time, a series of tests have been performed. For each test network, 4 problems each with a different number of demand pairs are run with a maximum of 3, 6, 9, and 12 candidate paths per  $(o,d)$  demand pair. Details of these test cases can be found in Table 5. The average number of hops is based on the paths selected from 12 candidate paths. Setting 3 distinct candidate paths as the base, the decrease or increase in cost and processing time by using a larger number of candidate paths is given in Table 6. Note that in all our tests, the routing and provisioning model is run with an optimality gap of 1%. For this reason, the cost for a problem with a fewer number of candidate paths can be less than the cost for a problem with more candidate paths. For test problem NA510 with 100 demand pairs, 12 candidate paths made a minor improvement on overall cost

(1.99%) from 3 candidate paths and required a negligible increase in processing time (about 1 minute). For the opaque network, there was no improvement using 12 candidate paths instead of 9 on the four US transport networks. However, there was a marginal benefit in using 12 candidate paths for most of the EU and NA transport networks. Table 7 summarizes the results obtained from the runs described in Table 6. Even though the processing times for 12 paths increased the run times by 113%, that only added a few minutes to the overall processing time.

-----  
Tables 5, 6 and 7 About Here  
-----

In Table 8, where the empirical results of two design strategies are summarized, a maximum of 12 distinct paths are used. The test cases are grouped into four groups based on the number of  $(o,d)$  demand pairs. The four groups of US and NA transport networks have 100, 150, 200, and 250 demand pairs, respectively. The EU transport network has 50 demand pairs for the first and increases by 25 demand pairs for each group, up to 125 demand pairs.

-----  
Table 8 About Here  
-----

For each of the 12 problems using the US transport network, at most  $(24)(42) = 1008$  hut selection problems are solved to determine the huts where amplification occurs. If the hut selection problem is infeasible for the link budget  $B$ , then it will also be infeasible for all link budgets smaller than  $B$  and these problems need not be solved. Even though hundreds of hut selection problems are solved, the total computational time to determine the best opaque design never exceeded 4 minutes. This is the time needed to search over

the 1008 (link, link-budget) combinations, plus the time to determine the routing and size and placement of equipment. Given best link budgets and the routing, the all-optical design strategy required at most 4.5 additional minutes. Note that the all-optical designs use significantly fewer TEs at the cost of 75 per unit at the expense of additional Rs at the cost of 130 per unit. The number of amplifiers for both strategies is approximately the same. The average cost reduction for the EU network by adopting an all-optical strategy was about 13%. The savings were higher for the two larger networks. The US transport network averaged 26% whereas the NA transport network averaged 24%. The average percent reduction in costs by adopting an all-optical design for the 12 test problem groups is illustrated in Figure 12.

-----  
Figure 12 About Here  
-----

Even though demand pairs and the resulting paths in the transport networks are expected to be long-lived, over time a small percentage of demands hence the paths may need to be revised. We have developed a strategy where approximately 50% of the demand pairs are affected by some change. When we applied this scheme to the example network in Figure 6, the demand pair (4,5) increased from 142  $\lambda$ s to 163  $\lambda$ s and the demand pair (2,4) is replaced by demand pair (1,2). The paths assigned to each demand pair along with the demands, in units of  $\lambda$ s may be found in Table 9. Note that with the changes in demands, some paths are no longer valid and some paths do not carry the same amount of traffic as before. With these changes we run our opaque network algorithm again but this time the equipment in the original design is provided to the routing and provisioning model at no additional cost. This ensured that the algorithm

made use of the equipment readily available in the network and the paths are chosen accordingly. This modified opaque network design is illustrated in Figure 13. Note that the changes in demands resulted in extra (spare) capacity on links (1,3) and (2,4) but the algorithm was able to reduce the upgrade costs by making use of the equipment already in place. With this upgrade the total cost of the network went up by 9,725 to 119,225.

Automatically updating an all-optical design and coming up with a low cost upgrade is a more difficult task. Although a capacity increase on the original paths can be easily achieved by adding more hardware, updates to these original paths in an all-optical setup may require O/E/O conversion at some new hut which previously only required amplification, whereas an opaque update never requires O/E/O conversion at some new hut. Hence, the link architecture is preserved. Changes only require additional equipment of the same type. There is the possibility that without equipment relocation, the cost of a modified all-optical network may increase beyond the cost of a modified opaque network.

---

Figure 13 and Table 9 About Here

---

## **5. Summary and Conclusions**

This investigation presents a simple multi-step procedure for obtaining good, but not necessarily optimal solutions to a complicated DWDM design problem. The first step is to determine the huts on a given link for which amplification equipment is required. A shortest path model (greedy algorithm) is used to answer this question for a given link budget. This problem is solved for each of the possible link budgets (24 different link

budget combinations were considered in this study) and O/E/O conversion is selected at certain hut and node locations based on both the link budget and PMD restrictions. The best (link, link budget) combination is determined by a merit function that assigns a value to each (link, link budget) combination based on the number of As and Rs required. Finally, using these best link designs and a set of candidate paths, the routing and provisioning algorithm determines the opaque network design.

An alternative to the opaque network design is an all-optical network design. Our all-optical strategy examines the demand pairs consecutively and only uses O/E/O conversion when needed. The empirical analysis part of this investigation presents a strong case for this improved strategy. All problems solved resulted in substantial cost saving (from 14% to 35%) at modest additional computation effort (less than 4.5 minutes).

Based on these results, it is clear that the all-optical network design strategy is superior to the traditional opaque network design approach. However, there is some controversy regarding the use of an all-optical design due to the issue of updating after some demand changes. Updating an opaque design appears to be easier than updating an all-optical design. Grover (2004) page 23, states that the paths on transport networks remain unchanged for long periods of time and a path-based approach is more appropriate for them. A natural extension of the network design approaches presented in this manuscript can be constructed by partitioning the traffic demand set into two disjoint sets corresponding to demands that are unlikely to change over the planning horizon, and demands that may be subject to some changes, respectively. Then, a hybrid design strategy produces an overlay network comprised of an all-optical design for the subset of

traffic demands that are not prone to change, combined with the opaque network design for the other traffic demand subset, which is likely to change frequently. The cost of such a hybrid network design should be bounded by the costs of the two different network design approaches.

A complementary approach to the hybrid strategy outlined above is to consider the traffic demand set variation as uncertainty in the given demand set and explore the potential for an extension to the robust network planning approach for the DWDM routing and provisioning problem described in Kennington et al. (2003a). The hybrid approach is relatively easy to implement since it only requires pre-partitioning of the traffic demand set and no changes to the underlying mathematical models, while the robust approach would necessitate significant additional effort with potentially excessive computational requirements for computing solutions to reasonably-sized problems.

Further research is needed to extend this approach to include additional elements, such as explicitly modeling optical cross-connect costs and incorporating potential use of PMD compensators in the model. The work described here can be extended to consider the effect of various network restoration strategies. This is a particularly difficult addition to include, since different link failure scenarios may result in the utilization of alternate paths with varying link budget selections. Nevertheless, it is possible to tackle this problem in a systematic manner.

## **Acknowledgments**

This investigation was partially supported by a grant from the Office of Naval Research under Award Number N00014-96-1-0315.

## References

- Ahuja, R. K., T. L. Magnanti, J. B. Orlin. 1993. *Network Flows: Theory, Algorithms, and Applications*, Prentice Hall, Upper Saddle River, NJ.
- Alanyali, M., E. Ayanoglu. 1999. Provisioning algorithms for WDM optical networks. *IEEE/ACM Transactions on Networking*. **7** 767-778.
- Banerjee, D., B. Mukherjee. 2000. Wavelength-routed optical networks: linear formulation, resource budgeting tradeoffs, and a reconfiguration study. *IEEE / ACM Transactions on Networking*. **8** 598–607.
- Berry, R., E. Modiano. 2000. Reducing electronic multiplexing costs in SONET/WDM rings with dynamically changing traffic. *IEEE Journal on Selected Areas in Communication*. **18** 1961-1971.
- Birkan, G., J. Kennington, E. Olinick, A. Ortynski, G. Spiride. 2002. Making a case for using integer programming to design DWDM networks. *Optical Networks Magazine* **4** 107-120.
- Calinescu, G., O. Frieder, P. Wan. 2002. Minimizing electronic line terminals for automatic ring protection in general WDM optical networks. *IEEE Journal on Selected Areas in Communications*. **20** 183-189.
- Dasylyva, A., R. Srikant. 1999. Optimal WDM schedules for optical star networks. *IEEE / ACM Transactions on Networking*. **7** 446-456.
- Dowdell, E., P. Dejneka, C. Weinstein. 2003. Economic modeling for long-haul systems. <http://www.corning.com/opticalfiber/pdf/economicII.pdf>.

- Fourer, R., D. Gay, B. Kernighan. 2003. *AMPL: A Modeling Language for Mathematical Programming*, Second Edition, Brooks/Cole – Thompson Learning, Pacific Grove, CA.
- Gerstel, O., R. Ramaswami, R. 2000. Optical layer survivability: a services perspective. *IEEE Communications Magazine*. **38** 104-113.
- Grover, W. D. 2004. *Mesh-Based Survivable Networks: Options and Strategies for Optical, MPLS, SONET, and ATM Networking*, Prentice Hall, Upper Saddle River, NJ.
- Kennington, J., E. Olinick. 2004. Wavelength translation in WDM networks: optimization models and solution procedures. *INFORMS Journal on Computing* **16** 174-187.
- Kennington, J., E. Olinick, K. Lewis, A. Ortynski, G. Spiride. 2003a. Robust solutions for the DWDM routing and provisioning problem: models and algorithms. *Optical Networks Magazine*. **4** 74-84.
- Kennington, J., E. Olinick, A. Ortynski, G. Spiride. 2003b. Wavelength routing and assignment in a survivable WDM mesh network. *Operations Research*. **51** 67-79.
- Krishnaswamy, R. K. Sivarajan. 2001. Design of logical topologies: a linear formulation for wavelength-routed optical networks with no wavelength changers. *IEEE/ACM Transactions on Networking*. **9** 186–198.
- Lee, T., K. Lee, S. Park. 2000. Optimal routing and wavelength assignment in WDM ring networks. *IEEE Journal on Selected Areas in Communications*. **18** 2146-2154.
- Maeda, M. 1998. Management and control of transparent optical networks. *IEEE Journal on Selected Areas in Communications*. **16** 1008-1023.

- Miyao, Y. H. Saito. 1998. Optimal design and evaluation of survivable WDM transport networks. *IEEE Journal on Selected Areas in Communications*. **16** 1190-1198.
- Mukherjee, B., D. Banerjee, S. Ramamurthy, A. Mukherjee. 1996. Some principles for designing a wide-area WDM optical network. *IEEE/ACM Transactions on Networking*. **4** 684–696.
- Mulvey, J., R. Vanderbei, S. Zenios. 1995. Robust optimization of large-scale systems. *Operations Research*. **43** 264-281.
- Ramamurthy, B., D. Datta, H. Feng, J. P. Heritage, B. Mukherjee. 1999. Transparent vs. opaque vs. translucent wavelength-routed optical networks. *Technical Digest, Optical Fiber Communications (OFC '99) Conference, San Diego, CA, TuF2, 59-61*.
- Ramaswami, R., K. Sivarajan. 1995. Routing and wavelength assignment in all-optical networks. *IEEE/ACM Transactions on Networking*. **3** 489–500.
- Ramaswami, R., K. Sivarajan. 2002. *Optical Networks: A Practical Perspective*. Second Edition. Morgan Kaufman Publishers, Inc. San Francisco, CA.
- Subramaniam, S., M. Azizoglu, A. Somani. 1999. On optimal converter placement in wavelength-routed networks. *IEEE/ACM Transactions on Networking*. **7** 754-766.
- Tada, Y., Y. Kobayashi, Y. Yamabayashi, S. Matsuoka, K. Hagimoto. 1996. OA&M framework for multiwavelength photonic transport networks. *IEEE Journal on Selected Areas in Communications*. **14** 914-921.
- Yang, X., Y. Chen, X. Liv. 2003 Regenerator placement algorithms for optical network design. <http://csce.unl.edu/~xyang/docs/823proj-rev.pdf>.

Zang, H., J. Jue, B. Mukherjee. 2000. A review of routing and wavelength assignment approaches for wavelength-routed optical WDM networks. *Optical Networks Magazine*. **1** 47-60.

Zhang, Z., A. Acampora. 1995. A heuristic wavelength assignment algorithm for multihop WDM networks with wavelength routing and wavelength re-use. *IEEE/ACM Transactions on Networking*. **3** 281-288.

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. Equipment Cost

Equipment	Wavelengths	Cost/Unit
TE	1	75
R	1	130
A	1 – 20	100
A	21 – 40	150
A	41 – 80	200
MUX/DMUX	1 – 20	120
MUX/DMUX	21 – 40	180
MUX/DMUX	41 - 80	240

Table 3. Demands and Routings for Example

(o,d)	Demand	Path #	Path	Traffic( $\lambda$ s)
(1, 3)	82	1	1 3	82
		2	1 2 4 3	
		3	1 2 4 6 5 3	
(2, 3)	93	4	2 1 3	75
		5	2 4 3	18
		6	2 4 6 5 3	
(2, 4)	101	7	2 4	101
		8	2 1 3 4	
		9	2 1 3 5 6 4	
(4, 5)	142	10	4 3 5	62
		11	4 6 5	80
		12	4 2 1 3 5	

Table 4. Test Problem Descriptions

Name	Nodes	Links	Average Node Degree	Demand	DPMD	Total Huts	Distance Between Huts
EU	18	35	3.89	[10,80]	[0.1,1.0]	438	[5,90]
US	28	42	3.15	[10,80]	[0.1,1.5]	423	[3,134]
NA	36	67	3.69	[10,80]	[0.1,1.0]	705	[5,100]

Table 5. Test Problems Characteristics

Problems	Number of Demand Pairs	Average Number of Hops	Average Total Demand ( $\lambda s$ )
EU110, EU120, EU130	50	2.29	2235
EU160, EU170, EU180	75	2.35	3339
EU210, EU220, EU230	100	2.24	4579
EU260, EU270, EU280	125	2.28	5697
US310, US320, US330	100	3.78	4379
US360, US370, US380	150	3.73	6615
US410, US420, US430	200	3.73	8755
US460, US470, US480	250	3.72	10926
NA510, NA520, NA530	100	3.46	4356
NA560, NA570, NA580	150	3.54	6622
NA610, NA620, NA630	200	3.33	8926
NA660, NA670, NA680	250	3.34	11449

Table 6. Impact of Number of Candidate Paths on Cost and Processing Time

Problem	Max Candidate Paths / (o,d)	Opaque Cost (millions)	% Reduction in Opaque Cost	All-Optical Cost (millions)	% Reduction in All-Optical Cost	Total Time
EU110	3	0.99		0.82		00:00:15
50	6	0.96	3.03%	0.84	-2.44%	00:00:20
(o,d)	9	0.96	3.03%	0.84	-2.44%	00:00:29
pairs	12	0.95	4.04%	0.84	-2.44%	00:00:35
EU160	3	1.54		1.30		00:00:23
75	6	1.50	2.60%	1.28	1.54%	00:00:31
(o,d)	9	1.49	3.25%	1.28	1.54%	00:00:49
pairs	12	1.48	3.90%	1.26	3.08%	00:00:58
EU210	3	2.15		1.82		00:00:34
100	6	2.10	2.33%	1.82	0.00%	00:00:51
(o,d)	9	2.07	3.72%	1.81	0.55%	00:01:08
pairs	12	2.07	3.72%	1.83	-0.55%	00:01:20
EU260	3	2.71		2.23		00:00:47
125	6	2.65	2.21%	2.27	-1.79%	00:01:04
(o,d)	9	2.63	2.95%	2.30	-3.14%	00:01:24
pairs	12	2.67	1.48%	2.31	-3.59%	00:01:55
US310	3	3.14		2.33		00:00:53
100	6	3.09	1.59%	2.30	1.29%	00:01:11
(o,d)	9	3.06	2.55%	2.27	2.58%	00:01:31
pairs	12	3.06	2.55%	2.27	2.58%	00:01:54
US360	3	4.65		3.50		00:01:39
150	6	4.55	2.15%	3.39	3.14%	00:02:12
(o,d)	9	4.53	2.58%	3.36	4.00%	00:02:42
pairs	12	4.53	2.58%	3.37	3.71%	00:03:18
US410	3	6.10		4.51		00:02:49
200	6	5.96	2.30%	4.36	3.33%	00:03:34
(o,d)	9	5.93	2.79%	4.34	3.77%	00:04:18
pairs	12	5.93	2.79%	4.35	3.55%	00:05:16
US460	3	7.79		5.83		00:04:42
250	6	7.61	2.31%	5.62	3.60%	00:05:41
(o,d)	9	7.56	2.95%	5.59	4.12%	00:06:46
pairs	12	7.56	2.95%	5.60	3.95%	00:08:00
NA510	3	3.01		2.18		00:00:51
100	6	2.98	1.00%	2.24	-2.75%	00:01:07
(o,d)	9	2.96	1.66%	2.21	-1.38%	00:01:36
pairs	12	2.95	1.99%	2.22	-1.83%	00:02:00
NA560	3	4.98		3.64		00:01:36
150	6	4.94	0.80%	3.71	-1.92%	00:02:04
(o,d)	9	4.93	1.00%	3.70	-1.65%	00:02:33
pairs	12	4.90	1.61%	3.70	-1.65%	00:03:11
NA610	3	6.52		4.78		00:02:33
200	6	6.43	1.38%	4.81	-0.63%	00:03:09
(o,d)	9	6.39	1.99%	4.80	-0.42%	00:03:59
pairs	12	6.37	2.30%	4.81	-0.63%	00:05:01
NA660	3	8.27		6.13		00:03:34
250	6	8.13	1.69%	6.13	0.00%	00:04:26
(o,d)	9	8.05	2.66%	6.09	0.65%	00:05:37
pairs	12	8.03	2.90%	6.12	0.16%	00:06:48

Table 7. Summary for Table 6

Maximum Number of Paths per (o,d) pair	Average Cost Reduction For Opaque Design	Average Cost Reduction For All-Optical Design	Average Increase in Processing Time
6	1.95%	0.28%	31.46%
9	2.59%	0.68%	73.20%
12	2.73%	0.53%	113.28%

Table 8. Empirical Analysis Comparing the Opaque Design Strategy with the All-Optical Design Strategy (Max of 12 paths/demand)

Problem	Opaque Design					All-Optical Design				
	As	Rs	TEs	Cost <sup>1</sup>	Total Time	As	Rs	TEs	Cost <sup>1</sup>	Total Time
EU110	640	672	9326	0.95	00:00:29	677	2454	4416	0.84	00:00:06
EU120	683	542	10264	1.01	00:00:29	719	2460	4672	0.87	00:00:06
EU130	718	740	9586	0.99	00:00:30	754	2608	4320	0.86	00:00:08
EU160	1085	1019	14544	1.48	00:00:43	1128	3628	6606	1.26	00:00:15
EU170	1179	1381	14850	1.58	00:00:44	1222	4285	6778	1.38	00:00:13
EU180	1140	1042	14657	1.51	00:00:44	1190	3956	6650	1.32	00:00:20
EU210	1493	1841	19608	2.07	00:00:59	1556	5796	9048	1.84	00:00:21
EU220	1629	1992	21570	2.27	00:00:59	1692	6358	9446	1.97	00:00:21
EU230	1460	1708	19882	2.07	00:00:59	1530	5772	8982	1.83	00:00:26
EU260	1798	2186	25256	2.62	00:01:16	1879	7107	11210	2.26	00:00:39
EU270	1881	2239	26098	2.71	00:01:16	1961	7586	11460	2.36	00:00:33
EU280	1788	2165	25954	2.67	00:01:16	1869	7317	11512	2.31	00:00:37
US310	1457	1122	33598	3.06	00:01:06	1555	8900	8692	2.27	00:00:48
US320	1469	1157	33678	3.08	00:01:05	1567	8910	8762	2.28	00:00:45
US330	1426	1195	33080	3.03	00:01:05	1507	8555	8818	2.22	00:00:43
US360	2101	1812	49536	4.53	00:01:46	2219	13066	13450	3.36	00:01:32
US370	2141	1938	50258	4.61	00:01:48	2273	13541	13168	3.43	00:01:42
US380	2168	1883	49510	4.55	00:01:47	2288	12996	13070	3.34	00:01:37
US410	2723	2581	64548	5.93	00:02:36	2886	16684	17358	4.33	00:02:40
US420	2784	2663	65480	6.02	00:02:37	2951	17281	17716	4.45	00:02:57
US430	2743	2556	64792	5.95	00:02:35	2900	16985	17456	4.38	00:02:53
US460	3457	3706	81588	7.56	00:03:33	3649	21898	22030	5.59	00:04:27
US470	3495	3529	82320	7.60	00:03:34	3699	22040	21928	5.61	00:04:36
US480	3432	3429	81366	7.50	00:03:31	3634	21707	21600	5.53	00:04:34
NA510	2248	2215	28410	2.95	00:01:18	2339	7510	8602	2.22	00:00:42
NA520	2495	2714	32748	3.42	00:01:17	2611	9130	8958	2.55	00:00:45
NA530	2248	2215	28410	2.95	00:01:17	2398	7661	8574	2.26	00:00:47
NA560	3736	3975	46540	4.90	00:01:58	3878	13263	13140	3.70	00:01:13
NA570	3536	3557	44782	4.67	00:01:59	3669	11935	13042	3.47	00:01:18
NA580	3594	4238	46230	4.88	00:01:58	3727	12921	13552	3.65	00:01:11
NA610	4806	5478	59988	6.37	00:02:48	4965	17117	17622	4.81	00:02:13
NA620	4461	4864	58276	6.08	00:02:46	4627	16197	17762	4.63	00:02:02
NA630	4685	5049	61362	6.40	00:02:47	4848	17229	18170	4.86	00:02:06
NA660	5920	6610	76408	8.03	00:03:41	6111	21548	23086	6.10	00:03:07
NA670	6025	6680	77314	8.13	00:03:36	6224	21879	22748	6.15	00:03:10
NA680	5916	6590	76580	8.04	00:03:39	6115	21745	22858	6.12	00:03:09

<sup>1</sup> In millions

Table 9. Modified Demands For The Example

(o,d)	Original			Modified			
	Demand	Path	Traffic( $\lambda_s$ )	Demand	Path	Traffic( $\lambda_s$ )	
(1, 3)	82	1 3	82	82	1 3	82	
		1 2 4 3			1 2 4 3		
		1 2 4 6 5 3			1 2 4 6 5 3		
(2, 3)	93	2 1 3	75	93	2 1 3	28	
		2 4 3			2 4 3		65
		2 4 6 5 3			2 4 6 5 3		
(2, 4)	101	2 4	101	0	-	-	
		2 1 3 4			-		
		2 1 3 5 6 4			-		
(4, 5)	142	4 3 5	62	163	4 3 5	83	
		4 6 5			4 6 5		80
		4 2 1 3 5			4 2 1 3 5		
(1, 2)	0	-	-	100	1 2	100	
		-			1 3 4 2		
		-			1 3 5 6 4 2		

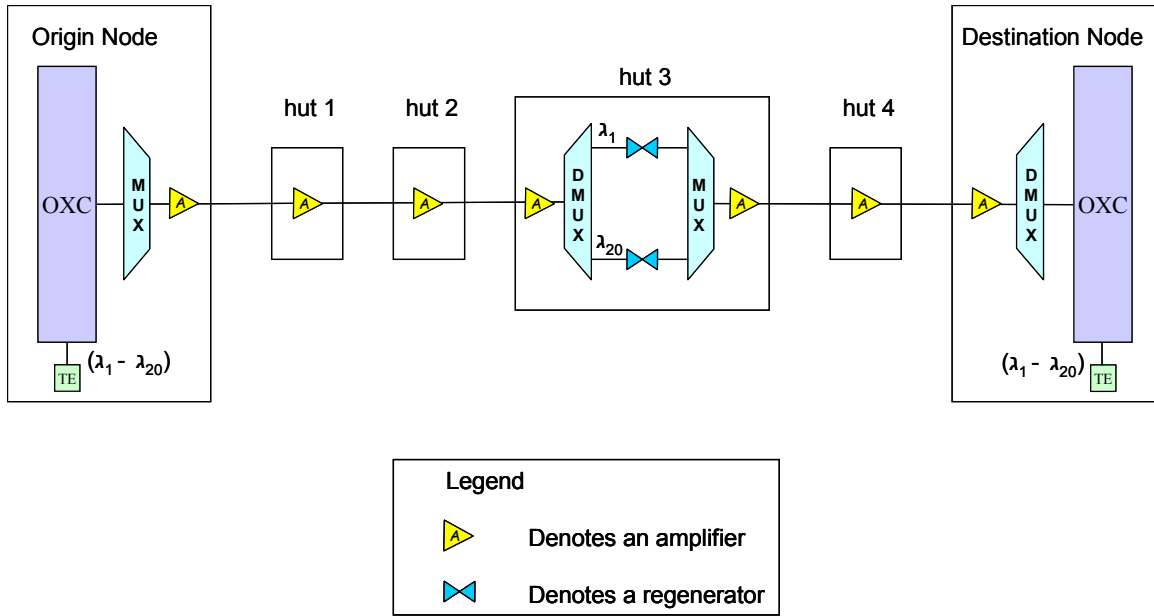


Figure 1. A Simple Link With Amplification and Regeneration for 20 Wavelengths

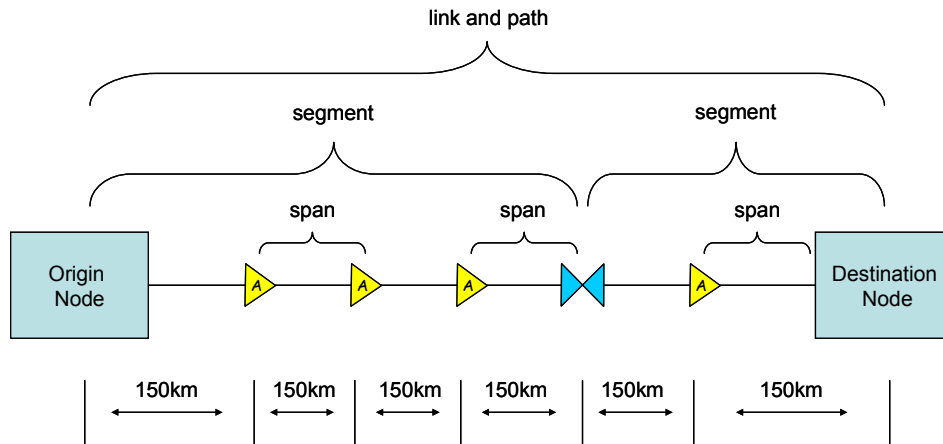


Figure 2. A Link Architecture that Satisfies the Rule for a Link Budget of 150 km.

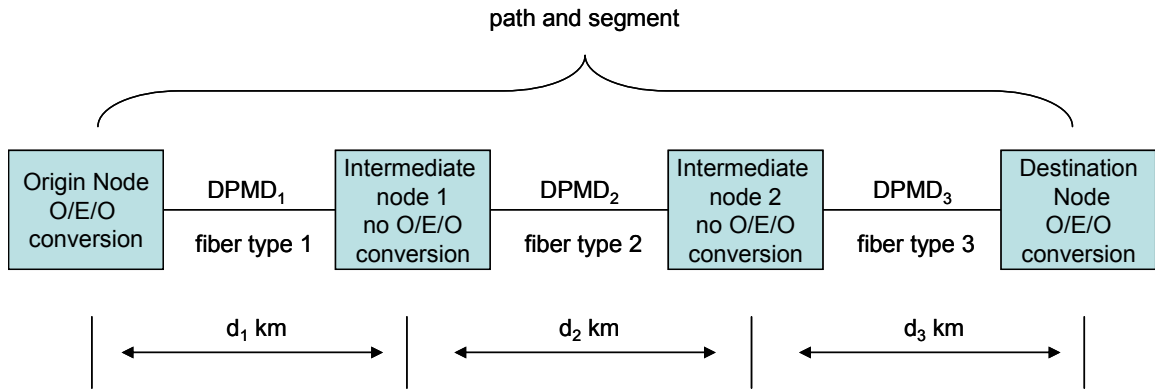


Figure 3. Example of Fibers with Different DPMD Values in a Path

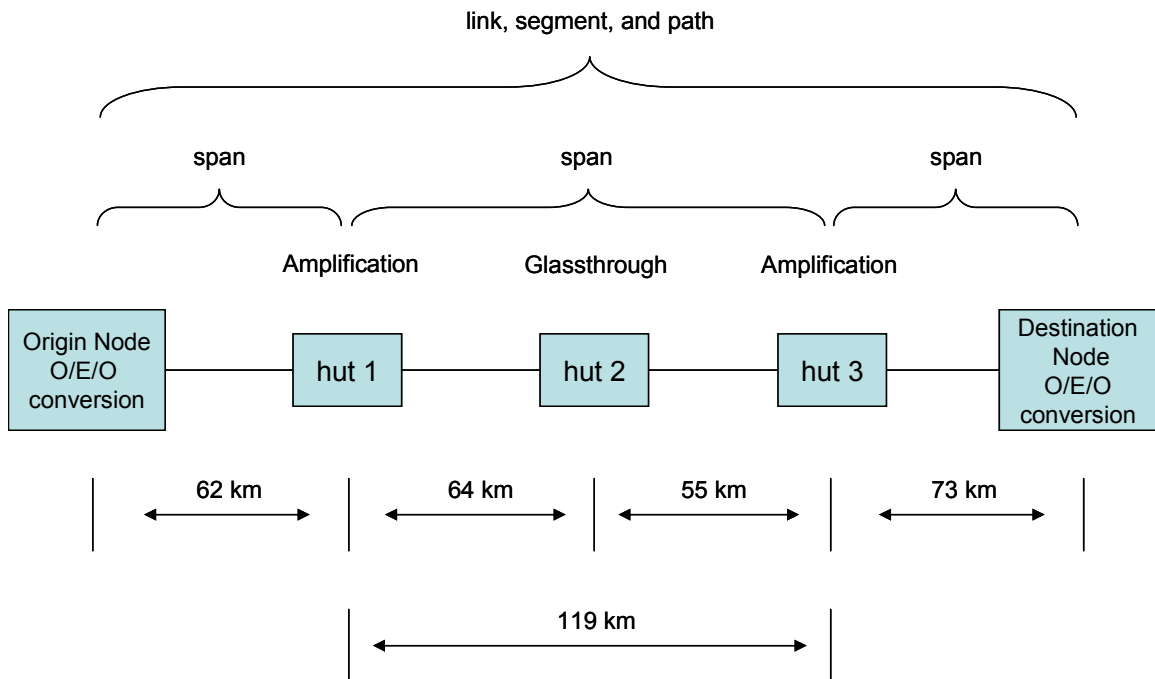


Figure 4. Amplification Requirements using a Link Budget of 120

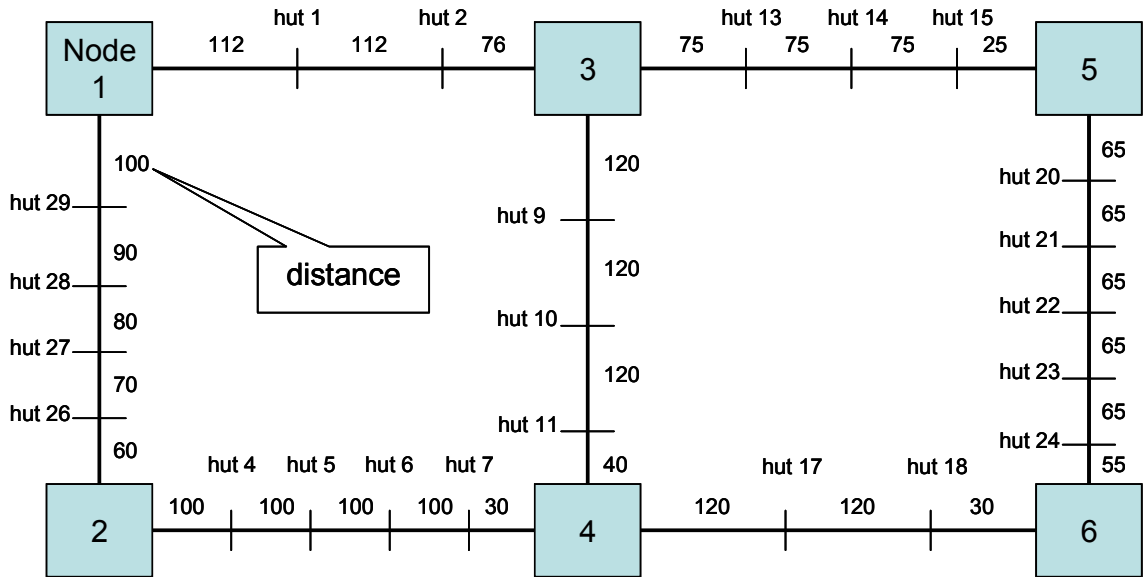


Figure 5. Example Network

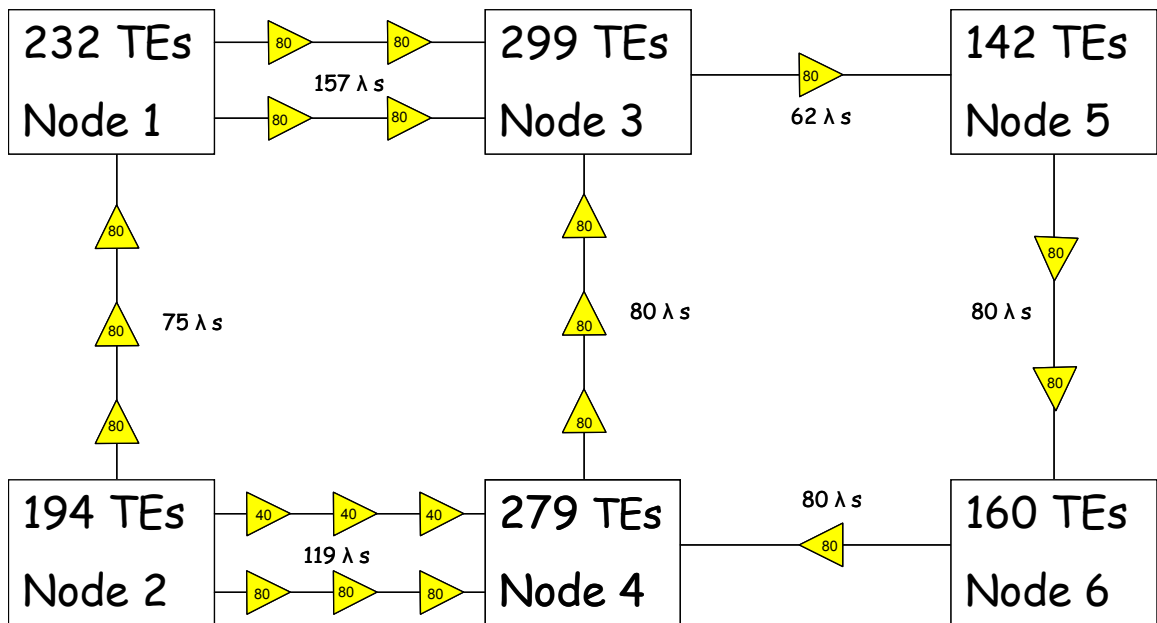


Figure 6. The Opaque Network Design  
(1306 TEs, 38As, 18 MUX/DMUX, Total Cost = \$109,500)

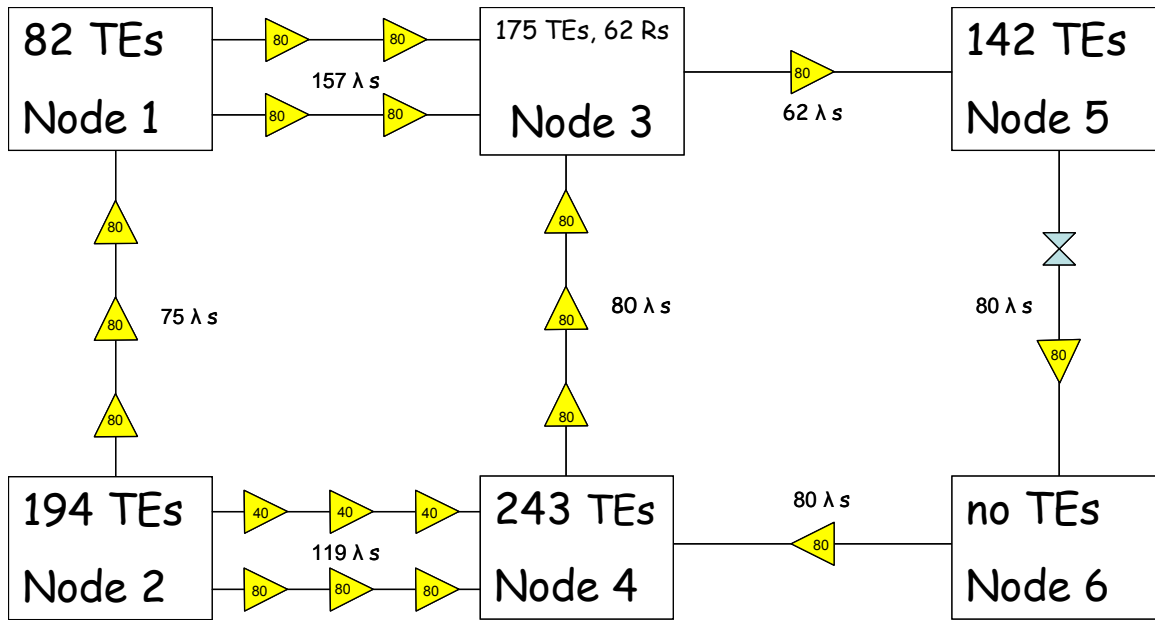


Figure 7. The All-Optical Network Design  
(836 TEs, 142 Rs, 39As, 20 MUX/DMUX, Total Cost = \$93,390)

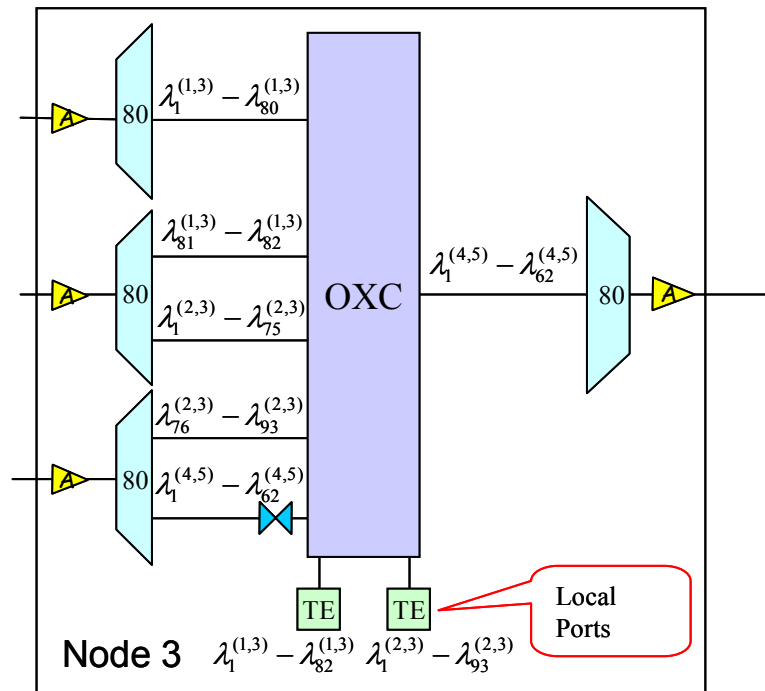


Figure 8. All-Optical Node Architectures for Node 3

Legend	
1	Brussels
2	Copenhagen
3	Paris
4	Berlin
5	Athens
6	Dublin
7	Rome
8	Luxembourg
9	Amsterdam
10	Oslo
11	Lisbon
12	Madrid
13	Stockholm
14	Zurich
15	London
16	Zagreb
17	Prague
18	Vienna

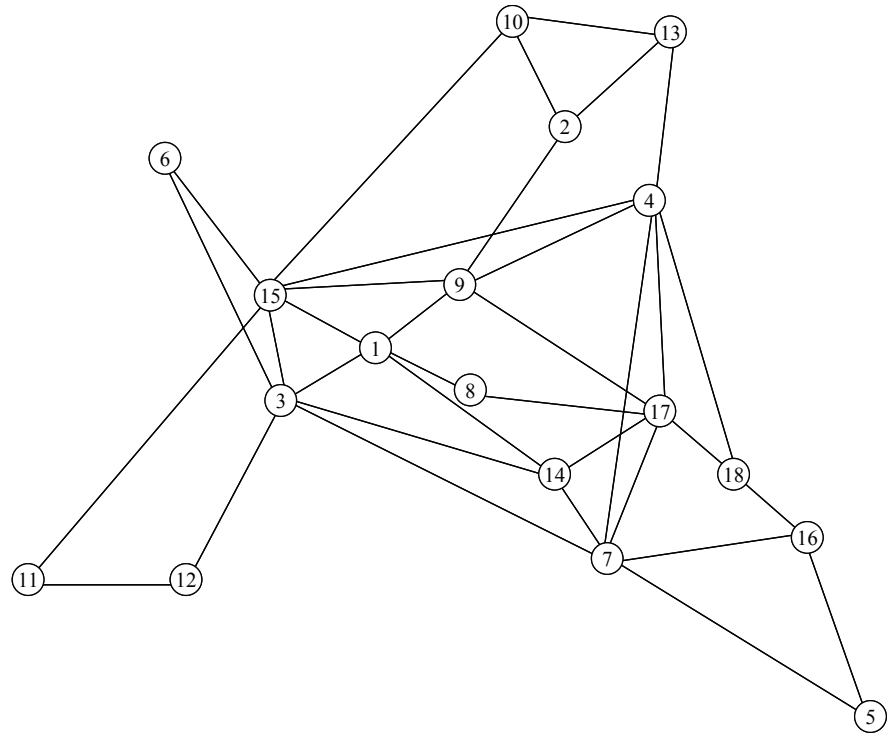


Figure 9. EU Test Network

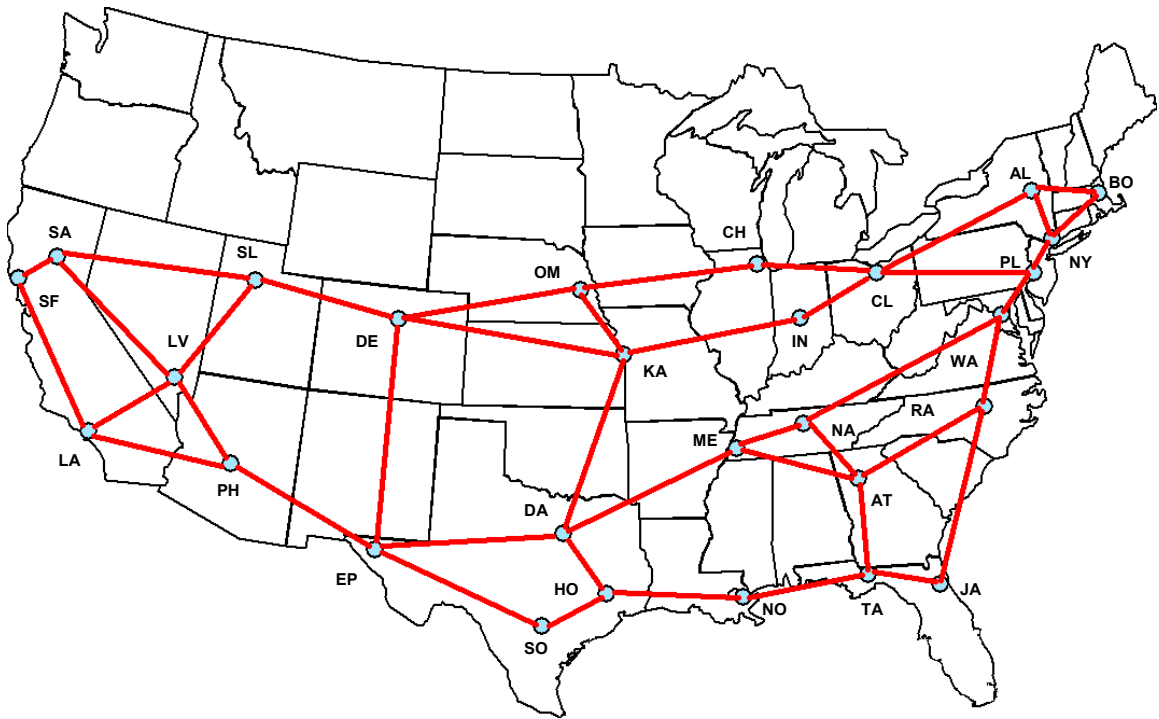


Figure 10. US Test Network



Figure 11. North American Network

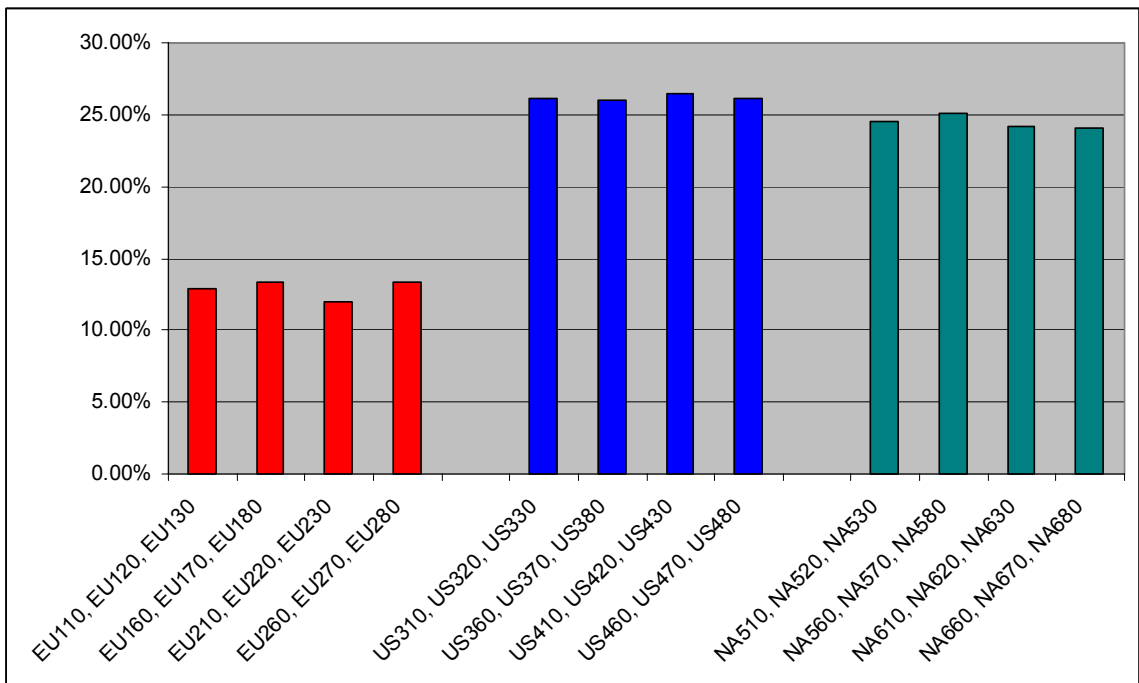


Figure 12. Cost Savings for the All-Optical Design Strategy

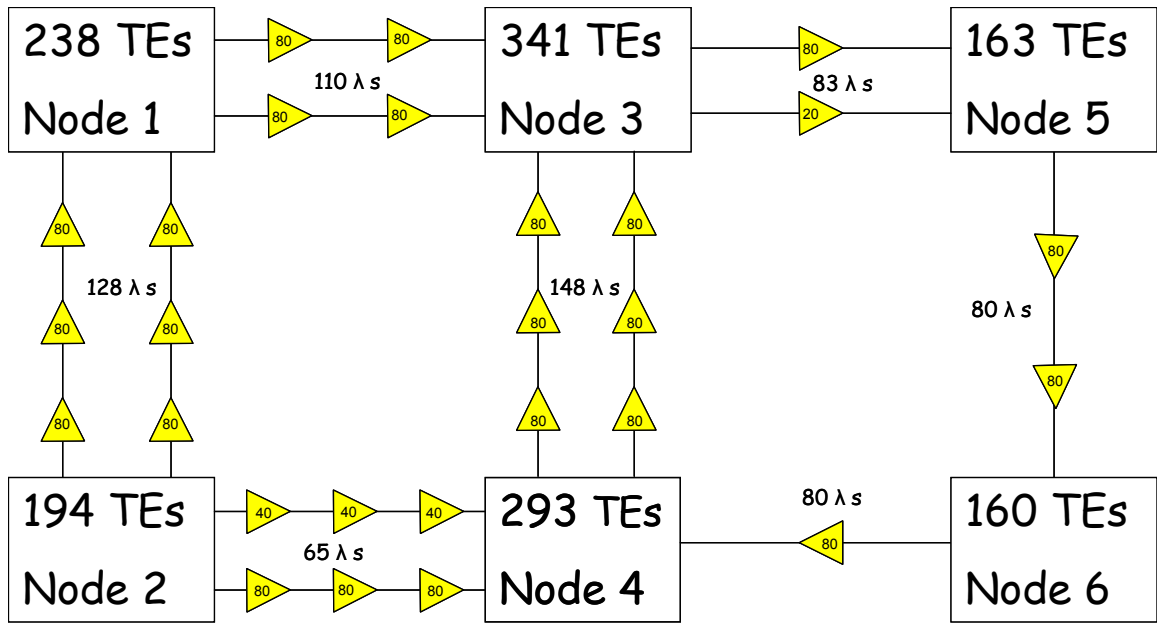


Figure 13. The Modified Opaque Network Design  
 (1389 TEs, 51As, 24 MUX/DMUX, Total Cost = \$119,225)