A SIMULATED ANNEALING APPROACH FOR TOPOLOGY PLANNING AND EVOLUTION OF MESH-RESTORABLE OPTICAL NETWORKS [*]

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Abstract This paper proposes a simulated annealing approach for near optimal routing of static connections in a mesh-restorable network and provides a generalized framework for network evolution in large networks with complex demand sets. We develop a simulated annealing framework to a) optimize both primary and backup capacity by exploring various route arrangements to improve wavelength sharing, and b) to develop a generalized methodology for capacity upgrade to meet increasing traffic demands. Our objective is to minimize the total network facility cost for the traffic demand at each evolutionary stage of the network. The output of this formulation is the dimensioning of the network in terms of number of fibers and wavelengths on each link, the number of OXCs required for each node, and more interestingly, a subset of links in the final topology that need to be activated to incrementally route the increased traffic at each stage of network evolution.

Keywords: Optical Networks, Wavelength Division Multiplexing, Network Dimensioning, Protection, Restoration and Design, Survivability, Network Facility Cost, Simulated Annealing.

1. Introduction

The explosive growth of the Internet in the past few years has created significant shifts in traffic patterns. Optical communication employing wavelength division multiplexing (WDM) has emerged as a viable solution for satisfying the

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ever increasing demand for bandwidth due to the emerging applications. WDM divides the available fiber bandwidth into multiple wavelengths each of which operates at peak electronic speeds. With the current technology, each wavelength is capable of supporting a capacity of upto 10 Gbps(OC-192). As the trend continues, networks in the near future are expected to have transmission capacities of the order of 40 Gbps(OC-768) per wavelength. Thus any single failure results in significant loss of data. It is therefore imperative to design survivable networks to avoid such a catastrophic loss of revenue. Today's Internet is dominated by applications and services based on the traditional Internet Protocol (IP) and the trend is likely to continue in the near future with more services and applications hogging for bandwidth.

Thus we need a methodology for network design that can incrementally add on services and upgrade, as the network evolves from one stage to the next. At each stage of network evolution, we need a way to cost effectively resource budget and minimize the total network operation cost.

Survivable network architectures based on mesh-based (arbitrary) topology offers better capacity efficiency and efficient rerouting on link failures as compared to ring-based networks. Typically mesh-restorable networks are characterized by a low spare capacity redundancy for achieving 100% restorability to single span failures and it also offers a greater flexibility for rapid provisioning of new wavelength demands. This is possible because of the route diversity in arbitrary topologies which is highly sensitive to the average nodal degree. Hence mesh-restorable networks based on WDM technology is considered as a viable transport medium for the upcoming era.

For research purposes we consider that for most common applications we will have an existing network with an established set of links and a set of possible new links to be considered for network evolution. Our goal is to develop a generalized methodology for incremental topology planning applicable to most modern networks, wherein most of the edges already exist. The methodology needs to consider dimensioning only a set of possible new edges or increase capabilities of existing links within limits of installed capacity, for supporting the increasing traffic demands from one generation to the next.

Restoration schemes can be classified as either *link restoration* and *path restoration* based on the initialization locations of the rerouting process. In link restoration, the nodes adjacent to the failed link are responsible for rerouting the effected traffic flow. In contrast, in path restoration, the end nodes of the effected flow traversing the failed link initiate the rerouting process. It has been established that path restoration requires less spare capacity reservation than link restoration [1]. Moreoever path based restoration is found to be the most capacity-efficient approach for mesh based networks as compared to link based rerouting schemes [7]. Hence the restoration model assumed in our work is *path restoration*. Moreover capacity among the primary and restoration paths can be dedicated or shared. The dedicated technique uses 1:1 protection where each primary path has a corresponding restoration path. In the case of shared restoration, several primaries can share the same backup path as long as the primaries are node and link disjoint. This technique is known as *backup multiplexing*.

Several methods have been already proposed in literature for the joint working and spare capacity planning in survivable optical networks [2], [3], [4], [6] [10]. These methods consider a static traffic demand and perform routing and wavelength assignment (RWA) to optimize network cost assuming different cost models and survivability paradigms. The application of some of these algorithms are limited to small networks with tens of wavelengths and moderate amount of traffic demands due to their high computational complexity. In this paper, we develop a simulated annealing framework to a) optimize both primary and backup capacity by exploring various route arrangements to improve wavelength sharing, and b) to develop a generalized methodology for capacity upgrade to meet increasing traffic demands.

1.1 Objective

This paper proposes a near optimal design and upgrade scheme for mesh-restorable WDM backbone networks. In mesh-restorable networks, fast restoration is provided by using predetermined paths and uses backup multiplexing techniques for improving wavelength utilization. In long haul networks the greater distance related cost makes capacity efficiency of utmost importance. Thus there is continued interest in the design and operation of mesh-restorable backbone networks.

The following cost model is assumed for the network design and operation. The total network facility cost can be mapped to a) link provisioning cost which may include digging cost, leasing cost, right of way cost, maintenance cost etc; b) fiber cost, which includes optical amplifier cost, multiplexer and demultiplexer cost, cost of dispensation compensation components etc; and c) per channel cost which includes cost of receiver and transmitter cards.

We assume that the network topology and the current traffic demand is given. For a given static traffic demand we need to find an optimal routing that minimizes the total network facility cost for the current generation of the network. Hence the output of the problem is the number of fibers and wavelengths on each active link, the size of the OXC's required at each node, and the links that need to be activated for realizing the current traffic demand.

Once the current demand set is realized, more spans can be cost effectively added as the traffic increases during the lifetime of the network, such that the total network facility cost is minimal at each evolutionary stage of the network. The terms spans and links are used interchangeably in the paper. Our routing approach can also be used as part of network operation to optimally route the ever increasing traffic demands from one generation to the next.

1.2 Outline of the paper

The remainder of the paper is organized as follows: Section II introduces the network model, restoration model and the cost model adopted for this paper. Section III describes the optimal channel establishment scheme to minimize the fiber utilization to route a given connection. Section IV describes the simulated annealing technique to optimally route static connections in a mesh-restorable WDM network. Section V describes the framework of upgrade using the simulated annealing approach. Section VI presents the numerical results and performance evaluation. Section VII presents our observations and conclusions.

2. Network Model

A WDM network consists of switching nodes interconnected by one or more optical fibers. For simplicity we assume a homogeneous network i.e the node architectures at each node of the network are identical. Each fiber carries a certain number of wavelengths. The number of wavelengths that can be carried on a fiber is a technological constraint, which is expected to increase from few hundreds to higher numbers in the coming years. A lightpath is an all optical channel from a source to destination to provide a circuit switched connection between the nodes.

Each node consists of an optical cross-connect (OXC) and some optical terminating equipment. However some nodes act as *pass-through* nodes, where optical channels are in transit. An optical channel passing through an cross-connect node maybe routed from an input fiber to an output fiber without undergoing optical-electronic-optical (O-E-O) conversions. In our model, we assume that the same wavelength is assigned on all the links along the route. Thus we do not consider wavelength conversion capabilities at a node, since its an expensive proposition.

All cross-connects are wavelength selective. An optical channel can be terminated by an optical line terminating equipment such as Wavelength Add/Drop Multiplexers(WADM's). WADM's are used to add or drop selected wavelengths to and from the fiber. Any node can be a source or destination to a connection. We also assume switching required to route an incoming wavelength on one fiber to go to any output fiber on the same wavelength. The architecture of a typical wavelength routing switch employed at each node is shown in Fig 1.

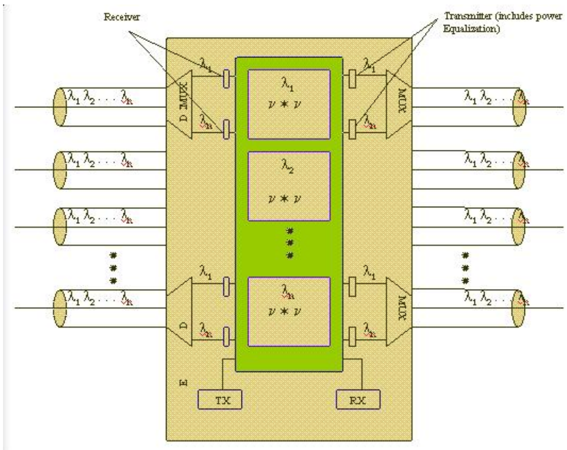


Figure 1. Wavelength Routing Switch Architecture

The network state information is collected at a node by link state [13]. In link-state protocols every node transmits its node and link specific information to every other node in the network. Each node in the network is assumed to maintain a global state information through a link state protocol. Hence every node in the network has a complete view of the entire network state at any given point of time. Since our network model is homogeneous in nature we develop an efficient framework for information collection and routing which is described in detail in Section III. Thus every link in the network is denoted by a *link state vector*. The vector consists of a set of properties associated with the link, such as available bandwidth on individual wavelengths, hop length, fiber length etc. Each of these entities in the vector can be referred to as *metric*. Hence every path from a source to a destination has a *path vector*, which is obtained by combining the link state vectors of all the links in the path.

A connection request between a source-destination pair is provided a primary lightpath and a backup lightpath .We assume that, each lightpath, primary or backup, always accommodates an OAM (operation, administration and maintenance) channel terminated at the same s-d pair as the lightpath. We also assume that wavelength continuity constraint is satisfied on all links along the route. When a primary lightpath fails, an alarm indication signal is generated by the node that detects the link failure, and is transferred over the OAM channel. When the source receives the alarm signal in its OAM channel, it prepares to setup the backup lightpath and sends messages to the controllers along the backup path to configure the ports accordingly.

The primary and backup paths for each request is found by the Shortest Cycle (SC) algorithm as described in [12]. The SC algorithm basically finds out the shortest vertex or link disjoint cycle which minimizes the sum of the path lengths in a given network. The primary is routed along the shorter of the two paths of the SC and the backup along the alternate path. Since the backup path is precomputed for a given primary and capacity is assumed to be reserved, so no run time link backup search needs to be performed. Once the backup path is setup, the destination prepares to receive on the backup path.

2.1 Restoration Model

We consider 100% protection guarantee for surviving any single link failure in the network. This means that the primary and backup paths of a demand are allocated the same capacity, and can be either node or link disjoint. In this present work, we employ backup multiplexing technique to improve the wavelength utilization. This allows multiple backup paths, belonging to demands of different node pairs, to share a wavelength λ on link l if and only if their corresponding primary paths are link disjoint.

It should be noted that, although every primary lightpath has a corresponding backup lightpath dedicated to it, wavelengths on a link can be shared by restoration paths belonging to demands to different node pairs, as long as their primaries do not share any common links. This improves wavelength utilization, while still providing 100% guarantee under the single fault scenario. This is due to the fact that no single failure will cause two primary paths to contend for the same backup capacity.

The network can be assumed to have L links, F fibers per link and W wavelengths per fiber. Hence the network can be represented by a 3-tuple (l, f, w). The backup multiplexing is done by maintaining a *Backup Request List (BRL)* on each wavelength of each fiber at every link. The Backup request List is a link-list of all the requests that are backup multiplexed on a particular fiber-wavelength at a link. The details of how the Backup Request List is used for the channel assignment is described in Section III.

2.2 Cost Model

The cost sources of a DWDM network can be mapped to the following four parameters: the link provisioning cost (C_{lp}), the fiber cost(C_f), the per channel cost (C_λ) and the cross connect cost(C_{oxc}). The link provisioning cost captures the investment required before any capacity on the link can be used. This may include digging cost, leasing cost, right of way cost, maintenance cost etc. Multiple fibers may be laid out as part of the initial investment, some of them may be lit and dark fibers used for future upgrades.

The fiber cost, C_f is a combination of optical amplifier costs, multiplexer and demultiplexer costs for fiber terminations, cost of dispersion compensation components. The maximum number of wavelengths per fiber is an important design parameter. Since the number of wavelengths per fiber decides the amount of dispersion components required, the laser power required and the amount of regenerators needed, the network provider should choose these design parameters appropriately.

In ultra long haul WDM backbone network design, the goal is to let the signal travel longer(thousands of kilometers) without any regeneration. Since regenerators make up a significant part of the facility cost, reducing the number of regenerators results in a direct reduction in the total facility cost. Longer distances without regeneration typically means that the signal to noise ratio is low, as each amplifier add noise to the signal. The noise can be reduced using forward error correction(FEC) and dispersion compensation.

Hence the total fiber cost can be subdivided as follows $C_f = A_f \cdot C_a + C_{mux} + C_{dmux} + C_{dc}$, where C_a, C_{mux},C_{demux},C_{dc} are costs of optical amplifiers, multiplexers, demultiplexers and dispersion compensation components respectively and A_f is the number of amplifiers along the fiber.

The per channel cost C_λ includes the receiver and transmitter card cost per wavelength and power equalization required per wavelength. The power equalization is included as part of the transmitter cost. Since depending on the current demand, the network provider may equip a certain number of wavelength cards out of the possible maximum, this cost depends on the number of wavelengths currently used.$C_\lambda = C_r \cdot w_f + C_t \cdot w_f$, where C_t, C_r are transmitter and receiver card costs and w_f is the number of wavelengths currently used in the fiber.

The number of cross-connects per node determines the switch size and hence the total facility cost. At each fiber port, the incoming wavelengths are demultiplexed and sent to a space switch where they can be switched and sent to any output fiber port. The only constraint is that no two connections going on the same output fiber can use the same wavelength. Connections on different wavelengths, destined for the same output fiber are multiplexed and sent out. The cost of the space switch for each wavelength depends on the size of the minimum crosspoint switching element ($\omega \times \omega$) available in the market. Let the cost of a 2×2 crosspoint switching element be C_{oxc}. The number of such switching elements required for a $(v \cdot v)$ switch is $\frac{v}{2} \log_2 v$ (assuming the switches are implemented as a multistage interconnection network (MIN). Hence the cost of each MIN is $C_{oxc} \cdot \frac{v}{2} \log_2 v$. The number of incoming and outgoing ports on a fiber is decided by the maximum number of wavelengths and fibers that needs to be activated at a particular stage of network evolution. The total network facility cost is hence given by the sum of all the links and node costs.

$$\textit{Total Network Facility Cost} = \sum_{l}^{L} (m_l C_{lp} + \; f_l C_f + \; w_l C_\lambda)$$

$$+ \sum_{n}^{N} (\psi \cdot C_{oxc} \cdot \frac{(o_n)}{\omega} \log_{\omega}(o_n))$$

where $m_l = 0, 1$ denotes if a link l is used or not. f_l, w_l denotes the number of fibers and wavelengths on a link l respectively. o_n denotes the number of cross-connects needed in a node, and ψ denotes the maximum number of wavelengths per fiber. The value of o_n is rounded off to the nearest higher integral power of ω. In the second term of the above equation, the cost of a MIN in each node is multiplied by ψ, since there is a MIN switch for each wavelength.

3. Connection Establishment

The incoming connections to the network are assigned a wavelength and a fiber based on an optimal channel assignment scheme which minimizes the fiber usage and also ensures that 100% guarantees can be met under a single fault scenario. For simplicity we assume that every request is of unit wavelength capacity. Hence no sub-wavelength traffic or grooming capabilities are considered in our work. The available capacity at each wavelength on a link forms an *Availability Vector* $A_i : \{ a_1, a_2, \cdots a_n \}$. where n denotes the total number of wavelengths in each fiber and each a_i indicates the available capacity on each wavelength across all fibers. The path selection for a request is done by the shortest-cycle algorithm. A *Minimum Availability Vector* is obtained at each wavelength on each link $M^l_{av} : \{ m_1, m_2, \cdots m_n \}$ such that each m_i is equal to one or zero depending on the following condition.

$$m_i = \begin{cases} 1 & if \; \{a_i = min(a_1, a_2, \cdots a_n)\} \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

The above vector M^l_{av} is combined on all the links along the path of the request to form the *Wavelength Selection* matrix $W_l : \{w_1, w_2 \cdots w_n\}$. wherein each w_i is given by

$$w_i = \sum_{1}^{L} M^i_{av} \tag{2}$$

where L denotes the number of links in the path of the request. The + (“add”) operator is used for the combining along all the links of the path. w_i indicates the number of fibers that are needed to route the given connection on the i^{th} wavelength along the path. Hence the wavelength with the minimum value in the Wavelength Selection Matrix is used for channel assignment. If more than one wavelength has the minimum value, a random selection is made between them.

Fig 2. demonstrates the fiber and wavelength selection algorithm for primary path. Let us suppose an incoming connection R_i demands a path between $1 \rightarrow 4$. Let us assume that every links has F fibers, with two wavelengths per fiber. The 2-tuples indicate the available capacity on each wavelength across all the fibers. Hence along path P_1 we have $\{P_1 : l_1(3,4), l_2(4,3), l_3(3,4)\}$. Similarly along path P_2 we have $\{P_2 : l_1(4,3), l_2(3,3), l_3(3,4)\}$. Hence the Minimum Availability Vector M^l_{av} on the links become $\{P_1 : (1,0),(0,1),(1,0)\}$ and $\{P_2 : (0,1),(1,1),(1,0)\}$. The Wavelength Selection matrix for both the paths become $\{2, 1\}$ and $\{2, 2\}$ respectively. This implies that if we assume to route the connection through the first path, and if we select λ_1 we would need to activate two new fibers whereas if we use λ_2 to route the connection, only one new fiber needs to be activated. Hence, λ_2 is chosen to route the connection. However if we have to route the connection along the path P_2, it does not matter which wavelength we pick to route the connection since both would activate two new fibers along its path.

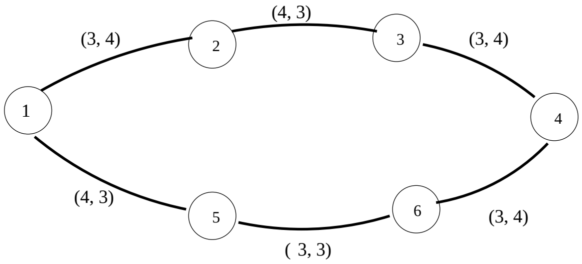


Figure 2. Fiber and Wavelength Selection Algorithm for primary path

To ensure backup multiplexing, a Backup Request List (BRL) is maintained on each wavelength on each fiber at every link. Hence the BRL on a link is denoted by $\{l_i,\ f_j,\ (w_1,\ w_2,\ \cdot\cdot\cdot\cdot,\ w_n)\ \}$, where l_i denotes the link id, f_j denotes the fiber id and each of w_i denotes the BRL on that fiber and wavelength. When an incoming request R_i arrives a check is made on its backup path on each fiber and wavelength to see if there is any conflict with the existing requests in the BRL. After the check two different matrices are obtained on each fiber and wavelength on the links of the backup path of the request namely the *Backup Availability Matrix* $B^{(f,w)}$ and the *Maximum Backup Availability Matrix* $B^{(f,w)}_{max}$.

The Backup Availability Matrix is filled up with 0 if there are no free backup possible at that fiber-wavelength combination or if that wavelength on that fiber is used as a primary. It is filled up with 1 if the incoming request finds no conflict with any of the requests on the BRL. Hence the information stored on the Backup Availability Matrix gives us whether the incoming request can be backed up for free on any fiber-wavelength combination. The maximum backup availability matrix is filled up with a 0 if that particular wavelength on that fiber is used as a primary else it is filled with 1. Hence the maximum availability matrix gives us information about the possibility of a request to be backed up at a particular fiber wavelength combination. This includes the case wherein an additional free fiber might be used to route the backup. Two matrices namely the *Routing-Info* matrix and the *Max-Routing-Info* matrix can be derived from the above two matrices at each link on the backup path. The routing info matrix can be obtained as

$$R^w_{info} = \sum_f B^{(f,w)} \tag{3}$$

$$R^{w}_{maxinfo} = \sum_{f} B^{(f,w)}_{max} \tag{4}$$

Similarly the max routing info matrix can be obtained as shown in Equation 4. A non zero entry at the routing info matrix indicates that the request can be backed up on any one of the fibers on that particular wavelength without accounting for any extra cost. If no such entry is found for any of the wavelengths, the wavelength selection is made based on the max-routing info matrix. The maximum entry of the max-routing info matrix is considered for wavelength selection for the backup path. The above channel establishment procedure ensures minimum fiber usage for routing both the primary and the backup paths for an incoming request.

In Fig 3, let us assume that we have two requests R_1 and R_2 both from $1 \rightarrow 2$. Hence the primary and the backup paths computed by shortest-cycle would be $1 \rightarrow 2$ and $1 \rightarrow 8 \rightarrow 2$. Let us assume that R_1 and R_2 are the first two requests. According to the above algorithm when the backup of R_1 is attempted to be routed the Backup Availability matrix is computed and it turns out to be $\{0, 0, 0 \cdots 0\}$ since no backups are free. Similarly the Maximum Backup Availability matrix returns $\{1, 1, 1 \cdots 1\}$.

The R^{w}_{info} and the $R^{w}_{maxinfo}$ matrices obtained are $\{0, 0, \cdots 0\}$ and $\{F, F, F \cdots F\}$ assuming that there are F fibers in the system. Hence backup path of the first connection R_1 uses the first fiber using any of the wavelengths selected from $R^{w}_{maxinfo}$. When the backup of the second connection is routed the $B^{(f,w)}$ and $B^{(f,w)}_{max}$ are $\{0, 0, 0 \cdots 0\}$ and $\{1, 1, 1 \cdots 0\}$, since R_2 has a conflicting primary path with R_1. The R^{w}_{info} and the $R^{w}_{maxinfo}$ matrices obtained are $\{0, 0, \cdots 0\}$ and $\{F, F, F \cdots max(0 \cdots F-1)\}$. Hence R_2's backup gets routed using a different wavelength than R_1 but they reuse the same fiber.

The above framework for information collection and routing is referred to as *MICRON*- Methodology for information Collection and Routing in Optical Networks [14]. This can be applied in general for any heterogeneous networks for wavelength routed networks the link state information reduces to a diagonal matrix. Hence the above methodology for channel allocation can be implemented using the same matrix notations as described in [14]and similar path information vectors can be derived.

4. A Simulated Annealing Approach for Routing Static Connections in Mesh-Restorable Optical Networks

This section describes a framework for using simulated annealing for routing static connections in mesh-restorable optical networks. In this context simulated annealing is used as an optimization tool to minimize the total network facility cost used to route a given demand matrix, which defines the set of connections in a network.

Integer Linear Programming (ILP) formulations has been already been attempted for the design and upgrade problem of mesh restorable optical networks in [6], [9], [11], and it has been observed that ILP is an effective optimization technique only for small networks with moderate amount of services or demand sets[10]. The complexity of the optimization problems grows exponentially as the size of the network grows or the demand sets increases. Under such scenarios simulated annealing can be an elegant technique to solve the same problem in a reasonable amount of time.

Simulated annealing is a Monte Carlo approach for minimizing multivariate functions. The simulated annealing progresses by lowering the temperature slowly until the system “freezes” and no further changes occur. At each temperature the simulation should run long enough for the system to reach a steady state or equilibrium. This process is known as *thermalization*. The sequence of temperatures and the number of iterations applied to thermalize the system at each temperature comprise an annealing schedule.

To apply simulated annealing, the system is initialized with a particular configuration. A new configuration is constructed by imposing a displacement. If the energy of this new state is lower than that of the previous one, the change is accepted unconditionally and the system is updated. If the energy is greater, the new configuration is accepted probabilistically. This ensures the system to move consistently towards lower energy states, yet still *jump* out of local minima due to the probabilistic acceptance of some upward moves. It also allows the search to explore a larger search space without being trapped in a local optima prematurely.

Simulated annealing can be used a network design tool to optimize the total network facility cost used to route static connections. To achieve 100% survivability each request should be assigned a primary path and a backup path computed using the SC algorithm. The primary and the backup paths for each arriving request is calculated dynamically based on the current link weights of the network.

After all the requests of the demand matrix are routed, the total network facility cost is computed. This becomes the *initial solution* for the annealing process. In the thermalization stage (which comprises of multiple sub-transitions at the same temperature), the request set is shuffled based on different parameters. Three different shuffling metrics were considered, random shuffling, one based on descending hop length of connections and another on ascending hop length required to route the connection. The request set considered for shuffling could be the complete initial request set or it can be a sub-set of the initial demand matrix.

This shuffling of request demands is repeated for a fixed number say (*X*) times at a particular temperature. At the end of each such sub-transition, the objective function is recomputed. If the total network facility cost used to route the shuffled set of connections is less than the initial cost, we update the best objective function to be the latest solution, else no update is made.

Hence after S sub-transitions at a particular temperature we obtain an equilibrate state wherein all the requests of the demand matrix are routed obeying a particular metric such that the overall network cost is minimized. At the end of each such S sub-transitions the link utilization on all links are computed. The link utilization of the i^{th} link, given by L_i is the total primary capacity used on the link divided by the total capacity available on a link.

At the end of X sub-transitions the link weights used for the computation of the *SC* is mutated by a factor of $\gamma(1 - L_i)$ during the first transition boundary. This is done such that shortest cycle explores different possible primary and backup path combinations for each request during each transition boundary at a fixed temperature. This process can be repeated for a fixed number of say (Y) times.

The temperature is scaled down linearly and the *thermalization* process restarts again. The objective function is recomputed after the routing of the pre-determined set of static requests. If the objective function is reduced from the optimum value the new solution is used to update the objective function value. If the objective function value is greater than the optimal value it is accepted with a certain probability which depends on two parameters, the difference between the objective values δ and the control temperature T at that point of time.

The probability of acceptance is generally given by $p_a = \exp^{-\delta/KT}$ where K is the *Boltzman's Constant* and T is determined by so called annealing or cooling scheme described in the next section. If this calculated probability at any point given by say (X_i, Y_j) is greater than a particular random number R_k (varying between 0 and 1), then the inferior solution is accepted and is used to update the current solution, else it is rejected. Initially p_a is very high,(i.e close to 1 and hence greater than R_k), so all bad solutions are accepted. This facilitates SA to explore bad solution states in the beginning. T decreases as the search proceeds, thus gradually decreasing p_a, the probability of acceptance of a bad solution. As T approaches zero, the search reduces to a greedy search and will be trapped in the nearest local optima.

As can be seen in Fig 3, the initial primary and backup routes selected by the SC algorithm for the requests $1 \longrightarrow 4$ and $7 \longrightarrow 4$ for uniform link weights is just the shortest paths between each source and destination. But as the edge weights are mutated between two transitions based on the link utilization, the shortest-cycle gave two new primary and backup paths for the same connection demands. Hence the routing through successive edge mutations is equivalent to exploring large number of route sets as part of the shortest cycle algorithm.

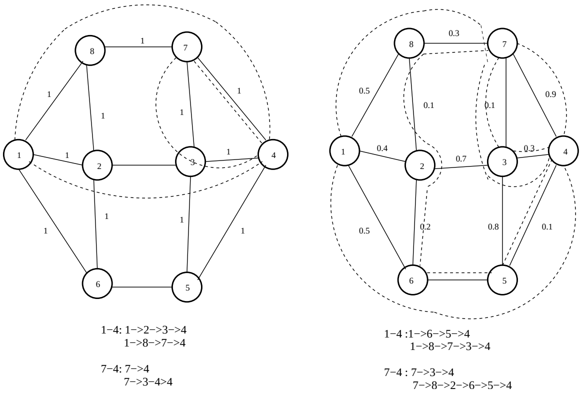


Figure 3. Path Mutation in Simulated Annealing

The fact that we try also different arrangements helps us get the best possible backup multiplexing and in turn improves capacity efficiency, and also for a given node pair, this in-effect emulates the K generalized shortest cycles because of edge weight mutations. The above search can be terminated by either repeating the *annealing* process for some predetermined number of iterations or if the search experiences no improvement in the best objective value for some pre-defined ψ number of annealing steps.

There are different possible annealing schemes to update the temperature T. We may use an annealing scheme where the temperature varies as $T_n = \alpha \times T_{n-1}$, where T is the temperature at the nth temperature update, and α is an arbitrary constant between 0 and 1. The parameter α decides how slowly T decreases. Typical values of α lie between 0.9 and 0.95. The parameters Y, α and the initial value of T plays a critical role for the performance of the simulated annealing. We have an annealing scheme where the temperature update is made as $T_n = T_0/(1 + \alpha \times T_{n-1})$. The typical values of α can be of the order of 0.01 to 0.1 in-order to have a graceful degradation of the temperature.

5. Methodology for Network Upgrade

The method of routing static connections using the simulated annealing technique can be extended for upgrade of networks. As network evolves over time, the challenge lies in how to route the incremental traffic demands over the pre-existing network such that the total network facility cost is minimized at every instant in the process of network evolution. The main idea is to reuse most of the resources from the previous generation of the network and evolve out of it to accommodate the additional traffic set.

Each link in the network maybe used to realize the working and spare capacity requirements. The objective would be to incur a one-time *fixed charge* for the acquisition and have an incremental step-wise increase in cost with increasing capacity as additional transmission systems are turned up.

In the most generalized model we assume a traffic model given by $\{R_l, R_a\}$, where R_l is the number of connections that leaves the system during transition from one generation to the next generation and R_a defines the number of connections that arrive in the next generation.

For our experimental studies we consider two scenarios, one in which all the demands from the first generation gets carried over to the next generation i.e.$\{|R_l| = 0, |R_a| \geq 0\}$ and secondly another scenario wherein $|R_l| \geq |R_a|$ hence the network going for an upgrade. In the second scenario the traffic matrix might be entirely or partially different from the previous generation. The routes of the demands which do not carry onto the next generation are removed but the installed capacity in the network(in terms of the no.of fibers, crossconnects at nodes etc) are taken as lower bounds for the simulated annealing framework in the next generation.

In our present work the static connections of the first generation are optimally routed using the simulated annealing approach. The total optimal network state at the end of the first generation is taken as the lower bound of the SA while routing the connections during the second generation of network evolution. The same process is repeated for each successive generation of network evolution.

Hence the final topology we arrive at, would have a subset of links that needs to be activated, a subset of fibers that need to be lit up, some number of wavelength cards that need to be installed and crossconnects that need to be configured to realize the traffic.

6. Performance Evaluation

The 14 node, 22 links NSFNET network as shown in Fig 4, is used for our experimental studies. Each of the links in the network is assumed to be bidirectional. The maximum number of fibers *F* in the network is assumed to be 5, since fibers are expensive components and we should try to minimize installation of fibers. The maximum number of wavelengths considered per fiber is 40. Each node in the network is assumed to be strictly homogeneous i.e. they employ the same switching architecture. A connection at a node is assumed to be switched between an incoming wavelength on one fiber to the same wavelength on the same or different outgoing fiber. We employ the following cost values for our experiments. The link provisioning cost $C_{lp} = \$160$ per mile, the fiber provisioning cost is kept at $C_f = \$1000$ per mile, the wavelength cost is kept at $C_\lambda = \$1$ and the cost of a $(2 \times 2)(\omega = 2)$ cross-connect is kept at $1000. The cost values employed here are conservative estimates obtained from literature.

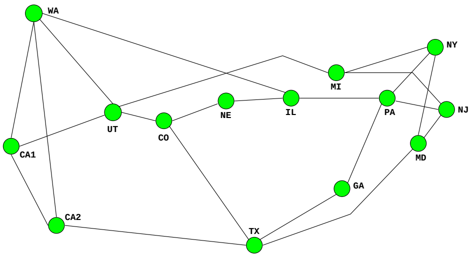


Figure 4. NSFNET backbone network

The total facility cost is computed using the equation derived in the cost model. The Boltzman's Constant was taken to be of the order of 5000 to 10000 such that,

$$0 \leq \exp^{-\delta/(K \times t_i)} \leq 1$$

where t_i is the temperature at the i^{th} iteration. The temperature mutation parameter α is taken to be between 0.005 and 0.01 so that that the temperature does not drop abruptly. Higher values of α leads to a fast convergence for the simulated annealing procedure. The edge weight mutation parameter γ is chosen to be between 0.5 and 1.0.

The MICRON routing algorithm is used to generate the initial solution to the SA process in the first generation. The network evolution is considered for a period of six years. In our model of network evolution the initial number of requests considered for the first generation were 75, 100, 150 and 200 distributed uniformly over the 22 node pairs. Every year the traffic is increased by a conservative growth estimate of 15% to 20%. For the second model of traffic upgrade some connections from the first generation were probabilistically terminated so that they are absent in the next generation and new connections were added in such that the overall connections increases across generations.

6.1 Results

Different observations were made from the study of the simulated annealing approach for routing static connections.

- Fig 5(a) shows an simulated annealing progress curve for all the three different shuffling schemes. As can be observed from the figure the higher values of the objective function were seen by each scheme because SA was trying to explore a bad solution, which would not have never been explored in all the previous studies done till far. So the claim is that simulated annealing actually tries to emulate the K-shortest paths (K-shortest-cycles in our case) and does so in an much more unconstrained manner as compared to our previous studies [15].

  The total number of sub-transitions at a given temperature considered for SA was 10 and the transition across different temperatures was considered to be 20. This numbers were chosen because they were moderate enough for the simulated annealing to show different possible solution sets.

- As an expected trend the mutation scheme based on the descending hop length of connections gave us the best optimal solution for routing connections as can be seen from Fig 5(b).

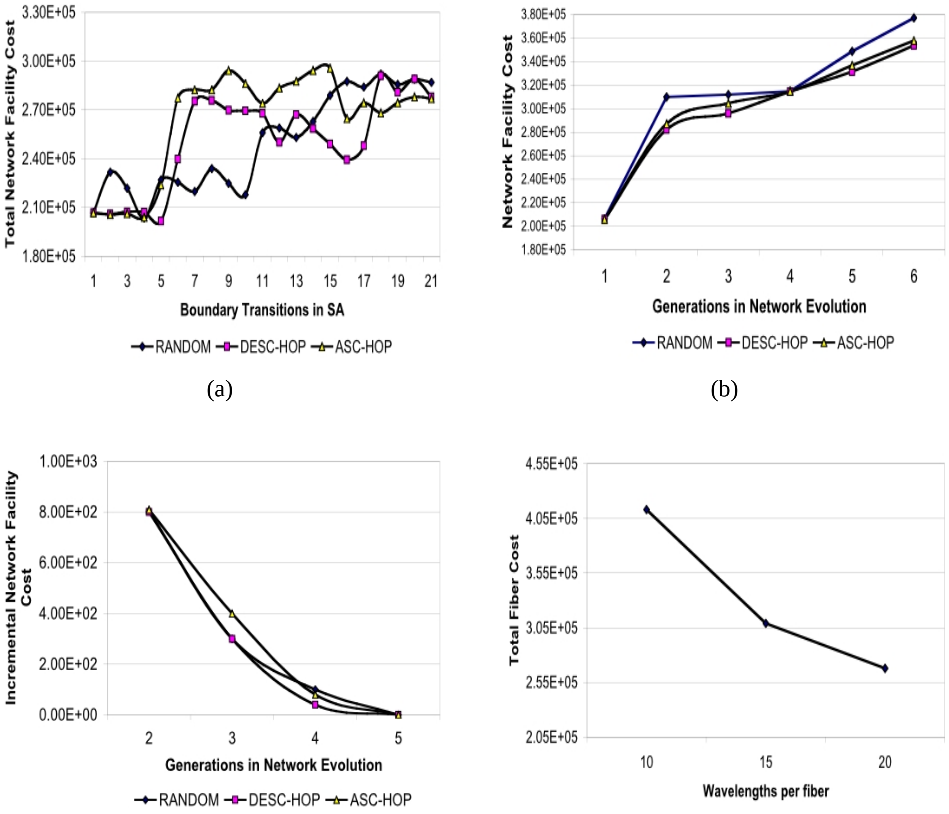
  This was an intuitive result as the network would ideally like to see higher hop connections getting routed prior to shorter hop connections, such that all the requests can get ideally packed in. The schemes based on descending hop length and the one based on random mutation performed significantly poorer as compared to the first scheme. In fact as we progress to higher and higher generations, a few longer hop connections starts getting blocked due to infeasibility of a route.

- Fig 5(c) shows the incremental costs that are incurred for the second model of upgrade. This figure shows that simulated annealing was actually successful in routing the connections in successive generation over the facility installed in the initial design itself. As can be seen, the descending hop length scheme performs the best. In future generations, the ascending hop length scheme performs almost similar to the random mutation scheme.

  The point to be noted here is that the initial design solution for the first generation itself is an inexpensive one and tries to route traffic using a sub-set of links out of the complete topology. The successive incremental costs that comes in future generations just tries to reuse the resources from the previous generation and sometimes dimensions new links to accommodate new connections. This is a significant point as every network designer would like to build a network, which not only accommodates current traffic, but can also carry a significant amount of future workload.

- Fig 5(d) shows the decrease in fiber cost across six generations as the number of wavelengths per fiber is increased for handling the same traffic demand.

- Table 1 represents the performance of the different mutation techniques for different initial traffic demands. #Req represents the initial number of requests to start with at the beginning of the first generation. The traffic demands are assumed to grow by an conservative estimate of 20% in between two successive generations. *Object* represents the optimal value of the Objective function i.e the total network facility cost found at



(a) (b)

(c) (d)

Figure 5. Performance Results of SA on NSFNET: (a) Behavior of Simulated Annealing within one generation, (b) Network Facility Cost across generations when initial demand set remains intact, (c) Incremental Network facility cost when we have entirely new traffic pattern in future generations and (d) Fiber Cost Vs Wavelengths per fiber

Table 1. Comparison Of Different SA Mutation Schemes

Metric	DESC Hop Length			ASC Hop Length			Random		
#Req	Object	CPU	E, F	Object	CPU	E, F	Object	CPU	E, F
75	3.23E7	54	14, 1	3.58E7	56	14, 1	3.77E7	54	14, 1
100	3.53E7	100	18, 2	3.63E7	104	19, 2	3.81E7	104	19, 3
150	3.63E7	183	22, 3	4.16E7	187	22, 4	3.97E7	191	22, 3
200	4.50E7	288	22, 4	4.61E7	294	22, 4	4.73E7	296	22, 4

Table 2. Comparison of Simulated Annealing with ILP

No.Of Reqs	Simulated Annealing (Objective Value)	ILP (Objective Value)
72	1.1687×10^8	1.14×10^8
92	1.684×10^8	1.46×10^8
112	1.8256×10^8	1.72×10^8

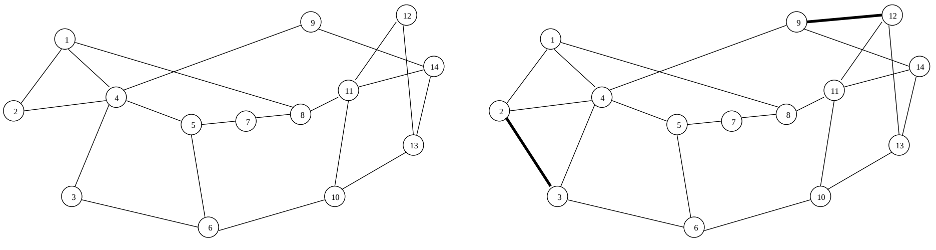
the end of the final generation. CPU represents the total CPU time needed to arrive at the solution for the complete design problem for six generations when the simulations were performed on a Sun Sparc III machine supporting OS-5.8 with a processor speed of 750Mhz. E represents the number of edges that were activated after finding a solution and F fibers represents the total numbers of fibers needed. As can be observed from the table the descending hop length metric scheme performs significantly better than the other two schemes when we consider lower traffic demands. But as the traffic demands increases the solutions given by all the schemes tend to merge.

- Table 2 represents the performance of simulated annealing as compared to an ILP solution. It can be seen that simulated annealing objective value is within 10% of the ILP optimal value. For the above chart we considered a demand set of 72 requests in the first generation and followed by an incremental demand of the order of 20 for the next two generations. The traffic demand used for this comparison is different from the traffic demand used for the previous experiments with SA.

Another interesting observation was the effect of topology sparsening, which happens in our design study as shown in Fig 6(a) which illustrates some missing links during a certain generation and Fig 6(b) indicates the links that gets added on to accommodate traffic that could not be facilitated on the existing links. Simulated annealing was able to show that the topology needed to route a set of connections for any given generation was actually the proper sub-set of the topology obtained for routing a future generation traffic.

7. Conclusions

In this paper we provided a framework for designing a network for a given static demand matrix. We also define a methodology for upgrade using the sim-



(a) (b)

Figure 6. Sparsening Effects in Simulated Annealing

ulated annealing approach which always tries to minimize the incremental costs needed for upgrade. The simulated annealing approach explores different possible solution sets and hence can be mapped on to the generalized K-alternate shortest path approach proposed in one of our previous work. We have shown that the simulated annealing finds solution close to the ILP optimal solution. The simulated annealing framework is a more generalized approach as compared to most ILP studies, since we try to explore different alternative path sets during the search of an optimal solution. Thus this scheme can be used as a heuristic to arrive at near optimal solutions in cases of complex demand sets and moderately large networks, where the run-time of the ILP becomes actually practically infeasible. The proposed framework can be implemented in networks that collect information through link-state protocols and employ source-based routing. This scheme is highly inexpensive, fast and can be ideally employed for all backbone networks. Furthermore this methodology can be extended for heterogeneous networks, wherein we can study the impact of switching architectures on route selections.

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