

## SCATTER SEARCH BASED METAHEURISTIC FOR ROBUST OPTIMIZATION OF THE DEPLOYING OF “DWDM” TECHNOLOGY ON OPTICAL NETWORKS WITH SURVIVABILITY

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**Abstract:** In this paper we discuss the application of a metaheuristic approach based on the Scatter Search to deal with robust optimization of the planning problem in the deploying of the Dense Wavelength Division Multiplexing (DWDM) technology on an existing optical fiber network taking into account, in addition to the forecasted demands, the uncertainty in the survivability requirements.

**Keyword:** Network planning, WDM, scatter search, robust optimization, survivability.

### 1. INTRODUCTION

Wavelength Division Multiplexing (WDM) is the transmission of multiple laser signals at different wavelengths (colors) in the same direction, at the same time and over the same strand of fiber. WDM creates multiple bi-directional ‘virtual fibers’ per physical fiber corresponding to the different wavelengths or frequencies that are called WDM channels. Dense Wavelength Division Multiplexing (DWDM) is the WDM technology that supports a high number of frequencies. DWDM solves the bandwidth bottleneck

resulting from growth in data traffic because it increases transportation capacity while preserving optical fiber equipment previously installed and enables a low cost per bit.

Therefore DWDM is the arising technology for increasing the capacity and survivability of fiber networks while reducing costs, when compared to traditional equipment and new fiber. To use DWDM technology, a DWDM equipment “unit” must be placed at both endpoints of each fiber link. For each wavelength, or channel in use, channel equipment must be also placed at both endpoints of the link. In the planning problem in the deploying of DWDM technology on an existing optical fiber network, the decision variables relate to how to add transportation capacity to an existing network at a minimum cost in order to satisfy the requirements. Due to the characteristic of the technology, the involved variable decision are modular therefore traditional approaches for continuous variables can not be applied.

Survivability is the ability to restore network services in the event of a failure. The survivability of the network is provided by installing spare capacity for the restoration of the traffic in case of a failure. The network planner looks for a design capable of absorbing all the traffic demand and with high survivability guaranties in the event of a failure. Each possible failure results in a scenario that corresponds to the realization of the uncertainty. Every possible design has a total cost, that is to be minimized, and spare capacity that allows to restore a proportion of the demand in the case of each failure. A design that allows to survive to all traffic in all the possible failures will be too costly. The amount of demand that can not be restored in the case of the failures gives a measure of the survivability.

Robust Optimization is a framework for modeling optimization problems that involve uncertainty. Robust Optimization methodology uses scenario-based approaches to deal with the uncertainty, where the scenarios correspond to the possible realizations of the uncertainty. The main feature of robust optimization formulations is the flexibility to deal with the tradeoff between *optimality robustness* and *feasibility robustness*. The optimality or solution robustness of a solution refers to how “close” to optimal solution it remains for any realization of the scenario. The feasibility or model robustness of the solution refers if it remains “almost” feasible for any realization of the scenario. The use of scenarios as a tool for modeling uncertainty has the advantage of not requiring specific knowledge of the underlying uncertainty measures. A solution method approaches to optimization problems with uncertainty usually by obtaining a deterministic equivalent optimization problem that is solved by known techniques. In the planning problem of the deploying of the DWDM technology on an existing optical network, the cost of the design is related to the solution robustness and its survivability measure to model robustness. The deterministic equivalent optimization problem is then a bi-objective problem with cost minimization and survivability maximization. The classical approach minimizes a linear combination of the cost and the demand not restored as penalization. However the Scatter Search metaheuristic is useful for providing a differentiated set of designs with several costs and survivability guaranties.

The Scatter Search is a population-based metaheuristic that constructs solutions by intelligently combining and improving others in a set of good and disperse solutions (*The Reference Set*) that is updated taking into account the results of the improvements. The reference set is a repository of good and disperse solutions that improves during the search and will provide the useful information for decision maker. The reference set is updated during the search process by using criteria based on comparisons and measures of the diversity between the new solutions and the existing solutions. The population

must consist in a wide set of good and very disperse solutions that can be initially obtained by adaptive procedures like GRASP. Scatter Search starts by generating a reference set from the population of solutions. Then subsets are iteratively selected from this reference set. The solutions of each selected subset are combined to get starting solutions to run an improvement procedure. The combination procedure tries to intelligently combine good characteristics of the selected solutions to get new high quality solutions after the improvement. The possible improvement solution methods applied to the solutions range from the simplest local searches to very specialized procedures. The improvement procedure must allow to use efficient tools like recent or intermediate memory or variable neighborhood. The reference set is updated according to the quality and the dispersion of the improved solutions found. The process is iterated with the new reference set until a stop condition is met. Finally, the set of disperse and high quality solutions in the reference set is provide by the method.

## 2. DWDM TECHNOLOGY

In the last decades, problems related to planning telecommunication networks have become a fertile ground for developing and applying optimization techniques. Two main events have driven these efforts: (1) the large investment in telecommunication, which offers significant opportunities for improving network designs and, and (2) the rapid changes in technology, which result in new operational environments. Several relevant events in the last years are the increasing in the volume of demand, the evolution of a wide range of user services and the increased competition between providers. Network managers have felt the need to increase the survivability, the connectivity and bandwidth among the locations.

WDM technology is nowadays the premier component in optical fiber telecommunication networks, due to its cost effectiveness, reliability and its, for all practical purposes, unlimited capacity. Technology advances have motivated the development of appropriate planning tools that respond to the characteristics of a new structural and operational environment. For instance, the high capacity in optical fiber links results in network designs that are sparser than those associated with copper technology. As a result, the traffic routed through a single link is significantly larger in optical fiber networks and so is the disruption of services if any single link or node were to fail. Since services can be restored in hours or days, most network planners do not consider more than a single node or link failure when designing for survivability because the probability of another failure during the repair period is small. Along with cost reduction, survivability against failures is one of the most important aspects that are considered when designing fiber networks. Survivability is defined as the ability to restore network services in the event of a catastrophic failure such as a faulty link or a defective node. Network providers typically use survivability as a competitive differentiator or offer it as a premium service.

To use DWDM technology, a DWDM equipment "unit" must be placed at both endpoints of each fiber link. For each wavelength, or channel in use, channel equipment must be also placed at both endpoints of the link. Each DWDM channel is bi-directional and has the same capacity as a pair of fibers. Amplification is the process restoring the optical signal to its original optical power and without distortion after the signal has lost

power when passing through a strand of fiber. The typical amplifiers do not have electronic elements; they are completely optical. Consequently, they do not require the classical electrical-optical and optical-electrical conversions, thereby avoiding the associated need for additional bandwidth.

The DWDM system is equipped with amplifiers that allow transmission in one channel. However, most of the capacity cost is related to the channel cards. Channel cards are added as needed and their cost is charged to the design accordingly. This means that a system capable of handling up to 96 channels can be installed where only eight channels are active, and the design would only consider the cost of equipping the eight active channels.

Optical cross-connects (OXC) are small space-division switches without waveband selectivity that can switch an optical signal from one wavelength to another on multifiber DWDM systems or on a single fiber. They route the signals on each input port to one or more selected output ports. Each DWDM system must originate and terminate at an OXC or DCS (Digital Cross-Connect Signal) port. Also, an OXC or DCS port is needed to add or drop traffic at the origin and destination of each demand carried by the network. The OXC and DCS ports are bi-directional. Optical signals originate and terminate at network nodes, which are typically SONET (Synchronous Optical Network) ring nodes carrying traffic expressed in OC-48 units, i.e., Optical Carrier level 48 SONET channels. Each such channel carries  $2.488 \cdot 10^9$  bits per second, equivalent to  $48 \cdot 672$  voice-grade digital channels digitized at 64,000 bits per second each, after subtracting out overhead bits used for routing and control.

### 3. THE DWDM DEPLOYING PLANNING PROBLEM

Two special network planning problems have been the focus in the telecommunications literature: the feasibility problem and the analysis problem. The first problem refers to the feasibility of a set of flows taken into account the link and node capacities installed on the network. If a set of demand requirements is also considered, the second problem refers to the determination of feasible flows such that the demand requirements are satisfied. A third type of network flow problem is the network synthesis or provisioning problem. A synthesis problem consists of minimizing the total cost of installing capacity on links of a given network so that the demand requirements are satisfied. A Survivability problem consists in a provisioning problem where the system must survive in the event of any link failure by rerouting the affected traffic.

In general provisioning problems, the decision variables relate to how to add transportation capacity to an existing network at a minimum cost in order to satisfy some requirements. In a provisioning problem a physical network topology is usually given. When the problem includes also the design of the network topology, that is, determining new links to install, then installation costs for the possible new links are included. If the whole network is to be designed then a complete graph is considered. In addition to the network topology and the demand requirements, the cost structure characterizes a typical instance of a synthesis problem. A general provisioning problem also considers survivability requirements so that the network must survive in a set of failure circumstances. Therefore, an instance of the provisioning problem is characterized by a cost structure (that could include installation costs) and a set of requirements (that could include demand and survivability requirements).

The cost structure of a provisioning problem depends on the problem at hand, on the available technology and on the installed infrastructure. It is customary to assume in optical network planning that the system does not add routing costs once the equipment has been installed and the optical traffic is expressed in OC-48 units. The synthesis problems typically deal with commodities involving a single source and a single sink. A demand requirement between two nodes is a single commodity flow requirement. Multi-commodity flow requirements are also considered as long as the commodities involve different origins and destinations while sharing the capacity of the network. When the set of requirements consists of a single demand, the synthesis problem reduces to solving the shortest path problem on a graph with incremental costs as arc weights. The incremental costs are due to the equipment required to route the smallest allowed demand increment. More likely, however, the set of demand requirements consists of several origin-destination pairs. Synthesis problems also consider non-simultaneous demand requirements, where the capacity installed to route one demand at a given time can be used to route another demand at a different time without additional cost. In this case, the demand requirements are routed taking into account the spare capacity in the current network. The spare capacity problem is carefully studied because the equipment installed on links and nodes to route a given demand under consideration can also be used to route another demand to be considered later, making the design more cost effective.

In a provisioning problem with survivability the system must survive in the event of a failure by rerouting the affected traffic. The literature considers mainly link and node failures, which are always limited to a single element; because it is assumed that the system is capable of repairing any single failure sufficiently fast. The fault-recovery techniques can be roughly classified in two types: *restoration* and *protection*. Restoration techniques should reroute the affected traffic dynamically and rapidly using the capacity provided in the network. Protection techniques pre-compute in advance backup routes for each possible failure. Planners consider two categories of restoration schemes: line or link restoration and path or end-to-end restoration. When a link fails under line restoration, the system redirects all the service traffic on the failed link to alternative paths that connect the origin and the destination nodes of the given link. Therefore, each single link failure results in a single commodity flow requirement. In path restoration, the system restores each requirement path passing through the faulty link. That is, the affected traffic is rerouted between the origin and destination nodes of each disrupted demand. With a intermediate and realistic link-path restoration scheme redirect every service traffic on the failed link to alternative path from the origin of the link to the destination of the demand. Therefore, each single link failure results in a multi-commodity flow requirement.

The optimization problem consists of deciding how to deploy the DWDM technology on an optical fiber network in order to satisfy a set of requirements at a minimum cost. The problem deals with a set of single demands to be routed through the optical network and a set of links to be restored in case of failure. In order to deploy the DWDM to increase the capacity of the network, it is necessary to decide where to place DWDM and OXC systems and dimensioning them. To know if the provisioning of the network satisfies the requirements it is necessary to know how to route each demand within the resulting network and how to reroute the traffic on each link in the event of failure. The provisioning for these goal phases have been usually completed sequentially and independently from each other because of the complexity associated with tackling the entire problem in one installment. However, our approach simultaneously deals with them.

#### 4. MATHEMATICAL FORMULATION

We formulate the optimization model for the WDM planning problems that incorporates both O-D demands and shared-link network protection scheme for single failures. We present first a mixed integer programming (MIP) formulation of the basic provisioning problem for the O-D demands. Then we present the model for obtaining the backup paths for each failed segment beginning with a solution of the previous problem. We use the segment-path model to determine the equipment required to route a set of point-to-point demands through the network and we use the shared-link protection scheme to determine the backup paths of each failed segment.

The network topology is represented as a graph  $G = (N, E)$ , where  $N$  denotes the set of nodes and  $E \subseteq N \times N$  denotes the set of segments. Therefore, in our formulation, links and segments are equivalent in that they represent a direct connection between two points. The cost of using an individual link or a segment is correctly computed in the objective function. For each  $n \in N$ ,  $A_n$  denotes the set of segments adjacent to node  $n$ . The origin/destination node pairs  $\{s, t\} \in N$  corresponding to the point-to-point demands are given by  $D \subseteq N \times N$ . For each  $\{s, t\} \in D$ ,  $d_{st}$  denotes the bandwidth requirements in OC-48 units and  $P_{st}$  denotes the set of possible paths from  $s$  to  $t$  that can be used to route this demand. Since the set of paths used for each demand may not consist of all the possible paths from  $s$  to  $t$ , the formulation described in this section may be used as a heuristic model for the provisioning and routing problem.

##### Cost Input Data

$C_e^F$  = cost of a fiber on segment  $e$  (sum of costs per link along that segment).

$C_e^W$  = cost of a WDM unit on segment  $e$ .

$C^O$  = cost of an OXC unit.

$C^c$  = channel cost of a WDM unit.

$C^p$  = port cost of an OXC unit.

##### Capacity Data

$M^W$  = capacity of a WDM unit.

$M^O$  = capacity of an OXC unit.

##### Existing Infrastructure

$g_e$  = spare WDM channels on segment  $e$ .

$h_n$  = spare OXC ports at node  $n$ .

##### Decision Variables

$x_p^{st}$  = 1 if demand  $(s, t)$  is routed on path  $p$  and 0 otherwise.

$f_e$  = number of stand-alone (no WDM) fiber pairs on segment  $e$ .

$w_e$  = number of WDM units on segment  $e$ .

$v_e$  = number of channels in the WDM systems installed on segment  $e$ .

$y_n$  = number of OXC units installed at node  $n$ .

$u_n$  = number of ports in the OXC systems installed at node  $n$ .

### Objective Value

The following objective function minimizes the sum of stand-alone fiber costs (first term), WDM costs (second term) and the OXC costs (third term), when only one type of WDM and OXC systems is used.

$$\text{Min} \sum_{e \in E} 2C_e^F f_e + \sum_{e \in E} \left( (C_e^F + C_e^W) w_e + C^c v_e \right) + \sum_{n \in N} (C^O y_n + C^P u_n) \quad (1)$$

### Constraints

The following constraints express the requirements that all demand must be carried, that no link should be assigned more demand than its capacity allows it to carry and that no switching element should be assigned more traffic than its capacity allows.

$$\sum_{p \in P_{st}} x_p^{st} = 1 \quad \forall (s,t) \in D \quad (2)$$

$$\sum_{(s,t) \in D} d_{st} \sum_{\substack{p \in P_{st} \\ e \in p}} x_p^{st} \leq v_e + f_e \quad \forall e \in E \quad (3)$$

$$v_e \leq M^W w_e + g_e \quad \forall e \in E \quad (4)$$

$$\sum_{e \in A_n} (v_e + f_e) \leq u_n \quad \forall n \in N \quad (5)$$

$$u_n \leq M^O y_n + h_n \quad \forall n \in N \quad (6)$$

$$x_p^{st} \in \{0,1\}$$

All other decision variables are nonnegative integer

There are five sets of constraints in this model. The first set of constraints, labeled as (2), ensures demand satisfaction and does not allow splitting demands. Constraint set (3) converts path capacity to segment capacity and segment capacity into fibers and channels. Constraint set (4) converts segment capacity to WDM units. The fourth set of constraints, labeled (5), accumulates channels on links to add the required number of ports to each node. The last set of constraints (6) converts node capacity to OXC units.

We then show a model for the provisioning and routing problem with single link failure protection using a *link-protection scheme*. At the time of demand setup, for each link of the primary path, a backup path is reserved around that link, allowing other backup paths to share the reserved capacity. The model assumes that the traffic on a segment cannot be split when is rerouted. The model uses the following new definitions:

$NC_e$  = number of channels on segment  $e$  required to get the working paths. Then, if segment  $e$  fails, the traffic  $NC_e$  must be rerouted between the origin and destination nodes of  $e$ .

$J_e$  = set of possible paths between the end nodes of segment  $e$  that can be used to reroute the traffic.

$z_q^e = 1$  if the traffic on segment  $e$  is rerouted on path  $q \in J_e$ , and 0 otherwise.

The model can be stated as the provisioning MIP model given above replacing constraints (2) and (3) by constraints (7) and (8) given as follows:

$$\sum_{q \in J_{e,od}} z_{q,e}^{od} = 1 \quad \forall (o,d) \in D, \forall e \in WP_{od} \quad (7)$$

$$\sum_{\substack{q \in J_{e'} \\ e \in q}} NC_e z_q^{e'} \leq v_e + f_e \quad \forall e, e' \in E, e' \neq e \quad (8)$$

When segment  $e$  fails, the working flow of this segment must be rerouted through one of the possible protection routes in  $J_e$ . Hence constraint set (7) must be met. If segment  $e$  fails, the spare capacity on the other segments must be sufficient for the flow on the protection routes. Therefore, constraint set (8) must be met.

## 5. THE SCATTER SEARCH BASED METAHEURISTIC

Scatter Search [5] is a population-based metaheuristic that uses a reference set to combine its solutions and construct others. The method generates a reference set from a population of solutions. Then a subset is selected from this reference set. The selected solutions are combined to get starting solutions to run an improvement procedure. The result of the improvement can motivate the updating of the reference set and even the updating of the population of solutions.

The initial population must be a wide set of disperse solutions. However, it must also include good solutions. Several strategies can be applied to get a population with these properties. The solutions for the population can be created, for instance, by using a random procedure to achieve a certain level of diversity. Then a simple improvement heuristic procedure must be applied to these solutions in order to get better solutions. The initial population can also be obtained by a procedure that provides at the same time disperse and good solutions like GRASP procedures.

A set of good representative solutions of the population is chosen to generate the reference set. The good solutions are not limited to those with the best objective values. By good representative solutions we mean solutions with the best objective values as well as disperse solutions. Disperse solutions should reach different local minima by the local search. Indeed, a solution may be added to the reference set if the diversity of the set improves. So the reference set must consist of a set of disperse and good solutions selected from the populations. The criteria for updating the reference set, when necessary, must be based on comparisons and measures of diversity between the new solutions and the existing solutions.

A subset of solutions from the reference set is selected for applications of a combination method to get good starting solutions for an improvement procedure. In general, the method consists in selecting all the subsets of a fixed size. The combination procedure tries to combine good characteristics of the selected solutions to get new current solutions. The purpose is to get better solutions which are not similar to those already in the reference set. The possible improvement solution methods applied to the solutions range from simplest local searches to a very specialized search. A very simple procedure is a local search based on basic moves consisting of selecting the best improving move or a first found improving move. The procedure must allow to use tools

like recent or intermediate memory, variable neighborhoods, or hashing scanning methods of the neighborhood. Then the method applied could be a Tabu Search, a Variable Neighborhood Search or any sophisticated hybrid heuristic search.

The metaheuristic strategy includes the decision on how to update the reference set taking into account the state of the search. The algorithm must also realize when the reference set does not change and seek to diversify the search by generating a new set of solutions for the population. In addition, the metaheuristic includes the stopping criterion for the whole search procedure. Then the best solution used in the reference set is provided by the method.

Usual stopping conditions are based on allowing a total maximum computational time or a maximum computational effort since the last improvement. The computational effort is measured by the number of iterations, number of local searches or real time.

The scatter search metaheuristic may be summarized as follows:

1. Create an initial population of solutions.
2. Generate a reference set from the population.
3. Select a subset from the reference set.
4. Apply a combination procedure to the subset.
5. Apply an improvement to the combinations.
6. Update the reference set accordingly.
7. Repeat 3 to 6 until a new reference set is needed.
8. Repeat 2 to 7 until a population is needed.
9. Repeat 1 to 8 until the stop criterion is met.

Therefore, the Scatter Search strategy involves 6 procedures and 3 stopping criteria to solve an optimization problem. The procedures are the following:

1. **The Initial Population Creation Method.** A procedure creates a random initial population of good and disperse solutions.
2. **The Reference Set Generation Method.** A procedure choose the best *representative* solutions in the population to be included in the reference set.
3. **The Subset Selection Method.** A procedure gets *good* subsets of solutions in the reference set to apply the next combination procedure.
4. **The Solution Combination Method.** A procedure *intelligently* combines the solutions in each selected subset to get new solutions.
5. **The Improvement Solution Method.** An specialized procedure improves the new solutions.
6. **The Reference Set Updating Method.** A procedure, provided with parameters used to modulate the intensification and/or diversification, updates the reference set by deciding when and how the obtained improved solutions are included in the reference set replacing some solutions already in it.

In addition to these six procedures, the metaheuristic involves three stopping procedures that implement the criteria to decide when to go to an above step.

1. **New Reference Set Criterion.** The first criterion decides when to generate a new reference set from the population.
2. **New Population Criterion.** The second criterion decides when to generate a new initial population.
3. **Termination Criterion.** Finally, the third criterion decides when to stop the whole search.

## 6. THE SOLUTION APPROACH

Our solution procedure employs the notion of a *base network*, which initially consists of the current network design. A base is an incomplete network design in the sense that does not need to satisfy the whole set of requirements. As the process iterates, the base network evolves and the estimated cost of satisfy a requirement becomes more accurate. An evolved base network includes additional equipment, which has been tentatively added to the original base. When a requirement is considered for being satisfied on an evolved base network, this requirement can share the additional capacity with other requirements. The evolution of the base network is linked to an adaptive memory mechanism that keeps track of where new equipment is added in the best solutions recorded during the search. The solution approach that we propose builds a list of paths for each requirement and identifies a controlled set of feasible paths for each requirement.

Our overall solution strategy consists of an adaptive metaheuristic method that adds to an scatter search ideas from multi-start [1] and tabu search [2]. The hybrid metaheuristic takes advantage of strategies that can explore a large solution space effectively. Specifically, tabu search contributes with a short term memory component that is designed to avoid cycling. The multi-start component uses a long term memory that forces construction of new solutions in a wider range of the solution space.

The solution approach starts with the generation of a set of promising segments using the shortest path algorithm (with distances as weights). Segments corresponding to any existing WDM systems are also included in the promising set. The procedure uses these segments to execute the  $k$ -shortest path algorithm for each demand (with incremental costs from a base network  $B$  as weights). The procedure builds a controlled set of feasible paths for each demand by making use of an efficient implementation of the  $k$ -shortest path algorithm. The paths for a given demand are found by calculating the incremental cost of routing the entire demand in the base network, which can have spare capacity given by previously obtained designs. A solution is then constructed by selecting a path for each demand requirement. Once each demand is assigned to a path, the cost of the resulting design is calculated. The cost is associated with the equipment that is required to satisfy the demands using the chosen paths. Once each demand has been assigned to a path in its list of potential paths, the evaluation of the solution consists of calculating the increase of capacity required in the elements of the network that route the demands through the assigned paths. The increased capacity is then translated into cost of installing additional fiber and adding WDMs and OXCs.

In the implementation of scatter search explained in this paper, the Diversification Generation Method constructs the disperse solutions to be included directly in the reference set, instead of being included in the Initial Population. The Diversification Generation Method is a constructive procedure that attempts to assign demands to paths in order to utilize efficiently the spare capacity in the base network. The rationale behind this initialization is that spare capacity for channels in the final network design should be zero except for channels on WDM systems covering a segment without slack. The strategy acknowledges that spare capacity in the original network simply accounts for existing network infrastructure. The solutions in the reference set are ordered according to their total cost, where the first solution, labeled  $RefSet_1$ , is the one with lowest cost.

The Subset Generation Method proposed for this problem generates a single subset consisting of all the solutions in the reference set. Then, in order to construct the combined solution, the Solution Combination Method takes account of the number of times a segment has appeared in the paths assigned to the demands in the reference solutions. Furthermore, the procedure uses global (referred to the whole search process) and local (referred to the current reference set) information in the form of counters that keep track of the number of channels used in each segment in order to decide where to add equipment to the current base. The difference between the maximum global and the maximum local number of channels used in each segment shows its importance. The smaller the difference the more important the segment is in the final network design.

The Improving Method is a local search based on changing one demand from its current path to another. The local search starts with the demand that has the largest unit cost. To calculate the unit cost, the demands are examined one by one. The examination consists of deleting the demand from the current solution and calculating the cost reduction. The cost reduction is then divided by the bandwidth requirement of the demand under consideration. Once all demands have been examined, the unit cost associated with each demand is known. The neighborhood search within the local search examines moves employing a certain ordering of the demands. That is, the first candidate move is to reassign the demand that is at the top of the unit cost list. If reassigning this demand leads to an improving move, the move is executed to change the current solution. If the new solution is better than the worst in the current reference set, then the reference set is updated. If an improving move that involves reassigning the first demand in the list cannot be found, then the second demand is considered. The process continues until a demand is found for which a reassignment of paths leads to an improving move. If all the demands are examined and no improving move is found, the local search is abandoned.

The Reference Set Updating Method uses a dynamic strategy that compares all the solutions reached by the Improvement Method with the solutions in the reference set, which is then updated if the new solution has an objective function value better than the worst reference solution.

Once the local search is finished, the procedure compares the current reference set with the reference set before the last time the local search was executed. If the reference set did not change after the last execution of the local search, the Reference Set Updating Method rebuilds the reference set by keeping the top  $|RefSet|/2$  solutions and generating new disperse solutions to substitute the worst  $|RefSet|/2$  in the set, as generally done in implementations of scatter search. The  $|RefSet|/2$  new disperse solutions are generated by the Diversification Generation Method.

## 7. COMPUTATIONAL RESULTS

To test the proposed method we carry out experiments with several sets of real instances (shared by Dr. Leonard Lu of AT&T Labs) with different number of links and demands. All the algorithms have been implemented in C and compiled with Microsoft Visual Studio.NET. All test runs were performed on a Pentium 4 machine with one processor at 2.53 Ghz and 512 Mbytes of RAM. The experiment consists of solving the MIP formulation developed for the link protection scheme with Cplex beginning with the solutions reported in [4]. Table 1 summarizes the computational results obtained by

solving the MIP formulation with Cplex and the provisioning and routing problem with the hybrid metaheuristic approach based on Scatter Search described in [4]. This metaheuristic solves the routing and provisioning problem without protection. The problem of provisioning the network to protect failed segments is also a provisioning and routing problem, where it is allowed sharing the capacity required to route the traffic from the origin to the destination of different failed segments. To solve the protection problem we run a modified version of this metaheuristic on every working network in the reference set that allows sharing resources.

**Table 1:** Summary of computational results

Set	$ N $	$ E $	$ D $	Cplex				Metaheuristic					
				Work Cost	Backup Cost	Survive Cost	CPU Time	Work Cost	Backup Cost	Cplex Bound	Survive Cost	CPU Time	
MD	11	16	10	4.09	5.64	9.73	0.57	4.14	3.88	3.88	8.02	4.47	
				20	4.38	6.23	10.61	0.43	4.48	4.93	4.93	9.41	6.03
				30	8.42	7.01	15.43	0.53	8.46	6.91	6.91	15.37	7.84
	27	10	54	14.03	14.05	28.08	1.6	14.25	12.63	12.49	26.88	14.07	
			20	2.75	3.81	6.56	0.31	2.76	3.25	3.25	6.01	4.14	
			30	4.26	4.32	8.58	0.85	4.30	4.23	4.23	8.53	8.25	
	42	10	54	6.46	5.66	12.12	1.66	6.52	5.47	5.42	11.99	11.54	
			20	11.16	10.23	21.39	4.16	11.26	10.12	10.12	21.38	17.80	
			30	1.96	2.20	4.16	0.29	2.01	1.69	1.69	3.70	4.16	
	48	10	20	3.08	2.65	5.73	0.36	3.54	2.81	2.52	6.35	12.62	
			30	5.38	3.12	8.50	1.97	5.71	5.06	4.83	10.77	12.74	
			54	7.08	4.84	11.92	5.72	7.91	5.80	5.48	13.71	21.41	
			54	8.41	5.87	14.28	8.35	9.22	6.96	6.60	16.18	24.20	
Ex0D	12	17	15	3.69	6.79	10.48	0.36	5.09	4.82	4.82	9.90	4.95	
				19	6.26	4.85	11.11	0.98	7.03	3.71	3.71	10.74	5.00
				21	6.21	7.15	13.36	0.83	9.35	2.15	2.15	11.50	6.24
	33	15	44	14.36	16.55	30.91	11.33	15.99	11.51	11.51	27.50	15.11	
			66	11.83	14.87	26.70	7.97	14.05	6.12	6.12	20.17	16.19	
			21	3.69	3.82	7.51	1.65	4.90	2.06	2.06	6.96	2.61	
	46	15	44	7.32	5.99	13.31	11.19	8.77	4.29	4.29	13.06	4.77	
			66	13.94	16.48	30.42	90.59	17.05	9.90	9.41	26.95	12.96	
			66	11.83	13.85	25.68	231.88	14.60	6.58	6.52	21.18	16.67	
			21	3.69	3.82	7.51	1.07	4.17	2.92	2.92	7.09	4.01	
	66	15	21	7.33	6.12	13.45	26.30	9.07	4.27	4.27	13.34	7.21	
44			13.95	16.56	30.51	471.97	16.91	7.95	7.95	24.86	14.52		
66			11.77	13.08	24.85	227.48	14.82	7.07	7.04	21.89	14.07		
66			11.77	13.08	24.85	227.48	14.82	7.07	7.04	21.89	14.07		
Ex2D	17	26	27	23.22	44.49	67.71	6.21	23.59	30.61	30.61	54.43	41.43	
				36	81.84	153.99	235.83	14.86	81.84	153.35	152.93	235.19	52.80
	68	27	81	96.81	169.11	265.92	298.22	97.66	152.54	152.54	250.20	129.97	
			36	24.43	33.37	57.80	20.36	27.65	27.20	26.33	54.67	44.46	
	36	67.79	69.18	136.97	300.88	69.23	68.76	68.76	137.99	51.58			

Columns 2, 3, and 4, of Table 1 contain the number of nodes, number of segments, and number of demands in each instance. Next three columns report the total cost of the working network, of the spare capacity required to protect the working network in the event of any single link failure, and the total cost of the survivable network. Column 8 shows the total CPU time required to obtain them solving the models described above with Cplex. Next two columns summarize the total cost of the working network and of the survivable network obtained using the proposed metaheuristic based on Scatter Search. Under the heading Cplex Bound we have reported the lower bound given by Cplex starting with the working solution provided by the metaheuristic. Last two columns show the total cost of the survivable network and the total CPU time obtained.

## 8. CONCLUSIONS

It is shown how the metaheuristic approach deals with the survivability problem by solving the protection problem beginning not only with the best working network. We conclude that the best network design for the whole problem is usually not obtained from the best design for the problem without survivability. Thus, by beginning to deal with the survivability requirements with the set of diverse and good solutions provided in the reference set by the scatter search based approach we tackle both working and restoration network problems. The metaheuristic approach has been successfully applied to other planning problems in the design of WDM optical networks [3], [4].

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