Genetic Optimization Methods for Traffic Engineering Problems in Multi-Service High Speed Optical Networks

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ABSTRACT

This paper presents two new methods for solving the offline Traffic Engineering (TE) problem in multi-service high speed optical networks. The methods are based on genetic optimization techniques. In the first method, the offline TE problem is formulated as an optimization model with linear constraints and then it is solved using a modified version of the Genetic Algorithm for Numerical Optimization for Constraint Problems (GENOCOP). In the second method, a hybrid method based on GENOCOP and a heuristic TE algorithm is presented to solve the above problem. The performance results of these methods are compared with that of a standard linear programming optimization method. Two different optical network topologies are considered for the comparison purposes.

KEYWORDS

genetic algorithms, optimization, high speed networks

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1. INTRODUCTION

The high speed optical networks are intended to fulfill different Quality of Service (QoS) and survivability requirements. Traffic Engineering (TE) mechanisms can be applied on these networks to utilize the network resources (e.g. link capacity, speed) effectively. Basically, TE mechanisms combine the traffic admission control and routing issues together. By applying TE mechanisms, appropriate paths for routing can be established, which essentially satisfy the QoS prerequisites, if any, of the traffic. The QoS prerequisites include end-to-end path delay, guaranteed link bandwidth along the path, packet loss, etc. A complete list of acronyms used in the paper is presented in the appendix.

The TE mechanisms can be used to distribute the network traffic evenly among the links, to balance the load and to avoid congestion. In order for the TE mechanisms to achieve the goals, the network resource (link) utilization should be more reasonable and there should not be very few or no overloaded or under-utilized links. Multiple protection (backup) paths between a pair of nodes can also be established using TEs. However, protection from link failure is not considered in this paper.

Traffic Engineering is a major issue in the emerging multimedia optical networks that support the following: Multi-Protocol Label Switching (MPLS), Asynchronous Transfer Mode (ATM), Differentiated Services or non-differentiated services supported Internet Protocol (IP) and *frame relay* (Debasis and Ramakrishnan, 2001). This paper concentrates on MPLS and differentiated services supported IP optical networks. In these networks, traffic flows (i.e., demands) that have the same source-destination address and the same QoS requirements are aggregated to form a *traffic trunk* (in IP networks) or a *label switched path* (in MPLS networks). Aggregated flows are referred to as traffic trunks in the rest of the paper. In these networks, traffic that corresponds to a specific trunk can be divided into multiple paths and this process enables a better load balancing strategy.

One of the main problems in TE is how to map traffic trunks in the optical network while satisfying the QoS requirements of the trunks. A number of online (Elwalid et al., 2001; Kar et al., 2000; Suri et al., 2002; Xiao et al., 2000) and offline (Debasis & Ramakrishnan, 2001; Girish et al., 2000; Karasan & Yetginer, 2002; Thirumalasetty & Medhi, 2001; Trimintzios et al., 2002) TE approaches have been developed to address this problem. In the online approaches, traffic trunks are mapped onto the optical network, one at a time, as soon as there is an arrival of demand for a trunk. Online TE is state-dependent and can be applicable over a short period. The main objective of the online approaches is to allow the optical network to respond rapidly to any changes in the traffic load or the network topology. The traffic demands, however, which may arrive randomly over time, may cause an unfair utilization of network resources. On the other hand, offline TE aims to establish some well-defined routes for trunks in such a way that the utilization of network resources is globally optimized. Specifically, instead of focusing on instantaneous network states and individual connections, the latter mechanism considers statistical behavior of the traffic trunks. Combining this information with a centralized view of the optical network topology and with link capacities, offline TE selects the topology of routes for traffic trunks by exploring the resources in such a way that the traffic is handled in an optimal manner. The offline TEs use some optimization models (usually based on mathematical programming) and algorithms. In fact, the output of each offline TE method is a set of paths that can be used for the following: (i) effectively routing all potential traffic trunks, (ii) efficiently satisfying the QoS requirements (if any), and (iii) enabling the load balance in the network.

Genetic Algorithms (GA) are based on the idea of natural selection (Holland, 1975). The study included in this paper uses the Genetic Algorithm for Numerical Optimization for Constraint Problems (GENOCOP) (Michalewicz, 1996). The study deals with the optimization of a linear/non-linear function based on a set of linear constraints.

The motivation for using GAs is that a non-linear problem can be expressed in such a way that the natural evolution can provide an attractive paradigm for implementing the nonlinear searches (Fogel, 1995; Michalewicz, 1996). A lot of research has been done on applying GA techniques to solve telecommunication network problems (Pedrycz & Vasilakos 2000). Elbaum and Sidi (1996) used GAs to design the topology of *local area networks* and Ko et. al. (1997) used it to design *mesh networks*. Shimamoto et. al. (1993) considered call blocking probability as a network constraint and applied GAs for network routing. Pan and Wang (1991) coded the traffic distribution to represent each chromosome and used the average delay, derived from an M/M/1 queuing model, as an optimization constraint to maximize bandwidth allocation. Taterdtid et. al. (1997a,b) addressed the network configuration problem (i.e., obtaining the best path for each source-destination pair), based on the virtual path concept. They used an M/M/1/K queuing model to derive the blocking probability and used the total average packet delay as a constraint to maximize the total network throughput. Swaminathan et al. (1999) used GAs to predict the bandwidth-demand patterns to enable better virtual path management. Medhi and Tipper (1996) used GAs to solve the capacity assignment and routing problem in multi-hour broadband networks, while Walkowiak (1999) presented GAs for backup path planning in ATM networks. Konak and Smith (1999) illustrated a hybrid GA for backbone network design. Riedl (2002) used a hybrid GA for routing optimization. Ericsson et al. (2002) presented a method for Open Shortest Path First (OSPF) weight setting based on GAs, while Pitsillides et al. (2002) solved the aggregated bandwidth allocation problem in ATM networks using GENOCOP by considering small networks. More details on the application of GAs for solving the network problems can be found in the literature (Buriol, 2002; Dengiz et al., 1997; Galiasso & Wainwright, 2001; Pierre & Legault, 1998; Walkowiak, 2001).

In this paper, genetic optimization is used for the solution of offline TE problem in multi-service high speed optical networks. Precisely, the basic offline TE problem is formulated as an optimization model with linear constraints, called Traffic Engineering Model (TEM), and is solved using GENOCOP. This procedure is referred to as GENOCOP Method (GM) in the rest of this paper. To the best of our knowledge, GENOCOP and more generally the numerically constrained optimization methods that are based on GAs have not been previously used for solving the offline TE problems in large high speed optical networks. In addition, this paper presents a hybrid method for solving the above mentioned problem. This method is referred to as Genetic Hybrid Method (GHM) in this paper. The GHM combines GM with heuristic TE algorithms. The rest of the paper is organized as follows: TEM is presented in Section 2. Section 3 presents GM and GHM. The simulation results concerning the efficiency of GM over standard Linear Programming (LP) techniques and the comparison between the offline TE methods are illustrated in Section 4. Section 5 concludes the paper.

2. OPTIMIZATION MODEL FOR MULTISERVICE OPTICAL NETWORKS

Consider a weighted undirected graph G = (N, L) where N denotes the set of nodes and L denotes the set of edges (links). The graph is 2-connected, i.e., even if one link or node fails then also there is a path between each source-destination pair. Each link $l \in L$ has capacity C_l, propagation and processing delay D_l, length L_l and cost K_l.

In this paper, the link cost K_l is defined based on the expected utilization of the corresponding link. Specifically, a special algorithm called Path Finding Algorithm (PFA) is used to find the set of candidate admissible routes for all trunks. Then for each link the number J_l of candidate paths traversing through this link is calculated. Next J_l is divided by the total number of candidate paths in the optical network, thus providing the new link cost K_l. Note that the defined link cost is more when a large number of candidate paths use the corresponding link. So, it is most probable that this link will be over-utilized in operating conditions. On the other hand, small link cost indicates that the corresponding link is most probable to be less or even under-utilized.

Let Σ denote the traffic trunk set and *Tqos* represent the set of service classes. Specifically, four service (priority) classes based on QoS requirements are defined in this paper: the High class with greater priority and stringent QoS constraints, the Medium class with less strict QoS requirements involving Virtual Private Network (VPN) traffic, the Low class (e.g. World-Wide-Web - WWW traffic), and the Best-Effort (BE) class with the lowest priority and no QoS requirements. Note that four traffic trunks for each source-destination pair are defined, typically one for each service class. For the sake of convenience, High, Medium, and Low class trunks will be referred to as QoS trunks in the rest of the section.

Let $T_{\sigma t}$ be the bandwidth demand of the trunk $\sigma \in \Sigma$, which belongs to a service class $t \in$ Tqos, with weight $Z_{\sigma t}$. Let S be the set of normal operating states plus failure states (corresponding to node and link failures) of the optical network. Note that $Z_{\sigma t}$ actually indicates the priority that a trunk $\sigma \in \Sigma$ of class $t \in$ Tqos has with respect to the admissibility/routing into the network. $Z_{\sigma t}$ can be determined based on either Service Level Agreements (SLA) and/or on user profile information or administrative criteria. Note that by considering the QoS framework, trunk traffic that belongs to the service classes with stringent QoS requirements should get more priority over other kinds of traffic. However, $Z_{\sigma t}$ considers the trunk to differentiate the traffic belongs to the same service (priority) class. Let $U_{\sigma t}$ also be the admitted demand of the trunk $\sigma \in \Sigma$, where σ belongs to the class $t \in Tqos$. Wp_t indicates the nominal admission priority of the trunks those belongs to the class $t \in Tqos$.

Let $Rs(t,\sigma)$ be the set of all candidate routes for the trunk $\sigma \in \Sigma$, where σ belongs to the service class $t \in Tqos$, where t contains only the operating links (links interconnecting operating nodes) in the network that is in state $s \in S$. Let Kp_i be the additive cost of the candidate route $i \in Rs(t,\sigma)$ for $\sigma \in \Sigma$ of class $t \in Tqos$. Specifically, in this paper it is assumed that the cost of each candidate route for a QoS trunk is equal to the sum of the link costs along the route, while for each BE trunk the candidate route cost is 1 unit, i.e. $Kp_i = 1$.

Let B be the maximum hop bound for a QoS route and H be the maximum hop bound for a BE route. The link utilization bound at a state $s \in S$ is denoted by cb_s.

The decision variable is denoted by X_{rs}, which is the flow or carried bandwidth on route $r \in Rs(t,\sigma)$. Here, r belongs to the trunk $\sigma \in \Sigma$ of class $t \in Tqos$ in the state $s \in S$. Note that X_{rs} is always greater than or equal to zero (bandwidth can not be a negative number).

The objective function of TEM attempts to minimize the routing cost for the QoS trunks without minimizing the total QoS throughput and maximize the BE throughput, while considering trunk priorities. The objective function is shown in Equation 1.

$$F = Max : \left(\sum_{t \in Tqos} \sum_{\sigma \in \Sigma} \sum_{r \in Rs(t,\sigma)} Wp_t \bullet \frac{Z_{\sigma t}}{Kp_r} \bullet X_{rs} \right) \quad (1)$$

Equation 2 indicates that the total carried bandwidth of trunk $\sigma \in \Sigma$, which belongs to a class $t \in Tqos$, should be at the most equal to $T_{\sigma t}$.

$$\sum_{r \in Rs(t,\sigma)} X_{rs} \leq T_{\sigma t}, \forall \sigma \in \Sigma, \forall t \in Tqos, s \in S \quad (2)$$

Equation 3 is the link capacity constraint

$$\sum_{t \in Tqos} \sum_{\sigma \in \Sigma} \sum_{r \in Rs(t,\sigma):l \in r} Xrs \leq cbs \bullet Cl, \forall l \in L, s \in S \tag{3}$$

The TEM model can optimally be solved using LP techniques. In fact, TEM can be formulated as a standard LP optimization problem and can be solved using a mathematical LP solver such as *lp_solve 4.0* (Berkelaar, 1995). The output of TEM is a set of paths that are used for routing all traffic trunks that may or may not have any QoS prerequisites. The traffic of a trunk $\sigma \in \Sigma$, where σ belongs to a service class $t \in$ Tqos, may go through more than one route $r \in Rs(t,\sigma)$.

In the rest of this paper, the LP problem involving TEM will be referred to as LP model and the related offline TE method is referred to as LP-based method. Note that the mathematical algorithm that solves TEM is deterministic. The deterministic algorithms have the advantage of always delivering the optimal solution if there is any (Wong et al., 2001).

PFA finds a set of candidate admissible routes with/without QoS guarantees for each traffic trunk. It is a step-by-step procedure based on the iterative execution of a modified version of the Floyd-Warshall all-pairs shortest path algorithm (FW) (Corman et al., 1994). The FW finds the shortest path between each source and destination in an optical network. PFA is described below.

1. Execute FW on the initial high speed optical network topology.
2. If a node or a link is failed, then exclude it from the standard topology and then execute the FW algorithm for the new topdogy.
3. Store the source-destination paths determined by the FW algorithm.
4. Compare the paths with the paths already included to the current set of candidate paths (if any exists).
5. Include the paths that are not previously established, to the set of candidate paths.
6. Repeat Steps 2 to 5, by excluding a different node or link from the optical network each time and continue this process for a specified number of iterations.

FW estimates the total path delay by summing the link propagation delays along the path. Since the link length accounts for link propagation delay, FW estimates the total path length by summing the link lengths along the path. FW also estimates the number of intermediate hops a candidate path has. Since each hop is associated with a node, each hop has some additional processing delay and variable delay (jitter) associated with it. Therefore, if there is less number of hops in a path, then the jitter and the delay will be less for the traffic trunk that is using the path. In addition, the usage of a smaller number of hops will increase the transmission reliability of the traffic trunks. This is because the probability of a failure on a particular path will decrease if the path consists of a less number of hops.

3. GENETIC OPTIMIZATION METHODS

3.1 Genocop Method (GM)

GM is implemented as follows:

1. PFA finds a set of candidate admissible routes with/without QoS guarantees for each traffic trunk.
2. A total of Σ x T_{qos} real valued chromosomes $U_{\sigma t}$ are initialized, where:

$$U_{\sigma t} = \sum_{r \in Rs(t,\sigma)} Xrs \, , \sigma \in \Sigma, t \in Tqos \qquad (4)$$

Each chromosome corresponds to the total maximum possible traffic flow $T_{\sigma t}$ of the trunk $\sigma \in \Sigma$; where σ belongs to the service class $t \in$ Tqos. This trunk traffic flow may essentially go through more than one routes $r \in Rs(t,\sigma)$. All traffic classes T_{qos} are considered.

3. All chromosomes $U_{\sigma t}$ are evaluated with respect to the fitness function F shown in Equation 1. Note that each chromosome should not violate the typical traffic demand and link capacity Equations 2 and 3.
4. Some chromosomes (the 'winners') of the population reproduce, while others (the 'losers') die.

5. Genetic operators are applied on the 'winners' and a new generation is produced to replace the members that are dead. The genetic operators are based on floating point representation.
6. During reproduction stage, randomly selected genetic operators are applied (one or two each time depending on the operator) on the random 'winner' chromosomes until all members that are dead are replaced.
7. Go to Step 2 and repeat the process for a predetermined number of generations.

The output of GM is the set of paths that are used for routing all traffic trunks with/without QoS prerequisites. More details on GENOCOP are available in (Michalewicz, 1996; Michalewicz et al., 1995).

3.2 GHM

GHM is a hybrid offline TE algorithm combining the GM method (see Section 3.1) and heuristic TE algorithms for establishing QoS and BE trunk routes. In GHM, the GM method is initially applied to get a set of QoS and BE trunk routes. Nevertheless, if the solution provided by GM does not provide all the required routes for the QoS traffic trunks then an attempt is made to find the routes for the unsatisfied trunk demands using a special QoS routing algorithm called TE Algorithm_1 (TEA_1). In addition, if GM does not provide all the required routes for the BE trunks, another routing algorithm called TE Algorithm_2 (TEA_2) is used.

Both the TEA_1 and TEA_2 algorithms are based on the Dijkstra's shortest path algorithm (Dijkstra, 1959). TEA_1 is used for admission control/routing of QoS traffic trunks. It consists of the following steps:

1. Sort the QoS traffic trunks in decreasing order based on their priority; i.e., the higher priority trunks are placed first. The sorting takes place in two phases. In the first phase, by considering the priority classes previously defined: the trunks belonging to the High service class are put first, followed by the trunks belonging to the Medium class, etc. In the second phase, the trunks of each class are re-arranged according to their earnings rates: The trunks with the higher earning rates are placed first followed by the trunks with the lower earnings rates. When two or more

trunks have the same earning rates then these trunks are placed in decreasing order of bandwidth demand: the trunks with the higher bandwidth demand are placed first followed by the trunks with the lower bandwidth demand.

2. Consider the higher priority trunk with demand $T_{\sigma\tau}$ first.
3. Create a sub-graph G′ where all the links with bandwidth less than the traffic demand $T_{\sigma\tau}$ are removed. This ensures that all the remaining links have bandwidth greater than or equal to $T_{\sigma\tau}$.
4. On the sub-graph G′, use Dijkstra's algorithm to determine the minimum link weight path between the source and the destination of the trunk by considering the special link weights based on the metrics presented in (Fortz and Thorup, 2002).
5. If a path exists and the number of intermediate hops along the path is less than the maximum hop bound H then establish the path and deduct the resources (e.g. link capacity) used by the path.
6. For each of the next trunks, placed in decreasing order of priority, repeat the Steps 3 to 5.

TEA_2 is used for admission control/routing of BE trunks only. It involves the same basic procedure and the same number of steps as TEA_1. However, at Step 1, the BE traffic trunks are sorted in decreasing order according to their earnings rates; i.e. the trunks with the higher earnings rates are placed first. When two or more BE trunks have the same earnings rate then these trunks are arranged in the decreasing order of bandwidth demand. Furthermore, at Step 4, Dijkstra's algorithm determines the minimum hop path between the source and the destination of the considered trunk. In Step 5, no hop count test is made. Note that in both TEA_1 and TEA_2, the complexity of Step 3 is $O(|L|)$ and the complexity of Step 4 is $O(|N|^2)$. Since the connected networks are considered, $|L| < |N|^2$. So, the overall complexity of the Steps 3 and 4 is $O(|N|^2)$.

4. SIMULATIONS AND NUMERICAL RESULTS

NetLab (Papademetriou & Pasias, 2003) is used for the simulation purposes. It was developed using the *Tcl/Tk* scripting language (Ousterhout, 1994) and is used for network topological design and simulation. GENOCOP is also implemented in NetLab, in order to conduct the tests.

The experiments are conducted on a PC equipped with a *Pentium IV* 1.8 MHz processor and 256 MB RAM. Note that the solution to the offline TE methods is both CPU and memory intensive.

Two network topologies are used for the tests. The first one (Network A) is a 15-node and 30-link topology, as shown in Figure 1. Fiber optic links are considered and each has 10 Gbps capacity. The second one (Network B) is a 9-node 18-link topology shown in Figure 2. Each link of B is assigned 5 Gbps capacity. Three sets of tests are conducted. The first set involved Network A only. In this set of tests, GM is solved for 1000, 2000 and 3000 generations and the obtained solutions from these three tests are compared with that of the equivalent LP model. The LP model is solved using the lp_solve 4.0 software. The goal of these tests is to evaluate the performance of GENOCOP in solving the optimization problems.

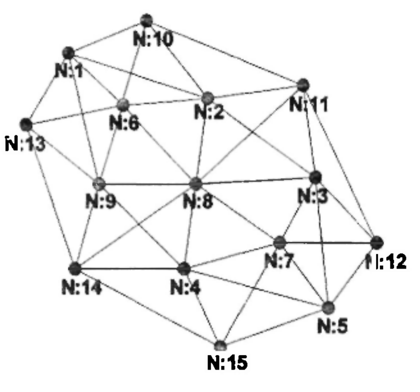

Fig. 1: Optical network A

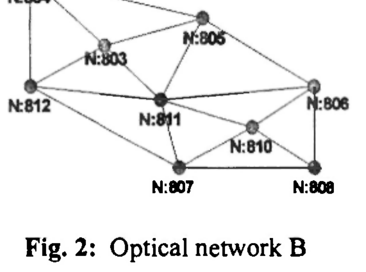

Fig. 2: Optical network B

For this purpose, blocking ratios are considered. Specifically, for each method the ratio of the number of admitted routes to the number of expected routes for the trunks of each class is calculated. The same traffic matrix is used in all the tests. For trunks belongs to the High and Medium classes, candidate paths with H = 7 are considered. For trunks belongs to the other classes, candidate paths with H = 15 are considered. In addition, the following values are assigned to the basic parameters of TEM: $Z_{\sigma t}$ = 5, 3, 2, 1 for each High, Medium, Low, and BE class trunk bandwidth demands respectively; Wp_t = 7, 5, 3, 1 for the High, Medium, Low, and BE class trunk traffic respectively and cb_s = 0.95. PFA has found totally 561 candidate admissible paths for all the trunks. For GM, the population size is 50 and the cumulative probability is 0.3.

The second and third set of tests involved Network B solely. The objective of these tests is to compare the performance of the two offline TE methods that are analyzed in Section 3 with that of the equivalent LP model that uses lp_solve 4.0 software. For this purpose, blocking ratios are also considered. Specifically, as in the previous set of tests, the ratio of the number of admitted routes to the number of expected routes for the trunks of each class is calculated for each method. Each set involved 30 tests. In each test, a different traffic trunk set/traffic matrix is used with 288 traffic trunks each, but with randomly chosen bandwidth demands in a 12 to 183 Mbps range. For the test of the second set, the priorities of the trunks of each class are randomly chosen. For the test of the third set, fixed priorities are used ($Z_{\sigma t}$ = 5, 3, 2, 1 for High, Medium, Low, and BE class trunk bandwidth demands respectively). For the trunks belonging to the High and Medium classes, candidate paths with H = 4 are considered and for the trunks belonging to the other classes, candidate paths with H = 11 are considered. Besides, the next values are assigned to the basic parameters of TEM. The next values are Wp_t = 7 for the High class trunk traffic, Wp_t = 5 for the Medium class trunk traffic, Wp_t = 2 for the Low class trunk traffic, Wp_t = 1 for the BE class trunk traffic and cb_s = 0.9. PFA identified totally 189 candidate admissible paths for all the trunks. In case of GM, the population size is 50 and the cumulative probability is 0.3. The number of generations used in GM by both the second and third set of tests is 3000. The obtained results from the first set of tests are presented in Table 1.

TABLE 1

Results from the first set of test

	Blocking Ratio (%)			
	High Class	Medium Class	Low Class	BE Class
GM-1000	19.076	22.123	20.612	33.575
GM-2000	13.458	16.04	18.149	26.399
GM-3000	12.967	15.782	17.044	26.419
LP	0	0	0	24

In the case of the GM method, the traffic blocking ratios for all the classes decrease as the number of generations increases, but they are still much higher than that of the LP-based method. However, in all the cases the High class traffic had the lowest blocking ratio and the BE class traffic had the highest. Note that the blocking ratio of each QoS class for the LP-based method is zero. Considering all four tests, the average solution time for GM is significantly higher than that of the LP-based method. Specifically, the solution times for GM-1000, GM-2000, and GM-3000 are 109:06, 218:30, and 357:42 minutes respectively and the value is only 0:31 minutes in case of LP-based method. The acquired results from the second set of tests are presented in Figure 3.

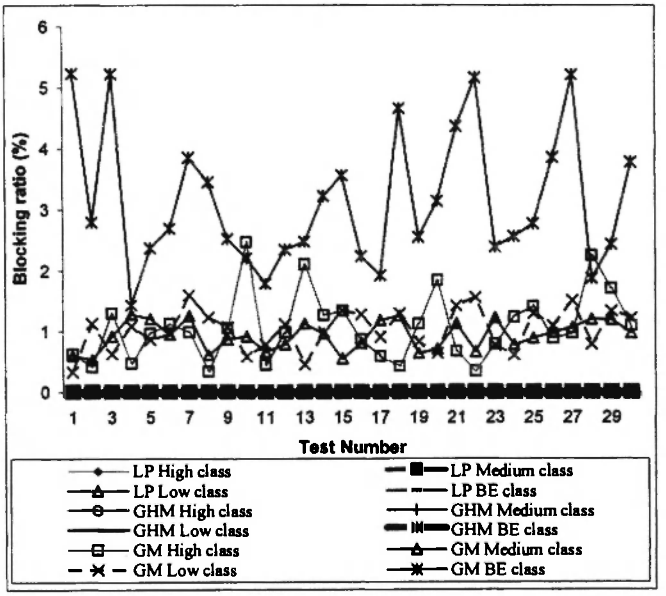

Fig. 3: Results from the second set of tests

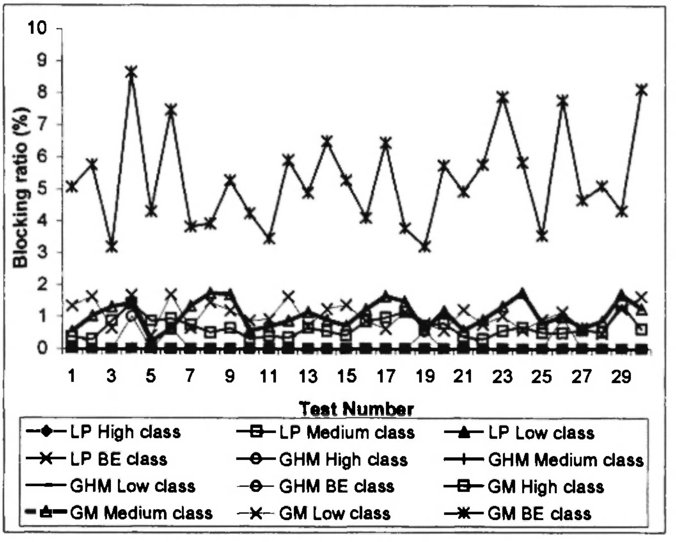

Fig. 4: Results from the third set of tests

The blocking ratios of all the classes for the LP-based method and the hybrid scheme are zero. However, blocking occurs when the GM method is used.

Note that the blocking ratio of each class depends on the assigned priority to each trunk of the class. Consequently, the blocking ratio of each class depends on the kind of test, as observed in Figure 3 for GM. Nevertheless the relative priority of the QoS traffic (i.e., High, Medium, and Low class traffic) over the BE traffic is preserved, resulting in a lower blocking ratios for the QoS traffic. The average solution time for the LP-based method is much shorter than that of the genetic-based methods. In particular, the solution time for GM alone is approximately 33 minutes, while for the LP-based method it is only 1 second.

The results obtained from the third set of tests are presented in Figure 4. The blocking ratios of all QoS classes for the LP-based method and the hybrid scheme are zero. In case of the BE class traffic the blocking ratio is zero. Note that the blocking ratio is nonzero when the LP-based method is used. Generally, the BE traffic blocking ratio for GHM is zero; this blocking ratio was nonzero only in two tests. When the GM method is used, traffic blocking is observed for all the classes. However in all of the tests, the High class traffic has the lowest blocking ratio and the BE class traffic has the highest. As in the second set of tests, the solution time for GM alone is approximately 33 minutes, while for the LP-based method it is only 1 second.

5. CONCLUSIONS

This paper presents two novel offline TE methods that utilize genetic optimization. Both of the methods are based on the GENOCOP algorithm and can be applied in real-world high speed optical networks.

The performance of the two methods, with respect to traffic blocking, is compared with that of a LP-based optimization method. The performance of GM is inferior to that of the LP-based and GHM methods. In fact, the performance of GHM is normally the same as that of the LP-based method. Note that the total time for finding a solution using a genetic-based method is higher than that of the LP-based methods. However, all the tests indicate that GENOCOP alone does not perform as well as the standard LP techniques for solving large optimization problems with linear objective function and with linear constraints. More improvements are required to improve the performance. Note that generally the relative class admission priorities are preserved in all the methods when fixed trunk priorities were used; i.e., in terms of each method, the High class traffic has the lowest blocking ratio among all traffic, followed by the Medium and Low class traffics respectively.

Nevertheless, certain characteristics of the methods, especially regarding load balancing, must be further studied. Genetic optimization will also be applied for the solution of new versions of the offline TE optimization model, which includes non-linear objective functions. However, survivability-supported offline TE methods that are based on the current work are under study.

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APPENDIX:

List of acronyms

B: QoS bound for the routes
BE: Best-effort
cb_s: The link utilization bound at a state $s \in S$
C_l: Capacity of the link l
D_l: Processing delay of the link l
FW: Floyd-Warshall all-pairs shortest path algorithm
GA: Genetic algorithm
GENOCOP: Genetic algorithm for numerical optimization for constraint problems
GHM: Genetic hybrid method
GM: GENOCOP method
H: Maximum hop bound for the routes
J_l: Number of candidate paths traversing through the link l.
K_l: Cost of the link l.
Kp_i: The additive cost of the candidate route $i \in Rs(t,\sigma)$
l: A link in graph G
L: Set of links (edges) in the graph G
L_l: Length of the link l.
LP: Linear programming
MPLS: Multi-protocol label switching
N: Set of nodes in the graph G.
OSPF: Open shortest path first
PFA: Path finding algorithm
$Rs(t,\sigma)$: The set of all candidate routes for the trunk $\sigma \in \Sigma$, which belongs to a service class $t \in Tqos$
S: The set of normal operating states plus failure states of the network
t: A member of *Tqos*
TE: Traffic Engineering
TEA_1: TE Algorithm_1
TEA_2: TE Algorithm_2
TEM: Traffic engineering model
Tqos: The set of service classes
$T_{\sigma t}$: Bandwidth demand of the trunk $\sigma \in \Sigma$, which belongs to a service class $t \in Tqos$
$U_{\sigma t}$: Admitted demand of the trunk $\sigma \in \Sigma$, which belongs to a service class $t \in Tqos$
Wp_t: Nominal admission priority of the trunks those belongs to the class $t \in Tqos$.
X_{rs}: Flow or carried bandwidth on route $r \in Rs(t,\sigma)$
$Z_{\sigma t}$: Weight of the trunk $\sigma \in \Sigma$, which belongs to a service class $t \in Tqos$
σ: A member of Σ
Σ: Traffic trunk set