Invited paper

Fault Tolerant Dense Wavelength Division Multiplexing Optical Transport Networks

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Abstract—Design of fault tolerant dense wavelength division multiplexing (DWDM) backbones is a major issue for service provision in the presence of failures. The problem is an NP-hard problem. This paper presents a genetic algorithm based approach for designing fault tolerant DWDM optical networks in the presence of a single link failure. The working and spare lightpaths are encoded into variable length chromosomes. Then the best lightpaths are found by use of a fitness function and these are assigned the minimum number of wavelengths according to the problem constraints using first-fit (FF) algorithm. The proposed approach has been evaluated for dedicated path protection architecture. The results, obtained from the ARPA2 test bench network, show that the method is well suited to tackling this complex and multi-constraint problem.

Keywords— *dedicated path protection architecture, and genetic algorithm, DWDM, fault tolerant networks, optical networks.*

1. Introduction

Dense wavelength division multiplexing (DWDM) optical transport networks provide bulk carriage for client networks such as Internet protocol (IP) networks or synchronous optical networking (SONET) and synchronous hierarchy (SDH) networks [1]. Such networks, based on optical cross-connects (OXCs) and optical add-drop-multiplexers (OADMs), have recently received much attention as backbones to design high speed next generation telecommunication networks [2]. The large capacity expansion resulting from DWDM enables satisfaction of the dramatically increasing bandwidth demanded by applications. It also delivers reduced cost core networks and simplified bandwidth management by virtue of the integration of IP over DWDM via generalized multiprotocol label switching (GMPLS) technology [3].

DWDM optical networks are prone to network component failures that may dramatically impact the network quality of service (QoS) delivered to applications. Therefore maintaining a high level of resiliency is a crucial issue in the design of fault tolerant DWDM optical networks [4]. A resilient network can operate at an acceptable performance level in the event of failure by utilizing redundant resources. The concepts, architectures, models and mechanisms of resilient optical network for fault management have been well addressed in the literature [5].

The design of resilient DWDM optical networks is known as an NP-hard problem [6]. The main object of the work to date has been to develop mathematical models for routing wavelength assignment (RWA) and capacity allocation (CA) problems. These are then solved by the application of integer linear programming (ILP) [6], [7] or heuristic approaches [8]–[11] to get feasible and near optimal solutions, where the objective is to design cost optimal backbone networks by efficient usage of network resources.

Evolutionary algorithms have increasingly been exploited to solve optimization problems in many diverse fields in science and engineering. Genetic algorithms (GAs) [12] comprise a subset of evolutionary algorithms based on natural biological evolution. Many different GA schemes have been developed for communication network design. For example, they have been used in capacitated network design [13], in the design of ring based SDH optical core networks [14] and for routing [15].

This paper presents an application of a GA to design fault tolerant DWDM optical transport networks by establishing a pair of working and spare lightpaths for each connection request in a demand matrix using the dedicated path protection (DPP) architecture. The DPP architecture is an offline survivability approach where the working and spare lightpaths are established before network operation. The backup resources along the spare lightpaths are specifically dedicated to a particular lightpath and can not be utilized by other spare ligthpaths.

The rest of the paper is as follows: Section 2 presents the genetic algorithm model of dedicated path protection. Section 3 describes the results obtained for a predefined demand matrix based on ARPA2 test bench network, while overall conclusions are presented in Section 4.

2. Genetic Algorithm Based Fault Tolerance Approach

This section describes the GA model for failure covering in DWDM optical transport networks. The network topology is represented as a directed graph $G\,(N,L,W)$, where $N=\{n_1,n_2,\ldots,n_N\}$ is the set of nodes, $L=\{l_1,l_2,\ldots,l_L\}$ is the set of connecting links in the network and $W=\{w_1,w_2,\ldots,w_W\}$ is the set of wavelengths per links. The demand matrix $D\,[d_{(o,d)}]_{N\times N}$ aggregates demand between origin and destination node pairs (o,d) in terms of requested wavelengths. The sets of eligible working paths $K^w_{(o,d)}$, and spare paths $K^s_{(o,d)}$, between each node pair before and after of the event of failure, are precomputed using the *K-shortest* paths algorithm.

2.1. Chromosomes

One of the most important steps of providing a GA model is mapping the problem decision variables into chromosomes that affect the accuracy of the GA based solution. The chromosome is defined by assigning integers to each link with corresponding wavelength sets containing $\hat{W}$ wavelengths. Then, each path of the K-shortest paths between each origin-destination node pair is assigned a binary code and is encoded as a string. The least significant value code is assigned to the shortest path and the most significant value code is assigned to the longest path. The chromosome is then formed by concatenation of the assigned codes for connection requests in the demand matrix.

2.2. The Next Generation

In its progress towards an acceptable solution, a GA utilizes methods to evolve its population to contain a better selection of individuals (as defined by the fitness function).

Crossover. This operation produces new, fitter chromosomes having some parts of their genetic material from both parents. In the context of optical networks, path crossover involves the exchange of two of the permitted lightpaths that are used to handle traffic between an origin and destination node pairs.

Mutation. Mutation is the random adjustment of one part of the chromosome and often enables the recovery of good genetic material that may be lost through the generations. In this case, a binary mutation operates on a gene (bit) of an element (binary path code) of a chromosome and complements it.

Selection. This process emphasizes the fitter solutions. In this work, a virtual roulette wheel is employed to select fitter parent chromosomes. Each chromosome in the population is associated with a sector in this wheel and the area of each sector is proportional to the fitness value of its chromosome, increasing the probability that the fitter chromosomes are selected.

2.3. The Initial Population

The initial path between origin and destination can be generated by randomly choosing any path between each (o,d) from the K-shortest paths available. Here, testing revealed that a better approach was to adapt a heuristic method in which the initial paths were chosen to be the shortest paths from the K-shortest paths for all requests, in the demand matrix.

2.4. Termination

The stochastic nature of GA searching means that it can be difficult to specify convergence criteria to terminate the evolution cycle. Here, the GA is terminated when one of three conditions are met. Firstly, the algorithm may determine that the rate of change, $\varepsilon = 10\exp(-3)$, of the fitness function means that it has reached a minimum; secondly, the error in the fitness function falls below the error threshold; thirdly, the number of generations exceeds a predetermined maximum.

2.5. Fitness Function and Constraints

The amount of working capacity (number of wavelengths required) allocated to working (spare) lightpaths is denoted by f_l^w (f_l^s) for link l. The minimization of the wavelengths utilized by working and spare lightpaths to service a given demand matrix may be written as

$$f_{itness} = \text{minimize}\left\{ \sum_{l=1}^{L} (f_l^w + f_l^s) \right\}, \tag{1}$$

$$f_l^w = \sum_{(o,d)} \sum_{p_l^{w,k}} \sum_{w} w_w^{k,od}\,,\ \forall D, \tag{2}$$

$$f_l^s = \sum_{(o,d)} \sum_{p_l^{s,k}} \sum_{w} s_w^{k,od}\,,\ \forall D. \tag{3}$$

Link l is traversed by a set of kth working (spare) paths $P_l^{w,k}$ $(P_l^{s,k})$. The decision variable $w_w^{k,od}$ $(s_w^{k,od})$ is set to 1 if the kth working (spare) path between node pair (o,d) uses wavelength w, and to 0 otherwise.

2.6. Constraints

The link-capacity constraint. The total number of occupied wavelengths, working and spare, on each link is bounded by the number of wavelengths per link $\hat{W}$:

$$f_l^w + f_l^s \le \hat{W},\ \forall l \in L. \tag{4}$$

The satisfaction constraint. Each link of the working and spare paths that is assigned for a connection request between each node pair (o,d) must satisfy the demand between that node pair:

$$\sum_{w=1}^{\hat{W}} w_w^{od} = d_{(o,d)},\ \forall (o,d) \in D, \tag{5a}$$

$$\sum_{w=1}^{\hat{W}} s_w^{od} = d_{(o,d)},\ \forall (o,d) \in D. \tag{5b}$$

The wavelength utilization constraint. Each wavelength can be utilized only by working paths or by spare paths:

$$w_w + s_w \le 1,\ \forall w \in W. \tag{6}$$

The w_w (s_w) is set to 1 if wth wavelength assigned to working (spare) path, and to 0 otherwise.

The disjoint constraint. The working path and the spare path, $(P^w_{(o,d)}, P^s_{(o,d)})$, between each node pair (o,d) must be link disjoint (so will not fail together) to accommodate single link failure:

$$P^w_{(o,d)} \cap P^s_{(o,d)} = \phi, \ \forall (o,d) \in D. \qquad (7)$$

This constraint is satisfied if and only if $K^w_{(o,d)} \cap K^s_{(o,d)} = \phi$, $\forall (o,d) \in D$.

3. Simulation Results

This section describes the results of application of the GA approach for establishing spare and working lightpaths in fault tolerant DWDM optical networks. To illustrate the method, the ARPA2 network (21 nodes, 25 links) is considered here, shown in Fig. 1. The solutions have been achieved by considering 40 wavelengths per link. All links in the physical layer were bidirectional and all nodes were capable of full wavelength conversion. The number of shortest paths considered during each iteration was four and therefore each path was assigned a two bit binary code. For the GA, the population size was maintained at 100, running for 150 generations with a crossover probability of 0.9 and a mutation probability of 0.01. The demand matrix employed was $\mathbf{D} = \big[(1,11,10);(2,7,6);\ (3,4,7);\ (6,4,5);\ (5,17,8);(6,11,9);\ (17,10,6);(11,4,11);(13,8,13)\big]$, where each element of this matrix is treated as (origin node, destination node, volume of demand).

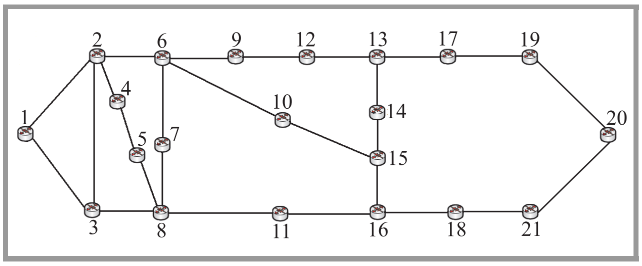

Fig. 1. The ARPA2 network topology.

3.1. Working Lightpaths

The RWA simulation results for the ARPA2 network with demand matrix **D** are shown in Table 1. Working wavelengths were assigned to paths using the simple but effective first-fit strategy, which chooses the available wavelength with the smallest index. The ARPA2 network requires 271 wavelengths with an average of 30.1 wavelengths per request. In the ARPA2 network, there are a few routes that may be employed, e.g., 13-14-15-16-11-8 between nod pair 13-8 and this result in extremely high usage of bandwidth (more than double the average in the case of the example route).

Table 1
RWA solutions for working paths for ARPA2 network

Node pair	Demand	Working path	Working wavelength
(1,11)	10	1-3-8-11	$(\lambda_1...\lambda_{10})$/all links in the path
(2,7)	6	2-6-7	$(\lambda_1...\lambda_6)$/all links in the path
(3,4)	7	3-2-4	$(\lambda_1...\lambda_7)$/all links in the path
(6,4)	5	6-2-4	$(\lambda_1...\lambda_5)$/(6-2), and $(\lambda_8...\lambda_{12})$/(2-4)
(5,17)	8	5-8-7-6-9-12-13-17	$(\lambda_1...\lambda_8)$/all links in the path
(6,11)	9	6-7-8-11	$(\lambda_1...\lambda_9)$/all links in the path
(17,10)	6	17-13-14-15-10	$(\lambda_1...\lambda_6)$/all links in the path
(11,4)	11	11-8-5-4	$(\lambda_1...\lambda_{11})$/all links in the path
(13,8)	13	13-14-15-16-11-8	$(\lambda_7...\lambda_{19})$/{(13-14)-(14-15)}, $(\lambda_1...\lambda_{13})$/{(15-16)-(16-11)}, and $(\lambda_{12}...\lambda_{24})$/(11-8)

3.2. Spare Lightpaths: Dedicated Path Protection

The dedicated path protection RWA solutions for the spare lightpaths are shown in Table 2. The working and spare lightpaths of all requests are link disjoint, the scheme thus protects against any single link failure because at most

Table 2
RWA solutions for spare paths by DPP for ARPA2 network

Node pair	Demand	Spare path	Spare wavelength
(1,11)	10	1-2-6-10-15-16-11	$(\lambda_1...\lambda_{10})$/{(1-2)-(6-10)-(10-15)}, $(\lambda_7...\lambda_{16})$/(2-6), and $(\lambda_{14}...\lambda_{23})$/{(15-16)-(16–11)}
(2,7)	6	2-3-8-7	$(\lambda_1...\lambda_6)$/(2-3), $(\lambda_{11}...\lambda_{16})$/(3-8), and $(\lambda_9...\lambda_{14})$/(8-7)
(3,4)	7	3-8-5-4	$(\lambda_{17}...\lambda_{23})$/(3-8), and $(\lambda_{12}...\lambda_{18})$/{(8-5)-(5-4)}
(6,4)	5	6-7-8-5-4	$(\lambda_{10}...\lambda_{14})$/{(6-7)-(7-8)}, and $(\lambda_{19}...\lambda_{23})$/{(8-5)-(5-4)}
(5,17)	8	5-4-2-6-10-15-16-18-21-20-19-17	$(\lambda_{24}...\lambda_{31})$/{(5-4)-(15-16)}, $(\lambda_{17}...\lambda_{24})$/(2-6), $(\lambda_{11}...\lambda_{18})$/{(6-10)-(10-15)}, and $(\lambda_1...\lambda_8)$/{(16-18)-(18-21)-(21-20)-(20-19)-(19-17)}
(6,11)	9	6-10-15-16-11	$(\lambda_{19}...\lambda_{27})$/{(6-10)-(10-15)}, $(\lambda_{32}...\lambda_{40})$/(15-16), and $(\lambda_{24}...\lambda_{32})$/(16-11)
(17,10)	6	17-19-20-21-18-16-11-8-7-6-10	$(\lambda_1...\lambda_6)$/{(17-19)-(19-20)-(20-21)-(21-18)}, $(\lambda_8...\lambda_{13})$/(18-16), $(\lambda_{33}...\lambda_{38})$/(16-11), $(\lambda_{25}...\lambda_{30})$/(11-8), $(\lambda_{15}...\lambda_{20})$/(8-7), $(\lambda_9...\lambda_{14})$/(7-6), $(\lambda_{28}...\lambda_{33})$/(6-10)
(11,4)	11	11-16-15-10-6-2-4	$(\lambda_1...\lambda_{11})$/{(11-16)-(10-6)}, $(\lambda_{12}...\lambda_{19})$/(16-15), $(\lambda_7...\lambda_{17})$/(15-10), $(\lambda_6...\lambda_{16})$/(6-2), $(\lambda_{13}...\lambda_{23})$/(2-4)
(13,8)	13	13-12-9-6-7-8	$(\lambda_8...\lambda_{20})$/(13-12), $(\lambda_1...\lambda_{13})$/{(12-9)-(9-6)}, and $(\lambda_{15}...\lambda_{27})$/{(6-7)-(7-8)}

one of the two working and spare lightpaths will fail. The number of assigned wavelengths to spare lightpaths is 434 meaning an average of 48.2 wavelengths per request have been additionally assigned to provide protection.

4. Conclusion

This paper has addressed the design of fault tolerant DWDM optical networks using a GA model based on variable length chromosomes. This has been employed to solve the static RWA problem based on dedicated path protection architecture for ARPA2 network in the context of a single link failure. The optimum number of shortest paths was four, with a greater number producing greatly diminished returns. The results demonstrated that the GA is able to design fault tolerant DWDM optical transport networks.

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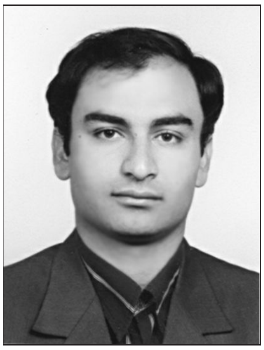

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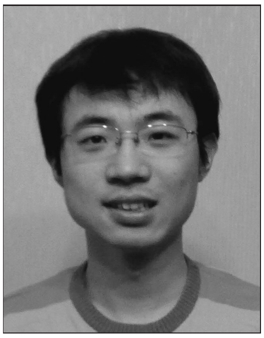

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