

GA-based dynamic survivable routing in WDM optical networks with shared backup paths

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Abstract. This paper considers the problem of dynamic survivable routing in WDM networks with single link failure model. This work mainly concerns in how to dynamically determine a protection cycle (i.e., two link-disjoint paths between a node pair) to establish a dependable lightpath with backup paths sharing. The problem is identified as NP-complete, thus a heuristic for finding near optimal solution with reasonable computation time is usually preferred. Inspired from the principle of genetic algorithms (GA), a GA-based survivable routing algorithm for the problem with a new fitness function, which allows us to improve blocking performance, will be proposed. Extensive simulation results upon the ns-2 network simulator and two typical network topologies show that our algorithm can achieve a significantly lower blocking probability than conventional algorithms.

1. Introduction

The optical networks using wavelength division multiplexing (WDM) could provide huge bandwidth capacity for next-generation Internet. These networks are promising candidate to meet the bandwidth demands from various emerging multimedia applications such that web applications, video on demand, multimedia conference, image access and distribution, home broadband services etc. [1]

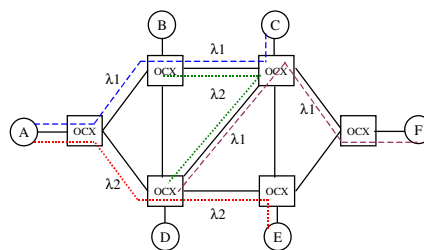


Fig. 1. Architecture of a wavelength-routed network.

An all-optical WDM network consists of optical cross-connects (OCXs) interconnected by fiber links, in which an OCX can switch an optical signal from an input to an output link without

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performing optoelectronic conversion. End-users communicate with each other via all-optical channels, which are referred to as *lightpaths* as shown in Fig 1. A lightpath is an optical channel that spans multiple fiber links to provide a connection between two network nodes. If there are no wavelength converters, a same wavelength must be used along a lightpath, which referred to the *wavelength continuity constraint*. An OXC equipped with wavelength converters is capable of changing the wavelength of incoming signal, so a lightpath can use many wavelengths on it. However, due to the technology requirement, the wavelength conversion cost is very expensive. This work just considers the case where the same wavelength must be used along a lightpath.

1.1. Routing and Wavelength Assignment

Given a set of connection requests, the problem of setting up lightpaths by routing and assigning a wavelength to each connection is called routing and wavelength assignment (RWA) problem [1]. If we cannot setup a lightpath for a connection request, then it is blocked. A well-designed RWA algorithm is critically important to improve the performance of WDM networks.

RWA problem can be classified into *static* and *dynamic* problems. In the static problem, the connection requests are given in advance. The static is always performed offline, the objective is to minimize the total blocking probability or to have the maximum number of setting up connections. This problem can be formulated as mixed-integer linear program, which is NP-complete [1]. In contrast, the dynamic RWA considers the case where connection requests arrive dynamically. The dynamic RWA is performed online, it is much more challenging; therefore, heuristic algorithms are usually employed in resolving this problem [1].

This work focuses on dynamic RWA problem. In literature, there are static routing approaches available for the dynamic RWA problem, such as shortest-path routing or alternate shortest-path routing [1]. These approaches use a set of pre-computed shortest paths for lightpath establishment. The advantage of these approaches is its simplicity, e.g. small setup time and low control overhead. Adaptive routing approaches [1] are more efficient than static routing methods in terms of blocking probability, because the route is chosen adaptively depending on the network state, and our approach follows this approach.

1.2. Survivable Routing in WDM Networks

The failure in optical communication networks such as accidental fiber link disruption or switching device disorder will affect a huge amount of bandwidth in transmission, thus *survivability* is one of the most important issues in the design of WDM optical networks [2]. Two major techniques to prevent failures are *protection* and *restoration* [3]. In protection schemes, backup resources are pre-computed and reserved for each connection before a failure occurs. In restoration schemes, the backup route is dynamically computed after the failure occurs. In compare with restoration schemes, protection schemes have a faster recovery time and can guarantee 100% of recovery ability, but require more network resources.

Protection schemes are divided into *path protection* and *link protection*. In the former, a working path and a link-disjoint protection path are pre-computed for each connection. In the later, each link of the working path is protected by separate backup resources. Path protection schemes

usually require lower backup resources and lower recovery delay than link protection [3]. The pair of working and protection paths forms a protection *cycle* between two network nodes. The routing problem that tries to determine a working path and a protection path for a connection request in dynamic WDM networks is referred to *dynamic survivable routing*. A connection that is setup from this cycle is called a *dependable connection*. Protection schemes can be further classified into dedicated protection and shared protection. In the former, the backup resources such as links or nodes are used for at most one connection. In the later, the backup resources can be used for multiple connections, because these connections rarely fail simultaneously. Dedicated protection consumes more resource but is simpler to implement. In contrast, share protection is more efficient but more complex for management [3, 4].

There are two kinds of failure in WDM networks: link failure and node failure. It is observed that most modern switching devices are equipped with built-in redundancy to improve their reliability. Therefore, link failure is more concern than node failure. Many studies in the literature justify that single link failure happens much more frequently than multiple link failures, thus the single link failure model attract more attentions in the optical survivability research.

1.3. Motivation and Contribution

In this paper, the problem of dynamic routing and wavelength assignment with lightpath protection (survivable routing) in WDM mesh networks is considered. The path protection scheme with shared backup resource is adopted and the single link failure model is concerned.

Many researchers proposed optimal approaches by formulating this problem as an Integer Linear Program (ILP), thus it is NP-complete [5]. However, it is not practical to solve such ILP problem by optimal approach because the dynamic connection setup requires a low computation time. To achieve that goal, these authors also proposed several heuristics to solve this problem.

In [3], Mohan et al. proposed an efficient protection scheme called primary independent backup wavelength assignment (PIBWA). This method uses the shared protection scheme by adopting the backup multiplexing technique. In PIBWA algorithm, a set of k link-disjoint paths is pre-computed for every source-destination node pair. Whenever a connection request arrives, a working (primary) path and a backup path with total minimized cost are selected from these k paths. If such working-backup path-pair has no wavelength available then the connection request is blocked. The PIBWA with backup multiplexing technique is simple but can still provide a protection mechanism with efficient network performance in terms of blocking probability. The main limit of PIBWA method is that it uses a set of fixed alternate link-disjoint routes, so it exists a big space to improve the network performance.

In [6], Bisbal et al. inherited the PIBWA algorithm and proposed a dynamic routing heuristic using a genetic algorithm, namely the fault-tolerance GA-based RWA (FT-GRWA) algorithm. By using a GA approach, the FT-GRWA algorithm can provide much better performance than the PIBWA algorithm with a reasonable computation time, but it still has a drawback. The authors defined the cost function as the sum of the cost of the primary path and the cost of the backup path, i.e., the cost of a unit of the network resource used for a primary lightpath and for a backup lightpath is the same. Thus, a cycle with higher primary path cost could be selected if the cost of its backup path is small enough to create a smaller total cost. This could result in a higher blocking probability because a higher primary path cost means more resources are reserved.

In this paper, we investigate the dynamic survivable routing problem for optical networks without wavelength conversion using a shared backup scheme and different wavelengths for primary and backup lightpaths, as described in [3]. To overcome the above mentioned drawbacks of the FT-GRWA method, we propose a new fitness function that not only utilizes the network resources more efficiently for establishing a protected lightpath. In addition, we introduce a general formula for determining the key parameter in the new fitness function. Our algorithm is very attractive in that it provides low blocking probability by adopting the shared protection scheme.

1.4. Paper's Organization

The rest of this paper is organized as follows. Section 2 presents the principle of GA-based dynamic survivable routing and new fitness function. The results of simulation experiments are described in Section 3. Finally, we conclude with some discussions in Section 4.

2. GA-based dynamic survivable routing algorithm

2.1. Genetic Algorithms

Genetic Algorithms (GA) are a class of probabilistic searching algorithms based on the mechanism of biological evolution. A GA begins with an initial population of individuals; each of them represents a feasible solution to the problem being tackled. Then the GA applies a set of genetic operations, such as crossover or mutation, to the current population to generate a better one. This process is repeated until a good solution is found or until a predefined number of iterations is reached [7].

2.2. The GA-based Dynamic Survivable Routing algorithm

In this algorithm, we use the presentation of individuals, initialization process, genetic operators, and reproduction process in the same way as described in [6]. An individual is presented as a cycle that is formed from two link-disjoint routes. Each route is encoded with integer numbers, each of which identifies a node of the route. For illustration, Fig.1 shows an example of a network topology and a cycle between node 0 and node 5: the coding of two routes from node 0 to node 5 are (0, 2, 5) and (0, 4, 5) that form the cycle (0, 2, 5, 4, 0). Furthermore, each individual is assigned a fitness value, which is calculated by a function called *fitness function*, to estimate its suitability to the problem.

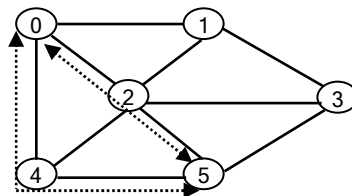


Fig. 2. Two disjoint-link routes $\Rightarrow$ cycle: (0 2 5) (0 4 5) $\Rightarrow$ (0 2 5) (5 4 0) $\Rightarrow$ (0 2 5 4 0).

The initial population consists of P_{size} cycles that are generated randomly (where P_{size} is a design parameter). This population is then evolved by genetic operators: the crossover and mutation operators. The crossover operator is applied to a pair of cycles that has at least one node in common.

The children are generated by interchanging the second half of their parents, as illustrated in Fig. 3. The children cycles must have two halves that are links-disjoint.

In the mutation operator, a node, say m , from a cycle is randomly selected. The route portion from the source node to node m remains intact and the route portion from node m to the source is created again. This newly created route portion must traverse the destination node in case node m is located before the destination node in the original cycle. Note that the next cycle has to satisfy the links-disjoint condition.

After applying the genetic operators above, the reproduction stage selects P_{size} fittest individuals that have the highest fitness value from both parents and children, for the next generation. This process is repeated until the stopping condition is fulfilled and the best individual is selected for setting up a dependable connection for the request.

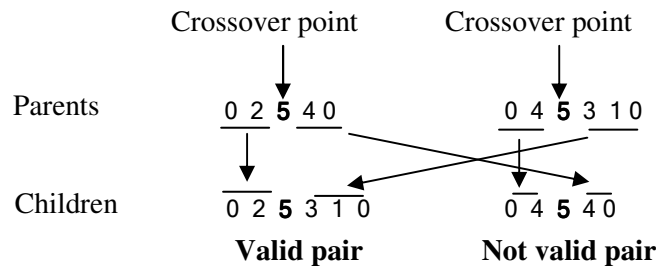


Fig. 3. Example of crossover operation.

Let G denote the maximum number of generations and S denote the satisfactory cost value of the primary route between a node-pair with its initial value being the cost value of the shortest route between the node-pair. The pseudo code of the GA-based dynamic survivable routing algorithm can be summarized as follows:

- 1: $t_G = 0$;
- 2: Generate and Evaluate fitness values for individuals of the first population;
- 3: S = the length of the shortest path between (s, d) nodes;
- 4: **While** ($t_G < G$ AND not exist a cycle in which the length of the primary route is shorter or equal S) **Do**
- 5: Do crossover & evaluate fitness value for children;
- 6: Do mutation & evaluate fitness value for children;
- 7: Select P_{size} fittest individuals for next generation;
- 8: $S = S + 1$;
- 9: $t_G = t_G + 1$;
- 10: **End while**
- 11: Select the best cycle ;}

2.3. A new fitness function

To yield the best performance for dynamic survivable routing, the key idea is to enable the selection of the cycle in which the primary lightpath is the shortest available path and the backup lightpath uses a minimum of free channels. In the following we propose a new fitness function which takes into account the above idea.

The cost of a cycle will be computed from the cost of its primary lightpath and its backup lightpath. The fitness function is defined as the inverse of the cost of the cycle.

Let CP be the cost of the primary lightpath. CP is defined as the number of hops (i.e. the length of the route), assuming there is at least one available wavelength on the primary path. If several wavelengths are available, the lowest indexed among them is assigned to the lightpath. If there is no wavelength available, CP is infinite.

Let CB be the cost of a backup lightpath and λ -channel denote a wavelength on a fiber link. Given a fiber link f , let $c_{f,w}$ ($w=0, \dots, W$) denote each λ -channel on that fiber link (where W is total number of wavelengths on a fiber link); $c_{f,w}$ is 1 if its λ -channel is used neither by any primary lightpath nor by any backup lightpath, 0 if its λ -channel is used by a set of backup lightpaths Φ and its primary route is links-disjoint with the primary route of each other backup lightpath in the set Φ , and infinite otherwise. Then, the cost of the backup lightpath for each wavelength w , denoted by CB_w , is computed as the sum of the costs of each λ -channel of the route.

$$CB_w = \sum_{f \in \text{route}} c_{f,w} \quad (1)$$

The cost of the backup lightpath is taken as the minimum over CB_w and this wavelength is assigned to the backup lightpath.

$$CB = \text{Min} \{CB_w : w = 0, \dots, W\} \quad (2)$$

A cycle (s - d - s) is interpreted as two s - d routes, one for the primary lightpath and the other for the backup lightpath. One way to do that is to let the first portion of the cycle represent the route of the primary lightpath and assign the second portion to the backup lightpath. The cycle could be also interpreted inversely, that is, its first portion is assigned to the backup lightpath, and the second portion to the primary one. The cost of the cycle is computed assuming both interpretations and the one with the lower cost is chosen. For each interpretation, Bisbal [7] defined the cost of the cycle as:

$$C = CP + CB + \left(\frac{1}{N}\right) \cdot h \quad (3)$$

where N is the number of network nodes and h is the number of hops of the primary lightpath.

Since in Bisbal's definition the cost of a free channel on a link of a primary lightpath or a backup lightpath is the same when evaluating the cost of a cycle, it is possible that a cycle with a higher primary lightpath cost could be selected if the cost of its backup lightpath is small enough to give a smaller total cost. The following example illustrates this situation.

Consider the NSF topology in Fig.4a with two wavelengths per link. A primary lightpath (0, 1, 7) is established between nodes 0 and 7, and a backup lightpath (0, 3, 4, 6, 7) is established between the same nodes. The wavelength λ_0 is assigned to both the primary and backup lightpaths. Assume now there is a request for the establishment of a protected connection from node 6 to node 11. We then need to compute the cost of the best cycle (6, 4, 3, 11, 12, 10, 7, 6), which represents two link-disjoint routes: (6, 4, 3, 11) and (6, 7, 10, 12, 11).

Case (a). The route (6, 4, 3, 11) serves as the primary lightpath. The route's cost is $CP = 3$ and it uses wavelength λ_l . The backup lightpath (6, 7, 10, 12, 11) travels through the link (6, 7) that is shared with the backup lightpath (0, 3, 4, 6, 7). Thus, the costs of the backup lightpaths for wavelength λ_0 and λ_l are determined as follows according to (1):

$$CB_0 = 0 + 1 + 1 + 1 = 3$$

$$CB_l = 1 + 1 + 1 + 1 = 4$$

Then the minimum cost of a backup lightpath is $CB = 3$ according to (2). The cycle's cost in this case is:

$$C = 3 + 3 + 3 \cdot 1/14$$

The pair of wavelengths used for primary and backup lightpaths are λ_l and λ_o , respectively.

Case (b). The route (6, 7, 10, 12, 11) serves as the primary lightpath using wavelength λ_l and its cost is $CP = 4$. The backup lightpath (6, 4, 3, 11) has two links (6, 4), (4, 3) that are shared with the backup lightpath (0, 3, 4, 6, 7). Thus, the costs of the backup lightpaths for wavelength λ_o and λ_l are:

$$CB_o = 0 + 0 + 1 = 1$$

$$CB_l = 1 + 1 + 1 = 3$$

Then the minimum cost of a backup lightpath is $CB = 1$ according to (2). The cycle's cost in this case is:

$$C = 4 + 1 + 4 \cdot 1/14$$

The pair of wavelengths used for primary and backup lightpaths are λ_l and λ_o , respectively.

In this example, according to Bisbal's definition, it is easily seen that case (b) is selected; however, as we will explain next, case (a) should have been selected because it has the shorter primary lightpath.

Note that, if we see the cost of a free channel on a link of a primary or backup lightpath is the same, then the total numbers of used channels are 6 (3 for the primary lightpath and 3 for the backup lightpath) and 5 (4 for the primary lightpath and 1 for the backup lightpath) for case (a) and case (b) respectively, i.e., case (a) needs more network resources than case (b). However, this is not right because we are using a backup multiplexing technique. As mentioned earlier, in the backup multiplexing technique, backup lightpaths can use the same wavelength on the same link if their primary lightpaths are links-disjoint. This means that channels used for the backup lightpaths can be used again for different backup lightpaths of future requests. On the other hand, we can not re-use channels used for primary lightpaths. Therefore here we could not count the total numbers of channels for case (a) and case (b) being 6 and 5 respectively as above. To describe more clearly this situation, let us consider the following example.

Assume that, now there is a request for the establishment of a protected connection from node 10 to node 11. We then need to compute the cost of the best cycle (10, 12, 11, 13, 10), which represents two link-disjoint routes: (10, 12, 11) and (10, 13, 11).

If we establish the protected connection from node 6 to node 11 according to case (b), the establishment of the protected connection for this request requires 2 new channels for the backup lightpath and 2 new channels for the primary lightpath (for both cases we choose (10, 12, 11) as the primary lightpath and (10, 13, 11) as the backup lightpath and vice versa). Thus, we need to use $2+4+2 = 8$ channels for primary lightpaths and $4 + 1 + 2 = 7$ channels for backup lightpaths for 3 requests.

However, if we establish the protected connection from node 6 to node 11 according to case (a), the establishment of the protected connection for this request only requires 2 new channels for the primary lightpath (10, 13, 11) because the backup lightpath (10, 12, 11) is shared with the backup lightpath (6, 7, 10, 12, 11). Thus, we need to use $2+3+2 = 7$ channels for primary lightpaths and $4 + 3 + 0 = 7$ channels for backup lightpaths for 3 requests.

In order to ensure that the cycle with the shortest available primary path is always chosen, thus avoiding the situation illustrated in the above example, we define the cost of a cycle as follows:

$$C = CP + \alpha \cdot CB \quad (4)$$

where $\alpha \in (0, 1)$ is a designed parameter. The parameter α should be chosen such that the cycle consisting of a shorter primary route has a smaller cost; If CP_1, CB_1, CP_2, CB_2 are costs of the primary and backup lightpaths of two cycles for a connection request respectively, and assuming that $CP_1 < CP_2$ (that means $CP_2 \geq CP_1 + 1$), $\forall CB_1, CB_2$, then α should meet the following requirement:

$$CP_1 + \alpha \cdot CB_1 < CP_2 + \alpha \cdot CB_2$$

If there is an available wavelength for the backup lightpath, its minimum cost is zero (all its links are shared with other backup lightpaths) and its maximum cost is denoted by L , which is the length of the longest path. Then we have:

$$CP_1 + \alpha \cdot L < (CP_1 + 1) + \alpha \cdot 0$$

Which is equivalent to:

$$\alpha < \frac{1}{L} \quad (5)$$

In summary, the value of the parameter α should be chosen as follows:

$$0 < \alpha < \frac{1}{L} \quad (6)$$

It is important to note that the value of parameter α is determined off-line before running the algorithm, thus our improvement does not increase the complexity of the original FT-GRWA algorithm.

3. Simulation Results

In this section, we examine the performance of our algorithm (i.e. GA-based dynamic survivable routing with the new fitness function) with an extensive simulation study based upon the ns-2 network simulator [8] and two typical network topologies, as illustrated in Fig. 4.

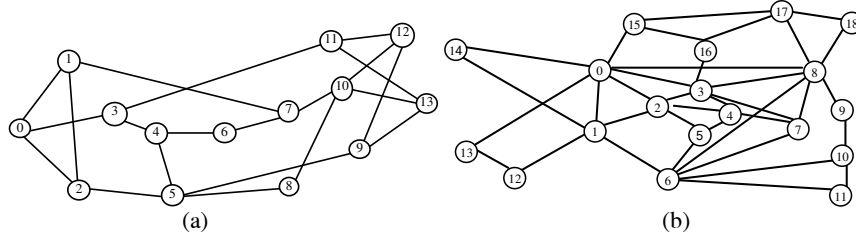


Fig. 4. Network topologies: (a) NSF network with 14 nodes and 21 links.
(b) EON network with 19 nodes and 35 links.

In our experiments, we use a dynamic traffic model in which connection requests arrive at the network according to a Poisson process with an arrival rate λ (call/seconds). The session holding time is exponentially distributed with mean holding time μ (seconds). The connection requests are distributed randomly on all the network nodes. If there are N sessions over the network, then the total workload is measured by $N \cdot \lambda \cdot \mu$ (Erlangs). Thus, we can modify the N , λ , μ parameters to control workloads. We also assume that all of links in the networks are bi-directional and each link has 8 wavelength channels ($W=8$). We set $\alpha=0.05$ to satisfy inequation (6), $P=8$ and $G=8$ is similar to [6].

To illustrate the overall performance of our algorithm, Fig. 5 compares the blocking probability of our algorithm, the PIBWA with three pre-computed alternate routes ($k=3$) and the FT-GRWA algorithm. The comparisons in Fig. 5 show clearly that the blocking probability of the algorithm is significantly lower than those of the PIBWA and the FT-GRWA algorithm for all the cases we studied. For example, for the NSF network, the blocking probability of PIBWA algorithm is about 0.074, the blocking probability of FT-GRWA algorithm is about 0.066 while that of our algorithm is only 0.038 when the workload is 56 Erlangs. Similar behaviors can be observed in the EON network. The blocking probability of PIBWA algorithm is about 0.060 and the blocking probability of FT-GRWA algorithm is about 0.046 when the workload is 80 Erlangs, about two times higher than the blocking probability of our algorithm, which is 0.024.

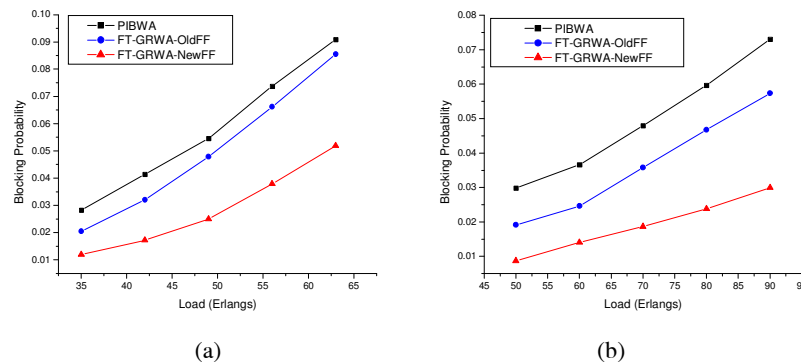


Fig. 5. Blocking probability vs. load (a) NSF network (b) EON network.

4. Conclusion

In this paper, we have proposed a new fitness function for the GA-based dynamic survivable routing algorithm, which enables the selection of a cycle for dependable lightpath setup so that network resources are used efficiently, thus significantly improving network performance compared with other algorithms. Extensive simulation results show that our algorithm can achieve a lower blocking probability than either the PIBWA or the FT-GRWA algorithm on NSF and EON networks. With such advantages, we expect that our approach can be extended and applied to dynamic survivable RWA in optical WDM networks with spare wavelength conversion. This will be our future research.

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