**Sub-graph based Multicast Protection in WDM Networks**

**Multi- and Many-objective Evolutionary Algorithms approaches**

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**Abstract**

In this paper is addressed the multicast routing-and-protection, and wavelength assignment (MRPWA) problem which is critical for the success of applications point-multipoint in WDM networks.

Basically, it is proposed the design of the primary and protection multicast routes, where the resources protection are based on sub-graph protection strategy subject to the quality requirements of the QoP protection: dedicated (1 + 1), shared (M: N) and better effort (without protection). In this way, NSGA-II and NSGA-III, evolutionary algorithms, are applied to MRPWA considering multi- and many-objectives optimization context, respectively. The evolutionary algorithms optimize simultaneously: (i) the total number of links used, (ii) the number of wavelength converters, (iii) the number of splitter nodes, and (iv) the number of destinations served-and-protected.

Considering Hyper-volume measure, the experimental tests on a set of instances indicate that the protection approach based on sub-graph proves to be promising in comparison to the dual-tree protection strategy. On the other hand, the evolutionary technique oriented to many-objectives (NSGA-III) is more convenient than the oriented towards multi-objectives (NSGA-II) in the study problem.

1. **Introduction**

The growth of Internet traffic caused to the use of applications that need high bandwidth, such as multimedia applications among others ([18, 17, 1, 16, 7]). Wavelength Division Multiplexing (WDM) technology is always the main candidates for transport these large traffic volumes. It is advantageous the enormous bandwidth of these networks, however, the failures of links and optical nodes are catastrophic for the significant losses caused even in small time lapses [18]. Therefore, the development of techniques based on the protection, recovering and restoration of traffic are critical issues. The protection problem can be divided into (a) the routing and wavelength allocation (RWA) problem for the primary path, and (b) protection problem for the secondary path. This problem becomes more complex when considering requests multicast and is called the Multicast Routing-and-Protection, and Wavelength Assignment (MRPWA) problem [7]. Since the multicast protection is very costly in terms of 'optical and computational resources’, the contribution proposes in this work is as follows:

1. Sub graph-based protection scheme [21]
2. Protection level assigned to the quality of protection (QoP) requirements [15]
3. Multi-objective mathematical formulation [14]
4. Solution based on multi- and many-objective evolutionary algorithms [3,4].

The approach proposed in this work has not yet been presented in the literature in our best knowledge.

This article is organized as follows: Section 2 deals with concepts of protection, quality of protection, and multicast protection. In section 3 the basic concept of multi- and many objective optimization are presented. Section 4 presents the multi-objective formulation of the MRPWA while the evolutionary algorithms are given in section 5. Finally, the experimental results, conclusions and future work which are exposed in 6 and 8 respectively.

1. SURVIVABILITY IN OPTICAL NETWORKS

The ability to recover from faults, either of links or nodes, is a very important requirement for networks of high speed, because as these networks take more and more data and provide communication service to several customers. The amount and time of interruptions caused by a failure in the network becomes more and more significant.

Survival can be treated in several layers. The main motivation to treat it in the WDM layer is the ability to use the optical layer to reduce the recovery time [20]. If it is addressed in the client layers, these would handle each request as an isolated fault, thus introducing more delay in the recovery and detection of the fault [12].

Figure 1: Dedicated protection 1: 1 applied to protection from a tree. Note that there are two 'trees, the primary and secondary, with disjoint links.

* 1. **Quality of Protection**

The Quality of Protection (QoP) is associated to the level that the resources (links with wavelengths) assigned to protection are shared. Zhong and Jaekel [21] proposed to apply the protection concept to achieve three levels of QoP where an alternative light-path (or path + wavelength) is assigned as a dedicated or shared backup according to the QoP requirements [21]. The previous work proposes the levels of protection to traffic unicast. This approaches were extended by Rodas and Pinto [15] considering several levels of protection quality. Similar to [21] we propose the three QoP levels to multicast traffic:

1. Level 1 dedicated protection (1: 1): protection resources they are exclusive of the request;

2. Level 2 shared protection (M: N): the resources of protect are assigned to several requests;

3. Level 3 best effort: does not assign any protection to application.

**2.2. Multicast protection**

The multicast protection protection is more complex than those oriented to protect point-to-point type transmissions. To apply dedicated protection (1:1) to multicast tree is very expensive. One of the first approaches considers the concept of dedicated protection (1:1) where a 'dedicated secondary tree’ protects a primary tree [7]. This is an approach based on dual-trees strategy which is very expensive because the protection needs, on average, at least the same amount of resources. An example of the aforementioned approach is given in figure 1.

In figure 1 it can be seen that if a link of the tree fails, transmission to all destinations is interrupted and re-transmitted over the secondary tree. This solution offers 100% protection at the cost of a major interruption in the destination nodes which could be unacceptable for a good quality of service and depending on the characteristics structures of a topology. Further, there may be configurations of 'unprotected trees’. Equally, considering sharing resources depending on the level of protection, we would only decrease the use of these, but not the recovery time.

An alternative approach is to consider a protection oriented to the destination nodes, that is, for each destination it is required a protection path. Under the previous concept, in [20, 9, 13] it has been proposed to expand the tree to a bi-connected sub-graph. This sub-graph is composed of a 'main tree’ and of extra links that are activated at the time of a failure. An example of a sub-graph is provided in Figure 2.

In the sub-graph approach, a failure to cause only a partial interruption, that is, the failure only generates interruption to some destination nodes before a new tree is configured.

Figure 2: Protection based on double-connection sub-graph. (a) Sub-graph formed with the primary tree and the secondary links. (b) to (f) Various configuration of protection trees according to the failure of links.

1. MULTI AND MANY OBJECTIVE OPTIMIZATION

A Multi- or Many-objective Optimization Problem (MOP) usually consists of a set of **n** decision variables, a set of k functions objectives and a set of ω constraints [2]. The objective functions and restrictions are functions of the decision variables. Therefore, a MOP generally is optimized:

z = f (x) = (f1 (x), f2 (x),, fk (x)) (1)

subject to

g (x) = (g1 (x), g2 (x),, gω (x)) ≥ 0 (2)

where x = (x1, x2, ..., xn) ∈ X is a decision vector, X denotes the decision space of f (x), z = (z1, z2, ..., zk) ∈ Z is an objective vector, while Z denotes the objective space of f (x). A Set of Solutions Feasible Ω ⊂ X is defined as a set of vectors of decision that satisfy the constraints given in the equation 2. Given two solutions u, v ∈ Ω, say that u dominate v (denoted as u? v) if u is better or equal to v in each objective function and strictly better in at least one objective. Thus, the Pareto Optimal Set is defined as P\* = {U ∈ Ω | v no-domina-a u∀v ∈ Ω}, while the objective space of P\* it is known as Pareto Optimal front, denoted as' F \* = F (P\*) [19]. In more simple words, a Pareto Front is a set of solutions considered equally good.

For several years, various evolutionary algorithms have been proposed for multi-objective optimization, several of which have proven to be competitive when optimizing problems with 2 or 3 objectives. However, they have concluded that the performance of most of these algorithms is significantly degraded with the increase in the number of objectives to be optimized ([11, 8, 5]). Because of this, it is proposed the term Many Objective to refer to the subset of problems where several objectives (more than three) require be optimized [6]. In the present work, for the search of solutions are used the evolutionary algorithms NSGA-II [4], which is a multi-objective algorithm and NSGA-III [3], which is a many objective algorithm, being the most referenced in the literature. Since the problem considers more than 3 objectives, we want to determine which of these algorithms it is the most appropriate for the problem in question.

4 . MRPWA FORMULATION

4.1 Problem details

For a better reading of this work, below the following nomenclature is indicated that will be used in formulating the MRPWA problem:

|. | Indicates cardinality of a set;

G Topology representing the optical network;

V Node set of topology G;

E Link set of topology G;

Λ Set of wavelengths supported by the optical system, where Λ = {λ1, λ2, .., | Λ |};

(i, j) Optical link from node i to node j, where i, j ∈V and (i, j) ∈ E; m Multicast request m = {s, (D), q} with source nodes ∈ V, a set of destination nodes D = {d1, d2, ..., d | D |} ⊂ V and its quality requirement of protection ~ q ∈ {1, 2, 3}; where 1 = dedicated, 2 = shared and 3 = better effort, no protection;

M set of multicast request, where M = {m1, m2, ..., m | M |};

(i, j, λ) Light-link with start node i, destination node j and channel λ;

Pathsd Unicast path with source node s and destination node d, where paths’ = {(i1, j1), (i2, j2), ..., (ip, jp)} with i1 = s and jp = d; it is also understood that j1 = i2, j2 = i2, ..., jp-1 = ip;

l-pathsd Light-path with source node s and destination node of a request m, where path\_sd = {(i1, j1, λ1), (i2, j2, λ2), ..., (ip, jp, λp)} with i1 = s y jp = d; it is also understood that j1 = i2, j2 = i2, ..., jp-1 = ip;

tm Light-tree primary for the multicast request m;

TM Primary trees for the set M, where TM ={tm1, tm2, ..., tm | M |};

pm Protective links for the tree tm, where pm = {(i1, j1, λ1), (i2, j2, λ2), ..., (i |p|, j | p |, λ | p |)};

Sm Sub-graph or light-graph for the form m application by tm and pm, this is Sm = tm ∪ pm;

SM Multicast protection for the M set; where SM = {sm1, sm2, ..., sm | M |)};

Xmi Binary variable. If node i performs a conversion of wavelength for sm then the variable is set to 1 otherwise 0. Here it is necessary equip node i with a length converter of wave for the request m;

Ymij Binary variable. If the link (i, j) is used by Sm then the variable is set to 1 otherwise 0;

Bmd Binary variable. If the destination node d ∈ m is about the light-tree tm then Bmd = 1, in another case Bmd = 0;

Zmi Binary variable. If node i bifurcates wavelength for sm then the variable is set to 1 otherwise 0. This implies that in node i a splitter is needed to the request m;

Hmd Binary variable. If the destination node d ∈ tm is found protected in the light-graph sm, then Hmd = 1, otherwise Hmd = 0;

Given a network topology G and a set of requests multicast M, the problem consists to calculate a set of ligth-graph SM such that they simultaneously optimize the following objective functions:

1. Minimize the total hop number: minimize the sum of the links used for each request m.

(3)

2. Minimize the number of wavelength conversions: we seek that only some nodes have capacity of wavelength conversion (scarce conversion) since a converter will bring more costs to the components of the network.

(4)

3. Minimize the number of wavelength bifurcation: minimize the number of splitter nodes. The number of amplifiers is minimized implicitly.

(5)

4. Minimize the number of blocked destinations: minimize the sum of the destinations that could not be achieved in each request. This calculation is done about the primary tree.

(6)

5. Minimize the number of unprotected destinations: minimize the sum of the destinations that could not be protected. This calculation is done about the alternative paths.

(7)

Subject to the following restrictions:

1. No overlapping: Given the light-graphs Sm1 and Sm2, they cannot use the same wavelength λ on the same link (i, j):

(8)

2. Channel capacity: The total number of light-graphs that use the same link cannot be greater than the number of wavelengths supported by the system:

(9)

3. Bifurcation capacity: The number of bifurcations in which an input wavelength is divided cannot be greater than the specific capacity of the splitter CS and the number of exit links θ of the node:

(10)

As we can see in the problem specification, we need find the routes for the traffic, protect these routes and assign wavelengths to each link that forms part of the light-graph. For address this is proposed to divide into two sub-problems the MRPWA problem: 1) Calculation of the primary ligth-tree tm, that satisfies the multicast request m, and 2) Calculation of ligth-paths secondaries pm, extending the light-tree tm to a light-graph Sm. These two steps will be observed in the approach of the next section.

5. PROPOSED APPROACH

For the use of evolutionary algorithms, we first need define the representation of a solution or individual (chromosome) and the processes corresponding to the operators evolutionary (evaluation, selection and crossing). In the following subsections we will see the proposals to define these structures and processes.

5.1 Chromosome representation

The representation of the individual for the MRPWA problem is formed by a vector of M elements C = {c1, c2, ..., cM} which represents a SM solution. Each element cm = {cm1, cm2, ..., cm | 2E |} is at same time a vector which represents a ligth-graph Sm of length |2E| due each link is direct. Each cme is a whole number associated with the link of the network e and a Sm. A cme element is a whole number indicating which wavelength in the link e is assigned to the sub-graph Sm. The states that can adopt me are: (a) cme = 0 if the link is not used, (b) cme = [1, | Λ |] if the link is primary, and (c) cme = [| Λ | + 1, 2 \* | Λ |] if it is secondary.

If cme ∈ [1, | Λ |] then the ligth-graph Sm is assigned the wavelength cme on the link e and corresponds to the primary tree. If cme ∈ [| Λ | + 1, 2 \* | Λ |] then the sub-graph Sm is assigned the wavelength cme - | Λ | at link e and corresponds to a secondary link. Figures 3a and 3b reflect the representation of a solution on a graph G and as a chromosome respectively.

5.2 Evolutionary Operators

The exchange of information between individuals and the evolution of the same to optimal solutions is achieved thanks to the evolutionary operators. Selection is a process by which the best individuals are chosen from the population to undergo the future action of other operators. The selection operator is the tournament binary [3]. The quality of an individual is determined according to the schemes proposed by NSGA-II [4] and NSGAIII [3]. The crossing operator was designed according to the structure of the chromosome representation while the mutation operator was not necessary since the crossing already introduces randomness in offspring.

Figure 3: Representation of a solution C = {c1, c2}. a) Solution on a ligth-graph, b) Chromosome. Note that nodes 2 and 3 are splitter nodes while node 3 is, in addition, a wavelength converter. The ligth-links used by protection ligth-paths have a number of λ> | Λ | to differentiate them from the primary ligth-links.

Wavelength 1 (ᵣ1)

Wavelength 2 (ᵣ2)

Primary link m1

Primary link m2

Protection link

We call TreeCrossover to the crossover operator designed. Given two individuals C and C’, TreeCrossover works with each Sm and in particular with the genes of the main tree, that is, with tm ∈ Sm. Basically, TreeCrossover generates a new individual corresponding to the primary ligth-tree tm. The crossing is done on sub-graphs corresponding to the same multicast request. If a link is used by the same primary trees this is automatically inherited in the new individual (the link and wavelength assigned to them if they are equal). It is clear that with the highest probability the new primary tree is incomplete, that is, it does not have a structure of tree. In this circumstance, new links are attached randomly to form a valid primary tree. Each link is added if it has at least one length of valid wave. Finally, an algorithm assigns wavelength to the tree, trying to assign the same wavelength to each light-path sd to minimize the use of converters.

In Figure 4 it can see the representation of two solutions for the request m1 = {1, (3, 8), 1} both in the tree as in the chromosome. Subsequently, in figure 5 an example of the cross between the chromosomes of the same request. In this case, the tree resulting from the crossing is valid but incomplete in the sense that the request it is not satisfied for the destination node 8; then you have to randomly add valid links if there are resources available to complete the tree. In figure 6 it is observed the complete tree with its corresponding representation in the chromosome.

Figure 4: Representation of two solutions for the request m1 = {1, (3, 8), 1}. a) Solution 1, b) Solution 2.

Figure 5: Crossing the solutions of figure 4. The two solutions have the common links (1,2) and (2,3), then, the son will inherit these two links and the wavelength used in them in case of that use the same wavelength, otherwise it's about assigning the same wavelength in all the haul.

6. EXPERIMENTAL TESTS

6.1 Experimental Environment

Characteristics of the environment in which they were made tests:

• Hardware. The simulations were carried out in a Intel (R) Core (TM) i7-6700HQ CPU 2.60 GHz CPU, RAM8 GB, 64-bit operating system, WINDOWS 10.

• Simulator. The JMetal java framework was modified [10] for the implementation of evolutionary algorithms. The version of the used jdk is 1.8.0 71.

• Traffic Model. WDM technologies with 8 wavelengths have been considered per fiber optic and two fibers per link, one for each direction. For the use of the wavelength converters we opted for sparse conversion, i.e. some nodes are conversion capability. Of the same way we consider spare splitters capability. To keep operational the entire network we use as a method of survival the protection, introducing protection quality for each request. We consider simple link failures.

• Evolutionary parameters. Population size N: 100 individuals, and run time ET: 15 minutes.

Figure 6: Tree completed after the crossing. Links are randomly added to the primary tree, in this case the link (2, 8) using λ2.

Figure 7: NSF network topology.

6.2 Test Stages

6.2.1 Topology

The used topology is the NSF network, which has 14 nodes and 22 links. It is presented in figure 7.

6.2.2 Generation of Applications

For the generation of requests we need to define:

• Source s, the origin node for each request. It is set up request that starts from each node of the network, i.e., each v ∈ V can be a source node.

• Destinations D, where we also need to define the amount of destination nodes for each request. To set up the number of destinations |D|, it is defined the set ∂ = {20, 40, 60, 80, 100}, where each ∂α (α = 1, ..., | ∂ |) indicates the percentage of the total number of destination nodes. To calculate each number of destination nodes we use the number of nodes | V | and each percentage ∂α as it is observed in equation (11).

Figure 8: Loads of traffic b

To choose the destination nodes, we build a table that we call Table of shortest hop. The set of |D| nodes for a request m whose origin is v, is complete as follows: they are selected from the table of shortest hop the |D|∂α nodes more distant from v.

• The QoP levels are defined by the set q = {1, 2, 3}.

6.2.3 Traffic Load

We define a traffic load b by the following combination:

1. Number of destinations for each request (| D | ∂α).

2. Number of requests for each node (γ): quantity of requests that depart from each node v ∈ V. γ = {4, 8, 12, 16, 20}.

This combination indicates that γφ (φ = 1, ..., | γ |) requests that have | D | ∂α destinations each, corresponds to a traffic load. Figure 8 shows this combination and therefore the traffic loads b ∈ B to be used for the simulations. For a given traffic load b = (| D | ∂α, γφ), the requests defined by it and that start from the node v will be all the same, that is, the same application that the number of destinations | D | ∂α defined by the traffic load, but we make the assumption that they transmit information to different clients of the destination nodes.

6.3 Experimental Schemes

For the analysis of the algorithms, a series of simulations are carried out to obtain the Pareto fronts and calculate its quality. To measure the quality of evolutionary algorithms we consider two aspects: minimize the distance of the Pareto front obtained by the algorithm in front of Exact Pareto of the problem (convergence) and, maximize the extension of solutions on the front so that the distribution be as uniform as possible (diversity). For this end we consider the Hyper-volume measure [22].

To obtain the Pareto Fronts and their hyper-volumes, the following experiment is performed:

• Set of traffic loads B. Each traffic load b = (| D | ∂α, γφ) defines a set of Mk requests (k = 1, ..., | V |) that will depart from each node v and the union of the same M = SM | V | Mk they form an instance.

• Set of algorithms A. In view of what we have two types of protections, based on Dual-Tree (DT) and based on Sub-graph (SGM), we combine algorithms NSGA-II and NSGA-III with them to have 4 algorithms: A = {SGM-NSGA-II, DT-NSGA-II, SGM-NSGA-III, DT-NSGA-III}.

• Number of independent run CE. Number of runs that an algorithm will be executed for a given instance is set up CE = 30.

• The execution time ET. Amount of minutes that is will execute an algorithm for a given instance. We establish ET = 15, since the solutions converge in that time according to a series of simulations made to define this parameter.

7. DISCUSSION

In this experiment, we seek to answer the following questions:

1. It is really better a graph-based protection than a protection based on dual tree?; i.e. sub-graph vs dual-tree protection

2. Which of the algorithms has a better performance for the problem raised?; i.e. NSGA-II vs NSGA-III algorithm

7.1 Discussion Sub-grafo vs Dual Tree Protection

To answer question 1, the averages of the hyper-volume values are compare considering (a) DT-NSGA-II and SGM-NSGA-II approaches (see Table 3), and (b) DT-NSGA-III and SGM-NSGAI-II (see Table 4). The idea is to compare the same evolutionary algorithm but using different types of protection, we see what kind of protection got better average of the hyper-volume for each instance.

According to the T-test [23], if there are significant differences (p - value ≤ 0.05) between the averages, we have enough evidence to conclude that they are different.

In table 3, the Dif. Average column = HV SGM - HV DT is greater than zero in 88% of the total instances existing (average sub-graph is greater). At 12% of instances DT-NSGAII is better, which is in cases where you have the maximum number of destinations for each request (| D | 100%). Numericaly, the average of the hyper-volume was higher for SGM-NSGAII in the majority of the cases. In the same table, we see that the column p-value is always less than 0.05, so we have enough evidence that there are significant differences between the averages between the two protection approaches.

Table 3: NSGAII-DT vs NSGAII-SGM. Comparison types of protection using the NSGAII algorithm

Table 4: NSGAIII-DT vs NSGAIII-SGM. Comparison types of protection using the NSGAIII algorithm

Table 5: NSGAII-DT vs NSGAIII-DT. Comparison of algorithms using DT protection.

In table 4, the Dif. Average column is greater or equal to zero always (average of sub-graph is greater or equal). For traffic loads where the maximum amount of destinations, it cannot be concluded which of the two protections is better (p - value> 0.005), in contrast to the charges remaining p - value ≤ 0.005.

Given that, in most cases there are significant differences between the averages in the two tables treated and the same is in favor of the protection based on sug-graph, we have enough evidence to conclude: Protection based on Sub-graph is better than Dual-Tree protection for requests that do not have the maximum number of destinations.

7.2 Discussion NSGAII vs NSGAIII

To answer question 2, the averages of hyper-volume obtained by NSGAII-DT and NSGAIII-DT are compared firstly (see Table 5), and then NSGAII-SGM vs NSGAIII-SGM is performed (see Table 6).

In table 5, the column Dif. Average = HV NSGAIII - HV NSGAII is greater than zero in most cases (NS-GAIII is better) and p - value ≤ 0.05, except for high traffic load. Note that, for this last case the differences are not significant (p-value> 0.05). In table 6, for subgraph-based protection, we see that the p-value> 0.05 for all cases, i.e. there is a weakly significant difference in terms of statistics between the averages of the hyper-volume.

We conclude that, by using Dual-Tree protection we have enough evidence that the NSGAIII algorithm will get a better performance. On the other hand, with sub-graph protection, NSGAIII is better than NSGAII; However, it is necessary to carry out more experimental tests to confirm this result.

8. CONCLUSION

In this paper the problem of MRPWA has been addressed considering an dual-tree and sub-graph protection as also multi- and many-objective optimization approaches. Experiments indicate that there is evidence that the NSGAIII performs better than the NSGAII and the sub-graph protection uses the resources better. As future work it is propose to extended the application on optical elastic networks and compare with other approaches of protection.

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