Sub-graph based Multicast Protection in WDM Networks
A Multi/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 [21, 20, 2, 18, 8]. 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 [8].

Since the multicast protection is very costly in terms of 'optical and computational resources', the contribution proposes in this work is as follows: (a) Sub graph-based protection scheme [24], (b) Protection level assigned to the quality of protection (QoP) requirements [17], (c) Multi-objective mathematical formulation [16], and (d) Solution based on multi- and many-objective evolutionary algorithms [5, 4]. The approach proposed in this work has not yet been presented in the literature in our best knowledge.

2 SURVIVABILITY IN OPTICAL NETWORKS

The Quality of Protection (QoP) is associated to the level that the resources (links with wavelengths) assigned to protection are shared. Zhong and Jaekel [24] 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 [24]. The previous work proposes the levels of protection to traffic unicast. These approaches were extended by Rodas and Pinto [17] considering several levels of protection quality. Similar to [24] we propose three QoP levels:

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.

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 [8]. 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.

In dual-tree approach 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 [23, 10, 15] 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 1. 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.

The literature reports several types of failures: link, node [22, 1] and shared risk groups [12]. In this paper we focus on link failures, considering only one failure at a time (simple failure).

3 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 [3]. The objective functions and restrictions are functions of the decision variables. Therefore, a MOP generally is optimized:

$$z = f(x) = (f_1(x), f_2(x), , f_k(x)) \tag{1}$$

sujeto a

$$g(x) = (g_1(x), g_2(x), , g_\omega(x)) \geq 0 \tag{2}$$

where $x = (x_1, x_2, ..., x_n) \in X$ is a decision vector, X denotes the decision space of $f(x)$, $z = (z_1, z_2, ..., z_k) \in Z$ is an objective vector, while Z denotes the objective space of $f(x)$.

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 [14, 9, 6]. 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 [7]. In the present work, for the search of solutions are used the evolutionary algorithms NSGA-II [5], which is a multi-objective algorithm and NSGA-III [4], 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

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

$\lvert . \rvert$	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 $\Lambda = \{\lambda_1, \lambda_2, .., \lambda_{\lvert\Lambda\rvert}\}$;

(i, j)	Optical link from node i to node j, where $i, j \in V$ and $(i, j) \in E$;
m	Multicast request $m = \{s, (D), q\}$ with source nodes $s \in V$, a set of destination nodes $D = \{d_1, d_2, ..., d_{\|D\|}\} \subset V$ and its quality requirement of protection $q \in \{1, 2, 3\}$; where 1 =*dedicated*, 2 =*shared* and 3 =*better effort, no protection*;
M	set of multicast request, where $M = \{m_1, m_2, ..., m_{\|M\|}\}$;
(i, j, λ)	Light-link with start node i, destination node j and channel λ ;
$path_{sd}$	Unicast path with source node s and destination node d, where $path_{sd} = \{(i_1, j_1), (i_2, j_2), ..., (i_p, j_p)\}$ with $i_1 = s$ and $j_p = d$; it is also understood that $j_1 = i_2, j_2 = i_2, ..., j_{p-1} = i_p$;
$l\text{-}path_{sd}$	Light-path with source node s and destination node d of a request m, where $l\text{-}path_{sd}= \{(i_1, j_1, \lambda_1), (i_2, j_2, \lambda_2), ..., (i_p, j_p, \lambda_p)\}$ with $i_1 = s$ y $j_p = d$; it is also understood that $j_1 = i_2, j_2 = i_2, ..., j_{p-1} = i_p$;
t_m	Light-tree primary for the multicast request m;
T_M	Primary trees for the set M, where $T_M = \{t_{m_1}, t_{m_2}, ..., t_{m_{\|M\|}}\}$;
p_m	Protective links for the tree t_m, where $p_m = \{(i_1, j_1, \lambda_1), (i_2, j_2, \lambda_2), ..., (i_{\|p\|}, j_{\|p\|}, \lambda_{\|p\|})\}$;
S_m	Sub-graph or light-graph for the form m application by t_m and p_m, this is $S_m = t_m \cup p_m$;
S_M	Multicast protection for the M; where $S_M = \{s_{m_1}, s_{m_2}, ..., s_{m_{\|M\|}})\}$;
X_i^m	Binary variable. If node i performs a conversion of wavelength for s_m 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;
Y_{ij}^m	Binary variable. If the link (i, j) is used by S_m then the variable is set to 1 otherwise 0;
B_d^m	Binary variable. If the destination node $d \in m$ is about the light-tree t_m then $B_d^m = 1$, in another case $B_d^m = 0$;
Z_i^m	Binary variable. If node i bifurcates wavelength for s_m then the variable is set to 1 otherwise 0. This implies that in node i a splitter is needed to the request m;
H_d^m	Binary variable. If the destination node $d \in t_m$ is found protected in the light-graph s_m, then $H_d^m = 1$, otherwise $H_d^m = 0$;

Given a network topology G and a set of requests multicast M, the problem consists to calculate a set of ligth-graph S_M 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.
$$z_1 = \sum_{(i,j)\in E} \sum_{m\in M} Y_{ij}^m \tag{3}$$
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.
$$z_2 = \sum_{i\in V} \sum_{m\in M} X_i^m \tag{4}$$

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

$$z_3 = \sum_{i \in V} \sum_{m \in M} Z_i^m \tag{5}$$

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.

$$z_4 = \sum_{i \in V} \sum_{m \in M} B_i^m \tag{6}$$

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.

$$z_5 = \sum_{i \in V} \sum_{m \in M} H_i^m \tag{7}$$

Subject to the following restrictions:

1. No overlapping: Given the light-graphs S_{m_1} and S_{m_2} , they cannot use the same wavelength λ on the same link (i, j):

$$\lambda_{ij}^{m_1} \neq \lambda_{ij}^{m_2} \tag{8}$$

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:

$$\sum_{(i,j) \in E} \left(\sum_{m \in M} Y_{ij}^m \leq |\Lambda| \right) \tag{9}$$

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

$$\sum_{i \in V} \sum_{m \in M} B_i^m \leq C_S, \theta_i \tag{10}$$

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, looking to optimally use the resources of a WDM network as in [13]. For address this is proposed to divide into two sub-problems the MRPWA problem: 1) Calculation of the primary ligth-tree t_m, that satisfies the multicast request m, and 2) Calculation of ligth-paths secondaries p_m, extending the light-tree t_m to a light-graph S_m. These two steps will be observed in the approach of the next section.

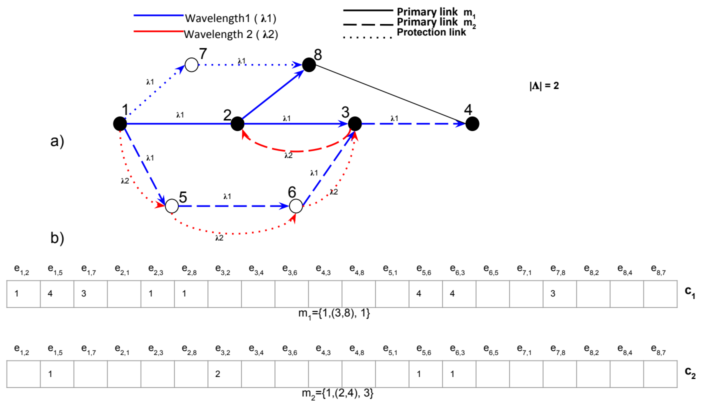

Fig. 1. Representation of a solution $C = \{c_1, c_2\}$. a) Solution on a ligth-graph, b) Chromosome. Note that nodes 2 and 3 are splitter nodes while node 3 is, in addition, a wavelength converter. The ligth-links used by protection ligth-paths have a number of $\lambda > |\Lambda|$ to differentiate them from the primary ligth-links.

5 PROPOSED APPROACHES

Chromosome representation. The representation of the individual for the MRPWA problem is formed by a vector of M elements $C = \{c_1, c_2, ..., c_M\}$ which represents a S_M solution.

Each element $c_m = \{c_{m1}, c_{m2}, ..., c_{m|2E|}\}$ is at same time a vector which represents a ligth-graph S_m; of length $|2E|$, due each link is direct. Each c_{m_e} is a whole number associated with the link of the network e and a S_m. A c_{m_e} element is a whole number indicating which wavelength in the link e is assigned to the sub-graph S_m. The states that can adopt me are: (a) $c_{m_e} = 0$ if the link is not used, (b) $c_{m_e} = [1, |\Lambda|]$ if the link is primary, and (c) $c_{m_e} = [|\Lambda| + 1, 2 * |\Lambda|]$ if it is secondary.

If $c_{me} \in [1, |\Lambda|]$ then the ligth-graph S_m is assigned the wavelength c_{me} on the link e and corresponds to the primary tree. If $c_{me} \in [|\Lambda| + 1, 2 * |\Lambda|]$ then the sub-graph S_m is assigned the wavelength $c_{me} - |\Lambda|$ at link e and corresponds to a secondary link. Figures 1a and 1b reflect the representation of a solution on a graph G and as a chromosome respectively.

Evolutionary Operators. The selection operator is the tournament binary [4]. The quality of an individual is determined according to the schemes proposed by NSGA-II [5] and NSGAIII [4]. 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.

We call TreeCrossover to the crossover operator designed. Given two individuals C and C', TreeCrossover works with each S_m and in particular with the genes of the main tree, that is, with $t_m \in S_m$. Basically, TreeCrossover generates a new individual corresponding to the primary ligth-tree t_m. 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.

6 EXPERIMENTAL TESTS

Experimental Environment. Characteristics of the environment in which they were made tests: 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. The JMetal java framework was modified [11] for the implementation of evolutionary algorithms. The version of the used jdk is 1.8.0 71. 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. Population size N: 100 individuals, and run time 15 minutes. The used topology is the NSF network [17].

6.1 Test Stages

Generation of Applications For the generation of requests we need to define:

- The origin node s for each request. It is set up request that starts from each node, i.e., each $v \in V$ can be a source node.
- Destinations D and the amount of destination nodes for each request. To set up the number of destinations $|D|$, it is defined the set $\partial = \{20, 40, 60, 80, 100\}$, where each ∂_α ($\alpha = 1, ..., |\partial|$) 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).

$$|D|_{\partial_\alpha} = \frac{(|V| - 1) \cdot \partial_\alpha}{100} \tag{11}$$

  The set of D nodes for a request m whose origin is v, is complete as follows: they are selected the $|D|_{\partial_\alpha}$ nodes more distant from v.
- The QoP levels are defined by the set $q = \{1, 2, 3\}$

Traffic Load We define a traffic load b by the following combination:

1. Number of destinations for each request ($|D|_{\partial_\alpha}$).
2. Quantity of requests (γ) that depart from each node $v \in V$, where $\gamma = \{4, 8, 12, 16, 20\}$.

This combination indicates that γ_φ ($\varphi = 1, ..., |\gamma|$) requests that have $|D|_{\partial\alpha}$ destinations each, corresponds to a traffic load. For a given traffic load $b = (|D|_{\partial_\alpha}, \gamma_\varphi)$, 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 $|D|_{\partial_\alpha}$ defined by the traffic load, but we make the assumption that they transmit information to different clients of the destination nodes.

6.2 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 [25].

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

- Set of traffic loads B. Each traffic load $b = (|D|_{\partial_\alpha}, \gamma_\varphi)$ defines a set of M_k requests ($k = 1, ..., |V|$) that will depart from each node v and the union of the same $M = \bigcup_{M_k}^{M_{|V|}}$ 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 runs that an algorithm will be executed for a given instance is set up to 30.
- Amount of minutes that is will execute an algorithm for a given instance, which we establish to 15, since the solutions converge in that time according to a series of simulations made to de
ne 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

Table 2. Comparison types of protection

NSGAII-DT vs NSGAII-SGM					NSGAIII-DT vs NSGAIII-SGM				
b	$\overline{HV}_{DT}$	$\overline{HV}_{SGM}$	Dif. Average	p-value	b	$\overline{HV}_{DT}$	$\overline{HV}_{SGM}$	Dif. Average	p-value
20,4	0.2323603698	0.2573254477	0.02496507	6.79E-27	20,4	0.2361064607	0.2573744383	0.0212679776	0
40,4	0.0244993712	0.0586544169	0.03415504	0	40,4	0.0275746089	0.0581370340	0.0305624251	0
60,4	0.0122738375	0.0369586866	0.02468484	0	60,4	0.0136550414	0.0372864462	0.0236314048	0
80,4	0.0067977764	0.0180158842	0.01121810	0	80,4	0.0077292608	0.0179260846	0.0101968237	0
100,4	0.0033107388	0.0122170437	0.00890630	0	100,4	0.0035325561	0.0121891873	0.0086566312	0
20,8	0.0598880466	0.0285227265	−0.03136532	0	20,8	0.0306797659	0.0598904203	0.0292106544	0
40,8	0.0060680632	0.0142355676	0.00816750	0	40,8	0.0063766420	0.0140736478	0.0076970058	0
60,8	0.0029525178	0.0092203052	0.00626778	0	60,8	0.0033442638	0.0092508493	0.0059065855	0
80,8	0.0010823532	0.0039336016	0.00285124	0	80,8	0.0012435180	0.0039078280	0.0026643100	0
100,8	0.0001726355	0.0005029431	0.00033030	2.15E-25	100,8	0.0001812103	0.0005194902	0.0003382799	0
20,12	0.0110262050	0.0254325232	0.01440631	0	20,12	0.0119395854	0.0255742734	0.0136346879	0
40,12	0.0023972031	0.0062027011	0.00380549	0	40,12	0.0027619120	0.0062022490	0.0034403370	0
60,12	0.0013936591	0.0040742890	0.00268062	1.01E-50	60,12	0.0016096991	0.0041669509	0.0025572518	0
80,12	0.0004536063	0.0017335382	0.00127993	9.47E-43	80,12	0.0005303039	0.0017506655	0.0012203616	0
100,12	0.0000022927	0.0000022225	−0.00000007	0.159606	100,12	0.0000022598	0.0000022605	0.0000000008	0.988
20,16	0.0072013978	0.0143556035	0.00715420	2.36e-33	20,16	0.0079485627	0.0142777841	0.0063292214	0
40,16	0.0007585924	0.0022885193	0.00152992	1.42E-53	40,16	0.0016106009	0.0035083686	0.0018977677	0
60,16	0.0002574399	0.0009864438	0.00072900	2.88E-47	60,16	0.0008637138	0.0023070869	0.0014433731	0
80,16	0.0002574399	0.0009864438	0.00072900	8.52E-43	80,16	0.0002934669	0.0009859702	0.0006925033	0
100,16	0.0000012437	0.0000012638	0.00000002	0.211740	100,16	0.0000012446	0.0000012510	0.0000000064	0.730
20,20	0.0049414549	0.0090157573	0.00407430	9.55E-36	20,20	0.0056295233	0.0089880571	0.0033585339	0
40,20	0.0008892322	0.0022212129	0.00133198	1.30E-46	40,20	0.0009736031	0.0022119132	0.0012383100	0
60,20	0.0004932688	0.0014340629	0.00094079	3.91E-50	60,20	0.0005549143	0.0014227901	0.0008678758	0
80,20	0.0001703874	0.0006149684	0.00044458	1.38E-49	80,20	0.0001849825	0.0006146430	0.0004296604	0
100,20	0.0000008086	0.0000007790	−0.00000002	0.081407	100,20	0.0000008051	0.0000008050	0.0000000000	0.999

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 2 left part) and (b) DT-NSGA-III and SGM-NSGAI-II (see Table 2 right part).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 [19], if there are significant differences ($p - value \leq 0.05$) between the averages, we have enough evidence to conclude that they are different.

In table 2 left part, the $Dif.\ Average = \overline{HV}_{SGM} - \overline{HV}_{DT}$ 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.

In table 2 right part, 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 pro-

Table 3. Evolutionary Algorithms comparison

NSGAIII-DT vs NSGAII-DT					NSGAII-SGM vs NSGAIII-SGM				
b	$\overline{HV}_{NSGAII}$	$\overline{HV}_{NSGAIII}$	Dif. Average	p-value	b	$\overline{HV}_{NSGAII}$	$\overline{HV}_{NSGAIII}$	Dif. Average	p-value
20,4	0.2323603698	0.2361064607	0.0037460909	0	20,4	0.2573254477	0.2573744383	0.0000489906	0.977
40,4	0.0244993712	0.0275746089	0.0030752377	0	40,4	0.0586544169	0.0581370340	−0.0005173829	0.4
60,4	0.0122738375	0.0136550414	0.0013812038	0	60,4	0.0369586866	0.0372864462	0.0003277596	0.512
80,4	0.0067977764	0.0077292608	0.0009314844	0	80,4	0.0180158842	0.0179260846	−0.0000897997	0.741
100,4	0.0033107388	0.0035325561	0.0002218172	0.115	100,4	0.0122170437	0.0121891873	−0.0000278564	0.893
20,8	0.0285227265	0.0306797659	0.0021570394	0	20,8	0.0598880466	0.0598904203	0.0000023736	0.995
40,8	0.0060680632	0.0063766420	0.0003085788	0.019	40,8	0.0142355676	0.0140736478	−0.0001619198	0.235
60,8	0.0029525178	0.0033442638	0.0003917460	0.002	60,8	0.0092203052	0.0092508493	0.0000305442	0.802
80,8	0.0010823532	0.0012435180	0.0001611648	0	80,8	0.0039336016	0.0039078280	−0.0000257736	0.617
100,8	0.0001726355	0.0001812103	0.0000085748	0.302	100,8	0.0005029431	0.0005194902	0.0000165471	0.373
20,12	0.0110262050	0.0119395854	0.0009133804	0.001	20,12	0.0254325232	0.0255742734	0.0001417502	0.299
40,12	0.0023972031	0.0027619120	0.0003647089	0	40,12	0.0062027011	0.0062022490	−0.0000004521	0.994
60,12	0.0013936591	0.0016096991	0.0002160400	0	60,12	0.0040742890	0.0041669509	0.0000926620	0.079
80,12	0.0004536063	0.0005303039	0.0000766977	0	80,12	0.0017335382	0.0017506655	0.0000171273	0.547
100,12	0.0000022927	0.0000022598	−0.0000000329	0.527	100,12	0.0000022225	0.0000022605	0.0000000381	0.429
20,16	0.0072013978	0.0079485627	0.0007471649	0	20,16	0.0143556035	0.0142777841	−0.0000778194	0.271
40,16	0.0014173188	0.0016106009	0.0001932822	0	40,16	0.0035381197	0.0035083686	−0.0000297511	0.452
60,16	0.0007585924	0.0008637138	0.0001051214	0	60,16	0.0022885193	0.0023070869	0.0000185676	0.535
80,16	0.0002574399	0.0002934669	0.0000360271	0	80,16	0.0009864438	0.0009859702	−0.0000004736	0.971
100,16	0.0000012437	0.0000012446	0.0000000009	0.960	100,16	0.0000012638	0.0000012510	−0.0000000129	0.574
20,20,	0.0049414549	0.0056295233	0.0006880683	0	20,20,	0.0090157573	0.0089880571	−0.0000277002	0.735
40,20	0.0008892322	0.0009736031	0.0000843709	0.001	40,20	0.0022212129	0.0022119132	−0.0000092997	0.695
60,20	0.0004932688	0.0005549143	0.0000616455	0	60,20	0.0014340629	0.0014227901	−0.0000112729	0.439
80,20	0.0001703874	0.0001849825	0.0000145952	0.012	80,20	0.0006149684	0.0006146430	−0.0000003255	0.969
100,20	0.0000008086	0.0000008051	−0.0000000036	0.837	100,20	0.0000007790	0.0000008050	0.0000000260	0.096

tections is better ($p - value > 0.005$), in contrast to the charges remaining $p - value \leq 0.005$.

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.

NSGAII vs NSGAIII. To answer question 2, the averages of hyper-volume obtained by NSGAII-DT and NSGAIII-DT are compared firstly (see Table 3 left part) and then NSGAII-SGM vs NSGAIII-SGM is performed (see 3 rigth part).

In table 3 left part, the column *Dif. Average* $= \overline{HV}_{NSGAIII} - \overline{HV}_{NSGAII}$ is greater than zero in most cases (NS-GAIII is better) and $p{-}value \leq 0.05$, except for high traffic load. Note that, for this last case the differences are not significant ($p - value > 0.05$). In table 3 rigth part, 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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