Routing and Spectrum Allocation in Elastic Networks. 
An approach based on Multi-objective Genetic Algorithms

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Abstract
The increasing network traffic and the need to expand the capacity and performance of transmissions are achieved through the use of optical fiber. The current working of the transmission networks are based on Wavelength Division Multiplexing (WDM). This technology has the ability to transport, route and assign multiple channels on a single optical fiber that supports the transmission of different wavelengths. Here, each channel is assigned a single type of traffic, which results in resource underutilization when channel does not operate at maximum capacity. Consequently, elastic optical networks emerge as an alternative to WDM networks to maximize the use of the bandwidth of the optical fiber based on flexible spectral grid. This enables the allocation of variable bandwidth to optical channels with low-speed traffic, resulting in an increased efficiency of the spectrum. In WDM networks, the routing and wavelength assignment (RWA) algorithm seeks a physical path through the network and assign a wavelength for information transport between source and destination nodes. The selected wavelength is set to be constant throughout the physical path (known as the wavelength continuity constraint). In elastic optical networks, the routing and spectrum allocation (RSA) algorithms are also subject to the contiguity constraint. This constraint requires that the frequency slots occupying each channel be contiguous in the medium. The scope of the paper is the RSA problem, which is a NP-hard problem and branches into the RWA problem as a particular case. In this work, RSA is addressed as a multi-objective optimization problem. In this context, we propose a multi-objective genetic algorithm (MOGA) that calculates the optimal routing and spectrum allocations for a set of unicast requests with static traffic requirements. The MOGA seeks to optimize the total number of frequency slots used and quality of service defined by the distance between source and destination node, simultaneously. Performed testing shows promising results with respect to the solution produced by an Integer Linear Programming, which provides a set of suitable solutions that can be selected based on the network administrator’s preferences.

Keywords: RWA, RSA, WDM Networks, Elastic Optical Networks, Multi-objective Optimization, Genetic Algorithms.

1. Introduction
The birth of interest in the elastic networks comes by the constant increase in network traffic and the need to increase the capacity and performance of the sections in transmission networks. Today transport technology used in optical networks is the wavelength multiplexing (WDM). This technology is capable of carrying multiple channels in the same fiber, based on carriers of different wavelengths. The implication of this technology would be channels having reduced to the maximum supported by the granularity imposed demand, infra-utilization resources given to this because the network traffic will be highly heterogeneous, flexibility in the provision of resources optical network it is a challenge. A major change in the architecture of elastic optical networks is the replacement of the fixed grid by a flexible new. ITU-T is working on the review of a new standard G.694.1. [1]
The optical spectrum of the C band (1530-1565 nm) is divided into slots (slots frequency) of a fixed size [2] and is assigned a center frequency (CF) to each Elastic Optical Path (EOP) which must match the beginning or the end of these grooves. To meet demands for increasing width band, the elastic optical networks are indispensable.
To generate an optical elastic path (EOP), we can divide operations routing, where calculations of the path between the source node and the destination through a network topology and selection of spectral resources to be allocated to the request is made (Spectrum Allocation, SA) defined by a center frequency and a bandwidth (slot width). In WDM networks planning algorithms routing and wavelength assignment, seeking a physical path through the network and assign a wavelength to transport that channel. The selection of this wavelength is conditioned to be the same during the course of the physical path, so that in this way it is not necessary to use wavelength converters in any hop. This condition is called, condition of continuity (continuity constraint). In elastic nets apart from this condition, there is a new condition of contiguity in the spectrum (contiguity constraint). The latter condition means that frequency slots occupying the channel should be together in the spectrum.
To solve the many problems that have multiple objectives, a good meta-heuristics for solve of this type of problems are genetic algorithms (GA). Traditional GA are customized to suit the multi-objective problems by using specialized fitness functions and the introduction of methods to promote the diversity of the solution. There are general approaches to optimization of multiple objectives. One is to combine the individual objective functions into a single composite function or move all but one of the goals for the set of constraints. The next approach is to determine a set of optimal solutions Pareto or a representative subset. Pareto optimal set is a set of solutions that are not dominated with respect to the other.
This paper presents a heuristic Multi-objective Genetic Algorithm (MOGA) for the RSA problem that takes into account the problem of contiguity in the spectrum is proposed. The ILP model is used to find optimal solutions for small networks and this helps to ensure the quality of the proposal with the heuristic genetic algorithms and demonstrate the feasibility find good solutions in larger networks solution. MOGA optimizes the spectrum used, the maximum number of hops, and the total cost subject to the restrictions of continuity and contiguity and conflict spectrum.
Our work is organized as follows, a first part (section 2) which conceptually explain the difference existing between WDM networks and EON networks, emphasizing the importance of flexible spectrum for more efficient use of spectrum, and also basic architecture of networks EON introduction. In the next section (section 3) we explain conceptually the problem of routing and spectrum allocation (RSA) in EON networks. In section 4 we see the work related to this problem. In section 5, the concepts of Genetic Algorithms and Genetic Algorithm Multi-objective (MOGA). In the next section (Section 6) Genetic Algorithm formulation. Section 7, ILP formulation. In the Section 8 we present the experimental environment and tests, the parameters used for the MOGA, the presentation of the results and the difference in performance between an algorithm in ILP versus the algorithm MOGA. Finally (section 9), conclusions and future work.

2. Elastic Optical Networks

In wavelength division multiplexing networks (WDM), the objective is to transmit multiple wavelengths in a single optical fiber simultaneously without overlapping. The range of wavelengths used in the fiber can be divided into several bands. The need for standardization of WDM networks made the International Telecommunications Union (ITU) developed a standard. The standard wavelength, is called ITU-grid and was defined in the 1550 nm region of low loss fiber, specifically this grid is at a frequency of 193.1 THz, corresponding to a wavelength of 1552, 52 nm [3]. Each of these channels at different wavelengths can transmit signals of different speeds and format. Therefore, by allowing multiple WDM channels that coexist on a single fiber, you can take advantage of the high bandwidth of the fiber [3].

We can define the EON (Elastic Optical Networks) as an OTN (Optical Transport Network) where all the equipment and the control plane can handle optical channels of variable bandwidth and all the switching elements can withstand different granularities in the spectrum of channels that transmit information. The traditional optical network based on WDM divides the spectrum into separate channels. The spacing between adjacent channels is between 50 GHz and 100 GHz that is specified by the ITU. Channel spacing is very large and if each channel contains a low bandwidth used and no traffic on the free gap, much of the spectrum is wasted. To fully exploit a network other than flexible bandwidth channels, it is necessary to have a network architecture that allows the transmission of different signal formats for transmission. This section describes the architecture of elastic optical networks consisting of Variable Bandwidth Transponder (BVT) and Variable Bandwidth Cross Connect (OXC-BV) will be discussed. One of the fundamental problems of the EON network is very similar to the problem in WDM networks is spectrum allocation that meets the conditions, continuity of the spectrum, contiguity in the spectrum and avoid spectrum conflict, which later discuss they.

3. Routing and Spectrum Allocation (RSA)

The RSA problem can be attacked as routing resolution and allocation of spectrum iterative together [6]. In this approach the problem RSA, the greatest difficulty arises, is the large number of conditions that poses the problem. This introduces greater computational complexity when calculating the optimal path for each request, in turn optimizing the allocation of spectrum, which ultimately translates into very large computing times.

The RSA problem in elastic optical networks is equivalent to the problem RWA networks based on optical WDM networks. The difference between these two technologies is the ability of the elastic networks to an assignment of flexible spectrum to meet the data rate requested, where a set of contiguous grooves of the spectrum is assigned to a connection, while in WDM networks is flexible assigns a channel to the application size. The assigned spectrum slots must always be together to satisfy the constraint of contiguity of the spectrum. The following restrictions are taken into account when calculating the routing and spectrum allocation.

- Restriction continuity of spectrum. That means the same spectral allocation of resources on each link along a canal route. Restriction and elastic WDM networks.
- Spectrum contiguity (or adjacency). Constraint ensures that the subcarriers are adjacent to each other on a channel. Restriction on elastic networks.
- Spectral Conflict. It is defined as spectrum allocation for non-overlapping of different channels on the same fiber. Restriction on WMD and elastic networks.

Basically RSA algorithms are concerned to allocate a contiguous fraction of spectrum for each connection request subject to the above restrictions. We see example in Figure 4 given by [4], as the constraints are met for a solution in elastic nets. A connection request from node 1 to node 4 that requires 2 adjoining slots to transmit data, we see the first figure in the 1-2-4 nodes, use the link 1 and link 4 slots are available for the requirement in the link 1, but in the link 4 there is only one slot available, then this does not meet the condition of contiguity. The following figure shows the 1-2-3-4 node, use the link 1, link 2 and link 3, to establish a route, and we see that in the three link’s meet contiguity condition since the slots are they found together in three links.
4. Related work

The RSA has been treated with two techniques, exact and heuristic. Among accurate are the Linear Programming Integer (ILP). The heuristic techniques are based on evolutionary algorithms.

In [9] the objective is to minimize the problem set different frequency ranges subcarriers. A heuristic method based on ILP to improve FA-FF (Fixed-Alternate routing and First-Fit frequency assignment), with restrictions for each demand is selected from a set of candidate routes proposed a frequency slots is selected in this way, the allocation of the contiguity of frequency slots (the restriction of continuity is imposed implicitly), excluding options frequency slots for which there is insufficient space in the frequency spectrum, capacity constraints, means that each frequency slots on each network link can be assigned at most one demand and establish a frequency slots used in at least one network link. The main idea of this paper is to release certain frequencies occupied on the network and reorganize the frequency assignment with the help of RSA problem formulation.

In [12], it seeks to minimize the slots frequency assigned to all claims, look for the best way to choose the correct modulation format and finally assign the frequency slots, with the same own restrictions RSA as being, continuity and contiguity, this paper presents the restriction that demands different intervals do not overlap, with the particularity that includes the problem of modulation.

In [13] a comprehensive study of the issue and the problem of spectrum allocation (RSA) in the slice network is made, the RSA problem is formulated using linear programming formulation (ILP) to minimize optimally the maximum number of subcarriers required in any fiber network. The aim of this paper is to minimize the maximum rate of the subcarriers of all fibers, with restrictions: traffic demand, Sub-carrier Capacity Constraint, Spectrum Continuity Constraint, Guard-Carrier Constraint and Constraint Sub-carrier Consecutiveness.

5. Multi-Objective Genetic Algorithm

The basic concept of a genetic algorithm is Darwin’s idea of natural selection, biological process where the winners are the players. The genetic algorithm consists of five steps where candidates are generated. Step 1. Where initialization is given, solutions possible candidates are generated. Step 2. For a fitness function, the best elements are selected to make the intersection of the population, this is called, selection of players. In step 3 crossing, where a new solution is created from two combined solutions it was performed. The new solutions reinserted in the population, depending on the result obtained in terms of fitness. Step 4 is the mutation process where change any element of the population, automatically selected, the aim of this is to broaden the range of solutions. Step 5. The latter one is the replacement step, a selection of new elements generated in the previous process (mutation) is performed to replace some elements in the original population. From step 2 to step 5 is repeated until a stopping criterion. The parameter used to classify the solutions is called Fitness [7].

As a population-based approach, GA are very suitable for solving multi-objective optimization problems. A simple genetic algorithm GA can be modified to find a set of multiple non-dominated solutions in a single run. The ability of GA to search simultaneously
different regions of the solution space makes it possible to find a diverse set of solutions to difficult problems. An operator GA crossing structures can exploit good solutions with respect to different objectives to create new solutions not dominated in unexplored parts of the Pareto front.

The decision problem of multi-objective minimization objectives $K$, can be defined as follows: given a vector of decision variables of $n$-dimensional $x = \{x_1, ..., x_n\}$ in the space $X$ solutions, find a vector $x^*$ that minimizes $K$ set of objective functions $z(x^*) = \{z_1(x^*), ..., z_k(x^*)\}$. A number of restrictions generally restricts Space $X$ solution, such as $g_j(x^*) = b_j for j = 1, ..., m$ and limits on the decision variables $[10]$.

To solve these problems several multi-objective GA, among which we mention the first multi-objective GA, called Vector Evaluated GA (VEGA) which was proposed by Shaffer developed. They were then developed several evolutionary algorithms multi-objective including Multi-Objective Genetic Algorithm (MOGA), niched Pareto Genetic Algorithm (NPGA), Weight-based Genetic Algorithm (CMOA), Random Weighted Genetic Algorithm (RWGA) and several variations of MOGA $[10]$.

For this work, the chromosome structure is next:

<table>
<thead>
<tr>
<th>&lt;Demand Id, Route ID, {Used Slots}&gt;</th>
<th>Cost</th>
<th>Maximum Distance</th>
<th>Maximum Spectrum</th>
<th>Fitness</th>
</tr>
</thead>
</table>

The chromosome structure has two parts. The first part codes, for each request, its route and frequency slots. In the second part has the objective functions and fitness of solution.

The reproduction of new solutions is based on: (a) binary tournament as selection operator, (b) Two-Point as crossover operator, and (c) mutation with $\mu$ probability for each route in the chromosome. In the Figure 5 is shown the relationship among chromosome, route table and network topology. This example considers a topology with five nodes and three demand request: $(1, 2), (2, 5)$ and $(1, 5)$. Each request has associated a pre-calculated set of paths, in this example is considered two paths. After path selection, the First-Fit algorithm is applied to assign slots frequency under contiguity, continuity and overlap constraints.

![Figure 5. Relationship among Chromosome Structure, Route Table and Network Topology.](image)

6. Genetic Algorithm Formulation

Given a set of demands $R$, a graph network $G$, a set of paths $P$, and network parameters, it seeks calculate the $z$ solution that simultaneously minimize the cost, the maximum distance, and the maximum frequency slots (spectrum) normalized according to the following formula:

$$f = f_1 + f_2 + f_3$$  \hspace{1cm} (6)

Where:

The cost is:

$$f_1 = \frac{\sum_{x_k \in Z} C(P_k) \cdot \lambda_k}{\max \{C(P_k); p \in P\} \cdot \lambda^s}$$ \hspace{1cm} (7)
The Maximum Distance:

\[ f_3 = \frac{\max \{ C(P_k) : z_k \in Z \}}{\max \{ C(P_k) : p \in P \}} \]  

The Maximum Spectrum

\[ f_2 = \frac{\max \{ \alpha_{ij} : (i,j) \in E \}}{\lambda} \]

Subject to the following restrictions:
1. Contiguity:
   \[ t_0^{kij} + \lambda_k - 1 = t_f \]  
2. Overlap:
   \[ t_0^{kij} \neq t_1^{kij} \]  
3. Continuity:
   \[ t_1^{kij} = t_f \forall_{ij} \]

Description:
The expression (7) calculates the cost, the sum (of the selected path \( z_k \) belonging to the set of paths \( Z \)) \( C(P_k) \) which is the set of the route used to k-th demand multiplied by the bandwidth requested by a lawsuit slot often done (number of frequency slots); \( C(P_k) \) is the sum of the link \( i, j \) in the set of links \( E \) where \( X_{ij}^k \) is equal to 1 if \( (i,j) \in P_k \) and 0 in the case where the route is not used to this so multiplied by the distance of the link \( (i,j) \in E \).

The expression (8) calculates the maximum distance. Takes the maximum value of \( C(P_k) \) which is the set of the route used to k-th demand.

The expression (9) calculates the maximum load. Find \( \alpha_{ij} \) the maximum value of which is the bandwidth used by demands that pass through the link \( (i,j) \in E \). The expression \( \alpha_{ij} \) equals 1 if \( (i,j) \in P_k \) and 0 if the route is not used, this is multiplied by \( \lambda_k \) which is the bandwidth requested by a lawsuit slots frequency (amount of frequency slots).

7. Multi-objective ILP Formulation

The proposed multi-objective ILP formulation is based on [11] but considering three objective functions in a weighted sum way. Note that, the objective functions are normalized to calculate a solution with maximum trade-off among objective functions. The ILP formulation is the next:

Variables:
\( x_{p}^{sd} \): 1 if route \( p \) is used to request \( (s,d) \), 0 in otherwise.
\( \alpha_{sd} \): Capacity required for the communication to request \( (s,d) \).
\( dist_p \): Distance of route \( p \).
\( R_{e}^{p} \): Matrix, 1 if route \( p \) with the request \( (s,d) \) uses the link \( e \), 0 in otherwise.

Constants:
\( dist_{max} \): Maximum route of all routes.
\( spectrum_{max} \): Total spectrum available.
\( cost_{max} \): Maximum cost, it is cost for the maximum route using the maximum spectrum.

Objective function:

\[ \min f = f_1 + f_2 + f_3 \]
Where:

- The cost is:
  \[ f_1 = \frac{\sum_{sd} \sum_{p} (\alpha_{psd} \cdot \text{dist}_{psd} \cdot x_{psd})}{\text{cost}_{max}} \]  \hspace{1cm} (14)

- The Maximum Distance is:
  \[ f_2 = \frac{\max (\text{dist}_{psd} \cdot x_{psd})}{\text{dist}_{max}} ; \forall sd, \forall p \]  \hspace{1cm} (15)

- The Maximum Spectrum:
  \[ f_3 \geq \frac{\sum_{sd} \sum_{p} R_{psd} \cdot x_{psd} \cdot a_{sd}}{\text{spectrum}_{max}} ; \forall e \in E \]  \hspace{1cm} (16)

The functions (14), (15) and (16) are the same of (7), (8) and (9).

The constraints of this ILP formulation are the same propose in [11].

8. Experimental

The ILP formulation was done over Cplex Version 12.6.3.0, and the MOGA algorithms was implemented on Java 8 1.8.0_11.

For each instance, 30 independence runs was carry out over NSF networks. This network is presented in Figure 9 where is considered 500 frequency slots and each request with 2, 4, 6 and 8 slots and a full traffic matrix.

The genetic algorithm was generated with 30 solutions (population individuals), and the initial population was generated randomly. The MOGA uses the parameter \( \mu = 0.2\% \) to mutation, and 2 reproductors to crossover operation. Also uses 5 minutes of runs as stop criteria.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Genetic Algorithm</th>
<th>ILP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Language</td>
<td>Java</td>
<td>Java / Cplex</td>
</tr>
<tr>
<td>Computer Ram</td>
<td>8Gb</td>
<td>8Gb</td>
</tr>
<tr>
<td>Computer Processor</td>
<td>i7 2.4Ghz</td>
<td>i7 2.4Ghz</td>
</tr>
<tr>
<td>Computer Operative System</td>
<td>Linux Ubuntu 14.4</td>
<td>Windows 8</td>
</tr>
<tr>
<td>Topology</td>
<td>NSF</td>
<td>NSF</td>
</tr>
<tr>
<td>Nodes</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Total Frequency Slots</td>
<td>500</td>
<td>500</td>
</tr>
</tbody>
</table>

Figure 9. NSF 14-nodes topology
Results

<table>
<thead>
<tr>
<th>Requested Frequency Slots</th>
<th>Genetic Algorithm</th>
<th>ILP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>First Generation</td>
<td>Last Generation</td>
</tr>
<tr>
<td>Cost</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Maximum Used Frequency Slot</td>
<td>485</td>
<td>409</td>
</tr>
<tr>
<td>Maximum Used Route</td>
<td>11</td>
<td>11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Requested Frequency Slots</th>
<th>Cost</th>
<th>Maximum Used Frequency Slot</th>
<th>Maximum Used Route</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>44</td>
<td>485</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>44</td>
<td>403</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>44</td>
<td>389</td>
<td>11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Requested Frequency Slots</th>
<th>Cost</th>
<th>Maximum Used Frequency Slot</th>
<th>Maximum Used Route</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>66</td>
<td>447</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>66</td>
<td>426</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>66</td>
<td>411</td>
<td>11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Requested Frequency Slots</th>
<th>Cost</th>
<th>Maximum Used Frequency Slot</th>
<th>Maximum Used Route</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>88</td>
<td>473</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>88</td>
<td>448</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>88</td>
<td>417</td>
<td>11</td>
</tr>
</tbody>
</table>

The GA results show that with more requested frequency slots, the difference between the first and last generations is less. With more requested slots, more generation shows better results.

In the ILP implementation with NSF 14-nodes topology, the time of execution suppurates 3 hours. It is the main difference between the best solutions with ILP and the proposed heuristic, the GA use less than the 10% of ILP time and obtains almost the same solutions. To get better solutions of GA, it can aggregate more generations and with this the aggregated time of execution is very small.

8. Conclusion

The routing and spectrum allocation problem in real networks is a NP-Hard problem. With this work, we demonstrated that the ILP model is the best option to small networks, but with a real network the execution time can be unacceptable. Our results indicate that the proposed heuristic, MOGA, can obtain so good results with greater networks in an acceptable period. The execution time of MOGA is less than 10% of ILP execution, with almost the same results. Also, the SLICE technology to use the available bandwidth applied with the presented MOGA, shows the improvement to optimize the bandwidth use.

5. References