WDM Mesh Networks with Dynamic Traffic

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Abstract: This article presents a mathematical model that results in a low-cost network design to satisfy a set of point-to-point demands that arrive and leave the network along of time. It considers the problem of routing working traffic and assigning wavelengths in an all-optical network avoiding if possible that wavelengths assignment changes and flow rerouting. The model allows to know when a reconfiguration/expansion is needed.

The model provides a physical network configuration selecting a lowest cost set of components of the network (subnetworks and OXCs) with sufficient capacities to attend the demands and the required wavelengths in all time.

Key-words: WDM, dynamic traffic, linear programming, optimization

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Réseaux WDM et trafic dynamique

Résumé : Ce rapport présentent une modélisation mathématique du problème de conception au meilleur coût de réseaux supportant un trafic évoluant au cours du temps. Considérant le problème du routage et de l'affectation de longueurs d'onde dans les réseaux tout optique, l'objectif est d'éviter autant que possible les reconfigurations et reroutages dans le réseaux lorsque trafic évolue. Ce modèle permet de mesurer quand une reconfiguration ou une expansion du réseau est nécessaire.

Le modèle calcule une configuration du réseau physique, c'est à dire un ensemble de composants du réseaux (sous-réseaux et routeurs) de capacité suffisante et de moindre coût.

Mots-clés : WDM, trafic dynamique, programmation linéaire, optimisation

1 Introduction

The dynamic nature of the Internet requires backbone networks to be reconfigurable. Wavelength Division Multiplexing (WDM) technology has the ability to adapt the network topology to traffic demands changing over time. A given node may transmit optical signals on different wavelengths that are coupled into a single fiber using wavelength multiplexers [7]. It is an excellent way to increase the capacity of optical networks. It is a necessity due to the increase of communication applications.

The Routing and Wavelength Assignment (RWA) problem is to find the suitable routing paths and wavelengths for each demand request so that no two paths sharing a link are assigned to the same wavelength. According to [9] the RWA problem is critically important to increase the efficiency of wavelength-routed all-optical networks. The solution of the RWA problem provides an optimal configuration to a WDM environment.

In an all-optical WDM network, a logical connection between a pair of nodes, say (o, d), is a path or route composed of a sequence of links from o to d called a lightpath [7]. Such a network consists of a number of optical cross-connects (OXCs) arranged in some arbitrary topology and each OXC can switch the optical signal coming in on a wavelength of an input fiber link to the same wavelength in an output fiber link. An OXC with n input and n output ports capable of handling w wavelengths per port can be thought as w independent $n \times n$ optical switches. These switches have to be preceded by a wavelength demultiplexer and followed by a wavelength multiplexer to implement an OXC [11], as shown in Fig. 1.

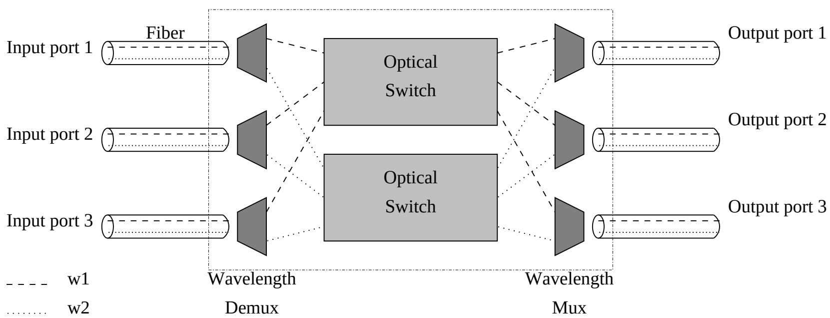

Figure 1: 3×3 OXC with two wavelength per fiber [11]

In the core of the backbone it is wished that a lightpath does not undergo any conversion to and from electrical form, in this way there is nothing in the signal path to limit the throughput of the fibers.

International Telecommunications Union (ITU) has developed standards that specify the architecture of WDM optical transport networks (OTN) [6].

A set of possible Alternate Paths (AP) was pre-defined for each demand pair. This is called a arc-path-based formulation. Each paths should be selected and get an adequate wavelength interval. According to [10] alternate routing can improve the blocking performance and generally provides significant benefits.

It have been used Evolving Graphs (EG) to represents our networks instances over time. According [12], a Evolving Graph (EG) have been proposed as a formal abstraction for dynamic networks, and can be suited easily to the case of FSDN's (Fixed Schedule Dynamic Networks). Let be given a graph $G(V, E)$ and an ordered sequence of its subgraphs, $S_g = G_1, G_2, ..., G_t$ such that $\bigcup_{i=1}^{T} G_i = G$. An Evolving Graph was defined a system $g = (G, S_g)$.

The actual EG definition is based on node-arc-based formulation. We are going to investigate how the AP concept could be used to change the definition of Edge Presence Schedule presented in [12] for Path Presence Schedule, and obtain a new arc-path-based EG definition. The journey time will be 0 to all demands because the environment is an all-optical network without conversions. In an arc-path-based EG what changes is the pre-defined paths presence according with the existent demands to each time period, see Figure Fig. 4c.

It was implemented a heuristic to the Static RWA problem in [5]. It uses components cost in a first time to selects several available routes in an adaptive way depending of the current state of the network. The second phase uses graph coloring to assign wavelengths. We pretend to extend this heuristic implementation to treat time periods, considering arc-path-based EG definition.

Scheduled Lightpath Demands (SLDs) is defined in [8]. A SLD is a demand for a set of lightpath, represented by a tuple $(s, d, n, \alpha, \omega)$ where s and d are the source and destination nodes of the lightpaths, n is the number of requested lightpaths and α, ω are the set-up and tear-down dates of the lightpaths. These definitions will be used to represent our demands over time.

In [13] were investigated different Integer Linear Programming (ILP) formulations for solving the RWA problem with two path protection schemes. We consider the instances and model in [7]. These instances have two link-disjoint routes between the source and the destination nodes in order to recover from any single link failure. We propose modifications of this mathematical formulation of the RWA problem over an all-optical network. It changes the definition of the OXC capacity and it adds time periods treatment, dynamic traffic evolution, and a prediction scheme to system reconfiguration necessity. The goal is to make the network manageable whitout undue expense, complexity, or disruption.

The RWA problem is NP-complete. It was proved in [3], by showing the equivalence of the problem to the graph-coloring problem. Therefore several research works have focused on developing efficient heuristics.

2 Model Description

We consider a network with N nodes and E links (i, j). The constant Li is the maximum value to a physical capacity to each component (OXC or subnetwork) in the network. The wavelengths are enumerated from 1 to the limit Li that will be assigned as necessary. The component capacity is measured in wavelength numbers such the set $W = \{4, 16, 20, 40, Li = 80\}$.

The set D represents the demands under the format (o, d) where $o \in N$ and $d \in N$. Let T be the set of time periods and $Ts_{o,d}$ the set of time periods when the demand (o, d) exists. The variables xt_p and mt_p compute respectively changes in allocated path and changes in assigned wavelengths along the time periods.

To represent the physical network structure, it was defined a set of subnetworks that are mesh-type and must be chosen to compose the network in terms of nodes and links costs. Each mesh of this set is created from the spanning tree of the network graph, adding edges that are in the original graph and not in the spanning tree. Each added edge creates a cycle in the graph. Each cycle represents a subnetwork in set S. These cycles can have new edges from the original graph to obtain mesh-type subnetworks. This kind of the graph creation is to reach k-connected graphs, that are graphs such it is possible defining k disjoint paths. This permits that paths are cycles composes of two disjoint paths to reserve a path backup. Nothing prevents other type of graphs to be used with our model.

The links that compose a subnetwork $s \in S$ generate the set Es_s. Let C be the set of available OXCs. OXCs are located between subnetworks to satisfy the existing demands; they join the subnetworks by means of some nodes in common permitting the communication as shown in Fig. 2.

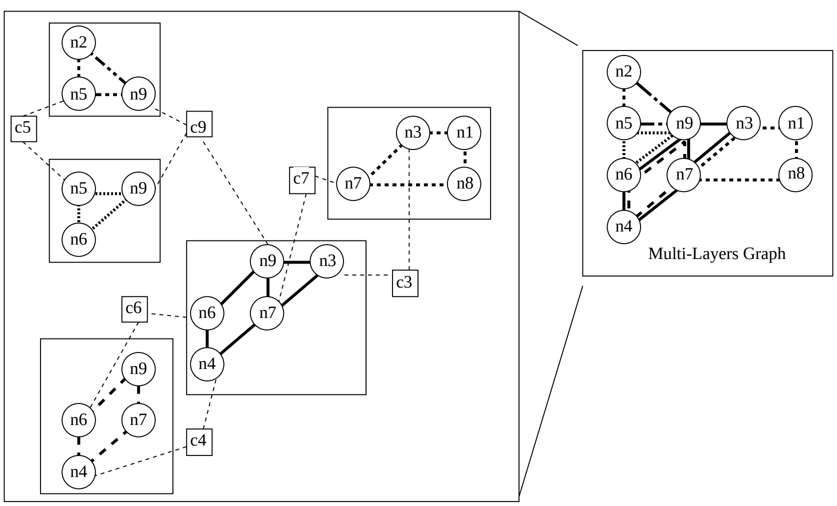

Figure 2: Subnetworks definition.

Let P be the set of routes that link the pairs $(o, d) \in D$. These routes are disjoint (fault tolerance) and represent the shortest paths found between the pairs (o, d) using Dijkstra algorithm. These paths are calculated on the complete graph taking into account all potential subnetworks and OXCs. Several paths can satisfy the same demand pair $(o, d) \in D$ and compose the set $J_{o,d}$. The routes that involve two or more subnetworks must use intermediate OXCs $c \in C$. All routes using a OXC c compose the set L_c. Let $Pes_{i,j,s}$ denote the set of paths going through the link (i, j) from the subnetwork s. The set H represents the set of ordered pair of paths (p, q) (with id$p$>id$q$) sharing a link.

A constant B exists to penalize the unsatisfied demand, the modifications of the paths allocation and the frequency assignment. The parameter $r_{o,d,t}$ is the number of wavelengths used by the pair $(o,d) \in D$ in a time period $t \in T$. $f_{c,w}$ is the cost of using an OXC $c \in C$ of size $w \in W$ and $a_{s,w}$ is the use of a subnetwork $s \in S$ of size $w \in W$. The variable $x_{p,t}$ stands for the number of wavelengths that must be assigned to the path $p \in P$. Let the variables ym_s and zm_c be the maximum value of the selected capacity along of time to each network component respectively subnetworks and OXCs. Let the integer variables $l_{p,t}$ and $h_{p,t}$ denote respectively the smallest and largest wavelength assigned to path p. Let the continuous variable $m_{p,t}$ be the midpoint of the interval $[l_{p,t}$,$h_{p,t}]$. Let the binary variable $b_{p,q,t}$ be 1 if $l_{q,t}$>$h_{p,t}$ and 0 if $l_{p,t}$>$h_{q,t}$. The pairs (p,q) with $b_{p,q,t}$=0 must be in the set R0 and (p,q) with $b_{p,q,t}$=1 must be in R1, the creation of the suited pairs (p,q) to these sets is showed in figure Fig. 3. Let the continuous variable $dp_{p,q,t} = m_{p,t}$-$m_{q,t}$ ($dm_{p,q,t} = m_{q,t}$-$m_{p,t}$) if $m_{p,t}$-$m_{q,t}$>=0 ($m_{p,t}$-$m_{q,t}$<0), and 0 otherwise.

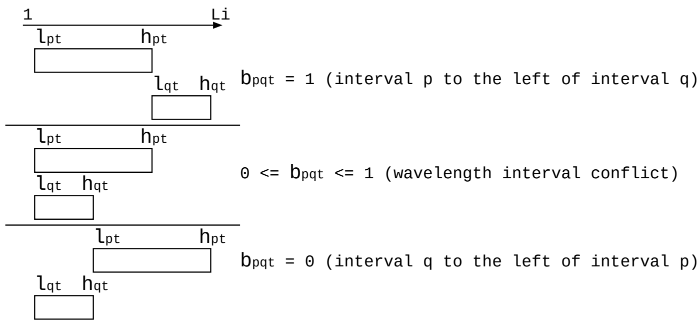

Figure 3: Wavelength interval assignment for paths with shared links and the variable $b_{p,q,t}$.

The unsatisfied demands appear in $u_{o,d,t}$. The variables $y_{s,w,t}$ and $z_{c,w,t}$ represent, respectively, the use of a subnetwork s or an OXC c with size w. $lf_{i,j,s,t}$ and $cf_{c,t}$ represent, respectively, the flow in number of wavelengths on the link (i,j) of a subnetwork s and on an OXC c.

The variable ut_t indicates the time when a demand is unsatisfied. It can be caused by the structural limitation or by impossibility to avoid reconfiguration. It is needed to put a minor weight to $u_{o,d,t}$ to get the variable ut_t.

The frequency $fr \in F$ is assigned to a path $p \in P$ in a time $t \in T$ if the variable $pfq_{p,fr,t}$ is 1. The variables $laux_{p,fr,t}$ and $haux_{p,fr,t}$ represent, respectively, the interval above $l_{p,t}$ and below $h_{p,t}$. These variables allow to have $pfq_{p,fr,t} = laux_{p,fr,t}\ AND\ haux_{p,fr,t}$ that correspond to the interval de wavelengths assigned to the path.

To compute the capacity of an OXC $c \in C$ it is needed to know all different frequencies that pass through c in each time period, that is $cfq_{c,fr,t}$. The OXC capacity can be determined by all different frequencies that pass through it along of time, the variable $cfqto_{c,fr}$ is 1 when in any time period the frequency f pass through the OXC c.

The modified model is shown below. The sets and variables were defined in [7] and we reuse them in our new model to be able to test in the same network instances.

$$\min \sum_{s \in S} ym_s + \sum_{c \in C} zm_c + B. \sum_{(o,d) \in D} \sum_{t \in T} u_{o,d,t} +$$
$$\sum_{t \in T} ut_t + B/2. \sum_{p \in P} xt_p + B/2. \sum_{p \in P} mt_p + \sum_{p \in P, fr \in F, t \in T} cfqto_{p,fr}t \quad (1)$$

$$\sum_{p \in J_{o,d}} x_{p,t} + u_{o,d,t} = r_{o,d,t},\ \forall (o,d) \in D, t \in Ts_{o,d} \quad (2)$$
$$\sum_{p \in Pes_{s,i,j}} x_{p,t} = lf_{i,j,s,t},\ \forall t \in T, s \in S, (i,j) \in Es_s \quad (3)$$
$$\sum_{f \in F} cfq_{p,fr,t} = cf_{c,t},\ \forall t \in T, fr \in F, c \in C \quad (4)$$
$$\sum_{w \in W} w.y_{s,w,t} \geqslant lf_{i,j,s,t},\ \forall s \in S, (i,j) \in Es_s, t \in T \quad (5)$$

$$\sum_{w \in W} w.z_{c,w,t} \geqslant cf_{c,t},\ \forall c \in C, t \in T \quad (6)$$

$$\sum_{w \in W} y_{s,w,t} \leqslant 1,\ \forall s \in S, t \in T \quad (7)$$

$$\sum_{w \in W} z_{c,w,t} \leqslant 1,\ \forall c \in C, t \in T \quad (8)$$

$$ym_s \geqslant \sum_{w \in W} a_{s,w}.y_{s,w,t},\ \forall s \in S, t \in T \quad (9)$$

$$zm_c \geqslant \sum_{w \in W} f_{c,w}.z_{s,w,t},\ \forall c \in C, t \in T \quad (10)$$

$$h_{p,t} = l_{p,t} + x_{p,t} - 1,\ \forall p \in P, t \in T \quad (11)$$

$$m_{p,t} = \frac{(l_{p,t} + h_{p,t})}{2},\ \forall p \in P, t \in T \quad (12)$$

$$dp_{p,q,t} + dm_{p,q,t} \geqslant \frac{(x_{p,t} + x_{q,t})}{2},\ \forall (p,q) \in H, t \in T \quad (13)$$

$$m_{p,t} - m_{q,t} = dp_{p,q,t} - dm_{p,q,t},\ \forall (p,q) \in H, t \in T \quad (14)$$

$$dp_{p,q,t} \leqslant Li.b_{p,q,t},\ \forall (p,q) \in H, t \in T \quad (15)$$

$$dm_{p,q,t} \leqslant Li.(1 - b_{p,q,t}),\ \forall (p,q) \in H, t \in T \quad (16)$$

$$b_{p,q,t} = 0,\ \forall (p,q) \in R0, t \in T \quad (17)$$

$$b_{p,q,t} = 1,\ \forall (p,q) \in R1, t \in T \quad (18)$$

$$b_{p,q,t} = binb_{p,q,t},\ \forall (p,q) \in H \cap \{R0 \cup R1\}, t \in T \quad (19)$$

$$xt_p \geqslant x_{p,t-1} - x_{p,t} \textit{ and } (x_{p,t} - x_{p,t-1}), \quad (20)$$
$$\forall (o,d) \in D, p \in J_{o,d}, t \in Ts_{o,d}$$
$$-1^{st} t \in \textit{ordered } Ts_{o,d}$$

$$mt_p \geqslant m_{p,t-1} - m_{p,t} \textit{ and } (m_{p,t} - m_{p,t-1}), \quad (21)$$
$$\forall (o,d) \in D, p \in J_{o,d}, t \in Ts_{o,d}$$
$$-1^{st} t \in \textit{ordered } Ts_{o,d}$$

$$u_{o,d,t} \leqslant ut_t.r_{o,d,t},\ \forall (o,d) \in D, t \in Ts_{o,d} \quad (22)$$

$$ut_t \geqslant ut_{t-1},\ \forall t \in T - 1 \quad (23)$$

$$fr - l_{p,t} + 1 \leqslant Li.laux_{p,fr,t},\ \forall p \in P, fr \in F, t \in T \quad (24)$$

$$h_{p,t} - fr + 1 \leqslant Li.haux_{p,fr,t},\ \forall p \in P, fr \in F, t \in T \quad (25)$$

$$laux_{p,fr,t} + haux_{p,fr,t} - 1 \leqslant pfq_{p,fr,t},\ \forall p \in P, fr \in F, t \in T \quad (26)$$

$$\sum_{p \in L_c} pfq_{p,fr,t} \leqslant Li.cfq_{c,fr,t},\ \forall c \in C, fr \in F, t \in T \quad (27)$$

$$\sum_{t \in T} cfq_{c,fr,t} \leqslant Li.cfqto_{c,fr},\ \forall c \in C, fr \in F \quad (28)$$

The objective function minimizes the network cost along of time. It selects OXCs and subnetworks with enough power to attend all demands. The demand not attended and modifications in the allocation of paths and wavelengths along of time are penalized.

- Eq.(2): For each pair (o,d), the demand must be attended assigning wavelengths to the paths $p \in J_{o,d}$ and considering the unsatisfied $u_{o,d,t}$ demand for the pair (o,d).
- Eq.(3): The total flow in the link (i,j) of a subnetwork s represents the sum of the wavelengths in each path using the same link and subnetwork.
- Eq.(4): The wavelength number in an OXC in the network is equal to the sum of the frequencies in all paths that use this OXC.
- Eq.(5): The adequate capacity of a subnetwork s must be greater or equal than the wavelength number in any link in this subnetwork.

- Eq.(6): The adequate capacity of an OXC c must be greater or equal than the number of wavelengths over it.
- Eq.(7-8): Each OXC and subnetwork must have a single size $w \in W$.
- Eq.(9-10): Selects the maximum allocated capacity to each network component (OXC or subnetwork) along of time.
- Eq.(11): Assigns wavelengths intervals to the paths used to satisfy demand.
- Eq.(12): It finds out the interval midpoints.
- Eq.(13): It determines the existing distance between intervals of pairs of paths with conflict.
- Eq.(14): It forces the overlapping intervals separation.
- Eq.(15-16): It ensures distinct wavelength assignment for the pairs of path with overlapping intervals.
- Eq.(17-18): The set R0 is formed from pairs of paths (p, q) such that path p is blocked to the left of the path q, and R1 is the contrary.
- Eq.(19): It forces the paths to be positioned into the sets R0 or R1.
- Eq.(20-21): The changes in allocated paths and in defined wavelength intervals are avoided along of time.
- Eq.(22-23): It shows the moment when doing a reconfiguration is necessary, trying to attend the unsatisfied demand.
- Eq.(24-26): It captures all frequencies into the assigned interval of wavelengths to each path based on defined interval between the variables $l_{p,t}$ and $h_{p,t}$.
- Eq.(27): It saves all different frequencies that pass through an OXC in each time period.
- Eq.(28): It saves all different frequencies that pass through an OXC in all time periods.

2.1 Example

In this subsection we give an example with changes in the network. We penalize all changes of flow or wavelength assign.

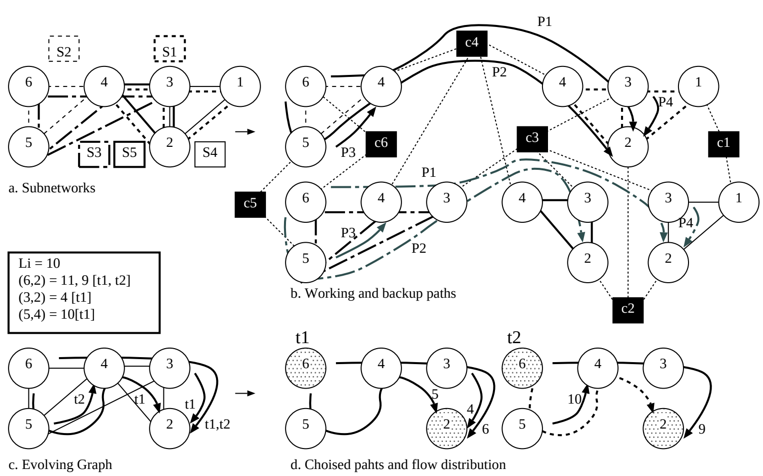

Figure 4: Penalized changes in the network.

In the item *a.* of the Fig. 4, you can see all subnetworks of a network instance. The item *b.* shows the working and backup (in gray color) paths to each demand. A simple evolving graph is showed in *c.* and the flow distribution to each time period is in *d.*, this item shows the changes along of the time.

Table 1: Results

Instance	Our Model	Attended Demand	Time
A01	*27421	100%	7
J03	*92306	87,2%	5
ATT03	**13505	98,9%	3
EUR05	***	0%	3

3 Experiments

The instances are 3 randomly generated problems of various sizes. The problem characteristics are showed below. The problems named ATT01 and EUR05 represent a European network described in [2], and they have topologies given in Fig. 5 and Fig. 6.

Instance	Nodes	Links	Demands	Subnetworks	OXCs	Paths
A01	6	9	9	5	5	15
J03-7	9	13	15	5	6	17
ATT01-5	11	23	16	6	7	22
EURO5	18	35	18	6	7	20

The instances also have different paths and demand requests. Our model was coded using the AMPL modeling language and CPLEX Linear Optimizer 7.0.0 on the SunBlade UltraSPARC 500MHz, 1GB RAM. Table 1[1] shows the results obtained by the proposed model using CPLEX.

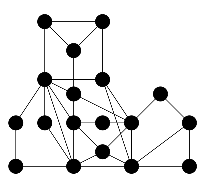

Figure 5: EUR05 graph

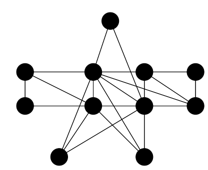

Figure 6: ATT01 graph

The Fig. 7,Fig. 8 and Fig. 9, represent the network growth in relation of time. They show the reconfiguration point ut_t.

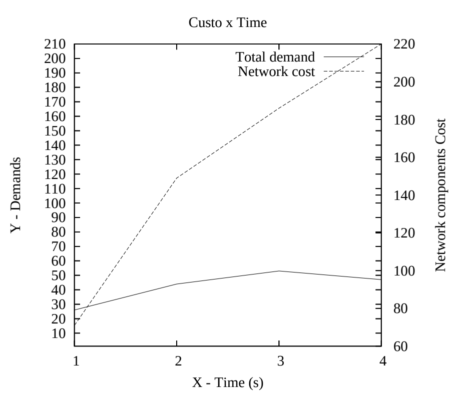

Figure 7: A01 Instance.

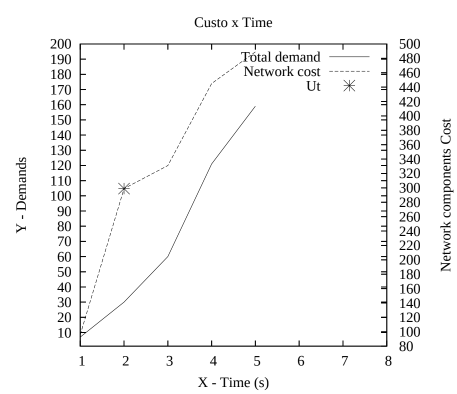

Figure 8: J03 Instance.

The ATT03 has a different comportment because the network cost is reduced while demand increases. It is justified by the flow allocation in a existent structure therefore no additional capacity was required.

[1]Meaning of symbols: * = time limit (30Min); ** = time limit (1h);*** = Memory Limit

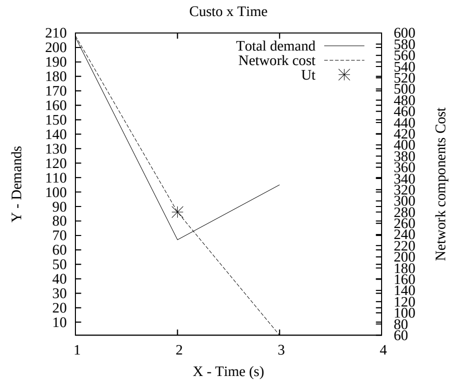

Figure 9: ATT03 Instance.

4 Heuristic

This heuristic not considers the time periods yet. We propose a two-phases heuristic for RWA. In the first phase, the flow is distributed over the paths in the network taking into account the path cost. The path cost is a sum of the components cost, subnetworks and OXCs, along of the path.

The flow is distributed until the path reaches the maximum capacity before to jump to the next level of capacity in W to its most critical component.

The path capacity is represented by free space in this path.

If this space goes to zero the algorithm chooses another path associated with the current demand. If all paths are full then the cheapest one is chosen.

It increases the capacity to the next level in W of some components in this path.

The demands are chosen considering their number of requests and their number of dedicated paths. They are sorted in a decrease order of the number of requests for each dedicated path. We consider a fairness method for the moment.

After completing flow distribution, the heuristic try to reduce the total cost. A component is chosen if it presents little flow above its current capacity w. For this reason it is easy to reduce its cost by moving the flow over and it will take a new capacity $w-1$ more cheap.

The algorithm manipulates the flow of the chosen components, trying to reduce the cost of this component. It saves the configuration if it gets a total network cost reduction.

The network cost is the sum of all components cost. When it reaches a value lower than the values given by designer for the maximum network cost and the number of unattended demands or maximum number of iterations, the algorithm goes to the second phase. In this phase, the wavelengths are assigned for each demand request by solving a coloring problem. We use a variant of the color degree heuristic [1] in this phase.

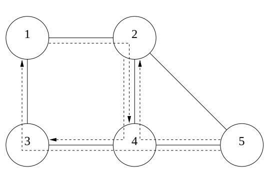

Figure 10: Network graph with demand path

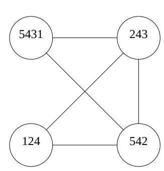

Figure 11: Graph representing the path conflicts

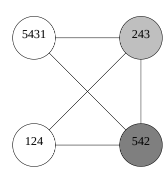

Figure 12: Color graph and associate the wavelength to each path

We illustrate an instance of coloring problem in Figs 10-12. A five nodes network is represented in Fig 10. In Fig 11 we show a graph where the nodes represent the requests over the defined paths for the network topology. These paths were selected in the first phase and they represent the set of a minimum cost to attend the given demand. There are the demands $5 \to 1$, $5 \to 2$, $2 \to 3$ and $1 \to 4$. Each demand has one dedicated path in this example and we consider only one request to facilitate the comprehension. All requests in the same path will have necessarily an edge in graph on Fig. 11. In Fig. 12 we show the graph coloring. The colored nodes define the used paths. The colors define the selected wavelengths to each demand request.

We denote by I the maximum number of iterations, L the number of links, P the number of paths and R the number of requests. The worst-case complexity order to this algorithm is $O\left(I\left(LP^2+R^2\right)\right)$.

5 Conclusion and Perspectives

The computation time of model is very high, even small instances. We are going to create a heuristic. A version without computing the real capacity to an OXC is improved to faster and can be used to a MPLS context where the paths are LSPs and the capacity is given only in function to the LSPs quantity through the node. In [4] this capacity can be seen as delay to network. We pretend proposing a new Oriented to Objects (OO) definition to represent EG, and exploring and implementing algorithms and heuristics with the new arc-path-based EG definition. We will change the model to compute the maximum flow and another classics algorithms to compare with the algorithms/heuristics over the arc-path-based EG. An instance generator using the SLD Diverse Routing (SLD DR) algorithm proposed in [8] or similar will be implemented. It defines for each SLD a pair of arc-disjoint to be used as a working and protection paths, such that the number of channels (both working and spare) required in the network to instantiate the demanded lightpaths is minimized.

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