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A Multi-Objective Integer Linear Programming Model for Path Optimization in Wavelength Division Multiplexing Networks

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A Thesis presented for the degree of
Master of Technology

Under the Guidance of

Dr. Ashok Kumar Turuk
Department of Computer Science and Engineering
National Institute of Technology
Rourkela

Dedicated to

My parents, teachers and friends

Computer Science and Engineering
National Institute of Technology, Rourkela
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Dr. Ashok Kumar Turuk
Professor

May 20, 2015

Certificate

This is to certify that the work in the thesis entitled *A Multi-Objective Integer Linear Programming Model for Path Optimization in Wavelength Division Multiplexing Networks* by *Subash Chandra Roul*, bearing roll number 710cs1031, is a record of an original research work carried out by him under my supervision and guidance in partial fulfillment of the requirements for the award of the degree of *Master of Technology* in *Computer Science and Engineering.* The matter embodied in this thesis is original and has not been submitted for the award of any other degree

Place:Rourkela
Date:May 20,2015

Ashok Kumar Turuk
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Subash Chandra Roul

Submitted for the degree of Master of Technology

Abstract

Optical networks with Wavelength Division Multiplexing (WDM) has been the solution for the need of increasing bandwidth demand. In this kind of networks the fiber link is divided into a number of channels. In each channel a light wave of a particular wavelength can be transmitted. So, in a single fiber more than one light waves of different wavelengths can be transmitted simultaneously with the use of multiplexers and demultiplexers.

In WDM optical networks there are two problems. First one is providing a path for a source to destination pair, and second one providing a wavelength to the path selected. The former is called routing problem and the latter is called wavelength assignment problem. Combining both the problems, it is called Routing and Wavelength Assignment (RWA) Problem. The RWA problem belongs to NP class, i.e. it can not be solved in polynomial time. So, different heuristic approaches are used to find a (sub)optimal solution for the problem.

An ILP model may be used to solve the RWA problem considering various parameters of the optical network like congestion, total route length, number of amplifiers used etc. In this project an ILP is designed for the RWA problem and is solved using genetic algorithm to find an optimal solution. The simulation is carried out on Advanced Research Project Agency NETwork (ARPANET) and National Science Foundation Network(NSFNET).

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Most importantly, I want to express my profound feeling of gratitude towards my supervisor Dr. A. K. Turuk, who has been the managing drive behind this work. I would like to thank him for introducing me to the topic of optical networks. I would also like to thank Mr. Ravi Sankar Barpanda for his constant help and valuable suggestions.

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Chapter 1

Introduction

Today, in a large scale optical fibers are used for information transmission. Optical fibers provide many advantages including low maintenance cost, low bit error rates, low signal attenuation, low signal distortion, low power requirement, Secured from tapping compared to copper cable, immune to interference and crosstalk etc. Also optical networks are faster than the traditional networks. The transmission is based on total internal reflection. There are two kinds of optical fibers: multi-mode fiber and single-mode fiber. In multi-mode fiber each light wave has a different mode because they bounce at different angles. It also causes interference among the signals. Single-mode fibers have very narrow core, i.e., light can travel in straight line.

The bandwidth of the optical fiber is divided into a number of channels in which a channel corresponds to a single wavelength. In each channel a signal belonging to the wavelength of the channel can be transmitted.

1.1 Wavelength Division Multiplexing

Wavelength division multiplexing is a technique in which a number of optical signals of different wavelengths are mixed together and transmitted simultaneously on the same fiber link. Each fiber is divided into many channels of different wavelengths which allows the signals to travel in a single optical fiber with different wavelengths.

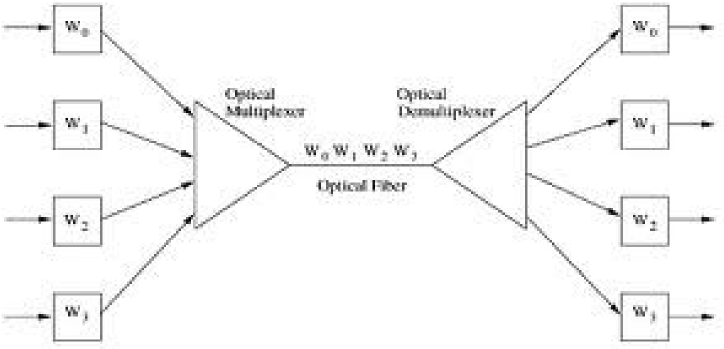

Figure 1.1: **Wavelength Division Multiplexing**

In a single optical fiber a number of wavelengths can be transmitted which are managed by optical technology, i.e. different wavelengths are combined to be transmitted in the same channel and at the other end they are separated which is called the optical transmission system.

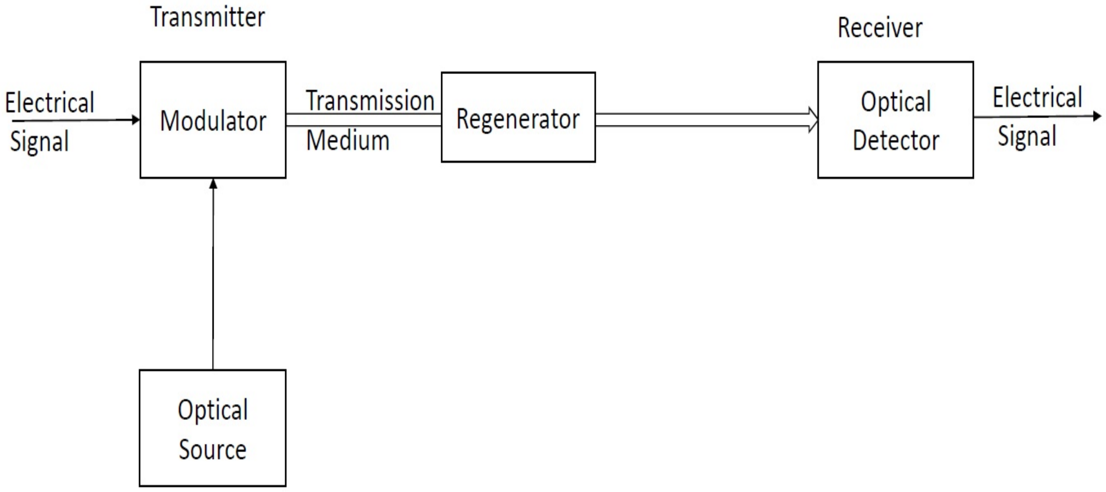

Figure 1.2: **Optical Transmission System**

Wavelength Division Multiplexing networks use lightpath for the transmission of information. A lightpath is a single hop logical connection that is used for transmission of information signal throughout the network. It does not need processing or buffering at intermediate nodes. A lightpath has a single wavelength throughout all of its physical links. Two lightpaths can share the same link if and only if they have different wavelengths.

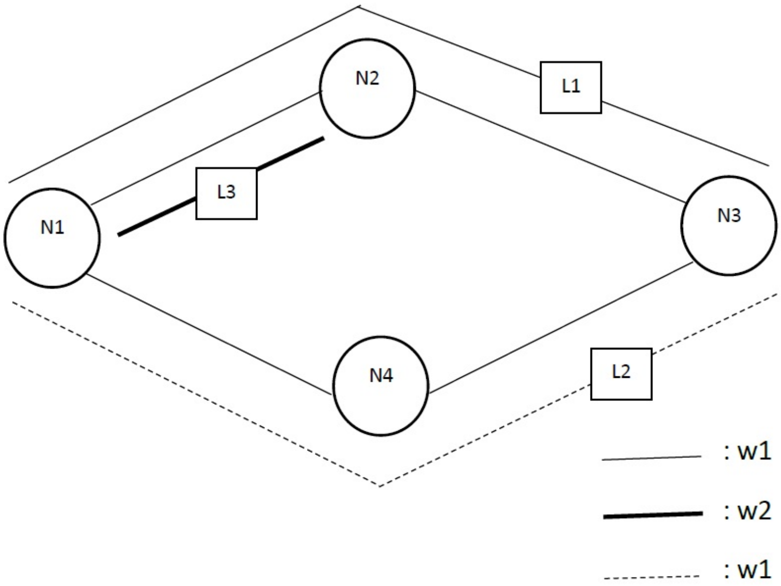

Figure 1.3: **Example of WDM networking**

1.2 WDM Optical Networking Evolution

- **WDM Point-to-Point Link** : Due to increasing demands on bandwidth, several telecommunication industries use WDM point-to-point link..

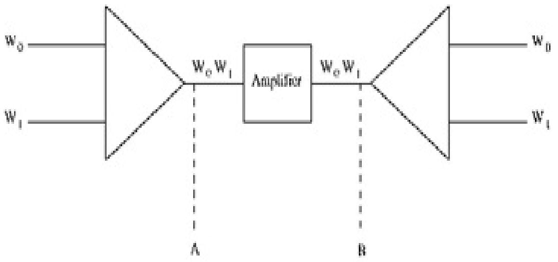

Figure 1.4: **Waelength Division Multiplexing Point-to-Point Link**

- **Wavelength Add/Drop Multiplexer** : It is used when there is a necessity to drop some signals at intermediate nodes. It is operated by two switches (S0 and S1 in the figure). If S1 is in set state, then the signal on that particular wavelength passes and if the switch S0 is in set state, then the signal on that corresponding wavelength is dropped. Another signal might be added on to the dropped wavelength.

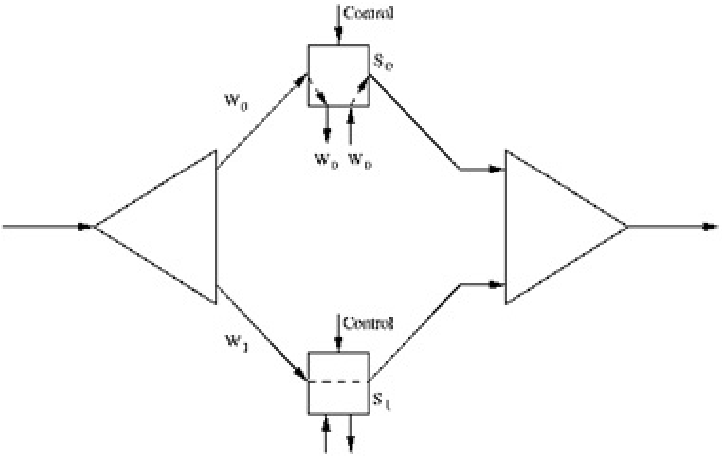

Figure 1.5: **Wavelength Add/Drop Multiplexer**

- **Wavelength Cross Connect** : A wavelength cross-connect (WXC) is capable of routing an incoming signal at an input port to any other output port.

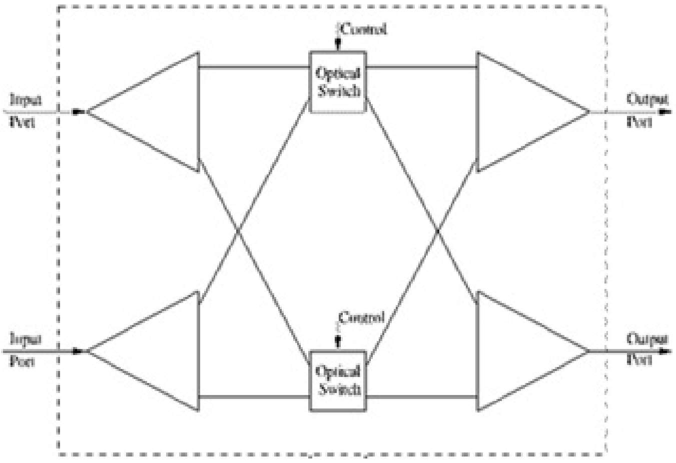

Figure 1.6: **Wavelength Cross Connect**

1.3 Routing and Wavelength Assignment Problem

Given a network and a set of soure to destination connection requests, the problem of assigning a route and wavelengths to these requests using minimum possible wavelengths is known as the Routing and Wavelength Assignment (RWA) problem.

RWA problem is a NP-complete problem. Its complexity arises from two facts:

- **Wavelength Continuity Constraint** : A lightpath has the same wavelength for all the links it is using for information transmission.
- **Wavelength Distinct Constraint** : In a single link, all the lightpaths have different wavelengths.

Routing and Wavelength Assignment problem has the following variations depending upon the traffic pattern:

- **Static Lightpath Establishment** : In static case, the all the connection requests are known beforehand and the objective is setting lightpaths for these requests, while minimizing the number of wavelengths used.
- **Dynamic Lightpath Establishment** : A lightpath is setup only when a lightpath request is received. It is removed after some time when it is not needed. The objective is to minimize the total number of blocked connections.
- **Incremental Lightpath Establishment** : A lightpath is setup only when a lightpath request is received. Unlike dynamic case the lightpath remains in the network. The objective is to minimize the total number of blocked connections.

Different routing methods are:

- **Fixed Routing** : In this routing strategy the minimum length route is provided for routing.
- **Alternate Routing** : In this routing strategy more than one routes are considerded for routing.
- **Adaptive Routing** : In this routing strategy all the paths are scanned for optimal routing. It is computationally complex but yields the best performance.

Various methods for wavelength assignment are: most used, least used, random-order, least-loaded etc. In most used method all the available wavelengths are scanned in decreasing order. It makes sure that more number of wavelength continuous paths are available for the lightpath requests. In least-used method all the available wavelengths are searched in an increasing order. It makes sure that the available wavelengths are distributed through all the lightpaths. In random-order method a wavelength is found randomly. In least-loaded method wavelength which is used by least number of lightpaths is selected.

1.4 Motivation

Most of the solutions to RWA problem attempt to optimize a single objective function. For example minimizing number of amplifiers used, network cost, congestion etc. The major challenge faced by the network designers is to identify the parameters in order to formulate a multi-objective ILP for the RWA problem. The formulated ILP should be able to establish a loop free lightpath that has shorter set-up time, lower congestion among the individual connections and lesser crosstalk.

The decision variables of an ILP increase in an exponential rate when number of nodes increase, or/and number of connection requests increase. This kind of problem results in higher running time. For a large network, it might happen that the route provided for the lightpath is too long, which is not practical for some cases. So, the decision variables and the path length are needed to be controlled by maintaining a trade-off between congestion and route length.

1.5 Objective

Considering the problems in formulating and solving multi-objective ILPs for RWA problem, I have identified the following objectives:

- To propose an ILP for path optimization of RWA problem in WDM networks.
- To solve the proposed ILP using a heuristic approach for lightpath establishment.

1.6 Outline

Chapter1: Introduction to WDM optical networks, RWA problem

Chapter2: In this chapter it it is proved that RWA problem belongs to NP class

Chapter3: A survey of RWA problem and their approaches

Chapter4: Formulation of multi-objective ILP considering the parameters congestion and route length.

Chapter5: Simulation of the formulated ILP using GA

Chapter6: Conclusion

Chapter 2

RWA Problem belongs to NP class

NP problems are the class of problems for which there are no deterministic polynomial time algorithms. NP problems are classified into:

- **NP-Hard**: A problem is NP-hard if an algorithm for solving it can be translated into one for solving any NP problem, i.e., at least as hard as any NP problem.
- **NP-Complete**: A problem L is NP-complete if $L \in NP$ and for every $L^{'}$ $\in NP$; $L^{'} \leq L$.

Following methods are adopted for solving any NP problem:

- Dynamic programming
- Backtracking
- Approximation algorithm
- Randomized algorithm
- Heuristics like greedy algorithm, simulated annealing and genetic algorithm

2.1 Interpretation of RWA Problem as Graph Coloring problem

According to wavelength distinct constraint more than lightpaths can not have a same wavelength if they share a common physical link. This problem can be interpreted as graph coloring problem. For an example, we have taken a graph with five vertices and five edges and there are five lightpath requests in the graph.

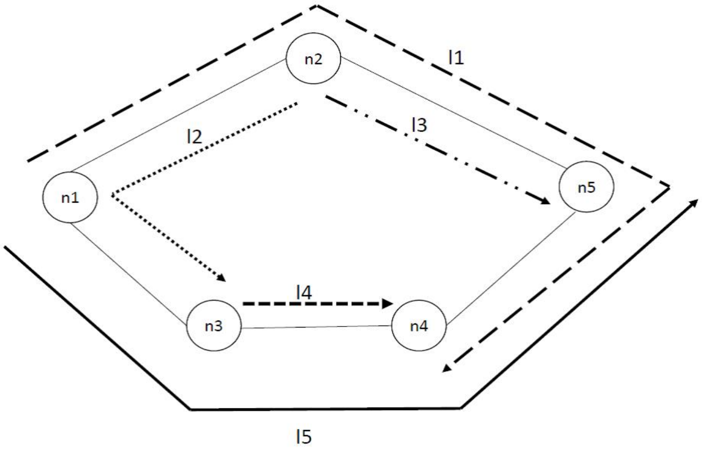

Figure 2.1: **A network with five lightpath requests**

In the figure l1, l2, l3, l4 and l5 are lightpaths and n1, n2, n3, n4 and n5 are network nodes. To interpret the problem as a graph coloring problem all the lightpaths are considered as nodes there is an edge between them if they share the sane link.E.g. l1 and l2 have a common physical link, so they have an edge and same for (l1, l3), (l1, l5), (l2, l5), (l4, l5).

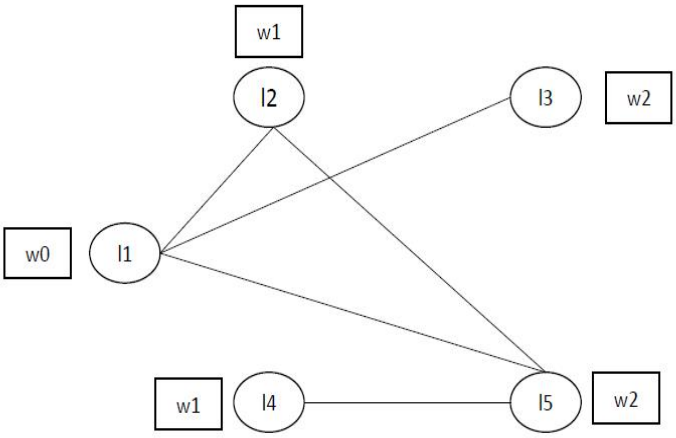

Figure 2.2: **Auxiliary graph**

Size of maximum clique is the minimum number of wavelengths required to setup all the lightpaths. To find the maximum clique we need to check all the subsets of the nodes, i.e., the powerset of the graph. So cardinality of the powerset of the graph is 2^n. And, to check if a subset is a clique or not time required is $O(n^2)$. So, the complexity is $O(2^n n^2)$ which belongs to a NP class.

2.2 Summary

In this chapter, by interpreting the RWA problem as a graph coloring problem, it is found that the minimum number of wavelengths required for the lightpaths is same as the maximum clique of the auxiliary graph. The complexity of finding the maximum clique increases exponentially with the number of lightpath requests. So it is made clear that RWA problem can not have a optimal solution in polynomial time, i.e. RWA problem belongs to NP class.

Chapter 3

Literature Survey

3.1 Related Work

Cardoso et. al. [2] proposed a simple solution to the RWA problem by using a Generic Objective Function. Considering it is known that how many wavelengths are available in each link of the network, they calculated labels for each link with their available wavelengths. The performance of Generic Objective Function is close to that of Weighted-Least-Congested-Route (WLCR) but gives better performance than Dijkstras algorithm i.e. GOF has lower blocking probability compared to Dijkstras algorithm. The proposed GOF algorithm solves both routing and wavelength assignment problem simultaneously whereas WLCR only solves the routing step followed by wavelength assignment problem leading it to be more complex.

Gomes et. al. [3] proposed a bicriteria model for multi-fiber networks. They have used two criterions for the problem. The first one is the hop count of the lightpath and the second one is the bandwidth usage of the network. They have used k-shortest path and Chebyshev distance for finding the topological path followed a heuristic approach to assign wavelengths. They have shown that the multi-objective approach has lower blocking probability compared to the single criterion approach.

Banerjee et. al. [6] used genetic algorithm to solve the RWA problem. They have initialized the population using k-shortest path algorithm. The main motive is to minimize the congestion and total average delay of the network. In case of the single objective function, the performance is same as compared to first-fit algorithm. In case of the multi-objective optimization, the solution obtained is of good diversity.

Simonis [12] has proposed a hybrid model for static lightpath establishment for a directed network. The two objective functions includes minimizing the total number of wavelengths used in the network and minimizing the maximum number of wavelengths used in any of the links. A decomposition method is adopted for the RWA problem. It is shown that decomposing the RWA problem into MIP and FD phases can give better performance for large dataset.

Banerjee and Mukherjee [10] proposed a practical approach for RWA problem in large wavelength routed optical networks. The simulation is done for both static (where all the lightpath requests are available beforehand) and dynamic (where lightpath requests arrive one by one) cases. For solving the static case, the RWA problem was partitioned into smaller sub-problems and an approximation technique is used. For the dynamic case simple heuristics is used.

Pakorn et. al. [13] proposed an ILP which has two objective functions. The first one is to maximize the number of accepted requests and the second one is to minimize the total number of required wavelengths. The result obtained from the heuristic approach showed that the lightpath establishment is maximum compared to first-fit and fixed alternative routing.

Many researchers try to increase the number of accepted lightpath requests, thus decreasing the blocking probability. Paramjeet et. al. [14] used different methods to decrase the blocking probability. First, connecions are established for all lightpath requests using minimum route length on first wavelength(according to the indexing). In other method lightpath requests are established using minimum route length considering first to last wavelengths. If that path can not be established, an alternate route is considered. in another method first wavelength is tried using shortest route. If unsuccesful, same wavelength is tried for alternate route. In another strategy, lightpath is established using shortest path on first wavelength. If lightpath can not be established, on the same wavelength alternate route is considered. This strategy gives the maximum performance.

3.2 Summary

In this chapter, we briefly described the previous works related to routing and wavelength assignment problem to allocate routes and assign wavelengths to the lightpath requests considering different parameters. This chapter providea a background of the work.

Chapter 4

Multi-Objective ILP Formulation for RWA Problem

The RWA problem can be represented in as ILP problem. Solving the ILP give the (sub)optimal solution. Considering the network is static and wavelength continuity constraint is maintained, the ILP is formulated.

4.1 Notations

The Notations used for formulating the ILP are as follows:

V : Set of nodes in the network

E : Set of links

N : $|V|$

M : $|E|$

W : Total number of wavelengths used in the network

Dsd: Distance between s and d

L_{sd}: Positive integer representing the number of lightpaths to be established from source node s to destination node d

$$\mathrm{b}_{\mathrm{lw}}^{\mathrm{sd}} : \begin{cases} 1, & \text{if } there\, exists\, a\, lightpath\, from\, node\, s\, to\, node\, d\, that\, uses\, wavelength\, w\, on\, link\, l \\ 0, & \text{otherwise} \end{cases}$$

4.2 Multi-Objective ILP Formulation

The Objective functions are as follows:

To minimize the number of wavelengths used in the network:

Minimize W

To minimize the total route length:

Minimize $\sum_{\mathrm{sd}} \sum_{\mathrm{l}} \sum_{\mathrm{w}} b_{\mathrm{lw}}^{\mathrm{sd}} \times D_{\mathrm{sd}}$

Constraints :

Flow reservation constraint and wavelength continuity constraint:

$$\sum_{\text{outgoing links from n}} b_{\mathrm{lw}}^{\mathrm{sd}} - \sum_{\text{incoming links from n}} b_{\mathrm{lw}}^{\mathrm{sd}} = \begin{cases} -L_{\mathrm{sd}}, & \text{if}\, n = d \\ L_{\mathrm{sd}}, & \text{if}\, n = s \\ 0, & \text{if } n \neq s\,, n \neq d \end{cases}$$

Wavelength distinct constraint:

$\sum_{\mathrm{sd}} b_{\mathrm{lw}}^{\mathrm{sd}} \leq 1$

4.3 Summary

In this chapter we have formulated an ILP for RWA problem considering the parameters such maximum number of wavelengths, route length, number of accepted connection requests for the objective functions. In the next chapter the formulated ILP is solved using GA to find a near optimal solution.

Chapter 5

Simulation and Results

In this chapter, the proposed multi-objective ILP is solved using genetic algorithm. The genetic algorithm is applied on ARPANET.

5.1 Steps for genetic algorithm for RWA Problem

- **Chromosome Structure** : Chromosome structure : Each chromosome is in the form of a matrix in which each row represents a lightpath.

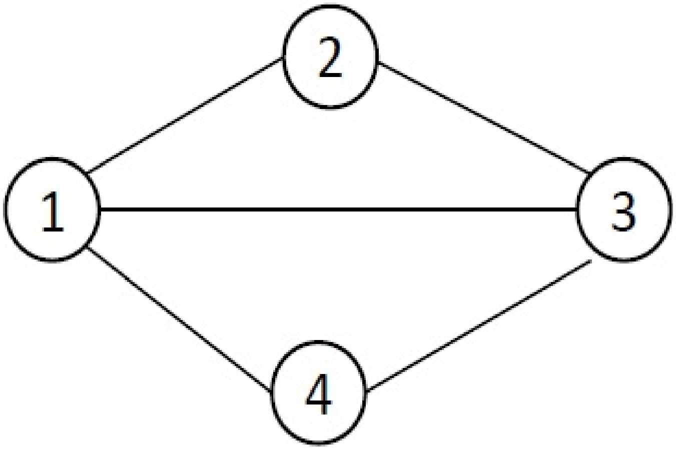

Figure 5.1: **Example network (with cost of each link 1)to show chromosome structure, crossover and mutation**

The chomosome in matrix format is: $\begin{bmatrix} 1\ 3\ 0\ 0 \\ 1\ 4\ 3\ 2 \end{bmatrix}$

- **Initial Population** : For the first chromosome shortest path for all the lightpaths is considered. For next chromosome shortest path of lightpath is considered after removing one link from a single lightpath. This process is repeated for the number of population size taken.

- **Fitness Function** : Fitness function in the GA algorithm is to be used for maximization and based on the fitness function chromosomes for the next generation are decided.
  overlaps : Maximum number of overlaps in the most congested link
  nlightpaths: Number of lightpath requests
  totalcost : Total cost of all the routed lightpaths
  maxlinkcost : Maximum link cost of the used network
  maxcost : Maximum routing cost for a single lightpath
  $y1 = 1 - \frac{overlaps}{nlightpaths}$
  $y2 = 1 - \frac{totalcost}{(N-1) \times nlightpaths \times maxlinkcost}$
  $y3 = 1 - 0.9 \times \frac{overlaps}{nlightpaths} - 0.1 \times \frac{totalcost}{(N-1) \times nlightpaths \times maxlinkcost}$

- **Crossover** : In this step chromosomes are selected according to the crossover rate for mating. Number of lightpaths to be used for crossover is decided by the crossover ratio. For example there are two chromosomes as:

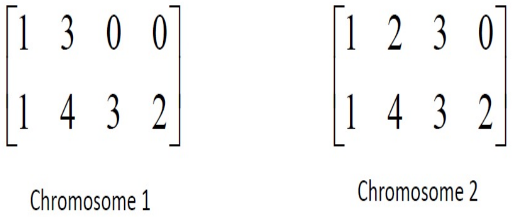

Figure 5.2: **Chromosomes before crossover**

After crossover the chromosomes will be modified as :

$$\underset{\text{Offspring 1}}{\begin{bmatrix} 1 & 2 & 3 & 0 \\ 1 & 4 & 3 & 2 \end{bmatrix}} \qquad \underset{\text{Offspring 2}}{\begin{bmatrix} 1 & 3 & 0 & 0 \\ 1 & 4 & 3 & 2 \end{bmatrix}}$$

Figure 5.3: **Chromosomes after crossover**

- **Mutation** : In this step chromosomes are mutated according to the mutation rate. Number of chromosomes to be mutated is calculated by mutation ratio. For mutation, for the selected lightpath one link is removed and shortest path is calculated.

$$\begin{bmatrix} 1 & 3 & 0 & 0 \\ 1 & 4 & 3 & 2 \end{bmatrix}$$

$$\Big\|$$

$$\begin{bmatrix} 1 & 4 & 3 & 0 \\ 1 & 4 & 3 & 2 \end{bmatrix}$$

Figure 5.4: **Mutation between two chromosomes**

5.2 Simulation

Simulation is carried out on ARPANET and NSFNET.

5.2.1 ARPANET

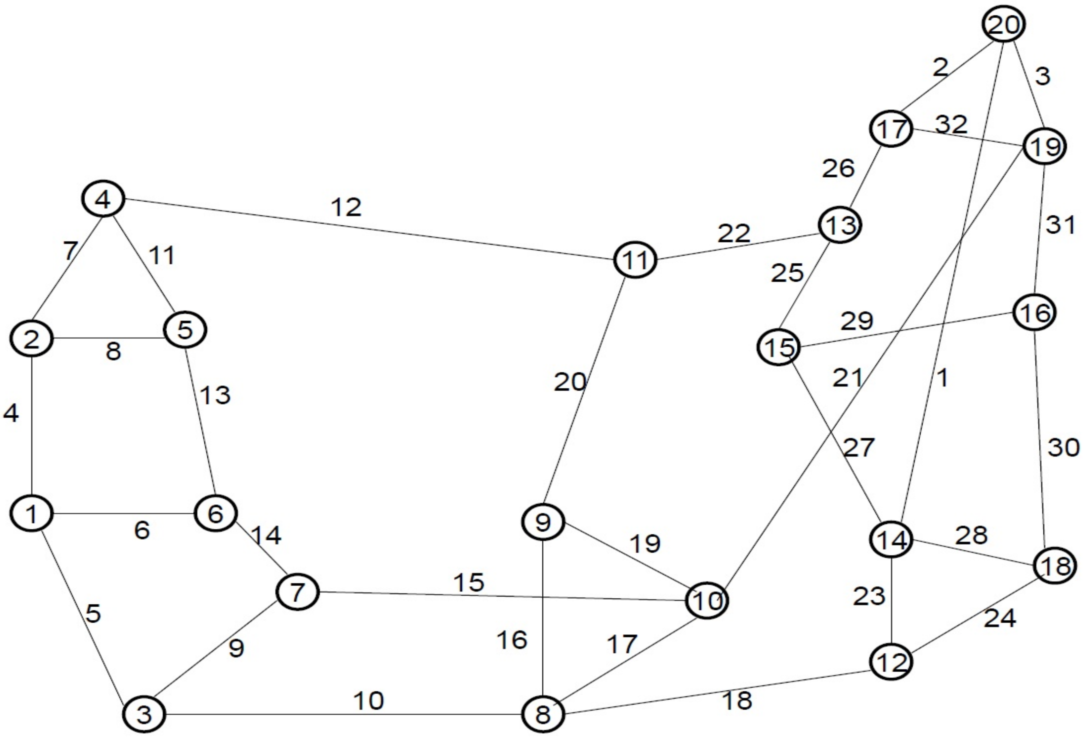

Figure 5.5: **ARPANET**

Lightpath requests and their shortest paths :

11-5	11-4-5
7-15	7-10-19-20-14-15
12-13	12-14-20-17-13
10-14	10-19-20-14
2-8	2-1-3-8
19-12	19-20-14-12
20-10	20-19-10
19-18	19-20-14-18
13-20	13-17-20
9-2	9-8-3-1-2

Lightpath requests and their paths using genetic algorithm:

11-5	11-4-5
7-15	7-10-19-16-15
12-13	12-8-9-11-13
10-14	10-8-12-14
2-8	2-1-3-8
19-12	19-20-14-12
20-10	20-19-10
19-18	19-16-18
13-20	13-17-20
9-2	9-8-3-1-2

For 10 lightpath requests congestion for shortest path technique is 5 and total route length is 332. For the same lightpath requests congestion for genetic algorithm is 2 and total route length is 452. Congestion and total route length for more number of lightpaths(20,30,40,50) is tested.

Congestion comparison between solution of genetic algorithm and shortest path routing :

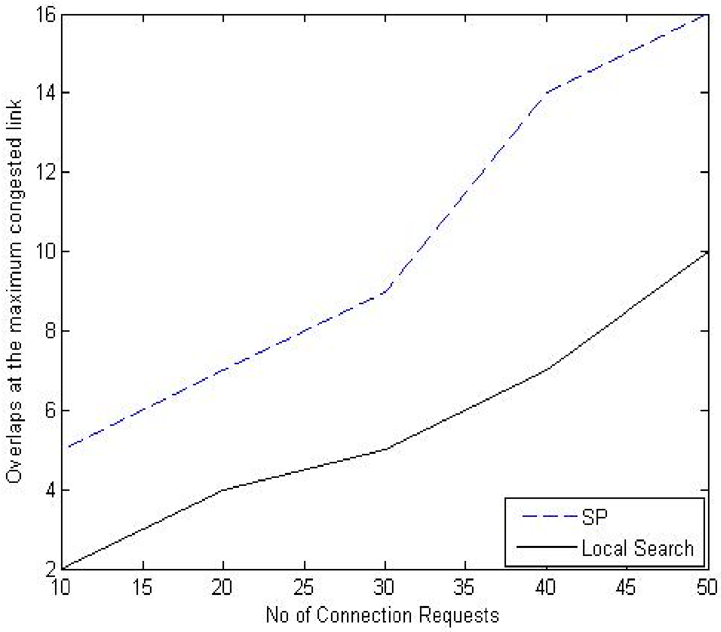

Figure 5.6: **Congestion comparison for ARPANET**

Total routing length comparison between solution of genetic algorithm and shortest path routing :

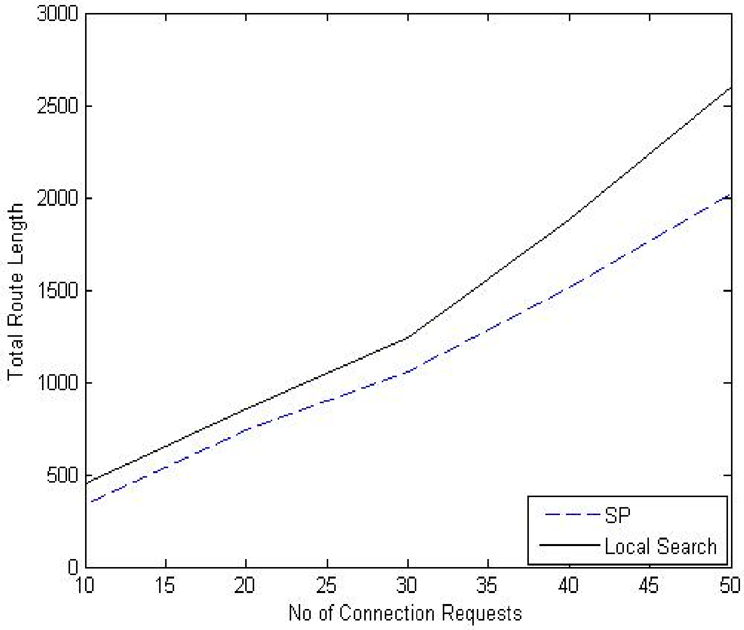

Figure 5.7: **Total route length comparison for ARPANET**

Comparison between single and multi-objective functions:

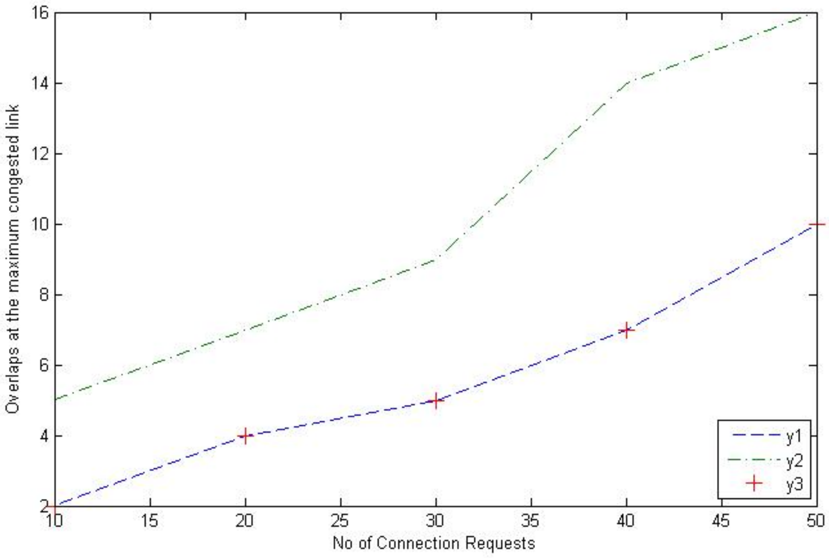

Figure 5.8: **Congestion comparison for ARPANET for single and multi-objective functions**

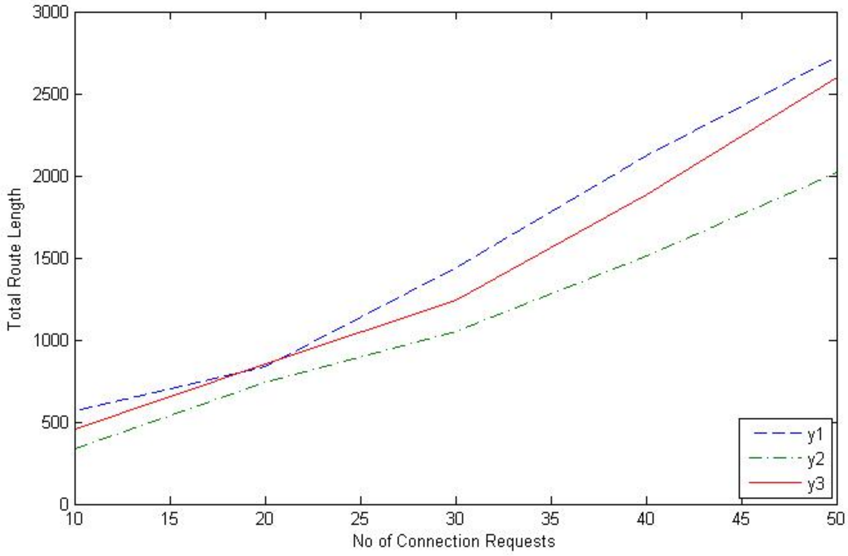

Figure 5.9: **Congestion comparison for ARPANET for single and multi-objective functions**

5.2.2 NSFNET

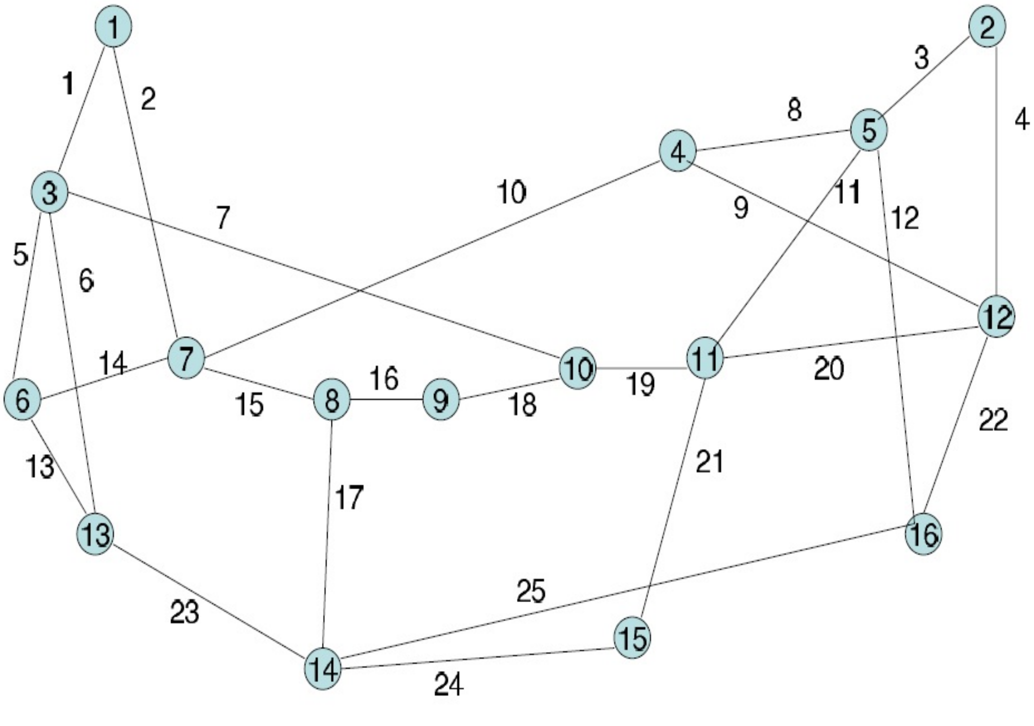

Figure 5.10: **NSFNET**

Lightpath requests and their shortest paths :

11-5	11-5
7-15	7-4-5-11-15
12-13	12-2-5-3-13
10-14	10-3-13-14
2-8	2-5-3-1-7-8
10-12	10-3-1-7-4-12
2-10	2-5-3-10
10-16	10-3-1-7-4-5-16
13-2	13-3-1-7-4-5-2
9-2	9-10-3-1-7-4-5-2

Lightpath requests and their paths using genetic algorithm:

11-5	11-5
7-15	7-8-14-15
12-13	12-2-5-3-13
10-14	10-3-13-14
2-8	2-5-3-1-7-8
10-12	10-3-6-7-4-12
2-10	2-12-11-10
10-16	10-3-1-7-4-5-16
13-2	13-3-1-7-4-5-2
9-2	9-8-14-16-12-2

For 10 lightpath requests congestion for shortest path technique is 5 and total route length is 313. For the same lightpath requests congestion for genetic algorithm is 3 and total route length is 395. Congestion and total route length for more number of lightpaths(20,30,40,50) is tested.

Congestion comparison between solution of genetic algorithm and shortest path routing :

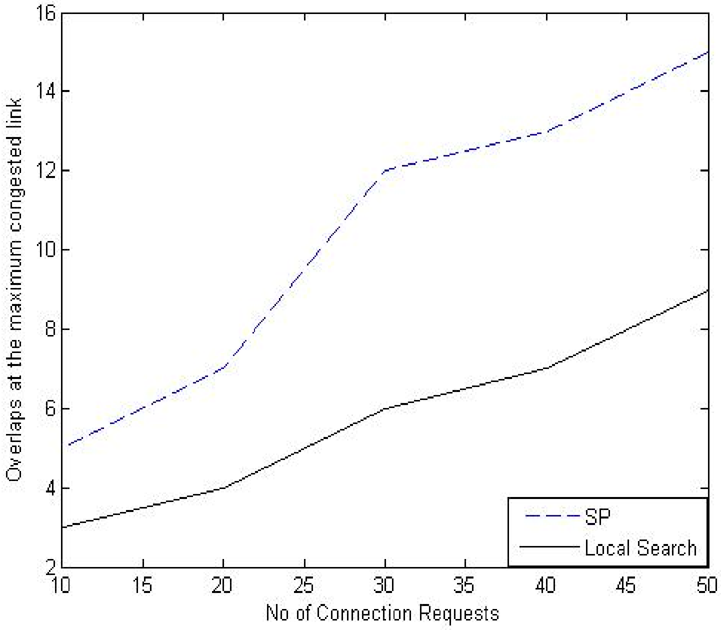

Figure 5.11: **Congestion comparison for NSFNET**

Total routing length comparison between solution of genetic algorithm and shortest path routing :

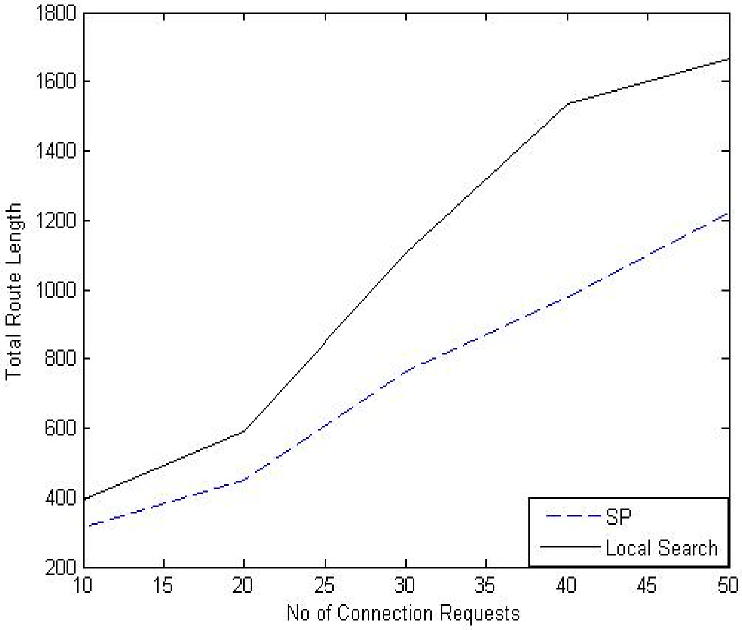

Figure 5.12: **Total route length comparison for NSFNET**

Comparison between single and multi-objective functions:

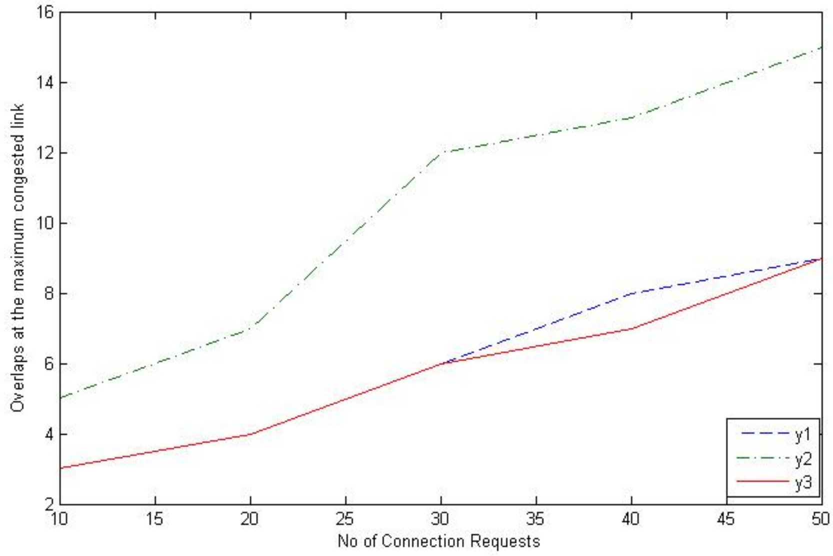

Figure 5.13: **Congestion comparison for NSFNET for single and multi-objective functions**

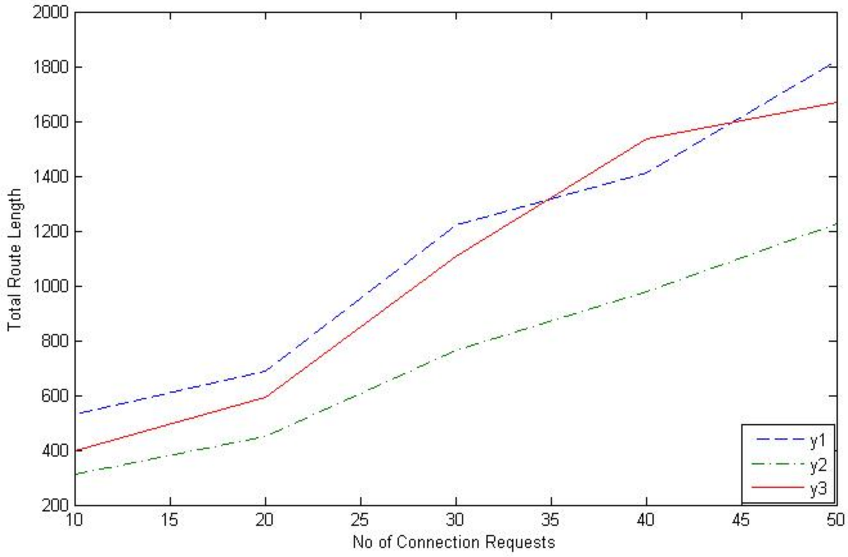

Figure 5.14: **Congestion comparison for NSFNET for single and multi-objective functions**

5.3 Summary

In this chapter RWA problem is solved using genetic algorithm and is compared with shortest path routing. Also multi-objective function is compared with all the single objective function. For all the cases genetic algorithm wtih multi-objective function gives the best result.

Chapter 6

Conclusion

In this work, the RWA problem for WDM networks is solved using genetic algorithm and the (sub)optimal solution is compared with shortest path routing technique. Our main objective is to have minimum number of overlaps, therefore minimizing the congestion. It was found that solving RWA problem using genetic algorithm minimizes the congestion but total route length of the lightpaths increased compared to shortest path technique.

Comparing the multi-objective fitness function with the single objective function it was found that multi-objective function gives better solution compared to all single objective solutions. Single objective functions gives importance only to congestion or only to route length but multi-objective function finds a better solution by maintaining a trade-off between congestion and route length.

Bibliography

[1] Hui Zang, Jason P. Jue, and Biswanath Mukherjee (2000), *A review of routing and wavelength assignment approaches for wavelength-routed optical WDM networks*, Optical Networks Magazine, **1.1**, pp 47–60.

[2] Cardoso, Afonso Jorge F., Joo Crisstomo WA Costa, and Carlos Renato L. Francs (2010), *A New Proposal of an Efficient Algorithm for Routing and Wavelength Assignment in Optical Networks*, Embrapa Amaznia Oriental-Artigo em peridico indexado.

[3] Teresa Gomes, J. Craveirinha, J. Clmaco, and Carlos Simoes (2009), *A bicriteria routing model for multi-fibre WDM networks*, Photonic Network Communications 18, **3**, pp 287-299.

[4] C. Simes, Teresa Gomes, Jos Craveirinha, and J. Climaco (2010), *Performance analysis of a bi-objective model for routing and wavelength assignment in WDM networks*, Journal of Telecommunications and Information Technology, pp 13-24.

[5] Zhensheng Zhang, and Anthony S. Acampora (1995), *A heuristic wavelength assignment algorithm for multihop WDM networks with wavelength routing and wavelength re-use*, Networking, IEEE/ACM Transactions on 3, **3**, pp 281-288.

[6] Nilanjan Banerjee, Vaibhav Mehta, and Sugam Pandey (2004), *A genetic algorithm approach for solving the routing and wavelength assignment problem in WDM networks*, 3rd IEEE/IEE international conference on networking, ICN, pp 70-78.

[7] Ayman Kaheel, Tamer Khattab, Amr Mohamed, and Hussein Alnuweiri (2002), *Quality-of-service mechanisms in IP-over-WDM networks*, Communications Magazine, IEEE 40, **12**, pp 38-43.

[8] Biswanath Mukherjee (2000), *WDM optical communication networks: progress and challenges*, Selected Areas in Communications, IEEE Journal on 18, **10**, pp 1810-1824.

[9] Shi Zhong Xu, and Kwan L. Yeung (2002), *New QoS measures for routing and wavelength assignment in WDM networks*, IEEE International Conference on, vol. 5, pp 2891-2895.

[10] Dhritiman Banerjee, and Biswanath Mukherjee (1996), *A practical approach for routing and wavelength assignment in large wavelength-routed optical networks*, Selected Areas in Communications, IEEE Journal on 14, **5**, pp 903-908.

[11] Mirosaw Klinkowski, Joo Pedro, Davide Careglio, Micha Piro, Joo Pires, Paulo Monteiro, and Josep Sol-Pareta (2010), *An overview of routing methods in optical burst switching networks*, Optical Switching and Networking 7, **2**, pp 41-53.

[12] Helmut Simonis (2011), *Solving the static design routing and wavelength assignment problem*, Recent Advances in Constraints, pp 59-75.

[13] P. Leesuthipornchai, N. Wattanapongsakorn, and , C. Charnsripinyo (2009), *Multi-objective design for routing wavelength assignment in WDM networks*, New Trends in Information and Service Science NISS'09. International Conference IEEE, pp 1315-1320.

[14] Paramjeet Singh, Ajay K. Sharma, and Shaveta Rani (2007), *Routing and wavelength assignment strategies in optical networks*, Optical Fiber Technology 13, **3**, pp 191-197.