Static RWA in All-Optical Network under Multifiber, Multiple Requests Assumption

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***Abstract*- This paper introduces a new approach targeting the RWA problem for static traffic and under the general assumptions of multiple requests between the same SD pairs and mulifiber links. The case of infeasibility of the problem is also discussed and integrated into our frame work. We first present a categorization of the RWA problems according to the different assumptions involved. In addition, a classification of the available approaches is presented along with a brief comparison and overview of each. The proposed approach is tested by applying it to different network models; results for NSFNET and cost239 networks are presented. Furthermore, the results are also compared with a recent heuristic approach [10].**

I. INTRODUCTION

As Wavelength Division Multiplexing (WDM) technology evolves, Wavelength division-multiplexing Routed Networks (WRON's) are widely considered to be the next generation networks and the solution for the continuous growth of high-speed and bandwidth requirements [1]. This multiplexing techniques enables multiple connections to be carried out in parallel on the same fiber link, where each is modulated at a different wavelength, hence the name.

This technology brings up a challenging design problem of the Wavelength division-multiplexing Routed Networks (WRON's). In such optimization problem it is required to benefit from the huge offered bandwidth to satisfy connection requests while maintaining the cost as minimum as possible. Specifically, the problem is to determine for each connection request of a given set a specific route and an associated wavelength, and is thus called Routing and Wavelength Assignment (RWA) problem. Each route and its associated wavelength is called a lightpath (also referred to as λ-channel), which is the main service offered by wavelength routed networks [1].

The RWA problem is a complex combinatorial problem that is proved to be an NP-Complete problem [2]. The complexity of an RWA problem is mainly due to the tight coupling between routing and wavelength assignments. RWA problems are considered under the following constraints; "Wavelength continuity constraint (A lightpath must use the same wavelength on all the links along its path from source to destination, in addition to the distinct wavelength constraint (All lightpaths using the same fiber must be allocated distinct wavelengths)", as quoted from[1].

It should be noted that optical cross connects (OXC's which are optical switches) may be equipped with a wavelength conversion capability which enables them to switch an incoming optical signal over a certain wavelength to another wavelength on its departure. This capability varies from converting between fixed wavelengths (fixed conversion), limited set of wavelengths only supported (limited conversion), or full conversion between any pair of wavelengths in input/output ports (full conversion). The availability of this capability at certain OXC's relaxes the wavelength continuity constraint at this node, if all network nodes are equipped with such OXC's the RWA problem is reduced to circuit switching routing problem [2]. However, this raises the issue of compromise between the improved resources utilization and increased network cost resulting from the use of such expensive devices [14].

RWA problems can be categorized according to various criteria, which are given in Table 1.

Table 1: RWA problem classification

Classification	RWA		
Traffic type	Static	Incremental	Dynamic
Objective function	Max-RWA	Min-RWA	
Wavelength conversion	Full	Sparse	None
Fiber multiplicity	Single	Multiple	
Request multiplicity	Single	Multiple	

First, the type of traffic under consideration can vary from Static (connection requests are already known in advance), Incremental (connection requests arrive sequentially), or Dynamic (connection are requested randomly and are released randomly) [3]. We point out that only the case of static traffic is under consideration, and thus we will focus our discussion on static RWA problems, or alternatively called Static Light path Establishment (SLE) problem.

Second, the objective function of an RWA problem varies according to the requirement but in most cases is either the minimization of the total network cost under the constraint of a limited number of wavelengths (which is referred to as Min-RWA), or alternatively, minimizing the block probability of connection request by maximizing the number of satisfied connection under limited number of wavelengths (Referred to as Max-RWA).

As presented, the wavelength conversion capability in optical cross connects switches (OXC's) plays an important role in the complexity of the problem. Such wavelength conversion capable OXC's may exist in all, few, or none of

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the network nodes, which refers to the Full, Sparse, or No wavelength conversion capability, respectively.

Also, fiber links in optical network can carry single or multiple fibers in the same bundle. Finally, each source-destination (S/D) node pair can request one or multiple connections.

An overview of the static RWA problem and solution approaches is presented in section II. Section III presents the proposed approach. The application of the approach for different network models, varying model parameters and the comparison with the heuristic approach ([10]) are given in section IV. The paper is then concluded in the last section.

II. The Static RWA problem

Different approaches already exist for the static RWA problem. As discussed the complexity of the problem arises from the coupling between the routing and wavelength assignment sub-problems. H. Zang, J. P. Jue, and B. Mukherjee presented in the review paper of [3] a summary of the static RWA schemes and the algorithms or techniques used for solving these sub-problems. Another classification is also provided in [4] based on the decomposition of the sub-problems into two functional stages, where each sub-problem is composed of search and selection components. Based on this functional classification, different solutions were compared and trade-offs were identified.

Another classification (based on the terminology appearing in [5]) for the static RWA problems is provided in Table 2, based on the approach formulation structure.

Table 2: classification for RWA approaches

Approach category	References
Link-Based	[5] (and [1]), and [6]
Path-Based	[7], [8], and [9]
Heuristics	[8], [10], and [11]

Link-based approach was presented in [5] and again in B. Mukherjee's book [1], and also more recently in [6]. The idea is to formulate the problem as a Multi-Commodity Flow (MCF) problem, where each connection request is considered as a different commodity. The formulation variables reflect flow on each link individually and hence the name. The authors in [5] only considered the Min-RWA problem, and studied the cases of single and multiple requests (as discussed in [2]). The problem was decomposed into routing sub-problem and wavelength assignment sub-problem. The Routing sub-problem is formulated as an Integer Linear Programming (ILP) problem and is solved by relaxation, while graph coloring heuristics are used for the wavelength assignment sub-problem. On the other hand, authors in [6] studied the Max-RWA problem for multiple requests. The authors formulated the complete problem into an ILP for both the routing and wavelength assignment sub-problems. The ILP is solved exactly for small sized problem and by Linear Programming (LP) relaxation for large networks. The main advantage of such approaches is the fact that it covers all the search space of the problem (in terms of possible paths for each SD pair). This advantage comes with an extra cost, as it leads to a large number of variables and constraints in the model making the model hardly tractable. Moreover, the problem decomposition into two sub-problems generally leads to sub-optimal solutions.

Alternatively, in Path-based approaches, for each connection request an initial set of candidate paths is calculated. Then, the problem is reduced to path and wavelength selection for each connection request, this problem is formulated as ILP. In [7] three different ILP formulations were provided. They target the Min-RWA for multiple connection request under full, no, and sparse wavelength conversion capabilities. These models shared a proposed objective function that aims to capture integer solutions. The models were solved by using Lagrangian multipliers to relax some of the constraints and using LP-relaxation. Another technique was presented in [8], where the authors address the Max-RWA problem for multiple requests and under multi-fiber assumption. The authors presented an ILP formulation for the problem, and provide a heuristics solution based on Max-Coverage theorem that guarantees the quality of the solution. The work presented in [9] originally aimed to provide bounds in Max-RWA problems; an upper bound on the carried traffic of connection (or alternatively a lower bound on the blocking probability) by comparing to the classical routing problem in circuit switching problems. It should be noted that the core of these approaches is the reduction of the search space by considering a limited set of candidate paths (note that the total number of paths grow exponentially in the number of network links in the network). This reduces the number of variables and constraints in the model, but may lead to sub-optimality if the number of candidate paths is below a certain threshold.

A common approach to target NP-Complete problems is based on heuristics as in [8], [10], and [11]. In these approaches the solution quality is traded for the techniques' complexity. We should point out that many other heuristics based approaches may exists, we have not referred to all of them, but only to some of the recent ones. The work In [10], targeted both Min-RWA and Max-RWA problem. Similar to path-based approaches candidate paths are initially calculated. The core idea is the fact that paths can be assigned the same wavelengths (and hence reduce the number of used ones) if they are edge disjoint. Thus, the authors made use of an already existing heuristic for solving the Edge Disjoint Path (EDP) problem as a core to build a heuristic solution for RWA problem. Another solution was provided in [11] based on the Tabu search framework.

III. Proposed Approach

Our proposed approach exploits one of the models presented in [9] for the purpose of bound calculations. The models targeted Max-RWA problem and single fiber case.

Our proposal is based on an integration of ideas to accommodate more general assumption of the RWA problem and make use of the formulation to solve the problem for large size networks. First, we address the more general case of multi-fiber links. Unlike, the formulation in [8], where handling the case of multi-fibers was part of the ILP formulation itself, we propose a modification in the phase of candidate path pre-calculation, where a certain link can be re-used in this calculation as many times as the fiber multiplicity. In other words, physical fiber links are differently used within the same network span. The advantage of such modification is that it can be incorporated in any path-based formulation and moves the complexity of handling the multi-fiber case off the path selection and wavelength assignment sub-problem.

Secondly, the path-based approach in [9] did not specify a criterion for candidate path pre-calculation for each of the source-destination pairs. Available criteria include: link-disjoint paths (paths must differ in all the links they traverse) and link-distinct paths (paths must differ in at least one link). We have adopted the link-disjoint paths criterion for a number of reasons;

- It helps avoid the use of already congested links over and over in such a way that favors to balance the load over used links.
- The number of link-disjoint paths is generally less than link-distinct path (which grows exponentially with the number of links in the networks).
- It contributes to lower the number of iterations consumed in the Branch and Bound algorithm used to enforce integrality constraints.

In addition, we propose a new objective function reflecting the Min-RWA alternative in order to minimize the designed network cost by minimizing the number of used wavelengths. As we adopted a path-based approach, the problem is reduced to path and wavelength assignment problem (where both a path and an associated wavelength, hence a lightpath, is to be assigned). Our idea is to formulate this assignment problem into a Minimum Cost Network Flow (MCNF) problem [12]. To overcome this dual assignment situation; we let the nodes represent the sets of request in one hand and all the possible path-wavelength combinations in the other hand. We also let links represent possible assignments. Now, in order to minimize the number of wavelengths used, we assign higher costs to links that assign the request to path-wavelength entities with higher indexes of wavelengths.

Formulation

The formulation will be based on the next notations. Representing the network by a graph G, Let N and L denotes the number of nodes and links respectively. The RWA problem is specified as follows; given a set of source-destination connection request pairs (with cardinality R), and the number of available wavelengths in each network link, W. In addition, as addressing the case of multiple connection request, we let m_i represent the number of connections to be established for source-destination pair i.

Adopting the same naming convention of the paper in [9], with the candidate path pre-calculation a set of P available paths are determined. Let $A=(a_{ij})$ be the PxR path-SD pair incidence matrix (i.e a_{ij} = 1 it path i is between source destination pair j and 0 otherwise), while matrix $B=(b_{ij})$ be the PxL path-link incidence matrix (i.e b_{ij} = 1 if link j is on path i and 0 otherwise).

The problem is to determine the assignment variables in $C=(c_{ij})$ the PxW path-wavelength assignment matrix (c_{ij} =1 if wavelength j is assigned to path i, and c_{ij} = 0 otherwise). This only leaves the weighting matrix G_{WxP}, which assigns weights to each assignment between a connection request and a lighpath (path-wavelength association) as discussed earlier.

The ILP model of this approach is presented as follows:

Minimize	$\sum_{\forall j}\sum_{\forall i} C_{i,j}G_{j,i}$,i= 1,…., P, j=1,…,W	(1)
Such that:	$C^T B \le 1_{WxL}$	(2)
	$m \le 1_W C^T A$	(3)
	$m_i \ge 0$, integer i =1, …. R	(4)
	$C_{i,j}$ = 0,1 integer i= 1,…., P, j=1,…,W	(5)

As discussed, the objective function in (1) is the weighted sum of the requests to lightpath assignments (with weights monotonically increasing with the increasing index of used wavelengths). Equation (2) formulates the capacity constraint where the same wavelength can be used at most once on a given link. Traffic demand constraint in (3) enforces that the assignment must satisfy at minimum the number of requests for each SD pair. The remaining constraints in (4) and (5) are the integrality constraints, where the input parameters mi must be given in integer units, and the assignment variables must be enforced to be integer.

We should also point out that the formulation of the objective function as illustrated above permits another dimension of control over the lightpath selection. So far, we mentioned that the weights should be monotonically increasing with the increasing index of wavelengths used (and equal for the candidate paths available). These weights satisfy the requirement to achieve the minimum number of wavelengths used, but may results in multiple optimal solutions of the problem and have no preference to the selected paths. By associating increasing weights to longer candidate paths, we can also establish shortest path preference and guarantee the uniqueness of the solution.

Network Growing Problem

In addition to the proposed model, we discuss a new arising problem and present a solution based on the above model as a framework. The problem arises in the case where the available resources of the network cannot satisfy the connection requests and the ILP model turns to be infeasible. At this point, we propose a special algorithm to handle this case and suggest modification in the network (network growing) to accommodate these requests.

The assumption made to incorporate this problem in our framework, is that the suggested modifications are only the addition of fibers to already existing links and we will not consider the addition of totally new links between originally un-connected nodes. This assumption is of reasonable practical value due to its economical advantage; in practice it is of less cost to add more fibers (in a bundle) to already existing links rather than to construct new links [8]. Moreover, most installed fiber links are composed of multi-core fiber (where different fibers already co-exist, but not all used), and thus the suggested addition in our solution would correspond to the lighting of some dark (unused) fibers.

In our proposed model the number of available wavelengths is a parameter to the model. The problem under consideration arises when this number cannot accommodate the requests. First, the problem is attempted to be solved using the original model, if it turns out to be infeasible then we are facing the network growing problem. At this stage, we modify the model by providing the maximum possible number of wavelengths (we let W=R). Using this number, the problem must be feasible and we calculate the congested links and the required number of fibers to be added to provide the needed wavelengths.

Of course, for the proper application of this feature (i.e., finding the minimum possible set of fiber links to add) the solution based on the first run must generate the minimum possible loads on all the links, so only critically congested links would require the addition of fiber links. This is guaranteed by the application of the complex weighted objective function to select the shortest paths and thus minimum link loads.

The calculation of the number of needed fibers takes into consideration the already existing multiple fibers existing on the link and the number of wavelengths available per fiber.

The flow chart diagram in Figure 1 illustrates the major steps of the approach, including the steps addressing the network growing problem.

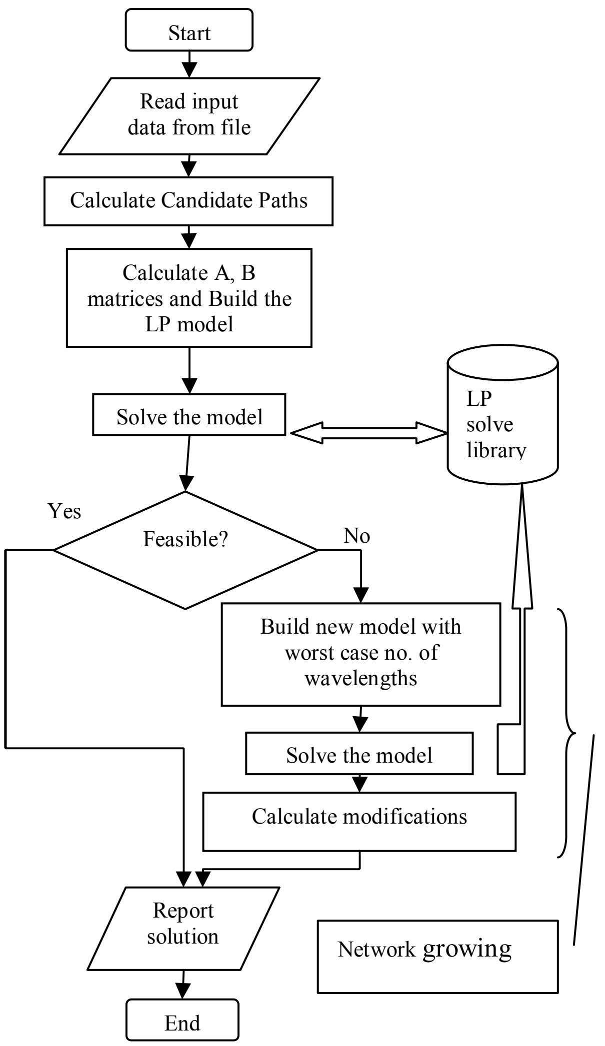


Figure 1: Flow chart diagram for the proposed approach

IV. RESULTS AND COMPARISON

To evaluate our proposed approach, we ran tests in three different directions; testing the approach directly under varying parameters, making a comparison with a recent heuristic approach, and finally testing the application of the network growing algorithm to solve the case of infeasibility.

The formulation was implemented using C++ code for the candidate path pre-calculation and integrated with an available Mixed Integer Linear Programming (MILP) solver (lp_solve, [13]).

The main metrics we collect during our tests are:

1. The optimal objective function, which is the minimum number of wavelengths used (will be referred to in the table as W).
2. The total elapsed time in milli-seconds (referred to as T in tables).
3. The total number of iterations.
4. Number of iterations consumed in the Branch and Bound technique (referred to as B&B iterations in tables).

It should be pointed out that the elapsed time is system dependent and thus we will not rely on it as a premium measure.

We have selected different network models for our tests ranging from simple illustrative examples to real world core networks. Results shown here are the ones obtained using the NSFNET and cost239 networks (for which topologies are shown in Figure 2).

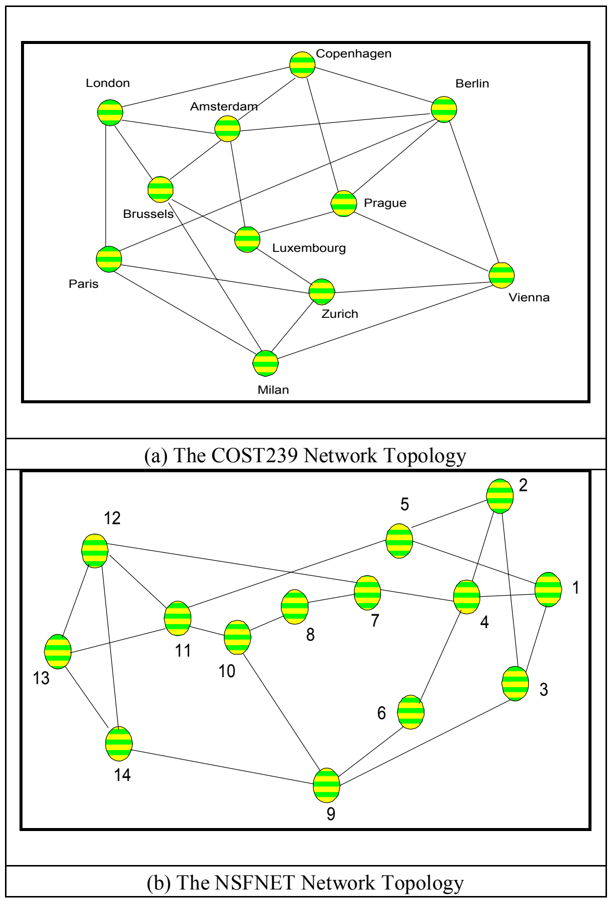


Figure 2: Network topologies of the COST239 and NSFNET networks.

Direct approach test

First, we tested the approach under increasing the number of connection requests, for both the cases where new requests are between new SD pairs or by increasing the multiplicity of existing pairs (Table 3 and Table 4). Results shows that although the number of wavelength required for the case of increasing the multiplicity of requests for the same SD pairs is higher, the models requires less iterations to reach optimality.

Table 3: NSFNET network, increasing SD requests

# of Requests	W	# of iterations	T (mSec)	B&B iterations
20	3	195	66	100
25	3	219	140	59
30	3	790	162	602
40	7	1635	1040	1295
60	7	4632	3E3	4005
80	8	16578	28E3	14085
100	9	16462	27E3	13912

Table 4: NSFNET network, increasing requests for the same SD pairs

# of Requests	W	# of iterations	T (mSec)	B&B iterations
10	2	23	19.5	0
20	4	66	40	0
30	5	176	60	28
40	7	205	87	8

Second, we run tests with varying the number of candidate paths pre-calculated per request (Table 5 and Table 6). As expected the number of link-disjoint paths in any network is relatively low (in comparison with the number of link-distinct paths which grows exponentially with the number of links in the network) but still generates the optimum objective function value. However, a low number of candidate paths may result in false objective value and increasing it unnecessarily also increases the iterations required to reach optimality.

Table 5: Cost239 network, 40 requests, varying candidate paths

# of Paths*	W	# of Iterations	T (mSec)	B&B iterations
1	4	71	50	0
2	3	135	70	0
3	3	333	170	149
4	3	704	270	466

(* number of candidate paths per SD pair)

Table 6: Cost239 network, 80 requests, varying candidate paths

# of Paths*	W	# of Iterations	T (mSec)	B&B iterations
1	8	225	190	0
2	4	1250	500	578
3	4	1656	900	737
4	4	1849	1470	1076

The final test was run under varying number of available wavelengths. Results show that the only requirement is that this number is large enough to ensure feasibility and increasing it does not considerably affect the number of iterations.

Comparison

To verify the solutions obtained by our proposed approach, we ran it in comparison with a recent heuristic approach (in [10]). This approach based on a greedy heuristic for Edge Disjoint Path Problem (referred to as Greedy-EDP approach) has been shown to be simple and of comparable performance with the more complex ILP approach based on Multi-Commodity Flow problem ([12]) of D. Banerjee, and B. Mukherjee [5]. Results for such comparison are shown in Table 7.

Table 7: Comparison between proposed and Greedy-EDP approaches

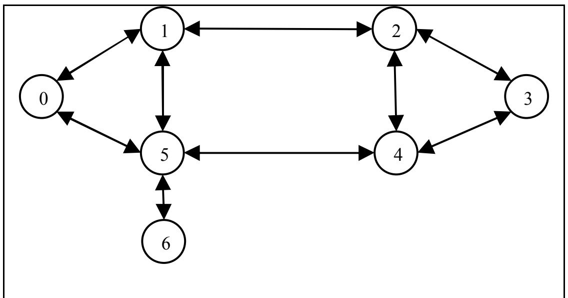
Model	Proposed Approach			Greedy-EDP	
(Nodes, links, requests)	W	# of Iterations	T (mSec)	W	T (mSec)
4,8,4	2	7 (0 B&B)	14.5	2	0.5
7,18,9	2	15(0 B&B)	17	2	1.5
5,10,6	3	12 (0 B&B)	17.5	3	0.5
26,56,3	1	3 (0 B&B)	17	3	15
14,42,120	12	63560 (61365 B&B)	17E4	21	280
11,46,80	4	1250 (578 B&B)	500	7	60

As indicated from the results, the Greedy-EDP approach is considerably faster in all cases. However, our proposed approach guarantees the correct optimum value with a reasonable computational effort while the EDP one may lead to false optimum values for certain cases due to its elimination for paths longer than a certain threshold. Furthermore, the EDP based approach is not a deterministic one and cannot guarantee the uniqueness of the solution or achieving the minimum link loads which are essential for the proper operation of the network growing algorithm.

Network growing problem application

In addition, we have tested the operation of our algorithm addressing the network growing problem. As indicated it suggests the minimum set of required fibers to be added to the network to satisfy the requested connection given that the proper weighting matrix has been used to ensure the solution uniqueness and shortest path preference.

For the purpose of illustration we have selected a rather simple network model (RWA7, shown in Figure 3). The figure shows the network topology and the connection requests which form the given data for the RWA problem. The optimal solution is also provided in the table included. As can be seen, the problem originally requires at least 2 wavelengths, as the connection from node 2 to node 6 is carried over the 2nd wavelength. To test the network growing, we run the same problem and limiting the available number of wavelengths to only one. In this case the problem turns to be infeasible, following the flow of the network growing algorithm (illustrated in the flow chart diagram of Figure 1), the problem is re-solved including 9 wavelengths (the number of connection requests). Again, the optimal solution will be obtained, showing that the three links; from 2 to 1, 1 to 5 and from 5 to 6 are the one which are congested (since each of them is used twice to satisfy connection over 2 different wavelengths). Thus, the solution in this case is the suggestion of adding extra fiber links to this set of congested links (one more fiber for each link).



Requests	Optimal lightpath
0 to 2	0→1→2 at λ1
0 to 6	0→5→6 at λ1
1 to 0	1→5→0 at λ1
2 to 4 2 to 4	2→4 at λ1 2→3→4 at λ1
2 to 6	2→1→5→6 at λ2
3 to 0	3→2→1→0 at λ1
5 to 2	5→4→2 at λ1
6 to 1	6→5→1 at λ1

Figure 3: RWA7 network model with connection requests and optimal solution

More tests were run for this feature, but further illustration requires specific problems with detailed requests and optimal solution.

CONCLSUIONS

In this work, we have provided an overview of the RWA problem and a classification according to the different assumptions involved. We also categorized the different approaches addressing the problem according to their structure and provided a brief discussion of their aspects.

Following this survey, we presented our proposed approach which is a path-based approach based on modifications made to one of the models appearing in [9] to provide bounds for the static RWA problem. In addition, we have targeted the case when the proposed model turns to be infeasible and propose an algorithm for the network growing to accommodate the connection requests.

Supporting results for NSF and cost239 network have been provided and show that our proposed approach has reasonable computational effort giving the fact that it guarantees the correct optimum values (in comparison with a recent heuristic) and is suitable for the case of multiple requests for the same SD pairs. In addition, it permits the preference for short paths and the integration of the network growing problem in its framework.

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