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Residual MinHop versus MaxSum in All-Optical Networks

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***Abstract*— Connection routing in all-optical WDM networks is examined in this paper. The network is modeled by a graph whose nodes represent the optical switching equipment, with full wavelength conversion capacity, and links represent optical fibers. The problem of establishing point-to-point connections, with a given in advance demand (static case) and with the objective of minimize the number of blocked connections, was formulated as a multi-commodity flow problem, resulting in an integer linear programming problem. A heuristic based on the use of the recursive shortest path technique on the residual capacity of the network is proposed and compared with the optimal solution of the multi-commodity flow problem. The proposed algorithm was also applied to the dynamic case (probabilistic knowledge of demands) and evaluated through discrete event simulation. Average values and confidence intervals estimates were obtained with the Bootstrap method. The proposed technique was compared with the Max-Sum technique, which highlights in the specialized literature.**

***Keywords*— Routing; Routing and Wavelength Assignment; WDM Networks.**

I. INTRODUCTION

Wavelength Division Multiplexing (WDM) in optical networks has rapidly gained acceptance as a technology capable of handling the ever-increasing demands of today's high capacity networks. In WDM networks end users communicate with each other via all-optical WDM channels, which are referred to as *lightpaths*. A lightpath is an optical path established between two end-to-end nodes, created by the allocation of a wavelength through the network.

In general terms, it would be desirable to allocate different wavelengths for each connection request accepted. However, in WDM routing networks, the number of wavelengths available limits the number of possible end-to-end connections due to physical constraints such as wavelength channel spacing in the optical fiber links and the tunability of the optical transceivers.

Given a set of connection requests, the problem of setting up lightpaths by routing and assigning a wavelength to each connection is called *Routing and Wavelength Assignment* (RWA) problem. Basically, a RWA problem can be formulated as follows. Given a set of lightpaths that need to be established on the network, and given a constraint on the number of wavelengths, it should be determined the routes and the wavelengths that should be assigned to the lightpaths, so that the maximum number of lightpaths may be established (or the minimum number of required wavelengths used, or the minimum lightpath blocking probability is achieved).

In the absence of wavelength converters, the lightpath must use the same wavelength on all the fiber links it traverses through the source-destination route. This property, known as *Wavelength-Continuity Constraint* (WCC), leads to an inefficient utilization of wavelength channels and results in a higher blocking probability. With wavelength converters available the WCC problem disappears and the routing problem is the same as in circuit-switched networks, in which the limiting factor is the number of available channels on each link. Therefore, the goal of a RWA algorithm is to maximize the throughput by optimally assigning routes and wavelengths to given connection requests.

Traffic assumptions for the RWA algorithms available in the literature are classified as: Static traffic, in which the set of connection requests for the source-destination pairs is known *a priori*; and Dynamic traffic, in which connection requests arrive to and depart from the network one by one in a random fashion.

The remainder of the paper is organized as follows. In Section 2, the performance of the Residual Shortest Path Algorithm (RSPA) is compared with the Integer Linear Programming (ILP) model for static connection requests. In Section 3, the performance of the RSPA is compared with the Max-Sum algorithm for dynamic connection requests. In Section 4, the conclusions of the paper are presented.

II. STATIC DEMAND

In a static demand context the lightpath requests are known in advance, and the routing and wavelength assignment are performed off-line. The typical objective is to minimize the number of blocked connections for a given number of wavelengths per link and a physical topology of the network. Some models allow wavelength conversion while others enforce the wavelength-continuity constraint [6]. Zang [8] gives a survey of a variety of wavelength assignment and routing problems in WDM networks.

The static case problem has been shown to be NP-complete (known algorithms that find an optimal solution require exponential computational time in the worst case) [3]. Therefore, polynomial-time algorithms which produce solutions close to the optimal one are preferred [5].

A. The Residual Shortest Path Algorithm

The *Residual Shortest Path Algorithm* (RSPA) uses a variation of Dijkstra‘s minimum distance algorithm [1] that finds shortest paths for every ingress-egress pair nodes of the network. The link distance is one unit for all links having residual capacity (links not saturated by the previous accepted

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connections). The shortest paths are ordered by their distances and the network topology is updated sequentially for each accepted connection. The list of demands is also updated for the accepted or blocked connection, producing the residual list of demands. If a link capacity of the updated network becomes saturated the RSPA is used again in the residual network. If there is no available path for a given connection request, it is blocked. This procedure is repeatedly applied until the list of residual demands is empty.

The RSPA calculates the route, from a source node to a destination node, dynamically, depending on the network state, which is determined by the set of all connections requests currently in progress. When any network link reaches its number of wavelengths available in use, it is automatically excluded from the topology matrix and all shortest paths are re-calculated.

B. The Integer Linear Programming Algorithm

The *Integer Linear Programming* (ILP) algorithm is popular in the literature as it provides a formal description of the static routing problem in telecommunications networks. The network is expanded considering some characteristics of the problem and modeled like a multi-commodity network flow problem.

1) Algorithm Formulation: The routing problem is formulated as an integer linear program which objective is to minimize the total number of lightpath connections in order to satisfy the requested demand.

$$\text{Minimize} \qquad F \tag{1}$$

subject to

$$F \geq \sum_{s,d,w} F_{ij}^{sdw} \tag{2}$$

$$\sum_i F_{ij}^{sd} - \sum_k F_{jk}^{sd} = \begin{cases} -\lambda_{sd} & \text{for } j = s \\ +\lambda_{sd} & \text{for } j = d \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

$$\sum_w F_{ij}^{sdw} = F_{ij}^{sd} \tag{4}$$

$$\sum_{sd} F_{ij}^{sdw} \leq n_{ij}^{w} \tag{5}$$

$$F_{ij}^{sdw} \in \mathcal{N} \tag{6}$$

where: F_{ij}^{sdw} denotes the number of connection requests from source s to destination d on link ij and wavelength w; λ_{sd} denotes the number of wavelengths needed between source s and destination d; n_{ij}^{w} denotes the number of available wavelengths w in link ij; $\mathcal{N}$ denotes the set of non-negative integer numbers.

This approach considers the static case in a multi-fiber network. The connection requests are known in advance and the objective is to determine a routing and wavelength assignment as to minimize the objective function. Congestion, number of wavelengths required and cost are typical metrics for minimization models.

C. Numerical Results

The performance of RSPA and ILP algorithms is compared in two networks.

A *six-node network* whose edges represent a pair of unidirectional fiber links in opposite directions is shown in Figure 1. The number of wavelengths in both directions of the unidirectional pair is the same and is shown as a label beside the link. There are 6 connection requests from node a to node d and 6 from node a to node f. Both algorithms RSPA and ILP have established 10 lightpaths and blocked 2 connection requests. The ten established lightpaths for both algorithms have the following paths: *ad, ad, ad, abd, abd, abd, abcf, abcf, abdcf* and *abdcf.*

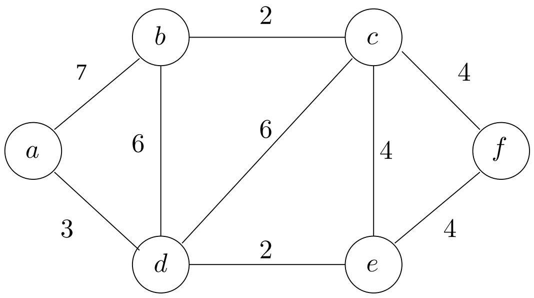

Fig. 1. Six node network whose label at each link shows its capacity.

The *European Optical Network*(COST239EON) [7], which has 11 nodes and 25 pair of links, is shown in Figure 2. The connection requests between nodes are given in Table I with a total number of 150 requests. The RSPA and ILP algorithms were analyzed for a number of wavelengths of unidirectional links varying from 1 to 6. The number of blocked connection requests as a function of the number n of wavelengths available in the links is shown in Table II. Note that there is no blocked connections for six wavelengths per link. The computational time (in seconds) for solving the routing problem are shown in Table III. For both algorithms only 2 connection requests were blocked when using 5 wavelengths, with a computational time of 7 seconds for the RSPA and $13,000$ seconds for the ILP.

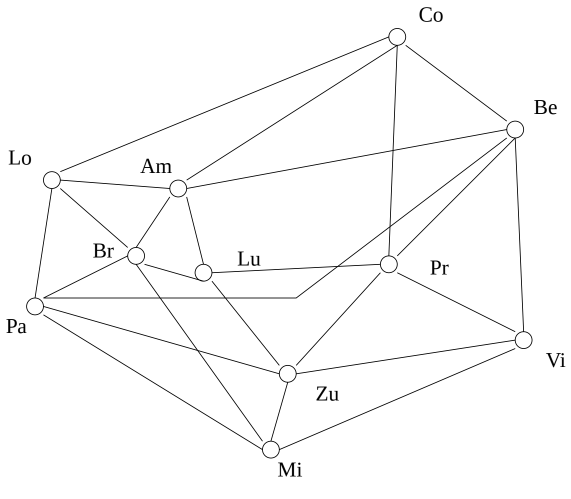

Fig. 2. The *European Optical Network* (COST239EON) [7].

TABLE I

NUMBER OF CONNECTION REQUESTS FOR COST239EON.

	Co	Be	Vi	Mi	Pa	Lo	Am	Pr	Zu	Lu	Br
Co	–	1	1	1	1	1	1	1	1	1	1
Be	1	–	3	3	4	2	2	1	3	1	2
Vi	1	3	–	1	1	1	1	1	1	1	1
Mi	1	3	1	–	2	1	1	1	2	1	1
Pa	1	4	1	2	–	3	2	1	2	1	2
Lo	1	2	1	1	3	–	2	1	1	1	1
Am	1	2	1	1	2	2	–	1	1	1	1
Pr	1	1	1	1	1	1	1	–	1	1	1
Zu	1	3	1	2	2	1	1	1	–	1	1
Lu	1	1	1	1	1	1	1	1	1	–	1
Br	1	2	1	1	2	1	1	1	1	1	–

TABLE II

NUMBER OF BLOCKED CONNECTIONS FOR COST239EON AS FUNCTION OF THE NUMBER n OF WAVELENGTHS AVAILABLE PER LINK.

n	1	2	3	4	5	6
ILP	100	66	40	18	2	0
RSPA	100	69	43	21	2	0

TABLE III

COMPUTATIONAL TIME (IN SECONDS) FOR COST239EON AS FUNCTION OF THE NUMBER n OF WAVELENGTHS AVAILABLE PER LINK.

n	1	2	3	4	5	6
ILP	260	650	5,000	9,000	13,000	18,000
RSPA	36	23	18	9	7	4

III. DYNAMIC DEMAND

In a dynamic traffic pattern, a lightpath is set up for each connection request as it arrives, and the lightpath is released after some finite random amount of time. When lightpaths are established and taken down dynamically, routing decisions must be made as connection requests arrive to the network. It is possible that, for a given connection request, there may be insufficient network resources to set up a lightpath, in which case the connection request will be blocked. Thus, the objective in the dynamic situation is to choose a route that maximizes the probability of setting up a given connection, while at the same time attempts to minimize blocking for future connections.

The Max-Sum algorithm and the RSPA are compared using *discrete event simulation*. The connection requests are generated randomly in accordance to the Poisson distribution, and the retention times are generated randomly in accordance to the negative exponential distribution. When there is no resource available in the network the connection request is blocked and eliminated from the system.

A. The MaxSum Algorithm

The Max-Sum heuristic for wavelength assignment in multi-fiber networks without wavelength conversion [2] is adapted for the routing problem in networks with full-wavelength conversion capacity. Consider a connection request between nodes i (source node) and j (destination node), and let

- ψ be the network state (the set of previous routing connection in the network).
- $c(\psi, l)$ be the number of wavelengths available in link l (in one or several fibers).
- p a path in the network (sequence of links between a source node and a destination node).
- P a pre-determined subset of feasible paths in the network.
- $\hat{p}$ the feasible path (with at least one wavelength available in every link that composes $\hat{p}$) between nodes i and j.
- $\hat{P}_{ij}$ the set of feasible paths between nodes i and j.

Then, the residual capacity in path p is

$$r(\psi, p) = \min_{l \in p} c(\psi, l) \tag{7}$$

and, the chosen path $\hat{p}^*$ is

$$\hat{p}^* = \arg\max_{\hat{p}\in\hat{P}_{ij}} \sum_{p\in P} r(\psi'(\hat{p}), p). \tag{8}$$

where $\psi^{'}(\hat{p})$ is the next state in the network if a connection is established in path $\hat{p}$. If there exists more than one solution, a path among those of least distance could be chosen.

The Max-Sum algorithm has two steps for solving the routing problem. In the first step the feasible paths are chosen, for which the following criteria is used.

- The paths are of minimum distance (they have the same number of links to travel).
- The links which compose these paths are disjunct.

In the second step the Max-Sum heuristic is employed for finding the path which produces the maximum sum of the residual capacities for the future connection requests.

B. Numerical Results

Three networks were analyzed for dynamic traffic: the six-node network (Figure 1), the COST239EON (Figure 2) and the NSFnet [4], shown in Figure 3.

The traffic matrix, in Erlangs, for the NSFnet is shown in Tables VI and VII and for COST239EON is shown in Table I. For the six-node network, the demand is 6 Erlangs from node a to node d and 6 from node a to node f. For all networks, the average retention time of the established lightpaths $1/\mu$ is normalized as one time unit.

The collected discrete event simulation statistics are: the average percentage of accepted connections (established lightpaths);the execution time t_c of the simulation and its 95% confidence interval ci .

The statistics of discrete event simulations are shown in Table IV for the six-node network, in Table V for the COST239EON and in Table VI for the NSFnet. The number of wavelengths available per link for both COST239EON and NSFnet is 5.

TABLE IV

DISCRETE EVENT SIMULATION STATISTICS FOR THE SIX-NODE NETWORK.

	RSPA	MaxSum
Accepted (%)	67.9	68.1
t_c (s)	170	494
ci (%)	1.85	1.84

TABLE V

DISCRETE EVENT SIMULATION STATISTICS FOR COST239EON.

	RSPA	MaxSum
Accepted (%)	65.2	63.7
t_c (s)	214	14,700
ci (%)	2.64	2.06

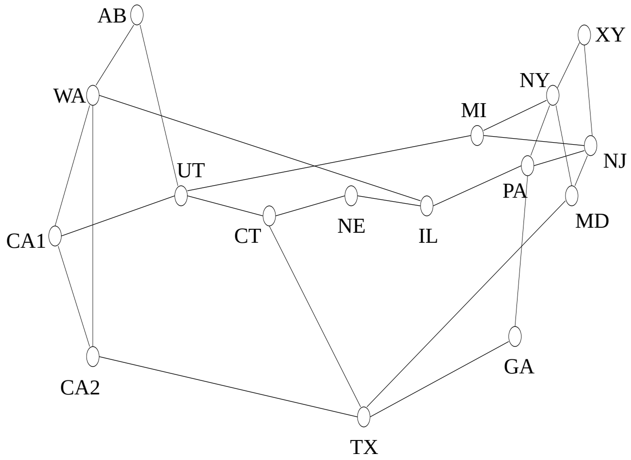

Fig. 3. NSFnet topology [4].

TABLE VI

CONNECTION REQUESTS IN ERLANGS FOR THE NSFNET.

	WA	CA1	CA2	UT	CO	TX	NE	IL
WA	–	1	0	0	0	1	0	1
CA1	1	–	1	1	0	0	1	0
CA2	0	1	–	0	0	0	0	0
UT	0	1	0	–	1	1	0	0
CO	0	0	0	1	–	0	1	0
TX	1	0	0	1	0	–	0	0
NE	0	1	0	0	1	0	–	1
IL	1	0	0	0	0	0	1	–
PA	0	0	0	0	0	0	0	1
GA	0	0	1	0	0	0	1	0
MI	0	0	0	0	1	0	0	0
NY	1	0	1	0	0	0	0	0
NJ	0	0	0	0	0	0	0	0
MD	0	0	0	0	1	1	0	1
AB	0	0	0	0	0	1	0	0
XY	0	0	1	1	0	0	0	0

TABLE VII

CONNECTION REQUESTS IN ERLANGS FOR THE NSFNET.

	PA	GA	MI	NY	NJ	MD	AB	XY
WA	0	0	0	1	0	0	0	0
CA1	0	0	0	0	0	0	0	0
CA2	0	1	0	1	0	0	0	1
UT	0	0	0	0	0	0	0	1
CO	0	0	1	0	0	1	0	0
TX	0	0	0	0	0	1	1	0
NE	0	1	0	0	0	0	0	0
IL	1	0	0	0	0	1	0	0
PA	–	1	0	1	1	0	0	0
GA	1	–	1	0	0	0	0	0
MI	0	1	–	0	1	0	0	1
NY	1	0	0	–	0	0	1	0
NJ	1	0	1	0	–	1	1	0
MD	0	0	0	0	1	–	0	0
AB	0	0	0	1	1	0	–	1
XY	0	0	1	0	0	0	1	–

TABLE VIII

DISCRETE EVENT SIMULATION STATISTICS FOR THE NSFNET.

Algorithm	RSPA	Max-Sum
% accepted	76.2	76.7
t_c (s)	302	3,800
ci (%)	2.24	2.46

IV. CONCLUSIONS

The Residual Shortest Path Algorithm (RSPA) and the Integer Linear Programming (ILP) algorithm were compared to solve the routing problem for the static demand of traffic in all optical networks. It was shown that the RSPA is a valid approach to solve the routing problem because the number of blocked connection requests, for both algorithms, is very similar. The ILP algorithm takes much more computational time than the RSPA to solve the routing problem due to the large complexity of the multi-commodity optimization algorithm, used by the ILP technique. However, the ILP algorithm may have some enhanced features: It may uniformly distribute the number of wavelength connections in the optical links and it may reduce the number of wavelength converters needed in the switching nodes, if full wavelength conversion capacity is not implemented. For the dynamic demand of traffic, an adapted version of the RSPA and the Max-Sum algorithm were compared. It was shown that, for the same set of wavelengths available, both algorithms have a similar blocking probability, despite the much smaller computational effort of the RSPA.

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