A Distributed WDM Routing and Wavelength Assignment Protocol

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Summary
The main contribution of this work is to propose a distributed on-demand routing and wavelength assignment algorithm for WDM networks. The proposed scheme, termed Distributed Light-path Allocation (DLA), is capable to select routes and establish light-paths via message exchanges without imposing a major overhead on the network. The proposed scheme is able to balance the load in a WDM network. The simulation results show that the proposed solution is comparable with the other algorithms that demands for a much higher computational and message costs.

Key words:
WDM, RWA, light-paths,wavelengths.

1. Introduction

In recent years, there has been a growing demand for networks able to transmit data at increasing speeds. Among the recent technologies used to increase the available link capacity is the Wavelength Division Multiplexing (*WDM*). WDM is a technology which multiplexes several optical signals onto a single optical fiber using different wavelengths, thus augmenting link capacity. In a WDM network, the connections between two nodes are established through channels of wavelengths that travel in a completely optical path, that is, a path without electro-optic conversion at the source node and optic-electro at the destination node. Such an optical path is referred as a light-path. A link may comprise several wavelengths, that is, λ_i for $0 \leq i \leq W$, where W represents the number of wavelengths available. The problem to find a path, *i.e.* a route, from a source to a destination node in a WDM network with a continuous and free wavelength along each link is non-trivial. Indeed, the above problem is known as the *Routing and Wavelength Assignment* (*RWA*) problem and was found to be NP-Complete [2]. With the aim to better use the *WDM* technology, a number of heuristics have been proposed in the literature to address the RWA problem [4] [5] [6] [11] [14].

In solving the RWA problem, it is usually assumed that the same λ_i is used along the selected path. A path p from a vertex s to a vertex d is said to be continuous if the same λ_i is used through the path. Such constraint is called *wavelength continuity constraint*. Such constraint can be relaxed by using an optical converter at each node, but then cost becomes a major concern. One way to tackle with the RWA problem, without resorting to optical converters, is to split the RWA into two sub-problems: Routing problem (*R*) and Wavelength Assignment (*WA*) problem. The RWA problem is usually tackled in the following way: first, a routing algorithm is used to select the best route from the source to the destination node; next, the wavelength assignment algorithm attempts to obtain a free continuous wavelength along the selected path.

The *blocking probability* can be defined as the probability of one request not to be attended by a free wavelength on the selected route. In this case, the request is blocked. Given a set of requests $R=\{r_1,r_2,...,r_k\}$, where each request r_i, $1 \leq i \leq k$ is formed by one source and destination pair (s_i,d_i), the RWA problem asks to find a path between (s_i,d_i), that has the same free wavelength λ_i in each link of the path. If this condition is not met the request is then blocked.

Among the routing strategies usually employed are fixed routing, fixed-alternate routing and adaptable routing. In the fixed routing, the same route is always selected for a given source-destination pair. These routes are usually computed with the Dijkstra's or the Bellman-Ford algorithms [5]. In the fixed-alternate routing, multiple

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Manuscript received April 5, 2009
Manuscript revised April 20, 2009

routes are considered and each node of the network keeps a routing table containing an ordered list of fixed routes for each destination node. On receiving a connection request for a given source/destination pair, a continuous wavelength is sought on the first route in the list. In case that no continuous wavelength is found on the first route, the next route in the list is verified. The process goes on until the request is served or the routes are exhausted [9].

In the adaptable routing, the route is selected dynamically and depends on the network state. The network state is determined by the set of connections in progress. The types of adaptable algorithms commonly used are shortest-cost path adaptable routing and least congested path adaptable routing [8]. Similarly to the fixed-alternate routing, the least congested path adaptable routing (LCP) [24] keeps a number of pre-computed routes for each source-destination pair. On a connection requests arrival, the least congested route is chosen. The congestion in a link is measured by the number of free wavelengths. If there is a standoff, the shortest path is chosen.

All the initially proposed WA's work under the wavelength continuity constraint. Later studies considered the use of wavelengths converters. However, due to cost of such devices, it may not be feasible to place a converter at each node. To see this, consider the following case. Let C be a set of converters and V be a set of nodes in the network, with $|C|<<|V|$. Certainly one has to develop a mechanism to find the best location to place the converter. Unfortunately, this problem is NP-Complete [9]. Thus, in this work we considered networks that do not employ wavelength converters.

In this work we propose a distributed on-demand routing and wavelength assignment algorithm for WDM networks. The proposed scheme, termed *Distributed Light-path Allocation* (DLA), is capable to select routes and establish *light-paths* via message exchanges without imposing a major overhead on the network. Simulation results and numerical results have shown that our proposed scheme is comparable with other solutions that demand for higher computational costs.

The remaining of this work is organized as follows. Section 2 presents a brief overview of the WDM technology and related works. The proposed Distributed Routing and Wavelength Assignment Protocol is presented in Section 3. Simulation results are presented in Section 4 and Section 5 concludes this work.

2. WDM Networks

2.1. WDM Technology

There are two basic multiplexing mechanisms used in optical networks, Wavelength Division Multiplexing (*WDM*) and Optical Time-Division Multiplexing (OTDM) [1]. The former can be viewed as a way to multiplex several wavelengths into a single fiber while *OTDM* is a technique where several optical signals are combined, transmitted together, and separated again based on different arrival times. In this work we focus on *WDM* networks.

The revolution in the transmission through fiber optics started in 1992 doubling the capacity at every six months reaching rates of 10 Tbps already in 2001. In a WDM networks, beams of laser are carried in different wavelengths, which are used to implement end-to-end fixed connections. These fixed connections are called a *light-path*. The main restriction in relation to *light-path* is that different *light-paths* cannot share the same wavelength in the same optical fiber [3].

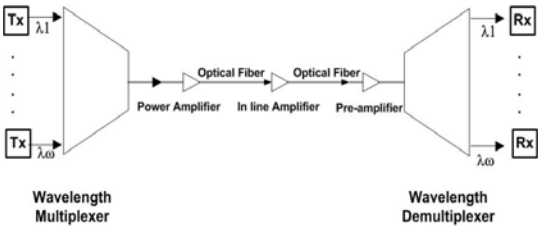

Fig. 1. Operation WDM Technology

As can be verified in the Fig. 1, the WDM technology works as follows: at the transmitter side reside W independent transmitters. Each transmitter, denoted as T_x, is a source of light, such a laser, and is modulated independently as a stream of data. The output of each transmitter is an optical signal, named wavelength, denoted as λ_i, where $0 \leq i \leq W$. The optical signal of transmitters W are combined into a single optical signal by a multiplexer and transmitted over the optical fiber. At the other end, the optical signals are demultiplexed into W individual signals, which are then addressed to the appropriate receiver. The amplification is used after the wavelength multiplexing and before the wavelength de-multiplexing [12].

A peer-to-peer WDM system provides W independent channels, all of them on the same fiber. As the WDM technology evolves, the number of wavelengths that can be transmitted at the same fiber increases as well. In other words, the link of a fiber can be increased without the need of adding new fibers, which is costly and time consuming. The addition or replacement of new fibers is considerably more expensive than the improvement of the necessary components.

2.2. Routing and Wavelength Assignment

In what follows, a formal definition of the RWA problem is given. Consider a WDM network modeled as graph G=(V,E), where V represents the nodes and E represents the links. Also, let $N=|V|$ be the number of nodes in a WDM network. Let W be the number of wavelengths available on each link. Then, each link in E consists of a fiber optic cable which carries W wavelengths. Given the wavelengths $\lambda_1, \lambda_2, \lambda_3,\ldots, \lambda_w$ and a sequence of connection requests R=($r_1,r_2,\ldots,r_k$) in an optical WDM network, each connection request r_j comprises of a source-destination pair such that $r_j=(s_j,d_j)$ for $1 \leq j \leq k$. The problem is to establish a *light-path* p_j for each connection request r_j using a free wavelength l_m, where $1 \leq m \leq$ W. The RWA is a combination of a routing and wavelength assignment strategy. The most significant routing algorithms were explained in Section 1 and the most significant WA's are shown below:

(i.) *Random* (Ra): An available wavelength is selected randomly among the available wavelengths [3].

(ii.) *First-Fit*(FF): All wavelengths are numbered and a lower-numbered wavelength is considered before a higher-numbered wavelength [5].

(iii.) *Least-Used* (LU): Selects the wavelength that is the least used in the network, thereby attempting to balance the load [11].

(iv.) *Most-Used*(MU): Is the opposite of LU in that it attempts to select the most used wavelength in the network [11] .

(v.) *Least-Loaded*(LL): Is a heuristic designed for multi-fiber networks which selects the wavelength that has the largest residual capacity on the most-loaded link [11].

(vi.) *Max-Sum* (M∑): Considers all possible paths with their pre-selected routes in the network and attempts to maximize the remaining path capacities after the light-path establishment [6].

(vii.) *Relative Capacity Loss* (RCL): Is based on MAX-SUM and is an attempt to improve it. The RCL calculates the relative capacity loss for each path on each available wavelength and then chooses the wavelength that minimizes the sum of the relative capacity loss on all the paths [8].

(viii.) *Distributed Relative Capacity Loss*(DRCL): The DRCL was proposed to be applied in distributed environments. The routing is fixed and is computed by the Bellman-Ford algorithm where each node exchange routing tables with their neighboring nodes [11].

(ix.) *Best-Fit* (BF): Here, W copies of the network topology is made available at each node. Each copy represents the current topology for λ_i, $1\leq i \leq$ W. A valid shortest path route is then sought among the W copies [22].

It was shown in [3] that the *Random* and *First-Fit* heuristics attain reasonable performance on a setting consisting of a single fiber. The advantage of *First-Fit* lies is the fact that it combines short communications and computation costs, since it is not necessary to have any global knowledge of the network [19]. The attribution of wavelengths for multi-fibers networks was proposed in [8], where the *RCL* algorithm was presented.

The Weighted Link Capacity Extended (WLCex) algorithm and the WA First-Fit were proposed in [23]. The proposed algorithm uses cost metrics based on number of hops, length of the link and capacity, among other parameters in order to compute the best available route. The WLCex was shown to perform better than previous fixed routing algorithm -- such as SDP(Shortest-Distance-Path) and SHP(Shortest-Hop-Path) -- as well as other adaptive routing algorithms -- such as LS-d (Link State distance) and LS-h (Link State hops). In [22] the Best-Fit scheme was proposed where the routing and wavelengths assignment are tackled together as mentioned in the previous section. An adaptive Impairment Aware Routing and Wavelength Assignment (IRWA) was proposed and analyzed in [26]. The IRWA takes into consideration physical aspects of an optical network, such as the Optical Signal to Noise Ratio - OSNR. With such information it is possible to select routes over the links that have better OSNR.

It is worth mentioning the above heuristics, in general, assume that the network topology is known and the routes are usually computed by a shortest-path algorithm. As the above solutions only maintain topological information, when the wavelengths on the shortest route are exhausted, most of the proposed solutions fail to find a valid route, even if a second route exists. Of course, backup routes may alleviate such problem. However, as the backup routes are pre-computed, the same problem is likely to occur latter on. Thus, to avoid such pitfalls, we advocate in this work that the RWA problem should be tackled together. Our proposal goes in this direction and shows that the RWA problem can indeed be tackled efficiently as a combined solution. The next section shows the details of our proposal.

3. A WDM Distributed Routing and Wavelength Assignment Protocol

One of the great challenges in WDM networks is to develop efficient algorithms to establish *light-paths*. For a RWA to be considered efficient, it has to be able to select routes and to attribute wavelengths in a way that the number of served requests is maximized. In addition, an efficient RWA should be able to establish *light-paths*, manage the distribution of control messages and network state information without precluding other services or incurring in much overhead.

As have pointed out, most of the proposed RWA's found in the literature compute routes using a link state or a distance vector algorithm. These algorithms work in either distributed or centralized manner. When a centralized algorithm is used, all the routing decisions are made at a central point. Should the central node fail, other nodes will have to be elected to carry on its task. With a distributed algorithm, node failure has a less significant impact on the routing decisions. On the other hand, distributed algorithms have a larger overhead due to the amount of control messages sent to advertise routes and exchange routing tables. Also, in an optical network, one may wish to create routing tables that reflect the current state of the network, including not only the available links, but also the available wavelengths on each link. The cost to maintain routing tables up-to-date has a direct impact on the amount of control messages issued. In this work we propose an algorithm that is able to compute routes and make wavelength assignment on-demand.

3.1. Distributed Light-path Allocation (DLA)

The proposed routing scheme in this work is based on the Dynamic Source Routing (DSR) protocol [26]. The DSR protocol has been extensively studied in the context of ad hoc networks and has been shown to be able to cope with network topology changes. Also, the amount of generated control messages is kept at acceptable levels even in the presence of dynamic network topologies. Our proposed scheme, the Distributed Light-path Allocation (DLA), uses the same underling idea proposed in [26]. However, unlike the original DSR, which focuses on route establishment, we incorporated means to disseminate wavelength state information to allow for efficient wavelength establishment.

The details of the DLA protocol are spelled out below.

`Algorithm DLA`

Input: Request(s,d);

Step 1:	Read a Route Request RREQ(s,d) and set HopCount > 0;
Step 2:	If HopCount > 0 then send the Route Request RREQ(s,d) message to all its adjacent neighbors whose links have unassigned wavelengths satisfying the continuous wavelength constraint. The node ID and $e(v_i,v_j)$ are appended to the RREQ.
Step 3:	On receiving a RREQ, each node performs the following actions:
Step 3.1:	If the RREQ was seen before, ignore the RREQ. Otherwise, if the node is not the desired destination then register the RREQ, decrement HopCount by one and proceed to **Step 2.**
Step 3.3:	If the node is the desired destination, then send a Route Reply (RREP) message back to node s using the information extracted from the RREQ message.
Step 4:	On receiving a RREP, each node performs the following actions:
Step 4.1:	If the node is not the source node, then reserves the necessary resources on its outgoing links on the path from d to s, as informed in the RREP.
Step 4.2.	If the node is the source node, then the route discover process is complete

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Fig. 2. DLA Protocol

When a request $r_j=(s_j,d_j)$ is received at node s, the node sends a route request (RREQ) message to its neighboring nodes via those links that still have unassigned wavelengths. The RREQ packet carries both the source and destinations addresses and, as it traverses the network, each intermediate node includes its own address in the RREQ. Note that, besides the node ID, each node also appends the wavelengths available on the link from which the RREQ was received. In other words, the RREQ carries the information about the nodes and the amount of free wavelengths on the path. Assuming that there is a path from s to d, the RREQ will eventually reach the destination node d. In this case, node d can identify the reverse path to the source node using the information available in the RREQ.

Suppose that the node v_1, v_2 and v_3 are on the path from node s to d. Let $e(v_i,v_j)$ denote de link on the path from s to d connecting nodes v_i and v_j. When node v_2 receives the RREQ from $_{v1}$, it knows which wavelengths are available in the link $e(v_1,v_2)$. Recall that such information is recorded in the RREQ. Let $Q(v_1,v_2)$ denote set of available wavelengths on the link $e(v_1,v_2)$. Thus, node v_2 can verify whether or not $Q(v_1,v_2)\cap Q(v_2,v_3)=\varnothing$. If this is the case, the *wavelength continuity constraint* is not satisfied.

Otherwise, there is a free continuous wavelength on the path v_1,v,$_2$,v_3.

From the above discussion, it should be clear that there are three cases in which a node is unable to forward the RREQ: (*i*) The HopCount reached zero; (*ii*) All the wavelengths on the outgoing links have been assigned or none of the unassigned wavelengths satisfy the *wavelength continuous constraint*; (*iii*) The message has been received previously. The HopCount is used here to prevent the RREQ to search for routes longer than specified by the source node. Suppose that node s had established a route to node d previously. Let h denote the number of links traversed to establish that route. Then, the next time node s searches for a route to node d, the HopCount can be set to h, thus preventing the establishment of longer routes.

In Step 3, the destination node may wait for a number of RREQs to arrive before an action is taken. In such case, if multiple RREQ arrives, the destination node may compare the routes and select the route that better suits the request at hand. When the RREP is sent, the path is known to the destination node. While the RREP travels towards the source node, the selected wavelength on the path is reserved. On receiving the RREP on Step 4, the route and wavelength have been reserved from d to s and the source node may proceed with data transfer.

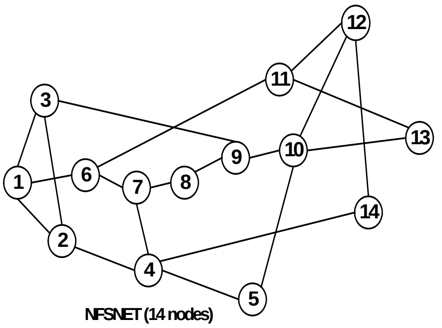

Fig. 3 NFSNET Topology

As an example, consider the NFSNET topology shown in Fig. 3. Suppose that node 5 (n_5 for short) receives the following request r=(5,12). Also, assume that the wavelengths λ_0 and λ_2 are available on the link between nodes $n_5 \rightarrow n_{10}$ and that λ_2 and λ_3 are available on the link between nodes $n_{10} \rightarrow n_{12}$. Thus, when the RREQ reaches node n_{10} it will contain the following information $n_5 \rightarrow n_{10,}$ $\lambda_{0,2}$. When the RREQ leaves n_{10} toward n_{12} it will have $n_5 \rightarrow n_{10} \rightarrow n_{12}$, $\lambda_{2,3}$. Note that λ_0 has been removed since n_{10} knows that λ_0 is not available on the $n_{10} \rightarrow n_{12}$ link. For the same reason λ_3 is not present either. Hence, when the RREQ reaches n_{12} via the path $n_5 \rightarrow n_{10} \rightarrow n_{12}$, the information regarding the traversed nodes as well as the available wavelengths on the links connecting the nodes on that particular path are known. Other packets may reach n_{12} via other paths which allows n_{12} to select the route that better suits its needs. In this work we use the shortest-path that contains a free wavelength on the path connecting s and d. When RREQ passes through a node that identifies that there is no free continuous wavelength on the upstream and downstream links, the RREQ is dropped. When multiple routes satisfying a given request r are found, the route having the smaller number of hops and the largest amount of free wavelengths along its path is selected.

As we have discussed above, our proposed scheme is able to select short routes that satisfy the *wavelength continuity constraint* while balancing the load. The next sections will present the analytical model and the obtained simulation results.

4. Analytical WDM Model

4.1. Simulation Environment

This section details the model used to evaluate the blocking probability in a *WDM* network. In this work we consider the well-known NFSNET topology. In our model we consider following characteristics:

(i.) The requests are randomly/incrementally generated and are served in a FIFO fashion.
(ii.) Requests which are not served are considered blocked;
(iii.) All the links are bidirectional;
(iv.) Once a request is served it is allocated during the entire simulation;
(v.) The wavelength heuristic used is the First-Fit.

The simulation results are carried out in the following way. Initially, a pool of R=($r_1,r_2...,r_k$) requests is generated. Each individual request r_j, for $1 \leq j \leq k$ is associated with a source and destination pair, that is r_j=(s_j,d_j). The number of available wavelengths per link varies from 4 up to 12. The simulation results are drawn from the average of one hundred simulation *runs*, with each run consisting of a hundred requests. Thus, the number of requests simulated is 10.000.

4.2. Routing Strategies

For comparison purpose, we have implemented the fixed, fixed-alternate, best-fit strategies and the DLA protocol that is being proposed. The routes are computed using the shortest-path algorithm. After computing the shortest path, we attempt to establish a *light-path* using the *First-Fit* approach. In the fixed-alternate strategy, if no wavelength on the primary route is available, we compute a second route (disjoint from the previous one) and repeat the process. It should be clear that if there are *m* disjoint routes from a source *s* to a destination *d*, we could repeat this process for *m* iterations. Here, however, we have repeated the process twice. As mentioned in the previous sections, the Best-fit attempts to compute the shortest route for each available wavelength. For that to be possible, the network topology and wavelengths state information has to be available at each node. Clearly, nodes will have to spend time in order to collect and disseminate such information. In this work, however, we assume that the topological information is present at each node.

4.3. Simulation Results

The performance of WDM networks is usually analyzed through the blocking probability of a given route request. It is arguable that alternative routes can have a significant impact on the blocking probability for WDM networks. In this work, we have compared the results of the proposed algorithm with the Best-fit, fixed and fixed-alternate. As for the WA heuristic, we have considered the First-Fit. The topology analyzed is the NFSNET, which is depicted in Fig. 3. In this work, the blocking probability (*Bp*) is computed the following way:

$$B_p = \frac{Bc}{Gc} \qquad (1)$$

Where *Bc* represents the number of blocked calls and *Cg* is the number of generated calls.

It is important to note that the NFSNET topology comprises only 14 nodes and has 20 links overall. The average routing distance for the NFSNET is approximated 2 hops. Thus, each request would demand for wavelengths satisfying the continuity constraint for 2 hops on average. In other words, each request consumes resources that span 2 links. Since the routing protocols studied attempt to find the shortest route, the 20 links are indeed reduced to the ratio of the number of links by the average number of hops, in this case 10 links. Thus, the expect number of route requests that can be served (*EAp*), can be expressed as follows:

$$EAp = \frac{NL \cdot W}{AvRT} \qquad (2)$$

Where *NL* is the number of links and *AvRT* is the average route distance.

Similarly, the expected blocking probability (EBp) can be expressed as *EBp*{max(0, (100-*EAp*)/100)}. The *EBp* provides an upper bound of the blocking probability

Fig. 4 shows the simulation results for the NFSNET network topology. The *x*-axis shows the number of wavelengths considered and the *y*-axis show the blocking probability for each of the simulated protocols. The *EBp* values are also shown in Fig. 4.

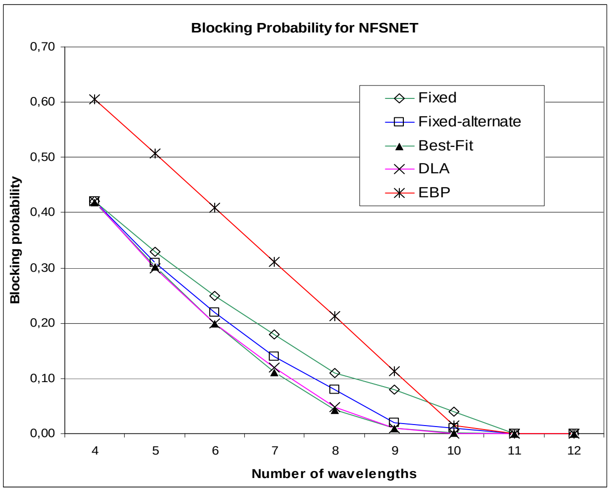

Fig. 4. Blocking probability results for the NFSNET topology with a varying number of wavelengths and routing protocols.

As shown in the figure, an increase in the number of wavelengths using the fixed-routing decreases the blocking probability by approximately 6% on average. Compared with the fixed-alternate routing, it is clear that a backup route can better exploit the availability of additional disjoint routes to serve a larger number of requests, offering a considerable reduction in the blocking probability. Compared with the fixed routing, the fixed-alternate gives an improvement of nearly 3% on average. Both Best-fit and DLA are comparable in terms of blocking probability. Indeed, the difference between the two is less than 1% on average. Compared with the fixed and fixed-alternate, the DLA and Best-fit reduce the blocking probability of nearly 3% on average. As W increases, the *EBp* tends to zero, which occurs for values of W=10 and above, which is confirmed by the simulation results for all the RWAs considered.

4.4 Suitability of the proposed routing strategies

From the results presented in the previous section, it is clear that the Best-fit and DLA have similar performance.

However, the cost of each solution must be carefully analyzed. In this subsection we take a closer look at the cost of each solution. The Best-fit can be implemented both in a centralized or decentralized manner. In either case, to be able to compute a route, the Best-fit needs to have network state information available at each node. To do so, each node will have to disseminate its network state information to other nodes. Assuming that each node send such updates at regular intervals, we have O(N) messages generated at each interval, where N is the number of nodes. If the messages are sent via unicast, then $O(N^2)$ messages are sent at each regular interval. Obviously, only those nodes that have experienced network state change will need to send updates. Although this may reduce the number of messages issued, a change in one link may trigger several updates on other nodes. The DLA does not need to maintain topological information and hence routing table advertisement messages are not necessary. As routes are computed via message exchanges, each node does not have to expend time computing routes. However, the DLA find routes by flooding route requests (RREQ). In the worst case, each node in the network will receive and forward one copy of the RREQ message. Thus, the amount of messages generated in this case is O(N). Clearly, the Best-fit message cost is much higher than that of DLA.

It is also important to note that the Best-Fit attempts to compute the shortest route for each available wavelength. For that purpose, the Best-Fit maintains W copies of the network topology. When a route is needed, W routes are computed and the best one is selected. Thus, the time complexity to compute a route can be expressed as $O(W \times N^2)$. In the DLA, routes are computed via message exchanges with simple operations.

5. Conclusion

In this work we have proposed a distributed routing algorithm for WDM networks. The proposed algorithm is capable to select routes on demand and establish *light-paths* via message exchanges without imposing a major overhead on the network. The results have shown our proposed solution is comparable with other costly solutions with similar performance. Our proposed solution is adaptable and can be easily implemented and incorporated in a WDM network.

References

[1] Internet Traffic to Keep Doublinghttp://www.pcworld.com/article/id,109715-page,1/article.html, last acess in April, 2008.

[2] I. Chlamtac, A. Ganz and G. Karmi, *Light-path Communications: An Approach to High Bandwidth Optical WAN ェs,* IEEE, 1992

[3] R. Ramaswami and K. N. Sivarajan, *Routing and Wavelength Assignment in All Optical Networks*, IEEE ACM Transactions on Networking,v. 3, No. 5, Outubro, 1995.

[4] E. Karasan, E. Ayanoglu, *Effects of Wavelength Routing and Selection Algorithms on Wavelength Conversion Gain in WDM Optical Networks*, IEEE , 1996.

[5] S. Subramanian and A. R. Barry, *Wavelength Assignment in Fixed Routing WDM Networks*, IEEE , 1997.

[6] R. Barry and S. Subramanian, *The MAX-SUM wavelength assignment algorithm for WDM ring networks*, OFC , 1997.

[7] M.M. Freire and A. M. F. Carvalho,*Estimativa da Probabilidade de Bloqueio em Redes Opticas WDM com topologia em anel e com encaminhamento de comprimento de onda*, CRC, 1998.

[8] X. Zhang and C. Qiao, *Wavelength Assignment for Dynamic Traffic in Multi-fiber WDM Networks*, 7th International Conference on Computer Communications and Networks (ICCCN98), 1998.

[9] S. Ramamurthy and B. Mukherjee, *Fixed-Alternate Routing and Wavelength Conversion in Wavelength-Routed Optical Networks* , IEEE/ACM Transactions on Networking , 2002

[10] D.R. Campelo, R. Camelo and H. Waldman, *Estratégias de Ampliação da Capacidade de Anéis Ópticos com Bloqueio*, SBrt 2000.

[11] H. Zang,J.P.Jue and B. Mukherjee, *A Review of Routing and Wavelength Assignment Approach for Wavelength Routed Optical WDM Networks,* Optical Networks Magazine, 2000.

[12] T.H. Cormen,C. E. Leiserson, L. R. Rivest and C. Stein,*Introduction to Algorithms*, Second Edition , McGraw Hill Book Company, 2001.

[13] M. A. Ali,A. Shami.,C. Assi and Y. Ye *Architectural Options in the Next-Generation Networks Paradigm: Is Optical Internet the Answer?*, Photonic Network Communications, 3:1/2, 7-21 , 2001

[14] H. Zang,J.P. Jue, L. Sahasrabuddhe , R. Ramamurthy and B. Mukherjee ,*Dynamic light-path Establishment in Wavelength-Routed WDM Networks*, IEEE Communications, Setembro, 2001.

[15] J. Strand and R. Doverspike, *Importance of Wavelength Conversion in an Optical Network*, Optical Network Magazine , Maio/Junho, 2001.

[16] X. Sun, Y. Li , I. Lambadaris and Y. Q. Zhao, *Performance Analysis of First-Fit Wavelenght Assignment Algorithm in Optical Networks*,7th ConTEL , 2003.

[17] B. Li and X. Chu, *Routing and Wavelength Assignment vs. Wavelength Converter Placement in All-Optical Networks*, IEEE , 2003.

[18] H. Waldman and D.R. Campelo, *Uma Nova Abordagem para Estimação da Probabilidade de Bloqueio em Redes de Roteamento de Comprimento de Onda Lineares*, SBrt 2003.

[19] H. Waldman and D.R. Campelo, *Analytical Calculation of Blocking Probabilities in WDM Rings with Wavelength Conversion*, IEEE, 2005.

[20] D.R. Campelo, R.C.A. Junior and H. Waldman, *Blocking Probabilities Generated by the First-Fit Wavelength*

Assignment Algorithm in WDM Rings, Novembro ,III TIDIA Workshop, 2006.

[21] A. Wason and R.S. Kaler, *Wavelength Assignment Problem in Optical WDM Networks*, IJCNS International Journal of Computer Science and Network Security, v. 7, No. 4 , Abril, 2007.

[22] K. Li, *Heuristics Algorithms for Routing and Wavelength Assignment in WDM Optical Networks*,7th International Workshop on Performance Modeling Evaluation and Optimization of Ubiquitous Computing and Network Systems-IPDPS, 2008.

[23] R. G. Dante, F. R. Barbosa, and E. Moschin, *An Optical Path Routing Strategy for WDM Networks with Imprecise state Infomation*, IEEE 2006.

[24] J. P. Jue, *Lightpath Establishment in Wavelength-Routed WDM Networks*,Optical Networks: Recent Advances, pg. 99-122, Kluwer Academic Publixhers, 2001.

[25] K. Chan and T. Yum, *Analysis of least congested path routing in wdm lightwave networks*. In: Proc. IEEE INFOCOM 94., 1994.

[26] David B. Johnson, *Routing in Ad Hoc Networks of Mobile Hosts. Proceedings of the Workshop on Mobile Computing Systems and Applications*, pp. 158-163, IEEE Computer Society, Santa Cruz, CA, December 1994.

[27] E. A. R. CHAVES et al, *Impairment aware routing algorithm for all-optical network based on power series and particle swarm optimization*, SBrT08-XXV Simpósio Brasileiro de Telecomunicações, 2008.

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