Research Journal of Applied Sciences, Engineering and Technology 7(13): 2646-2654, 2014
DOI:10.19026/rjaset.7.581
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: June 28, 2013 Accepted: July 30, 2013 Published: April 05, 2014

Research Article

Comparative Analysis of Routing and Wavelength Assignment Algorithms used in WDM Optical Networks

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Abstract: This study aims at highlighting the Routing and Wavelength Assignment (RWA) problems in WDM Optical networks and describes the Routing Algorithms and their performance comparison. Since routing decisions play an important role in evaluating the blocking performance of a network it is critical to choose a wavelength assignment scheme that should take into account its compatibility with the chosen routing protocol in addition to its blocking performance. This study presents problems in Wavelength Assignment, describes various Routing schemes and different approaches to solve both the static and the dynamic RWA problems. RWA algorithms' role is to assign a light-path (a route and a wavelength) to incoming calls in a network. RWA algorithms block calls if a continuous wavelength from source to destination cannot be found (wavelength blocking), thus degrading the performance of All Optical Networks, by call blocking. The failure of RWA algorithm to find an available wavelength on all links from source to destination causes congestion resulting in packet loss. This study examines the RWA algorithms and their problems in WDM Optical networks. The various measures taken to improve the blocking performance of WDM optical networks are also studied. We compared the performance of two wavelength assignment schemes, the Random wavelength assignment and the First-Fit wavelength assignment scheme via simulation. It was observed that the Random wavelength assignment algorithm performs well under low load, while for high load First Fit algorithm performs better.

Keywords: Blocking probability, light-path, performance analysis, routing, wavelength division multiplexing

INTRODUCTION

Blocking is a major challenge in the design of WDM networks. Paper Sridharan and Sivarajan (2004) talks about Wavelength Blocking that occurs due to the RWA algorithm's inability to find a wavelength available on all links from source to destination. A light-path is an all-optical wavelength channel connecting two end nodes (source node and destination node). It may span across multiple fiber links. In the case of without wavelength conversion, the same wavelength must be reserved along these fiber links, which is known as wavelength continuity constraint. This needs to be considered during light-path establishing phase in WDM network. This may result in a high blocking probability (Wang, 2007).

In WDM Optical networks data is transmitted over multiple wave-lengths on each fiber. Figure 1 presents a WDM transmission system. Several communication channels, each carried by a different wavelength, are multiplexed into a single fibber strand at one end and de-multiplexed at the other end, thereby enabling multiple simultaneous transmissions (Gençata, 2005).

To improve blocking performance, two existing approaches are Routing Wavelength Assignment (RWA) and Wavelength Conversion (WC) technique. In this study, a review of the different approaches to solve both the static and the dynamic RWA problems is presented (Wason and Kaler, 2007).

LITERATURE REVIEW

In WDM networks, the end users exchange information with each other through all optical WDM channels, called light-paths. A light-path that supports a connection in WDM network may be of multiple fibber links as shown in Fig. 2.

In all optical networks, a light-path must occupy the same wavelength on all the fiber links through which it traverses; Fig. 2 illustrates a wavelength-routed network in which light-paths have been set up between pairs of access nodes on different wavelengths. In a WDM optical network, with a given set of connections, the question of setting up light-paths by routing and allocating a wavelength to each connection is called the RWA problem.

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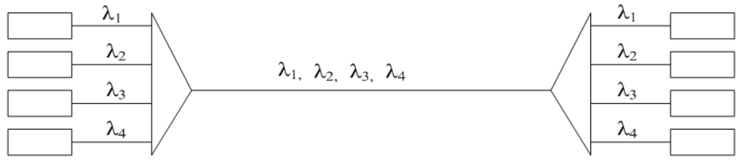

Fig. 1: A basic WDM transmission system configuration

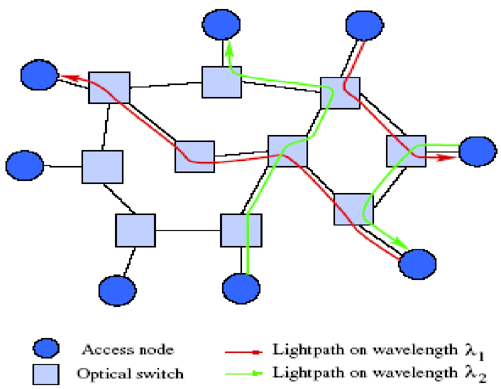

Fig. 2: A wavelength-routed optical WDM network with light-path connections

Due to limited number of wavelengths in fibbers, RWA becomes a challenging network problem for transmission of data and hence routing in WDM networks (Minh *et al*., 2007).

The connection requests on networks may be static, incremental or dynamic. For static traffic, the connection requests are known in advance and light-paths for these connections are set up. The objective is to minimize network resources The RWA problem for static traffic is known as Static Light-path Establishment (SLE) (Byungkyu, 2006).

In the incremental-traffic case, connection requests arrive sequentially, a light-path is established for each connection and the light-path remains in the network indefinitely (Zang *et al*., 2000).

On the other hand, for dynamic traffic, a light-path is established for each connection request when a connection request arrives. The objective in the incremental and dynamic traffic cases is to set up light-paths and assign wavelengths in a manner that minimizes the amount of connection blocking, or that maximizes the number of connections that are established in the network at any time (Zang *et al*., 2000). The RWA problem for dynamic traffic is known as Dynamic Light-path Establishment (DLE) (Byungkyu, 2006).

Based on static or dynamic traffic demand, RWA problem may be classified into two subgroups: Routing sub-problems and Wavelength Assignment sub-problems. To solve these problems, many algorithms exist as are shown in Fig. 3.

For the routing sub-problem, there are three well-known approaches in literature: fixed routing, fixed alternate routing and adaptive routing.

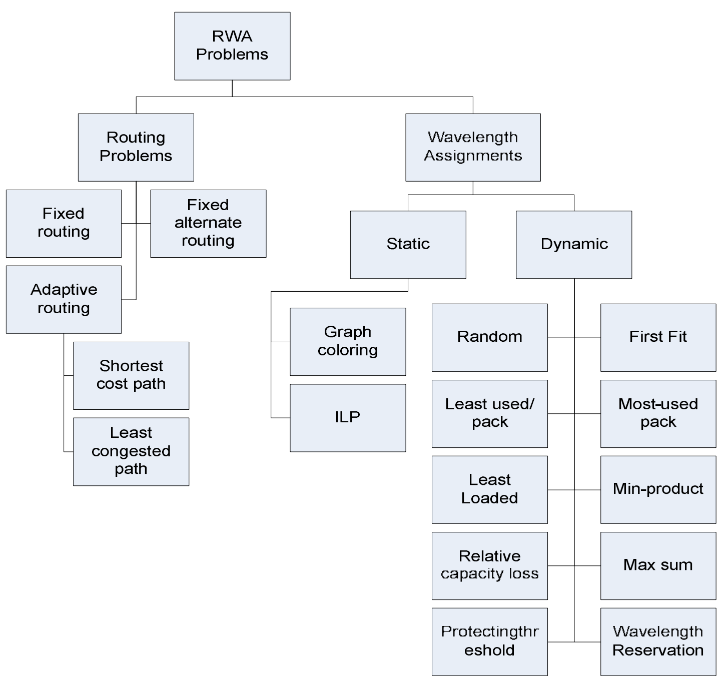

Fig. 3: Algorithms for RWA problems

For the wavelength assignment sub-problem, various heuristics and an ILP model have been proposed.

Hence, it is important to measure the call blocking performance of optical networks.

ROUTING ALGORITHMS AND THEIR PERFORMANCE COMPARISON

This section presents approaches to connection requests routing:

Fixed routing: In this approach, a fixed path is selected between the source node and the destination node. One such method is the fixed shortest path routing, Fig. 4. The route is pre-determined using standard shortest path algorithm such as Dijkstra's algorithm or the Bellman Ford algorithm or the modified Dijkstra algorithm (Byungkyu, 2006). Using the pre-determined route a connection is then established.

Although this approach is the simplest but it results in high blocking probability due to unavailability of sufficient wavelength channels. Thus, in this approach a large number of wavelengths along the path are required.

In Fig. 4, the fixed shortest-path route from Node 0 to 2 is illustrated. This approach to routing connections is very simple; however, the disadvantage of such an approach is that, if resources (wavelengths) along the path are tied up, it can potentially lead to high blocking probabilities in the dynamic case, or may result in a large number of wavelengths being used in the static case. Also, fixed routing may be unable to handle fault situations in which one or more links in the network fail. To handle link faults, the routing scheme must either consider alternate paths to the destination, or must be able to find the route dynamically. Note that, in Fig. 4, a connection request from Node 0 to 2 will be blocked if a common wavelength is not available on both links in the fixed route, or if either of the links in the fixed route is cut (Zang *et al*., 2000).

Fixed alternate routing: In fixed alternate routing, multi-routes between a source node and the destination node are selected and a source node sets up connection when a connection request arrives. If the connection is not able to find an available wavelength along the shortest path route, a source node attempts to establish a connection along the second shortest path route from an ordered list of a number of fixed routes. Therefore, the fixed alternate routing can reduce the blocking probability compared with fixed shortest path routing. Moreover, this approach is flexible and simple to establish a connection (Byungkyu, 2006).

The term “alternate routes” is also employed to describe all routes (including the primary route) from a source node to a destination node. Figure 5 illustrates a

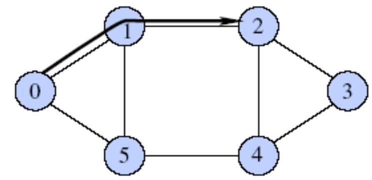

Fig. 4: Fixed shortest-path route from node 0 to 2

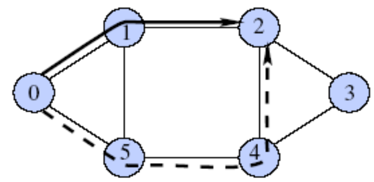

Fig. 5: Primary (solid) and alternate (dashed) routes from node 0 to 2

primary route (solid line) from Node 0 to 2 and an alternate route (dashed line) from Node 0 to 2. In most cases, the routing tables at each node are ordered by the number of fiber link segments (hops) to the destination. Therefore, the shortest path to the destination is the first route in the routing table. When there are ties in the distance between different routes, one route may be selected at random. Fixed-alternate routing provides simplicity of control for setting up and tearing down light-paths and it may also be used to provide some degree of fault tolerance upon link failures (Zang *et al*., 2000).

Adaptive routing: In adaptive routing, the connection is dynamically selected dependant on the current network state such as traffic patterns and channels available. Two well-known approaches are adaptive shortest cost path routing and least loaded path routing. For adaptive shortest cost path routing, each unused link has a cost of 1 unit, a route selects a shortest cost path upon arrival of a connection request. For least loaded path routing, a connection is determined by the number of wavelengths available on a link. The link which has enough available wavelengths is first considered to establish a connection. Both of these approaches always provide shortest paths. If there exist multiple paths with the same distance, one of them is dynamically selected (Byungkyu, 2006).

Adaptive shortest-cost-path routing, is suitable for use in wavelength-converted networks. Under this approach, each unused link in the network has a cost of 1 unit, each used link in the network has a cost of ∞ and each wavelength-converter link has a cost of c units. If wavelength conversion is not available, then $c = \infty$. By choosing the wavelength-conversion cost c appropriately, we can ensure that wavelength-converted routes are chosen only when wavelength-continuous paths are not available. In shortest-cost adaptive routing, a connection is blocked only when there is no

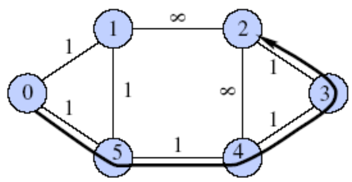

Fig. 6: Adaptive route from node 0 to 2

route (either wavelength-continuous or wavelength-converted) from the source node to the destination node in the network. Adaptive routing requires extensive support from the control and management protocols to continuously update the routing tables at the nodes. An advantage of adaptive routing is that it results in lower connection blocking than fixed and fixed-alternate routing. For the network in Fig. 6, if the links (1, 2) and (4, 2) in the network are busy, then the adaptive-routing algorithm can still establish a connection between Nodes 0 and 2, while both the fixed-routing protocol and the fixed-alternate routing protocols with fixed and alternate paths as shown in Fig. 5 would block the connection (Zang *et al*., 2000).

Least-Congested-Path (LCP) is another form of adaptive routing. It is similar to alternate routing. A sequence of routes is pre-selected for each source-destination pair (Chen-Shie and Chiang, 2009).

When a connection request arrives, the least-congested path among the pre-determined routes is selected.

The congestion on a link is calculated by the number of wavelengths existing on the link. Links with fewer available wavelengths are measured as more congested. The path congestion is determined by the traffic congestion on the most congested link in the path. In case of a tie, shortest-path routing may be used to break the tie. Another approach is to use shortest paths as priority and then use LCP to break the ties.

A drawback of LCP is its computational complexity. All links on all candidate paths have to be examined, in selecting the least-congested path.

PROBLEMS IN WAVELENGTH ASSIGNMENT

Two types of wavelength assignment problems are discussed: static and dynamic wavelength assignment problems. In static wavelength assignment, a set of light-paths and their routes are given. Each light-path is assigned a unique wavelength on a given fibber link i.e., no two light-paths share the same wavelength on a given fiber link.

Heuristic approaches are required in dynamic wavelength assignment to route a connection.

In Fig. 3, the first eight methods are to reduce the blocking probability for the new connection. Wavelength Reservation and Protecting Threshold improve blocking performance for a connection that traverses more than one link.

Static wavelength assignment: Once a path has been chosen for each connection, the number of light-paths traversing any physical fiber link defines the congestion on that particular link. Wavelengths must be assigned to each light-path such that any two light-paths that are sharing the same physical link are assigned different wavelengths (Zang *et al*., 2000).

The Static Light-path Establishment (SLE) with the wavelength-continuity constraint can be formulated as an Integer Linear Program (ILP) in which the aim is to minimize the traffic flow in each link, which, in turn, corresponds to reducing the number of light-paths passing through a specific link.

The ILP formulation is expressed as follows (Byungkyu, 2006).

Notation:

s	:	Source node
d	:	Destination node
ω	:	Wavelength on link
Γs, d, ω	:	The traffic demand from source node to destination node on any wavelength
$T_{i,j}^{s,d,\omega}$	:	The traffic demand from source node (s) to destination node (d) on link i, j using wavelength
$\vartheta_{s,d}$	:	The number of connections requested between source node and destination node

Objective:

$$\min T_{max} \tag{1}$$

Subject to:

$$T_{max} \geq \sum_{s,d,\omega} T_{i,j}^{s,d,\omega} \quad \forall i,j \tag{2}$$

$$\sum_i T_{i,j}^{s,d,\omega} - \sum_k T_{ij,k}^{s,d,\omega} = \begin{cases} -\Gamma^{s,d,\omega} & if\ s=j \\ \Gamma^{s,d,\omega} & if\ d=j \\ 0 & otherwise \end{cases} \tag{3}$$

$$\sum_\omega \Gamma_{s,d,\omega} = \vartheta_{s,d} \tag{4}$$

$$\sum_{i,j} T_{i,j}^{s,d,\omega} = 0, 1 \tag{5}$$

$$\sum_{s,d} T_{i,j}^{s,d,\omega} \leq 1 \tag{6}$$

This methodology may also be used to obtain the least number of wavelengths needed for a given set of connection requests by searching on the minimum number of wavelengths in the network.

Dynamic wavelength assignment: In dynamic wavelength assignment problem, we try to minimize connection blocking and assume the number of wavelengths to be fixed.

The following heuristics have been proposed in the literature:

- Random
- First-fit
- Least-used/SPREAD
- Most-used/PACK
- Min-product
- Least loaded
- MAX-SUM
- Relative capacity loss
- Wavelength reservation
- Protecting threshold

These heuristics can all be implemented as on-line algorithms and can be combined with different routing schemes. The first eight schemes attempt to reduce the overall blocking probability for new connections, while the last two approaches aim to reduce the blocking probability for connections that traverse more than one link.

The wavelength-assignment heuristics are described below:

Random wavelength assignment (R): In this scheme the space of wavelengths is first searched to find out the set of all available wavelengths on the required route. Amongst the available wavelengths, one is selected at random (generally the one with uniform probability).

First-Fit (FF): In FF scheme, all wavelengths are numbered. While searching for free wavelengths, a lesser numbered wavelength is given priority before a higher-numbered wavelength. The first free wavelength available is then selected. No global information is required in this scheme. The computation cost of this scheme is lower than random wavelength assignment, because search for the entire wavelength space for each route is not required. This scheme is preferred over Random wavelength assignment because of its low complexity and small computational overhead.

FF also performs well in terms of fairness and blocking probability (Batayneh *et al*., 2007).

Least-Used (LU) /SPREAD: This scheme selects the least used wavelength in the network and tries to balance the load amongst all the wavelengths. The performance of LU is worse than Random, while also introducing additional communication overhead, requiring additional storage and computation cost; thus, LU is not preferred in practice (Zang *et al*., 2000).

Most-Used (MU) /PACK: In this scheme, the most-used wavelength in the network is selected. This scheme performs better then LU and FF. It packs connections into fewer wavelengths and conserves the less-used wavelengths' unused capacity.

Min-Product (MP): MP is used in multi-fibber networks. In a single-fiber network, MP becomes FF. The goal of MP is to pack wavelengths into fibers, thereby minimizing the number of fibers in the network (Zang *et al*., 2000).

Compared to the multi-fiber version of FF in which the fibers, as well as the wavelengths, are ordered MP does not perform well. Its computation costs are also high.

Least-Loaded (LL): This heuristic is designed for multi-fibber networks, like MP, It selects the wavelength with the biggest residual capacity on the most-loaded link along route. When it is used in single-fibber networks, the remaining capacity is either 1 or 0; thus the lowest-indexed wavelength with residual capacity 1 is selected. Thus LL is reduced to FF in a single fiber networks.

LL outperforms MU and FF in terms of blocking probability in a multi-fiber network (Zang *et al*., 2000)

MAX-SUM: This scheme was proposed for multi-fiber networks but is also applicable to the single-fiber case. It considers all feasible light-paths with their preselected routes in the network and tries to maximize the remaining path capacities after light-path setup.

This scheme is based on the assumption that the set of possible connection requests are known in advance and their routes are preselected.

Relative Capacity Loss (RCL): RCL scheme is based on the study that minimizing total capacity loss sometimes does not direct to the best selection of wavelength (Yang *et al*., 2007).

Suppose a wavelength i is chosen, that results in blocking one light-path p1 and another wavelength j, if chosen would reduce the capacity of light-paths p2 and p3, but does not block them. In such a case wavelength j would be preferred over wavelength I irrespective of the capacity loss. Thus, RCL computes the Relative Capacity Loss for each path on each available wavelength and then selects the wavelength that minimizes the relative capacity loss sum on all the paths.

Both MAX-SUM and RCL can be used for non-uniform traffic by taking a weighted sum over the capacity losses (Zang *et al*., 2000). RCL has been observed to perform better than MAX-SUM in most cases (Yang *et al*., 2007).

Wavelength reservation: In this scheme, a given wavelength on a particular link is held in reserve for a traffic flow, usually a multihop flow. In Fig. 4, suppose a wavelength λ_1 is reserved on link (1, 2) for connections from Node 0 to 3; thus if a connection request comes in for node 1 to 2, it cannot be established on wavelength λ_1, link (1, 2) even if the wavelength is available (Byungkyu, 2006).

This scheme minimizes the blocking for multi-hop traffic, but increases the blocking for single-hop traffic that is connections that go across only one fiber link.

Protecting threshold: In Protecting Threshold, a single-hop connection is assigned a wavelength only if the number of idle wavelengths on the link is at or above a given threshold (Zang *et al*., 2000). This scheme makes use of the current network state information, hence can work on-line. It can also work off-line, if the network traffic is static. This is done by managing the static set of light-paths in sequence.

Another issue when assigning wavelengths to the static problem is of arranging the light-paths (Byungkyu, 2006).

Fault tolerant routing: In WDM networks, it is often desirable to provide some level of protection against link and node failures in the network when setting up connections. This may be achieved by reserving some additional capacity.

Protection: For protection a common approach to is to set up two light-paths (link-disjoint), a primary light-path for transmitting data and a backup path such that the routes for the two light-paths do not share any common links for all incoming connection request.

The reserved backup path is used in case a link failure occurs in the primary light-path.

Fixed-alternate routing provides protection by selecting the alternate paths such that their routes are link-disjoint from the primary route.

A connection can be protected from any single-link failure by assigning one of the alternate paths as a backup path (Pointurier *et al*., 2007).

Implementing a protection scheme in adaptive routing requires that a backup path is set up immediately after the primary path has been established.

Same routing protocol is used to determine the backup path except that the cost of the link that is being used on any wavelength by the primary path is set to ∞. This results in a disjoint link from the primary path (Zang *et al*., 2000).

Restoration: Restoration is an alternative approach, in which the backup path is set up dynamically after the link failure has occurred. Restoration process can only be successful if adequate resources are existing in the network. When a fault occurs, dynamic discovery and setting up of a backup path under the restoration method take considerably longer than switching over to the pre-established backup path using the protection technique.

Wavelength conversion: In a wavelength-routed WDM network, the wavelength-continuity constraint can be eliminated if we are able to use a wavelength converter to convert the data arriving on one wavelength on a link into another wavelength at an intermediate node before forwarding it on the next link. Such a technique is feasible and is referred to as wavelength conversion. WDM networks equipped with wavelength conversion capability are referred to as wavelength-convertible networks.

Light-paths between two nodes cannot be established if the available wavelengths on links (in that path) are different even if there are free wavelengths available. This is due to wavelength continuity constraint; however, if the nodes in the network support Wavelength Conversion (WC) capability at every node than this problem does not exist.

Wavelength conversion may be classified into two forms: Optical-Electronics-Optical (OEO) conversion and All Optical Conversion (Houmaidi and Bassiouni, 2006).

Optical-Electronics-Optical conversion (OEO): Converts signals from the optical domain to the electronic domain and then back to the optical domain. Optical Cross connects are used in this type.

All optical conversion: Signals remain in the optical domain, no conversion is needed. All Optical Cross connections are used in this type.

Figure 7 shows an example of wavelength conversion.

If a wavelength converter has the capability to change any wavelength to any other wavelength, it is said to have full-range capacity. Wavelength assignment is not an issue in such networks; only the routing problem is of concern (Zang *et al*., 2000). The objective in most approaches is to have minimum overall blocking probability while using a few number of wavelength converters.

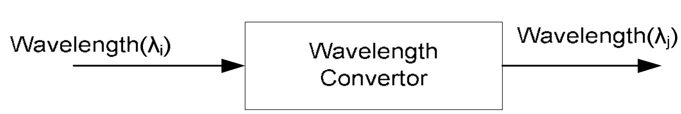

Fig. 7: Wavelength conversion

METHODOLOGY AND APPROACHES

The random and first-fit wavelength assignment algorithms were compared on an arbitrary topology for without wavelength conversion. Approximate analytical model for the clear channel blocking probability of the network has been considered. The objective of this analysis is to calculate the blocking probability.
Following assumptions were made for the analysis:

- An arbitrary topology was chosen for the network with fixed number of wavelengths in each link
- Let W be the wavelengths carried by the fiber
- L represent the Load
- Pb (L, W) = blocking probability
- Assume Point to point traffic
- No Queuing of connection request
- Blocked connection will be rejected
- Mutually independent link loads
- Assume Static Routing

Assuming no wavelength conversion taking place we calculate the blocking probability.

For the wavelength assignment we considered the following two constraints:

- **Wavelength continuity constraint:** Same wavelength must be used on all links in the light-path between source and destination nodes.
- **Distinct wavelength constraint:** Distinct wavelengths must be assigned to all light-paths using the same link.

The blocking probability is calculated as the ratio of Total number of calls blocked to the Total number of calls generated.

Erlang-B formula has been used to calculate the blocking probability on the link:

$$P_{b(L,W)} = \frac{\frac{L^W}{W!}}{\sum_{i=0}^{W} \frac{L^i}{i!}}$$

Simulations were carried out using Random wavelength Assignment Algorithm and First Fit algorithm which are discussed in Random wavelength assignment (R) and First-Fit (FF).

RESULTS AND DISCUSSION

Performance of Random wavelength Assignment and First Fit algorithm was analyzed using MATLAB 7.2 of Math works. The blocking probability of the network is compared keeping the number of channels (C = 11) and number of links = 10, as fixed and varying the load in Erlangs.

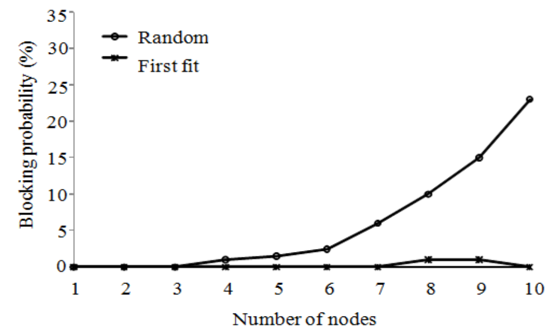

Fig. 8: Blocking probability vs. number of nodes for 2 erlangs per link load

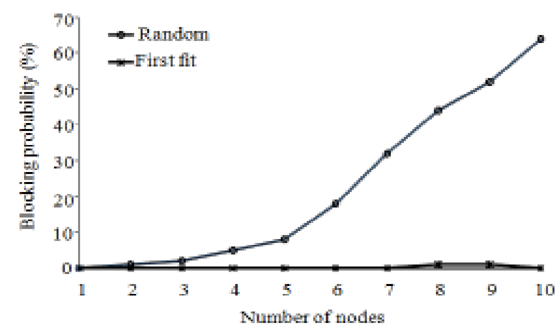

Fig. 9: Blocking probability vs. number of nodes for 3 erlangs per link load

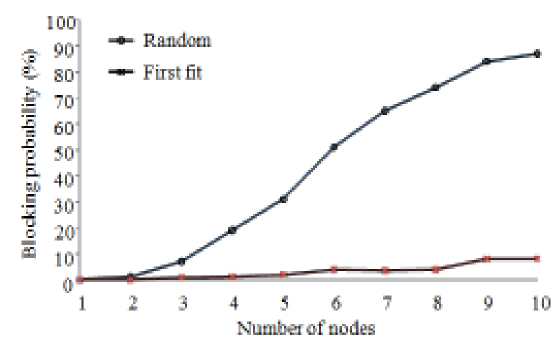

Fig. 10: Blocking probability vs. number of nodes for 4 erlangs per link load

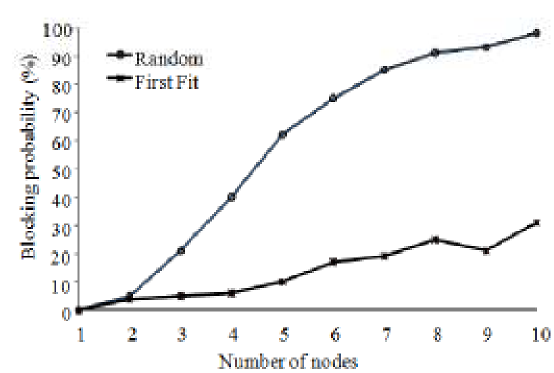

Fig. 11: Blocking probability vs. number of nodes for 5 erlangs per link load

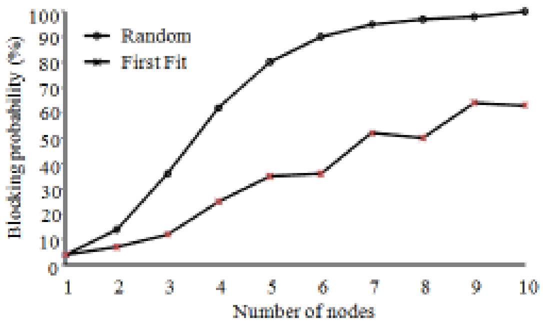

Fig. 12: Blocking probability vs. number of nodes for 6 erlangs per link load

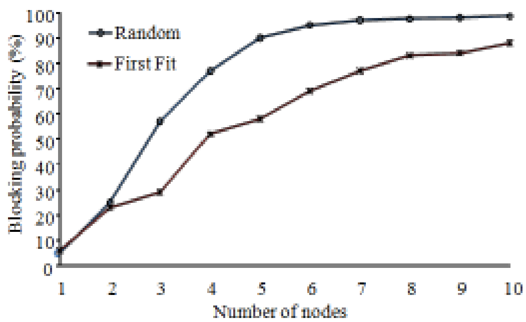

Fig. 13: Blocking probability vs. number of nodes for 7 erlangs per link load

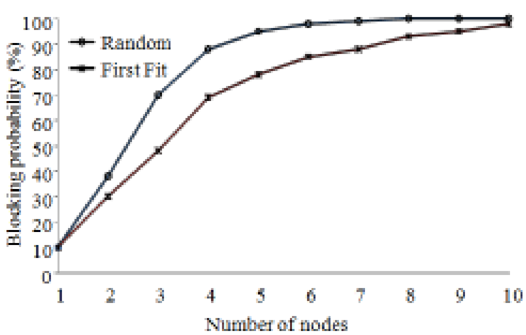

Fig. 14: Blocking probability vs. number of nodes for 8 erlangs per link load

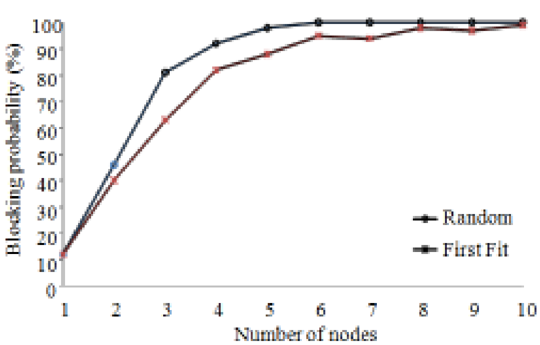

Fig. 15: Blocking probability vs. number of nodes for 9 erlangs per link load

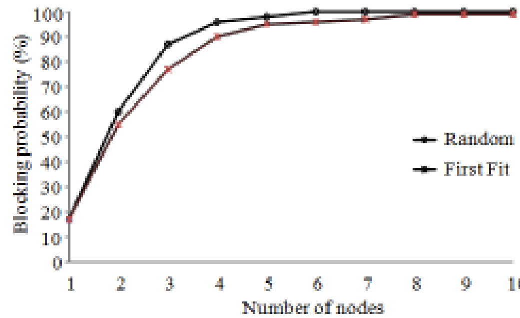

Fig. 16: Blocking probability vs. number of nodes for 10 erlangs per link load

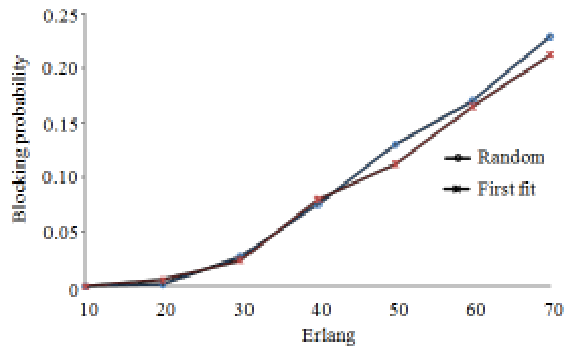

Fig. 17: Blocking probability vs. traffic in erlangs (for single fiber and 16 wavelengths)

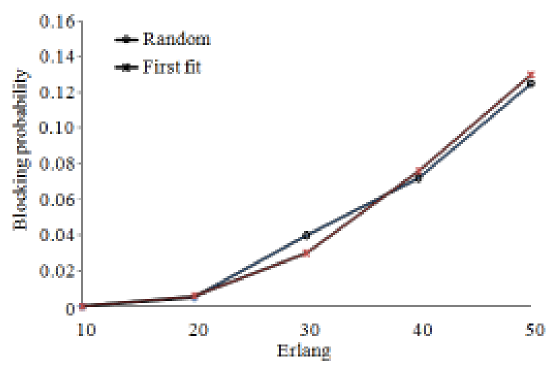

Fig. 18: Blocking probability vs. traffic in erlangs (for two fibers and 8 wavelengths)

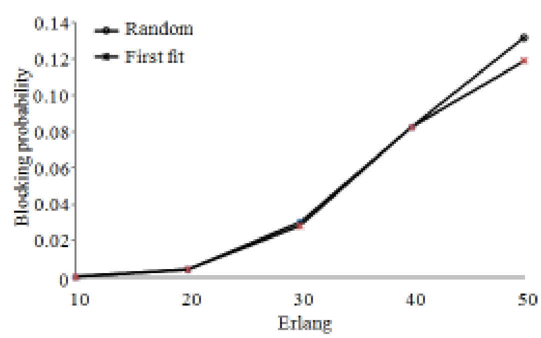

Fig. 19: Blocking probability vs. traffic in erlangs (for four fibers and four wavelengths)

Simulation results for Random wavelength Assignment and First Fit algorithm are shown in Fig. 8 to 16.

The simulation results shown in the above figures reveal that the blocking probability increases with the number of nodes. The blocking probability in case of First Fit wavelength assignment algorithm is lower than that of Random algorithm.

Further results were obtained for blocking probability vs. Erlangs keeping number of fibers per link (1, 2 and 4) and number of wavelengths (16, 8 and 4), respectively as shown in Fig. 17 to 19. It was observed that the Random wavelength assignment algorithm performs well under low load, Fig. 17, while for high load First Fit algorithm performs better as shown in Fig. 18 and 19.

CONCLUSION

In this study we have presented an overview of the routing and wavelength assignment algorithms, with various problems and approaches to connections in WDM optical networks. An analysis of the response of blocking probability of a network for varying load is analyzed for the First Fit algorithm and the Random wavelength assignment algorithm. It is observed that as the traffic (in Erlangs) in each link increases the blocking probability increases. The simulation results show that the First Fit algorithm performs better than the Random wavelength assignment algorithm. Since routing decisions play an important role in evaluating the blocking performance of a network it is critical to choose a wavelength assignment scheme that should take into account its compatibility with the chosen routing protocol in addition to its blocking performance. Further research may be performed in comparing the RWA algorithm's other features such as bandwidth requirement of headers which may include overhead calculations and control messages.

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