

Efficient heuristic algorithms for light-path routing and wavelength assignment in WDM networks under dynamically varying loads

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Abstract

This paper presents heuristic algorithms that may be used for light-path routing and wavelength assignment in optical WDM networks under dynamically varying traffic conditions. We consider both the situations where the wavelength continuity constraint is enforced or not enforced along a light-path. The performance of these algorithms has been studied through simulations. We also compare their performance with that of a simpler system that uses fixed shortest-path routing. Our proposed algorithms provide lower blocking probabilities and are simple enough to be applied for real time network control and management. The heuristic algorithms are computationally simple and efficient to implement and provide good wavelength utilisation leading to efficient usage of the network's resources. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Wavelength division multiplexing; Non-wavelength continuous; Wavelength continuous; Wavelength assignment; Light-path routing

1. Introduction

Wavelength Division Multiplexing (WDM) [1–3] is expected to be a popular technique for constructing large optical networks interconnecting a large number of nodes. With suitable optical cross connects (OXC) [4] at the nodes, such a network will allow very flexible switching of the various wavelengths and light-paths between the active source–destination pairs. This flexibility in routing will make these networks easy to configure and operate and will also improve the reliability of the network by providing easy-to-set-up alternate paths in case of node and link failures.

In contrast to the traditional wavelength assignment problem for a WDM network with static traffic loading [4–6], this paper considers the problem in a network where traffic conditions may change dynamically. In such a dynamic network, the traffic requirements will lead to dynamically changing light-path requirements that will vary with time. This will lead to new light-path requests being generated and older light-paths terminated as the traffic pattern and loading change over time. Various heuristic algorithms for WDM networks have been developed in [7–8]. A least loaded algorithm (LLA) had been proposed for

this earlier in Ref. [7] using a traffic overflow model and a first-fit wavelength assignment strategy [4]. It dynamically chooses the least congested path and wavelength among k shortest paths. Different wavelength assignment strategies and some relevant adaptive routing algorithms for this were proposed and compared in Ref. [8]. For WC–WDM and NWC–WDM networks, this issue of operation under dynamic loading has also been addressed in this paper by proposing various efficient heuristic algorithms that may be used under these conditions. To the extent possible, these heuristic algorithms allow full flexibility in routing. They are also considerably simpler to implement than those of Refs. [7,8] and can therefore be readily used for real-time operation of WDM networks. Simulation studies indicate that they are efficient and will allow network operation with low light-path blocking probabilities over a wide range of offered traffic.

The rest of this paper is organised as follows: Section 2 introduces the concepts of non-wavelength continuous (NWC) and wavelength continuous (WC) light-paths in a WDM network. In Section 3, we present a traffic model for the optical network that is subsequently used to model the dynamic behaviour of a WDM network where the light-path loads vary with time. Section 4 presents the heuristic algorithms proposed by us to operate a WC or NWC WDM network with dynamically varying load. The performance of the proposed algorithms is tested by applying them to a

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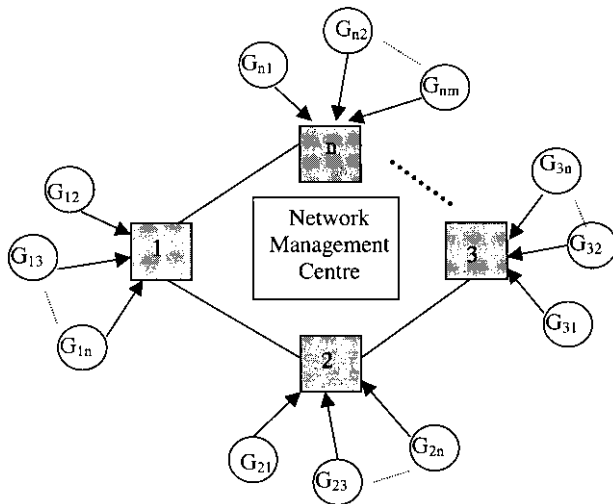


Fig. 1. Network traffic model for dynamic traffic loading.

model of the ARPA-2 network where the light-path loads between the various nodes vary with time. The results of these simulation based studies have been reported in Section 5. The conclusions of the paper are presented in Section 6.

2. Wavelength continuous and non-wavelength continuous WDM networks

Consider a WDM network where different source-destination node pairs communicate with each other using the network's optical links with appropriate routing. The route between a particular source-destination node pair is typically referred to as its *light-path*. This light-path will be set up between the end nodes following the optical links along the specific route being used. An important issue that needs to be considered in this case is whether the system will have the flexibility of changing the wavelength that is being used as we traverse the light-path from the source to the destination (and vice versa). Depending on whether the system has no flexibility or full flexibility, two types of WDM optical networks may be configured. They are WC and NWC networks. It is also possible [9–11] to suggest networks that use partial wavelength conversion (PWC); however, we will not be considering these in this paper.

A wavelength continuous network leads to the simplest choice where no wavelength conversion is allowed along the light-path, i.e. the same wavelength must be used in all the links going from the source to the destination along the selected light-path. Due to the absence of wavelength converters, such a network must satisfy the *wavelength continuity* constraint requiring that a uniquely same wavelength must be used everywhere on any particular light-path in the system.

A non-wavelength continuous (NWC) network will provide the maximum flexibility in wavelength conversion. Each node in the network has a sufficient number of

wavelength converters so that any wavelength on any incoming link may be switched to any wavelength on any outgoing link—this is of course conditional on the fact that the same wavelength on an outgoing link cannot be used twice. These wavelength converters would then permit different wavelengths to be used on different links of a particular light-path making these NWC networks very similar to what one would encounter in traditional circuit switched telephone networks.

3. Traffic model

Consider an n -node WDM network as shown in Fig. 1. We make the simplifying assumptions that:

- every node is reachable from every other node; and
- the maximum available wavelength numbers on all the links have the same value W .

A *light-path generator* G_{ij} is used to model the light-path requirement for traffic between the end nodes i and j . Light-path requests between the end nodes i and j will be generated by this generator and will be representative of the traffic requirement between these end nodes. If a light-path request can be satisfied then the route and wavelengths to be used for this are provided; otherwise, the light-path request fails. The light-path is terminated when its holding time expires and the corresponding wavelengths are released for subsequent use by another light-path. We make the following assumptions in this regard:

- The light-path generators G_{ij} are assumed to be independent of each other. With a large number of nodes generating bursty data, this would be a reasonable assumption which is typically made.
- Light-path generators are assumed to be bi-directional, that is $G_{ij} = G_{ji}$ for $i \neq j$, and $G_{ii} = 0$. This assumption is justified for typical full-duplex bi-directional data communications between nodes, and it simplifies our modelling. However, the approach given in this paper can be extended to cover non-symmetrical cases as well.
- The light-path generators are assumed to generate light-paths following a Poisson arrival process and the holding times for the light-paths are assumed to have an exponential distribution. This is justified following the analogy of typical assumptions made in traditional circuit-switched traffic models, which would also be applicable here.

Assumptions similar to those above have also been made for typical investigations on wavelength routing networks in Refs. [5,7,8,10].

The actual functions of light-path routing and wavelength assignment for a successful light-path request and wavelength release on light-path termination may be done in either a centralised or distributed fashion [12]. In a

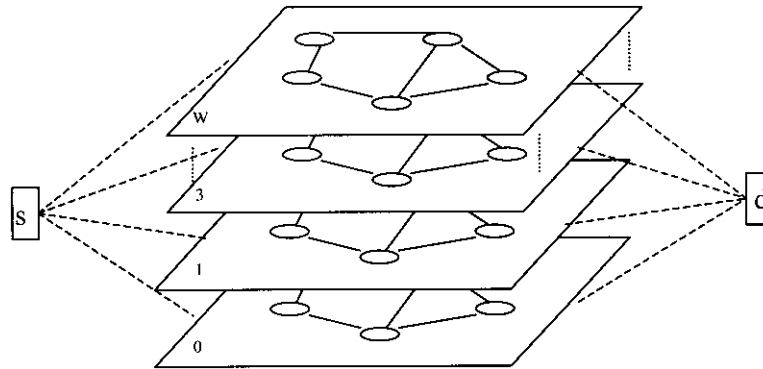


Fig. 2. Wavelength mesh graphs for a network ($W = \text{Wavelength Number}$).

centralised system, a central management node will be needed for this. This node will maintain the required databases, which would have to be updated appropriately, and its decisions will need to be conveyed to the other nodes of the network. This issue of network management has not been addressed in this paper.

4. Heuristic algorithms for light-path routing and wavelength assignment in dynamically loaded networks

In a network where the traffic between the various source and destination nodes is known, one essentially needs to consider optimising light-path routing and wavelength selection so as to satisfy system constraints. The typical constraints are the limited wavelength numbers on each link (for all WDM networks) and the wavelength continuity constraint specific to WC-WDM networks. The problem becomes more complex when one considers the corresponding dynamic situation where new light-path requests are generated randomly between the various source-destination nodes and older light-paths terminate and release their resources for reuse. In this case, a static optimisation approach cannot be followed. Instead, we need to propose methods and algorithms that can be used to tackle the routing of a new light-path and its wavelength assignment in the context of the light-paths already present in the system. In addition, we need to ensure that these algorithms work efficiently so that future (essentially, unknown and random) light-path requests can also possibly be accommodated in the system.

Algorithms for handling the dynamic operation of WDM networks will have to work in different fashions depending on whether the network imposes the wavelength continuity constraint or not. For a NWC network without a wavelength continuity constraint, the algorithm would basically have to find the best possible path (i.e. the shortest or the least loaded) for the new light-path from the source to the destination which has free wavelengths available for use at that instant. The actual wavelength choice on the individual links will not be of concern given the full wavelength

conversion capability of the individual nodes. For a WC network with the wavelength continuity constraint, one would need to consider additionally the issue of the particular wavelength to be assigned to the light-path, in case more than one such wavelength can be chosen. The overall objective of the proposed algorithms for both the WC and NWC cases would be to reduce as much as possible the chances of a new light-path request getting blocked and discarded because a suitable light-path for this request could not be found. Lowering the overall blocking probability of light-path requests will lead to higher values of the overall carried traffic and better utilisation of the network's resources. We present three heuristic algorithms proposed by us for tackling this problem in a dynamically loaded network.

4.1. Greedy algorithm

This algorithm has been proposed for use in WC-WDM networks where a light-path must use the same wavelength throughout between its source and destination. At any particular instant, given the current state of the network, the wavelength mesh graphs of Fig. 2 are used to indicate the current occupancy state of each of the wavelengths on each link of the given network. If a certain wavelength is free on a link, the edge on the corresponding wavelength mesh graph stays connected; otherwise, this edge is removed. When a light-path terminates, the links corresponding to its route are restored in the wavelength mesh graph corresponding to the wavelength used by that light-path. On the other hand, when a new light-path is established, the links corresponding to its route are removed from the wavelength mesh graph corresponding to the wavelength used by that light-path. If there are W wavelengths available on each link, then there would be W such wavelength mesh graphs for the network being considered. These wavelength mesh graphs would change dynamically as light-paths terminate or new light-paths are assigned based on the light-path arrival requests at the various nodes of the network.

Given a new light-path request between node s and node d , the basic approach of the GA is to first find those

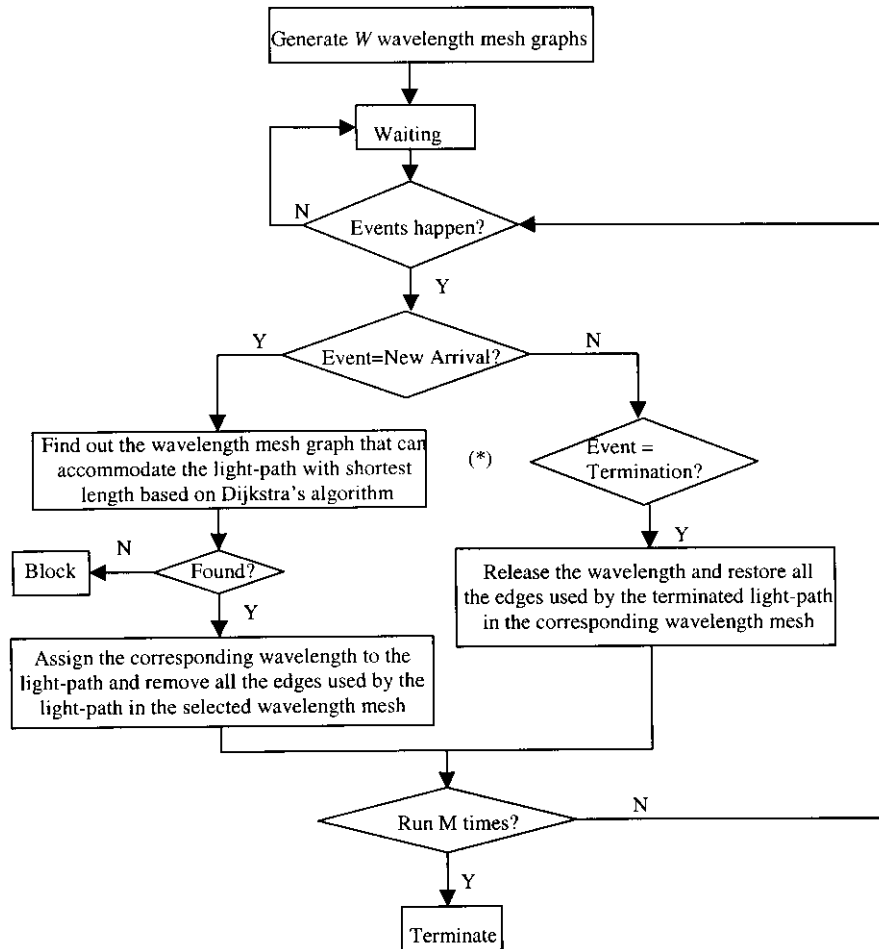


Fig. 3. Flow Chart of Greedy Algorithm (GA) with *Shortest Path Strategy*.

wavelength mesh graphs where a route may be established between these two nodes. If no such graph can be found, then the light-path request is blocked and will be rejected. If only one such graph exists, then the shortest path between s and d on that graph is established as the route of the light-path and the wavelength of this particular wavelength mesh graph is assigned for its use. The links corresponding to this route are also removed from that wavelength mesh graph so that this wavelength is no longer available for subsequent assignment on the links of this light-path until the light-path terminates.

It is possible that there may be more than one such wavelength mesh graphs where node s and node d may be connected by a feasible light-path. In that case, the particular wavelength and route may be chosen following either of the following techniques:

- For the *shortest length preference* (WC-s) method, the wavelength is chosen to be the one for which the wavelength mesh graph provides the shortest path between the two nodes. Note that this will require the shortest path between s and d to be found for each wavelength mesh graph where these two nodes may be connected; the

overall shortest path and the corresponding wavelength is then chosen for assignment to the new light-path requested.

- For the *first-fit preference* (WC-f.f) method, the wavelength mesh graphs are sequentially ordered in a fixed pre-determined sequence. The wavelength mesh graphs are searched in this sequence until we find the first wavelength mesh graph where the nodes s and d may be connected. The shortest route between these nodes in this particular wavelength mesh graph is taken to be the route of the new light-path to be established and the wavelength selected is the one corresponding to this wavelength mesh graph.

The flow chart for WC-s strategy of this algorithm is shown in Fig. 3. The flow chart for the WC-f.f will be a simple modification of this and can be easily obtained by suitably modifying Fig. 3. Note that in both cases, once the new light-path request is given its route and the wavelength to use, the links on this route must be removed from the corresponding wavelength mesh graph.

This algorithm adopts a *greedy* approach toward assigning wavelengths. This would be simple to implement when

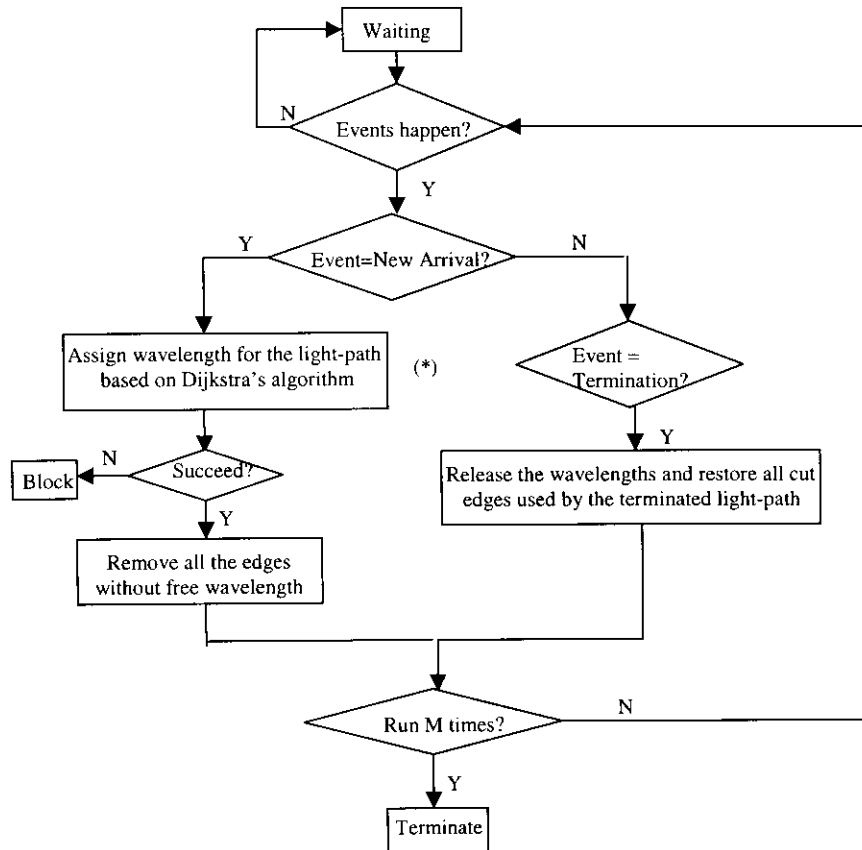


Fig. 4. Flow chart of the exhaustive algorithm.

the wavelength numbers are not very large. The effort involved in searching for the route and the wavelength to be assigned will increase as the wavelength number of the links increases. For very large networks with large wavelength numbers, the effort involved in searching for and evaluating the path lengths of the feasible light-paths in all the wavelength mesh graphs may make this approach unattractive. For networks of medium complexity, such as the ARPA-2 network, our simulation studies show this approach to be quite practical to implement. Of the two choices, WC-s and WC-f.f, the former would be more complex as more computations would be required to evaluate every possible light-path in all the wavelength mesh graphs. The WC-f.f approach would be easier to implement and appears to give almost comparable results in our simulation studies.

4.2. Exhaustive algorithm

This algorithm is proposed for use in NWC WDM networks with dynamic traffic loading. (A modified version of this algorithm may be proposed for WC WDM networks.) The detailed flow chart for the algorithm is given in Fig. 4. In this algorithm, we always maintain a current graph of the network such that only those edges are connected where the corresponding links have *one or more* free wavelengths. For

a new light-path request, the approach then is to apply the shortest-path algorithm using the current graph to find the shortest route, if any, between the source and destination nodes. If no such path can be found, the light-path request is blocked and discarded. If a path can be found then this path is assigned to the light-path; for each link on this path, any of the wavelengths available may be chosen for use as there would not be any wavelength continuity constraint in this NWC network. When a new light-path is established, the current graph of the network may need to be changed. This will happen if a link (on the route of the new light-path) runs out of free wavelengths once the new light-path has been assigned; the edges corresponding to all such links will have to be removed from the current graph once this light-path has been assigned. When a light-path is terminated, the corresponding wavelengths are freed and can be used for assigning new light-paths. Note that the current graph of the network may also need to be suitably modified after a light-path is terminated. Restoring edges that may be missing earlier (because no wavelengths were free on the corresponding links) may be possible, in case the light-path termination leads to a free wavelength on any such link.

It is possible to propose a version of this algorithm for use in WC networks. This will be essentially the same as the algorithm given above for the NWC case except that the additional constraint of *wavelength continuity* will need to

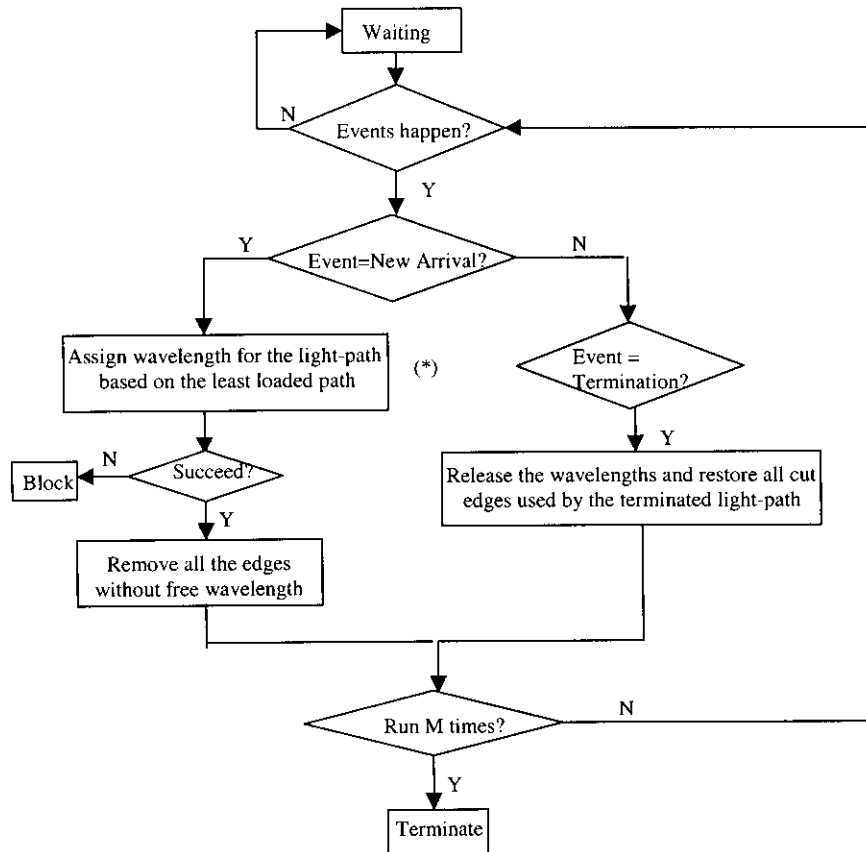


Fig. 5. Flow chart of least loaded algorithm.

be imposed. In this case, the current graph of the network will be used to find the shortest length route where the wavelength continuity constraint can be met. Simulation studies of the performance of this algorithm have not been done in this paper and may be examined in the future.

4.3. Least loaded algorithm

This algorithm is similar to the Exhaustive Algorithm proposed above except that the criteria used for path selection is to choose the one that is least loaded (rather than select the shortest one as in EA). As for the EA algorithm, we consider this first in the context of a NWC network. The flow chart for this would be the same as that for EA except for the block marked with a (*) in Fig. 4. The Exhaustive Algorithm uses the shortest-path algorithm to route the light-path based on the hop number, while in this algorithm, the light-path routing will depend on the current network traffic state. The path with the lowest traffic load (least loaded path) will be selected.

Our procedure for selecting the least loaded path is based on the current graph of the network, as in the case of EA, but uses the number of busy wavelengths on each link as the “length” of the link. The least loaded path can then be found by applying Dijkstra’s shortest-path algorithm to this graph

using this modified definition of “length”. The detailed flow chart for this algorithm is shown in Fig. 5.

It should be noted that this algorithm actually tries to route the new light-path along a route with least number of busy wavelengths. This would, in effect, tend to keep the bandwidth usage of the various links as uniform as possible and would, therefore, tend to distribute the traffic in the network as uniformly as possible over the various possible routes. Even though the complexity of shortest-path computation may be somewhat higher in this case because of the modified definition of the link “lengths”, we expect that it will perform better than the Exhaustive Algorithm. This has indeed been borne out by our simulation studies—these simulation results are given in Section 5.

It should be noted that the LLA approach of [8] uses only the spare capacity of the bottleneck link on the light-path as the reference measure of congestion. On the other hand, we have tried to consider the total wavelength occupancy along the light-path as our load measure that we try to minimise. The approach of [8] is also more computationally complex as it requires the computation and relative evaluation of the k -shortest paths in the network.

Apart from its implementation in a NWC network (as discussed above), we have also studied our proposed LLA algorithm for implementation in a WC network. For the WC

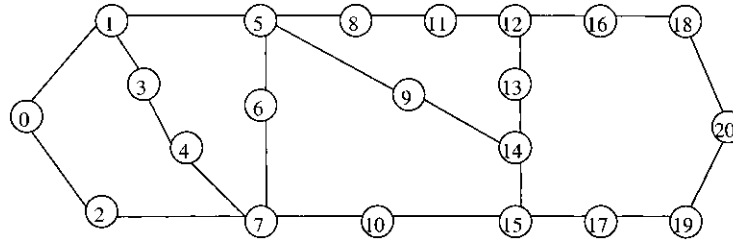


Fig. 6. The ARPA-2 network.

case, the additional constraint of *wavelength continuity* will have to be imposed while selecting the light-paths. Using the current graph of the network and the modified definition of “link length” as given above, the shortest path (if any) between the source and the destination satisfying the wavelength continuity constraint will be found. Note that as for the GA case, the wavelength assignment method used may either be the *first-fit strategy* or the any one of the possible wavelengths can be chosen randomly. (We have used the *first-fit strategy* in our simulation studies of this algorithm.)

5. Performance results

We have studied the performance of the GA, EA and LLA algorithms proposed in Section 4 using simulations. The simulation studies were carried out on a model of the ARPA-2 network shown in Fig. 6, with wavelength number $W = 16$, i.e. a maximum of 16 wavelengths are available for use in each link of the network. Each node pair in the network is assumed to have a light-path generator as mentioned earlier in Section 3. (We need $21 \times (20)/2$ light-path generators for the ARPA-2 network following this traffic model.) The generators are considered to be identical to each other. As mentioned in the traffic model of

Section 3, we assume that a generator generates new light-path requests following a Poisson arrival process with an arrival rate of λ per second. Each light-path request has a mean holding time of $1/\mu$ s following an exponential distribution. This assumption is in line with the overall modeling assumptions made earlier. We normalise our time measurements using $1/\mu = 1$ so that the light-path traffic load of each generator may be considered to be λ erlangs. Note that this has been shown as the traffic load in results of Figs. 7–9. The table of data for these are given in Appendix A. Each simulation run is done for 10^6 light-path arrival requests as this was observed to be generally capable of providing statistically significant results. However, confidence level measurements have not been computed or shown for the individual simulation results.

Fig. 7 shows the performances of the NWC algorithms under dynamic traffic loading in the ARPA-2 network. This has been shown as the overall probability of a new light-path request getting blocked (i.e. the Blocking Probability) as a function of the light-path traffic load from one traffic generator. It should be noted that the total light-path traffic load of the overall network would correspond to the sum of light-path traffic of all the (210, identical) generators in the network. The results shown for the caption “Shortest(NWC)” correspond to the case where the fixed

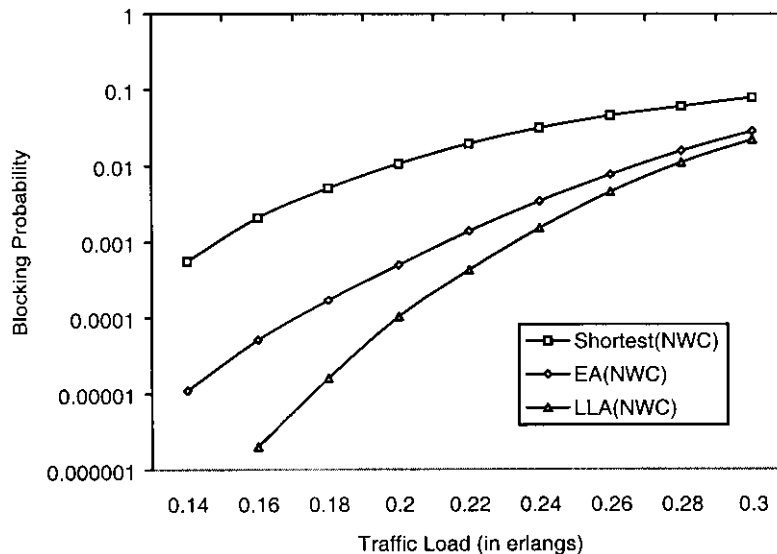


Fig. 7. The blocking probability of NWC algorithms in the ARPA-2 network ($W = 16$).

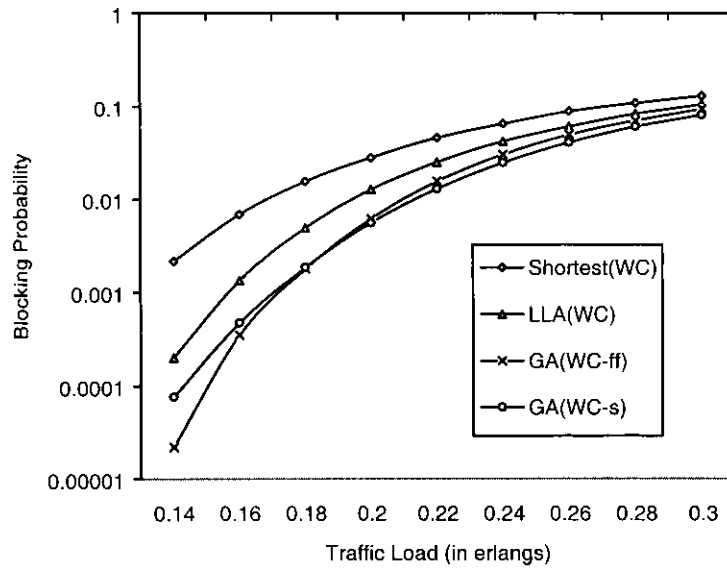


Fig. 8. The blocking probability of WC algorithms in the ARPA-2 network ($W = 16$).

shortest-path between the source and the destination nodes is always the one used for the light-path, if possible. In case routing along this path is not possible because of unavailability of free wavelengths along this route, then the new light-path request is blocked and rejected. This fixed shortest path strategy will be simple to implement and can also be used to handle dynamic network loading.

Our proposed algorithms will always allow greater flexibility for light-path routing than this “fixed shortest-path” scheme and is therefore expected to perform better under all values of traffic loads. This can be seen in Fig. 7 where both the Exhaustive Algorithm (EA) and the Least Loaded Algorithm (LLA) provide lower blocking probabilities than the fixed shortest-path algorithm over the entire range of traffic loads. It should also be noted that the LLA shows better

performance with lower blocking probabilities than the EA. The reason for this probably is that, in exchange for its greater complexity, it is better able to distribute the traffic evenly over the network—this is expected to lead to fewer bottlenecks and allows the links to be used better overall than the EA. The EA tries to be efficient by always selecting the shortest path currently available but that may actually lead to concentration of traffic on a few routes leading to higher overall blocking. However, as the traffic loading increases, the advantage gained by LLA through this even distribution of traffic is expected to diminish and the results of the two algorithms tend to approach each other as can be seen in Fig. 7.

Similar results for the WC case have been shown in Fig. 8. This shows the blocking probability of a light-path

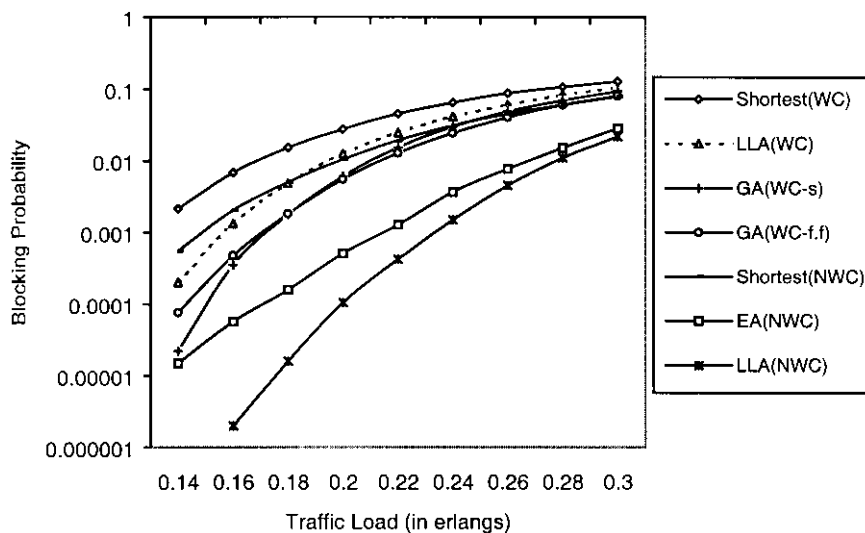


Fig. 9. The blocking probability of different algorithms in the ARPA-2 network (NWC and WC, $W = 16$).

request as a function of the offered light-path traffic load from one generator for the Least Loaded Algorithm (LLA) (applied with the WC constraint) and the Greedy Algorithm (GA) (suggested only for WC). For the GA case, we have shown the results for both the wavelength assignment strategies—GA(WC-s) and GA(WC-f.f)—mentioned in Section 4. For purposes of comparison we have also showed the simulation results obtained by applying the fixed shortest-path algorithm mentioned earlier—in this case, this algorithm is applied with the wavelength continuity constraint.

As expected, we find that even for this case, the Least Loaded Algorithm and the Greedy Algorithm show less blocking (because of their additional routing flexibility) than the fixed shortest-path algorithm. In this case, the GA outperforms the LLA by providing lower blocking probabilities for the same level of offered traffic. This is possibly because of the fact that by trying to distribute the traffic evenly over the links, the LLA may some times force light-path routing over a longer path. In this case (i.e. with the restriction imposed by the wavelength continuity constraint), the GA's greedy strategy of grabbing the shortest-path currently available seems to result in a somewhat better performance. (Note that is in contrast to the trend observed for the EA and the LLA results for the NWC case.)

The two GA strategies show performance results fairly similar to each other with some minor differences over the traffic range considered. When the traffic load is small, GA-f.f displays a better performance whereas at higher loads, GA-s performs marginally better. We actually expect GA-s to provide better performance than GA-f.f at high loads because of its ability to choose paths of shorter lengths. This will also mean than under such loading, the bulk of the traffic accepted will arise from light-path requests which need relatively shorter path lengths. When the traffic loading is light, this may not be significant and GA-f.f may perform better as it will tend to keep the wavelengths with higher sequence numbers consistently less loaded—this will in turn reduce blocking for traffic which cannot do without longer light-paths because of the topology of the network.

Finally, we have shown in Fig. 9 an overall comparison for the different NWC and WC algorithms. The NWC approach always provides a lower blocking probability than the corresponding WC case because of its inherent flexibility in wavelength assignment and routing. One can therefore generally conclude that if the cost of wavelength converters is not too large, incorporating them in the system will allow better overall usage of the wavelength resources of the network. Interestingly, however, we do find that the efficient versions of the WC techniques can approach closely the performance of some of the NWC methods.

6. Conclusion

For optical networks using WDM and wavelength rout-

ing, we have presented several heuristic algorithms, which may be used to efficiently operate the network under dynamic traffic loading. These algorithms handle light-path routing and wavelength assignment in systems where the light-path traffic can vary with time. We have proposed algorithms suitable for use in networks where the wavelength continuity constraint is imposed along the light-path as well as ones, which may be used where this constraint is not present. These algorithms have been studied through the simulations on a model of the ARPA-2 network. These performance results have been presented and compared in this paper.

The advantages of seeking a compromise between the no-conversion approach of WC and the full-conversion requirement of NWC are an area of future research. This may be done with PWC strategies, which may also be able to handle light-path routing efficiently with proper choice of converter placement and wavelength selection. We plan to address this and related issues in our subsequent research.

Appendix

Table 1

| Traffic load | Shortest (WC) | LLA (WC) | GA (WC-s) | GA (WC-f.f) | Shortest (NWC) | EA (NWC) | LLA (NWC) |
|--------------|---------------|----------|-----------|-------------|----------------|----------|-----------|
| 0.14 | 0.002155 | 0.000201 | 0.000022 | 0.000076 | 0.000555 | 0.000015 | – |
| 0.16 | 0.006882 | 0.001337 | 0.000351 | 0.000474 | 0.002069 | 0.000057 | 0.000002 |
| 0.18 | 0.015549 | 0.004894 | 0.001783 | 0.001845 | 0.005089 | 0.000159 | 0.000016 |
| 0.20 | 0.027931 | 0.012664 | 0.006130 | 0.005584 | 0.010565 | 0.000509 | 0.000104 |
| 0.22 | 0.045787 | 0.025000 | 0.015564 | 0.012889 | 0.019491 | 0.001288 | 0.000424 |
| 0.22 | 0.064794 | 0.041845 | 0.030101 | 0.024599 | 0.031361 | 0.003680 | 0.001505 |
| 0.26 | 0.088077 | 0.060684 | 0.049305 | 0.040580 | 0.045719 | 0.007762 | 0.004541 |
| 0.28 | 0.107602 | 0.082842 | 0.070064 | 0.060705 | 0.060788 | 0.015422 | 0.011054 |
| 0.30 | 0.128525 | 0.104500 | 0.093214 | 0.080433 | 0.079017 | 0.028827 | 0.022030 |

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