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Efficient Wavelength Assignment Algorithms for Light Paths in WDM Optical Networks With/Without Wavelength Conversion

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Abstract. In order to reduce the overall wavelength number required in a wavelength division multiplexing (WDM) network with static traffic loading, new heuristic algorithms for wavelength assignment are proposed in this paper. A new parameter called ''one-wavelength-decrease cost'' is defined and used to compare the efficiency of these algorithms. Comparative simulation studies have been carried out for various network topologies to investigate the effectiveness of the proposed algorithms.

Keywords: wavelength routing, non-wavelength continuous, wavelength continuous, NWC, WC, one-wavelength-decrease cost

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 alternative paths in case of node and link failures.

In a network with static traffic loading, the traffic requirements between different node pairs would be known *a priori*. From the viewpoint of the network's optical complexity, it would be desirable to support all the static network traffic with as small a set of different wavelengths as possible. The size of this set, i.e., the number of different wavelengths required in the overall network, will be referred to as the wavelength number of the network [4]. This is usually directly related to the cost of the WDM optical network.

Various algorithms have been proposed [4–10] for minimizing the wavelength number of a network. In Chlamtac et al. [4], a task scheduling method is used to carry out wavelength assignments; the author also subsequently shows that, in case of static traffic, the wavelength number in a wavelength continuous (WC) network will be virtually the same (or only slightly larger) as that in a non-wavelength continuous (NWC) network. A new method of computing the lower bound for the required wavelength number is proposed in Nagatsu et al. [5]; a new algorithm is also proposed to get a low cost network implementation where the wavelength number of a link is taken to be the weight (or cost) of that link. In Chlamtac et al. [6], an approach using a topology conversion technique is given for designing a low cost WDM network. In Ramaswami and Sivarajan [7], the mathematical formulation of the design problem is given along with heuristics for solving it by relaxing some of the constraints one-by-one. A heuristic algorithm has been given in Wauters and Demeester [8] and it is shown that networks with and without wavelength converters require roughly the same number of wavelengths. A hybrid solution is also proposed [8] where wavelengths are electrically regenerated in some specific nodes. A multi-commodity flow model with randomized routing is applied [9] followed by graph coloring algorithms. In Cinkler et al. [10], global methodologies and optimization options are proposed for dimensioning the WDM optical layer in future transport networks.

It should be noted that in most of these papers, the sole objective is to minimize the total wavelength number of the system. This is done regardless of the effect this may have on other parameters such as the light-path lengths encountered in the system. In fact, all algorithms, which optimize the light-path search problem, will tend to increase the average light-path length when they try to decrease the wavelength number. For today's optical transmission systems (especially in international networks and considering the dispersion and the non-linear effects in the fibre) light-path length considerations may in fact be of crucial importance. As a matter of fact, it would probably be better to characterise the efficiency of such algorithms by a one-wavelength-decrease cost parameter apart from the more typical wavelength number considerations. We have defined this to be the increase in the average light-path length incurred in the network when one wavelength is decreased in the system [11]. In this paper, we propose three heuristic algorithms for wavelength assignment in a WDM network that tries to decrease wavelength number. At the same time, the one-wavelength-decrease cost performances of these algorithms are also evaluated.

2 Wavelength Continuous, 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, different types of WDM optical networks may be configured. This will lead to networks which are either wavelength continuous (WC) or non-wavelength continuous (NWC). A partial wavelength conversion (PWC) approach for WDM networks has also been proposed [12–14], but would not be considered by us in this paper.

A WC 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 [4] requiring that the same wavelength must be used everywhere on any particular light-path in the system.

A 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 encounters in traditional circuit switched telephone networks. The techniques used to analyze circuit switched networks will also be of use in analyzing NWC-WDM networks.

To see the effects of WC and NWC based wavelength assignment in a WDM network, consider the examples shown in Fig. 1(a) and (b). In Fig.1(a), the source destination pairs are 0–3, 0–2 and 2–3. In this case, two wavelengths are needed by the NWC approach whereas the WC scheme, which maintains wavelength continuity, is forced to use three different wavelengths. In general, the NWC schemes provide more flexibility in wavelength assignment and will require smaller wavelength numbers than their WC counterparts. The former would, however, incur the added complexity of wavelength conversion on a light-path from the source to its destination. Fig. 1(b) illustrates the effect of light-path choice (and wavelength number) on the path length encountered in individual source destination paths. In the network shown, the source-destination pairs are 0–2 and 1–2. If we use the shortest-path algorithm to assign the wavelengths, then two different wavelengths are needed. However, if we change route $1 \rightarrow 2$ to the route $1 \rightarrow 3 \rightarrow 2$, then only one wavelength is needed. Note that doing this reduces the wavelength number but that the length for the $1 \rightarrow 2$ path is now higher because it has to traverse two links rather than just one.

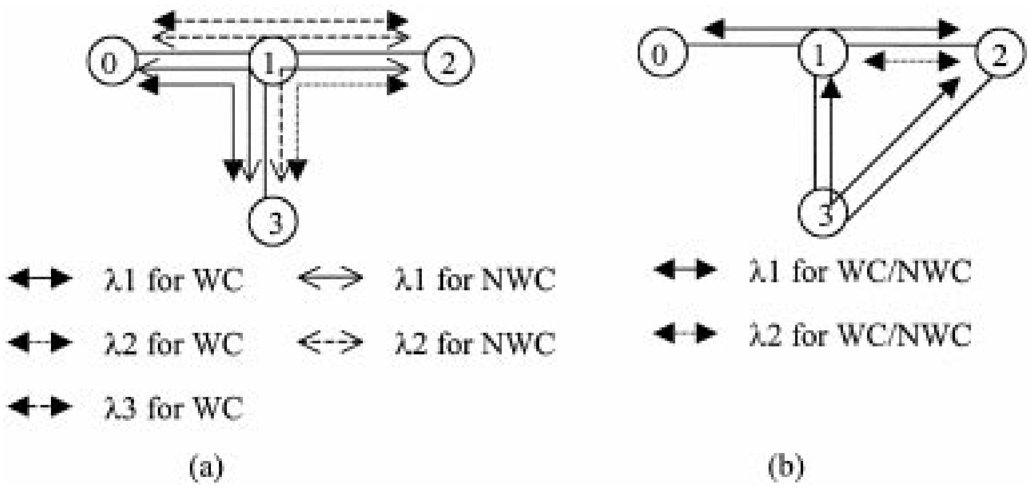

Fig. 1. Wavelength assignment in a WDM network.

3 The One-Wavelength-Decrease Cost Parameter

In a WDM network there will be a trade-off between the total number of wavelengths used and the average light-path length incurred in the network between the various source-destination pairs. We define a new parameter one-wavelength-decrease cost to evaluate this trade-off. The way this is defined for a particular algorithm, say algorithm B, is as follows:

Let A denote the mean length of all light-paths in the network and $W_{\max}$ the maximum wavelength number required. With L_i as the length of i-th light-path, we get:

$$A = \frac{1}{M}\sum_{i=0}^{M-1} L_i,$$

given there are M light-path requests in total.

We define the following:

- A_D: the mean length of all light-paths in the network using Dijkstra's shortest-path algorithm;
- A_B: the mean length of all light-paths in the network using algorithm B (the algorithm being considered);
- $W_{\max D}$: $W_{\max}$ using Dijkstra's shortest-path algorithm;
- $W_{\max B}$: $W_{\max}$ using algorithm B;
- $\mathrm{Cost_B}$ denotes the one-wavelength-decrease cost of algorithm B as defined below.

(Note that this cost definition is done in a normalized fashion with Dijkstra's algorithm being taken as the reference.)

$$\mathrm{Cost}_B = \frac{\left(\frac{A_B - A_D}{A_D}\right) \Big/ \left(\frac{W_{\max D} - W_{\max B}}{W_{\max D}}\right)}{(W_{\max D} - W_{\max B})}.$$

Here, A_B and A_D denote the respective average lengths (measured in terms of number of hops) of the light-paths obtained through algorithm B and Dijkstra's shortest-path algorithm and $W_{\max B}$ and $W_{\max D}$ denote the respective maximum required wavelength numbers obtained from these two algorithms. Note that Dijkstra's shortest-path algorithm will typically give the highest value of $W_{\max}$ and the smallest value of A and is useful as a reference for comparing the performance of other algorithms. Note that $(A_B - A_D)/A_D$ denotes the fractional length increase of algorithm B compared to the length of Dijkstra's shortest-path algorithm. Similarly, $(W_{\max D} - W_{\max B})/W_{\max D}$ denotes the fractional wavelength number decrease of algorithm B. For a good algorithm, we expect the fractional delay increase to be small and the fractional wavelength number decrease to be large. Their ratio actually denotes the total cost for algorithm B to decrease $(W_{\max D} - W_{\max B})$ wavelengths. Normalizing by $(W_{\max D} - W_{\max B})$ then gives the one-wavelength-decrease cost, Cost_B.

4 Heuristic Algorithms for NWC and WC Networks

As in Banerjee and Mukherjee [9], we will divide the whole problem into two steps. The first one is light-path search, and the second is wavelength assignment. Since these two steps are both NP-complete [15–16], it may be efficient to solve them using heuristic algorithms. In this section, three heuristic algorithms will be proposed for doing light-path search. For wavelength assignment, the simple first-fit method is adopted. In addition, Dijkstra's [17] shortest-path algorithm will be used to search for low-delay light-paths based on suitable modifications to the original network topologies.

4.1 Greedy Algorithm (GA)

In this algorithm, we begin by searching for a light-path for the first *s-d* node pair and assign wavelength λ_1 to it. Next, we remove all the links on the light-path of the first *s-d* node pair from the network and start searching for a light-path for the second *s-d* node pair based on the current topology. If a light-path can be found, we will continue to assign wavelength λ_1 for it and will remove all links on this light-path for the subsequent steps; otherwise, we keep the light-path problem for this *s-d* pair as pending and move on to the other node pairs. We repeat this process for all the other *s-d* node pairs so as to make full use of λ_1. After all *s-d* node pairs have tried, we restore the network to its original topology and use a new wavelength λ_2 to assign wavelengths for the remaining light-paths repeating the earlier strategy. This process is repeated with more wavelengths until wavelengths have been assigned for all the required light-paths. A flow chart for this algorithm is shown in Fig. 2, where C denotes the number of node pairs that require light-paths, and T_j denotes the *j*-th such kind of node pair (Note: The notations for these two terms will keep the same in the following other flow charts). The flow chart is similar for WC and NWC networks, except that the wavelength continuity constraint also needs to be considered in the former. Note that in Fig. 2, the steps shown inside the dotted lines are only required for WC networks.

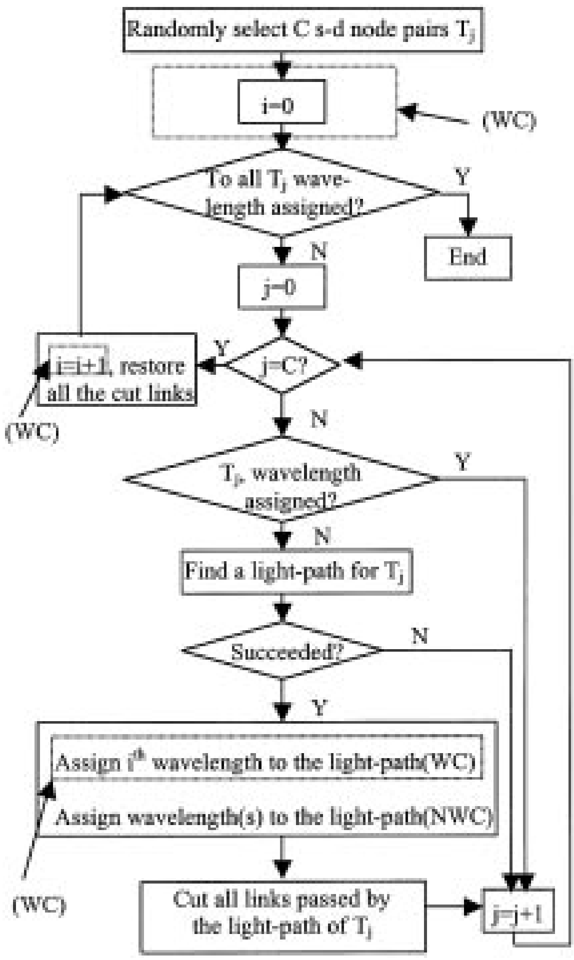

Fig. 2. The flow chart for GA.

4.2 Exhaustive Algorithm (EA)

This algorithm is only meant for NWC networks. It first finds light-paths and assigns wavelengths for all the *s-d* node pairs and then uses this to find the maximum number of wavelengths ω required overall by the network. It then tries to repeat the process by decreasing the maximum number of wavelengths by one, i.e., $(\omega - 1)$, and then searches for light-paths and assigns wavelengths for all the *s-d* node pairs once again. During this repetition, whenever the number of wavelengths in a link becomes equal to $(\omega - 1)$, the link is removed so that the remaining light-paths cannot be assigned a path through this link any further. (This actually ensures that the number of wavelengths used will not exceed $(\omega - 1)$.) After the light-paths for all the *s-d* node pairs have been found and wavelengths for them have been assigned, the process is again attempted with the maximum number of wavelengths limited to $(\omega - 2)$. This process is continued until the wavelength number becomes such that no light path can be found between at least one *s-d*

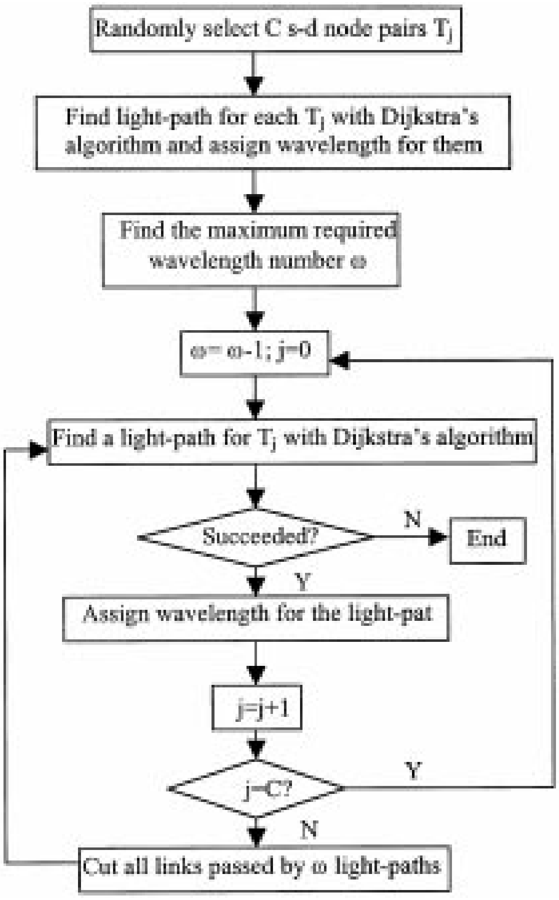

Fig. 3. The flow chart for EA.

node pair in the network. The flow chart for this algorithm is shown in Fig. 3.

4.3 Congestion Rerouting Algorithm (CRA)

This algorithm is only meant for WC networks. It first sorts the light-paths of all *s-d* node pairs from the longest to the shortest, (similar to task scheduling method in Chlamtac et al. [4]) based on their shortest-path lengths. It then reassigns the wavelengths for these sequenced light-paths from lower order wavelength to higher order wavelength, and finds the maximum wavelength number ω required overall by the network. It then finds all the light-paths using the highest order (i.e., the ω-th) wavelength, randomly selects one of them, and removes all the links that it passes through. Next, it removes all links using the first wavelength, then tries to find a new light-path for the *s-d* node pair (i.e., of the selected light-path) such that the first wavelength may be used for this. If this fails, all the previously removed links using the first wavelength are restored and then the second wavelength is tried. In the process, if all the attempts using the first to the $(\omega - 1)$-th wavelength fail, the procedure terminates. Otherwise, the same procedure is repeated for the other light paths which use the ω-th wavelength. When all the light paths using the ω-th wavelength have been examined, the algorithm sets $\omega = \omega - 1$ and repeats the same steps once again. The flow chart for this algorithm is shown in Fig. 4.

An algorithm similar to this can also be proposed for a NWC network. Even though we had originally studied such an algorithm, it has not been included here as it was found to be more complicated and did not show adequate performance improvement to justify its increased complexity.

5 Simulation Results

In the following, we present simulation results obtained for wavelength assignment for the ARPA-2 network shown in Fig. 5. The ARPA-2 network with 21-nodes and 26-links has a fairly rich set of interconnections and has been used to study the performances of various network protocols and algorithms. Each of the algorithms proposed earlier is individually studied by applying them in this network.

Consider a situation where a particular algorithm is to be studied for traffic corresponding to *M* active source-destination pairs. For a particular simulation run, *M* such node pairs are randomly selected in the network and the algorithm to be studied is applied. In order to get statistically averaged results, the simulation experiment is run 100 times choosing the *M* source-destination pairs randomly for each run. The results of these 100 runs are then averaged to obtain the overall mean result when there are *M* active node-pairs in this network and the particular algorithm considered is being applied. This procedure is repeated by varying *M* from 10 to 100 in steps of 5 in order to get an idea of the algorithm's performance with increasing number of active source-destination node pairs. Note that in this approach, increasing the number of source-destination pairs also effectively increases the total traffic in the network, i.e., increases the network loading.

The results obtained from simulations of the

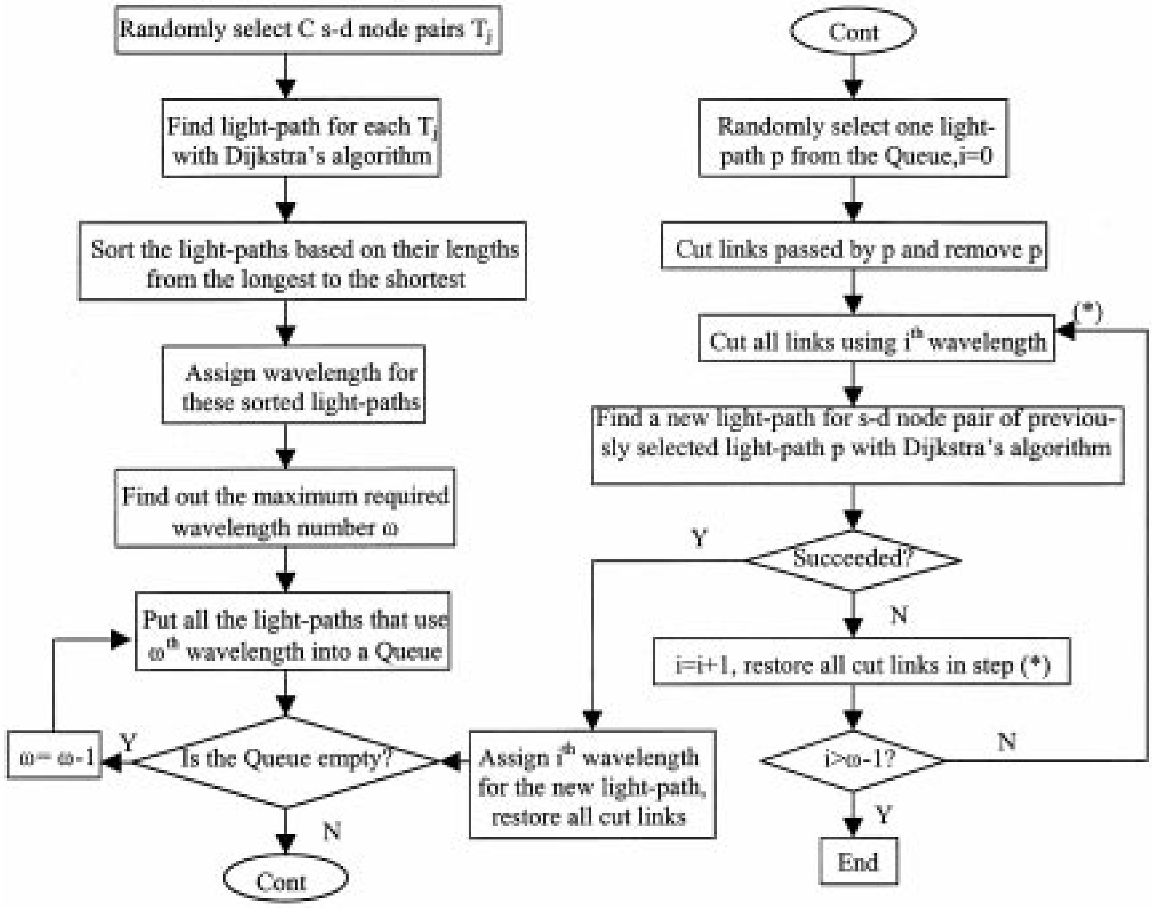

Fig. 4. The flow chart for CRA.

wavelength assignment algorithms for NWC networks are shown in Figs. 6–8. The mean wavelength number required is shown in Fig. 6, as a function of increasing number of active source-destination node pairs. The corresponding mean light-path lengths are shown in Fig. 7, and the one-wavelength-decrease costs are given in Fig. 8. These results have been presented both for Dijkstra's algorithm and the two

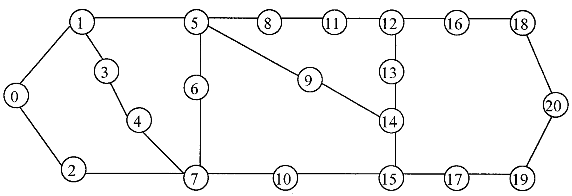

Fig. 5. The ARPA-2 network.

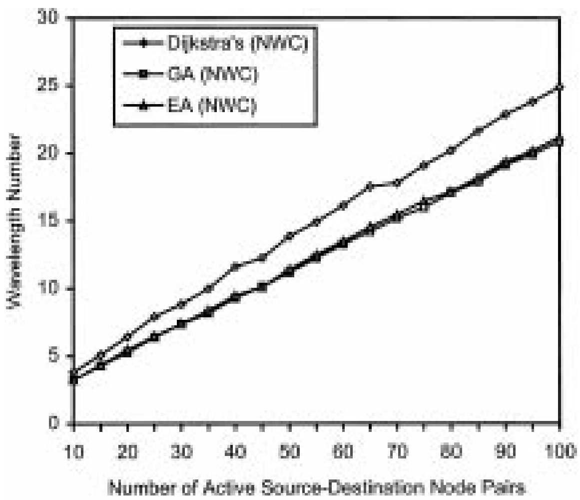

Fig. 6. Wavelength number for NWC network (ARPA-2).

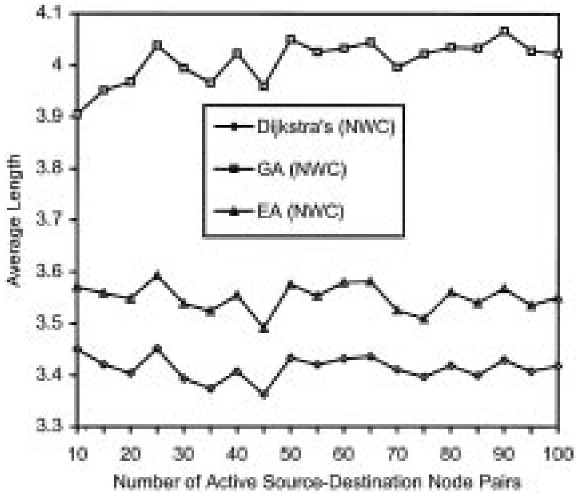

Fig. 7. Average light-path length for NWC network (ARPA-2).

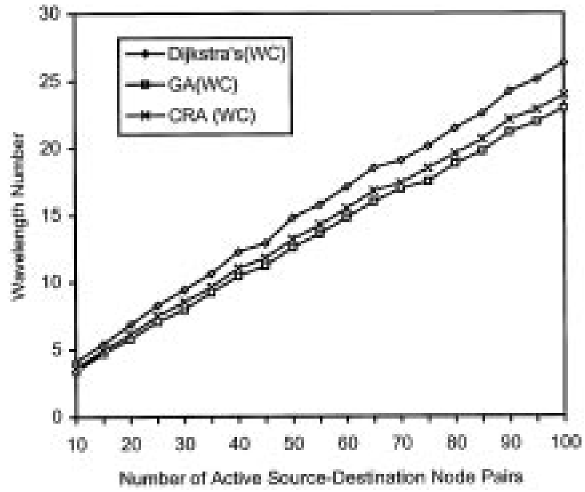

Fig. 9. Wavelength number for WC network (ARPA-2).

heuristic wavelength assignment algorithms, GA(NWC) and EA(NWC), proposed for NWC networks in the previous section. We expect Dijkstra's algorithm to give limiting results with highest wavelength number and shortest light-path length and this is indeed demonstrated by our simulations. We also observe that GA(NWC) gives the longest average light-path length—substantially longer than EA(NWC)—even though the wavelength numbers offered by these two schemes are roughly similar. This indicates that the EA(NWC) algorithm provides better performance than the simpler GA(NWC) scheme. This is supported by the fact that the one-wavelength-decrease cost parameter for GA(NWC) is higher than that of the corresponding EA(NWC). However, with increasing number of *s-d* node pairs, this parameter decreases for both these algorithms and the difference between them also decreases. This means that the algorithms in general perform better when more source-destination node pairs are accommodated in the system. However, the marginal improvement is

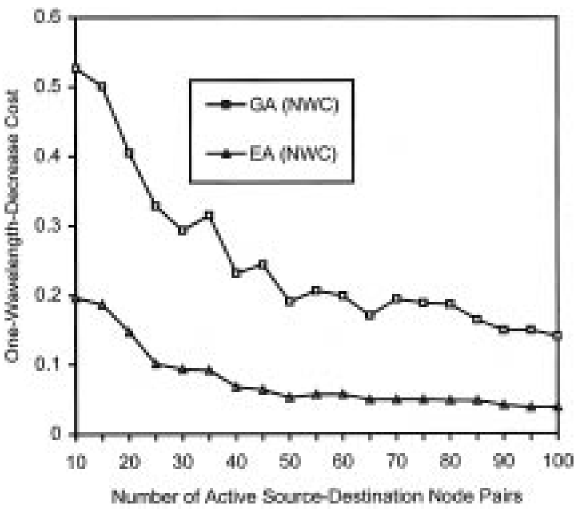

Fig. 8. One-wavelength-decrease cost for NWC network (ARPA-2).

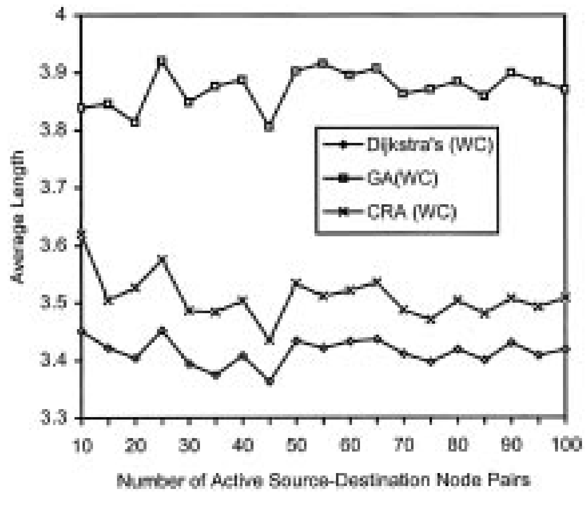

Fig. 10. Average light-path length for WC network (ARPA-2).

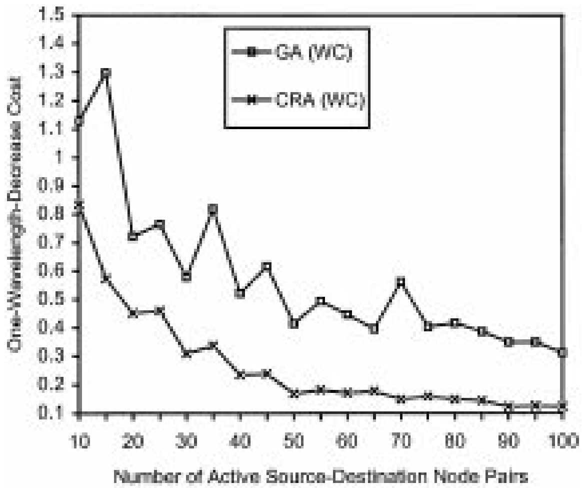

Fig. 11. One-wavelength-decrease cost for WC network (ARPA-2).

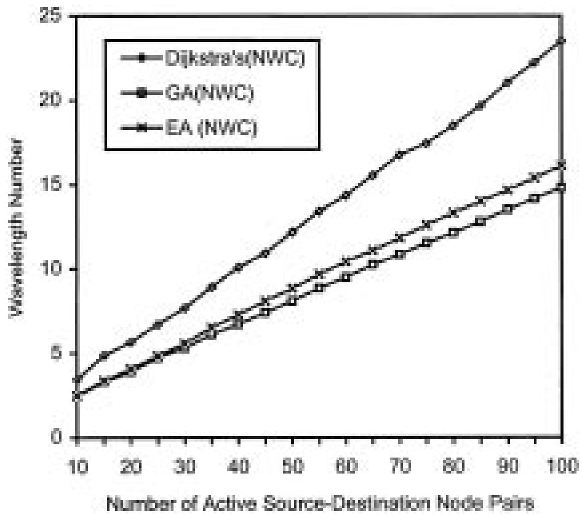

Fig. 13. Wavelength number for NWC network of Fig. 12.

lower as the number of source-destination pairs increases.

Similar simulation results for a WC network have been shown in Figs. 9–11 for the different wavelength assignment algorithms. The basic performance trends are similar to those observed for the NWC examples in the previous figures. The GA(WC) and CRA(WC) need similar wavelength numbers, with requirement for CRA being marginally higher. In addition, comparing the costs for NWC and WC, we observe that the WC network requires higher cost to decrease one wavelength than NWC, i.e., the WC networks have a higher one-wavelength-decrease cost than the corresponding NWC network.

Apart from the irregular mesh topology of ARPA-2, we have also done simulations for the regular mesh network topology shown in Fig. 12. All the simulation strategies are the same as in the ARPA-2 network, and the corresponding results are shown in Figs. 13–15 for NWC and in Figs. 16–18 for WC. The results show

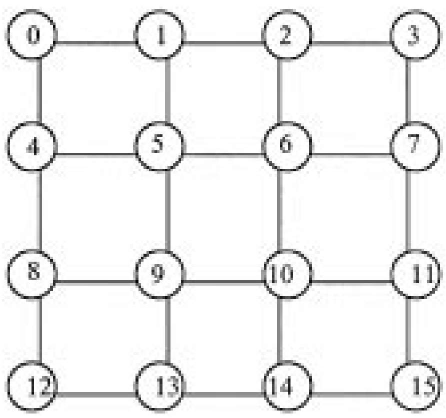

Fig. 12. A 16-node mesh regular network.

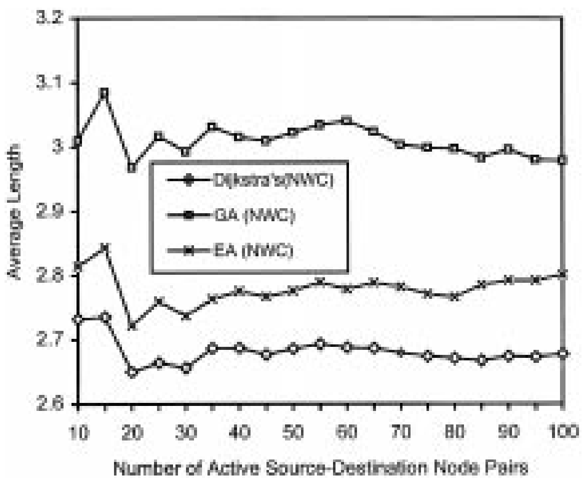

Fig. 14. Average light-path length for NWC network of Fig. 12.

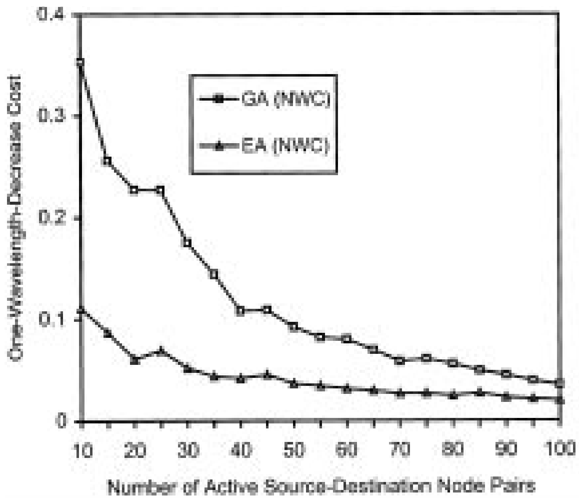

Fig. 15. One-wavelength-decrease cost for NWC network of Fig. 12.

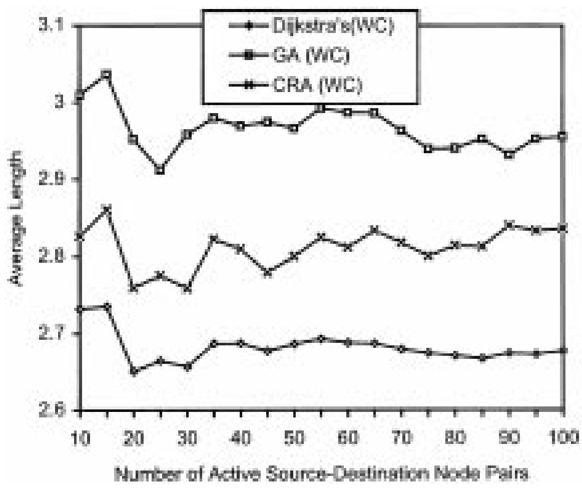

Fig. 17. Average light-path length for WC network of Fig. 12.

similar trends in this topology as in the ARPA-2 example. However, we find that the performance of the greedy algorithm (GA), especially in a WC network, is better than that of CRA. This implies that the efficiency of the different algorithms may be different in different network topologies.

6 Conclusion

This paper investigates the problem of wavelength assignment in a WDM network with static traffic loading. We have defined a new performance measure referred to as the one-wavelength-decrease cost to compare the performance of the new heuristic algorithms proposed by us. These new algorithms are presented and their performance has been studied through simulations, both for the ARPA-2 network and a 16-node regular mesh network. We find that our heuristic algorithms are able to efficiently decrease the total wavelength number required for a specified static traffic load. It was observed that the algorithms yield different one-wavelength-decrease costs and that wavelength conversion will give the network some benefits both in terms of lower wavelength numbers and lower one-wavelength-decrease costs.

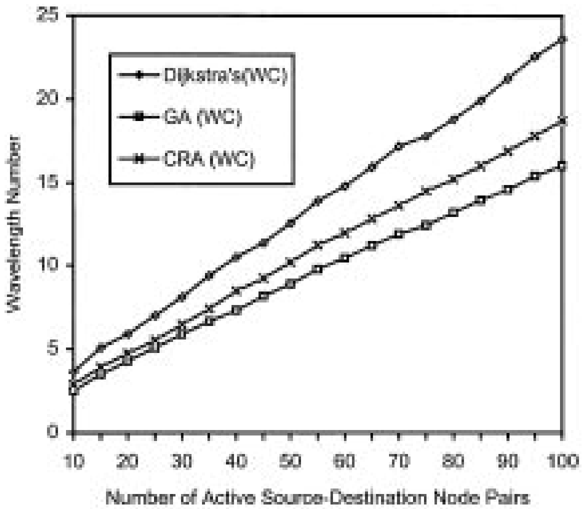

Fig. 16. Wavelength number for WC network of Fig. 12.

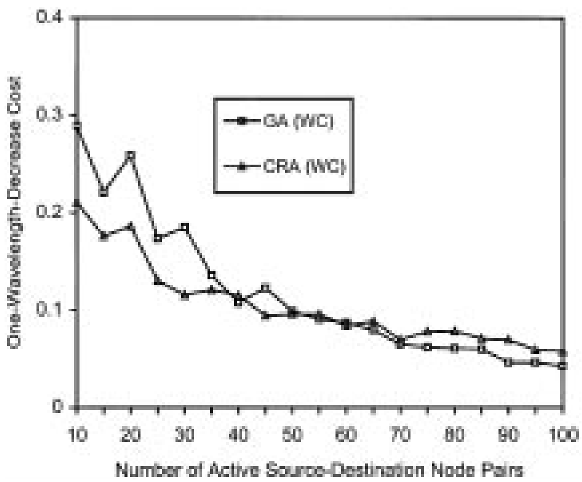

Fig. 18. One-wavelength-decrease cost for WC network of Fig. 12.

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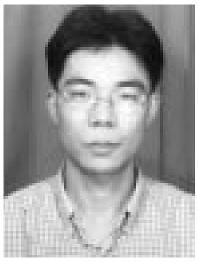

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