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Approximate analysis of limited-range wavelength conversion all-optical WDM networks

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Abstract

We use the analytical model for multi-fibre WDM networks to approximately analyse the network performance of limited-range wavelength conversion WDM networks. In addition, we develop a simple analytical model for multi-fibre networks with limited-range wavelength conversion capability by combining the multi-fibre network model and the limited-range wavelength conversion network model. Extensive calculations based on these models have been done for networks with a single light-path and with different wavelengths on each link. Based on the results obtained, we conclude that our analytical model is simple and yet can effectively analyse the impact of wavelength conversion range and fibre number on the network performance. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: WC; NWC; PWC; Multi-fibre; Analytical model; Blocking probability; Conversion degree; Conversion percentage

1. Introduction

Wavelength routed all-optical WDM network has been researched widely because of its benefits such as huge transmission capacity, good routing flexibility and good protocol transparency [1–3]. There are a few ways to classify WDM networks. Based on the wavelength conversion capability of the nodes, a WDM network can be classified as non-wavelength continuous (NWC), wavelength continuous (WC) or partial wavelength conversion (PWC) WDM. In an NWC network, each node is equipped with the full number of wavelength converters and each converter has the full-range wavelength conversion capability. We can assign wavelengths to a light-path link by link just like the process in a public switched telephone network. Unlike the NWC WDM network, there is no wavelength converter in the WC-WDM network. Therefore, the same wavelength has to be used in all the hops of a light-path from the source node to the destination node. This limitation is often called the *wavelength continuity constraint*.

PWC is an alternative that has been proposed recently because of the high cost of wavelength converters. In this kind of network, each node only has limited wavelength conversion capability. A partial wavelength conversion network, in which the wavelength converters in each node were shared by different links, was proposed in Ref. [4]. In order to assign the wavelength converters and the wavelengths to the links efficiently, a heuristic algorithm with a super-graph was proposed in Ref. [4]. *Sparse converter placement* is another kind of partial wavelength conversion scenario, which was initially studied in Ref. [5]. In this type of network, some nodes are equipped with the full number of wavelength converters, while other nodes do not have any wavelength conversion capability at all. For simplicity, we shall call the nodes in the former case NWC nodes and those in the latter case WC nodes. Consider the practical difficulties in the fabrication of high-performance wavelength converters, some researchers have proposed the limited-range wavelength conversion network, in which the wavelength converters can only convert a wavelength to a limited number of neighbouring wavelengths. In Ref. [6], an analytical model has been proposed to recursively compute the blocking performance of this kind of network. However, the author only applied the method to single light-path networks. Also, for ring and mesh networks, only simulations were done. Another analytical model, which can be used to analyse irregular mesh networks, was proposed in Ref. [7]. The model is also based on a recursive computation process and it makes use of some approximations to obtain the blocking probabilities. Another analytical model that makes use of the BPP/M/1/1 queuing model and allows

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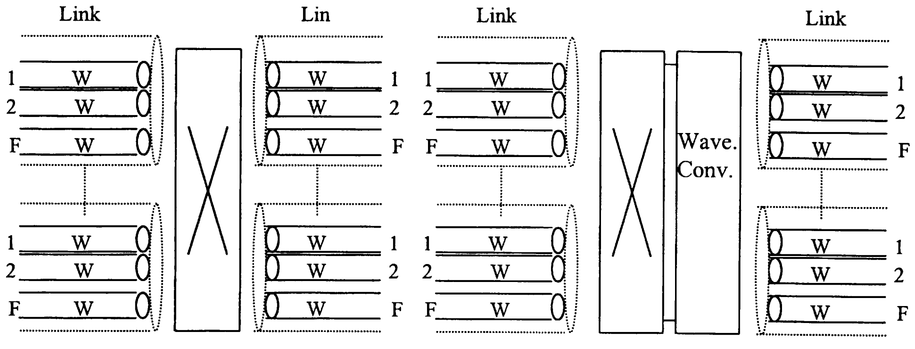

(a) (b)

Fig. 1. (a) WC multi-fibre node architecture; (b) NWC multi-fibre node architecture.

flexible wavelength assignment policies was proposed in Ref. [8]. Although the above-mentioned models could be used to analyse the performance of small and simple networks, the high mathematical and computational complexities render them unsuitable to be used for large and complex networks. The paper focuses on the analysis of limited-range conversion networks. It proposes a simple model for analysing the impact of the wavelength conversion range of the wavelength converters on the network performance. Because the model is simple, it can be used to analyse large and complex networks.

Apart from classifying WDM networks based on wavelength conversion capability, we could also classify WDM networks based on the number of fibres on each link. Here, we distinguish *link* from *fibre* as we allow more than one fibre in each link. Single-fibre WDM network is the simplest case and is the subject of many studies [1–3]. Despite the fact that real networks tend to have more than one fibre per link, there are very few references on the analysis of multi-fibre WDM networks. In Ref. [9], an analysis on the performance pertaining to wavelength conversion in multi-fibre network was conducted. In order to reduce the blocking probability and correspondingly increase the network throughput, a heuristic algorithm on light-path routing and wavelength assignment was proposed in Refs. [10,11]. In this paper, we will modify the model in Ref. [9] to analyse the limited-range wavelength conversion network.

The rest of this paper is organized as follows. Multi-fibre WDM networks and limited-range wavelength conversion networks are described in Section 2. In Section 3, we list the assumptions made and the notations used. In Section 4, we describe the analytical models for multi-fibre WDM networks. Then, based on this model, we deduce the analytical models for limited-range wavelength conversion networks. In Section 5, the impact of wavelength conversion capability and the number of fibres per link on the network performance is found by applying our model onto different network topologies. Conclusions are drawn in Section 6.

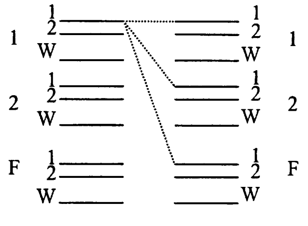

Fig. 2. Wavelength switching relationship between wavelengths in the input and output links for a multi-fibre WDM network.

2. Multi-fibre WDM network and limited-range wavelength conversion WDM network

2.1. Multi-fibre WDM network

With the explosive increase of network traffic, multi-fibre WDM network will become the technology of choice for transport networks. The node architecture of this type of network is likely to be that shown in Fig. 1(a) or (b). The difference between (a) and (b) is that the latter has a wavelength converter array and thus has the wavelength conversion capability. We call the network with node architecture (a) as WC multi-fibre WDM network and (b) as NWC multi-fibre WDM network. As shown in Fig. 1(a), there are F fibres on each link and W maximum available wavelengths on each fibre. Through the intermediate all-optical switches, a wavelength in an input fibre can be switched to the same wavelength in any output fibre. The structure of (b) is the same as that of (a) except for the extra wavelength converter array. Therefore, it allows a wavelength in an input fibre to be switched to the same or another wavelength in any output fibre.

In order to analyse the node architecture shown in Fig. 1(a), we use Fig. 2 to illustrate the wavelength-switching relationship between the input and output links. In Fig. 2, each possible output wavelength that the input wavelength can be switched to, is represented by a dotted-line. As no wavelength converter array is available in a WC multi-fibre node, these dotted-line connections can only exist between a wavelength in an input fibre and the same wavelength on all the output fibres in the same link. We call the number of these dotted-line connections for each wavelength as its

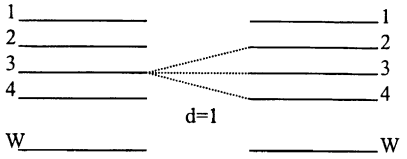

Fig. 3. Wavelength switching relationship between wavelengths in input and output fibres in a single-fibre WDM network.

output degree, which indicates the number of possible ways to establish a light-path using this wavelength. We can also use a similar illustration to indicate the wavelength-switching relationship for an NWC multi-fibre WDM network. However, because the NWC networks are actually the same as the traditional switched telephone networks, we will not discuss it in this paper.

2.2. Limited-range wavelength conversion WDM network

In a limited-range wavelength conversion WDM network, all the nodes are equipped with the full number of wavelength converters; however, each converter only has a limited-range wavelength conversion capability. Like Ref. [6], we assume four-wave mixing as the technique for wavelength conversion technology. We use *conversion degree*, d, to express the conversion capability of each wavelength converter. With the above assumptions, the wavelength-switching relationship for a typical single-fibre network with $d = 1$ is illustrated in Fig. 3. Like Fig. 2, we also use dotted-line connections to show all the possible wavelength-switching scenarios. Obviously, with the increase of the value d, the capability to establish a light-path using these wavelengths will also increase. In order to compare our results with those in Ref. [6], we define another parameter called *conversion percentage*, which was used in Ref. [6] to indicate the wavelength conversion capability. This parameter is expressed as

$$D = \frac{100d}{W - 1}(\%)$$

where d is the wavelength conversion degree and W is the maximum wavelength number on a fibre.

We could also construct the wavelength-switching relationship for a multi-fibre limited-range wavelength conversion WDM network in a similar way. It is just a combination of Figs. 2 and 3; therefore, we do not show it here.

3. Assumptions and notations

In order to simplify the problems and make our analyses more easily understood, we will list the assumptions made and the notations that will be used in the analyses.

Assumptions:

1. More than one fibre is allowed to exist on a link, and the number of fibres on each link is assumed to be same.
2. The maximum number of wavelengths on each fibre is assumed to be same.
3. Each node pair in the network always receives requests to establish light-paths between them.
4. All light-path requests between any node pair in the network are assumed bi-directional and their arrivals are governed by the Poisson distribution with the same mean.
5. The connection times for all light-paths are assumed to be exponentially distributed with the same mean. Moreover, to simplify the problem, the mean is assumed to be one unit.
6. The random wavelength assignment scheme is used to assign wavelength for each light-path.
7. Following the assumption adopted in Ref. [12], the utilizations of different wavelengths on different links are assumed independent. We call this the *traffic link independence* assumption.

Notations:

1. W: the maximum number of wavelengths on each fibre.
2. F: the number of fibres on each link.
3. N: the total number of wavelengths on each link, which is equal to WF.
4. d: wavelength conversion degree.
5. D: wavelength conversion percentage, $D = 100d/(W-1)(\%)$.
6. ρ: utilization of a wavelength on a link (general term).
7. ρ_l: utilization of a wavelength on link l.
8. H: hop-count of a light-path.
9. R: a light-path in the network.
10. L_R: the offered traffic load of light-path R.
11. P_R: the blocking probability of light-path R.
12. P_B: the average blocking probability of the network.

4. Model design and analysis

4.1. Analysis for multi-fibre WDM network

We will only use the multi-fibre model to approximate and analyse the performance of limited-range WC networks; hence, we will only dwell on the multi-fibre model for the WC case.

4.1.1. Model for a single light-path

In Ref. [13], a single-fibre WC analytical model has been proposed. The assumption is that the utilization, ρ, of a wavelength on a link is known. For an H-hop light-path, R, the blocking probability can be expressed as

$$P_R = (1 - (1 - \rho)^H)^W \quad (1)$$

where W is the maximum number of wavelengths on a fibre.

An extended model for the multi-fibre WDM network has also been proposed in Ref. [9]. As shown in Fig. 2, in

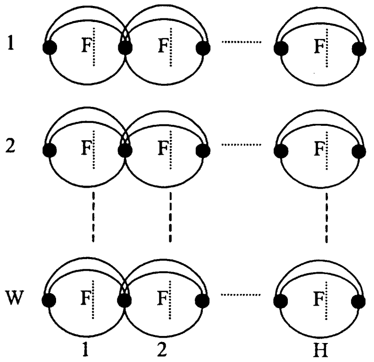

Fig. 4. Wavelength chains for an H-hop path with F fibres on each link and W wavelengths on each fibre.

an F-fibre link, there are W *wavelength groups* (wavelength 1, 2,…,W), there are F channels of the same wavelength in each group (one in each fibre). We can construct a chain for each *wavelength group* as shown in Fig. 4. We call the chain a *wavelength chain*. We also call the edge between a neighbouring node pair in a wavelength chain as *arc*. Obviously, for a network with F fibres on each link and W wavelengths on each fibre, there are W wavelength chains and F arcs between any neighbouring node pair in a wavelength chain as shown in Fig. 4.

Therefore, the blocking probability for an H-hop light-path R is

$$P_R = (1 - (1 - \rho^F)^H)^W \tag{2}$$

where the term $1 - (1 - \rho^F)^H$ is the probability that light-path R is blocked on a certain wavelength chain.

Given that the wavelength number $N = FW$ on a link is fixed, we can adjust the combination of F and W to see how the performance changes. Obviously, the combination of ($F = N$, $W = 1$) should have the lowest blocking probability because this particular configuration is equivalent to an NWC network. On the contrary, the combination of ($F = 1$, $W = N$) should have the highest blocking probability because it is simply a single-fibre WDM network with N wavelengths on each fibre. For the other combinations, it is expected that their performances will lie between the performances of the above two extreme scenarios. Their performances are also expected to improve when F (*output degree*) increases. The performance of multi-fibre networks appears to exhibit the same trend as that of limited-range wavelength conversion networks, in which an increase in the wavelength conversion degree results in a decrease in the blocking probability. Therefore, in the following section, we will modify this multi-fibre model to analyse the performance of the networks with limited-range wavelength conversion capability.

4.1.2. Model for a network

Consider a network with n nodes and m links. Given that the offered traffic loads on all the node pairs (all the light-paths R) are known, we can find out the wavelength utilization on an arbitrary link l from

$$\rho_l = \frac{\sum_{R:l\in R} L_R(1 - P_R)}{N} \tag{3}$$

where the term $L_R(1 - P_R)$ is the carried load on light-path R; therefore, Eq. (3) gives the carried load of each wavelength on link l, which is just equal to the utilization of each wavelength.

Similar to Eq. (2), the blocking probability of the light-path R should be

$$P_R = \left(1 - \prod_{l\in R}(1 - \rho_l^F)\right)^W = \left(1 - \prod_{l\in R}(1 - \rho_l^F)\right)^{N/F} \tag{4}$$

For the whole network, the average blocking probability of the light-paths is

$$P_B = \frac{\sum_R P_R L_R}{\sum_R L_R} \tag{5}$$

We can use the iterative process (*relaxation method*) proposed in Refs. [12,14] to find the blocking probability from Eq. (5). Let ρ_l^n, P_R^n, P_B^n be the values of ρ_l, P_R, P_B in the nth iteration of the process. The detail steps of the process are as follows:

(1) Let P_R^0, P_B^0 be 0 and ρ_l^0 be an arbitrary value between 0 and 1.
(2) $n = 1$
(3) Calculate ρ_l^n using Eq. (3).
(4) Calculate P_R^n using Eq. (4).
(5) Calculate P_B^n using Eq. (5). If $|P_B^n - P_B^{n-1}|$ is smaller than a certain threshold, then the iteration terminates; otherwise, $n = n + 1$ and go to step 3.

This iteration may sometimes fail to converge to the solution. Alternatively, other more sophisticated numerical methods, e.g. Newton's method [14] (which is guaranteed to converge when the unique solution exists) may be used instead. For simplicity, we may even directly use the offered load L_R on each light-path, to replace the carried load $L_R(1 - P_R)$ in Eq. (3)—this is because in a real-life situation, the blocking probability will be very low and the difference between the offered load and carried load may be ignored. This has actually been done to simplify the computations in Section 5.

4.2. Analysis for single-fibre limited-range wavelength conversion WDM network

We have introduced in the previous section the multi-fibre WDM network and mentioned about the similarity in performance between the multi-fibre network and the single-fibre limited-range wavelength conversion network.

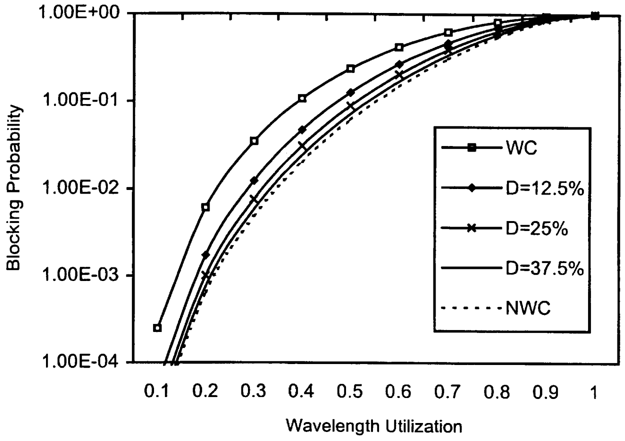

Fig. 5. Blocking probability change with the different wavelength conversion ranges for a two-hop light-path with five wavelengths on each link.

In this section, we will use the analytical model proposed for multi-fibre WDM networks to analyse the performance of single-fibre limited-range wavelength conversion networks.

Consider a WDM network in which only one fibre exists on each link, a maximum of W wavelengths are available on each fibre, and each wavelength in the incoming link could be converted to any of the $2d + 1$ neighbouring wavelengths in the outgoing link with conversion degree, d. The wavelength-switching relationship in a node for this kind of network is depicted in Fig. 3. By comparing the wavelength-switching relationship for multi-fibre WDM network depicted in Fig. 2 and that of the limited-range single-fibre WDM network depicted in Fig. 3, the similarity in the dotted-line connections becomes apparent. Therefore, we can use the analytical model for multi-fibre networks to approximate the performance of the single-fibre limited range wavelength conversion networks. For a single-fibre limited-range wavelength conversion network with N wavelengths on each fibre and the wavelength conversion degree of d, we use the model of a multi-fibre network with $2d + 1$ fibres on each link and $N/2d + 1$ wavelengths on each fibre to approximately analyse it. Correspondingly, all the formulae used in multi-fibre model in the previous section will change as follows, Eq. (2) ⇒ Eq. (6)

$$P_R = (1 - (1 - \rho^{2d+1})^H)^{N/(2d+1)} \tag{6}$$

Eq. (4) ⇒ Eq. (7)

$$P_R = \left(1 - \prod_{l \in R}(1 - \rho_l^{2d+1})\right)^{N/(2d+1)} \tag{7}$$

Based on these new formulae and the rest of the formulae in Section 4.1, we can calculate the blocking probability for a single light-path and a network with limited-range wavelength conversion capability using the method adopted for the previous multi-fibre model.

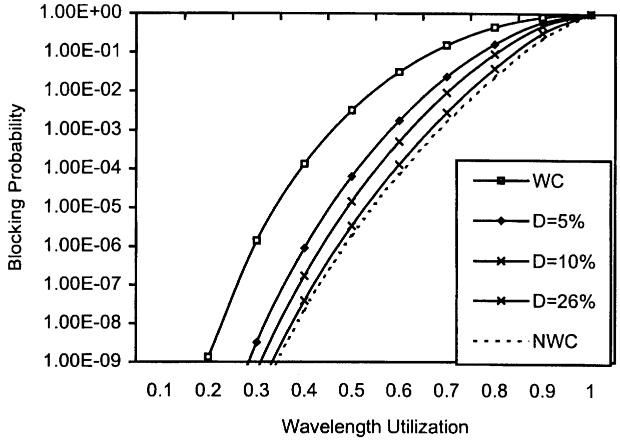

Fig. 6. Blocking probability change with the different wavelength conversion ranges for a two-hop light-path with 20 wavelengths on each link.

4.3. Analysis for multi-fibre limited-range wavelength conversion network

For a multi-fibre limited-range wavelength conversion network with N wavelengths and F fibres on each link, $W = N/F$ wavelengths on each fibre and a wavelength conversion degree of d for each wavelength converter, we can easily develop an approximate analytical model by combining the two models in the previous two sections. The resulting formulae are as follows, Eq. (2) ⇒ Eq. (8)

$$P_R = (1 - (1 - \rho^{(2d+1)F})^H)^{N/((2d+1)F)} \tag{8}$$

Eq. (4) ⇒ Eq. (9)

$$P_R = \left(1 - \prod_{l \in R}(1 - \rho_l^{(2d+1)F})\right)^{N/((2d+1)F)} \tag{9}$$

We can see from Eqs. (8) and (9) that if two systems have the same product value of $(2d + 1)F$, even their individual d and F are different, they still have the same performance. This implies that equipping wavelength converters or adding more fibres will produce the same effect in improving the network performance. We can continue to use the method applied in Section 4.1 to calculate all these formulae and get the final results.

5. Performance results

5.1. Performance of single-fibre limited-range wavelength conversion network

We have calculated—using the analytical model in Section 4—the blocking probabilities for light-paths and networks with different topologies and wavelengths. In order to compare our results to those in Ref. [6], we use wavelength conversion percentage in all the figures to express the wavelength conversion capability for each wavelength converters.

For a single light-path case, we list out the results for different combinations of the wavelength number and the

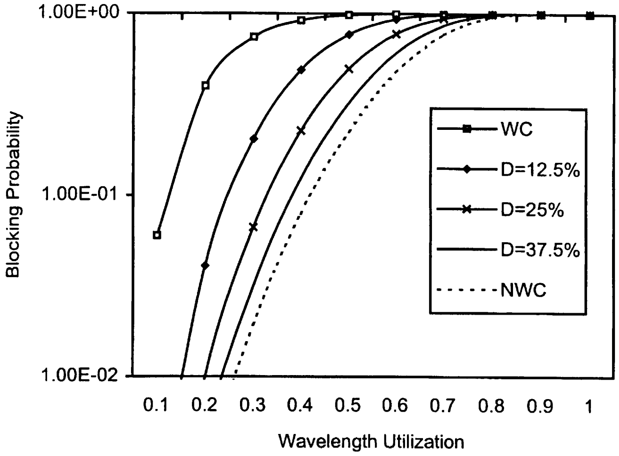

Fig. 7. Blocking probability change with the different wavelength conversion ranges for an eight-hop light-path with five wavelengths on each link.

light-path length. Figs. 5 and 6 show the results for a light-path with two hop-counts and 5 and 20 wavelengths on each link (the results for 10 wavelengths have also been obtained but due to the space constraints, the graph is not shown). From these figures, we come to the following conclusions:

- With the increase of wavelength conversion range in each converter, the network performance will improve; furthermore, adding a small percentage of wavelength conversion capability in each node can lead to a significant improvement in the network performance.
- Full-ranged wavelength conversion is not necessary because 25–40% wavelength conversion capability already can lead to a performance that is very close to that of full-ranged wavelength conversion (NWC) network. We call the 25–40% wavelength conversion capability the *threshold wavelength conversion range*.
- Through comparing the three figures, we found that an increase in the number of wavelengths on each link will lead to a decrease in the threshold wavelength conversion range. This means that limited-range wavelength conversion is more beneficial in networks with larger number of wavelengths.

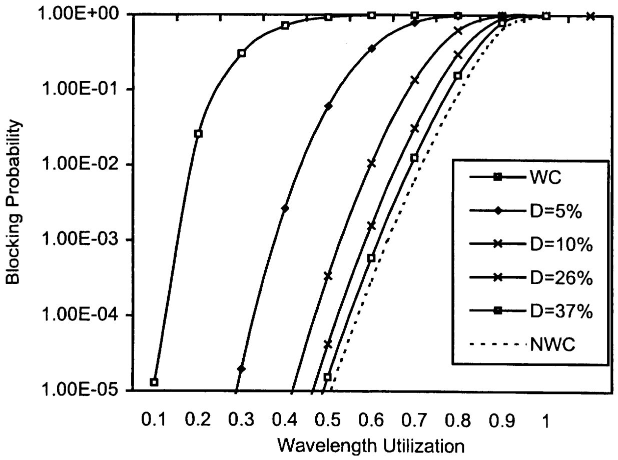

Fig. 8. Blocking probability change with the different wavelength conversion ranges for an eight-hop light-path with 20 wavelengths on each link.

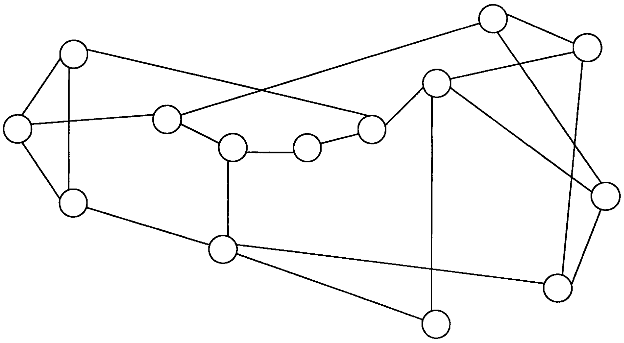

Fig. 9. 14-node, 21-link NSFNET backbone network.

We compare our results to those in Ref. [6], where the blocking probabilities for a two-hop light-path with 5 and 10 wavelengths on each link were calculated. It is found that the results are similar; particularly, the threshold wavelength conversion range reported in Ref. [6] was also around 25–40%. This shows that our model is quite accurate.

The merit of our approach is that it does not require a recursive process to compute the blocking probabilities. As such, it has a much lower computation complexity and is suitable for use for analysing large networks. Specifically, the computational complexity of the recursive approach proposed in Ref. [6] is $O(Wd^{H-1})$ while that of our approach is $O(H)$.

We also made similar evaluations for a light-path with eight hop-counts and 5 and 20 as the maximum number of wavelengths on each link (the results for the maximum number of wavelengths of 10 were also obtained but not shown), The results are shown in Figs. 7 and 8. Apart from the conclusions that have already been made from the results for the two-hop light-path network scenarios, another important conclusion can be drawn by comparing the results of two-hop and eight-hop light-path scenarios as follows:

- With the increase of light-path length, the benefit of limited-range wavelength conversion will decrease gradually; therefore, we conclude that it is better to use limited-range wavelength conversion in a network with a short average light-path length (with high network connectivity). This conclusion is also supported by the

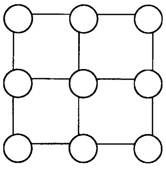

Fig. 10. Nine-node mesh regular network.

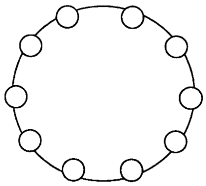

Fig. 11. 10-node ring network.

results obtained for other network topologies, which will be discussed next.

Apart from single-light-path networks, we have also applied our model to the following networks:

1. 14-node and 21-link NSFNET backbone network as shown in Fig. 9;
2. Nine-node regular mesh network as shown in Fig. 10;
3. 10-node ring network as shown in Fig. 11.

For these three networks, the shortest-path routing algorithm has been used to find a path for each node pair.

The results for the NSFNET backbone, regular mesh and ring networks are shown in Figs. 12–17. Figs. 12 and 13 show the blocking probabilities for the NSFNET backbone network. The blocking probabilities are plotted against the traffic load on each node pair (we assume that each node pair has the same traffic load) for different wavelength conversion ranges. It is found that with the increase of the wavelength conversion range, the blocking probability will decrease correspondingly; furthermore, only around 20–30% wavelength conversion range is required in each wavelength converter to achieve a performance close to that of the NWC network. This means that the threshold wavelength conversion range for the NSFNET network is around 20–30%. Similarly, Figs. 14 and 15 show the results for the nine-node mesh network. Its threshold wavelength conversion range is also found to be around 20–30%. The performance for the 10-node ring network has also been evaluated and its results are shown in Figs. 16 and 17. We found that its threshold of wavelength conversion range is larger than those of the other two networks: it is about 25–40%.

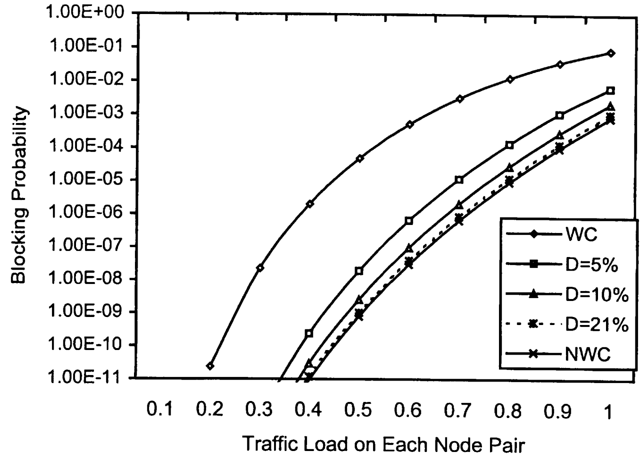

Fig. 13. Blocking probability change with the different wavelength conversion ranges for NSFNET backbone network with 20 wavelengths on each link.

Based on the comparison of the performances of different networks, and the performances of the same network with different number of wavelengths on each link, we reach the following conclusions:

- In a limited-range wavelength conversion network, there is a threshold wavelength conversion range. When the conversion range of the wavelength converters in the network reaches this threshold, the performance of this network will be very close to that of an NWC network.
- The benefits of limited-range wavelength conversion to networks with different connectivity densities are different. Normally, it is more beneficial to use limited-range

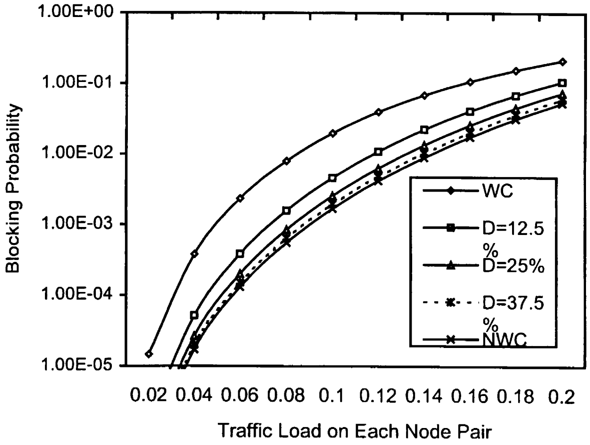

Fig. 12. Blocking probability change with the different wavelength conversion ranges for NSFNET backbone network with five wavelengths on each link.

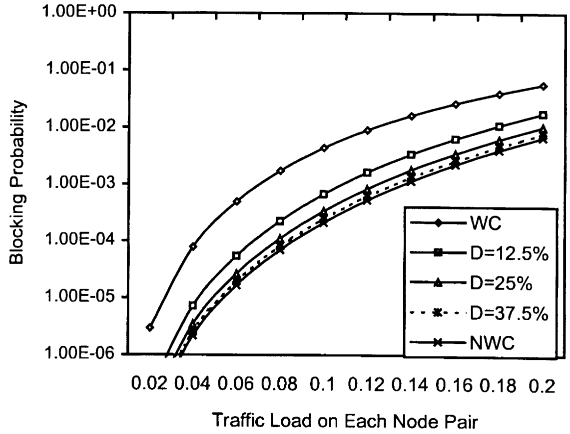

Fig. 14. Blocking probability change with the different wavelength conversion ranges for nine-node mesh network with five wavelengths on each link.

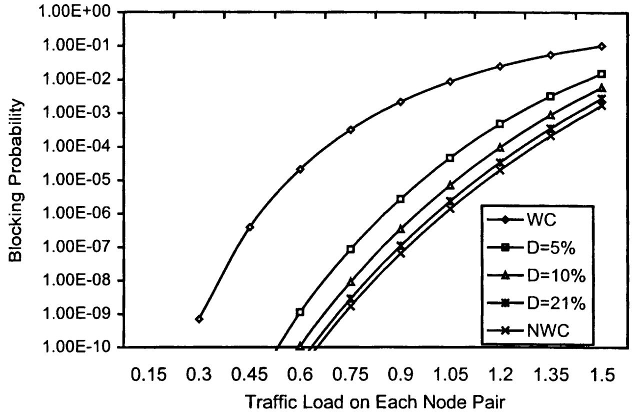

Fig. 15. Blocking probability change with the different wavelength conversion ranges for nine-node mesh network with 20 wavelengths on each link.

wavelength conversion in a network with dense connectivity. This could be verified by comparing the threshold wavelength conversion ranges of the three networks that have been studied. For example, the 10-node ring, which has a sparser connectivity than the other networks, has the highest threshold.

- For the same network topology, it is found that when the number of wavelengths on each link increases, the limited-range wavelength conversion yields larger performance improvement.

5.2. Performance of multi-fibre limited-range wavelength conversion network

We evaluate the performance of a multi-fibre light-path network with limited-range wavelength conversion capability. Fig. 18 shows the blocking probability of a two-hop multi-fibre light-path network with $d = 1$. Fig. 19 shows the performance of a two-hop multi-fibre light-path network for $d = 2$. The numbers of wavelengths per link for these two light-paths are both 20. As what we have expected, if the wavelength conversion degree (d) is small, more fibres are required to achieve a performance close to that of the NWC network. In addition, we also found that if the products $(2d + 1)F$ for two light-paths are the same, the performances of these two light-paths will be very close.

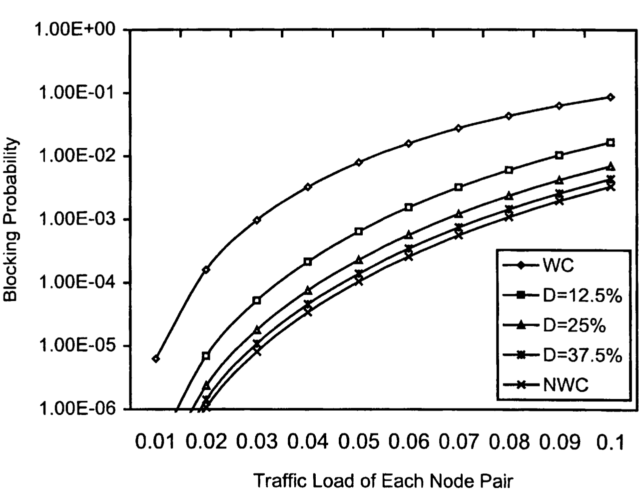

Fig. 16. Blocking probability change with the different wavelength conversion ranges for 10-node ring network with five wavelengths on each link.

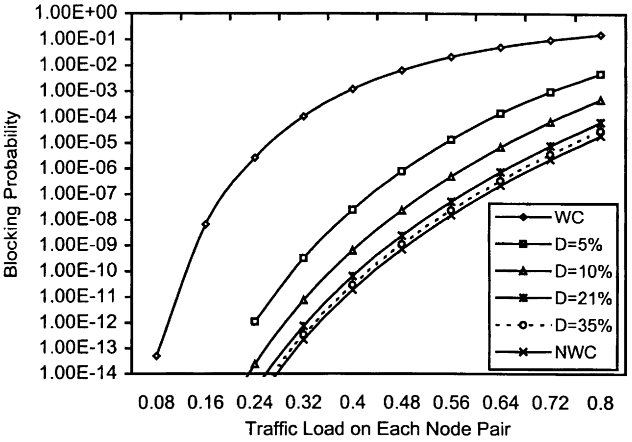

Fig. 17. Blocking probability change with the different wavelength conversion ranges for 10-node ring network with 20 wavelengths on each link.

Fig. 20 shows the blocking probabilities of an eight-hop multi-fibre light-path with $d = 1$. By comparing them to the results in Fig. 18, we found that with the increase of light-path length, a larger product, $(2d + 1)F$ is required in order to achieve a network performance close to that of the NWC network.

6. Conclusions

We adapted the analytical model for multi-fibre WDM networks to analyse the network performance of limited-range wavelength conversion networks. This approach has a lower computational complexity compared to other

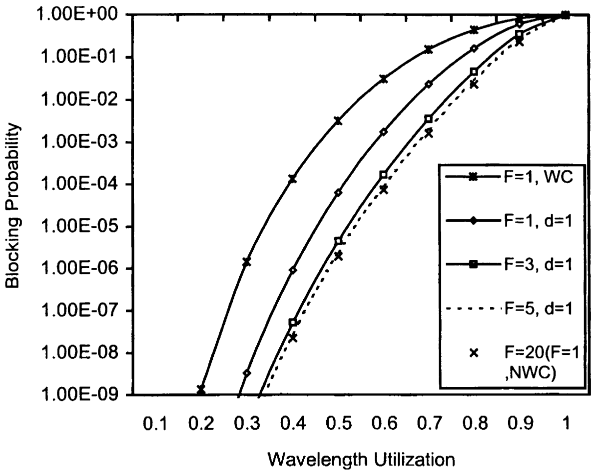

Fig. 18. Blocking probability change with the different fibre numbers on each link for $d = 1$ wavelength conversion range on a two-hop light-path ($FW = 20$).

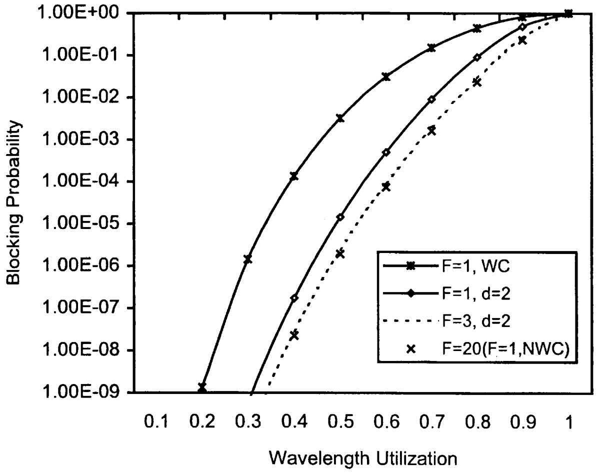

Fig. 19. Blocking probability change with the different fibre numbers on each link for $d = 2$ wavelength conversion range on a two-hop light-path ($FW = 20$).

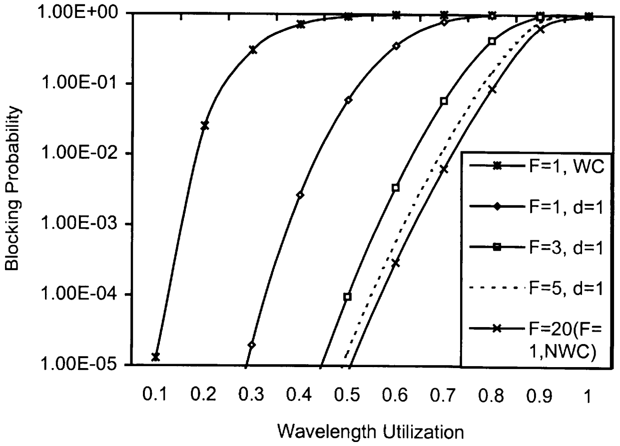

Fig. 20. Blocking probability change with the different fibre numbers on each link for $d = 1$ wavelength conversion range on an eight-hop light-path ($FW = 20$).

models that involve the use of some recursive processes for the computation. In addition, we combined the multi-fibre network model and limited-range wavelength conversion network model into a simple analytical model for multi-fibre networks with limited-range wavelength conversion capability. Extensive computations based on these models have been carried out for single light-path networks, and several other networks with different number of wavelengths per link. From the results, we found that our analytical model is simple and yet effective in analysing the impact of wavelength conversion range and number of fibres on the network performance.

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