Re-Routing at Critical Nodes to Enhance Performance of Wavelength Reassignment in All-Optical WDM Networks Without Wavelength Conversion

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***Abstract*—Reassignment of calls to different wavelengths on blocking can be used in WDM networks without wavelength conversion to get almost the same performance as that of WDM networks with wavelength conversion for circuit switched traffic [11]. However, in a few networks, we did find that while the reassignment on blocking does improve the performance of WDM networks without wavelength conversion, the performance falls short of that of wavelength conversion networks. In this paper, we analyze the reasons for this behavior in these networks. On identifying certain critical nodes as a cause of this behavior, we propose a rerouting technique around the critical node. With a small amount of rerouting, this bottleneck can be removed and the performance of WDM networks without wavelength conversion becomes almost equal to that of networks with wavelength conversion, thus making the wavelength conversion (costly) feature, as redundant. In this paper, we also propose a technique to carry out seamless wavelength reassignment so as not to disrupt traffic during the wavelength reassignment process.**

***Index Terms*—Critical nodes, re-routing, seamless reassignment, wavelength reassignment.**

I. Introduction

ALL-OPTICAL networks with a throughput of the order of Tb/sec per node is made practical by using wavelength-division multiplexing (WDM) [1] in conjunction with wavelength routing, which offers wavelength reuse and removes the electrooptic bottleneck [2]. The network nodes are equipped with optical cross connects (OXCs) which can perform add-drop multiplexing and wavelength routing and optionally wavelength conversion [3], [4]. The performance of WDM networks without wavelength conversion is limited by *wavelength continuity constraint* (wcc) blocking, apart from the capacity exhaustion blocking, where as in networks with wavelength conversion, only the latter exists. Hence, wavelength conversion networks have the lowest possible blocking probability and are considered as the *optimal performance networks* [5]. However, implementing all-optical full wavelength converters is difficult as all-optical wavelength converters are still in the early stages of development [4], [6]. We consider all-optical circuit switched WDM networks without wavelength conversion in this work. As each lightpath in backbone networks is a substantial revenue for the network operators [10], any lightpath request rejection due to wcc is highly undesirable. Therefore, to combat the *wcc* blocking, *wavelength reassignment* techniques are used, in which the already established calls in the network are wavelength reassigned, so as to create a wavelength-continuous route for the blocked call. Referring to the previous works on wavelength rerouting, in [7], *move-to-vacant wavelength-retuning* (MTV-WR) was proposed to alleviate the effects of wcc; in [8], a faster retuning algorithm based on MTV-WR was proposed; and in [9], a much simpler and a faster algorithm, *move-to-vacant naive-wavelength-retuning* (MTV-NWR) was proposed. The results of all these works, show a considerable reduction in the blocking probability, however, the performance was still far away from that of wavelength conversion performance.

In [11], we showed that for WDM networks without wavelength conversion, reassignment of calls to different wavelength on wcc blocking, using *minimum-overlapping-to-least-congested* (MOLC) wavelength reassignment technique, can give performance equivalent to that of WDM networks with wavelength conversion. We had considered fixed shortest path routing (to ensure minimum resource allocation), dynamic traffic model with uniform loads and analyzed the performance of MOLC technique on a number of standard backbone networks [17], [18]. While in most networks, the performance obtained by reassignment was equivalent to that in networks with wavelength conversion, we found that there was performance deviation in some networks [11]. In this paper, we would analyze the *feature* of the network which causes this deviation. We would then propose techniques to overcome this deviation.

During the reassignment of calls in the circuit switched networks, the impact of smallest interruption is significant [11] and need to be avoided. In this paper, we propose a *seamless reassignment technique*, which is incorporated with the reassignment algorithm, to prevent any loss of data or interruption at all, for the wavelength shifted calls.

The rest of the paper is organized as follows. Section II presents the feature of the network which prevents the reassignment from removing all the wcc blocking and the solution to overcome the bottleneck. In Section III, the performance analis on standard backbone networks is done. In Section IV, the technique to seamlessly reassign the calls is discussed. Section V concludes the paper.

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TABLE I
SUMMARY OF RESULTS FOR DIFFERENT NETWORKS AT $Pb = 0.01$

Network	N, E	L_{noconv}	L_{conv}	L_{reassn}	Dev_L (%)
NSFNET	14, 21	8.93	9.76	9.76	0
BELL	15, 28	7.9	8.3	8.3	0
EON	19, 38	7.7	8.4	8.4	0
INDIANET	20, 33	4.2	4.51	4.51	0
LATA	11, 23	9.45	10.06	10.06	0
MULRING	15, 20	5.20	5.65	5.65	0
USIP	24, 43	5.64	6.35	6.35	0
ARPANET	20, 32	5.34	5.96	5.82	2.3
ARPA2	21, 25	3.8	4.6	4.3	6.5

II. FEATURE OF THE NETWORK WHERE REASSIGNMENT PROVIDES LIMITED GAINS

In this section, we describe the feature of the network where the wavelength reassignment can not remove all the wcc blocking. Uniform traffic loads are considered, where all the routes carry equal traffic. Before getting into the analysis of the networks in which reassignment provides limited gains, we would like to briefly summarize the results presented in [11].

A. Summary of Results on Various Backbone Networks

Table I [11] gives the load supported without wavelength conversion (L_{noconv}), with wavelength conversion (L_{conv}), with reassignment (L_{reassn}) on wcc blocking and deviation of reassignment from wavelength conversion (Dev_L), at a blocking probability Pb of 1%, for the different standard backbone networks, each with N nodes and E communication links. From the table, it is very clear that wavelength reassignment on wcc blocking achieves almost wavelength conversion performance in most of the networks without wavelength conversion. In these networks, wavelength reassignment ensures only the capacity exhaustion blocking. However, in ARPA and ARPA2 networks, there is a performance deviation as shown in Table I, which in turn means that wavelength reassignment could not remove all the wcc blocking, even when there exists free wavelengths in the links of the path. We would like to analyze these networks in the following section. Let us begin our discussions by first giving a simple example where the wavelength reassignment is not possible even though there are free wavelengths (not continuous) available on all the links of the path.

B. Simple Example

Let us define a network status matrix, NS_{W*E}, where W is the number of wavelengths in each link and E is the number of links, denoting the live calls in the network at any time instance. Table II shows a part of one such matrix, where "a," "b," and "c" are the three live calls in the network occupying certain wavelengths and links. A new call "d," which requires links 1 and 3 is blocked due to wcc, as there is no continuous wavelength available in links 1 and 3. The reassignment algorithm also can not establish call 'd' in the network. Any new call whose route involves any of these link combinations: (1,2), (1,3), or (2,3), cannot be established by the reassignment in this example. This is so even though, wavelength 3 in link 1, wavelength 2 in link 3 and wavelength 1 in link 2 is free. If the conversion capability existed, one could establish the new call involving links (1,2) or (1,3) or (2,3). The subgraph of this example matrix with such route distribution on the links is shown in Fig. 1. A subgraph, where such a situation exist, in which, even when wavelengths in two links are available, a call cannot be established through them, is defined as **critical triplet** of the network and such type of blocking is defined as the **hard continuity constraint (hcc) blocking**. Reassignment fails to remove hard continuity constraint blocking. The terminating node "v" becomes the **critical node** of the network. Let us further analyze these triplets in detail.

TABLE II
NS'_{3*3}: REASSIGNMENT NOT POSSIBLE

W/E'	1	2	3
1	a		a
2	b	b	
3		c	c

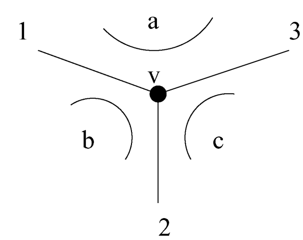

Fig. 1. Subgraph of network status matrix shown in Table II.

C. A Detailed Discussion on the Triplet

Whenever we find that performance of wavelength reassignment on networks without wavelength conversion falls short of wavelength conversion performance, we identify the call or traffic distribution around such a triplet and hcc to be the cause for the deviation. We now study when a subgraph of three links terminating on a node "v" (triplet) would become a critical triplet.

For a N node network, there are $R = (N \times (N-1))/2$ bidirectional routes. As fixed shortest path routing is used, there exists a predetermined route for each node pair in the route table. The *frequency of usage* of any link i, F_i, is the number of routes traversing through link i and can be obtained from the route table. The link with the highest frequency of usage, $F_{\max}$, has the maximum carried traffic and gets congested before any other link in the network and, therefore, is the *most congested link* of the network. If we consider the congestion level of this most congested link as 1 (100%), then the congestion level of any link i is obtained by normalizing its frequency of usage, F_i by $F_{\max}$, i.e., $F_i/F_{\max}$. At least one of most congested or near-most congested links (generally links with congestion level above 90%) are involved in the capacity exhaustion blocking of the network [11].

Consider the generalized triplet shown in Fig. 2. Let the three links of the triplet be 1, 2, and 3 terminating on the node "v" with the frequency of usage being F_1, F_2, and F_3, respectively (denoted by the encircled number in Fig. 2). Only when a triplet has one or more "most congested links," it can potentially be a critical triplet. Let us now examine the causes of blocking.

1) **Capacity Exhaustion Blocking**: Such blocking occurs both for networks with wavelength conversion as well as networks without wavelength conversion. If the traffic on the network is such that X_u calls are set up on each route (we have already assumed uniform traffic), then traffic on any link of the triplet, is $A_i = F_i \times X_u, \textit{for } i\epsilon(1,2,3)$. Blocking due to capacity exhaustion occur on a triplet if traffic on either of the three links of the triplet is greater than the number of wavelengths, W. In other words, the condition to avoid blocking due to capacity exhaustion on the links is

$$W > \max_{1,2,3}[F_1, F_2, F_3] \times X_u. \tag{1}$$

2) **Hard Continuity Constraint Blocking**: If the triplet has a traffic distribution like the one defined in the previous subsection (as shown in Table II), then blocking may occur, even when capacity exhaustion has not occurred. Let the traffic on each links be divided into independent traffic and dependent traffic. The independent traffic is such that it occurs only on one link of the triplet, implying that the route must originate/terminate at node n. For the triplet shown in Fig. 2, we denote this traffic by ID_i, where $i\epsilon(1,2,3)$. The dependent traffic uses two links of the triplet and, therefore, is *pass through* at node n. We call this dependent traffic, $D_{i,j}$, where $(i,j)\epsilon(1,2,3)$ and $i \neq j$. Thus, for link 1 of Fig. 2, ID_1 is the independent traffic and the dependent traffic will be $D_{1,2}$ and $D_{1,3}$, and similarly for other links of the triplet. The frequency of usage of any link on the triplet can be written in terms of this dependent and independent traffic, which is given by

$$F_i = ID_i + D_{i,j} + D_{i,k}, \text{ for } (i,j,k)\epsilon(1,2,3) \text{ and } i \neq j,\ i \neq k\ j \neq k. \tag{2}$$

Note that calls $D_{1,2}$, $D_{2,3}$, and $D_{1,3}$ require independent wavelengths to be completed, if there is no wavelength conversion at node "v." Thus, to avoid hard continuity constraint blocking because of triplet, the number of wavelengths has to be higher than the dependent traffic at the node "v." In other words, hard continuity constraint blocking is avoided if and only if

$$W > (D_{1,2} + D_{2,3} + D_{3,1}) \times X_u. \tag{3}$$

3) **Critical Triplet**: Now if capacity exhaustion blocking has to *precede*[1] the hard continuity constraint blocking discussed above, it is required that $\max_{1,2,3}[F_1, F_2, F_3] \times X_u > (D_{1,2} + D_{2,3} + D_{3,1}) \times X_u$. If this condition is not satisfied, the triplet becomes a *critical triplet* causing hard continuity constraint blocking before capacity exhaustion blocking. In such a situation, the reassignment would fail to deliver performance almost equal to that of a WDM network with wavelength conversion. Therefore, the condition for route distribution on *noncritical triplet* is

[1]Occur at a load less that in.

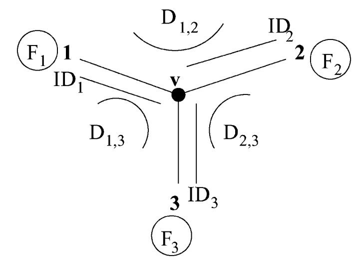

Fig. 2. Generalized triplet with route distribution.

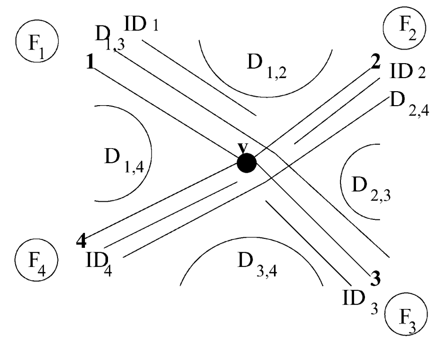

Fig. 3. Generalized quadruples with route distribution.

$$\max_{1,2,3}[F_1, F_2, F_3] > (D_{1,2} + D_{2,3} + D_{3,1}). \tag{4}$$

Substituting for frequency of usage from (2), (4) can be simplified to

$$\max\left[(ID_1 - D_{2,3}), (ID_2 - D_{1,3}), (ID_3 - D_{1,2})\right] > 0. \tag{5}$$

Equation (5) can also be written as

$$\max\left[ID_i - D_{j,k}\right] > 0, \text{ for } (i,j,k)\epsilon(1,2,3) \text{ and } i \neq j,\ i \neq k,\ j \neq k. \tag{6}$$

Thus, to avoid hard continuity constraint blocking, the number of independent routes through the most congested link of the triplet must be greater than the number of dependent routes on the other two links of the triplet as is given by (6). We will extend this analysis to a node with four or more links.

D. Nodes With n Links—ntuples

We will now analyze similar continuity constraint blocking due to nodes with more than three links. First let us consider a node with *four links*, which we call ***quadruples***, and analyze the route distribution around it. A generalized quadruple formed by links 1, 2, 3, and 4 terminating on node "v," with the route distribution consisting of dependent and independent routes is shown in Fig. 3.

Extending (2), the frequency of usage of any link i in the quadruple can be written as

$$F_i = ID_i + D_{i,j} + D_{i,k} + D_{i,l}, \text{ for } (i,j,k,l)\epsilon(1,2,3,4) \text{ and } i \neq j,\ i \neq k,\ i \neq l,\ j \neq k,\ j \neq l,\ k \neq l. \tag{7}$$

Now let us consider a particular link, namely, link 1 to be the most congested link among all the links of the quadruple. To ensure **capacity exhaustion blocking** in quadruples, the number of wavelengths W must be such that

$$W > F_1 \times X_u \tag{8}$$

where from (7) $F_1 = ID_1 + D_{1,2} + D_{1,3} + D_{1,4}$.

From Fig. 3, it should be noted that without wavelength conversion at node "v," the dependent routes, $D_{1,4}$ and $D_{2,3}$ can share the same wavelength as they do not use any link in common. Similarly, $D_{1,2}$ and $D_{3,4}$ can share the same wavelengths. It is only the dependent routes involving any three links of the quadruple [links (1, 2, 3) or links (1, 2, 4) or links (1, 3, 4) or links (2, 3, 4)] requires independent wavelengths to be completed. Thus, **hard continuity constraint blocking** can occur due to any of the three links of the quadruple. As we have assumed link 1 to be the most congested link of the quadruple shown in Fig. 3, any of the following link combinations involving link 1 namely, links (1, 2, 3) with dependent routes $(D_{1,2}, D_{1,3}, D_{2,3})$ or links (1, 2, 4) with dependent routes $(D_{1,2}, D_{1,4}, D_{2,4})$ or links (1, 3, 4)) with dependent routes $(D_{1,3}, D_{1,4}, D_{3,4})$, can cause the hard continuity constraint blocking, in which even inspite of the availability of free slots in the required links of path, reassignment of already established call is not possible (similar to Table II), thereby making the node v, a "critical node." To avoid such kind of continuity constraint blocking, the number of wavelengths must be

$$W > \max\left[\underbrace{(D_{1,2}+D_{1,3}+D_{2,3})}_{\text{due to links(1,2,3)}}, \underbrace{(D_{1,2}+D_{1,4}+D_{2,4})}_{\text{due to links(1,2,4)}} \underbrace{(D_{1,3}+D_{1,4}+D_{3,4})}_{\text{due to links(1,3,4)}}\right] \times X_u. \tag{9}$$

Now, if we require the capacity exhaustion blocking to precede the hard continuity constraint blocking at node v, then [from (8) and (9)]

$$F_1 > \max\left[(D_{1,2}+D_{1,3}+D_{2,3}), (D_{1,2}+D_{1,4}+D_{2,4}) (D_{1,3}+D_{1,4}+D_{3,4})\right]. \tag{10}$$

Substituting for frequency of usage, F_1, (10) can be simplified to

$$ID_1 > \max\left[(D_{2,3}-D_{1,4}), (D_{2,4}-D_{1,3}), (D_{3,4}-D_{1,2})\right]. \tag{11}$$

Generalizing for any link i, $i\epsilon(1,2,3,4)$, which is the most congested link of the quadruple, the condition to ensure *noncritical quadruples* is

$$ID_i > max\left[(D_{j,k}-D_{i,l}), (D_{j,l}-D_{i,k}), (D_{k,l}-D_{i,j})\right] \text{ for } (i,j,k,l)\epsilon(1,2,3,4) \text{ and } i\neq j,\ i\neq k,\ i\neq m\ j\neq k,\ j\neq l,\ k\neq l. \tag{12}$$

Let us further extend this to a node with *five links*, which we call as ***quintuples***. Again, if link 1 is the most congested link of the quintuple, then the condition to ensure capacity exhaustion blocking to precede the hard continuity constraint blocking at node v is

$$ID_1 > \max\left[\underbrace{(D_{2,3}-D_{1,4}-D_{1,5})}_{\text{due to links(1,2,3)}}, \underbrace{(D_{2,4}-D_{1,3}-D_{1,5})}_{\text{due to links(1,2,4)}} \underbrace{(D_{2,5}-D_{1,3}-D_{1,4})}_{\text{due to links(1,2,5)}}, \underbrace{(D_{3,4}-D_{1,2}-D_{1,5})}_{\text{due to links(1,3,4)}}, \underbrace{(D_{3,5}-D_{1,2}-D_{1,4})}_{\text{due to links(1,3,5)}}, \underbrace{(D_{4,5}-D_{1,2}-D_{1,3})}_{\text{due to links(1,4,5)}}\right]. \tag{13}$$

One can similarly extend the analysis for a node with *n links*, which is called as ***ntuples***. If link1 is the most congested link of the ntuple, then the condition to ensure capacity exhaustion blocking is

$$ID_1 > \max\left[\underbrace{(D_{2,3}-D_{1,4}-D_{1,5}-D_{1,6}-\cdots-D_{1,n})}_{\text{due to links(1,2,3)}} \underbrace{(D_{2,4}-D_{1,3}-D_{1,5}-D_{1,6}-\cdots-D_{1,n})}_{\text{due to links(1,2,4)}}, \cdots \underbrace{(D_{2,n}-D_{1,4}-D_{1,5}-D_{1,6}-\cdots-D_{1,n-1})}_{\text{due to links(1,2,n)}}, \cdots \underbrace{(D_{n-1,n}-D_{1,2}-D_{1,3}-D_{1,4}-\cdots-D_{1,n-2})}_{\text{due to links(1,n-1,n)}}\right]. \tag{14}$$

Let us now compare the (6) of triplets and (11) of quadruples for link 1. The former requires $ID_1 > D_{2,3}$, while the latter requires $ID_1 > max[(D_{2,3} - D_{1,4}), (D_{2,4} - D_{1,3}), (D_{3,4} - D_{1,2})]$. One can see that the condition to ensure capacity exhaustion blocking for quadruple is weaker due to a term being subtracted. Thus, a node with four links (quadruples) is less likely to cause hard continuity constraint blocking as compared to triplets. Looking at (13), one finds that the condition becomes still weaker for nodes with five links, quintuples (as two terms are subtracted). Similarly from (14), the condition for ntuples is much more weaker as $n-3$ terms get subtracted. Thus, it is the *triplets*, which would be the principal cause of hard continuity constraint blocking limiting the reassignment performance.

E. Proposed Rerouting Technique at the Critical Nodes

In the previous section, we identified the traffic around certain critical nodes of the network as the cause for the performance deviation of wavelength reassignment from that of networks with wavelength conversion. In this section, we propose a rerouting technique, which will make the critical nodes noncritical.

Consider the node with three links, triplets. We propose a rerouting technique to modify the route distribution on the critical triplet to make it noncritical. *The rerouting on the triplet must be done such that (6) is satisfied, i.e., the number of independent routes through the critical links are greater than the number of dependent routes on the other two links of the triplet.*

In the rerouting process, the shortest path constraint for few routes is relaxed for few routes involving the links of critical triplet. The main steps in the rerouting algorithm at the critical triplet are as follows.

1) Choose the least congested link in the triplet. First, reroute the independent routes on this link, by temporarily removing this link from the graph to find the new routes. This will automatically increase the number of independent routes on the other two links of the triplet. However, during rerouting, not all the independent routes are rerouted, only those, whose hoplength is greater than 2 are chosen for rerouting. This is to ensure that there is no significant increase in hoplength, which inturn minimizes the increase in resource allocation in the network.
2) If (6) is still not satisfied, then reroute the required number of dependent routes. Again during rerouting, only routes whose hoplength is greater than 2 are chosen, to minimize the increase in hoplength. Replace the link removed in step 1, back in the network.
3) In the rerouting process to make a critical triplet noncircital, if a new critical triplet arises in some other part of the network, perform similar rerouting (step 1 and 2) to make it noncritical. During this rerouting process, remove the least congested link of the former triplet from the network, to prevent it from becoming critical again. Replace the removed links, after the creation of the modified route table.

The proposed rerouting technique, even though relaxes the shortest path constraint in the network, takes care to see that there is no significant increase in the overall hoplength of the network. Similar rerouting can be performed at quadruples or nodes with higher number of links, whenever they limit the reassignment performance due to hard continuity constraint blocking.

III. Performance Analysis

We have developed an automated tool [14], *optical network performance optimizer* (ONPO), using *C* language in *LINUX* operating system. The graph of any arbitrary network topology is the input to ONPO. GNU scientific library [16] is used to generate the dynamic traffic. The values are averaged over 500 different batches each run for one thousand time units. Whenever wavelength reassignment performance in any given network without wavelength conversion deviates from the wavelength conversion performance, the tool runs the critical node identification algorithm. At the identified critical node, the rerouting algorithm is then applied to create the modified route table. To get the best performance from networks without wavelength conversion, hard continuity constraint are checked while building the network (route table) and re-routing applied to avoid hcc. Once this is done, reassignment would never encounter the hcc blocking. The entire simulation with wavelength conversion, with wavelength reassignment and without wavelength conversion is carried out for the network with new modified route table.

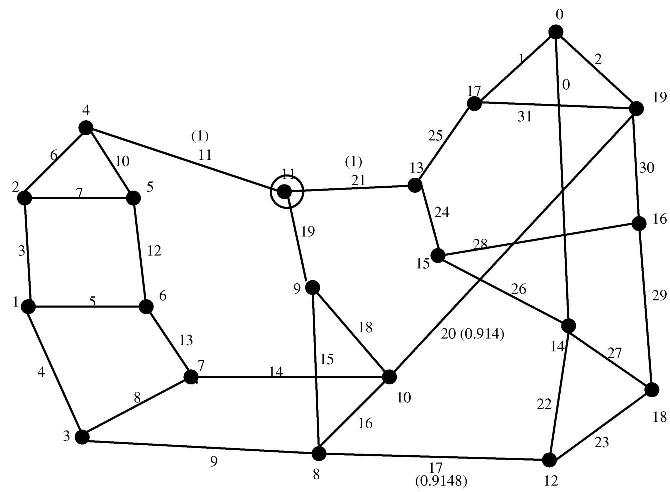

Fig. 4. ARPANET with critical links marked.

Let us consider the two networks with performance deviation (shown in Table I), namely ARPANET and ARPA2. The number of wavelengths per link, W, is 30. First consider the 20 node, 32 links **ARPANET** shown in Fig. 4. The most congested links with their congestion levels for the fixed shortest path routing are marked in the graph. ARPANET has four most congested links, namely, link 11, 17, 20, and 21. Fig. 5 plots the blocking probability, Pb versus load per node for shortest path routing. The figure shows results obtained with the reassignment algorithm invoked at the time of wcc blocking, with wavelength conversion and without wavelength conversion scenario. As shown in the figure, the reassignment at wcc blocking gives a significant performance improvement from that of networks without wavelength conversion. However, there is deviation in reassignment performance from conversion, which is around 2.3% (can be seen from Table I). Whenever there is wcc blocking involving links 11, 19, and 21, reassignment could not establish the call, even though there exist free slots in the link required of the route, leading to hard continuity constraint blocking. This is because of the triplet, formed by links 11, 21, and 19 terminating on node 11 encircled in Fig. 4. Note that the congestion level of these links are 1, 1, and 0.6571, respectively. The route distribution on this triplet: $D_{11,21} = 22$, $D_{11,19} = 8$, $D_{19,21} = 7$, $ID_{11} = 5$, $ID_{21} = 6$, and $ID_{19} = 8$ as shown in Fig. 6(a). It is observed that $(F_{11} = F_{21} = F_{\max} = 35) < (D_{11,21} + D_{11,19} + D_{19,21} = 37)$. Hence, this triplet is a *critical triplet*, making node 11 to be the critical node of the network causing the deviation.

One can also see that there are two quadruples with most congested links 20 and 17 in Fig. 4. They are, quadruple at node 10 formed by links 14, 16, 18, 20 and the quadruple at node 8 formed by links 9, 15, 16, 17, whose route distribution for the shortest path routing are shown in Fig. 7(a) and (b). First consider the quadruple at node 10. The most congested link is link 20. The route distribution on this quadruple

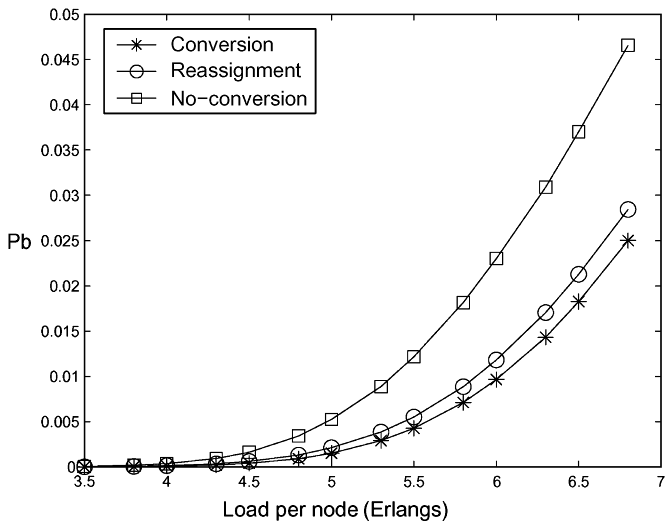

Fig. 5. Blocking probability versus load per node for shortest path routing.

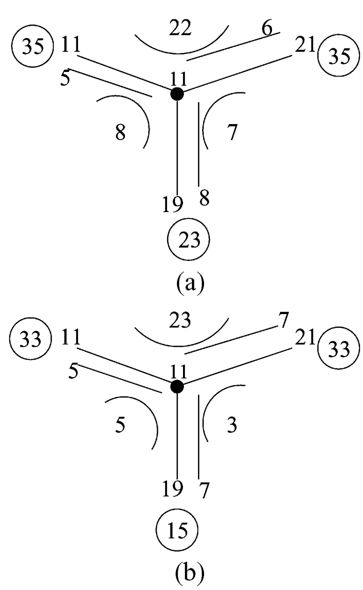

Fig. 6. Route distribution on triplet of ARPANET. (a) Triplet for shortest path routing; (b) re-routed triplet.

is such that $(ID_{20} = 6) > (max[(D_{18,16} - D_{20,14}), (D_{18,14} - D_{20,16}), (D_{14,16} - D_{20,18})] = max[(0-18), (4-3), (0-5)] = 1)$ [using (11)]. Therefore, it is a noncritical quadruple. Similarly, the route distribution of quadruple at node 8 as shown in Fig. 7(b) is also noncritical. Therefore, the critical triplet formed by links 11, 21, and 19 alone contribute for the performance deviation.[2]

On applying the rerouting technique proposed in Section II-E on this critical triplet of the ARPANET, it is seen that the triplet becomes noncritical as shown in Fig. 6(b), where $ID_{11} > D_{19,21}$ and $ID_{21} > D_{11,19}$, which will inturn lead to $(F_{11} = F_{21} = 33) > (D_{11,21} + D_{11,19} + D_{19,21} = 31)$. It should be noted, that only eight routes (out of the 190 total

[2]For all the networks (randomly generated) that were studied as a part of this work, not a single instance of a node with more than three links was found to be the cause of continuity constraint blocking preceding capacity exhaustion blocking.

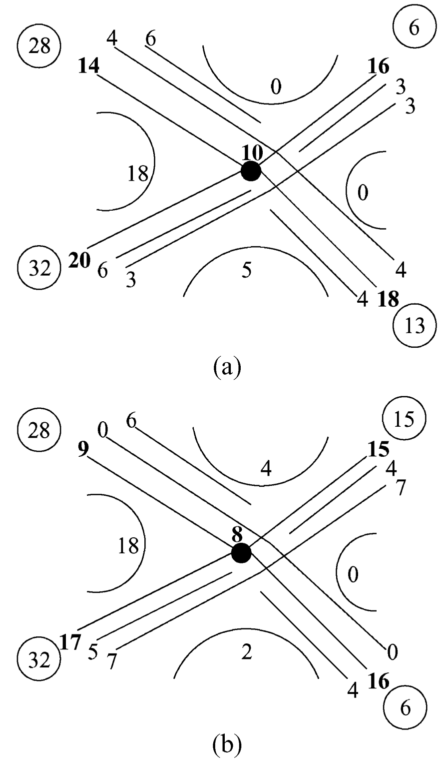

Fig. 7. Route distribution on quadruples of ARPANET. (a) Quadruple at node 10 formed by links 14, 16, 18, 20; (b) quadruple at node 8 formed by links 9, 15, 16, 17.

bidirectional routes in ARPANET) are rerouted in the routing table of the network, to make the critical triplet, noncritical. By rerouting, there is only a marginal increase in the total number of hops (obtained by addition of the number of hops of all the routes in the network), which is from 523 to 529, leading to a small increase in average hoplength of calls from $havg_{\rm old} = 2.7526$ to $havg_{\rm new} = 2.7842$ in the network.

The simulation with wavelength conversion, without wavelength conversion and with wavelength reassignment algorithm is again carried out for the network with this modified route table. The blocking probability is plotted once again. Fig. 8 plots the Pb across the different load per node. From the figure, it is seen that the reassignment achieves almost the wavelength conversion performance. Further, for a $\rm Pb = 0.01$, $L_{\rm noconv} = 5.582$ Erlangs/node, $L_{\rm conv} = 6.08$ Erlangs/node and $L_{\rm reassn} = 6.07$ Erlangs/node. There is a negligible performance deviation of $Dev_L = 0.001$, which is 0.1%. Thus, by the appropriate modification of few routes (less than 5%), the critical triplet, which caused hard continuity constraint blocking, is removed.

Let us now consider the 21 node, 25 links **ARPA2** network (Fig. 9) with the critical links marked. The wavelength reassignment has performance deviation from the wavelength conversion for shortest path routing as can be seen from Fig. 10, which plots Pb versus load per node and from Table I. The reason is the triplet which is formed by the links 14, 20, and 19 terminating on node 15, encircled in Fig. 9. The route distribution on the triplet [Fig. 11(a)], shows that it is a *critical triplet*, with node 15 being critical node of the network. Here

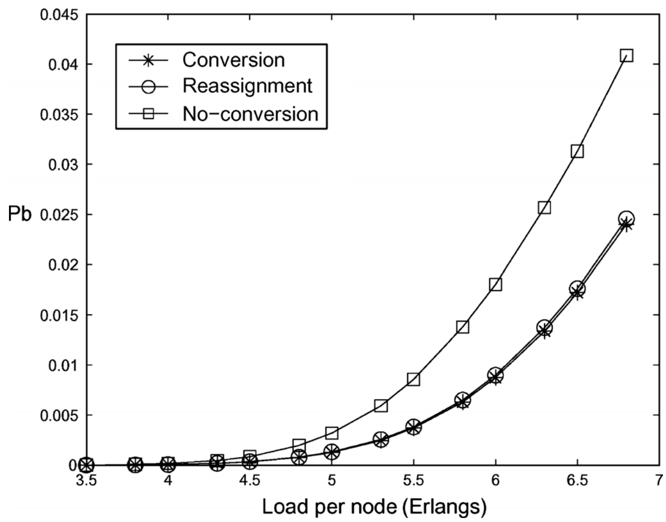

Fig. 8. Blocking probability versus load per node for rerouted ARPANET.

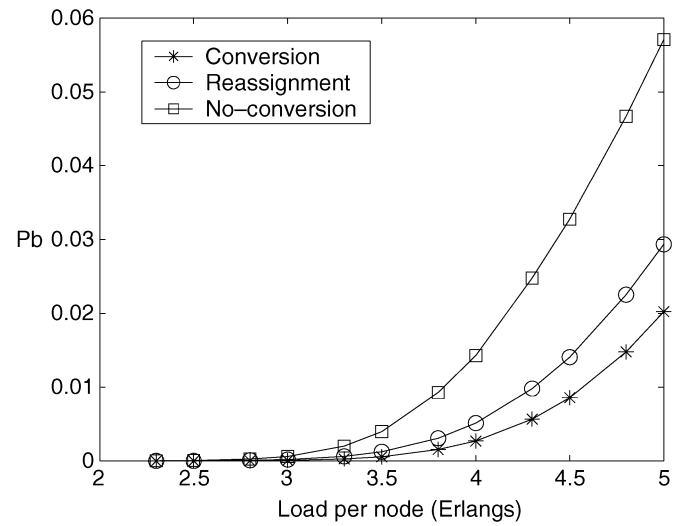

Fig. 10. Blocking probability versus load per node for shortest path routing.

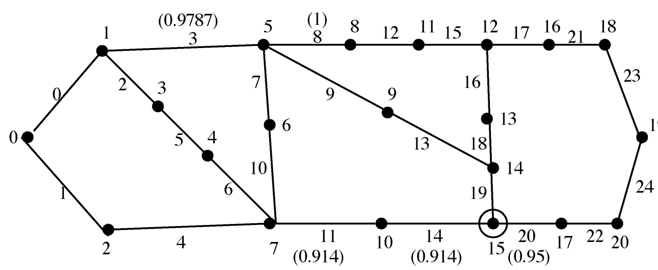

Fig. 9. ARPA2 with critical links marked.

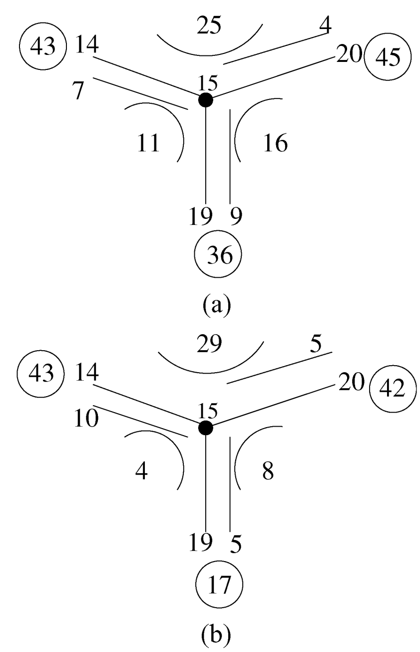

Fig. 11. Route distribution on triplet of ARPA2. (a) Triplet for shortest path routing; (b) re-routed triplet.

again one can see two quadruples formed at node 5 and node 7 with the most congested links 3, 8, and 11. The route distribution of these quadruples are shown in Fig. 12. Fig. 12(a) shows the route distribution of quadruple formed at node 5 with two most congested links 3 and 8. As $(ID_8 = 6) > (D_{3,9} - D_{7,8} = 3)$ and $(ID_3 = 5) > (D_{8,9} - D_{3,7} = 3)$ at this quadruple, it is noncritical. Similarly the quadruple at node 7 is also noncritical as can be seen from Fig. 12(b). Thus, the critical triplet formed by links 14, 19, and 20 alone contribute for the performance deviation. Appropriate rerouting of few routes using the proposed rerouting technique makes the critical triplet, noncritical, as shown in Fig. 11(b). It should be noted that only 19 routes (out of the 210 routes) need to be rerouted to make the triplet non critical. By rerouting, there is only a marginal increase in average hoplength of calls, from $havg_{\rm old} = 3.4619$ to $havg_{\rm new} = 3.5523$, in the network. The wavelength reassignment in network with the modified routing table results in the elimination of the performance deviation. This can be seen from Fig. 13, which again plots Pb across varying load per node for ARPA2 after rerouting.

Thus, the results show that by using wavelength reassignment techniques in networks without wavelength converters, a performance almost equal to wavelength conversion can be achieved, when the calls are appropriately routed in the network.

IV. Seamless Reassignment Technique

The technique proposed here and in [11] for improving the performance of WDM networks without wavelength conversion, involves wavelength reassignment of few already established calls in the networks. A concern is whether such a reassignment would lead to traffic disruption. Here, we briefly introduce a *seamless reassignment technique*, which is analogous to the SOFT HANDOFF used in cellular networks [15]. This enables wavelength reassignment with no service disruption in traffic.

A. Reassignment Algorithm

Circuit switched optical networks are considered, where only a few calls are setup and torn down in a day. Therefore, a centralized system can be used as a network manager, to decide and establish the lightpath in the network. The system uses the basic RWA algorithm [12], [13], where for routing, the shortest path finding algorithm, *Dijkstra's* algorithm and for wavelength

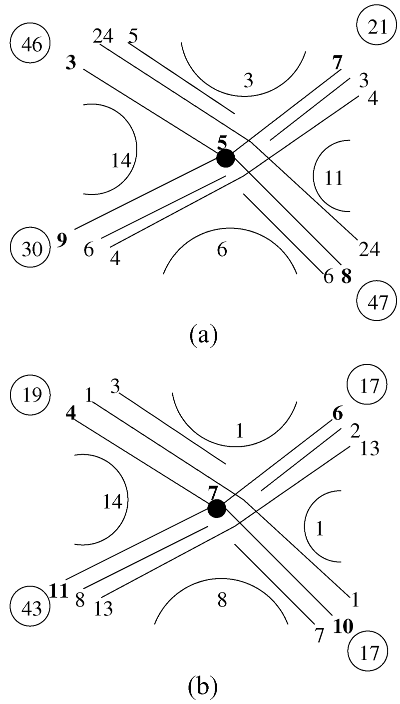

Fig. 12. Route distribution on quadruples of ARPA2. (a) Quadruple at node 5 formed by links 3, 7, 8, 9; (b) quadruple at node 7 formed by links 4, 6, 10, 11.

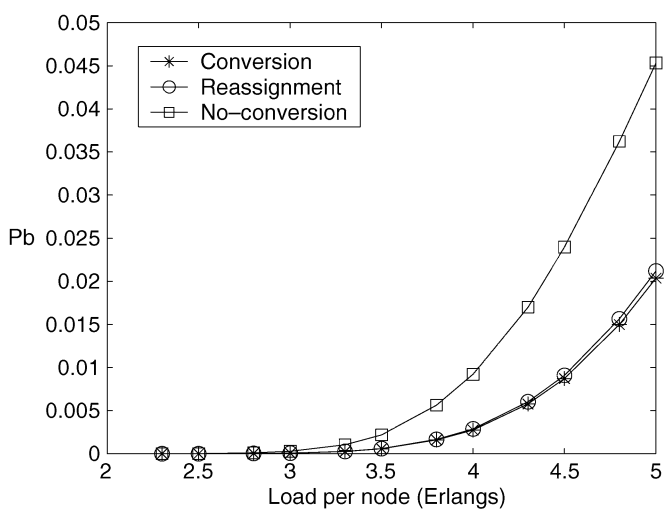

Fig. 13. Blocking probability versus load per node for rerouted ARPA2.

assignment, the *first fit* algorithm is used. When the lightpath cannot be established due to wcc blocking, the wavelength reassignment algorithm, *minimum overlap wavelength to least congested wavelength*—MOLC, establishes the blocked call. A detailed description of this algorithm is given in [11] and [14].

B. Seamless Wavelength Reassignment Technique

For wavelength reassignment, calls have to be shifted from one wavelength to another keeping the route fixed. It is seen that the MOLC reassignment algorithm, reassigns less than 2 calls per reassignment process on an average, for the entire range of the load considered during the simulation [11]. Even though only few calls are reassigned, there could be loss of data for the wavelength shifted calls during the reassignment process. To obviate this problem of data loss during the reassignment process, we propose a seamless wavelength reassignment technique. According to this technique, when a wcc blocking occurs, the network manager determines the following.

1) Routes/wavelengths to be reassigned.
2) Determine a sequence of steps for reassignment. One call is reassigned at a time.
3) First, the alternate route/wavelength is assigned, before the existing call is pulled out. Thus, for an instant, a call will be assigned two routes/wavelengths and the data travels in parallel on both the routes. Once the new route/wavelength is established, the original route/wavelength is torn down.
4) After one such call is reassigned, the next call to be reassigned is taken up in the similar manner. After the reassignment is carried out, the new call is set up.

The centralized system using the control channel/information can convey the destination nodes, as to which channel has to be further used for communication.

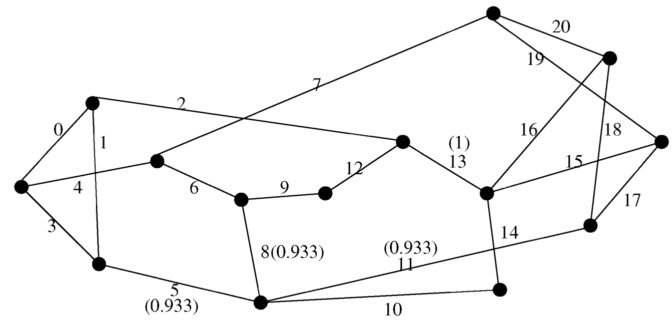

Fig. 14. NSFNET with critical links marked.

C. Results

Let us analyze the performance of reassignment algorithm with the seamless reassignment technique incorporated, on the different standard backbone networks. We present the results of 14 node, 21 link NSFNET (Fig. 14), as the others follow similar pattern. Fig. 15 plots the blocking probability, Pb versus load per node, which shows results obtained with seamless reassignment technique without seamless reassignment technique, with wavelength conversion and without wavelength conversion scenario. From the figure, the reassignment algorithm incorporating seamless reassignment technique, achieves a performance equivalent to that of the reassignment algorithm without seamless reassignment technique. Further, for a $Pb = 1\%$, the load supported, $L_{\text{seamless-reassn}} = 9.76$ Erlangs/node, $L_{\text{no-seamless-reassn}} = 9.76$ Erlangs/node, and $L_{\text{conv}} = 9.76$ Erlangs/node. Thus, the results show that wavelength reassignment with the proposed seamless reassignment technique, can achieve a performance equivalent to that of wavelength conversion, ensuring no loss of data or interruption for the wavelength shifted calls.

V. Conclusion

In this paper, we have analyzed the performance of routing and wavelength reassignment technique in optical WDM net-

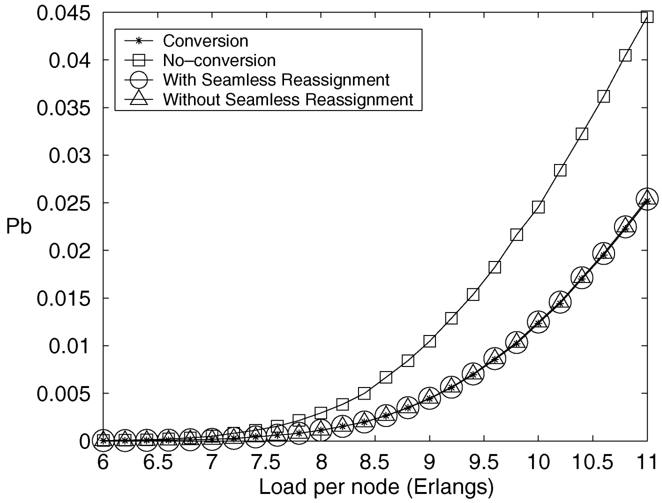

Fig. 15. Blocking probability versus load per node for NSFNET with seamless reassignment.

works without wavelength conversion. In some of the networks, where wavelength reassignment falls short of wavelength conversion performance, the critical nodes were found to be the reason for the performance deviation. We have identified the condition under which a node becomes critical and have proposed a rerouting technique at this critical node to make it noncritical. It was observed that only few routes need to be rerouted by the rerouting technique, to form the new route table. The wavelength reassignment algorithm, now applied to the network with modified route table achieves almost wavelength conversion performance, thereby making the wavelength conversion (costly) feature of the optical backbone networks redundant.

Further, we have also proposed a seamless reassignment technique, which ensures no data loss for the wavelength shifted calls during the reassignment process. The reassignment algorithm with the seamless reassignment technique, achieves wavelength conversion performance in optical WDM networks without wavelength conversion.

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