Link-Disjoint Routing Algorithms with Link-Disjoint Degree and Resource Utilization Concern in Translucent WDM Optical Networks

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Abstract— **Link-disjoint routing strategy can offer a set of reliable alternate paths when the active best path fails. However, simply employing a set of fully disjointed paths may not necessarily result in the efficient network resource utilization in some circumstances, which degrades the performance of the network system under a highly loaded traffic condition. In this study, we propose two heuristic link-disjoint routing algorithms to recruit a set of link-disjoint paths considering network resource optimization. Resource balance-based link-disjoint routing (RBR), as the first proposed scheme, selects a set of link-disjoint paths under a balanced condition between resource consumption and the link-disjoint degree (the percentage of the disjointed level between links of the selected paths and the links of the new path to be selected). The second scheme, resource optimization-based with customized link-disjoint degree routing (ROR), computes a set of link-disjoint paths which prioritize the minimum resource consumption and a required link-disjoint degree. The simulation results show that RBR and ROR significantly outperform the traditional shortest path in term of blocking probability. RBR works relatively at the same level as ROR. ROR's effectiveness is rather various depending on the given link-disjoint degree and the network size. We also find out that the link-disjoint degree of approximately 90% enables ROR to produce its best blocking performance in USANet backbone network topology while a lower degree suits a smaller network size.**

Keywords— **Routing, Link-Disjoint, Resource Optimization, Translucent, Optical, Network, WDM, Wavelength Division Multiplexing**

I. INTRODUCTION

The wavelength division multiplexing (WDM) optical network can offer a large capacity satisfying the continuously increased bandwidth demands from network users. An opaque optical network which employs WDM links between adjacent nodes not only provides a high-capacity but also a high-quality signal transmission by employing optical-electrical-optical (O-E-O) conversion at each wavelength per fibre link. However, the requirement for O-E-O conversion at each wavelength per fibre link results in the high cost and high energy-consumption. On the contrary, a transparent WDM all-optical network eliminates the presence of O-E-O conversion from the network, saving the cost and energy consumption. Meanwhile, the high-speed and high-quality all-optical signal transmission in a long distance is still a challenge. The linear/non-linear physical impairment (PI) problem in the long-distance transmission is the major cause which restricts the scale of the transparent all-optical networks.

Being an alternate candidate between the opaque optical network and the transparent all-optical network, a translucent optical network which employs sparsely located O-E-O converters (i.e. regenerators for signal amplifying, re-shaping, re-timing (3R)) can offer both high-speed and high-quality transmission with enlarged distance. In particular, it can reduce the number of expensive O-E-O conversions remarkably compared to the opaque optical networks. Moreover, as the 3R regeneration is an optional function for long distance transmission, certain degree of transparency can be pertained within the translucent network. However, introducing sparsely located 3R regenerators in data-plane needs an advanced network design for optimal 3R regenerator placement. In addition, sophisticate network control is important in control-plane in order to achieve efficient network resource utilization. More specifically; the resource in translucent optical networks, especially 3R regenerators, need to be optimistically utilized as much as possible during routing process.

Our previous study [1], resource utilization-based routing scheme (RUR), aims at optimizing network resource when selecting a set of candidate paths. With respect to the routing, a set of k-shortest paths might not guarantee a high possibility of survivability when the active best path fails. Since link-disjoint paths provide a reliable connection, [2], [3] uses a disjointed path candidate as a path protection when the failure occurs with the active best path. Similarly, a disjointed path can also be used for backup to achieve a better survivability comparing to a set of simple paths [4]-[6]. However these studies do not consider the challenges of limited 3R resource in translucent optical networks. In [7] the author shows how to find a set of fully link-disjointed paths in WDM optical networks to be applied in routing, while in [8] the disjointed path selection is done based on the intensity of the traffic pattern. Although a fully link-disjoint path is a reliable alternate path, it does not always promise the best optimization of the network resource. Therefore, in this paper we propose two new link-disjoint routing algorithms which enhance connection survivability while keeping low resource consumption for each traffic demands in translucent WDM optical networks. In the routing process, a criterion for link-disjoint paths selection is used: link-disjoint degree (D_{degree}). D_{degree} is defined as the percentage of disjointed links between the selected paths and path to be selected. For instance, a higher value of link-disjoint degree shows that less common links exist among the link-disjoint paths.

The first proposed scheme is resource balance-based link-disjoint routing (RBR). RBR selects a set of link-disjoint paths under a balanced condition between resource consumption and the link-disjoint degree. Resource optimization-based with customized link-disjoint degree routing (ROR), the second scheme, computes a set of link-disjoint paths which prioritize the minimum resource consumption and a given link-disjoint degree. These two routing algorithms are objectively designed to: 1) collect a set of link-disjoint paths to obtain reliable alternate paths when the best path fails to carry the lightpath, 2) optimize network resource utilization to enhance the scalability of the system and 3) stabilize the system performance by balancing the traffic load among the candidate paths. The rest of the paper is organized as follows. In section II, we introduce the characters of translucent WDM optical Network. Then we describe related routing algorithms in section III. Later in section IV, we detail the proposed algorithms. The simulation results are presented in section V. Finally we give the study conclusion in section VI.

II. TRANSLUCENT WDM OPTICAL NETWORK

A. Network Architecture and Model

Optical networks enable data to be transmitted in multiple channels simultaneously in the same fibre link using WDM technology. In the core network, each node is equipped with optical cross-connect (OXC) which can operate wavelength switching. Between adjacent nodes, bidirectional fibres are employed. Different from opaque and transparent WDM optical networks, translucent networks consist of transparent nodes (i.e. without any process of O-E-O conversion) and some sparely distributed opaque nodes. Each opaque node is equipped with an array of O-E-O processing devices (each element of processing devices is a pair of transmitter and receiver, called a T/R pair) and an electronic processing module that is capable in performing 3R regeneration or optical bypass if regeneration is not needed, often called regeneration capable node. These nodes are placed in the assumption that all network traffic could be well balanced by sharing these nodes to the entire network when regeneration required. This network architecture is designed to obtain a cost effective system while maintaining the performance close to a fully opaque optical network. Figure 1 depicts an example of a translucent network with two sparely placed 3R nodes.

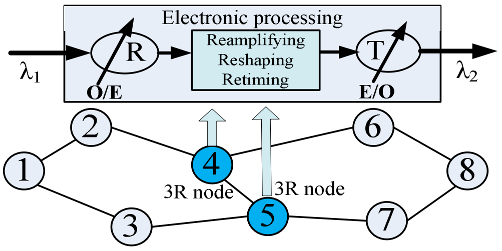

Figure 1. An example of a translucent network with two opaque nodes

In this study, the network topology is presented by an undirected graph $G(V, E)$, where V is a set of network nodes, and E is a set of edges labelled with the geographical fibre-link distance in *km*. A subset of V, for example, around 30% of V nodes is the 3R regeneration capable nodes N_R which optimally placed [10]. Each pair of adjacent nodes is connected via a bidirectional optical fibre link with W number of wavelengths in each direction, and a addresses the number of available wavelengths ($0 \leq a \leq W$). R and r represent the total number of 3R regenerators (the array of O-E-O processing devices) and available 3R regenerators respectively in a regeneration capable node ($0 \leq r \leq R$). A lightpath ($P_{s\text{-->}d}$) between a source-destination node pair s and d, with total length (L), consists of a number links along the route. The length of each link (i,j) is represented by L_{ij}, and max$L$ is the longest acceptable transparent length or optical reach (*OR*).

B. Routing Problem

In translucent optical networks, routing problem is referred to as routing, wavelength assignment (RWA) and 3R regenerator allocation problem. Like all-optical networks, RWA concerns the deployment of optical wavelength resources when routing a path. Based on routing protocol, e.g, OSPF-TE, node and link state information can be advertised and collected for routing process. Additionally, RWA in translucent optical networks needs to solve the problem of allocating sparely placed 3R regenerator at some intermediate nodes of a lightpath to accommodate 3R regeneration when the signal degrades to a threshold value. In this study, *maxL* is used to define a limited optical distance which signal can be carried along the optical wavelength without the degradation of signal quality exceeding the threshold value. After the best path is found, there is a need of wavelength selection (wavelength assignment) to strategically choose a wavelength for lightpath establishment.

III. RELATED ROUTING ALGORITHMS

A. 3R-Aware Shortest Path Routing(SPR)

SPR is a simple and straightforward scheme. It computes the path dynamically using Dijkstra algorithm considering the current state of the network. Hop-based metric is measured to determine the best path. The length of the path must stay under optical reach criterion or regeneration capable node(s) is sought to satisfy the transparent gaps along the path. Furthermore, SPR investigates the availability of optical wavelengths of each link along the path to validate the feasibility for lightpath setup. If any of the conditions above is missed, the path is discarded. The calculation is on-the-fly to select the shortest path under the challenge of a computational delay time.

SPR Algorithm

```
Online-calculation:
Step 1:  Demands arrive //from source $s$ to destination $d$
Step 2:  While (computational time $T_{\text{delay}} < T_{\text{limit}}$) do
     2.1:  Find path $P^x_{s\text{-->}d}$ between $s,d$
           (using Dijkstra algorithm)
             If (wavelength resource $a_{ij}$ of $P^x_{s\text{-->}d}$ >0)
                 If (length $L^x$ of $P^x_{s\text{-->}d}$ > $maxL$)
                   If ($N_R$ allocated and $r_j$>0)
                     Set cost $C^x$ = number of hop $H^x$ of $P^x_{s\text{-->}d}$
                   Else
                     $P^x_{s\text{-->}d}$ is discarded
                     Goto Step 2.1
                 Else
                   Set cost $C^x$ = number of hop $H^x$ of $P^x_{s\text{-->}d}$
             Else
                 $P^x_{s\text{-->}d}$ is discarded
                 Goto Step 2.1
Step 3:  Select $P^x_{s\text{-->}d}$ (holds the minimum $C^x$)
Step 4:  First-Fit wavelength assignment
End.
```

B. Resource Utilization-based Routing Algorithm (RUR)

RUR, a fixed alternate routing, selects a set of k-shortest paths offline based on minimum resource consumption, prioritizing number of 3R regenerators, hop count, and lastly physical length. Eligible paths are required to stay under the limit of optical reach; otherwise regeneration capable nodes are needed along the paths. When the demands arrive, RUR sets new weight C_{sd} to each candidate path depending on the availability of optical wavelengths and regeneration pools of current state of the network.

$$C_{\text{sd}} = \sum C_{ij}. \tag{1}$$

$$C_{ij} = \begin{cases} \left(\dfrac{W - a_{ij} - 2}{W}\right) . \left(\dfrac{R - r_j - 2}{R}\right) . L_{ij} & (R_j = 1) \\ \left(\dfrac{W - a_{ij} - 2}{W}\right) . \dfrac{L_{ij}}{R} & (R_j = 0) \end{cases} \tag{2}$$

Where:

C_{ij}	represents the weight of each link (i,j) along the path;
W	is number of the total equipped wavelengths;
a_{ij}	is the number of available wavelengths in link (i,j);
R	is the total equipped regenerators in node j;
r_j	is the number of available regenerators in node j;
L_{ij}	refers to the length of link (i,j);
$R_j=1$	means 3R regeneration is required at node j, and it is opposite when $R_j = 0$.

Each path is deployed in their order of lowest C_{sd} until the connection succeeds or all the paths are used up.

RUR Algorithm

```
Offline-preprocessing:
Step 1:  For each source-destination node pair $s$ and $d$
         1.1:  Find $N$ number of path $P^i_{s\text{-->}d}$ between $s,d$ (using
               Dijkstra-based heuristic algorithm)
                 If ( length $L$ of $P^i_{s\text{-->}d}$ > $maxL$)
                     If (3R allocation succeeded)
                         Add $P^i_{s\text{-->}d}$ to path-table $\text{Tab}_p$
                     Else
                         $P^i_{s\text{-->}d}$ is discarded
                         Goto Step 1.1
                 Else
                     Add $P^i_{s\text{-->}d}$ to $\text{Tab}_p$
Step 2:  In ascending order, sort $\text{Tab}_p$ based on 1st: 3R
         node $N_R$, 2nd: hop $H$, 3rd: $L$
Step 3:  For $x$ =1to number of candidate $k$ do
         3.1:  Add $P^x_{s\text{-->}d}$ to k-table $\text{Tab}_k$
Online-calculation:
Step 4:  Demands arrive //request for node pair $s$ and $d$
Step 5:  For each $P^x_{s\text{-->}d}$ in $\text{Tab}_k$ do
         5.1:  For each link $(i, j) \in P^x_{s\text{-->}d}$ (node $i$ adjacent to $j$)
                 If ($R_j$ = 1) //regeneration needed at node $j$
                     Calculate $C_{ij}$ using Eq. (2) \\$R_j$ = 1
                 Else
                     Calcualte $C_{ij}$ using Eq. (2) \\$R_j$= 0
                 Set $P^x_{s\text{-->}d}$ new weight: $C_{sd} = C_{sd} + C_{ij}$
Step 6:  Sort $\text{Tab}_k$ by $C_{sd}$ in ascending order
Step 7:  Do (each $P_{s\text{-->}d}$ in $\text{Tab}_k$ )
         7.1:  If (current resource availability $a_{ij}$>0, $r_j$ >0)
                 First-Fit wavelength assignment
End.
```

IV. PROPOSED ROUTING ALGORITHMS

A. Resource Balance-based Link-Disjoint Routing (RBR)

As its name described, RBR selects link-disjoint paths based on a balanced condition between resource optimization and the disjointed level of the paths. In case that a fully link-disjoint path consumes too much of network resource, a partially jointed path may be used instead. This depends on the weight of each path (resource consumption level) which is calculated below:

$$C^i_{\text{off}} = 2R^i_{\text{node}} \; (H^i - R^i_{\text{node}}) \; 10\log(L^i) \tag{3}$$

Where for path i:

C^i_{off}	refers to the weight of path computed offline;
R^i_{node}	is the necessary times of 3R required in the path;
H^i	refers to number of total hops;
L^i	represents the total length.

This cost function gives the higher weight to the expensive 3R node than a simple node. In contrast, it moderates the length L^i since each path selected is assumed to stay under the worst case of optical reach. According to this function, RBR can determine the resource consumption level of each path. Based on C^i_{off}, a Dijkstra-based heuristic algorithm is applied, before the demands arrive, to compute for K numbers of paths of a source-destination node pair in topology graph G. The least weighted path is recruited as the best path and will be used for calculating the link-disjoint alternate paths. After the first path is found, C^i_{off} of each path(i) is further updated to find the second best path:

$$C^i_{\text{off}} = C^i_{\text{off}} + C_{\text{best}} \frac{|L_{\text{common}}|}{|L_{\text{last}}|} \tag{4}$$

Where:

C_{best}	is the weight of the active best path;
$\lvert X \rvert$	refers to the function that returns number of elements in the set X;
L_{common}	represents the set of common links in the previously selected link set L_{last};
$L_{\text{last.}}$	is the set of links of the last selected path.

At this stage, L_{last} is the links of the best path selected earlier. However it will change each time a new path is recruited. Now the second best path is obtained based on the least value of C_{off} that has just been updated. This process is repeated until a set of k paths has been selected.

B. Resource Optimization-based with Customized Link-Disjoint Degree Routing (ROR)

ROR computes a set of link-disjoint paths by prioritizing on minimum network resource consumption and a required link-disjoint degree. This means that the collection of link-disjoint paths may be different depend upon the predetermined degree (D_{required}). In this scheme, the best path is selected in the same method as RBR. Then C_{off} is sorted in the ascending order. In each sorted path, except the selected path, ROR calculates D_{degree} based on equation below:

$$D_{\text{degree}} = 100.\left(1 - \frac{\lvert L_{\text{last}} \cap L_{\text{path}} \rvert}{\lvert L_{\text{last}} \rvert}\right) \tag{5}$$

Where: L_{path} is links of the considering path.

$$L_{\text{last}} = \bigcup_{i=1}^{n} L_{\text{path}(i)} \qquad (0<n<k) \tag{6}$$

Where:

$L_{\text{path}(i)}$	refers to links of the selected path i;
n	is number of selected paths.

From order of the least weighted path, the one meets the requirement ($D_{\text{degree}} \geq D_{\text{required}}$) is recruited as the second best path. This process is repeated until a set of k link-disjoint paths obtained. A condition may happen that none of the paths meets the required degree ($D_{\text{degree}} < D_{\text{required}}$). In that case, the path holds the highest D_{degree} and its C_{off} is not higher than twice of that of the best path is chosen. L_{last} changes each time a new path is obtained using Eq. (6).

C. RBR and ROR (Common Scenario)

The above strategy enables RBR and ROR to obtain a set of link-disjoint paths which optimize the resource utilization in the offline scenario. When the demands arrive, the candidate paths will be further evaluated using the current information of the network state. This evaluation is performed to avoid the exhaustion of best path resource which, in return, affects other lightpath of a different source-destination pair that attempt to deploy any of links of the best path. By examining the current available wavelength resource and 3R regeneration pool, RBR and ROR is able to provide a new online weight (C_{on}) to each candidate path. C_{on} is designed to balance the traffic load among candidate paths based on the occupied level of the resources. $C_{\text{on}} = \sum C_{ij}$, where C_{ij} is computed based on Eq. (1).

RBR Algorithm

```
Offline-preprocessing:
Step 1: For each source-destination node pair $s$ and $d$
        1.1: Find $N$ number of path $P^{i}_{s\text{-->}d}$ between $s,d$ (using
             Dijkstra-based heuristic algorithm)
             If (length $L^{i}$ of $P^{i}_{s\text{-->}d} > maxL$)
                 If (3R allocation succeeded)
                     Set $C_{\text{off}}$ to $P^{i}_{s\text{-->}d}$ using Eq. (3)
                     Add $P^{i}_{s\text{-->}d}$ to path-table $\text{Tab}_{\text{p}}$
                 Else
                     $P^{i}_{s\text{-->}d}$ is discarded
                     Goto Step 1.1
             Else
                 Set $C_{\text{off}}$ to $P^{i}_{s\text{-->}d}$ using Eq. (3)
                 Add $P^{i}_{s\text{-->}d}$ to $\text{Tab}_{\text{p}}$
Step 2: Select the best $P^{i}_{s\text{-->}d}$ with lowest $C_{\text{off}}$
Step 3: Set $L_{\text{last}}$ = links of the selected $P^{i}_{s\text{-->}d}$
Step 4: Move $P^{i}_{s\text{-->}d}$ from $\text{Tab}_{\text{p}}$ to k-table $\text{Tab}_{\text{k}}$
Step 5: While (size of $\text{Tab}_{\text{k}} < k$) do
        5.1: For each $P^{i}_{s\text{-->}d}$ in $\text{Tab}_{\text{p}}$
             Set $C^{i}_{\text{off}}$ using Eq. (4)
        5.2: Move $P^{i}_{s\text{-->}d}$ with lowest $C^{i}_{\text{off}}$ to $\text{Tab}_{\text{k}}$
        5.3: Set $L_{\text{last}}$ = links of the moved $P^{i}_{s\text{-->}d}$

Online-calculation:
Step 6:Demands arrive//request for node pair $s$ and $d$
Step 7: For each $P^{x}_{s\text{-->}d}$ in $\text{Tab}_{\text{k}}$ do
        7.1: For each link $i, j \in P^{x}_{s\text{-->}d}$ (node $i$ adjacent to $j$)
             If ($R_j = 1$) //regeneration needed at node $j$
                 Calculate $C_{ij}$ using Eq. (2) //$R_j = 1$
             Else
                 Calculate $C_{ij}$ using Eq. (2) //$R_j = 0$
             Set $P^{x}_{s\text{-->}d}$ new weight: $C_{\text{on}} = C_{\text{on}} + C_{ij}$
Step 8: Sort $\text{Tab}_{\text{k}}$ by $C_{\text{on}}$ in ascending order
Step 9: Do (each $P^{x}_{s\text{-->}d}$ in $\text{Tab}_{\text{k}}$)
        9.1: If (current resource availability $a_{ij}>0$, $r_j>0$)
             First-Fit wavelength assignment
End.
```

ROR Algorithm

```
Offline-preprocessing:
Step 1: For each source-destination node pair $s$ and $d$
        1.1: Find $N$ number of path $P^{i}_{s\text{-->}d}$ between $s,d$ (using
             Dijkstra-based heuristic algorithm)
             If (length $L^{i}$ of $P^{i}_{s\text{-->}d} > maxL$)
                 If (3R allocation succeeded)
                     Set $C_{\text{off}}$ to $P^{i}_{s\text{-->}d}$ using Eq.(3)
                     Add $P^{i}_{s\text{-->}d}$ to path-table $\text{Tab}_{\text{p}}$
                 Else
                     $P^{i}_{s\text{-->}d}$ is discarded
                     Goto Step 1.1
             Else
                 Set $C_{\text{off}}$ to $P^{i}_{s\text{-->}d}$ using Eq.(3)
                 Add $P^{i}_{s\text{-->}d}$ to $\text{Tab}_{\text{p}}$
Step 2: Move $P^{i}_{s\text{-->}d}$ (holds lowest $C_{\text{off}}$) from $\text{Tab}_{\text{p}}$
        to k-table $\text{Tab}_{\text{k}}$
Step 3: Set $L_{\text{last}}$ = links of the moved $P^{i}_{s\text{-->}d}$
Step 4: Sort $\text{Tab}_{\text{p}}$ by $C_{\text{off}}$ in ascending order
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```
Step 5:  While (size of $Tab_k < k$) do
         5.1: For each $P^i_{s\text{-->}d}$ in $Tab_p$
                  Set $D^i_{degree}$ using Eq. (5)
                  If ($D^i_{degree} \geq D_{required}$)
                      Move $P^i_{s\text{-->}d}$ to $Tab_k$
                      Goto 5.3
         5.2: Move $P^i_{s\text{-->}d}$ (holds $C^i_{off} \leq 2 * C_{best}$ and
              highest $D^i_{degree}$) to $Tab_k$
         5.3: Set $L_{last}$ using Eq. (6)
Online-calculation:
Step 6: Demands arrive //request for node pair $s$ and $d$
Step 7:  For each $P^x_{s\text{-->}d}$ in $Tab_k$ do
         7.1: For each link $i, j \in P^x_{s\text{-->}d}$ (node $i$ adjacent to $j$)
                  If ($R_j = 1$) //regeneration needed at node $j$
                      Calculate $C_{ij}$ using Eq. (2) //$R_j = 1$
                  Else
                      Calculate $C_{ij}$ using Eq. (2) //$R_j = 0$
                  Set $P^x_{s\text{-->}d}$ new weight: $C_{on} = C_{on} + C_{ij}$
Step 8:  Sort $Tab_k$ by $C_{on}$ in ascending order
Step 9:  Do (each $P^x_{s\text{-->}d}$ in $Tab_k$)
         9.1: If (current resource availability $a_{ij} > 0$, $r_j > 0$)
                  First-Fit wavelength assignment
End.
```

In this study, we employ conventional First Fit algorithm to conduct the wavelength assignment [9]. All wavelengths are indexed from 1 to W (total number of wavelength). The search for the available wavelength proceeds in an order from the lowest index to the higher index.

V. NUMERICAL RESULTS

A. Simulation Environment

Simulation experiment is conducted to evaluate the routing performance of RBR and ROR. Omnet++ discrete event network simulator is used in this study with two network topologies, NSFNet in Figure 2 and USAnet in Figure 3. *OR* is defined variously depending on the network topology [10]. The requested demands between a source-destination node pair arrive in Poisson process and the holding time is exponentially distributed with mean 1*s*. The state information of the network is governed by interval triggering policy. The simulation data is collected after 1000s simulation time. To focus on the observation on the influence of 3R, the wavelength continuity constraint was relaxed. Namely, we assumed that all nodes in V can perform wavelength conversion, in order to observe the potential of the proposed schemes.

B. Performance Evaluation

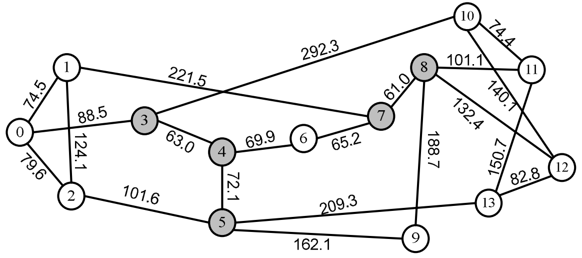

Figure 2. NSFNET backbone network, with 14 nodes, 21 bi-directional links. 5 regeneration capable nodes are filled in grey [10]

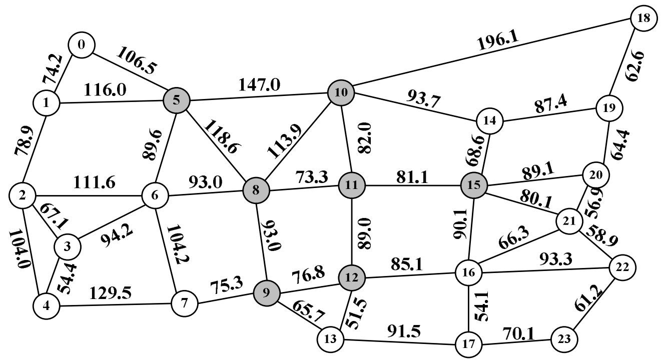

Figure 3. USANET backbone network, with 21 nodes, 43 bi-directional links. 7 regeneration capable nodes are filled in grey [10]

Blocking performance was evaluated to compare the proposed schemes with 3R-aware shortest path routing (SPR) and resource utilization-based routing (RUR). We also investigate the different degree of link-disjoint in ROR scheme and show the effectiveness of fully link-disjoint comparing to link-disjoint path with some common links in the corner view of resource optimization.

As shown in Figure 4, our proposed schemes outperform conventional shortest path significantly. However RBR seems to stay very close to RUR, while ROR perform the best. In NSFNet topology there are very limited choices of paths for routing. Therefore as long as the candidate paths can optimize the resource, a set of simple paths and link-disjoint paths offer similar outcome. With good the optimization of the network resource and a well balance of the traffic load among candidate paths, RBR and ROR show a remarkable improvement comparing to conventional SPR. SPR searches the best path any time resource is available to serve the demands. It is very likely that the selected path for the same pair of nodes will be the similar unless the best path is exhausted. Therefore, in case of a long-distance pair of nodes, the exhaustion of the path will significantly affect other lightpaths which utilize any links of the exhausted path, thus accelerate the blocking probability.

More interestingly, from observation in Figure 5, while RBR and ROR perform relatively at the same level, they both can enlarge their better blocking performance gap from RUR showing their clearly reliable result, and even far better than SPR in USANet topology in Figure 3. RBR and ROR compute the path in offline scenario without any computational delay constrain. This highly ensures best path candidates in term of resource optimization among N possible paths (N=50 in this experiment) which in turn offer the robustness of the system in serving demands. Furthermore, RBR and ROR even out the traffic and share a balanced load among candidate paths of a pair of nodes, introducing smooth traffic flows without interfering with other pairs of nodes. Although RUR and the new proposed schemes have their similar function of utilizing network resource, RUR produces a precise poorer result than RBR and ROR in a larger network. This shows the clear distinction of the effectiveness of link-disjoint alternate paths over a set of simple alternate paths. The reason is that there is a high risk of getting the connection blocked for the alternate path which has links in common

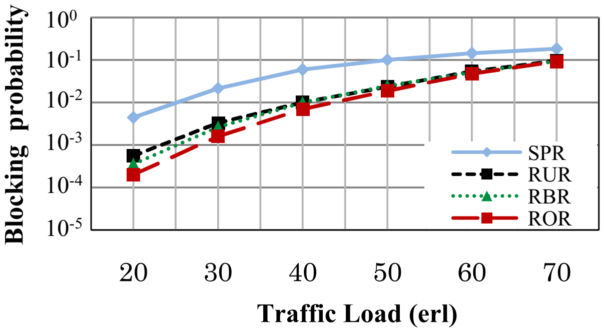

Figure 4. Blocking performance comparison using NSFNet topology $W = 8$, $R = 4$, $OR = 400$km, $k = 3$ and D_{required} of ROR = 80%

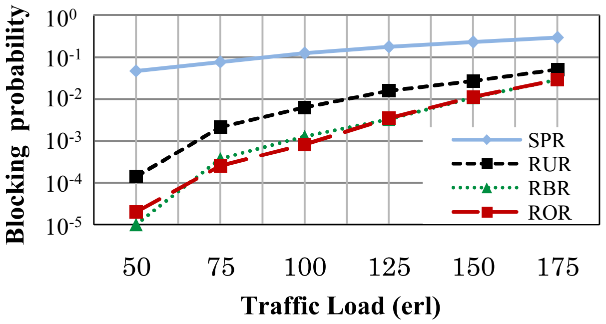

Figure 5. Blocking performance comparison using USANet topology $W = 16$, $R = 16$, $OR = 300$km, $k = 3$ and D_{required} of ROR = 90%

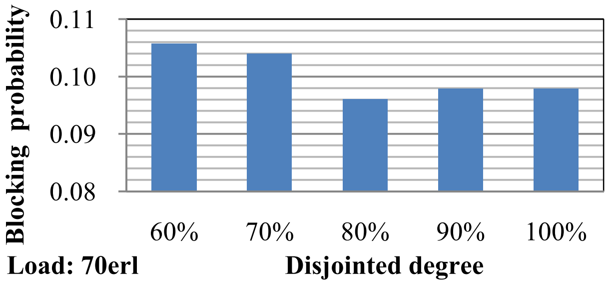

Figure 6. Blocking probability of ROR with different D_{required}. in NSFNet $W = 8$, $R = 4$, $OR = 400$km, $k = 3$

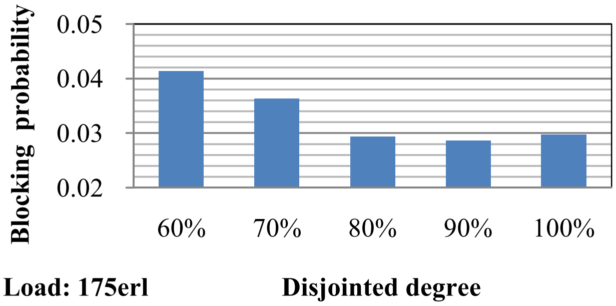

Figure 7. Blocking probability of ROR with different D_{required}. in USANet $W = 16$, $R = 16$, $OR = 300$km, $k = 3$

when the active best path fails. To minimize this problem, link-disjoint path provide more reliable alternate paths and ensure a better survivability.

Figure 6 and Figure 7 present the different performance of blocking probability of ROR in the different scenario of D_{required}. As the result, 90% of D_{required} tents to be the best input for USANet topology, while 80% shows the most effective result in NSFNet topology. In all likelihood, we can know that a set of alternate paths with too much common links cannot achieve a good performance. On the other side, a set of alternate paths which is fully link- disjointed does not always can guaranty the network resource optimization. From the two figures, it also can be seen that the D_{required} may be shifted to a smaller degree to obtain a good outcome in a smaller network size.

VI. CONCLUSION

In this paper, we discussed routing problem in translucent WDM optical networks. Two new routing algorithms are proposed to find a set of link-disjoint paths under a well optimized condition of network resource. The first proposed scheme, RBR, balances the minimum resource consumption and link-disjoint degree when selecting the paths. ROR, the second scheme, selects the paths which consume the least resource and meet the requirement of link-disjoint degree. As the result, both schemes work relatively at the same level of blocking performance, but show a significant improvement from previous proposed scheme RUR and even much better than conventional shortest path SPR. We also notice that 100% link-disjoint degree may not offer a good utilization of network resource in some circumstances. For a betterment of the future work, the fixed candidate paths shall be recalculated when all the alternate paths have failed to carry out the lightpath and the best alternate path shall be resumed once a number of occupied resources released.

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