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Dynamic routing, modulation level and spectrum allocation (RMLSA) in FWDM with modulation format conversion

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ABSTRACT

This paper proposes a dynamic routing, modulation level and spectrum allocation (RMLSA) scheme in the flexible optical wavelength-division multiplexing (FWDM) networks with modulation format conversion ability. The scheme considers the modulation format conversion at the intermediate nodes and addresses the fragmentation problem by avoiding appearance of them. The influence of routing to the emergence of the fragmentation is quantified, which is referenced to decide which one route of k-paths to use. Simulation results demonstrate efficient reductions in blocking rates and improvements in failure recovery rates for the scheme in the network.

1. Introduction

In recent years, the demand for bandwidth is increasing with the development of the Future Internet. At the same time, the rate of traffic is from 10 Gb/s up to 1 Tb/s and more various. The flexible optical wavelength-division multiplexing (FWDM) networks which have elastic optical paths can address the growing traffic demand in a spectrum efficient and flexible way. FWDM networks are different from the traditional fixed-grid WDM networks, the channels spacing of which is fixed. The channels spacing of FDWM networks is characterized by a given bit-rate and spectral width, ensuring adapt to traffic demands and physical path properties to attain a trade-off between higher spectral efficiency and cost-effectiveness [1]. The carrier of FWDM networks can be single carrier or multicarrier. The multicarrier solutions such as coherent wavelength-division multiplexing (CoWDM) [2], coherent optical orthogonal frequency-division multiplexing (CO-OFDM) [3], Nyquist-WDM, as well as dynamic optical arbitrary waveform generation (OAWG) [4] have been used in FWDM networks extensively. Fig. 1 shows the waveforms of them. The CO-OFDM generates many low-speed subcarriers using an inverse fast Fourier transform (IFFT) to ensure orthogonality. Different number of subcarriers supports different symbol rate and bring different path rate. To maintain the orthogonality between the OFDM bands, the frequency spacing of the guard bands ΔGf equals $k \times \Delta f$, where k is an integer values.

Higher-order modulation format is also adopted to improve the spectrum efficiency and the selection of modulation format is based on the transmission constraints. For example, a channel with 100 Gbps using QPSK modulation format needs 50 Gband. If the bandwidth of a subcarrier is 12.5 GHz, the channel needs 4 subcarriers. While using 16QAM modulation format, the channel only needs 25 Gband that means 2 subcarriers are enough. With the format flexible transponder, the FWDM networks can change the channel modulation format to suit the rate and the transmission constraints of the traffic demand on it. Previous researches focus on the modulation format flexible at the source node or destination node [5]. If the modulation format of the channel can be changed at the intermediate node, the networks may be more flexible and the blocking rate can be lower.

Although FWDM optical networks are more flexible and spectrum efficiency, however, there are still some drawbacks. One of them is that under a dynamic traffic scenario, connection setup and release may lead to fragment throughout the network, by separating the available spectrum into small non-contiguous spectrum bands [6]. Because of the non-contiguous of these fragmentations the probability of using them is low, which will degrade the spectrum utilization efficiency. A number of solutions have been recently proposed for flexible optical networks. There are two mainly ways to deal with the fragmentations, one is avoid the emergence of them; another is defragmentation, which means unit the non-contiguous spectrum bands together [7–9]. The first one needs the dynamic routing and spectrum allocation (RSA) strategy considering the fragment. And the second one can be achieved by rerouting [7–9], optical channel re-tuning [10,11], and so on. However, the defragmentation may change the existed routing and

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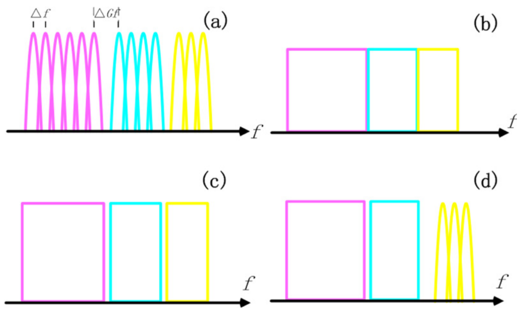

Fig. 1. CO-OFDM, CoWDM, Nyquist-WDM, and OAWG waveforms. (a) CO-OFDM uses different number of subcarrier carry different bit-rate channel; (b) CoWDM combines many orthogonal subcarriers together to form a waveform; (c) Nyquist-WDM combines many independently generated channels together with a minimum guard band, the channels can be single-carrier or multicarrier; (d) OAWG flexible generates any combination of single-carrier or multicarrier waveforms. Δf: subcarrier frequency spacing; ΔGf: frequency spacing of the CO-OFDM guard band.

need changing their transceivers, which may cause more control operations, time delay and energy consumption. Using the fragmentations by the format conversion at the intermediate node and considering the fragmentations in the routing, modulation level and spectrum allocation algorithms (RMLSA) is a new way to solute it.

In this paper, we propose RMLSA algorithm, which is deployed to investigate its performance improvement to the networks. The node in developed FWDM network can convert the modulation formats of the paths with the center frequency of paths unchanged. The RMLSA algorithm considers avoiding the fragmentations, the modulation conversion and so on. The rest of this paper is organized as follows. In Section 2, we first review related work on format conversion, fragmentation problem in FWDM and then propose our node architecture and RMLSA approach and discuss the algorithms strategy. Section 3 details the formulation of the RMLSA algorithms, based on *k*-path algorithm and greedy algorithm. In Section 4, we provide numerical analysis to demonstrate the benefits of the algorithms versus the normal algorithms and FWDM without intermediate node format conversion. Concluding remarks are given in Section 5.

2. The dynamic RMLSA approach

2.1. Related work

In FWDM networks, conventional routing and wavelength assignment (RWA) algorithms are not applicable, because the resource in the network is not the wavelength only but more flexible. So the extended versions of the routing and spectrum allocation algorithms (RSA) are developed. However, when considering the modulation level, the problem becomes more complex. The spectrum needing of a path is various with different modulation level. Hence the modulation level affects the spectrum allocation a lot, especially with modulation format conversion at the intermediate node. In [5] the modulation level has been considered. In the research, the modulation level is related with distance and the whole path is with only one modulation level that means the modulation format changed at source node and destination node only. For these reasons the dynamic RMLSA is needed for the complex problem in FWDM networks with modulation format conversion at the intermediate node.

To use the spectrum more efficient in FWDM networks, the problem of fragmentation should be handled. The effect of fragmentation can be seen in Fig. 2, link *a* and link *b* have the same number of free slots (each slot stands for a spectrum band). But when a

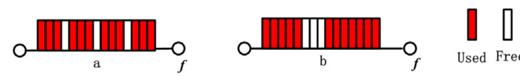

Fig. 2. Links with 3 slots free.

connection which needs 3 slots coming, link *b* is available while link *a* is not available because the free slots of it are non-contiguous.

With the ability of format conversion at the intermediate node and the developed RMLSA scheme, the networks can avoid the fragmentation more efficiently. Owing to using high-level modulation format, the fragmentation slots may be turn to available resources. Actually, the definition of a fragmentation depends on both the service bit-rate and the modulation format of the path. For example, using PDM-QPSK modulation format, the spectral efficiency of a 40 GHz spectrum band can be as high as 2.5 b/s/Hz [12], that means the 40 GHz spectrum band can carried service with 100 Gb/s. When the most of the service bit-rate in the networks is over 100 Gb/s, the spectrum band can be seen as fragmentation. While using 16QAM modulation, only when the most of service bit-rate in the networks is over 200 Gb/s, it will be seen as fragmentation. In some researches, each path can have different modulation format which is distance adaption [13,14]. A narrow spectrum band may be not available most of time when using the distance adaptive modulation format. But using a more spectral efficient modulation format it may turn to be available while the transmission characteristic may be low. So convert the modulation format before the OSNR or other transmission characteristic is too low to ensure transmission quality. By this way, the spectrum band can be used; the number of fragmentation is reduced, as well as the networks are more spectral efficient and blocking rate decreases.

2.2. The dynamic RMLSA principle

Under a dynamic traffic scenario, the problem of fragmentation must be considered. The effects of the fragmentation have been described in the related work, and Fig. 3 shows how the format conversion can reduce the blocking rate. From the example in Fig. 3 scene 1, as show in Fig. 3 scene 1 (a) we can see that the traffic path needs 6 slots using QPSK, while at the link A–B only 5 free slots is continuous and 1 free slot is not contiguous to them. That means, there is not enough spectrum resource for the path of traffic with 6 slots, and traffic is blocked. With the defragmentation technology [10], shown in scene 1 (b), we can moves the single slot to contiguous to the other 5 free slots so that the path can be carried at

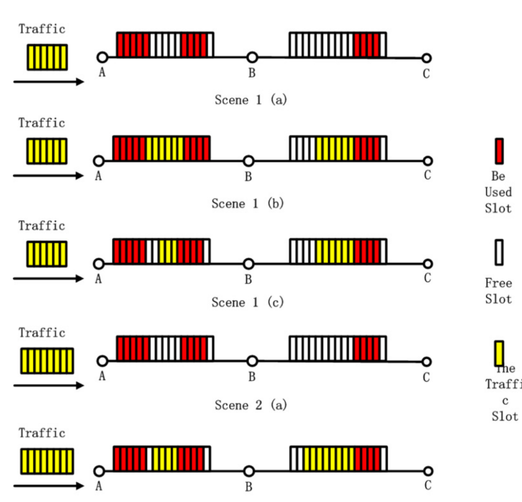

Fig. 3. Two examples of link spectrum allocation.

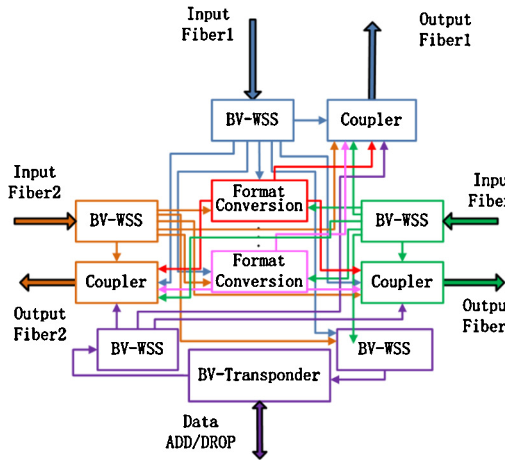

Fig. 4. The architecture of D/C/D node with modulation format conversion modules.

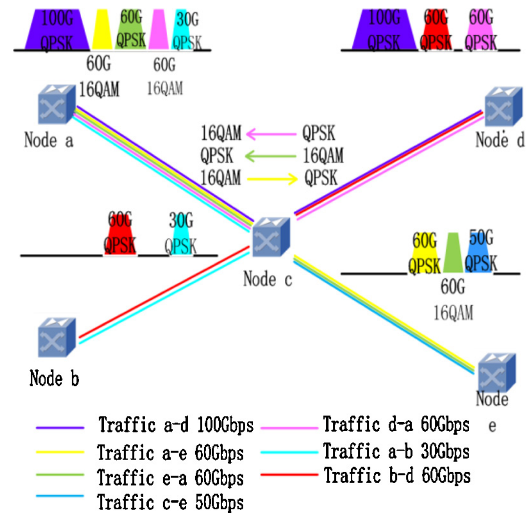

Fig. 5. The flexible-grid optical network with modulation format conversion.

the link A–B and the traffic will not be blocked. But this will affect the traffic which has been assigned routing and spectrum, and that is not what we want to see. In scene 1 (c), the modulation format of the path is converted from QPSK to 16QAM at node A, so the path needs only 3 free slots, and there are enough spectrums for 3 slots. Because of the transmission characteristic limit, the modulation format of the path should be converted to QPSK at Node B as shows in scene 1 (c). In this way, the earlier coming traffic in the network would not be affected. As showing in scene 2 (a), we need 8 slots for the path with QPSK. Even moving the free slot together, there would not be enough free slots for the path and traffic will be blocked. While using the modulation format conversion (scene 2 (b)), 4 free continuous slots are enough and traffic will not be blocked.

The modulation format conversion can reduce the blocking rate of the networks. But at the same time, we can see in Fig. 3 scene 1 (c) that there are still some single slots (fragmentation), which will not be used frequently when most of the paths need more than one or two slots. We develop the dynamic RMLSA algorithm to avoid the emergence of them, and to reduce the blocking rate of the network. The modulation format conversion can be achieved with SOA-MZI or QD-SOA (all-optically) [15,16], or with the flexible transceivers (modulation format recognition) [17,18].

2.3. Equipment requirements

The RMLSA is based upon the efficient allocation of traffic on elastic optical path and the flexible modulation format conversion. The node in the networks should be able to convert the modulation format of the signal for spectrum efficiency and establish the elastic path with suitable spectrum. As a selected switch, the node in the networks should offer Colorless, Directionless, and Contentionless (C/D/C) add/drop capabilities. So the node architecture includes bandwidth-variable wavelength-selective switches (BV-WSSs) at the input ports, the add/drop ports, the optical couplers at the output ports, the BV-transponders and the modulation format conversion modules (Fig. 4). At each input port the optical paths can go to the output port with the same direction of the input port. The paths which should cross connect go to the BV-WSS. They are selective switched with suitable spectrum to the coupler at the destination direction. Any spectrum on any node degree can be dropped at a certain drop-port and any spectrum on an add-port can be switched to any outbound node degree. That means the node architecture is CDC. Till now, The BV-WSS and BV-transponder used in switch node (BV-OXC), and the CDC ROADM architecture have been researched [19–21]. On the other hand, the format conversion modules offer the modulation format conversion ability and they support spectral BPSK to QPSK, QPSK to 16QAM, 16QAM to QPSK and QPSK to BPSK format conversion functionality. The format conversion modules are time division multiplexing by all the degrees.

Fig. 5 illustrates a FWDM network with modulation format conversion. The modulation format of the traffic path *d*–*a*, *a*–*e* and *e*–*a* is converted at node *C*. In this circumstance, the modulation format of traffic *d*–*a* must be changed from QPSK to 16QAM so that the spectrum of link a–c will be enough for the path and traffic would not be blocked. The modulation format of traffic *a*–*e* and traffic *e*–*a* is 16QAM at the source node, but that is for lower blocking rate, instead of for satisfying transmission characteristic. To satisfy transmission characteristic, the modulation format of them is converted to QPSK. Without the modulation format conversion, the modulation format of the paths cannot be changed at node *c*, and the traffic *d*–*a*, *a*–*e* and *e*–*a* will be blocked or arrive at the destination node with poor transmission characteristic.

3. Heuristic algorithms

In this section, we develop dynamic RMLSA algorithm that is essential for planning FWDM networks with modulation format conversion. The modulation format conversion adds complexity to RSA problems in FWDM networks, and we need to constrain the format conversion modules for modulation format conversion.

With the dynamic path establishment, blocking occurs when there are not enough continuous slots on links for building the path of a route. The algorithm will try to find the best route, resource assignment and considering format conversion for the coming traffic to avoid the blocking and fragmentation. The given network can be represented by an undirected graph $G(V,E)$, where V is a set of nodes and E is a set of fiber links. Each link has the same capacity of spectrum resource (4400 GHz), and the same spectral width of the slot. The total number of slots on a link is S. The routes of the networks should be assigned with continues spectrum. So when we enumerate the available spectrum slots for the paths, we only consider the available slots units on the first link of the route enough. With the enumerate method, the time complexity of algorithm is still $O(n)$, which can be acceptable. In FWDM networks with modulation format conversion, the format conversion modules can improve the spectrum efficiency by using more slots with less blocking. At the same time it brings more cost and complex. So the number of format conversion modules should be limited.

Although the modules are time multiplexing, there should not be too many modulation format conversion processes. To reduce the number of fragmentation, the algorithm should avoid the appearance of them. As described in Section 2, the fragmentation relates with the traffic rate and the modulation format. The scheme takes this into account by identifying the fragmentation referring to the spectrum need of the average-rate traffic with the 16QAM modulation format. The non-contiguous spectrum bands can be seen as fragmentation, if it is more narrow than the spectrum band (presented by N_{mid}) which is needed by the average-rate traffic with the 16QAM modulation format. And the narrower the band is, the worse it is. So in the algorithm, the RMLSA candidates are evaluated by the sum of the weight $\phi_{\mathrm{Link}}(p)$ in the path. Weight $\phi_{\mathrm{Link}}(p)$ presents the influence of candidate p to the emergence of the fragmentation at the Link. Links are parts of the route in candidate p:

$$\varnothing_{\mathrm{Link}}(p)=\begin{cases}\infty & \text{when } n_{\mathrm{Link}}^{\mathrm{free}}(p) < n_{\mathrm{Link}}(p) \\ 0 & \text{when } n_{\mathrm{Link}}^{\mathrm{free}}(p) = n_{\mathrm{Link}}(p) \text{ or } n_{\mathrm{Link}}^{\mathrm{free}}(p) \geq N_{\mathrm{mtd}}+n_{\mathrm{Link}}(p) \\ \dfrac{\beta}{\alpha n_{\mathrm{Link}}^{\mathrm{free}}(p)-n_{\mathrm{Link}}(p)} & \text{the others}\end{cases}$$

where p is a candidate for traffic, including the route, the modulation format and the start slot. The start slot of p means the candidate p uses the continuities slots which from the start slot for the traffic, and the start slot presents the spectrum allocation scheme. $n_{\mathrm{Link}}^{\mathrm{free}}(p)$ is the number of free slots from the start slot of p. $n(p)$ is the number of the slots which is needed by p. α and β are the variables to describe the fragmentation at the Link, when using p for the traffic. The smaller $\varnothing_{\mathrm{Link}}(p)$ is, the better p is.

The RMLSA algorithm processes are given below.

Step 0: At the time t, if there are traffics coming to the end, release the resource they used.
Step 1: Arrange the coming traffic in descending order of their rate.
Step 2: Pick the first connection from the ordered set and calculate k shortest-paths for each node pair with the minimal distance length of the route. Set $j=1$.
Step 3: To the j shortest-path route, choose the suitable modulation format for the route according to the length of the route.
Step 4: To the j shortest-path route, at the first link of it, take the free slot as the start slot of the route; find the first free slot to the last one.
Step 5: The route, modulation format, and the start slot make up a candidate p. and the different start slots leading to different ps. Calculate the $\sum_{\mathrm{Link} \in \mathrm{route}} \varnothing_{\mathrm{Link}}(p)$ for them, and choose the start slot with the smallest $\sum_{\mathrm{Link} \in \mathrm{route}} \varnothing_{\mathrm{Link}}(p)$ as the spectrum allocation for the j shortest-path route. If $j=k$, then go to step 6, else, set $j=j+1$, then back to step 3.
Step 6: To the k candidate ps, if $\sum_{\mathrm{Link} \in \mathrm{route}} \varnothing_{\mathrm{Link}}(p) < \infty$ exists, then select the p with the smallest $\sum_{\mathrm{Link} \in \mathrm{route}} \varnothing_{\mathrm{Link}}(p)$ as the RMLSA for the traffic. Then go to step 11, Else set $j=1$, go to step 7.
Step 7: In the j shortest-path route, finding the bottleneck link, which has not enough free slots and makes the traffic blocked. Using the modulation format with fewer slots needing at this link and determine the start slot by the available slots of this link with the modulation format. If the original modulation format at step 3 is 16QAM already or even with 16QAM with no enough free slots, go to step 9, else go to step 8.
Step 8: So the route, new modulation format, and the start slot make up a candidate p. Calculate the $\sum_{\mathrm{Link} \in \mathrm{route}} \varnothing_{\mathrm{Link}}(p)$ for different start slot ps, and choose the start slot with the smallest $\sum_{\mathrm{Link} \in \mathrm{route}} \varnothing_{\mathrm{Link}}(p)$ as the spectrum allocation for the j shortest-path route. Go to step 9.
Step 9: If $j=k$, then go to step 10, else, set $j=j+1$, then back to step 7.
Step 10: In the k candidate ps, if $\sum_{\mathrm{Link} \in \mathrm{route}} \varnothing_{\mathrm{Link}}(p) < \infty$ exists, then select the p with the smallest $\sum_{\mathrm{Link} \in \mathrm{route}} \varnothing_{\mathrm{Link}}(p)$ as the route and spectrum allocation for the traffic. Then go to step 11. Else the traffic is blocked. Then go to step 11.
Step 11: Repeat step 2 to step 10 for all connections in the ordered set.

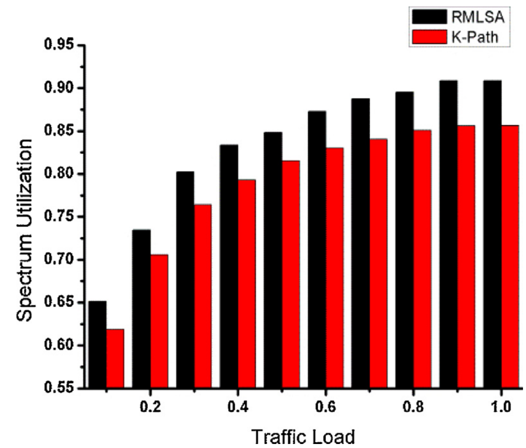

Fig. 6. Comparisons on spectrum utilization.

4. Numerical analysis and conclusions

The algorithm can be used both in work scene (normal communications) and survival scene (failures appear) of the networks. In the work scene the algorithm should reduce blocking rate, and in the survival scene the algorithm should raise the recovery rate.

We evaluated the dynamic RMLSA algorithm in the FWDM networks with modulation format conversion. The NSFNET networks topology (14 nodes and 44 links) is used for simulations, with the assumption that each fiber has 4400 GHz total spectrum. The traffic demand is 10 Gbps, 30 Gbps, 40 Gbps, 50 Gbps, 60 Gbps, 80 Gbps and 100 Gbps. New traffic connection requests arrive according to a Poisson process at a rate of λ, and their holding time conforms to a negative exponential distribution. The average holding time is 40 time units. In these simulations, 50% bandwidth is used as background traffic in the network.

In the work scene, we compare the spectrum utilization and the blocking probability between the k-path algorithm without format conversion and RMLSA with format conversion in the same network with the same background (50% bandwidth has been used) and k ($k=3$, in our simulation). The k-path algorithm use first-fit to choose the spectrums and only use length as weight to choose the route. The result (Figs. 6 and 7) shows about 5% increase in the spectrum utilization and about 20% reduction in the blocking probability of the network.

In the survival scene, the whole number of time units we simulate is 200, and at the 100th time unit, random select one link to failure. When a link failing, the communication of the traffics taken by it are interrupted. To keep the Qos (quality of service), the traffic should find a new route without the failed link. The influenced traffics recovery their routes with the same algorithm as in the work scene. After 50 times simulation we use the average failure recovery rate to compare. We compare the failure recovery rate between the k-path algorithm without format conversion and the algorithm with format conversion in the same network with the same background (50% bandwidth has been used) and k ($k=3$, in

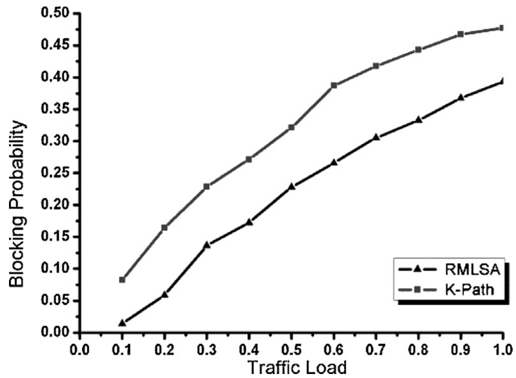

Fig. 7. Comparisons on blocking probability.

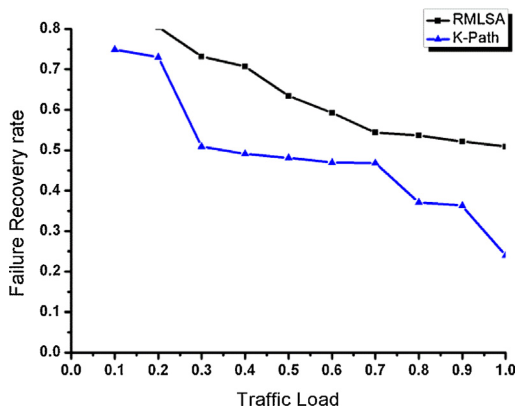

Fig. 8. Comparisons on failure recovery rate.

our simulation). The result in Fig. 8 shows with the raise of traffic load in network, whether using *k*-path or RMLSA the failure recovery rates decrease. But using the RMLSA with modulation format conversion the failure recovery rates decrease more slowly. And in the worst situation the recovery rate of network using RMLSA with modulation format conversion has about 45% better than using the *k*-path without format conversion.

5. Conclusion

The recently proposed FWDM networks have immense flexibility in spectrum allocation. It opens up a new prospect to the network architecture for the future Internet. However, the fragmentations and blocking are still the bottlenecks for FWDM networks. To address these problems, we proposed a novel dynamic RMLSA algorithm in the FWDM networks with modulation format conversion, which supports the modulation format conversion at the intermediate node without influence other traffics. Simulation results demonstrate that the RMLSA algorithm with modulation format conversion ability makes the FWDM networks achieve significant reduction in blocking probabilities without requiring additional the bandwidth or change the existing traffic. And in the survival scene, it has a better performance than the one without modulation format conversion by bring in higher failure recovery rate.

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