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Delay Aware RSA Algorithm Based on Scheduling of Differentiated Services With Dynamic Virtual Topology Construction

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ABSTRACT The fast and diversified development of Internet services leads to numerous services with differentiated delay tolerance of optical connections set-up are converging in the optical network. Consequently, the average set-up delay of optical connection is increased, which will inevitably bring pressures to optical networks. To solve this problem, a delay aware routing spectrum assignment (RSA) algorithm based on services scheduling in priority queues with dynamic virtual topology construction (QVT-RSA) is proposed. First, the QVT-RSA algorithm reasonably identifies various different services and arranges them in order according to their priority, waiting time and delay tolerance requirements. Then, software defined networks (SDN) controller with multi-threads technology is adopted to innovatively parallel serve the ordered service requests to reduce the average set-up delay of optical connections, which also offset the induced delay caused by services scheduling. The network resource is accurately shared among multi-threads using the proposed mutual exclusive resource utilization model realized by dynamic virtual topology construction. The continuously coloring and usable virtual topology linkage reconfiguration can provide topology resources for service requests and adapt the dynamic transformation among serving, waiting and new arriving service requests. The shortest-path routing and first fit spectrum assignment (SPFF-RSA) algorithm is used as the baseline algorithm. Furthermore, by combining the SPFF-RSA algorithm and partial strategy of our strategy, the QSPFF-RSA and V-RSA algorithms are proposed as baseline algorithms as described in V-B. The simulation experiment results demonstrate that the average optical connections set-up delay of QVT-RSA algorithm is reduced compared with SPFF-RSA and QSPFF-RSA algorithms, and the blocking probability of QVT-RSA algorithm is reduced compared with SPFF-RSA, QSPFF-RSA and VRSA algorithms. The optical connections set-up success probability within delay tolerance about high, medium and low priority services of QVT-RSA algorithm is higher than that of the SPFF-RSA, QSPFF-RSA and VRSA algorithms.

INDEX TERMS Low delay, QoS, reconfiguration of virtual topology, RSA, services scheduling.

I. INTRODUCTION

With the rapid development of novel network services, such as the cloud service and big data, the Internet services are booming in an exponential growth rate. Driven by the present services expansion, the transmission capacity of network has continuously grown, and the advanced transmission technologies have been deployed in optical networks with a capacity of 10.16 Pbit/s per fiber [1]. However, although there are amount of services and enough spectrum resource, owing to sequential optical connections set-up without consideration of the delay tolerance of services, many optical connections of services cannot be set up timely, which will cause a service level agreement violation and penalty due to that service requests cannot be handled within the delay tolerance [2]. Meantime, the emergence of a variety of delay sensitive services such as remote medical, financial data and cloud computing results to that the technologies of optical

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transmission and networking are developing toward timely end-end response and flexible and efficient solutions [3].

Elastic optical network (EON) is anticipated one of the possible solutions for the future high-speed network due to its inherent flexibility and the efficiency of resource utilization [4]. EONs are managed and controlled by the advance software-defined network (SDN) controller, reconfigurable optical network architecture as well as automated network functionalities [5]. As a centralized software control architecture, software defined elastic optical network (SD-EON) enabled by OpenFlow protocol has gained popularity by supporting programmability of network functionalities, which can provide a unified control over various resources for the joint optimization of functions and services with a global view [6]. SD-EONs provide users with more control over networking and facilitate automation of complex network operations, thereby resulting in flexibility, efficient and intelligent in the deployment of new services and protocols about lower delay, higher network utilization and better quality of service (QoS) [7]. As the core of SD-EON, open source SD-EON controllers, e.g. ONOS, ODL, Floodlight, MUL, Beacon and Maestro, support the multi-thread technology and can design and supply the function according to specific demands of service requests [8]–[10].

Generally, different services have different requirements on QoS [11], and such requirements include the delay, delay tolerance, reliability, availability, scalability, effectiveness, grades of service etc. [12]. Among them, the delay performance is an important index to measure the quality of transmission and service in optical networks [13]. The delay of optical network mainly includes the delay of signals propagation, optical connections set-up of requests and processing of software and hardware devices. The optical connections set-up delay is vital objects to be optimized because the processing delay of hardware devices has formed during the evaluating and design period of the network and the delay of signals propagation is determined by the distance of selected routing path. The optical connections set-up delay is composed with the requests queueing delay, RSA scheme shaping delay of SD-EON controller and communication delay between the optical network devices and SDN controller. Note that the queueing delay of subsequently arrived requests will gradually increase once abundant burst services converged, which greatly affects the delay performance of optical network [14]. Thus, the way to improve delay performance of optical network and reduce the set-up delay of optical connections is relay on reducing the requests queueing delay composed with both the RSA scheme shaping and communication delay of abundant requests.

Owing to the advance and advantage of central intelligent control, SD-EON can improve QoS of optical networks and enables less service level agreement (SLA) violation. In this paper, we first propose a delay aware RSA algorithm based on scheduling of differentiated services with dynamic virtual topology construction (QVT-RSA) in SD-EON. First, QVT-RSA algorithm reasonably identifies the various differentiated services and arranges the service order for service requests according to their delay tolerance, priority, and waiting time. Then, threads in SD-EON controller with multi-threads technology innovatively parallel serve the ordered service requests to reduce the average set-up delay of optical connections and offset the induced delay caused by services scheduling. Consequently, QVT-RSA algorithm can reduce the average optical connections set-up delay of various differentiated requests and set up more optical connections for requests within their delay tolerance. The main contribution of this paper is that the parallel resource utilization by continuous dynamic virtual topology construction can be used in either the parallel manner defragmentation or the routing and spectrum assignment in broadcast and multicast routing. This algorithm is also adaptive for requests grooming at the scenario of IP over OTN and Radio over Fiber (RoF).

The rest of the paper is organized as follows. Related work on the RSA problem is presented in Section II. Section III firstly presents the network model and the optical connections set-up strategy of sequential RSA algorithm. Then, the mutual exclusive resource utilization model is designed. Finally, the optical connections set-up strategy of parallel RSA algorithm is proposed based on the model. We describe the scheduling and serving model of services in Section IV, which also includes the instance of QVT-RSA algorithm. The performance of QVT-RSA algorithm is evaluated in Section V. Conclusions are drawn in Section VI.

II. RELATED WORKS

New advanced technologies and equipment have been acceleratedly deploying to existing network in purpose of meeting users' differentiated QoS demands, especial delay and delay tolerance demands. However, it still is an urgent issue to enhance the relevant mechanism while proposing RSA algorithms.

In order to overcome the long-time routing and high traffic blocking in complex multi-domain optical networks, the paper [15] proposed a path computation strategy. First, the multi-domain networks are abstracted into a low complex virtual topology through single node topology convergence, and more than one domain sequences are calculated. Then, these domain sequences are fitted to some different centre points. The optimal centre point, that is the optimal domain sequence, is selected using the weighting formula. Finally, the route is computed according to the selected domain sequence. Simulation results indicate that the proposed strategy not only ensures a shorter path computation time but also reduces the traffic blocking effectively. In order to reduce the delay of optical connections set-up and the influence caused by Cross Phase Modulation (XPM) to quality of transmission (QoT), the paper [16] provided a low delay and impairment aware algorithm by parallel pre-computing RSA scheme. The set-up delay of optical connections does not extra augment because the impairment aware strategy has been computed before the requests arrived. The validity of the proposed algorithm is verified by experiment simulations. Compared to the sequential manner defragmentation (Seq-DF), the paper [17] proposed to perform the DF operations in a parallel manner (Par-DF). The paper focuses on proactive Par-DF and proposes a Lagrangian-relaxation (LR) based heuristic to solve it time-efficiently. The proposed algorithm decomposes the original problem into several independent subproblems and ensures that each of them can be solved efficiently. The simulations verify that the proposed proactive Par-DF approach outperforms Seq-DF in terms of the DF Latency, Disruption and Cost. However, the routing and spectrum assignment is not considered owing to the increased complexity caused by optical connections rerouting and modulation-level reassignment.

Although above algorithms reduce the set-up delay of optical connections, which do not consider the effect of delay tolerance. Delay tolerance of optical connections set-up is an important metric, which is defined by customer and stated in service level agreement. Considering the service differentiation based on the delay tolerance and holding time, the service classes with high delay tolerance could have been serviced with some delay. The paper [18] proposed a strategy which intentionally inserts these service classes into a queue to save optical resources for future requests, schedules the queue after each departure event and chooses the best group of the waiting connections to provision. The approach results in significant decrease in overall blocking probability (BP), while reducing the BP of the service classes with stringent delay tolerance as well. Due to the fact that heterogeneous applications call for different levels of service differentiation, the paper [19] investigated an efficient scheduling algorithm to adopt set-up delay tolerances. Requests holding-time awareness in the scheme is not taken into account to represent unpredictability of expiry times in most realistic situations. The scheduling algorithm prioritizes waiting requests based on the magnitude at the onset of scheduling cycle. The magnitude depends on both remaining delay tolerance and volume of required resources. The efficiency of proposed scheme is then verified through numerical simulations, and the scheme could achieve significant improvement in the blocking performance over a wide range of offered traffic loads. The paper [20] presents a spectrum optimization scheme based on transfer learning in SDM-EONs. When the resource reservation is about to fail, corresponding strategies are designed for different types of requests to reduce the probability of resource reservation failure. For IR requests, they will occupy the resources that are reserved for the AR requests with the latest starting time. For AR requests, the strategy exploits transfer learning to predict the spectrum defragmentation time in advance. The simulation results show that the strategy can decrease the proportion of affected services and reduce the failure probability for resource reservation compared with the baseline algorithms. Real world traffic is composed by some connections with strict delay requirements and others which can be delayed without severe penalties. The paper [21] analyses how traffic tolerance to delay impacts on the EON performance. The idea of delaying some connections and processing them in a future slot is the central idea of this work. If connections cannot find free resources, they are just buffered and their allocation is retried after a certain time interval. Simulation results shown that the proposed strategy has a reduction of requests blocking probability under generic dynamic conditions when the percentage between delay tolerant traffic and all requests augmented.

Although part of above algorithms consider the effect of delay tolerance while setting up optical connections or reserving resource for requests, which do not consider the average set-up delay of optical connections. The paper [22] considers the delay tolerance and average initial delay of AR requests while solving the routing, spectrum and modulation level assignment, and scheduling problems. However, the strategy does not consider the queuing delay of requests and average set-up delay of optical connections, let alone an overall consideration of the delay tolerance and reducing the optical connections set-up delay by setting up optical connections in parallel manner. In the survey paper [23], the authors comprehensively survey delay relevant and QoS-motivated researches in OpenFlow-enabled SDN networks. Among them, the research of virtualization-based QoS provisioning is a new trend to support the network development.

III. NETWORK MODELING, THE MUTUAL EXCLUSIVE RESOURCE UTILIZATION MODEL AND OPTICAL CONNECTIONS SET-UP STRATEGY

A. NETWORK MODELING

To describe the thought of QVT-RSA algorithm, symbols used by the algorithm are defined as Table 1, and the notations and definitions of symbols are shown as follows:

In this work, we assume that there is no spectrum converter in the SD-EON and each connection is provisioned all-optically end-to-end. Hence, the spectrum assignment stays the same for all the links on C_n, i.e., satisfying the spectrum continuity constraint. Note that as we denote the spectrum assignment, the spectrum continuity constraint is taken care of automatically. There are two additional constraints for the RSA to obey.

Spectrum Non-Overlapping Constraint: the slot assigned to C_n cannot be used by other connections, i.e.,

$$\sum_{i=1}^{N_s} BIT_n\left[i\right] BIT_l\left[i\right] = 0, \quad \forall n! = l; \quad C_n, \quad C_l \in E_{uv} \qquad (1)$$

Spectrum Contiguity Constraint: all the assigned slots have to be spectrally contiguous to form a slot block, i.e.,

$$\sum_{i=Y}^{S+Y-1} BIT_n\left[i\right] = S \qquad (2)$$

$$\sum_{i=1}^{Y-1} BIT_n\left[i\right] + \sum_{i=S+Y}^{N_s} BIT_n\left[i\right] = 0 \qquad (3)$$

Some important concepts regarding QVT-RSA algorithm are defined as follows:

TABLE 1. Notations and their definitions.

Notation	Definition
V_i	Node i, the set of all nodes is called V
$E_{i,j}$	Edge from node i to node j, the set of all edges is E
$e_{i,j}$	Link form node i to node j
$G(V,E)$	Physical topology of network (G for short)
$G^*(V^*,E^*)$	Coloring virtual topology(G^* for short), V^* and E^* are the sets of coloring nodes and edges respectively
$G'(V',E')$	Usable virtual topology (G' for short), V' and E' are the sets of usable nodes and edges respectively
V'_i	Virtual node i in G'
$E'_{i,j}$	Virtual edge from virtual node i to j in G'
$R(i,j,nslot)$	Request from node i to node j in service queue, need $nslot$ slots; the set of all requests is called R
$R'(i,j,nslot)$	The request with affordable resource in G' is from node i to node j, need $nslot$ slots; The set of all requests with affordable resource in G' is called R'
C_n	The connection n
S	Number of used slots on an optical connection
Y	Value of first slot in used slots on an optical connection
$BIT_n[i]$	If the ith slot is allocated to C_n, $BIT_n[i]$=1, otherwise, $BIT_n[i]$=0.
$\lambda^n_{i,j}$	The used times of nth slot in $E_{i,j}$ at an instant of time
N_r	Number of requests
N_s	Spectrum number in the single optical fiber
N_{node}	Number of nodes in the network topology
L_q	The maximal queue depth of service queue while setting up optical connections
N_t	The number of requests set up connections within delay tolerance
N_{th}	The thread number of QVT-RSA algorithm
$Q(n)$	The queueing delay of the nth request
$f(n)$	The delay to set up optical connections for n requests
$A(n)$	The average optical connections set-up delay for n requests

Definition 1: Reconfiguration of virtual topology based on the mutual exclusive resource utilization model means that the nodes set or edges set is added and deleted from the G^* according to that the resources are used and released while setting up and tearing down the optical connections. G' is the usable virtual topology when G^* is removed from G.

Definition 2: Selecting $R'(i, j, nslot)$ means QVT-RSA algorithm searches the request whose needed resources are not conflicted with G^*. If the set of nodes or edges on found path for the request is conflicted with G^*, the algorithm abandons this request until the algorithm founds the right service request to serve.

Definition 3: The thread coloring means that the thread calculates the path for $R'(i, j, nslot)$ by Floyd algorithm, finding the resources set in the path, and adds the set into the coloring virtual topology and casts different colors according to the order number of the thread.

Definition 4: The constraint of resource utilization during the optical connections set-up means that the nodes or links in G^* cannot be used to the set-up of new optical connections, and new optical connections can only select resources from G'.

Definition 5: Not Intersecting Optical Connections (NIOC) denotes the optical connections set, in which the optical connections have not common links.

QVT-RSA algorithm is evaluated by performance metrics such as the average optical connections set-up delay, spectrum utilization and blocking probability. There is another important metric to evaluate network performance, i.e., optical connections set-up success probability within delay tolerance (*SWT*), which denotes the proportion of requests set up optical connections within delay tolerance to all arrived requests.

Definition 6: The optical connections set-up success probability within delay tolerance is defined as:

$$SWT = N_t/N_r \tag{4}$$

B. THE MUTUAL EXCLUSIVE RESOURCE UTILIZATION MODEL AND OPTICAL CONNECTIONS SET-UP STRATEGY

Either only based on reducing the set-up delay of optical connections, or merely considering delay tolerance of services cannot efficiently meet the evolving and variety requirements of service requests. Moreover, either the augmented optical connections set-up delay or optical connections setting up out of delay tolerance will inevitably bring pressure to the optical network. Nevertheless, the combined optimization issue of the delay and delay tolerance has not been addressed in previously researches.

The QoS improved works based on OpenFlow-based software defined optical networking architectures have been introduced in the survey paper [23], and this paper will concentrate on the core and essence of QVT-RSA algorithm. First, the optical connections set-up strategy of sequential RSA algorithm is analyzed. After that, the mutual exclusive resource utilization model is presented in detail which is realized by reconfiguration of virtual topology. Finally, based on the mutual exclusive resource utilization model, the optical connections set-up strategy of parallel RSA algorithm is proposed.

1) SEQUENTIAL OPTICAL CONNECTIONS SET-UP STRATEGY

Most of traditional RSA algorithms are single thread algorithms, and sequentially set up the optical connection for requests even though the requests are converged, seizing all the network resources by the main function thread during the interval that the single request is served. Many traditional RSA algorithms [24] are frequently used to compare with the proposed algorithm to illustrate the expectant performance. Among these baseline algorithms, the commonly referencing RSA algorithm is SPFF-RSA algorithm, which realizes the routing by shortest-path and assigns the spectrum by the way of first fit. Traditional sequential RSA algorithms always have optical connections set-up strategy as follows just like the SPFF-RSA: (1) The request arrived. (2) The algorithm

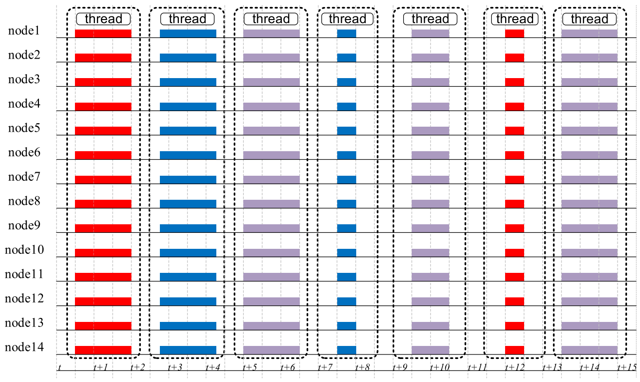

FIGURE 1. **The resources lock and release of traditional RSA algorithm.**

provides optical connection set-up scheme for the request, holding the whole network resources. (3) The optical connection is set up, or the request is blocked. Among RSA algorithms, the used resource is nodes set or edges set of physical topology. In purpose of concise presentation, the time sequence indicating diagram of resource utilization about sequential RSA algorithm is exampled by nodes set as shown in Fig. 1.

Fig. 1 is composed with the relationship of nodes, time and main function thread. In Fig. 1 every request approximately needs two time units to set up the optical connection, and there are 7 requests sequentially served during the 15 time units. The block in the dashed line reflects the locked time of resources during the interval of RSA scheme calculation and resource assignment, while other time overhead in the dashed line includes the time of selecting $R'(i, j, nslot)$ and timer setting, etc. The block color in the dashed line denotes the priority of the request. During the interval of RSA scheme calculation, all the resources are locked by the main function thread. However, not all resources are used, which leads to the waste of network resource and augment of the average set-up delay of optical connections.

Generally, service requests arrive at the network following a Poisson process, and the holding time of service requests is negatively exponentially distributed. Supposing the requests are evenly distributed among the nodes, the process of requests optical connections set-up approximately conforms to M|M|1 queue theory model when the optical connections set-up of requests is stable in the long time according to [25]. On the basis of M|M|1 queue theory model, the average waiting time, i.e. the average queuing delay of requests is shown in (5), and the average system delay, i.e. the average connections set-up delay of requests is shown in (6).

$$\omega = \frac{\rho}{\mu(1-\rho)} \tag{5}$$

$$s = \frac{1}{\mu - \lambda} \tag{6}$$

λ is requests arrival rate, and equals the reciprocal transformation of average requests arrival interval. μ is the requests serving rate, and equals the reciprocal transformation of average requests holding time. ρ is stable parameter of M|M|1 queue theory model, and $\rho = \lambda/\mu$. ω is the average queuing delay of requests. s is the average optical connections set-up delay of requests. When using (5) and (6) to calculate the average optical connections set-up delay of requests, the default precondition requires the system is stable, i.e., ρ <1. However, when abundant burst requests converged in a short time as described in Section I, the requests arrival rate is greater than the requests serving rate, i.e., the stable parameter ρ >1. It is irrational that calculating the average optical connections set-up delay of requests by using (6) although the holding time of service requests conforms to the negative exponential distribution. Furthermore, it is difficult to find the queue theory model to calculate the average optical connections set-up delay of requests at burst requests converged scenario owing to the specific probability distribution function of requests arrival time is hard to derived. Thus, we need reanalysis the delay of optical connections set-up when numerous requests converged.

Based on [25], when a request arrives on the occasion of there have existed n requests in the queue, the request needs wait to be served until all requests are served. Therefore, the waiting time of the request is the sum of serving time of previous n requests. In addition, the average system time equals the sum of average waiting time and average serving time. Thus, the optical connection set-up delay for the *nth* request mainly includes the queuing delay and the serving delay T_n at burst requests converged scenario when the network has enough spectrum resources as described in Section I. T_n is the sum of RSA scheme shaping delay and communication delay.

$$f(n) = Q(n) + T_n \tag{7}$$

According to the experiment data, each service request approximately has the equal RSA scheme shaping delay and the average communication delay of requests is stable. In order to approximately derive the equation of average set-up delay of optical connections, the sum of RSA scheme shaping delay and average communication delay for one request is approximately set as constant T. Supposing there has converged $n-1$ service requests, the approximation of queuing delay for the *nth* request is $(n-1)T$ according to (8) if the network has enough spectrum resources as described in Section I. Putting (8) into (7), we get the optical connection set-up delay for the *nth* request as (9).

$$Q(n) = \sum_{i=1}^{n-1} T_i \tag{8}$$

$$f(n) = nT \tag{9}$$

The average set-up delay of optical connections is the mathematical mean of connections set-up delay for all requests. By using (9), we get the average set-up delay of optical connections for N_r requests as (10). Equation (10) is an arithmetic sequence, and consequently we get the formula of average optical connections set-up delay of N_r requests as (11) according to the sum formula of the arithmetic sequence.

$$A(N_r) = \frac{1}{N_r}\sum_{n=1}^{N_r} f(n) \tag{10}$$

$$A(N_r) = T \times (N_r + 1)/2 \tag{11}$$

The conclusion is drawn from (11) that the average set-up delay of optical connections for traditional RSA algorithm has the liner relationship with the variant N_r when requests converged. The object of QVT-RSA algorithm is to decrease the augment velocity of average set-up delay of optical connections with respect to N_r.

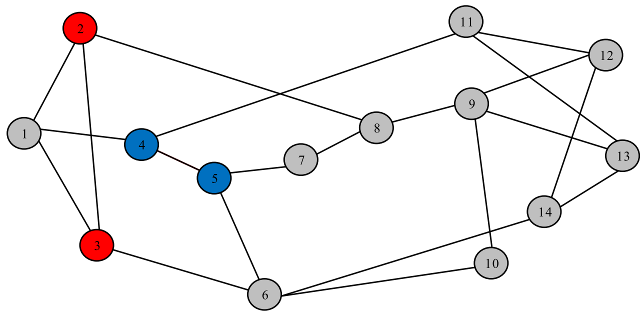

FIGURE 2. **NSFNET topology.**

2) THE MUTUAL EXCLUSIVE RESOURCE UTILIZATION MODEL

As shown in Fig. 2, the optical connections set of 2→3, 4→5 and 5→6 is the NIOC in the NSFNET topology. If the connections of 2→3 and 4→5 are setting up in a virtual topology, the connection of 5→6 can be simultaneously set up using the resources in the different topology. This means virtual topology can provide the topology of resources utilization for parallel optical connections set-up. In view of this, it is possible to propose the mutual exclusive resource utilization model to avoid resources reutilization while parallel setting up optical connections.

Virtual topology technology is a promising technology to break the restrictions of network development, decouple the network functions from dedicated hardware elements and set up the new generation network architecture. Virtual topology technology can make full use of the resources on infrastructure layer and provide customized and various differentiated end-to-end services for users. Virtual topology technology allows the coexisting of several different virtual topologies mutually logically isolated in the public infrastructure. The topologies provided by virtual topology technology are dynamic and adaptive, which can be readjusted to adapt to the dynamic transformation of service requests. Considering the serving and waiting requests change with time, QVT-RSA algorithm needs to timely construct the topologies in purpose of providing topology resources for parallel optical connections set-up.

The construction of virtual topology is the core of QVT-RSA algorithm. However, three issues should be considered in the construction of virtual topology: (1) When to reconfigure the virtual topology considering the resource lock and release. (2) Reconfiguring new virtual topology needs to meet the dynamic transformation of serving, waiting and new arriving requests, and the new topology must change as little as possible to the original topology. (3) How to switch to the new virtual topology to make the existing connections suffering least loss.

To solve above questions, the mutual exclusive resource utilization model is proposed as follows: (1) With consider of the resource lock and release as shown in Fig. 1, it is rational that the reconfiguration of virtual topology triggers at the beginning and end of optical connection set-up. The coloring and usable virtual topology linkage reconfiguration can adapt the dynamic transformation of serving, waiting and new arriving requests. The coloring virtual topology is reconfigured according to the transforming of serving requests, and usable virtual topology is reconfigured to provide topology resource for waiting and new arriving requests to parallel set up optical connections. (2) The reconfiguring of virtual topology is a continuous process to adapt the occupation and release of network resources. In the model, once finding proper resources for the service request, QVT-RSA algorithm will add the set into the coloring virtual topology and color the resources set. Then, the coloring virtual topology is reconfigured by converging the previous coloring virtual topology and the resources set; the usable virtual topology is reconfigured by separating the resources set from the previous usable virtual topology. Once QVT-RSA algorithm has set up the optical connection for the request, the resource used by the thread will be released; reconfiguring the coloring virtual topology by separating the released resource set from the previous coloring virtual topology. Then, the usable virtual topology is reconfigured by converging the previous usable virtual topology and the released resources set. The coloring and usable virtual topology separate and converge based on the previous topology to adapt the dynamic transformation among serving, waiting and new arriving requests, which changes as little as possible to the original topology. (3) Owing to continuous topology reconfiguration and the topology reconfiguration happens at the beginning and end of optical connection set-up, the optical connections are not interrupted. The set up optical connections do not suffer any losses when the old virtual topology transforms to the new virtual topology.

3) PARALLEL OPTICAL CONNECTIONS SET-UP STRATEGY

Based on the mutual exclusive resource utilization model, QVT-RSA algorithm has the parallel optical connections set-up strategy as follows in brief: (1) The requests arrived. (2) The serve order of requests is shaped. (3) Threads parallel provide optical connections set-up scheme for the request. (4) The optical connection is set up, or the request is blocked. The time sequence indicating diagram of resource utilization of QVT-RSA algorithm is shown in Fig. 3.

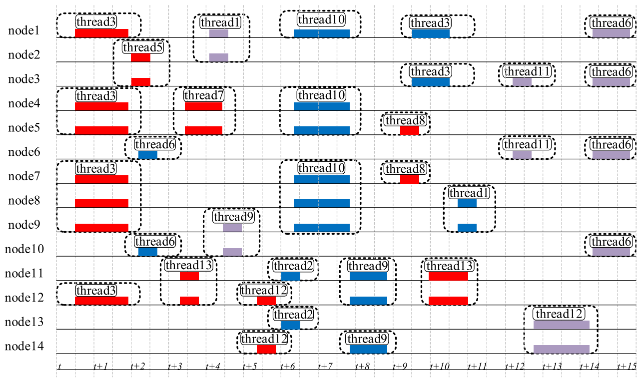

FIGURE 3. **The resources lock and release of QVT-RSA algorithm.**

Fig. 3 is composed with the relationship of nodes, time and threads. During the 15 time units, there are 18 requests served in the same time interval as Fig. 1. As shown in Fig. 3, different nodes sets are used to the different request connections set-up at the same time by using the mutual exclusive resource utilization model. This improves the resource utilization and reduces the average set-up delay of optical connections. To approximately calculate the average optical connections set-up delay of QVT-RSA algorithm, we ignore the difference of calculation quantity among threads and the invalid calculating delay once the mutual exclusion in resource utilization occurred. Thus, the requests quantity that a single thread served is approximately Nr/Nth. Putting the number into (8), we get the approximation of queuing delay for the nth request about parallel optical connections set-up strategy is $(n/Nth - 1)\,T$. Compared to the queuing delay of sequential optical connections set-up strategy, the queuing delay of parallel optical connections set-up strategy nearly reduces according to N_{th} in the way of the liner relationship. Putting Nr/Nth into (11), we get the average optical connections set-up delay of QVT-RSA algorithm as (12).

$$A(N_r) = T \times (N_r/N_{th} + 1)/2 \tag{12}$$

The conclusion is drawn from (12) that the average optical connections set-up delay of QVT-RSA algorithm has the liner relationship with the variant N_r and N_{th}, increasing accompanied with N_r and reducing according to N_{th}. The augment velocity of the optical connections average set-up delay accompanied with N_r is notably reduced due to the existing of N_{th}. Comparing Fig. 1 with Fig. 3, it is obvious that the QVT-RSA algorithm sets up more optical connections than traditional algorithms during the same interval. Although there exists the mutual exclusion of resource utilization, the QVT-RSA algorithm continuously constructs the virtual topology to support the parallel optical connections set-up. This not only improves the resource utilization but also exploits the advantages of multi-thread SDN controller.

IV. SCHEDULING AND SERVING MODEL OF SERVICES

With the mutual exclusive resource utilization model and the above parallel optical connections set-up strategy, QVT-RSA algorithm can parallel set up optical connections on the multi-thread hardware platform. However, it is necessary to propose scheduling and serving model of services for shaping the proper serve order to improve the success probability of connections set-up within delay tolerance. In this section, the identifying and enqueuing strategy of the services and the shaping strategy of the service queue are firstly introduced in Section IV-A. Then, the specific serving strategy of service requests is proposed in Section IV-B. After that, the flow chart of QVT-RSA algorithm is presented, and the time complexity is calculated. Finally, an instance of QVT-RSA algorithm is exampled in Section IV-C. The basic responsibilities and interactions of these functional modules are described as follows.

A. SCHEDULING MODEL OF SERVICES

The service order of requests has great effect on the quality of service. When a request arrived to the optical networks, the request perhaps has very small delay tolerance and higher priority than other requests in the request queue, which means it need be served immediately. When various services with differentiated delay tolerance requirement compete network resources, the services with lower delay tolerance set up optical connection preferentially will improve the connections set-up success probability within delay tolerance of all service requests. However, many above depicted algorithms either haven't a queue mechanism to support the services sort or else augment the set-up delay of optical connections owing to services scheduling.

1) IDENTIFYING AND ENQUEUING STRATEGY OF THE SERVICES

The delay tolerance of various services in optical networks is distinguishing, which can be divided into 3 grades, i.e. high, medium and low priority classes. For example, the real-time service request such as financial data and remote medical is high priority service [26]–[28], requiring immediate set-up of optical connections to provide timely services. Video conference belongs to the medium grade services in terms of delay tolerance. Data service such as email service is low priority service according to delay tolerance of services, and allows relatively long delay tolerance [29]. In QVT-RSA algorithm, the above way of service classification in [29] is adapted. In addition, to design the enqueuing strategy, QVT-RSA algorithm overall considers the parameters of services, including source node, destination node, waiting time, duration, priority, and delay tolerance. Moreover, the strategy designs an emergency flag for the request which means the request is an emergency request if the flag is set. Once requests arrived, they are instantly identified according to his priority property. Then the request weight to enqueue onto the accordingly priority queue will be calculated according the weight calculation equation as shown in (13):

$$W_1 = F + C/L + (S - A) \times T \tag{13}$$

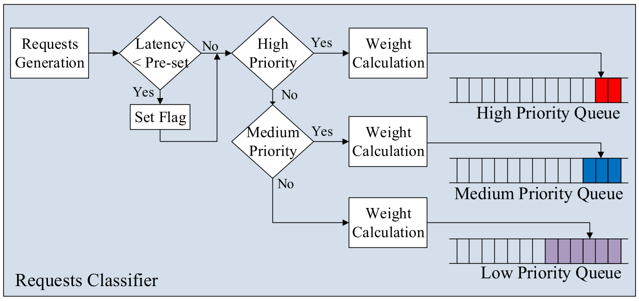

FIGURE 4. Queueing the requests.

The meanings of parameters in the equation are defined as follows: W_1 is the request weight when enqueueing the request onto the accordingly priority queue. The value of F will be set if the request is an emergency request, and the value of F is set according to the pre-set value about high, medium and low priority of request. C is a constant, and L is the delay tolerance of the request. S is the system time, which is determined by the specific running platform, such as the timer in optical network devices and computer time. A is the time of request arrived. T is a constant that means the proportion between the augmented weight and waiting time.

After calculating the request weight, the request will be inserted to the proper position of priority queue in descending order according to the priority and weight of request. Putting the request with low delay tolerance and longer waiting time on the front of the priority queue will guarantee the request to be served in time, and improving the QoS of various requests. As shown in Fig. 4, the flag of request is set when the value of delay tolerance is less than pre-set value, which means the request needs to be served as soon as possible due to his delay tolerance.

2) SHAPING STRATEGY OF THE SERVICE QUEUE

Above subsection has provided a strategy to enqueue requests onto priority queues according to their priority and weight. Then the service queue should be shaped by using requests of high, medium and low priority queues in purpose of scheduling and serving requests more promptly and fairly. To realize this object, the paper proposes an equation to calculate the request weight in the service queue with considering of the priority, delay tolerance, waiting time and the flag. The delay tolerance and inherent priority of requests are dominant factors at calculating request weight because prompt set-up of optical connections is the most important according to the service level agreement. The waiting time of requests is subdominant factor because the waiting time is related to the fairness which cannot be ignored. The design and parameter setting of weight calculation functions should consider the main and subdominant factors at optical connections set-up to efficiently arrange service requests order and embody the fairness of strategy. The requests weight calculation equation to enqueue the request onto the accordingly service queue is shown in (14):

$$W_2 = F + C/L + P + (S - A) \times T \tag{14}$$

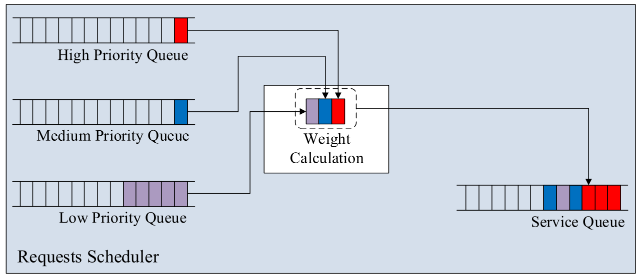

FIGURE 5. Requests scheduling.

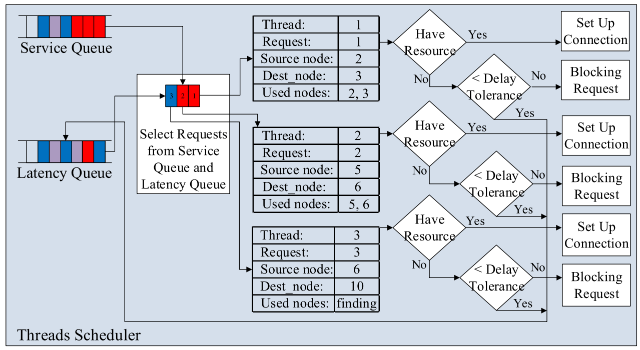

FIGURE 6. Threads scheduling.

The parameters meanings in the equation are defined as follows: W_2 is the request weight while enqueueing the request onto the service queue. P takes the different constant value according to the high, medium and low priority of request. Other parameters have the same meanings as defined in (13). With respect to the weight calculation equation, it can promote the weight for requests with the high priority and low delay tolerance. Moreover, the weight of low priority requests can increase fairly according to the waiting time augmented.

Note that searching the highest weight request in priority queues is also very important, therefore QVT-RSA algorithm proposes a requests scheduler to perform service scheduling efficiently. The requests scheduler selects the first request in each priority queue to find the request with highest weight instead of finding the highest weight request from all requests, which simplifies the calculation process and saves the delay caused by services scheduling. After found the request with highest weight in the priority queues, the request will be inserted to the proper position of service queue in descending order according to request weight calculated by (14). Then the enqueued request will be dequeued from the original priority queue, and the request following the dequeued request in the original priority queue will become the first request in the queue. The above process of requests scheduler is shown in Fig. 5.

B. SERVING MODEL OF SERVICES

Above proposed scheduling mechanism can render the optimized service order of differentiated requests to set up more optical connections within their delay tolerance. However, the scheduling mechanism augments the average set-up delay

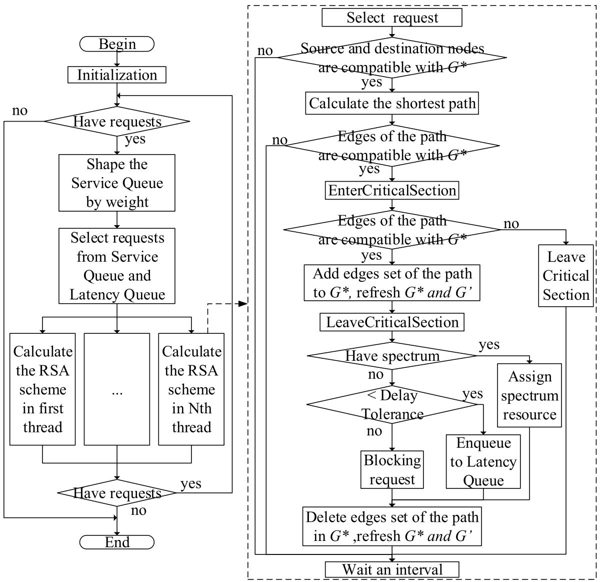

FIGURE 7. Flow chart of QVT-RSA algorithm.

of optical connections because of the operation of judging, calculating and sorting. Several threads in QVT-RSA algorithm are used to realize the parallel serving of requests to reduce the average set-up delay of optical connections, which also offset the induced delay caused by services scheduling. The threads sort in descending order according to the priority as follows: (1) Requests Generation Thread is responsible for generating requests. The parameters of request include the source node, destination node, priority, delay tolerance, arrival time and duration. To test the practicability and reliability of QVT-RSA algorithm, the algorithm designs a burst requests generator and a request generating function of Poisson interval in this thread. The burst requests generator continuously generates 1000 requests at a time, and the request generating function generates requests according to Poisson intervals. (2) Requests Identification Thread is responsible to identify the request grades, calculate the request weight, put requests into corresponding priority queue and shape the service queue. (3) RSA Thread is responsible for providing RSA schemes for requests and accumulating the set-up delay of optical connections. In order to reduce the code size, the thread is designed as a reentrant thread. Every reentrant RSA Thread has the same priority and its own thread resource, which shares the global network resources by the mutual exclusive resource utilization model. (4) Requests Release Thread is used to release the request which has reached his duration. (5) The Main Function Thread is responsible for creating other threads, setting priority of threads, specifying the CPU that threads run on, starting threads and obtaining the clock frequency of the internal timer in the running platform. As shown in Fig. 6, the requests connections are setting up by several RSA threads within the delay tolerance of request. If the request has not reach the delay tolerance and cannot set up optical connections,

TABLE 2. The coloring nodes and usable links based on nodes set.

Time	Coloring nodes/thread	Usable links in usable virtual topology
t+1	*1 4 5 7 8 9 12/3*	*2→3, 3→2, 3→6, 6→3, 6→10, 6→14, 10→6, 11→13, 13→11, 13→14, 14→6, 14→13*
t+3.5	*4 5/7 11 12/13*	*6→10, 6→14, 7→8, 8→7, 8→9, 9→8, 9→10, 9→12, 9→13, 10→6, 10→9, 11→12, 11→13, 12→9, 12→11, 12→14, 13→9, 13→11, 13→14, 14→6, 14→12, 14→13*
t+10	*1 3/3 11 12/13*	*2→8, 4→5, 5→4, 5→6, 5→7, 6→5, 6→10, 6→14, 5→7, 7→5, 7→8, 8→2, 8→7, 8→9, 9→8, 9→10, 9→13, 10→6, 10→9, 13→9, 13→14, 14→6, 14→13*

the request will be enqueued onto the latency queue and wait a time to set up optical connections again.

Well supported by the mutual exclusive resource utilization model and scheduling and serving model of services, QVT-RSA algorithm can parallel set up connections for requests, shapes the reasonable service order of requests by requests scheduling and preferentially set up optical connections for requests with low delay tolerance. Consequently, QVT-RSA algorithm can promptly groom the converged differentiated service requests within their delay tolerance and reduce pressures of optical networks. The flow chart of QVT-RSA algorithm by using edges set as the constraint of resource utilization based on the mutual exclusive resource utilization model is shown in Fig. 7, and the time complexity of QV-RSA algorithm approximate is $O(N_r \times N_s \times N_{node}/N_{th} + L_q \times N_r)$.

C. INSTANCE OF QVT-RSA ALGORITHM

As mentioned above, the continuously coloring and usable virtual topology linkage reconfiguration can adapt the dynamic transformation of serving, waiting and new arriving requests. As shown in Fig. 3, thread3 and thread13 respectively denote different coloring color, specifying as fill mode in coloring virtual topology, are used to thread coloring at *t+10*, i.e., coloring the used resource sets of connections of $R'(1, 3, 1)$ and $R'(11, 12, 1)$. In order to vividly illustrate the algorithm, the reconfiguration of the coloring and usable virtual topology is respectively illustrated by using the nodes set and edges set as the constraint of resource utilization. By using the nodes set as the constraint of resource utilization, the coloring nodes in coloring virtual topology and usable links in usable virtual topology according to the mutual exclusive resource utilization model at several time instants are shown in table 2.

Among these time instants, the topology state of coloring and usable virtual topology at *t+1* is formed at *t+0.5* according to the mutual exclusive resource utilization model as shown in Fig. 3. The details to obtain coloring and usable virtual topology in table 2 at *t+1* is clearly presented as shown in Fig. 8 and Fig. 9. First, the coloring

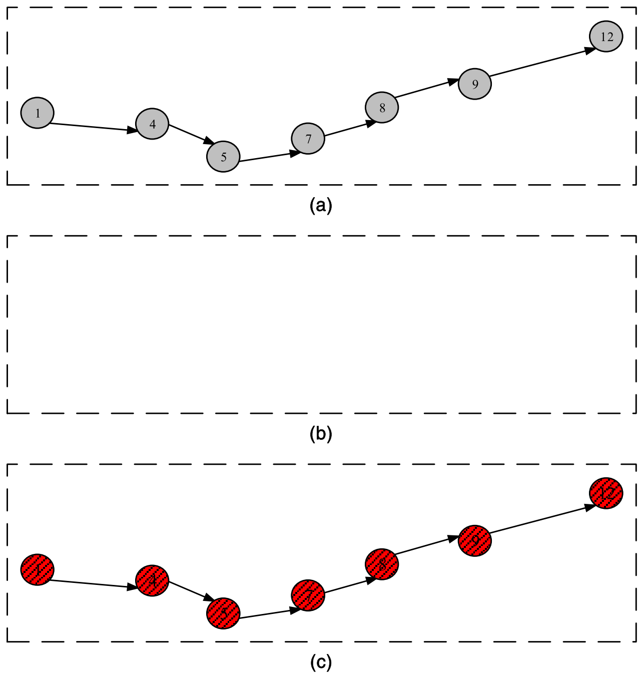

FIGURE 8. (a) the needed nodes set at t+0.5 (b) previous coloring virtual topology (c) reconfigured coloring virtual topology at t+0.5.

virtual topology is reconfigured according to the transforming of serving requests as follows. (1) QVT-RSA algorithm finds proper resources, the nodes set {1,4,5,7,8,9,12}, for the service request at *t+0.5*, which triggers the coloring virtual topology reconfiguration. (2) Supposing the previous coloring virtual topology has not coloring nodes as shown in Fig. 8(b), the nodes set {1,4,5,7,8,9,12} is colored and ready to converge with the previous coloring virtual topology. (3) The coloring virtual topology is reconfigured by converging the previous coloring virtual topology and the nodes set {1,4,5,7,8,9,12} at *t+0.5*. The reconfigured coloring virtual topology is shown in Fig. 8 (c). Then, the usable virtual topology is reconfigured to provide topology resource for waiting and new arriving requests as follows. (1) Having supposed the previous coloring virtual topology has not coloring nodes, which indicates the previous usable virtual topology has all network resources as shown in Fig. 9(b). (2) The usable virtual topology is reconfigured by separating the nodes set {1,4,5,7,8,9,12} from the previous usable virtual topology. (3) All edges connected with the nodes set are removed from the previous usable virtual topology. After topology reconfiguration, the coloring virtual topology at *t+1* is shown in Fig. 8(c), and the reconfigured usable virtual topology is shown in Fig. 9(c).

The coloring virtual topology at *t+10* is shown in Fig. 10, which uses nodes set as the constraint of resource utilization based on the mutual exclusive resource utilization model, and the reconfigured usable virtual topology is shown in Fig. 11.

The reconfiguration of coloring and usable virtual topology by using the edges set as the constraint of resource utilization has the similar procedure as describe in above

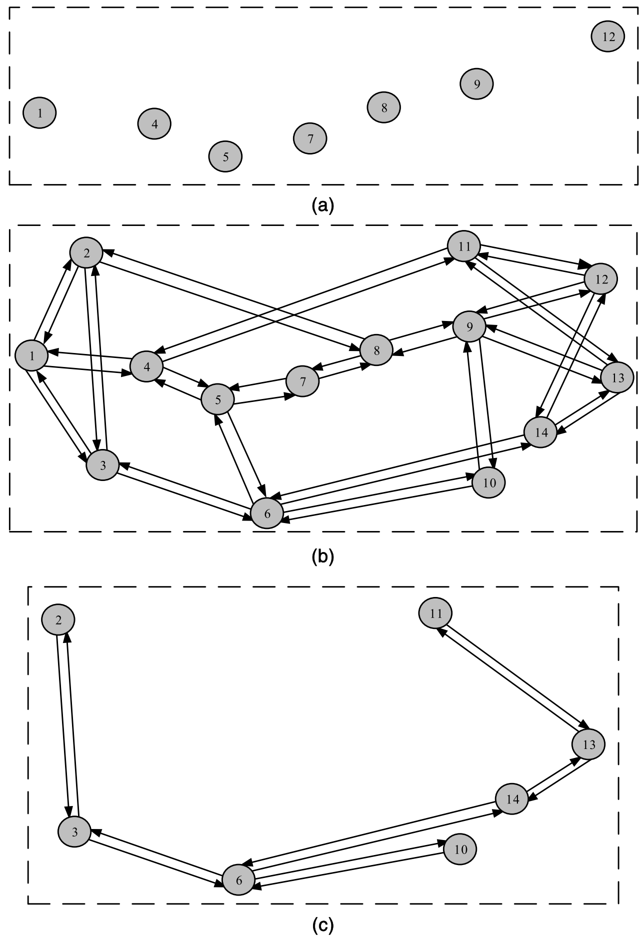

FIGURE 9. (a) the need removed nodes set at t+0.5 (b) previous usable virtual topology (c) reconfigured usable virtual topology at t+0.5.

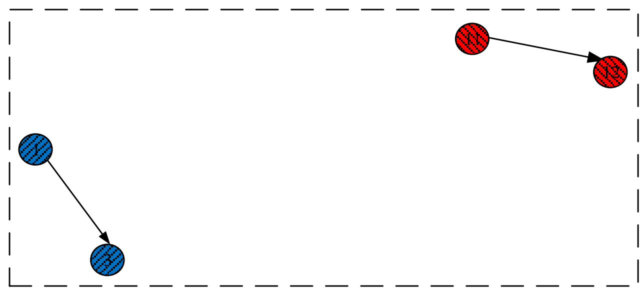

FIGURE 10. Coloring virtual topology based on nodes set at t+10.

details except the used resource set is edges set. Furthermore, the strategy by using the edges set as constraint of resource utilization slightly facilitates the sharing of the physical resources of the optical network while setting up optical connections. By using the edges set as the constraint of resource utilization, the coloring links and usable links according to the mutual exclusive resource utilization model at several time instants are shown in table 3.

The coloring virtual topology at *t+1* is shown in Fig. 12, which uses edges set as the constraint of resource utilization based on the mutual exclusive resource utilization model, and the reconfigured usable virtual topology is shown in Fig. 13.

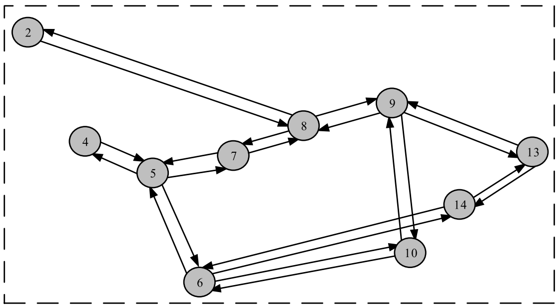

FIGURE 11. Usable virtual topology based on nodes set at t+10.

TABLE 3. The coloring and usable links based on edges set.

Time	Coloring links/thread	Usable links in usable virtual topology
t+*1*	*1→4→5 →7→8→9 →12/3*	*1→2, 1→3, 2→1, 2→3, 2→8, 3→1, 3→2, 3→6, 4→1, 4→11, 5→4, 5→6, 6→3, 6→5, 6→10, 6→14, 7→5, 8→2, 8→7, 9→8, 9→10, 9→13, 10→6, 10→9, 11→4, 11→12, 11→13, 12→9, 12→11, 12→14, 13→9, 13→11, 13→14, 14→6, 14→12, 14→13*
t+*3*	*4→5/7 11→12/13*	*1→2, 1→3, 1→4, 2→1, 2→3, 2→8, 3→1, 3→2, 3→6, 4→1, 4→11, 5→4, 5→6, 5→7, 6→3, 6→5, 6→10, 6→14, 7→5, 7→8, 8→2, 8→7, 8→9, 9→8, 9→10, 9→12, 9→13, 10→6, 10→9, 11→4, 11→13, 12→9, 12→11, 12→14, 13→9, 13→11, 13→14, 14→6, 14→12, 14→13*
t+*10*	*1→3/3 11→12/13*	*1→2, 1→4, 2→1, 2→3, 2→8, 3→1, 3→2, 3→6, 4→1, 4→5, 4→11, 5→4, 5→6, 5→7, 6→3, 6→5, 6→10, 6→14, 7→5, 7→8, 8→2, 8→7, 8→9, 9→8, 9→10, 9→12, 9→13, 10→6, 10→9, 11→4, 11→13, 12→9, 12→11, 12→14, 13→9, 13→11, 13→14, 14→6, 14→12, 14→13*

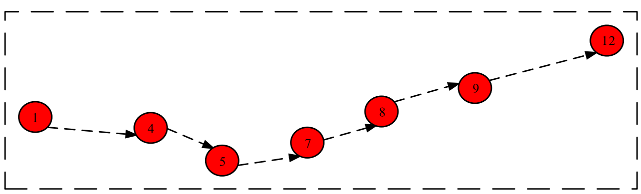

FIGURE 12. Coloring virtual topology based on links set at t+1.

The coloring virtual topology at *t+3.5* is shown in Fig. 14, which uses edges set as the constraint of resource utilization based on the mutual exclusive resource utilization model, and the reconfigured usable virtual topology is shown in Fig. 15.

V. SIMULATION RESULTS AND DISCUSSIONS

A. SIMULATION SETUP

In this paper, the simulation experiment program runs on the computer with a four-core processor, and the processor model is AMD A10-7300 Radeon R6, 10 Compute Cores 4C+6G 1.90 GHz. The simulation experiment program is designed by the VC++, running on the VS2010 development platform, and the number of RSA Thread is 14. To calculate the optical connections set-up delay, the 10 microseconds level precise

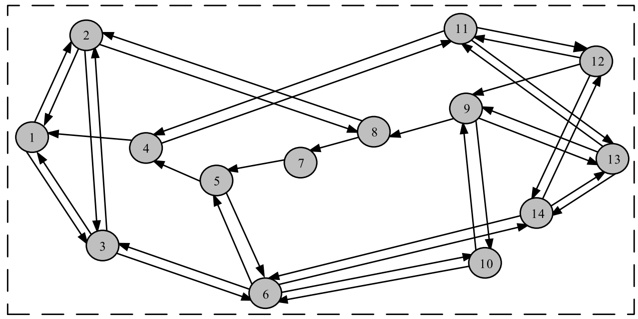

FIGURE 13. Usable virtual topology based on links set at t+1.

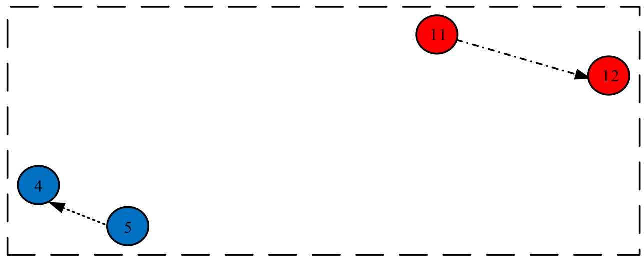

FIGURE 14. Coloring virtual topology based on links set at t+3.5.

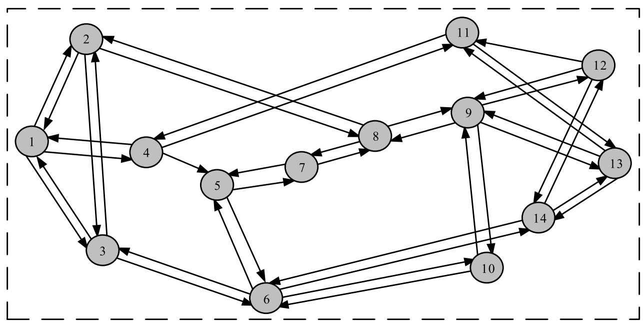

FIGURE 15. Usable virtual topology based on links set at t+3.5.

time scale provided by precise timer of the computer is used, which is realized through the way of system calls by using two functions of VC++, i.e., QueryPerformanceFrequency() and QueryPerformanceCounter.

The NSFNET and USNET network topologies are used in the simulation. NSFNET topology is the National Science Foundation Network composed with 14 nodes and 21 bidirectional optical links as shown in Fig. 2. USNET topology is US Nation Wide Network composed with 24 nodes and 43 bidirectional optical links as shown in Fig. 16.

The parameters of network are configured as follows: There exists 4.47THz spectrum in each optical link. There are 358 available slots in each optical link owing to that 12.5GHz is typically used in elastic optical networks as the minimum divided frequency slot. The simulation experiment uses 100000 requests, and the burst requests account for 10%. The burst requests generator generates 1000 requests at a time after every 9000 requests generated by the request generating function. The duration of service requests conforms to

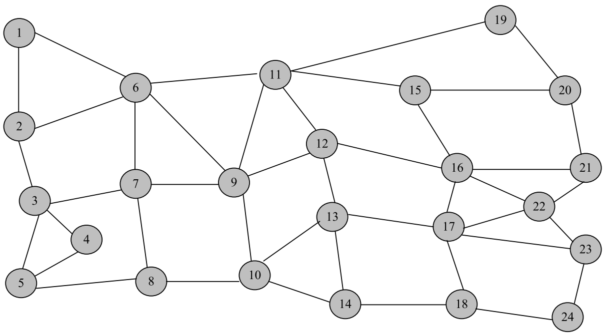

FIGURE 16. USNET topology.

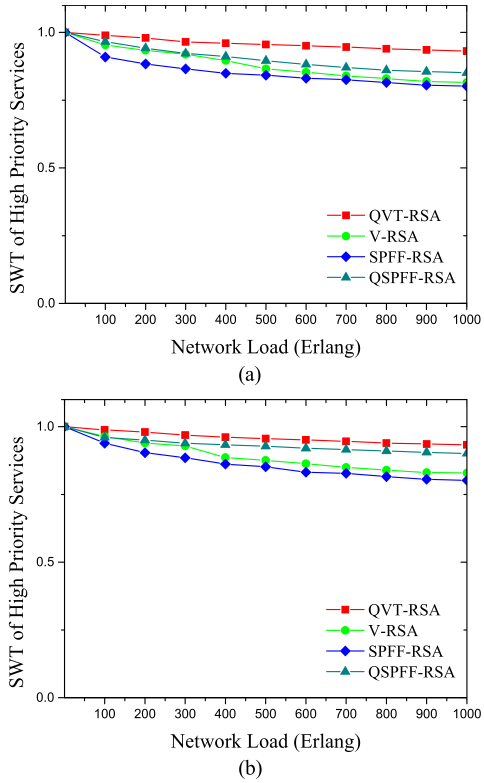

FIGURE 17. The success rate within delay tolerance of requests with high priority: (a) NSFNET. (b) USNET.

the negative exponential distribution. The delay tolerance of requests with high, medium and low priority respectively is 2.5s, 5s and 20s. The pre-set value of emergency requests about high, medium and low priority respectively is 1.5s, 2.5s and 10s. The requests that need 1, 2, and 4 slots respectively account for 50%, 30% and 20% at all network requests. The requests with high, medium and low priority respectively take the percentage of 20%, 30% and 50% at all network requests.

B. BASELINE ALGORITHMS

The SPFF-RSA algorithm, i.e., shortest-path routing and first fit spectrum assignment algorithm, is set as the baseline algorithm. Except the SPFF-RSA algorithm, we also design algorithms by using the partial strategy of QVT-RSA algorithm to illustrate the comprehensive performance of proposed QVT-RSA algorithm. By combing the SPFF-RSA algorithm, the parallel optical connections set-up strategy and the mutual exclusive resource utilization model, the V-RSA algorithm is constructed, which is used to illustrate the advantage of parallel optical connections set-up strategy on average optical connections set-up delay. The time complexity of V-RSA algorithm approximate is $O(N_r \times N_s \times N_{node}/N_{th})$. The QSPFF-RSA is the combination of SPFF-RSA algorithm and the scheduling and serving model of services, which is used to illustrate the benefit of services scheduling strategy on the optical connections set-up success probability within delay tolerance. The time complexity of QSPFF-RSA algorithm approximate is $O(N_r \times N_s \times N_{node} + L_q \times N_r)$. Floyd and FF algorithms are used to assign the routing and spectrum resources for all baseline algorithms and QVT-RSA algorithm.

C. THE ACCURACY TEST OF MUTUAL EXCLUSIVE RESOURCE UTILIZATION MODEL

The accuracy and effect of mutual exclusive resource utilization model are illustrated by the experiment. In our experiment, $\lambda_{i,j}^n$ presents the used times of *nth* slot in edge from node *i* to node *j* at an instant of time. During the set-up of optical connection, $\lambda_{i,j}^n$ adds 1 while the *nth* slot in $E_{i,j}$ is used to set up the optical connections, and $\lambda_{i,j}^n$ subtracts 1 while tearing down the optical connections used the *nth* slot in $E_{i,j}$. The program judges the value of $\lambda_{i,j}^n$ after every assignment of routing and spectrum resources for the service request. If $\lambda_{i,j}^n > 1$, it indicates that the spectrum resources are reused. The program sets breakpoints at positions $\lambda_{i,j}^n$ greater than 1. The program runs plenty of times, and does not trigger a breakpoint. The phenomenon verifies there has not resource reutilization, and the resource utilization of parallel optical connections set-up is accurately realized by mutual exclusive resource utilization model.

D. SIMULATION RESULTS

By simulation results, it is known that QVT-RSA algorithm has nearly approximately simulation results at all performance metrics while either using nodes set or edges set as constraint of resources utilization. The slightly higher performance is observed at all performance metrics while using edges set as the constraint of resources utilization. Thus, all simulation results of V-RSA and QVT-RSA algorithms are discussed based on simulation results generated by using edges set as constraint of resources utilization.

1) THE SET-UP SUCCESS PROBABILITIES WITHIN DELAY TOLERANCE

Firstly, the success probabilities of optical connections set-up within delay tolerance about high, medium and low priority service requests are shown in Fig. 17, Fig. 18 and Fig. 19 respectively. Compared to the SPFF-RSA algorithm in both topologies, the optical connections set-up success

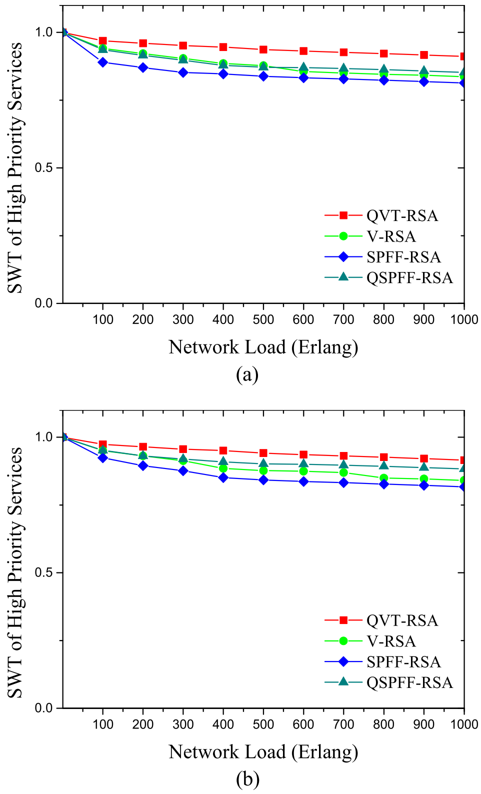

FIGURE 18. The success rate within delay tolerance of requests with medium priority: (a) NSFNET. (b) USNET.

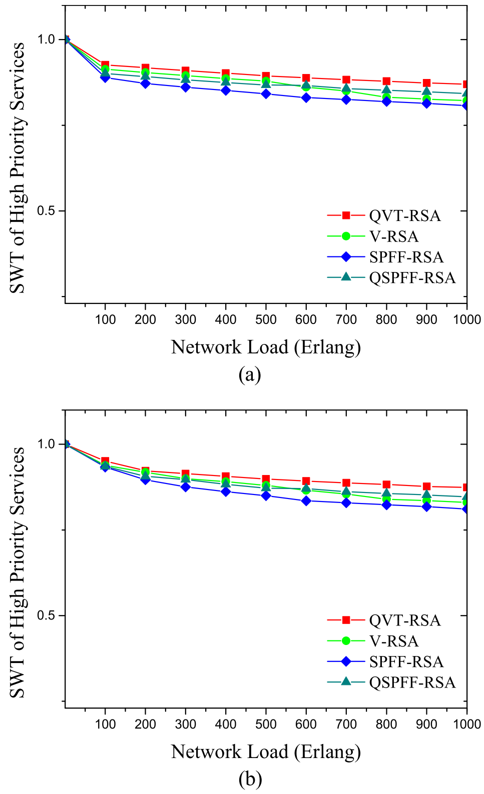

FIGURE 19. The success rate within delay tolerance of requests with low priority: (a) NSFNET. (b) USNET.

probability within delay tolerance of high priority services about QSPFF-RSA algorithm is higher as shown in Fig. 17.

This is because that the QSPFF-RSA algorithm shapes the more reasonable service order for requests by requests scheduling, which can preferentially set up optical connections for requests with low delay tolerance. It is obvious that the optical connections set-up success probability within delay tolerance of high priority services about V-RSA algorithm is higher than that of the SPFF-RSA algorithm in both topologies as shown in Fig. 17. This is because that V-RSA algorithm reduces the requests queueing delay and average optical connection set-up delay by parallel optical connections set-up, which can timely set up more connections for high priority services within delay tolerance. Compared to the QSPFF-RSA algorithm, the optical connections set-up success probability of QVT-RSA algorithm increases 3% at the USNET network topology as the network load is 600 Erlang. This is because that QVT- RSA algorithm not only shapes more reasonable serve order for high priority service request but also parallel sets up optical connections, which has higher comprehensive performance to set up more connections for high priority services within delay tolerance.

The optical connections set-up success probability within delay tolerance of medium and low priority services about QVT-RSA algorithm is higher than that of the SPFF-RSA algorithm in both topologies as shown in Fig. 18 and Fig. 19. This is not only because that the QVT-RSA algorithm shapes the more reasonable service order for requests, but also owing to that the algorithm can parallel set up optical connections for the medium and low priority requests. Compared to the V-RSA algorithm in both topologies, the QVT-RSA algorithm has better performance on optical connections set-up success probability within delay tolerance for medium and low priority service as shown in Fig. 18 and Fig. 19. This is because that the QVT-RSA algorithm shapes the more reasonable service order for requests by services scheduling. Moreover, the above phenomenon is also contributed by that the medium and low priority requests can be fairly served according to the request weight augmented with waiting time. It is obvious that the QVT-RSA algorithm has better performance on the optical connections set-up success probability within delay tolerance about medium and low priority services than that of the QSPFF-RSA algorithm in Fig. 18 and Fig. 19, and the success probability increases 6% as the network load is 600 Erlang in the NSFNET network topology of Fig. 18. This is because that QVT-RSA algorithm sets up more optical connection within delay tolerance by parallel setting up optical connections. Furthermore, reducing the average optical connection set-up delay improves the efficiency of resource utilization, which will accommodate more medium and low priority services.

2) THE PERFORMANCE OF SET-UP DELAY

Then, the delay performance is exclusively calculated, preventing the interference caused by the calculation of blocking

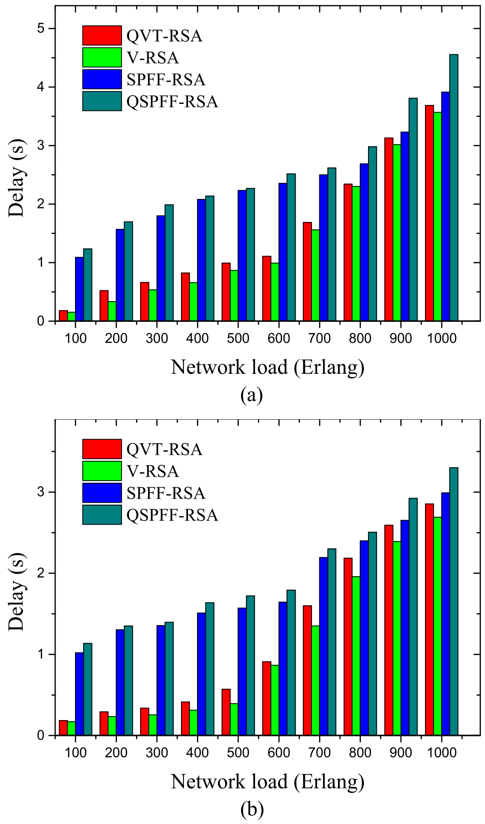

FIGURE 20. The Average set-up delay of optical connections: (a) NSFNET. (b) USNET.

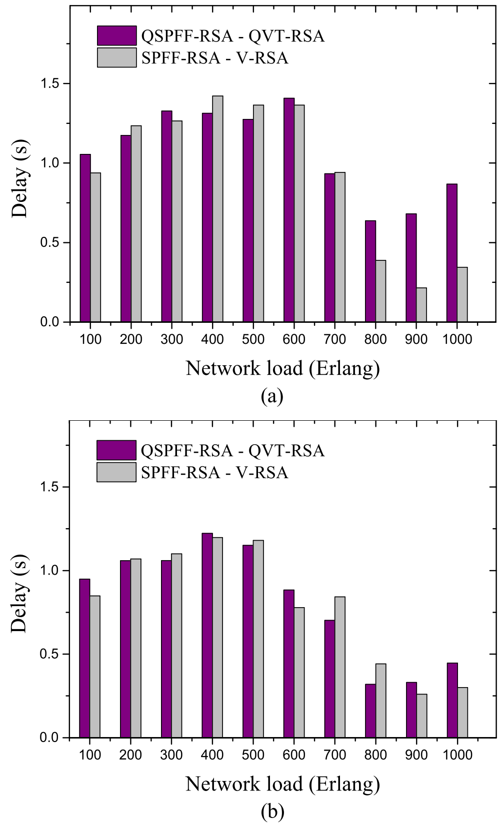

FIGURE 21. Saved set-up delay of optical connections by comparing multi-thread strategy to single-thread strategy: (a) NSFNET. (b) USNET.

probability and spectrum utilization. The delay performances of different algorithms at the two network topologies are respectively shown in Fig. 20 (a) and (b). Compared to the SPFF-RSA algorithm, the QSPFF-RSA algorithm has more stable delay performance, and this is because the services scheduling strategy more orderly serves the service requests according to their delay tolerance and waiting time. Compared to the QSPFF-RSA algorithm in the USNET network topology of Fig. 20, the average optical connections set-up delay of QVT-RSA and VRSA algorithms respectively reduces 50% and 51.6% as the network load is 600 Erlang. This is because that the QVT-RSA and VRSA algorithms efficiently reduce the queueing delay of requests and facilitate the resource usage by parallel setting up optical connections. Furthermore, the linkage reconfiguration of coloring and usable virtual topology and the mutual exclusive resource utilization model efficiently restrict the reutilization of network resource, and avoid to the repeated judgement and invalid occupation of the resources. Thus, the QVT-RSA and VRSA algorithms have better performances on the average set-up delay of optical connections. It is obvious that the average set-up delay of optical connections of V-RSA algorithm is lower than that of the QVT-RSA algorithm. In the NSFNET network topology of Fig. 20, the average set-up delay of optical connections reduces 9% as the network load is 600 Erlang. This is because the services scheduling strategy of QVT-RSA algorithm augments the set-up delay of optical connections.

In addition, the phenomenon is observed that QVT-RSA algorithm in USNET topology has the lower average set-up delay of optical connections compared to that of the NSFNET topology under the same network load, and this is because USNET topology has larger scale which will benefit the parallel set-up of optical connections. Also, as shown in Fig. 21, we provide how much time that parallel optical connections set-up strategy reduces compared to sequential optical connections set-up strategy under consideration of with services scheduling and without services scheduling.

3) THE SPECTRUM UTILIZATION

After that, the spectrum utilization of simulation results is compared. The comparing of spectrum utilization on different algorithms is shown in Fig. 22. Compared to the SPFF-RSA algorithm, the spectrum utilization of QSPFF-RSA algorithm is very slightly higher. This is because the services scheduling strategy shapes more reasonable serve order of the service requests, which sets up more optical connections within delay tolerance and facilitate the resource usage. In addition, it is obvious that the spectrum utilization of QVT-RSA and VRSA algorithms is higher compared to the QSPFF-RSA algorithm. This is because that the QVT-RSA and VRSA algorithms parallel set up optical connections and have the

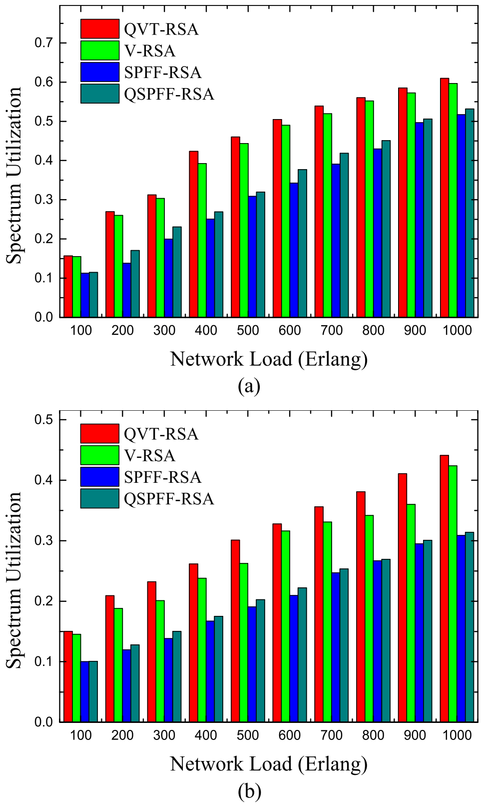

FIGURE 22. **The rate of spectrum utilization: (a) NSFNET. (b) USNET.**

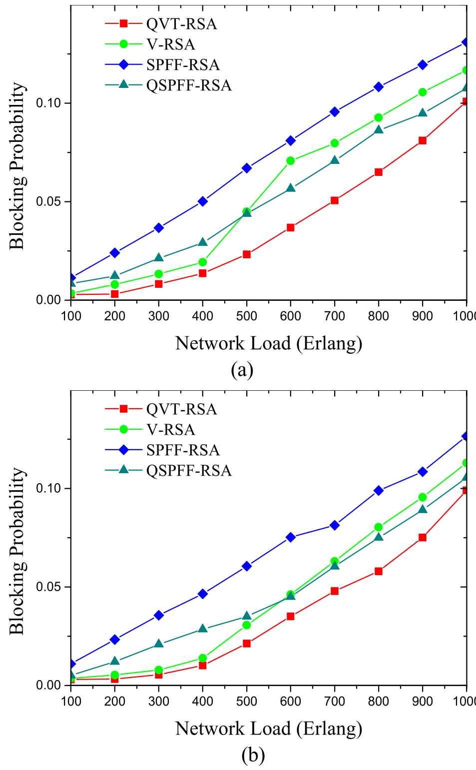

FIGURE 23. **The rate of blocking probability: (a) NSFNET. (b) USNET.**

lower optical connections set-up delay, which benefits the spectrum utilization.

4) THE BLOCKING PROBABILITY

Finally, the comparing of blocking probability is shown in Fig. 23. The SPFF-RSA algorithm has the higher blocking probability than other algorithms owing to the insufficient spectrum resource utilization and overlong optical connection set-up delay. Compared to the SPFF-RSA algorithm, the QSPFF-RSA algorithm has the lower blocking probability. This is because the services scheduling strategy shapes more reasonable serve order for the service requests, which can set up more optical connections within their delay tolerance and make full use of the network resources. It is obvious that the blocking probability of VRSA algorithm is lower than that of the SPFF-RSA algorithm. This is because that VRSA algorithm parallel sets up optical connections, and sets up more optical connections in the same time interval. Compared to the SPFF-RSA algorithm, the blocking probability about QVT-RSA algorithms reduces 3.5% as the network load is 600 Erlang in the NSFNET network topology. This is because that QVT-RSA algorithm not only shapes reasonable serve order for service requests but also provides timely service to requests by parallel optical connections set-up strategy. It is obvious that the blocking probability of QVT-RSA algorithm is lower even when the network is heavily loaded compared to that of the VRSA algorithm. This is because that QVT-RSA algorithm provides preferentially service for the low delay tolerance requests and can promptly groom the converged service requests.

VI. CONCLUSION

To meet the development of differentiated services, this paper presents a delay aware RSA algorithm based on scheduling of differentiated services with dynamic virtual topology construction. To the best of our knowledge, we first propose the parallel optical connections set-up algorithm. QVT-RSA algorithm can efficiently identify the service requests and arrange them in order according to their priority, waiting time and delay tolerance requirements, and parallel set up optical connections for them. The simulation results demonstrate that multi-threads of QVT-RSA algorithm accurately share the network resource by using the proposed mutual exclusive resource utilization model. The parallel optical connections set-up strategy benefits on reducing average optical connections set-up delay and the services scheduling strategy benefits on setting up more optical connections set-up success probability within delay tolerance. Although the QVT-RSA algorithm increases network energy consumption, the algorithm can be combined with the optimized routing spectrum assignment strategy while compensating the augmented delay of optimization strategy. To practice our strategy, we intend to deploy our algorithm in a practical multi-thread hardware platform provided by the Floodlight SDN controller and the MiniNet emulator in further work.

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