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Research Article

An Optimal SDN-Based Wavelength Allocation and Routing Method for 5G Network

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Optical networks are changing as new advanced technologies emerge. With each passing year, their sizes and capabilities expand. The standard architecture for network control and management cannot handle all of these complexities. The proliferation of cloud services and the massive volume of traffic provided by content delivery networks are driving the present fast increase in Internet traffic. This obviously exacerbates congestion concerns in communication networks, with a focus on the core and backbone components in particular. Software-defined networking (SDN) is evolving into a consolidated network management system that comprises a variety of strategies aiming at network management that are based primarily on one basic principle: decoupling control plane decisions from data plane activities. An essential resource allocation strategy in an all-optical network is routing and wavelength assignment. A novel SDN-based approach is proposed to address the problem of old methods mixed with new architecture in optical networks. The network resources were optimized for optimal scheduling using a binary hybrid topology particle swarm optimization method. In terms of recovery time, blockage rate, and resource consumption, simulation results demonstrate that the suggested technique outperforms previous classical methods.

1. Introduction

The all-optical network has the characteristics of all-optical domain information exchange [1]. It abandons the traditional photoelectric conversion mode, greatly improves the data transmission speed, and effectively increases the capacity of information exchange. It is receiving more and more attention from the industry [2, 3], simultaneous routing and wavelength allocation (RWA) as its resource allocation has always been a research hotspot, and many methods have been proposed [4, 5] to improve the efficiency of resource allocation. With the introduction of software-defined network (SDN), many traditional applications in the industry are facing challenges. It has become a problem that needs to be analyzed at present, so this article conducts research from this perspective.

In an optical network, information is transmitted through different wavelength channels in different links. RWA is a method of selecting appropriate links and matching corresponding channels according to transmission requirements to realize information transmission. It operates in two main ways: static RWA and dynamic RWA. Among them, the static method is relatively stable and the scheduling success rate is high, but it is difficult to adapt to the needs of complex network changes, the resource utilization rate is low, and the allocation method is not flexible enough. The dynamic mode usually operates in an online mode, and can be deployed in a timely manner according to the changes in the network. Different operation modes have different influences on the operation effect of the system, so it has always been the focus of research, and the dynamic mode is the research object of this article.

In view of this, this article proposes an SDN-based multi-objective adaptive routing and wavelength allocation (SO-MO-RWA) method.

The main contributions of this work are as follows:

(i) This method takes into account the need for high-speed transmission and efficient link scheduling in all-optical networks, and takes scheduling time and link quality as joint scheduling goals.

(ii) A 0–1 integer programming RWA problem model is constructed, and binary hybrid topology particle swarm optimization is used to solve the problem.

(iii) The whole method adopts the scheduling method based on SDN, which can obtain the status information of network resources in real time, and realize the dynamic allocation of network resources in an on-demand manner.

The remaining article is organized as follows. In Section 2, the related work is described. In Section 3, the proposed framework is discussed in detail. In Section 4, the proposed system model is discussed. In Section 5, the proposed algorithm is explained and pseudocode. Section 6 provides the numerical results while Section 7 concludes the article.

2. Literature Review

The research content of RWA can be analyzed from the following aspects. First, different evaluation indicators are set from different research angles, such as resource allocation ratio, link damage perception, and blocking rate [6] proposed a minimum-hop fixed-alternating algorithm to reduce the blocking rate based on the research of fixed routing, alternate routing, and adaptive routing methods of RWA. Tyagi et al. [7] studied the connection blocking rate minimization problem in the RWA problem by using an improved water drop algorithm for dynamic optical networks. Abdo and D'Amours [8] estimated the calculated optical path quality on the basis of establishing a linear physical layer damage model, and proposed a dynamic damage-aware RWA scheme. This method collects link wavelength occupancy information and adopts adaptive routing technology to establish suitable links. Marsden et al. [9] proposed a fast computational method for routing and wavelength assignment involving four-wave hybrid-induced crosstalk to minimize the time to establish a dynamic optical path. Wang et al. [10] evaluated the performance indicators of the physical layer impairment RWA (PLI-RWA) algorithm based on the classification of physical layer damage and the comprehensive research on RWA-related algorithms. Velasco et al. [11] designed a probabilistic model to calculate the number of wavelengths used in each link in an optical network, and on this basis, proposed a novel damage-aware RWA algorithm. The above methods can be analyzed and designed according to the state index of the link, but they are mainly based on single-index scheduling and fail to consider the scheduling needs under complex scheduling conditions.

Second, different scheduling methods will have an impact on the operating effect of the system. Yu et al. [12] developed a set of heuristic algorithms for all-optical networks that can solve the RWA issue in polynomial time while consuming less energy from network resources. Jaumard and Daryalal [13] studied the problem of optical path rearrangement in RWA and used the e-optimal method to evaluate the minimum number of optical path rearrangements required to maximize the service level. Virgillito et al. [14] proposed a routing and wavelength allocation algorithm based on prediction and hierarchical graph model, considering the needs and characteristics of service differentiation, and realized routing and wavelength resource allocation through the wavelength number prediction mechanism combined with the hierarchical graph model. Ricciardi et al. [15] can realize the balanced utilization of network resources through dynamic switching between load balancing and energy sensing according to the network load in the process of link resource allocation. Pavarangkoon and Oki[16] proposed a routing and wavelength allocation scheme considering all-optical carrier replication to minimize wavelengths required for multi-carrier distributed networks with wavelength reuse. According to the nondeterministic polynomial (NP) characteristics of the RWA problem in optical networks, Hsu et al. [17] proposed an algorithm based on the maximum disjoint path to achieve routing and wavelength allocation. The above researches have carried out algorithm design according to the problem scenarios studied, but there is still a lack of design and research on specific scheduling methods under the platform structure similar to SDN.

The proposal of SDN provides a good opportunity for the development of optical networks. In recent years, many scholars have also conducted a lot of research on the integration of optical networks and SDN. Aiming at the inefficiency of traditional configurations, Moreno-Muro et al. [18] proposed an efficient topology discovery method based on SDN using the test signal mechanism and the OpenFlow protocol, allowing the transparent optical network (TON) to automatically learn the physical adjacency between optical devices, to improve the efficiency of data transmission. The development of the optical network is accompanied by an increase in complexity, which makes the traditional network control and management framework unable to match it. Literature [19, 20] expound on various management and control mechanisms and applications in SDN optical networks. Yan et al. [21] considered that a full understanding of the current network state is crucial for better realization of software-defined schedulability in a short period of time, and designed a centralized network database that combines network monitoring data and network configuration information to enable network analysis. Applications can better support dynamic programmable optical networks. Zhou et al. [22] proposed a joint SDN controller architecture for optical networks, which fully combines clustering strategies with rich hierarchical path computation to improve routing performance. Considering the exponential data rate growth of the optical network in the future, Mata et al. [23] used cognitive technology to analyze and design

the optical layer and controller of SDN. Literature [24, 25] proposed a data center virtualization architecture with a corresponding all-optical SDN structure, which can provide a data expansion environment on demand, realize dynamic segmentation of network and computing resources, dynamically translate and provide requests from virtual data centers to the optical layer, and provide users with high-bandwidth and low-latency connection services. The above literature has studied the technology integration and application of SDN and optical network from different perspectives, but there is still a lack of research on how to carry out the specific scheme of path resource allocation such as RWA under the new network architecture.

3. Proposed Framework

SDN is a new type of network architecture and its core idea is to change the traditional way of integrating control and scheduling, decoupling control plane and data plane functions, and through network programmability and network function virtualization. It realizes the flexible scheduling of network resources and improves the overall operation efficiency of the system. At the same time, with the continuous improvement of the technical level, the all-optical network is becoming an important information transmission carrier of the global Internet backbone network by virtue of its own transmission characteristics. It is of broad interest [26, 27], and the International Internet Engineering Task Force (IETF) also defines the structure accordingly. The structure of the all-optical network based on SDN is shown in.

The SDN-based all-optical network structure is mainly composed of three layers: the application layer, the control plane, and the data plane. The top layer is the application layer, which corresponds to various application requirements, such as the data center services [28] and cloud tenant applications. The second layer is the control plane, and its core component is the controller. The controller connects with the application layer through the northbound interface and provides different interface protocols to meet the compatibility with different applications. The southbound interface is connected to the data plane. The southbound interface is responsible for docking with infrastructure resources and can support multi-vendor and multi-protocol scenarios. The main protocol is OpenFlow, which adopts the form of character stream and can accommodate transmission formats of different networks and provides a unified data transmission interface. At the beginning of the SDN design, it was mainly aimed at IP networks, and did not consider the signal transmission characteristics of optical networks. Therefore, in recent years, related research has also expanded the structure of OpenFlow [29, 30] to adapt it to the transmission mode of optical networks. The main functional modules of the controller include resource management, topology management, scheduling algorithm module, network service abstraction, etc. The bottom layer is the data plane, which is mainly composed of all-optical network infrastructure, such as optical cross-connector (OXC), reconfigurable optical add-drop multiplexer (ROADM), and wavelength selective switch (WSS). In the process of integration with SDN, many new devices also have built-in OpenFlow protocol [31] to realize direct interaction with the controller, but most optical network devices currently cannot support direct interaction with the controller, so the proposed OpenFlow Protocol Agent (OA) [32] is responsible for the forwarding of information between the controller and the optical switching equipment, and realizes the seamless connection between the signal transmission and the all-optical domain switching under the SDN structure Figure 1.

In traditional networks, users obtain resource information in an end-to-end manner, and resource allocation in all transmission processes cannot be adjusted in real time as needed due to the limitation of the scheduling structure. The network function virtualization (NFV) realizes the abstraction of network resources, realizes network functions through software methods, and completes the deployment of resource service functions, which can not only optimize the transmission path of information flow and flexibly allocate information transmission flow, but also it can shorten the service scheduling period and improve the scheduling efficiency of resources. With the combination of SDN and NFV, the flexibility of all-optical network resource scheduling has been effectively improved, and resources can be allocated on demand without being limited to a certain region, equipment, or a certain supplier. In this context, the IETF gives the service function chain. The concept of service function chaining (SFC) [33] corresponds to the allocation of a series of resources required for end-to-end transmission. Under the all-optical network structure based on SDN, this method can dynamically allocate functional nodes carrying services according to business logic, and realize network function services and resource deployment. During the running process, the service abstraction module of the controller abstracts several resources required by the service according to the business requirements, and provides corresponding service function instances. At the same time, the scheduling algorithm selects resources according to the network status information provided by the resource management module. Perform resource mapping of service functions, realize resource scheduling with different granularities, and adapt to resource selection of optical network links and optical path construction. The resource allocation method of the service function chain has positive significance for the all-optical network, solves the problems of traditional scheduling inefficiency and resource waste, further improves the reconfiguration of network resources, and realizes efficient network management and rapid and effective resource allocation.

4. System Model

In the process of resource virtualization scheduling by SDN, infrastructure resources such as links and corresponding wavelengths carry data traffic. Therefore, in order to provide effective transmission services in the process of service function chain resource deployment, it is necessary to

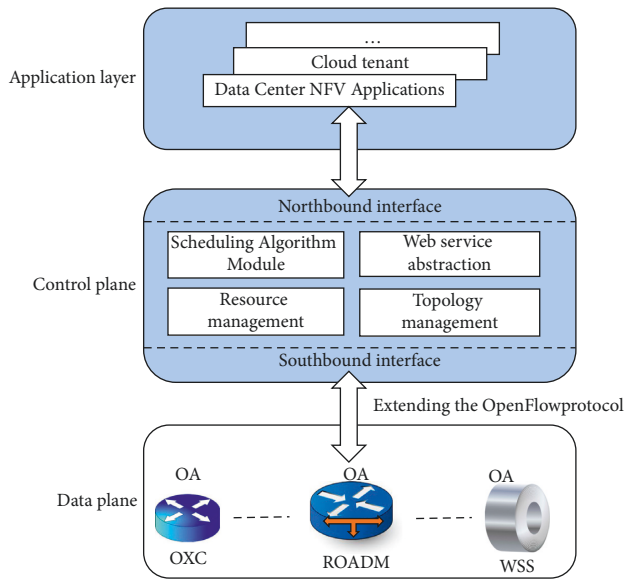

Figure 1: Proposed optical network structure.

comprehensively consider the transmission quality and link quality of optical communication. Factors such as road scheduling efficiency.

4.1. Scheduling Indicator Design. The RWA is considered to be an effective means for all-optical networks to solve resource allocation. In the scheduling process of RWA, the SDN controller adjusts the link resources according to the established scheduling goals of RWA by sensing the physical damage information and resource allocation status of the network link. Based on the characteristics of all-optical network scheduling requirements, this article takes scheduling time and link quality as scheduling goals. Among them, the scheduling time refers to the time spent in a series of processes from accepting requests and executing path planning to resource mapping. When the SDN controller receives a service request, it abstracts the service function of the requested resource using the resource allocation method of the service function chain and generates a series of service function sets (SFS), each of which consists of multiple service function instances (SFI) that can be provided by different service providers, to realize the construction of complete link resources. Therefore, m service function sets SFS_1, SFS_2 ,. . ., SFS_m can be obtained, when scheduling service instances inside the service function set follows a heavy-tailed distribution, and the request time of each service function instance obeys the Poisson distribution, and the corresponding average arrival rate is $\lambda_1, \lambda_2, \ldots, \lambda_n$, according to network traffic characteristics [34]. The appointment time for the service T_i is the service instance that is expressed as:

$$T_i = \frac{\overline{h}_i^2}{2\overline{h}_i\left(1-\lambda_i\overline{h}_i\right)}\left[1+\frac{1-\lambda_i\overline{h}_i}{\lambda_i\overline{h}_i}\right]^{-1}. \tag{1}$$

Among them, λ_i represents the request arrival rate of SFI_i, $\overline{h}_i$ and $\overline{h}_i^2$ represent the first-order moment and the second-order moment of the scheduling time, respectively, as shown in (2) and (3), respectively.

$$\overline{h}_i = \frac{\alpha}{\alpha-1}\frac{k^\alpha}{1-(k/p)^\alpha}\left(\frac{1}{k^{\alpha-1}}-\frac{1}{p^{\alpha-1}}\right), \tag{2}$$

$$\overline{h}_i^2 = \frac{\alpha}{\alpha-2}\frac{k^\alpha}{1-(k/p)^\alpha}\left(\frac{1}{k^{\alpha-2}}-\frac{1}{p^{\alpha-2}}\right). \tag{3}$$

The probability density function of the heavy-tailed distribution is

$$f(x) = \frac{\alpha k^\alpha}{1-(k/p)^\alpha}x^{-\alpha-1}, \quad k \le x \le p. \tag{4}$$

Link quality is an important indicator of network transmission. During the operation of an all-optical network, due to optical propagation characteristics and other reasons, the signal will be affected by optical loss, crosstalk, etc., resulting in signal damage. The SDN controller has a global network view, can perceive the network topology status information in real time, and evaluate the physical damage of the optical path according to the information change, and judge the service status of different links to provide the basis for link allocation. The evaluation models mainly include optical signal-to-noise ratio (OSNR) and Q factor. In practical applications, the Q factor model is widely used due to its good adaptability to different measurement environments. The calculation of the Q factor model will involve different physical damage indicators, so as to comprehensively evaluate the line, including cross-phase modulation (XPM), four-wave mixing effect (FWM), amplified spontaneous emission (ASE), etc., so the SFI_i's link quality calculation is shown in (5) as follows:

$$\begin{aligned} Q &= 10\log\frac{P_s}{\sigma_{\text{total}}+\sigma_0} \approx 10\log\frac{P_s}{\sigma_{\text{total}}}, \\ \sigma_{\text{total}}^2 &= \sigma_{\text{ASE}}^2+\sigma_{\text{FWM}}^2+\sigma_{\text{XPM}}^2. \end{aligned} \tag{5}$$

Among them, σ_{total} represents the standard deviation of cross-phase modulation, four-wave mixing effect, and amplified spontaneous emission, P_s represents the power peak value of the corresponding optical channel, and σ_0 represents the intensity standard deviation when the signal is 0.

4.2. Objective Function definition. Based on the preceding analysis and definition, an SDN-based multi-objective adaptive routing and wavelength allocation model is built. On the infrastructure of different service providers, the unified control logic of SDN is used for scheduling, and the virtualized configuration of service resources is performed by using the characteristics of network programmability, so as to realize the effective deployment of RWA. During the resource deployment process, the following points need to be considered: (1) construction of service function sequence; (2) the choice of service infrastructure provided by different suppliers; and (3) select the matching optical path according to the scheduling objectives and constraints. Combined with the above analysis, this article constructs the resource allocation problem of all-optical network based on SDN as a 0–1 integer programming problem, and its model can be

expressed as $M = (C, I, W)$, where C represents the abstraction by the network as needed constructed service function chain consists of service function sets; I represents the link resource instance inside the service set; and W represents the set of bands available within the link resource. The corresponding objective function is defined as.

$$\begin{aligned}
&\min \sum_{k=1}^{m}\sum_{j=1}^{n_j}\sum_{i=1}^{w_i}\left(\omega_1 T_{kji} + \omega_2 \frac{1}{Q_{kji}}\right)X_{kji},\\
&s.t\\
&1)Q_{kji} \geq Q_{\text{th}},\\
&2)B \geq B_{\text{th}},\\
&3)X_{kpi} = X_{kqi}, \quad p, q \in \{1, \ldots, n_j\},\\
&4)X_{kji} \in \{0, 1\}, \quad i \in \{1, \ldots, w_i\},\\
&\quad j \in \{1, \ldots, n_j\}, \quad k \in \{1, \ldots, m\},\\
&5)\sum_{j=1}^{n_j}\sum_{i=1}^{w_i} X_{kji} = 1, \quad j \in \{1, \ldots, n_j\},\\
&\quad i \in \{1, \ldots, w_i\},\\
&6)\omega_1 + \omega_2 = 1, \quad \omega_1 > 0, \quad \omega_2 > 0.
\end{aligned} \tag{6}$$

Among them, Q_{th} and B_{th} represent the Q factor threshold and bandwidth capacity threshold, respectively. The k, j, i, m, n_j, and w_i, respectively, represent the service function set in the chain, the link resource instance, the resource variable corresponding to the band set available for the link, and the corresponding resource quantities for j-th and i-th instances.

The model integrates the two indicators of link quality and scheduling time to achieve fast and efficient resource scheduling. The corresponding constraints are described as follows: (1) Q factor threshold, the selected link needs to meet the specified threshold to ensure that the channel quality of the selected link meets the transmission requirements; (2) bandwidth capacity threshold, provide effective bandwidth according to business requirements, and ensure the transmission requirements of QoS; (3) wavelength consistency, the link sequence adopts a unified wavelength; (4) the value of X is 1 or 0 to represent whether the corresponding resource is selected or not; (5) guarantee the uniqueness of the allocation of optical path resources; and (6) weight constraints.

5. Proposed Algorithm

Since RWA is an NP-complete problem, the scheduling algorithm directly affects the performance of the proposed SO-MO-RWA algorithm. According to the characteristics of the proposed model, the binary hybrid topology particle swarm optimization (BHTPSO) algorithm [35] is used to solve the path planning problem.

5.1. Description. The particle swarm optimization (PSO) algorithm is widely used in different fields due to its high search efficiency and has also developed multiple versions. Among them, the binary particle swarm optimization (BPSO) algorithm is often used to solve NP optimization of discrete space problems such as integer programming. The BHTPSO is optimized for the shortcomings of BPSO, which is easy to fall into the local optimal solution and slow in the convergence speed, which effectively improves the performance, accelerates the convergence speed while avoiding the local optimal solution, and further improves the efficiency of solving integer programming problems.

Like BPSO and PSO, the BHTPSO is also obtained by discretization based on the hybrid topological particle swarm optimization (HTPSO) algorithm. In BHTPSO, vectors $(\mathbf{X}_i, \mathbf{V}_i, \quad \mathbf{P}_{\text{best}_i})$ represent the position, velocity, and optimal position of the i-th particle, respectively, $\mathbf{P}_{l\text{best}_i} = (p^1_{l\text{best}_i}, p^2_{l\text{best}_i}, \ldots, p^d_{l\text{best}_i}, \ldots, p^n_{l\text{best}_i})$ and $\mathbf{P}_{\text{gbest}} = (p^1_{\text{gbest}}, p^2_{\text{gbest}}, \ldots, p^d_{\text{gbest}}, \ldots, p^n_{l\text{best}_i})$ represent its neighbors, respectively. The optimal position is found by the particle and the optimal position obtained by the entire population. BHTPSO uses a combination of local topology and global topology to search, and the next velocity of the i-th particle is

$$\begin{aligned}
v^d_i(t+1) = {} & w(t)v^d_i(t) + c_1(t)\text{rand}_1\left(p^d_{\text{best}_i}(t) - x^d_i(t)\right)\\
& + c_2(t)\text{rand}_2\left(p^d_{l\text{best}_i}(t) - x^d_i(t)\right).
\end{aligned} \tag{7}$$

Among them, the inertia weight $w(t)$ is

$$w(t) = w_{\max} - \frac{t\left(w_{\max} - w_{\min}\right)}{T}. \tag{8}$$

The next position of the current particle can be obtained according to the group optimal $\mathbf{P}_{\text{gbest}}$, as shown as follows:

$$\begin{aligned}
x^d_i(t+1) = {} & x^d_i(t) + v^d_i(t+1)\\
& + c_3(t)\text{rand}_3\left(\mathbf{P}_{\text{gbest}}(t) - x^d_i(t)\right).
\end{aligned} \tag{9}$$

Among them, the acceleration factors c_1, c_2, and c_3 are calculated by (10).

$$c_j(t) = c_{j\min} + \frac{t\left(c_{j\max} - c_{j\min}\right)}{T}, \quad j = 1, 2, 3. \tag{10}$$

In order to improve the ability to explore unknown solutions, the algorithm expands the search range in the early stage of the search to highlight the effect of the global search. With the increase of the number of iterations, the global search is weakened and the local search is accelerated to obtain the optimal solution. During this period, the optimal solution of each particle needs to be obtained with reference to $\mathbf{P}_{\text{best}_i}$, $\mathbf{P}_{l\text{best}_i}$ and $\mathbf{P}_{\text{gbest}}$.

(1) Initialization: Particle X^i, velocity V_i, position $\mathbf{P}_{\text{best}_i}$, and the number of iterations.
(2) Get $\mathbf{P}_{l\text{best}_i}$, update particle velocity.
(3) Calculate the next position of the particle through the velocity $v_i^d(t+1)$, the group optimal position $\mathbf{P}_{\text{best}}$, etc.
(4) If the conditions are met, end the operation to derive the optimal solution, otherwise update $\mathbf{P}_{l\text{best}_i}$, $\mathbf{P}_{\text{gbest}}$, and go to step 4.
(5) Update parameter w.
(6) Update parameters c_1, c_2, c_3.
(7) If the optimal position does not change in multiple iterations, add the E value to jump out of the local search, and perform step 1.

Algorithm 1: Proposed SO-MO-RWA scheme.

In the discretization process of the BHTPSO algorithm, the velocity of the particle is calculated by (11). The speed of the particle is directly related to the position change, that is, 0 means that the current position of the particle does not need to be changed and 1 is the opposite.

$$S(a) = |\tanh(a)|. \tag{11}$$

In order to avoid the phenomenon of stagnation in multiple iterations and the inability to obtain the optimal solution, the E value shown in (12) can be added to (11) to jump out of this iteration and continue to accelerate the convergence.

$$E = \operatorname{erf}\left(\frac{NF}{T'}\right) = \frac{2}{\sqrt{\pi}}\int_0^{NF/T'} e^{-t^2}\,\mathrm{d}t. \tag{12}$$

Thus, the next position of each particle is shown as follows:

$$\begin{cases} a_i^d(t+1) = v_i^d(t+1) + c_3(t)rand_3\left(p_{\text{gbest}}^d(t) - x_i^d(t)\right) \\ S\left(a_i^d(t+1)\right) = E + (1-E)\left|\tanh\left(a_i^d(t+1)\right)\right| \\ x_i^d(t+1) = \begin{cases} \text{complement}\left(x_i^d(t)\right), rand_4 < S\left(a_i^d(t+1)\right) \\ x_i^d(t), \text{otherwise} \end{cases} \quad i = 1, 2, \ldots, N. \end{cases} \tag{13}$$

In the process of solving the proposed method, each particle X^i represents a link candidate solution, and the objective function is used as the fitness function. The calculation steps are described as follows in Algorithm 1.

5.2. Parameter Optimization. Parameter optimization requires particle swarm optimization to select suitable parameters for specific problems to improve the computational efficiency of the model (Figure 2).

(1) Inertia weight: for the value range of the inertia weight, this article selects the four intervals [0.1, 0.2], [0.3, 0.6], [0.7, 0.9], and [1.0, 1.2] for experiments, as shown. The test results of different interval values show that in the continuous iterative process, they show different variation amplitudes, and when the parameter values are [0.1, 0.2] and [0.3, 0.6], the operating effect of the system is optimal. Furthermore, the impact when parameter value is [0.1, 0.2] is better than [0.3, 0.6].

(2) Acceleration factor: there are three acceleration factors in this algorithm: c_1, c_2, and c_3. According to experience, when the values of particle swarm optimization c_1 and c_2 are close to or equal to the value of the system, the system works well, so the parameters are set in three cases, and two of them are set to equal values, which are 1.5 and 1.5, respectively; 2.5, the other is to equalize c_1, c_2 and differentiate the value of c_3. As shown in, the test results show that when the value of c_3 is differentiated, the operating effect of the system is better than the case where the three values are the same.

(3) Number of particles: in order to test the effects of different numbers of particles on the system, this article selects 4 particle numbers of 30, 50, 70, and 100 in a gradient. The parameter settings such as acceleration factor and inertia weight are consistent in scenarios with different particle numbers, as shown in. The experimental results show that when the number of particles is $N = 100$, the system works best, that is to say, when the number of particles is large, the operating efficiency of the algorithm can be improved.

(4) Maximum particle update speed: in the maximum particle update speed test, the three values of 3, 6, and 9 are uniformly selected, as shown in. When $v = 6$, the test results are better than the other two cases, indicating that the update speed should be kept at a relatively moderate value is preferred.

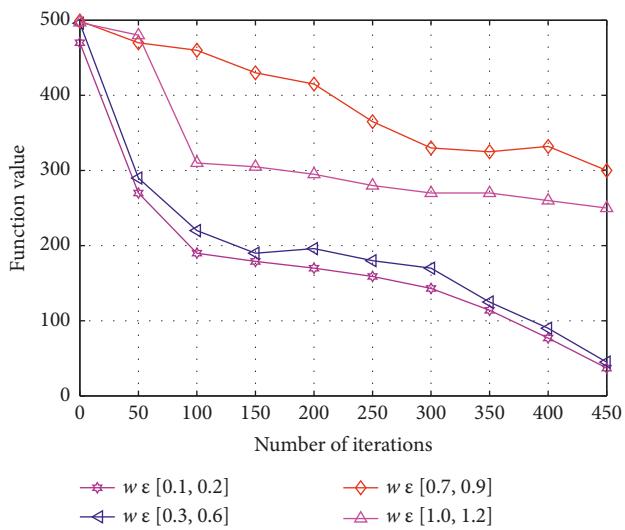

Figure 2: Inertia weight parameter test.

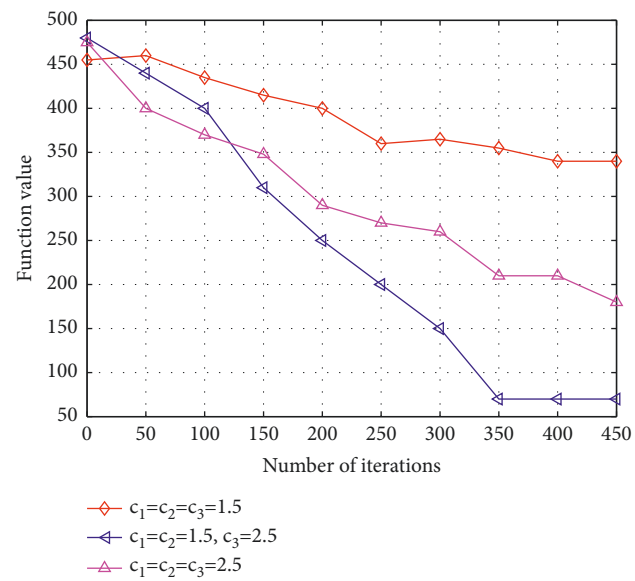

Figure 3: Acceleration factor parameter test.

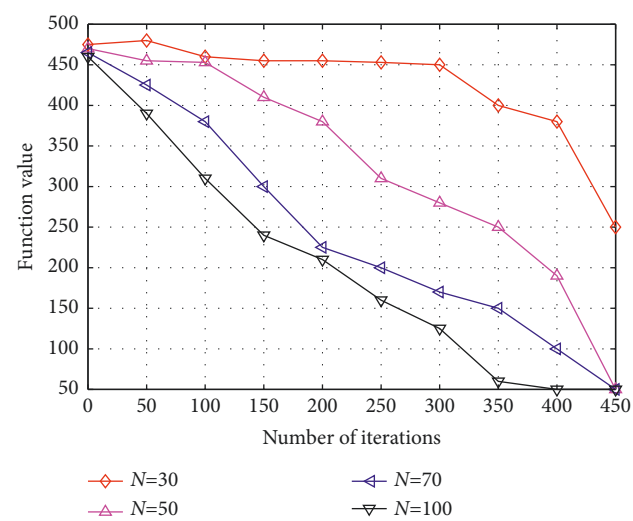

Figure 4: Particle number parameter test.

Compared with the BPSO algorithm, the BHTPSO algorithm further improves the performance of obtaining the global optimal solution. Figure 3 When solving integer programming problems, the BHTPSO algorithm can find the optimal feasible solution in the solution space according to the corresponding search strategies and rules. Compared with the traditional method, the BHTPSO algorithm can face the situation that the solution space is too large and the complexity increases, making it difficult to calculate. It can better adapt to the change of the solution space and obtain a better approximate optimal solution. At the same time, in order to effectively evaluate the accuracy of the calculation results of the algorithm, this article chooses to compare with the implicit enumeration method. As a classification of branch and bound method, implicit enumeration method is mainly used to calculate 0–1 integer programming problem, and this method can usually obtain the optimal solution of the problem. Based on the model defined in this article and the setting of parameters, the calculation result of the implicit enumeration method is 40.78. In order to ensure the validity of the calculation result of the BHTPSO algorithm, the interval estimation method is used to statistically analyze the effective range of its numerical value, and the confidence level is set to 0.95. Figure 4 According to the statistics of the operation results, the optimal solution obtained by the BHTPSO algorithm conforms to the normal distribution $N(\mu, \sigma^2)$ with the parameters $\mu = 41.17$ and $\sigma = 0.42$, and the confidence interval is [41.02, 41.31], that is, the BHTPSO algorithm solves the accuracy of the difference between the optimal solutions in the range of 0.6%~1.3%. It is often close to the optimal solution, which shows that the algorithm can effectively solve the 0–1 integer programming problem Figure 5.

The complexity of the BHTPSO algorithm is mainly composed of two parts, one part is the scale of the problem itself, including the dimension D of the solution, the number of iterations I, the number of particles N, etc. In addition, it also includes the operation steps of various parameters of the particles in the solution process. It can be seen from the relationship that the complexity of the algorithm can be expressed as a function of the size of the problem, so the complexity can be expressed as O(D.I.N).

5.3. Model Process. The function realization of the whole model in this article requires the scheduling cooperation of multiple modules, and the scheduling process is shown in Figure 6. First of all, the system can perceive various link damages and status information of link scheduling at the bottom layer in real time. The information is aggregated into the resource management module and the multi-scheduling indicator information is provided to the BHTPSO algorithm for calculation. At the same time, the perceived resource dynamic request is transformed into a set of different functional components of the service function chain through network abstraction. After the

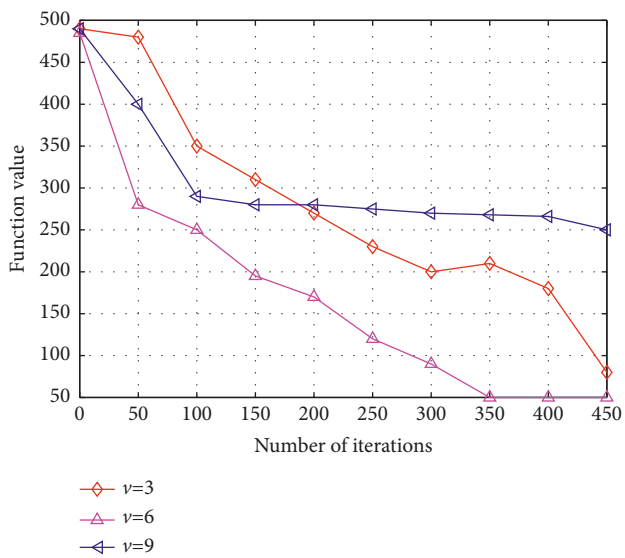

Figure 5: Maximum particle update speed parameter test.

optimization of the scheduling algorithm, a reasonable resource scheduling scheme, and finally, realize the resource reconstruction of the network by resource mapping through topology management. The SFC is transferred to BHTPSO scheduling algorithm, then its topology management is performed and finally, the patch optimal path switching is realized. If the link is damaged, then it is sensed and its information is feedback to the BHTPSO scheduling algorithm to determine the optimal route.

6. Simulation Results

In this article, a corresponding test platform is developed to simulate the proposed method. The test platform uses the discrete event simulator OMNeT++ to design the components and functions of the network. The test platform is configured with Intel i7, 8 GB DDR4 memory, Windows 7 64 bits. The network topology selects the European all-optical network standard test topology Pan-European [36], as shown in Figure 7, which includes 40 bands, 33 links, and 17 nodes, and the extended OpenFlow protocol is used to realize the communication between components. The relevant parameters are shown in Table 1.

The impairment-aware-based routing and wavelength assignment (IA-RWA) has always been considered as the main resource allocation method for optical networks. Two typical methods used in this article, the wavelength assignment by random-fit (IA-RWA-RF) and wavelength first impairment-aware-based routing and wavelength assignment by first-fit (IA-RWA-FF) were compared with the proposed method. The main routing algorithm adopted by the two methods is short-path priority, and resource allocation is realized in combination with their respective wavelength allocation forms.

6.1. Time of Recovery. It refers to the time from the perception of abnormal damage to the completion of system scheduling to realize resource reconstruction. For a large-capacity and high-speed transmission network such as an all-optical network, a shorter recovery time can further reduce the impact on the system and ensure the quality of service. This indicator is mainly to evaluate whether the system has the scheduling ability of efficient and flexible allocation of resources. For this reason, different numbers of failed links are set under different load conditions to test the scheduling effect of the system under different loads and failed links. At the same time, each case was tested 30 times, and the average value was taken as the valid test result. The experimental results are shown in Figures 8 and 9, respectively.

First, in the case of low load, as shown in Figure 8, when the number of failed links is in the range of (1) and (4), due to more available resources, the time used for IA-RWA-RF scheduling is slightly less than IA-RWA-FF with the increase of the number of failed links, the time used by IA-RWA-RF shows a continuous growth trend. Within the range of failed links in (5) and (10), the recovery time increases from 4.45 to 6.91 ms, and the growth rate reaches 55%. Compared with IA-RWA-RF and IA-RWA-FF, the SO-MO-RWA has a smaller variation in the time spent, and the curve is also flatter. Also in the range of (5) and (10), its recovery time ranges from 2.92 to 3.65 ms, an increase of 25%. Second, at higher loads, as shown in Figure 9, IA-RWA-RF takes more time than IA-RWA-FF, and both are higher than SO-MO-RWA. The experimental results show that in the range of (6) and (10) failed links, the three methods show certain differences, IA-RWA-RF from 5.13 to 7.91 ms with a 54% change, IA-RWA-FF from 4.64 to 6.25 ms with a 35% change, and SO-MO-RWA from 3.71 to 4.09 ms with a 10% change.

It can be seen from the test results that under different load conditions, the time spent by the proposed method is less than that of existing algorithms. The reasons are as follows: first of all, in terms of scheduling structure, SO-MO-RWA adopts the SDN controller to obtain the running status information of the link in real time through a unified control interface, and adaptively adjusts the link resources to ensure the continuous and effective service. Second, in terms of scheduling method, the virtualized resource scheduling method enables fast and flexible resource deployment and optimizes network resource configuration for business needs. Finally, the SO-MO-RWA takes the scheduling time as the goal, and selects an efficient global optimization algorithm to match the resources of the scheduling goal, which further improves the execution efficiency of the mapped resources and shortens the scheduling time. In contrast, the other two methods use short-path priority, which is simple but has local characteristics. It is necessary to further allocate optical paths on the basis of routing to achieve complete resource scheduling. The efficiency of resource allocation is relatively low, and it cannot be guaranteed that multiple paths occur and scheduling performance in case of link failure.

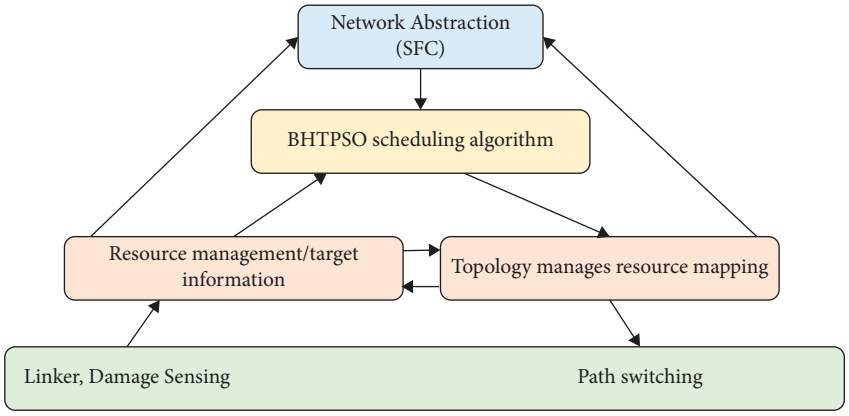

Figure 6: Proposed algorithm flowchart.

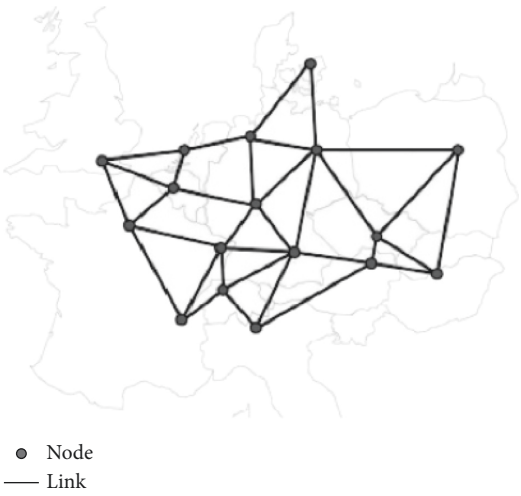

Figure 7: Deployed topology.

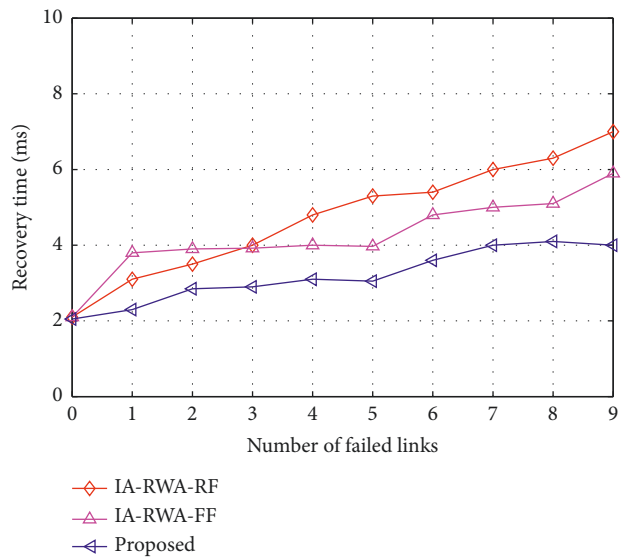

Figure 8: Recovery time under 100 Erlang conditions.

Table 1: Experimental parameters.

Parameter	Value
c_1	1.5
c_2	1.5
c_3	2.5
w_i	10~40
w	0.4~0.6
n_j	2~4
m	5~10
ω_1	0.6
ω_2	0.4
Number of iterations	500
Number of initial particles	100

6.2. Blocking Rate. The bandwidth resources of the optical network are composed of different wavelength channels, and different transmission requirements will allocate different bandwidths. In order to meet the requirements of wavelength consistency, different links should select the same wavelength channel to transmit signals. When some links cannot allocate effective resources, the scheduling will be blocked, and the blocking rate reflects the allocation of

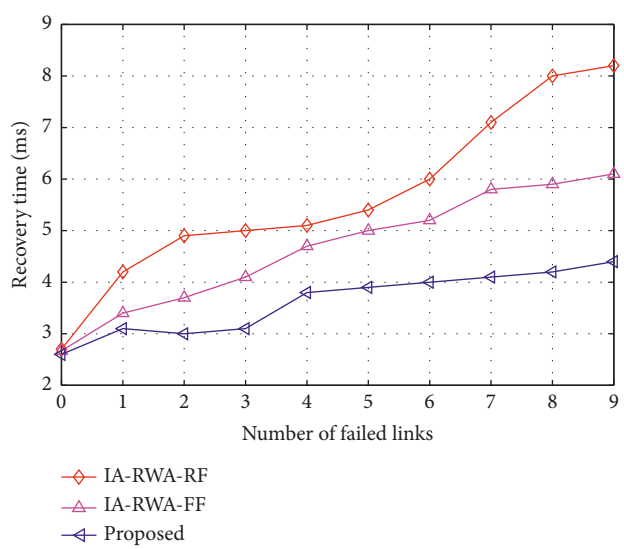

Figure 9: Recovery time under 300 Erlang conditions.

effective link resources. Since the resource scheduling methods of different algorithms directly determine the channel allocation method, this indicator is also an important indicator for evaluating the resource allocation performance of the scheduling algorithm. As shown in Figure 10, as the network load continues to increase, the three methods have different magnitudes of increase. Among them, due to the greater randomness of channel allocation, the load of IA-RWA-RF in (40, 200) blockage rate in the interval increased obviously, which was higher than that of IA-RWA-FF. Compared with these two algorithms, the index change of SO-MO-RWA is relatively gentle. In the load interval of (90, 160), its blocking rate changes from 2.19% to 2.47%, with an increase of 12.8%. The blocking rate of IA-RWA-RF and IA-RWA-FF increased from 2.52% to 4.24% and 4.03% to 6.67%, respectively, with an increase of 68% and 65%, respectively. At the same time, in the load interval of [170, 200], the SO-MO-RWA index does not show a significant increase with the increase of the load, while the increase of the other two algorithms changes more obviously. Therefore, the test results show that in the whole test interval, SO-MO-RWA has a lower blocking rate than the other two algorithms.

The reasons for the analysis are as follows: first, the SDN controller can manage the network topology information in a unified manner, aggregate the underlying link damage information and the state information required for link switching from a global perspective, and then perform link selection for the service resource sequence with traffic planning, matching effective resources to avoid blocking. Second, the optimal deployment of resource sequences is realized through the service function chain method, which guides the rational allocation of link resources and improves the efficiency of resource allocation. Finally, this article constructs the link resource allocation problem as a 0–1 integer programming problem, takes the link transmission requirements as constraints, and uses an improved binary particle swarm optimization algorithm for global optimization, which further improves the allocation efficiency of effective resources and the success rate of link establishment. The IA-RWA uses Markov chains to construct the path resources. Compared with the global resource allocation method based on SDN, this probability model has certain uncertainties. The uncertainty is more pronounced, so the blocking rate increases significantly as the load increases in the experiment.

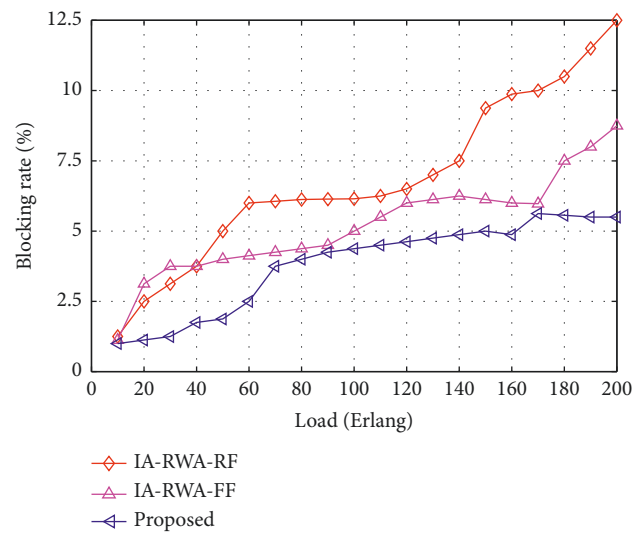

Figure 10: Comparison of blocking rate.

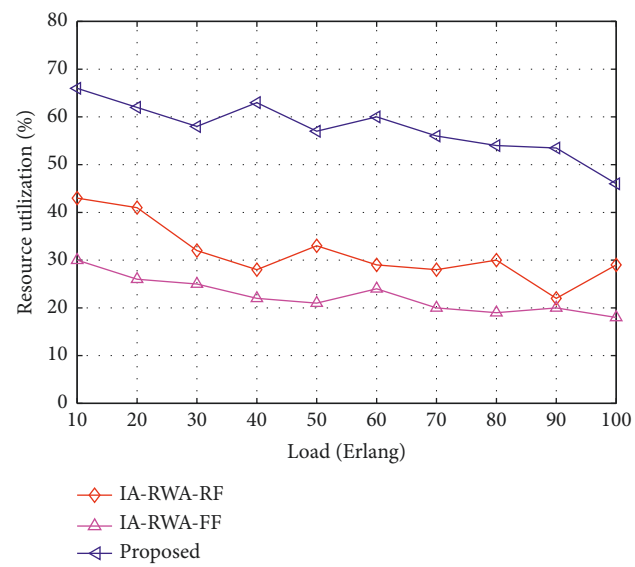

Figure 11: Comparison of resource utilization.

6.3. Resource Utilization. Resource utilization is an index to evaluate the utilization efficiency of components involved in information transmission. Resource utilization is closely related to the way the network operates. In the IA-RWA scheduling methods represented by IA-RWA-RF and IA-RWA-FF, network scheduling and physical topology are tightly coupled, and resource scheduling lacks flexibility, which leads to the integration of resource allocation into more redundant resources further reducing network resource utilization. Figure 11 tests the resource utilization of the three algorithms. Under different load conditions, the resource utilization corresponding to the IA-RWA-RF and IA-RWA-FF algorithms is in the range of 19% to 41%, while the resource utilization of SO-MO-RWA is much higher and the range is 40%~64%. The results show that the proposed method has higher performance than the other two during the same load condition. Although as the load increases, more resources are required to participate in scheduling, and the resource utilization decreases, but the relative trend does not change.

This is due to the decoupling of the relationship between control and data forwarding under the SDN architecture, as well as the application of service function virtualization, which greatly improves the flexibility of network resource allocation and enables targeted resource allocation, thereby effectively improving resource allocation. At the same time, the SDN unified control logic can carry out policy planning

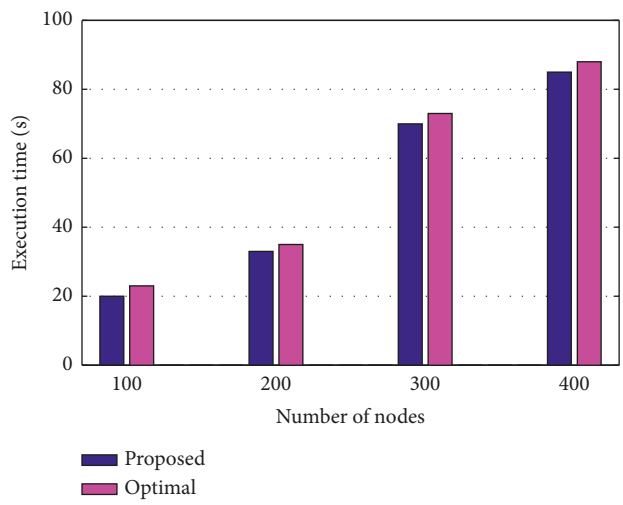

Figure 12: Comparison of execution time.

according to the global information, and formulate the corresponding resource demand plan, thereby improving the allocation and utilization of resources. The SO-MO-RWA optimizes resources and improves the effectiveness of resources and paths. Compared with the local optimization scheduling strategies of the other two methods, SO-MO-RWA has more advantages in resource utilization. In addition, SDN can support scheduling of different granularities, has better adaptability to different resource scheduling requirements, and match resources on demand according to scheduling requirements, effectively improving resource utilization.

6.4. Execution Time. compared the execution time of the proposed algorithm with optimal method. As can be seen from Figure 12, the execution time of both methods increases with an increasing number of nodes. Furthermore, the execution time of the proposed method conforms with the optimal method which validates its effectiveness Figure 12.

7. Conclusion

In this article, adaptive multiobject routing and wavelength allocation method is proposed for all-optical networks based on SDN. This method considers multiple scheduling objectives of scheduling time and link quality. The resource allocation structure defines the RWA problem as a 0–1 integer programming model. Simultaneously, the improved binary particle swarm technique is employed to solve the built model, which enables routing and wavelength allocation under SDN. The experimental results show that the proposed scheme outperforms the existing methods in performance indicators such as recovery time, blocking rate, and resource utilization. This shows that SDN-based routing and wavelength allocation have better performance than traditional methods, and also provides a new idea for further research on optical networks. In the next research work, we will consider designing an autonomous scheduling scheme for different requirements under the condition of all-optical network failure.

Data Availability

The data used for the findings of this study is available upon request from the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest.

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