

Article

Node-Selective Cross-Layer Routing for Delay-Differentiated Services in Fine-Grained Optical Transport Networks

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Abstract

Fine-grained optical transport networks (fgOTNs) have attracted increasing interest in recent years for their ability to deliver small-granularity services with high flexibility and efficiency. To further improve the performance of fgOTNs in delivering small-granularity services having diverse delay requirements, this paper proposes and investigates a node-selective cross-layer service routing (NSCR) algorithm. By selecting a path based on both wavelength occupation and the quantity of currently active services that can be aggregated in the last optical hop, and by selecting proper intermediate nodes to participate in fgOTN layer exchange and aggregation under service delay constraints, the service blocking rate is reduced and resource utilization is maximized. Further, a variation of the proposed NSCR scheme is investigated that incorporates load balancing by selecting a path based on wavelength occupation, currently active service routes, and the remaining bandwidth. The performance of the two schemes is evaluated under both the NSFNET and Cost239 topologies, and the results demonstrate the superiority and effectiveness of the proposed schemes in terms of wavelength utilization rate and service blocking rate while satisfying the diverse delay requirements of different services.

Keywords: fine-grained OTN; routing; resource scheduling; delay-sensitive service; service blocking rate; resource utilization

1. Introduction

Due to their low cost, high capacity, and high reliability advantages, optical transport networks (OTNs) are now the key platform to carry network services. In recent years, with the rapid development of intelligent society, increasing numbers and types of network services are emerging, resulting in current OTNs evolving not only toward high bandwidth and high capacity but also toward flexibility and high efficiency in delivering small-granularity and high-quality services, such as industrial control and power grid control [1,2].

Fine-grained optical transport networks (fgOTNs), as a new generation of OTN technology promoted by ITU-T standardization, are designed to cater to the needs of delivering small-granularity services with high flexibility and high efficiency [3–5]. Unlike traditional OTNs, which are based on 1.25 Gbps optical data units (ODUs) as the minimum time-slot granularity, fgOTNs reduce the minimum bandwidth granularity to 10 Mbps by

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introducing a new optical payload structure and time-slot multiplexing mechanism, supporting fine-grained, hard-isolated, and flexible bandwidth-adjustable dedicated bearers. This feature not only retains the TDM-based deterministic transmission advantages of OTNs but also realizes on-demand matching of service bandwidth, which is suitable for carrying high-density, small-granularity, and QoS-sensitive services.

To date, the service routing and scheduling strategy of fgOTNs usually follows the strategy of traditional OTNs, where the source-destination path is selected based on the shortest path policy and delay-sensitive services are prioritized by scheduling a single optical hop path, as shown in Figure 1 [6]. However, the fitness of this policy may degrade for future fgOTN environments. This is because for fgOTNs, the main clients (i.e., small-granularity services) are close to end-users, and depending on the service and different user-end time budgets for data processing, the true delay budget left to the fgOTN domain can vary from service to service. Also, with the further development of intelligent society, more and more advanced services can emerge on the fgOTN and be categorized as delay-sensitive, which means that simply adopting the traditional strategy can result in a dominant number of services requiring a single optical hop path. Consequently, without involving these delay-sensitive services in cross-layer routing (i.e., electrical exchange and aggregation in the fgOTN layer at an intermediate node, hereinafter referred to as fgOTN cross-connection), overuse of wavelength resources and underutilization of optical payload unit (OPU) resources are inevitable, thereby increasing the blocking rate of services. Therefore, developing a service routing policy that comprehensively considers service delay constraints, node fgOTN cross-connection processing delay, wavelength resource utilization, and remaining bandwidth (i.e., remaining fine-grain tributary slot (fgTS)) is beneficial for the effective and efficient operation of future fgOTNs.

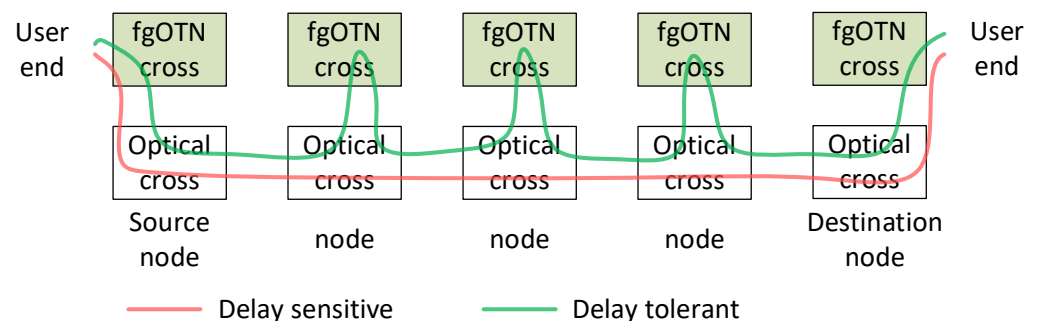


Figure 1. Common service routing and scheduling strategy of fgOTNs.

This paper proposes and investigates a node-selective cross-layer service routing algorithm (NSCR) for fgOTNs. The proposed NSCR scheme considers the service delay target of the incoming fgOTN service and integrates wavelength occupation and currently active service-based path selection from the K-shortest path (KSP), intermediate node selection for fgOTN cross-connection, and load balancing-aware wavelength allocation during service path selection and resource scheduling. By (a) selecting a proper path based on delay target, wavelength occupation, and the quantity of services that can be aggregated in the last optical hop, (b) setting appropriate intermediate nodes for participating fgOTN cross-connection and service convergence, and (c) prioritizing the usage of a low-load active wavelength during per-hop resource scheduling, the proposed NSCR scheme reduces the optical layer switching pressure and improves wavelength utilization, thereby reducing the service blocking rate and wavelength occupation rate while satisfying the delay target of each service. Moreover, an NSCR scheme variation that selects paths considering both load balancing and service aggregation potential is proposed and investigated. The main contributions of this paper are as follows:

A node-selective cross-layer service routing algorithm for fgOTNs is proposed, which includes path selection based on both wavelength occupation and the quantity of current active services that can be aggregated in the last optical hop and intermediate fgOTN cross-connection node selection. The scheme realizes collaborative scheduling of path, optical layer wavelength resources, and fine-grained layer bandwidth resources to decrease the service blocking rate and wavelength occupation rate.

For the path selection phase in the proposed scheme, another variation that selects a path based on the remaining bandwidth, wavelength occupation, and routes of currently active services is proposed and investigated, which further enhances the resource utilization of the proposed scheme.

A complete set of simulation results under the NSFNET and Cost239 topologies with three classes of service having diverse delay targets are presented. The superiority of the proposed schemes over the traditional scheme in terms of service blocking/acceptance rate and wavelength occupation rate is verified.

The rest of this paper is organized as follows. Section 2 introduces related work. Section 3 details the proposed NSCR scheme and its variation. Section 4 gives the simulation results and analysis. Section 5 summarizes the paper.

2. Related Work

In recent years, research on fgOTNs has mainly focused on system architecture, protocol design, resource scheduling, and typical scenario applications. Zhao et al. proposed a service-oriented optical network architecture based on an fgOTN and designed a resource scheduling strategy based on multi-layer collaboration to perform differentiated scheduling for services with different priorities [6]. Lian et al. addressed the resource allocation problem of geo-distributed machine learning tasks supported by fgOTNs, constructed a mixed integer linear programming model, and proposed a genetic algorithm-based resource allocation scheme, which significantly improved the task completion rate [7]. For power communication networks, Lu et al. proposed a unified transmission architecture, which used the fgOTN hard-isolated plane to guarantee deterministic low-latency transmission for critical control services while leveraging the optical service unit elastic bandwidth plane to improve bandwidth utilization for ordinary services [1]. Jiang et al. investigated fgOTN-based VR service provisioning and developed a weighted multi-factor scheduling algorithm that jointly considered bandwidth demand, path load, and bottleneck status, effectively reducing the service blocking rate [8]. To support large-model inference services, Yu et al. proposed a burst-aware dynamic path-slot protection scheme for fgOTNs, which minimized idle resource reservation during low-demand periods and ensured adequate protection during traffic surges or failure-prone conditions [9]. Jiang et al. [10] proposed a multi-user latency synchronization algorithm based on fgOTN-enabled optical cloud networks, which jointly optimized cloud node selection and a routing strategy to maximize immersive metaverse service experience. He et al. analyzed the application prospects of fgOTNs in power system communication networks and proposed SDH-to-fgOTN and OTN-to-fgOTN evolution schemes for power communication networks [11]. Rahimi et al. designed a standards-compliant platform integrating fgOTN and PON slicing, enabling end-to-end on-demand quality provisioning for latency-sensitive cloud AR/VR services [12]. Zhao et al. systematically analyzed the key technologies of fgOTNs and discussed the future evolution of fgOTNs for the power industry [13]. Liu et al. proposed a maximum bandwidth segmented shared protection scheme for fgOTNs, ensuring uninterrupted transmission of services and rapid recovery after failure [14]. Yu et al. developed an entropy-coupled incremental learning framework with hierarchical deep Q-network to optimize fgOTN resource mapping for AI computing services, significantly reducing latency and improving resource utilization [15].

Clearly, these studies have greatly benefited the development of fgOTNs. However, for fgOTNs, service routing algorithms that simultaneously consider service delay constraints, paths, and fgOTN cross-connection node selection to enhance service aggregation, service acceptance, and resource utilization are still lacking investigation, which finally motivated us to propose and investigate the NSCR scheme for fgOTNs.

Notably, although recent studies show a trend of incorporating machine learning in network management and optimization, we still chose to investigate heuristic-based algorithms in this paper because such algorithms can provide fully traceable and stable decisions even under unexpected network scenarios. Moreover, heuristic-based algorithms can be efficient sample generators for facilitating the development of machine learning-based algorithms. Therefore, the value of heuristic-based algorithms remains significant.

3. Node-Selective Cross-Layer Service Routing Algorithm

The proposed NSCR scheme operates as follows. Here, we consider a network manager (NM) that keeps the information (including source node, destination node, intermediate node arrangement, bandwidth (i.e., fgTS) occupation, and path delay) of the currently active service of the network and controls the routing and scheduling of incoming fgOTN services. The notations used are organized in Table 1.

Table 1. Notation explanations.

Notation	Description
S	The service awaiting scheduling
SRC	Source node of service S
DST	Destination node of service S
BW	Bandwidth requirement of service S
DT	Delay target of service S
k	The number of paths generated by KSP
i	Candidate path index
D_i	The single optical hop delay of path i
P	Node processing delay for performing fgOTN cross-connection
j, m, l	Node index
NS_m	Node score of node m
AJW	Average adjacent node wavelength occupation rate for the segment from SRC to the last optical hop start node on the candidate path i
n, u	The number of intermediate nodes to find based on the wavelength availability and service convergence score
EW_l	Wavelength availability rate for the connection from node l to the next node on the path
SC_l	Quantity of current active services whose first optical hop starts at SRC and ends at node l and the remaining bandwidth on the wavelength of the hop can afford service S
MSC	The maximum SC_l value for the nodes on the SRC to the last optical hop start node segment
r	Total node number on the SRC to the last optical hop start node segment on the selected path
e	Total node number on the selected path
MPC	The maximum SC_l value for the nodes on the selected path
PL	The length of the selected path
v	The speed of light
g	The total number of intermediate nodes for the selected path

MJW	The average adjacent node wavelength occupation rate for the segment from SRC to node j on path i
BAR	The bandwidth availability rate on the wavelength of the last optical hop of service R

When a fgOTN service S arrives, the NM first obtains the basic information of the service, which includes source node SRC , destination node DST , bandwidth requirement BW , and delay target DT . Then, the NM starts the path calculation and corresponding intermediate node selection for service S and decides whether to accept the service through three steps, as follows.

Step 1: Attempt to adopt path and intermediate node arrangement from currently active service. The NSCR scheme first tries to derive a path and the corresponding intermediate node arrangement for service S from currently active services. In this step, the NM searches all services that are currently active, and from the active services that satisfy the criteria (a) the service has the same source and destination nodes as service S , (b) on each optical hop of the service, the remaining bandwidth (i.e., remaining fgTS) on the wavelength carrying the service can afford service S , and (c) the path delay of the service satisfies the delay target of service S , the NM finds the service that has the maximum value in terms of the minimal remaining bandwidth (i.e., the minimal remaining fgTS among the remaining fgTS of each optical hop of the service) on the wavelengths carrying the service, and sets the path as well as the intermediate node arrangement of this service as the selected path and intermediate node arrangement for service S .

Step 2: Attempt to create path and intermediate node arrangement based on currently active service. If the NM cannot find any active services satisfying the requirements in step 1, the NM creates a path and intermediate node arrangement for service S as follows.

Step 2.1: Path selection. The NM first generates k candidate paths based on the conventional KSP algorithm. Next, for each candidate path, the NM calculates the score of each path through the following process.

For a candidate path (e.g., path i), if the single optical hop delay D_i (i.e., end-to-end optical propagation delay without participating fgOTN cross-connection) of the candidate path i cannot satisfy the delay target of service S (i.e., $D_i > DT$), the score of path i is set to -1 . Otherwise, the NM initializes the score of path i as 0. Then, if path i can also satisfy $D_i + P < DT$, where P is the node processing delay for performing fgOTN cross-connection on a node, the NM further initializes the score of each node on path i as 0 and then searches all currently active services having DST as the destination node. Once the NM finds a currently active service R destined to DST that satisfies the criteria (a) the start node of the last optical hop of the path of service R is also a node (e.g., node j) on path i , and (b) the remaining bandwidth (i.e., remaining fgTS) on the wavelength of the last optical hop of service R can afford service S , the NM increases the score of node j by 1. After searching all of these currently active services, if there is a node on path i having a node score higher than 0, the NM finds the node having the highest score (e.g., node m , and its node score is NS_m), notes the node as the last optical hop start node (LOHN) for path i , and calculates the average adjacent node wavelength occupation rate AJW for the segment from SRC to the LOHN on path i . Then, the score of path i is updated using formula (1):

$$\text{Score of path } i = NS_m \times (1 - AJW), \quad (1)$$

Clearly, the formula simultaneously reflects the service aggregation potential on the last optical hop (i.e., by NS_m) and the probability of successfully finding resources to accommodate service S on path i (i.e., by $(1 - AJW)$), and is therefore designed for path score evaluation.

Step 2.2: Intermediate node selection. Then, if service S is not rejected, the NM determines the corresponding intermediate nodes on the selected path.

If the selected path has a score larger than 0, the corresponding LOHN (i.e., the node having the highest node score on the path) is first selected as an intermediate node. Then, the NM further selects n intermediate nodes for the SRC to the LOHN segment, where n is calculated using formula (2):

$$n = \min((DT - D_i) / P - 1, r - 2), \quad (2)$$

where r is the total node number on the SRC to the LOHN segment. To select these n nodes, the NM calculates the wavelength availability and service convergence score (WS score) for each node (e.g., node l) on the segment (except SRC and the LOHN) using formula (3):

$$\text{WS score for node } l = EW_l + SC_l / \max(MSC, 1), \quad (3)$$

where EW_l is the wavelength availability rate (calculated by inactive wavelength number dividing total wavelength number) for the connection from node l to the next node on the path; SC_l is the quantity of current active services whose first optical hop starts at SRC and ends at node l and the remaining bandwidth (i.e., remaining fgTS) on the wavelength of the hop can afford service S ; and MSC is the maximum SC_l value for the nodes on the segment. Then, the n nodes with the highest scores are selected.

If the selected path has a score of 0, the NM selects u intermediate nodes for the selected path, where u is calculated using formula (4):

$$u = \min((DT - D_i) / P, e - 2), \quad (4)$$

where e is the total node number on the selected path. To select these u nodes, the NM calculates the WS score for each node (e.g., node l) on the selected path (except SRC and DST) using formula (5):

$$\text{WS score for node } l = EW_l + SC_l / \max(MPC, 1), \quad (5)$$

where MPC is the maximum SC_l value for the nodes on the path. Then, the u nodes with the highest scores are selected.

Step 3: Assign wavelength and bandwidth for service S . After selecting path and intermediate nodes for service S , the corresponding optical hops can be obtained, and the NM schedules wavelength and bandwidth (i.e., fgTS) resources for the service on each optical hop. For each optical hop of the selected path, the NM finds the wavelength that is currently active, can accept service S , and has the largest remaining bandwidth to accommodate service S on the hop. If none of the active wavelengths can accept service S , a new wavelength is activated to accommodate the service. If no new wavelength is available, service S is rejected. For each hop, after successfully finding a wavelength, the NM adopts the first fit policy to assign bandwidth (i.e., fgTS) on the wavelength for service S .

After these three steps, the path, the intermediate nodes for participating cross-layer exchange, the wavelength, and fgTS resource assignment of each optical hop are decided for service S , and then the service can be accepted. Also, the NM calculates the path delay of the service using formula (6):

$$\text{Path delay} = PL / v + g \times P, \quad (6)$$

where PL is the length of the selected path, v is the speed of light, and g is the total number of intermediate nodes selected (which equals $n + 1$ if the path has a score larger than 0, or equals u if the path has a score of 0). The path delay, the path, and the intermediate node selection information of the service are saved until the service is terminated.

To further enhance load balancing during the path selection phase of the NSCR scheme, a variation of the NSCR scheme, called NSCR-load balancing (NSCR-LB), is proposed. The basic operation process of the NSCR-LB scheme is similar to that of the NSCR scheme, and the main difference is that in the NSCR-LB scheme, the path selection phase (i.e., step 2.1 in the NSCR scheme) is modified as follows.

Step 3.1 for the NSCR-LB scheme: The NM first generates k candidate paths based on the conventional KSP algorithm. Next, for each candidate path, the controller calculates the score of each path through the following process.

For a candidate path (e.g., path i), if the single optical hop delay D_i of the candidate path i cannot satisfy the delay target of service S (i.e., $D_i > DT$), the score of path i is set to -1 . Otherwise, the NM initializes the score of path i as 0. Then, if path i can also satisfy $D_i + P < DT$, the NM further searches all currently active services having DST as the destination node. Once the NM finds a currently active service R destined to DST that satisfies the criteria (a) the start node of the last optical hop of the path of service R is also a node (e.g., node j) on path i and the last optical hop path overlaps with the node j to DST segment of path i , and (b) the remaining bandwidth (i.e., remaining fgTS) on the wavelength of the last optical hop of service R can afford service S , the NM calculates a score using formula (7):

$$\text{Score} = (1 - MJW) + BAR, \quad (7)$$

where MJW is the average adjacent node wavelength occupation rate for the segment from SRC to node j on path i , and BAR is the bandwidth (i.e., fgTS) availability rate on the wavelength of the last optical hop of service R . Clearly, the logic behind this scoring formula is that it can comprehensively represent both the probability of successfully finding resources to accommodate service S on path i and the preference for greater available bandwidth on the wavelength of the last optical hop. Then, if the calculated score is higher than the current score of path i , the score of path i is updated to the calculated score, and node j is recorded as the LOHN for the path. After searching all of these currently active services, the score of path i can be obtained, and a LOHN for the path can be also obtained if the score is larger than 0.

After calculating the score of each candidate path, if there is a path having a score larger than 0, the path having the highest score is selected for service S . If none of the paths have a score larger than 0 but there are one or more paths having a score of 0, the shortest path having a score of 0 is selected for service S . If none of the paths have a score larger than or equal to 0, service S is rejected.

It is worth mentioning here that the NSCR-LB scheme is not proposed as a superior alternative to the NSCR scheme but rather as a parallel design to simultaneously show whether a load balancing-oriented path scoring design can affect performance. As will be shown in the simulation results, the two schemes exhibit comparable service blocking performance, while the NSCR-LB scheme shows certain advantages in wavelength occupation rate under specific conditions.

For a better understanding of the operations of the NSCR and NSCR-LB schemes, the pseudo-code listings describing the detailed operation processes of the NSCR and NSCR-LB schemes are organized in Appendix A.

4. Simulation Results and Discussions

In this section, the performances of the proposed NSCR and NSCR-LB schemes are evaluated using MATLAB 2022b. We consider both the 14-node NSFNET network topology and the 11-node Cost239 network topology, and the network node connections and distances (i.e., link fiber lengths, in kilometers) are shown in Figure 2. Note that in Figure 2, the number beside each link refers to the length of that link. Considering that fgOTNs

are usually adopted for providing provincial area services, we scale the node distances by 1/10 compared to the conventional values. Node connections are all bidirectional, and in each direction of a connection, the capacity is 8 wavelengths, with each wavelength supporting a bandwidth of 10 Gbps (i.e., ODU2). The node fgOTN cross-connection processing delay is set to 100 μ s. We adopt Yen's algorithm for generating k shortest paths [16], and k is set to 3. We consider three types of fgOTN services, with type 1 services having the most stringent delay constraint, type 2 services having a slightly less stringent delay constraint, and type 3 services having no delay constraint. The proportion of the three types of services in the network is 1:1:1. The number of services generated in a second follows a Poisson distribution. For each service, its source and destination nodes are randomly selected, and the bandwidth requirement is randomly generated in the range of 10 Mbps to 300 Mbps (i.e., from 1 to 30 fgTSs). Service duration follows a negative exponential distribution, with an average value of 200 s. In Table 2, we organize the basic simulation parameters. Data collected in the first 400 s is ignored as we consider this period to be the system warmup period.

Table 2. Simulation parameters.

Parameter	Value/Description
Network topology	NSFNET (14 nodes, 21 bidirectional connections); Cost239 (11 nodes, 26 bidirectional connections)
Propagation delay	5 μ s/km
Capacity per connection per direction	8 wavelengths, 10 Gbps per wavelength
Node processing delay for performing fgOTN cross-connection	100 μ s
Services	Type 1 (delay sensitive) Type 2 (delay sensitive) Type 3 (delay tolerant)
Service bandwidth requirement	10–300 Mbps, uniform distribution
Service duration	200 s, negative exponential distribution
Type 1 service delay constraint	2 ms (NSFNET), 1 ms (Cost239)
Type 2 service delay constraint	2.5 ms (NSFNET), 1.2 ms (Cost239)
Simulation time	800 s
K-shortest path	Yen's algorithm, with $k = 3$

Based on ref. [6], a conventional scheme is derived for comparison, which schedules an incoming service S as follows: (a) first, the NM finds currently active services that have the same source and destination nodes and the same service type as the service S and the remaining bandwidth on the wavelengths carrying the services can afford service S ; (b) if the finding result is not empty, from the services found, the NM adopts the path of the service that has the maximum value in terms of the minimal remaining bandwidth on the wavelengths carrying the service for service S ; (c) if the finding result is empty, the NM generates k candidate paths using the conventional KSP algorithm and adopts the path that has the lowest average adjacent node wavelength occupation rate for service S ; (d) after path decision, the NM adopts the single optical hop scheduling policy for delay-sensitive services (i.e., type 1 and type 2 services) and adopts the one optical hop per neighboring node connection scheduling policy for delay-tolerant service (i.e., type 3 ser-

vices); (e) finally, the allocation of wavelength and bandwidth (i.e., fgTS) follows the same policy as that in the NSCR scheme.

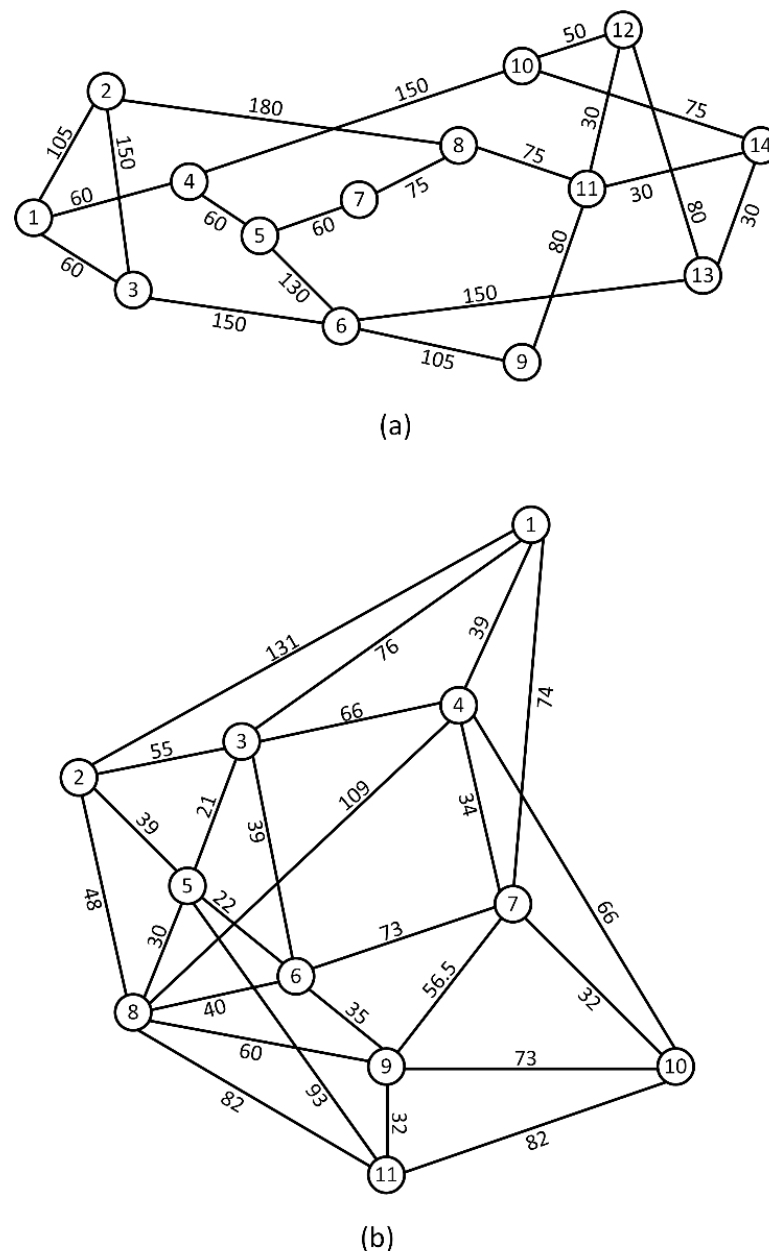


Figure 2. Network topology: (a) NSFNET topology; (b) Cost239 topology (Link lengths are marked beside each link).

4.1. Performance Under the NSFNET Topology

For simulations under the NSFNET topology, considering the maximum path length, we set the delay constraints for type 1 and type 2 services to 2 ms and 2.5 ms, respectively.

Figure 3 presents the network average wavelength occupation rate performance of the conventional scheme, the NSCR scheme, and the NSCR-LB scheme when the network load grows from 20 service arrivals per second to 80 service arrivals per second (i.e., from 4000 erlang to 16,000 erlang). As shown in the figure, the wavelength occupation rates of all three schemes grow as the network load increases. It can be seen that both the NSCR and NSCR-LB schemes show lower wavelength occupation rates than the conventional scheme, especially under low-load conditions. This is because the two proposed schemes

properly select paths and adopt intermediate nodes to enhance path overlapping and service aggregation on the overlapped segment, thereby efficiently utilizing wavelength resources and reducing wavelength usage. Moreover, as the NSCR-LB scheme further incorporates load balancing in path selection, it alleviates the use of heavily loaded wavelengths and paths, and therefore presents a lower wavelength occupation rate than the NSCR scheme under low-load conditions.

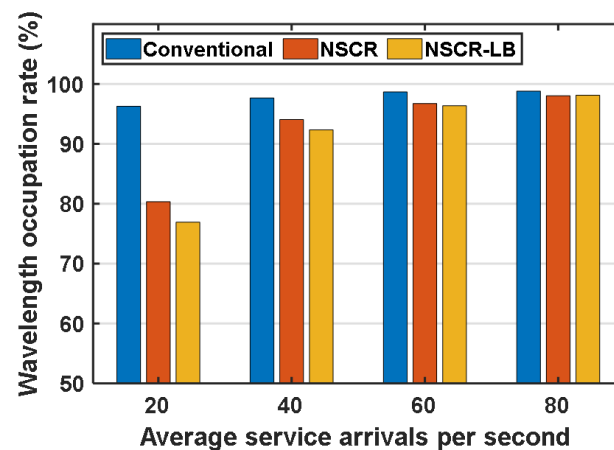


Figure 3. Network wavelength occupation rates under the NSFNET topology.

Figure 4 presents the service blocking rate performance of the three schemes as the network load grows from 20 service arrivals per second to 80 service arrivals per second. As shown in Figure 4a,b, for both type 1 and type 2 services, the conventional scheme shows a much higher service blocking rate than the NSCR and NSCR-LB schemes. This is because the conventional scheme follows the single optical hop scheduling policy for type 1 and type 2 services, and therefore under the NSFNET topology with limited node connectivity and wavelength resources, available wavelengths are used up easily, resulting in a low probability of finding an available wavelength for scheduling a single optical hop path from source to destination for an incoming service. By contrast, as the NSCR and NSCR-LB schemes properly select paths and employ intermediate nodes for fgOTN layer exchange and aggregation, the two schemes ensure a high probability of finding an available wavelength for each optical hop on the selected path, and therefore significantly outperform the conventional scheme in terms of type 1 and type 2 service blocking rates, especially under low-load conditions. For the type 3 service blocking rate, Figure 4c shows that as the conventional scheme allows a type 3 service to perform fgOTN layer exchange and aggregation on all nodes on the path, the type 3 service blocking rate of the conventional scheme is much lower than the type 1 and type 2 service blocking rates under low-load conditions. However, as the conventional scheme inevitably results in a low wavelength utilization efficiency due to the single optical hop routing policy for type 1 and type 2 services, the wavelength availability for type 3 services is affected. Therefore, the type 3 service blocking rate of the conventional scheme is still higher than those of the NSCR and NSCR-LB schemes under low-load conditions and also higher than the type 1 and type 2 service blocking rates under high-load conditions. In Figure 4d, we present the average service blocking rates of all services. Clearly, the NSCR and NSCR-LB schemes reduce the average service blocking rate by around 10% to around 30% across the considered load conditions compared to the conventional scheme, proving the significant value of the two proposed schemes.

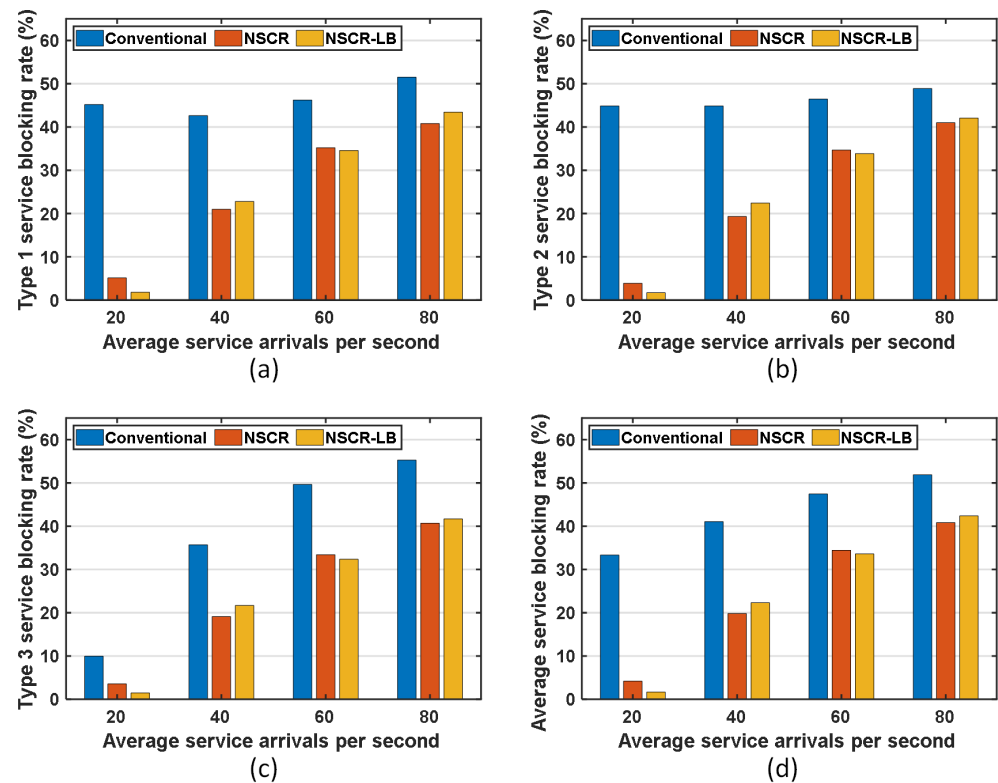


Figure 4. Service blocking rates under the NSFNET topology: (a) type 1 services; (b) type 2 services; (c) type 3 services; (d) average of all services.

Note that the results shown in Figures 3 and 4 only present performance under saturated network conditions. To further evaluate the performance of the proposed schemes under unsaturated network conditions, we reduce the average service duration to 50 s, and present the performance under a service arrival rate of 20 average service arrivals per second (i.e., 1000 erlang) in Figure 5. Considering that under low-load conditions the service blocking rate can be close to 0, here we present the service acceptance rate as a substitution. As shown in Figure 5a, comparing to the conventional scheme, both the NSCR and NSCR-LB schemes show an over 30% reduction in terms of network average wavelength occupation rate, and the NSCR-LB scheme further outperforms the NSCR scheme by 6% due to its load balancing based path selection policy. In terms of service acceptance rate, Figure 5b shows that the conventional scheme only accepts less than 60% of type 1 and type 2 services, whereas the NSCR scheme accepts over 99% of type 1 and type 2 services. Notably, the NSCR-LB scheme accepts 100% of type 1 and type 2 services. For type 3 services, all three schemes show a 100% service acceptance rate. Overall, as the conventional scheme inevitably overuses wavelength resource due to its single optical hop scheduling policy for type 1 and type 2 services, its average service acceptance rate only reaches 70.8%. By contrast, by properly selecting paths and employing intermediate nodes for performing fgOTN layer exchange and aggregation, the NSCR and NSCR-LB schemes show average service acceptance rates of 99.7% and 100%, respectively, highlighting the superiority of the proposed schemes under unsaturated load conditions.

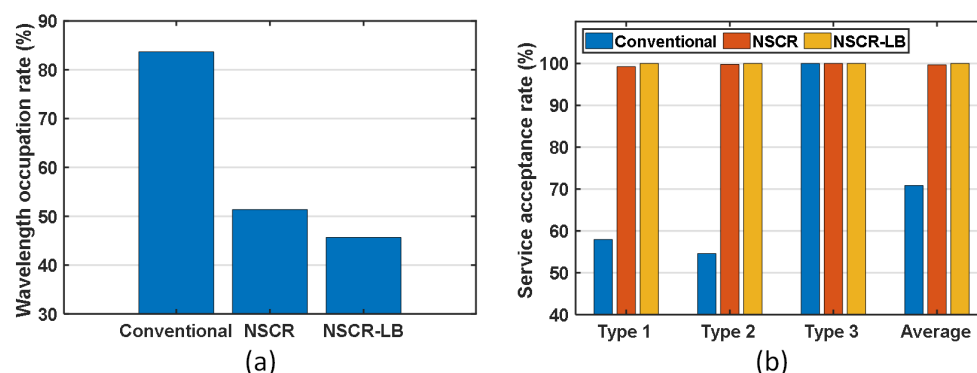


Figure 5. Performance under 20 service arrivals per second with 50 s average service duration (under the NSFNET topology): (a) network wavelength occupation rate; (b) service acceptance rate.

In Table 3, we present the maximum delay of each type of service under the NSFNET topology with the considered load conditions. It is obvious that although the NSCR and NSCR-LB schemes show higher delays for type 1 and type 2 services than the conventional scheme due to intermediate nodes for fgOTN layer exchange and aggregation, the maximum delay value still satisfies the delay constraint. Therefore, the proposed NSCR and NSCR-LB schemes can be considered proper solutions for scheduling future fgOTN services with diverse delay constraints.

Table 3. Maximum delays of accepted services (NSFNET).

Scheme (Average Service Arrivals Per Second, Average Service Duration)	Type 1 (μ s)	Type 2 (μ s)	Type 3 (μ s)
Conventional (20, 200)	2000	2400	2925
Conventional (40, 200)	2000	2325	2925
Conventional (60, 200)	2000	2025	2925
Conventional (80, 200)	1900	2025	2925
Conventional (20, 50)	2000	2100	2975
NSCR (20, 200)	2000	2500	2975
NSCR (40, 200)	2000	2500	2925
NSCR (60, 200)	2000	2500	2925
NSCR (80, 200)	2000	2500	2825
NSCR (20, 50)	2000	2500	2825
NSCR-LB (20, 200)	2000	2500	2975
NSCR-LB (40, 200)	2000	2500	2975
NSCR-LB (60, 200)	2000	2500	2925
NSCR-LB (80, 200)	2000	2500	2925
NSCR-LB (20, 50)	2000	2500	2825

4.2. Performance Under the Cost239 Topology

For simulations under the Cost239 topology, considering the maximum path length, we set the delay constraints for type 1 and type 2 services to 1 ms and 1.2 ms, respectively.

Similarly, here we first consider saturated load conditions and set the network load to vary from 40 service arrivals per second to 100 service arrivals per second (i.e., from 8000 erlang to 20,000 erlang). Note that the load range is higher than that for the NSFNET topology, as the Cost239 topology has a much higher connectivity than the NSFNET topology. Figure 6 presents the network average wavelength occupation rate performance of the three schemes. As shown in Figure 6, both the NSCR and NSCR-LB schemes reduce wavelength usage in the network with respect to the conventional scheme, and under the

40 service arrivals per second scenario, up to 16.6% and 16.3% of wavelength resources are saved by the NSCR and NSCR-LB schemes, respectively. Note that compared to the result under the NSFNET topology (i.e., Figure 3), the low wavelength occupation rate advantage of the NSCR-LB scheme over the NSCR scheme under low-load conditions disappears under the Cost239 topology because increased node connectivity under the Cost239 topology inherently results in higher path diversity and fewer bottleneck links, thereby minimizing the benefit of considering load balancing during path selection.

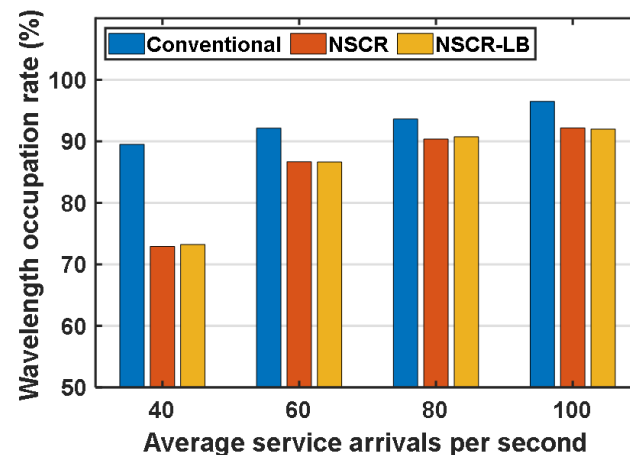


Figure 6. Network wavelength occupation rates under the Cost239 topology.

Figure 7 presents the corresponding service blocking rate performance of the three schemes. As shown in Figure 7a,b, for type 1 and type 2 services, the NSCR and NSCR-LB schemes still show lower service blocking rates than the conventional scheme. However, due to the enhanced node connectivity, the advantage is not as significant as that under the NSFNET topology and is negligible when the network load increases to 100 service arrivals per second. For the type 3 service blocking rate, the conventional scheme still underperforms the NSCR and NSCR-LB schemes by more than 8.5% due to wavelength occupation by the type 1 and type 2 services. Clearly, this result proves the superiority of the NSCR and NSCR-LB schemes by properly selecting paths and selectively employing intermediate nodes for enhancing fgOTN layer exchange and aggregation while considering the delay target of each service. In terms of average service blocking rate, compared to the conventional scheme, the NSCR and NSCR-LB schemes achieve up to 7.3% and 8.8% reductions (60 service arrivals per second), respectively.

The performance of the three schemes under the Cost239 topology with unsaturated load conditions is presented in Figure 8. Here, we adopt a network load of 40 service arrivals per second, with an average service duration of 50 s (i.e., 2000 erlang). As shown in Figure 8a, in terms of network average wavelength occupation rate, the NSCR and NSCR-LB schemes save 45.4% and 46.6% of wavelengths compared to the conventional scheme, respectively, showing the significant wavelength utilization efficiency of the proposed schemes under low-load conditions. In terms of service acceptance rate, Figure 8b shows that the NSCR and NSCR-LB schemes achieve a 100% service acceptance rate for all three types of services, whereas the conventional scheme only accepts 92.1% of type 1 services and 92.6% of type 2 services.

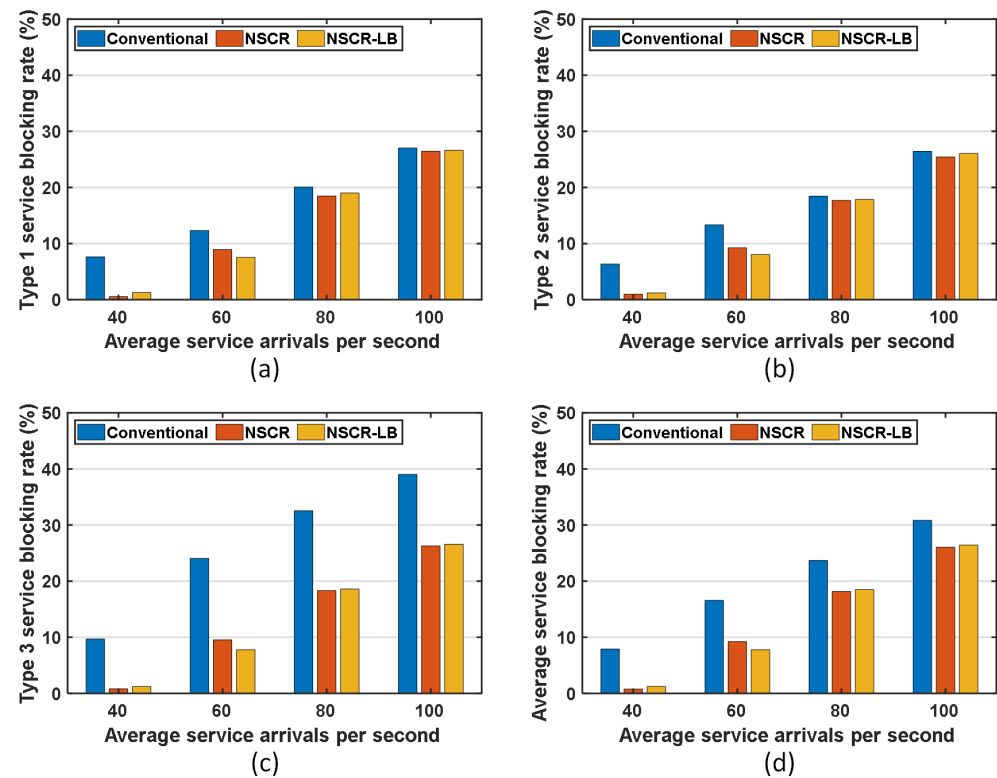


Figure 7. Service blocking rate under the Cost239 topology: (a) type 1 services; (b) type 2 services; (c) type 3 services; (d) average of all services.

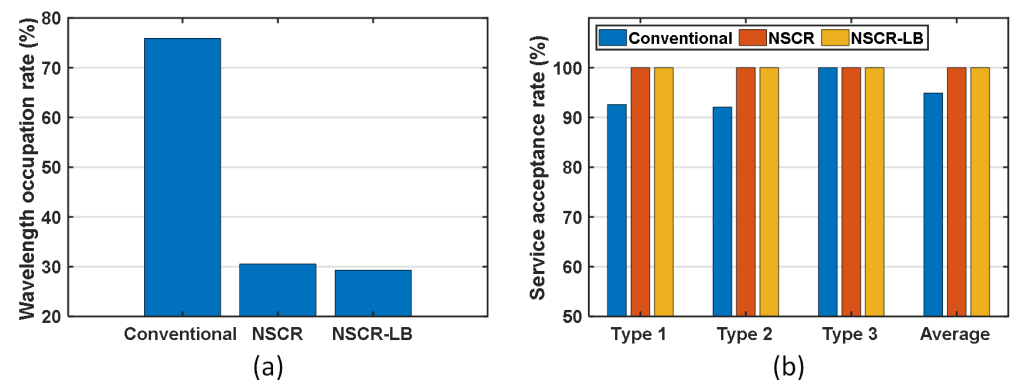


Figure 8. Performance under the 40 service arrivals per second with 50 s average service duration (under the Cost239 topology): (a) network wavelength occupation rate; (b) service acceptance rate.

In Table 4, we present the maximum delay of each type of service under the Cost239 topology with the considered load conditions. It is easy to understand that for the NSCR and NSCR-LB schemes, the maximum delay of type 1 services and the maximum delay of type 2 services are higher than those of the conventional scheme due to the employment of intermediate nodes for fgOTN layer exchange and aggregation. Nevertheless, the delays are still within the acceptable range, and the type 1 and type 2 services are served well.

Overall, these results prove that the NSCR and NSCR-LB schemes improve the service acceptance rate while simultaneously reducing the use of wavelength resources, making them suitable for fgOTN services with diverse delay requirements.

Table 4. Maximum delay of accepted services (Cost239).

Scheme (Average Service Arrivals Per Second, Average Service Duration)	Type 1 (μs)	Type 2 (μs)	Type 3 (μs)
Conventional (40, 200)	905	870	1210
Conventional (60, 200)	905	830	1145
Conventional (80, 200)	910	905	1210
Conventional (100, 200)	910	910	1210
Conventional (40, 50)	910	910	1210
NSCR (40, 200)	975	1130	1210
NSCR (60, 200)	975	1145	1210
NSCR (80, 200)	975	1145	1210
NSCR (100, 200)	975	1145	1210
NSCR (40, 50)	975	1145	1210
NSCR-LB (40, 200)	975	1130	1210
NSCR-LB (60, 200)	975	1145	1210
NSCR-LB (80, 200)	975	1145	1210
NSCR-LB (100, 200)	975	1145	1210
NSCR-LB (40, 50)	975	1145	1210

5. Conclusions

In this paper, we propose and investigate the NSCR and NSCR-LB schemes for fgOTNs to facilitate the accommodation of diverse delay requirement services with low service blocking rates and high resource efficiency. The two proposed schemes select paths based on the routes of currently active services and select proper intermediate nodes to participate in fgOTN layer exchange and aggregation under the constraint of service delay target, thereby reducing the service blocking rate and improving network resource utilization. Specifically, the NSCR scheme selects a path based on the quantity of currently active services that can be aggregated in the last optical hop and wavelength occupation, whereas the NSCR-LB scheme selects a path based on the currently active service that can be aggregated in the last optical hop, the remaining bandwidth, and wavelength occupation. The two proposed schemes are evaluated under both the NSFNET and Cost239 topologies, and the results prove that while satisfying the diverse delay requirements of different services, the proposed schemes achieve substantial wavelength occupation and service blocking rate reductions.

In future, we will incorporate artificial intelligence in selecting paths and intermediate nodes and design a service routing algorithm with further consideration of node exchange capability and service protection.

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Appendix A

The pseudo-code of the NSCR scheme is presented in Algorithm A1, and that of the NSCR-LB scheme is presented in Algorithm A2.

Algorithm A1 Process of scheduling fgOTN service S using the NSCR scheme

```

1.  Obtains  $SRC$ ,  $DST$ ,  $BW$ , and  $DT$  of service  $S$ 
    Searches all currently active services, and finds services that (a) have the same source and destination nodes as service  $S$ , (b)
2.  on each optical hop of the service, the remaining bandwidth on the wavelength carrying the service can afford service  $S$ , and (c)
    the path delay of the service satisfies  $DT$ 
3.  If the finding result is not empty
4.      From the services found, further finds the service that has the maximum value in terms of the minimal remaining bandwidth
        on the wavelengths carrying the service, and sets the path and the intermediate node arrangement of this service for service  $S$ 
5.  Else
6.      Generates  $k$  candidate paths using the KSP algorithm
7.      For each candidate path  $i$ , do
8.          If  $D_i > DT$ 
9.              The path is scored with  $-1$ 
10.         Else
11.             Initializes the score of the path with 0
12.             If the path can also satisfy  $D_i + P < DT$ 
13.                 Initializes the score of each node on path  $i$  with 0
14.                 For each currently active service having  $DST$  as the destination node, do
15.                     If the start node of the last optical hop of the service is a node on path  $i$  and the remaining bandwidth on the
                        wavelength of the last optical hop of the service can afford service  $S$ 
16.                         Increases the score of the node by 1
17.                 End
18.             End
19.             Finds the highest score node on path  $i$  and notes the node as the LOHN for the path, and calculates  $AJW$  for the
                segment from  $SRC$  to the LOHN on the path
20.             Updates the score of path  $i$  using (1)
21.         End
22.     End
23. End
24. If none of the paths have a score larger than or equal to 0
25.     Rejects service  $S$  and ends the process
26. Else
27.     If there is a path having a score larger than 0
28.         Selects the path having the highest score for service  $S$ 
29.     Else
30.         Selects the shortest path having a score of 0 for service  $S$ 
31.     End
32. If the selected path has a score larger than 0
33.     Selects the LOHN of the path as an intermediate node, and then from the  $SRC$  to the LOHN segment, further selects  $n$ 
        nodes as intermediate nodes by calculating node WS score using (3) and choosing the nodes having the highest scores
34. Else
35.     From the selected path, selects  $u$  nodes as intermediate nodes by calculating node WS score using (5) and choosing
        the nodes having the highest scores
36. End
37. End
38. End
39. For each optical hop of the selected path, do

```

40. Find a wavelength that is currently active, can accept service S , and has the largest remaining bandwidth for service S
 41. **If** no active wavelength can accept service S but an inactive wavelength is available for accepting service S
 42. Activate a new wavelength to accommodate service S on the optical hop
 43. **Else**
 44. Rejects service S and ends the process
 45. **End**
 46. Assign bandwidth on the selected wavelength for service S on the optical hop
 47. **End**
 48. Accepts service S and saves the relative information in the NM
-

Algorithm A2 Process of scheduling fgOTN service S using the NSCR-LB scheme

1. Obtains SRC , DST , BW , and DT of service S
 2. Searches all currently active services, and finds services that (a) have the same source and destination nodes as service S , (b) on each optical hop of the service, the remaining bandwidth on the wavelength carrying the service can afford service S , and (c) the path delay of the service satisfies DT
 3. **If** the finding result is not empty
 4. From the services found, further finds the service that has the maximum value in terms of the minimal remaining bandwidth on the wavelengths carrying the service, and sets the path and the intermediate node arrangement of this service for service S
 5. **Else**
 6. Generates k candidate paths using the KSP algorithm
 7. **For** each candidate path i , **do**
 8. **If** $D_i > DT$
 9. The path is scored with -1
 10. **Else**
 11. Initializes the score of the path with 0
 12. **If** the path can also satisfy $D_i + P < DT$
 13. **For** each currently active service having DST as the destination node, **do**
 14. **If** the start node of the last optical hop of the service is also a node (e.g., node j) on path i , and the remaining bandwidth on the wavelength of the last optical hop of the service can afford service S
 15. Calculates a score using (7)
 16. **If** the calculated score is higher than the current score of path i ,
 17. Updates the score of path i by the calculated score, and records node j as the LOHN for the path
 18. **End**
 19. **End**
 20. **End**
 21. **End**
 22. **End**
 23. **End**
 24. **If** none of the paths have a score larger than or equal to 0
 25. Rejects service S and ends the process
 26. **Else**
 27. **If** there is a path having a score larger than 0
 28. Selects the path having the highest score for service S
 29. **Else**
 30. Selects the shortest path having a score of 0 for service S
 31. **End**
 32. **If** the selected path has a score larger than 0
 33. Selects the LOHN of the path as an intermediate node, and then from the SRC to the LOHN segment, further selects n nodes as intermediate nodes by calculating node WS score using (3) and choosing the nodes having the highest scores
 34. **Else**
 35. From the selected path, selects u nodes as intermediate nodes by calculating node WS score using (5) and choosing the nodes having the highest scores
 36. **End**
 37. **End**
 38. **End**
 39. Same as step 39~47 in Algorithm A1
 40. Accepts service S and saves the relative information in the NM
-

References

1. Lu, S.; Li, Z.; Xie, T.; Xu, Q.; Gao, Q.; Jiang, C.; Jia, H. A Study on a Unified Transmission Method for Multiple Services in Power Grids Based on SDN-Controlled OSU/fgOTN Hybrid Bearer Networks. In Proceedings of the 2025 IEEE 7th Advanced Information Management, Communicates, Electronic and Automation Control Conference (IMCEC), Chongqing, China, 5–7 December 2025.
2. Zhao, Y.; Lin, Y.; Li, Y.; Wang, D.; Liu, Y.; Liu, X.; Li, H.; Zhang, D. Intelligent Service-Oriented Optical Network based on Fine-Grain OTN and Edge-Cloud Coordination. In Proceedings of the 2023 IEEE Future Networks World Forum (FNWF), Baltimore, MD, USA, 13–15 November 2023.
3. Overview of Fine Grain OTN, ITU-T Recommendation G.709.20, 2024. Available online: <https://www.itu.int/rec/T-REC-G.709.20/en> (accessed on 1 April 2024).
4. Pan, B.; Liu, Z.; Bi, Y.; Yan, F. Flexible and Efficient Network Slicing for Integrated Optical Metro Networks With Diverse Access Applications. *IEEE J. Light. Technol.* **2024**, *42*, 7032–7043.
5. Interfaces for the Optical Transport Network Amendment 3, ITU-T Recommendation G.709/Y.1331 (2020) Amd.3, 2024. Available online: <https://www.itu.int/rec/T-REC-Y.1331/en> (accessed on 1 June 2020).
6. Zhao, Y.; Lin, Y.; Li, Y.; Zhang, D.; Liu, Y.; Zheng, Y.; Wang, D.; Liu, S.; Cao, S.; Feng, H.; et al. Multi-layer resource scheduling architecture and algorithm for a service-oriented optical network based on a fine grain OTN. *IEEE J. Opt. Commun. Netw.* **2024**, *16*, F13–F25.
7. Lian, M.; Zhao, Y.; Li, X.; Liu, W.; Li, Y.; Tornatore, M.; Zhang, J. Resource Allocation in Flexible-Bandwidth Fine-Grained Optical Transport Networks for Geo-Distributed Machine Learning. *IEEE Internet Things J.* **2025**, *12*, 25601–25619.
8. Jiang, Y.; Li, X.; Zhao, Y.; Zhang, J. Latency and Bandwidth Co-Optimization for Service-Oriented Scheduling in fgOTN-Based VR. In Proceedings of the 2025 13th International Conference on Information and Communication Networks (ICICN), Beijing, China, 8–11 August 2025.
9. Yu, T.; Yang, H.; Yao, Q.; Zhao, Y.; Zhang, J.; Cheriet, M. Multi-dimensional Feature-Self-Organizing Mapping-based Dynamic Path-Slot Joint Protection for Fine-Grain OTN. In Proceedings of the 2025 23rd International Conference on Optical Communications and Networks (ICOON), Zhangjiajie, China, 28–31 July 2025.
10. Jiang, Y.; Li, X.; Zhao, Y.; Lian, M.; Zhang, J. Multi-user latency synchronization algorithm for an immersive metaverse experience in optical cloud networks. *IEEE J. Opt. Commun. Netw.* **2025**, *17*, 936–949.
11. He, L.; Cao, L.; Ye, X.; Jing, H.; Zhu, Y.; Jin, L.; Wang, H.; Huo, Y.; Huang, C. Analysis of fgOTN technology in the application prospect of power system services. In Proceedings of the 2025 5th International Conference on Intelligent Power and Systems (ICIPS), Xi'an, China, 24–26 October 2025.
12. Rahimi, H.; Gifre, L.; Vilalta, R.; Muñoz, R.; Yu, H.; Wang, Y.; Cai, R.; Janz, C. Enabling Quality-on-Demand and Service Differentiation on a Novel Network-as-a-Service Platform Using Slicing Technology for Control and Management of Optical Networks. In Proceedings of the 2024 20th International Conference on Network and Service Management (CNSM), Prague, Czech Republic, 28–31 October 2024.
13. Zhao, J.; Tang, R.; Guang, Z.; Tang, J.; Guo, X. Research on key technologies and applications of fine grain Optical Transport Network (fgOTN) for Electric Power Communication Network. In Proceedings of the 2025 IEEE 7th International Conference on Communications, Information System and Computer Engineering (CISCE), Guangzhou, China, 9–11 May 2025.
14. Liu, W.; Zhao, Y.; Li, Y.; Li, X.; Rahman, S.; Zhang, J. Segmented protection scheme based on maximum bandwidth sharing in F5G. *IEEE J. Opt. Commun. Netw.* **2024**, *16*, 1145–1158.
15. Yu, T.; Yang, H.; Yao, Q.; Zhao, Y.; Gong, S.; Zhang, Z.; Zhang, J.; Cheriet, M. Network for AI: Efficient Mapping with Fine Grain OTN for AI Computing Services Via Entropy-Coupled Incremental Learning. In Proceedings of the 2025 30th OptoElectronics and Communications Conference (OECC) and 2025 International Conference on Photonics in Switching and Computing (PSC), Sapporo, Japan, 29 June–3 July 2025.
16. Yen, J.Y. Finding the K Shortest Loopless Paths in a Network. *Manag. Sci.* **1971**, *17*, 712–716.

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