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Dynamic RMSA in Spectrum-Sliced Elastic Optical Networks for High-Throughput Service Provisioning

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***Abstract*—We propose several novel dynamic routing, modulation and spectrum assignment (RMSA) algorithms for high-throughput service provisioning in spectrum-sliced elastic optical networks. The proposed algorithms can be applied to network provisioning, where a network operator needs to figure out an efficient way to serve each dynamic connection request based on current network status. The proposed algorithms can be categorized into two categories, dynamic RMSA using online path computation and dynamic RMSA using path-set updates. The former one updates link metrics based on their spectrum utilization status dynamically, and performs RMSA with online routing path computation for each request. The latter one pre-computes K shortest routing paths as the path-set for each source-destination pair in the network topology, performs RMSA based on different path-selection policies during dynamic provisioning, and updates a path-set by adding a new path in when a path in the set is not available for a request. We evaluate the proposed algorithms with simulations using the Poisson traffic model in a 14-node NSFNET topology. Simulation results indicate that the proposed algorithms outperform existing dynamic RMSA algorithm by providing lower bandwidth blocking probability, and reduce the blocking probability by one magnitude or more when the traffic load is light ($\leq$ 700 Erlangs). The comparisons on network resource utilization also indicate that the proposed algorithms achieve larger resource utilization and hence provide higher throughput for network operations.**

***Index Terms*—Elastic optical networks, dynamic routing, modulation and spectrum assignment (RMSA), dynamic service provisioning**

I. INTRODUCTION

Traditional optical transport networks are built based on point-to-point wavelength division multiplexing (WDM) transmission systems, in a circuit-switching manner [1]. Since the bandwidth allocation granularity of WDM technology is usually coarse, i.e. 50 or 100 GHz per channel, these optical circuit-switching networks have been considered as with rigid infrastructures that only have minimum intelligence and flexibility in optical layer. To support highly dynamic IP data traffic, repeated optical-to-electrical-to-optical (O/E/O) conversions are used to forward data to electrical routers for packet-switching. However, it is well known that high-speed O/E/O conversions associate with relatively high equipment cost and energy consumption. To this end, the skyrocketing capital expenditures (CAPEX) and operational expenditures (OPEX) greatly limit the scaling of network infrastructures, and project the inevitable trend of developing more elastic, agile and intelligent optical technologies. Some researchers have been trying to implement statistical multiplexing in optical layer for agile all-optical switching, and proposed several technologies, such as optical packet switching (OPS) [2], optical label switching (OLS) [3,4], and optical burst switching (OBS) [5]. These technologies have demonstrated sub-wavelength bandwidth allocation granularity and flexible access to the vast bandwidth of optical fibers. However, their practicability is still restricted by the maturity of optical buffering techniques.

Recently, optical orthogonal frequency-division multiplexing (O-OFDM) technology [6,7] and its applications in spectrum-sliced elastic optical networks have attracted intensive research interests. Working in a multi-carrier scenario, O-OFDM supports ultra-high speed data transmission by grooming the capacities of several low-speed subcarrier channels [7]. Due to the fact that the subcarriers are orthogonal in the frequency domain, their spectra can overlap with each other for high spectral efficiency. Compared to single-carrier WDM, O-OFDM provides finer bandwidth allocation granularities as a bandwidth-variable O-OFDM transponder [8] can adjust spectral resource and assign just-enough subcarrier slots to serve a lightpath request.

Together with all these benefits, O-OFDM also brings challenges to future optical networks. Its elastic nature has determined that more sophisticated network control and management algorithms would be required for efficient and robust operations, especially in dynamic network environments with time-variant connection requests. In WDM networks, routing and wavelength assignment (RWA) is the fundamental problem for dynamic service provisioning, while the corresponding problem in O-OFDM networks is routing and spectrum assignment (RSA). In dynamic RSA, network operators have to manipulate contiguous subcarrier slots instead of discrete wavelengths. Moreover, the spectrum-continuity constraint for RSA is stricter than the wavelength-continuity constraint for RWA since wavelength conversion of contiguous subcarriers is still immature for practical applications. Hence, RWA algorithms cannot be applied to RSA problems directly. In O-OFDM networks, the modulation-level of subcarrier channels can be adaptive to accommodate various transmission reach and quality-of-transmission (QoT) [9,10]. As the modulation-level becomes higher with more bits per symbol (e.g. changing from BPSK to QPSK or 8-QAM), the transmission reach decreases due to lower receiver sensitivity. Fig. 1 shows the

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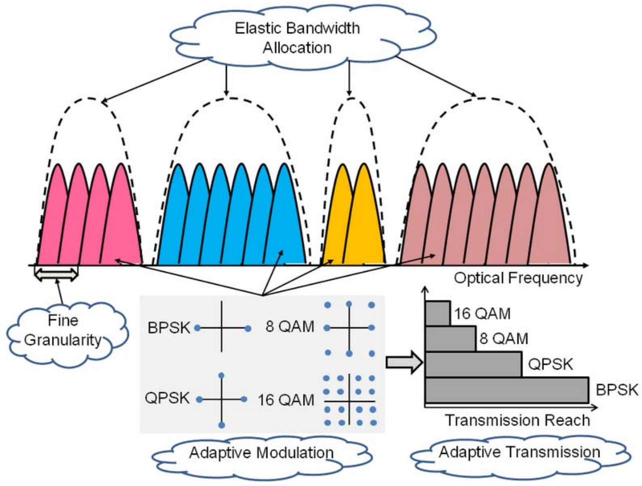

Fig. 1. Elastic bandwidth allocation and QoT adaptive modulation assignment in spectrum-sliced elastic optical networks.

working principle of elastic bandwidth allocation and QoT adaptive modulation assignment in O-OFDM networks. When we need to consider QoT-adaptive modulation assignment, the original RSA becomes a routing, modulation and spectrum assignment (RMSA) problem.

There have been some research works in the literature on dynamic service provisioning in spectrum-sliced elastic optical networks [11-16]. In [11], Wei *et al.* investigated virtual topology design and flow routing in adaptive IP/O-OFDM networks and proposed a minimal spanning tree based routing algorithm for dynamic service provisioning. With a simple RSA algorithm that utilized shortest path routing together with First-Fit spectrum assignment, [12] investigated the relation between request blocking probability and spectrum allocation granularity in O-OFDM networks. Three routing algorithms, K-shortest paths, modified Dijkstra and path vector trees, were compared in [13] for dynamic RMSA. Several distributed spectrum allocation schemes were proposed and experimentally evaluated in [14] for GMPLS-controlled elastic optical networks. Sambo *et al.* proposed a distributed lightpath setup mechanism with GMPLS signaling, which incorporated a dynamic RMSA algorithm that chose the least congested one among K shortest routing paths based on modulation assignment, and used First-Fit for spectrum assignment. A dynamic RSA algorithm that employed a metric to quantify the consecutiveness of available subcarrier slots among relevant fibers was developed in [16] for incremental network provisioning.

In this paper, we propose several novel dynamic RMSA algorithms for high-throughput service provisioning in spectrum-sliced elastic optical networks. The proposed algorithms can be categorized into two categories, dynamic RMSA using online path computation and dynamic RMSA using path-set updates. The former one updates link metrics based on their spectrum utilization status dynamically, and performs RMSA with online routing path computation for each request. The latter one pre-computes K shortest routing paths as the path-set for each source-destination pair in the network topology, performs RMSA based on different path-selection policies during dynamic provisioning, and updates a path-set by adding a new path in when a path in the set is not available for a request. We evaluate the proposed algorithms with simulations using the Poisson traffic model. Simulation results indicate that the proposed algorithms outperform existing dynamic RMSA algorithm by providing lower bandwidth blocking probability.

The rest of the paper is organized as follows. Section II formulates dynamic RMSA for service provisioning in spectrum-sliced elastic optical networks. The dynamic RMSA algorithms using online path computation and path-set updates are discussed in Sections III. Section IV shows the simulation setup and results for performance evaluations. Finally, Section V summarizes the paper.

II. PROBLEM FORMULATION OF SERVICE PROVISIONING USING DYNAMIC RMSA

With a physical network topology as $G(V,E,B,D)$, where V is the node set, E is the fiber link set, each fiber link can accommodate B frequency slots at most, and $d_e \in D$ represents the distance of $e \in E$. We assume that the bandwidth of each subcarrier slot is unique as BW_{slot} GHz. The capacity of a slot is $M \cdot C_{slot}$, where M is the modulation level in terms of bits per symbol, and C_{slot} denotes the capacity of a slot when the modulation is BPSK ($M = 1$) and is a function of BW_{slot} [10]. In this work, we assume that M can be 1, 2, 3 and 4 for BPSK, QPSK, 8-QAM and 16-QAM, respectively. For a lightpath request $LR(s,d,C,\Delta t)$ that is from node s to d for a capacity of C with a duration of Δt, the dynamic RMSA provisioning algorithm first needs to determine a routing path $R_{s,d}$ to serve the request. When the transmission distance of the routing path $R_{s,d}$ is known, we derive the modulation level M the path can support. Specifically, we assume that each modulation M can support a maximum transmission distance based on the receiver sensitivities [9], and when the distance permits, we always assign the highest modulation level to the request for high spectral efficiency. Then, we can figure out the number of contiguous slots N we need to assign on the path as:

$$N = \lceil \frac{C}{M \cdot C_{slot}} \rceil + N_{GB} \qquad (1)$$

where N_{GB} is the number of slots for the guard-band.

We use spectrum assignment to finalize the allocations of contiguous slots along the fiber links on $R_{s,d}$. For each fiber link $e \in E$, we define a bit-mask b_e that contains B bits. When the j-th slot on e is taken, $b_e[j] = 1$, otherwise $b_e[j] = 0$. When assigning the slots, we define a bit-mask a for the path, which also contains B bits. Then, the spectrum assignment on $R_{s,d}$ becomes the problem of finding N contiguous bits in a to turn on based on all current b_e, $e \in R_{s,d}$. We use two approaches in spectrum assignment, First-Fit (FFSA) and Best-Fit (BFSA). The FFSA approach tries to assign a request to the first available block of contiguous slots that can satisfy the capacity requirement, while the BFSA approach tries to serve a request in a way that creates the smallest left-over block of contiguous slots. Finally, the RMSA for $LR(s, d, C, \Delta t)$ is obtained as $\{R_{s,d}, M, a\}$. We say LR is blocked, if we cannot find a feasible $\{R_{s,d}, M, a\}$ for it. We define bandwidth blocking probability (BBP) as the ratio of blocked connection bandwidth versus total requested bandwidth. The objective of service provisioning is to minimize BBP or to maximize network throughput.

III. DYNAMIC RMSA ALGORITHMS FOR HIGH-THROUGHPUT SERVICE PROVISIONING

A. Dynamic RMSA using Online Path Computation

The dynamic RMSA algorithm discussed in this section considers link spectrum usage on-the-fly with online path computation. Instead of d_e, we define a link-metric as

$$d'_e = \begin{cases} +\infty, & MaxBlock(b_e) < N_m \\ d_e \cdot \frac{sum(b_e)+N_m}{B}, & MaxBlock(b_e) \geq N_m \end{cases} \tag{2}$$

where N_m is the number of contiguous slots that a request $LR(s, d, C, \Delta t)$ needs when the modulation scheme is BPSK ($M = 1$). The value of N_m is obtained using Eqn. (1) with $M = 1$. Basically, a link e is omitted from the online path computation, if it does not have a block of available contiguous slots with the size $\geq N_m$. Otherwise, the link-metric d'_e is proportional to the product of the transmission distance d_e and the number of used slots $sum(b_e)$. When serving a request $LR(s, d, C, \Delta t)$, we calculate K shortest routing paths for s-d with the virtual topology based on d'_e, and then select the available path that has the shortest distance. After determine the routing path $R_{s,d}$ for $LR(s, d, C, \Delta t)$, we calculate the physical distance of $R_{s,d}$ based on d_e of $e \in R_{s,d}$, and determine the modulation M to use based on it. The number of required contiguous slots N is obtained using Eqn. (1) with M. Finally, we figure out spectrum assignment a with the First-Fit (FFSA) or Best-Fit (BFSA). If we cannot find a spectrum assignment to serve the request, it is blocked.

B. Dynamic RMSA using Path-Set Updates

The major drawback of dynamic RMSA using online path computation is the high computation complexity, as we need to update the virtual topology based on d'_e for each request and to calculate the shortest path on-the-fly. To overcome them, we investigate dynamic RMSA using path-set updates. We pre-compute K shortest routing paths for each s-d pair in G before operating the network, as the path-set of s-d. During the provisioning a lightpath request $LR(s, d, C, \Delta t)$, we sort the paths in the path-set of s-d based on a path-selection policy and then process the paths one by one. If one or more paths in the set is unavailable for the request due to spectrum resource limitation, we try to calculate an equal number of new path(s) and update the set with them. In the context of this study, we evaluate the following path-selection policies:

a) *Shortest path first (SPF)*, we sort the routing path candidates in an ascending order based on the total transmission distance:

$$dist(R_{s,d}) = \sum_{e \in R_{s,d}} d_e \tag{3}$$

, and then select the available path that has the shortest distance.

b) *Most slots first (MSF)*, we order the paths in a descending order based on the available slots on each of them, and then select the available path that has the most available slots. The number of available slots on a path is:

$$bw(R_{s,d}) = B - sum(\bigcup_{e \in R_{s,d}} b_e) \tag{4}$$

c) *Largest slots-over-hops first (LSoHF)*, we order the paths in a descending order based on the following metric:

$$asoh(R_{s,d}) = \frac{bw(R_{s,d})}{hop(R_{s,d})} \tag{5}$$

where $hop(R_{s,d})$ returns the lengths of $R_{s,d}$ in terms of hops. We then select the available path that has maximum metric from Eqn. (5).

d) *Largest slots-over-square-of-hops first (LSoSHF)*, we order the paths in a descending order based on the following metric:

$$asosh(R_{s,d}) = \frac{bw(R_{s,d})}{\sqrt{hop(R_{s,d})}} \tag{6}$$

We then select the available path that has maximum metric from Eqn. (6).

After determining the routing path $R_{s,d}$ for $LR(s, d, C, \Delta t)$ based on one of the policies above, the modulation and spectrum assignments are obtained with similar procedures as discussed on Section III.A.

IV. SIMULATION SETUP AND RESULTS

We evaluate the proposed dynamic RMSA algorithms in the 14-node NSFNET topology, as shown in Fig. 2. Table I shows the simulation parameters. We set the bandwidth of a subcarrier slot as 12.5 GHz, and assume that the transmission reach for BPSK, QPSK, 8-QAM, and 16-QAM signals in it as 9600 km, 4800 km, 2400 km, and 1200 km, respectively, based on the experimental results in [9]. We set $B = 300$ as the number of slots on each fiber. The connection requests are generated using the Poisson traffic model. The capacity C of each request is randomly chosen within 10 - 200 Gb/s, and their s-d pairs are randomly selected too. Table II summarizes the abbreviations of dynamic RMSA algorithms we evaluated in this Section. Fig. 3 shows the comparisons on bandwidth blocking probability for the proposed algorithms using FFSA and BFSA approaches. It can be seen that the performance of these two spectrum assignment approaches are comparable and FFSA is slightly better than BFSA for SP-OPC, SPF-PSU and LSoHF-PSU when the traffic load is light ($\leq$ 700 Erlangs).

We implement two existing algorithms, the shortest path and First-Fit spectrum assignment (SP-FFSA) [12], and the K-shortest paths and balanced-load spectrum assignment (KSP-BLSA) [17], as the reference algorithms. Note that both algorithms were proposed as RSA that did not consider modulation assignment, we modify them to RMSA algorithms. Fig. 4 compares the request blocking probabilities from the proposed algorithms with those from the reference algorithms.

TABLE II
ABBREVIATIONS OF ALGORITHMS UNDER INVESTIGATIONS

Reference Algorithms	SP-FFSA	Shortest routing path and First-Fit spectrum assignment
	KSP-BLSA	K-shortest routing paths and balanced-load spectrum assignment
Algorithms using Online Path Computation	SP-OPC-FFSA	Shortest routing path from online path computation and First-Fit spectrum assignment
	SP-OPC-BFSA	Shortest routing path from online path computation and Best-Fit spectrum assignment
Algorithms using Path-Set Updates	SPF-PSU-FFSA	Routing path selected using the shortest path first policy with path-set updates and First-Fit spectrum assignment
	SPF-PSU-BFSA	Routing path selected using the shortest path first policy with path-set updates and Best-Fit spectrum assignment
	MSF-PSU-FFSA	Routing path selected using the most slots first policy with path-set updates and First-Fit spectrum assignment
	MSF-PSU-BFSA	Routing path selected using the most slots first policy with path-set updates and Best-Fit spectrum assignment
	LSoHF-PSU-FFSA	Routing path selected using the largest slots-over-hops first policy with path-set updates and First-Fit spectrum assignment
	LSoHF-PSU-BFSA	Routing path selected using the largest slots-over-hops first policy with path-set updates and Best-Fit spectrum assignment
	LSoSHF-PSU-FFSA	Routing path selected using the largest slots-over-square-of-hops first policy with path-set updates and First-Fit spectrum assignment
	LSoSHF-PSU-BFSA	Routing path selected using the largest slots-over-square-of-hops first policy with path-set updates and Best-Fit spectrum assignment

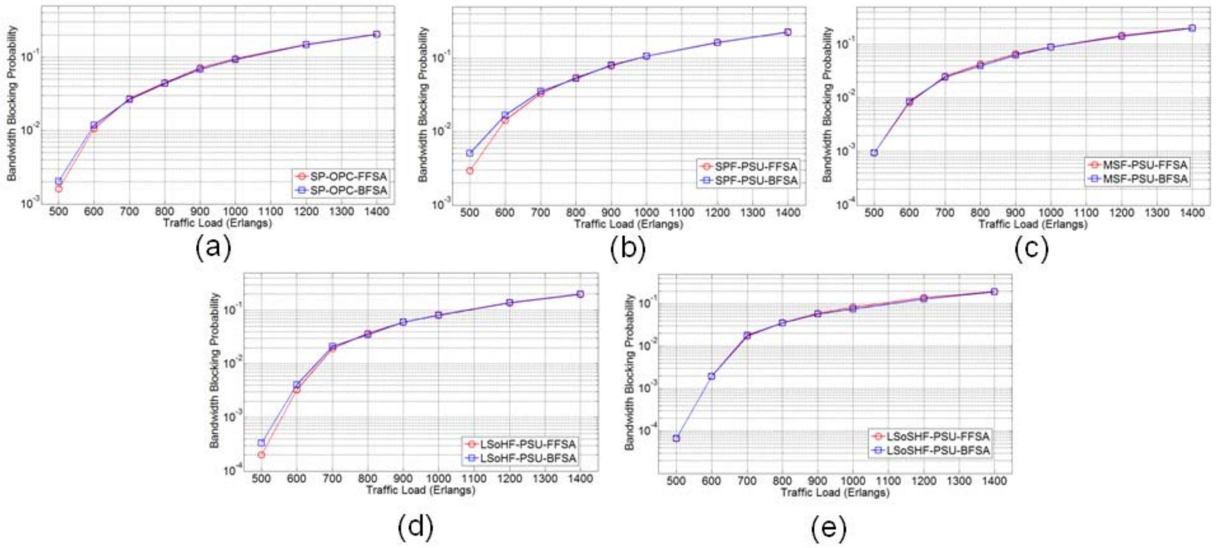

Fig. 3. Comparisons on bandwidth blocking probability for RMSA algorithms using First-Fit and Best-Fit, (a) SP-OPC, (b) SPF-PSU, (c) MSF-PSU, (d) LSoHF-PSU and (e) LSoSHF-PSU.

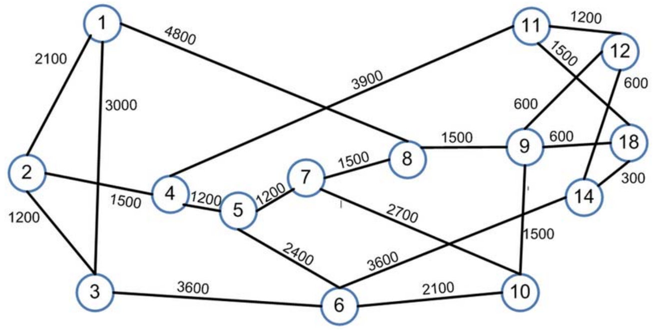

Fig. 2. 14-node 22-link NSFNET topology (link distances are in kilometers).

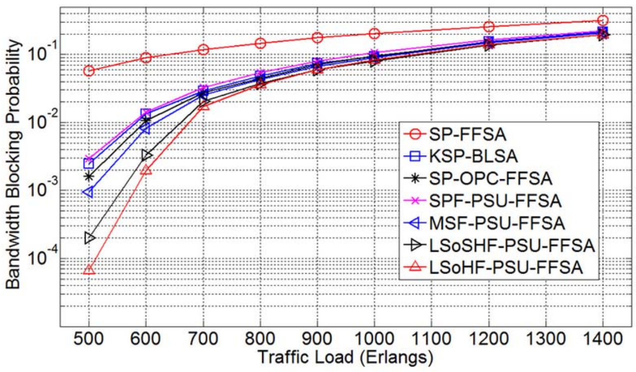

Fig. 4. Comparisons on bandwidth blocking probability.

TABLE I

SIMULATION PARAMETERS

B, number of frequency slots per link	300
B_{slot}, bandwidth of a frequency slot	12.5 GHz
Transmission reach of BPSK ($M = 1$)	9,600 km
Transmission reach of QPSK ($M = 2$)	4,800 km
Transmission reach of 8-QAM ($M = 3$)	2,400 km
Transmission reach of 16-QAM ($M = 4$)	1,200 km
K, number of path candidates for a s-d pair	5
Range of requested capacity (C)	10 - 200 Gb/s

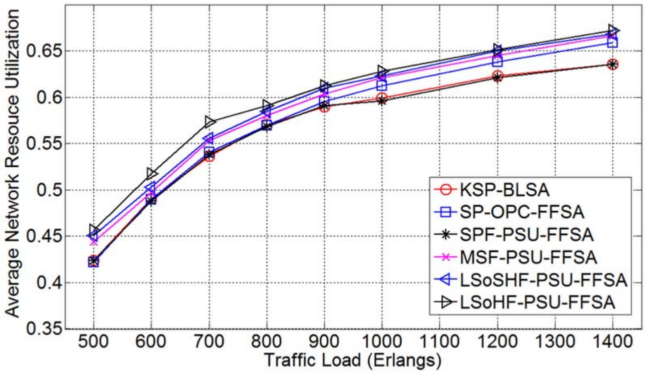

Fig. 5. Comparisons on network resource utilization.

It can be seen that SP-FFSA yields the worst performance due to its simplicity. KSP-BLSA can effectively reduce blocking probability, but it is far from optimized. With online path computation, the SP-OPC-FFSA algorithm outperforms KSP-BLSA. For the algorithms with path-set updates, the SPF-PSU-FFSA has comparable performance with KSP-BLSA, but all the other three achieve much lower bandwidth blocking probabilities. Among all proposed algorithms, the LSoHF-PSU-FFSA has the best performance. Compared to KSP-BLSA, LSoHF-PSU-FFSA reduces the bandwidth blocking probability by one magnitude or more when the traffic load is light ($\leq$ 700 Erlangs). Fig. 5 shows the comparisons on network resource utilization. As expected, compared to KSP-BLSA, the proposed algorithms achieve larger resource utilization and hence provide higher throughput for network operations.

V. CONCLUSION

In this paper, we proposed several novel dynamic RMSA algorithms for high-throughput service provisioning in spectrum-sliced elastic optical networks. The proposed algorithms were in two categories, dynamic RMSA using online path computation and dynamic RMSA using path-set updates. The former one updated link metrics based on their spectrum utilization status dynamically, and performed RMSA with online routing path computation for each request. The latter one pre-computed K shortest routing paths as the path-set for each s-d pair in the network topology, performed RMSA based on different path-selection policies during dynamic provisioning, and updated a path-set by adding a new path in when a path in the set was not available for a request.

We evaluated the proposed algorithms with simulations using the Poisson traffic model in a 14-node NSFNET topology. Simulation results indicated that for proposed algorithms, the two spectrum assignment approaches, FFSA and BFSA, had comparable performance in terms of bandwidth blocking probability. Simulation results also showed that the proposed algorithms outperformed existing SP-FFSA and KSP-BLSA algorithm by providing lower bandwidth blocking probability, and could reduce the blocking probability by one magnitude or more when the traffic load was light ($\leq$ 700 Erlangs). Among all proposed dynamic RMSA algorithms, the LSoHF-PSU-FFSA achieved the best performance.

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