Dynamic Routing and Spectrum Allocation to Minimize Fragmentation in Elastic Optical Networks

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Abstract—**The exponential growth in Internet traffic requires a high-capacity transmission platform and emphasizes the importance of a multi-granularity transport network due to heterogeneous connection requests. Elastic Optical Network has been considered as a promising solution because of large transport capacity and bandwidth flexibility. Routing and spectrum allocation is one of important problems in EON. However, with spectrum continuity constraint and contiguity constraint, the set-up and tear-down of light paths may cause fragmentation problem which refers to small-sized and un-contiguous spectrums. The fragmentation increases the connection blocking probability and decrease spectrum utilization. In this paper a novel routing and spectrum allocation algorithm is proposed to minimize fragmentation in EON. The proposed algorithm consists of routing problem and the spectrum allocation problem. In the first step, K-shortest paths algorithm is employed and candidate paths are found according to the distance between source and destination. In the second step, fragmentation-aware spectrum allocation algorithm is applied. We define block cost function to determine appropriate spectral block for connection request. The block cost function is based on the state of neighboring frequency slots to minimize the fragmentation after spectrum allocation. The performance of proposed algorithm is evaluated in terms of blocking probability and spectrum utilization.**

I. INTRODUCTION

In current growth rates, Internet traffic will increase by a factor of one thousand in roughly 20 years. It will be challenging for transmission and routing/switching systems to keep pace with this level of growth without requiring prohibitively large increases in network cost and power consumption [1]. The challenge should be addressed network infrastructure with high optical resource efficiency. The wavelength division multiplexing (WDM) has been studied to support the exponential growth of traffic. In WDM networks, the fixed bandwidth 50 GHz is allocated to a request with coarse spectrum granularity [2]. Furthermore, it leads to inefficient spectrum utilization because a wavelength is assigned for low-traffic demand. Elastic optical networks (EONs) have been proposed to support variable bandwidth allocation by utilizing an optical orthogonal frequency division multiplexing (O-OFDM) [3]. The O-OFDM enables continuous optical carriers and variable numbers of subcarriers on a channel. In OFDM-based EONs, the optical spectrum is divided into a number of frequency slots (FSs) with 6.25 or 12.5 GHz width [4]. The EON supports fine granularity and saves spectrum because the frequency slots can be combined and allocated according to the required bandwidth of demand.

In this paper, we propose a routing and spectrum allocation algorithm to improve spectrum efficiency while minimizing spectrum fragmentation. In order to this, block cost functions for link and path are defined to evaluate candidate spectrum blocks.

The rest of this paper is organized as follows. Section II introduces the architecture of EON and routing and spectrum allocation. Section III presents the proposed dynamic routing and spectrum allocation algorithm to minimize fragmentation. In Section IV, the performance of proposed algorithm is evaluated by simulation. Finally, section V concludes this paper.

II. RELATED WORK

In this section, we begin with the concept of routing and spectrum allocation in elastic optical network. The elastic optical network adopts a finer granularity and elastic “just-enough” size bandwidth allocation [4-6]. The comparison among current fixed grid standard and EON scenarios is shown in Fig.1.

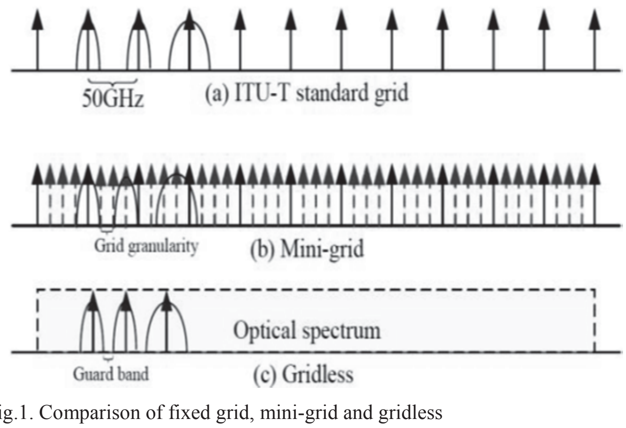

Fig.1. Comparison of fixed grid, mini-grid and gridless

The Fig.1 (a) depicts the standard fixed grid which is used in WDM networks. If the wavelength channel is fixed at low data rate, e.g., 10 Gbps, the large space on the spectrum between two neighboring channels is wasted. To improve spectrum resource utilization, the research topic is recently based on OFDM technique, which gains the most extensive study among various mini-grid approaches as shown in Fig.1 (b). In OFDM-based EON, data is transmitted over a block of consecutive FSs. Each FS can be processed individually through digital signal processing (DSP) implemented at both the transmitting and the receiving ends. Thus, the modulation format can be adjusted according to the traffic demand and the transmission distance of optical path. The further elasticity of spectrum allocation is to make the spectrum gridless as shown in Fig.1 (c).

The OFDM-based EON can allocate the appropriate amount of frequency spectrum according to the required traffic of source and destination pair. The EON consists of bandwidth-variable transponders (BVTs) and bandwidth-variable wavelength cross connects (BV-WXCs). The BV-WXC is used to establish a lightpath by a cross-connection with the appropriate spectrum bandwidth [8]. The BVT is used to tune the bandwidth by adjusting the transmission data rate or modulation format [3]. The high-speed transmission is supported by BVTs with high modulation format for short distance lightpaths. Meanwhile, low modulation format is used to extend the transmission reach. Table I shows the relationship between spectrum efficiency and transmission reach for various modulation formats [9].

TABLE I. CHARACTERISTICS OF MODULATION FORMATS

MF	SE (bps/Hz)	Data Rate/Subcarrier (Gbps)	Reach (km)
BPSK	1	12.5	4000
QPSK	2	25	2000
8QAM	3	37.5	1000
16QAM	4	50	500

RSA in the elastic optical network is crucial problem similar to the RWA in the WDM networks. RSA is divided into two part: i) find the path for a source and destination pair ii) allocate spectrum to the request. The spectrum allocation scheme are subject to the following constrains.

- Spectrum-contiguity: If the connection request requires n FSs, n contiguous FSs must be assigned to the request.
- Spectrum-continuity: This constraint requires that the same set of contiguous FSs are assigned to the request on each link along the path.
- Non-overlapping: Allocated FSs for request are separated by the guard band in order to avoid interference. And the used spectrum is not able to be allocated to next request. This implies that a FS can be employed by one connection request.

The example is illustrated to explain the concept of spectrum contiguity and contiguity of spectrum allocation in Fig.2. We suppose the arriving request needs two FSs to transmit the traffic from source A to destination C. Frequency slots 4 and 5 through the route A-D-C satisfy both continuity and contiguity constraints. Several work proposed integer linear formulations for the static RSA problem. Reference [10],[11],[12] introduced a path-based ILP formulation with objective to minimize the maximum utilized spectrum slot index assigned on links in the network. This work considered pre-computed k-shortest path for source and destination pairs. Reference [13] proposed a link-based ILP model to minimize the maximal index of used FSs in network.

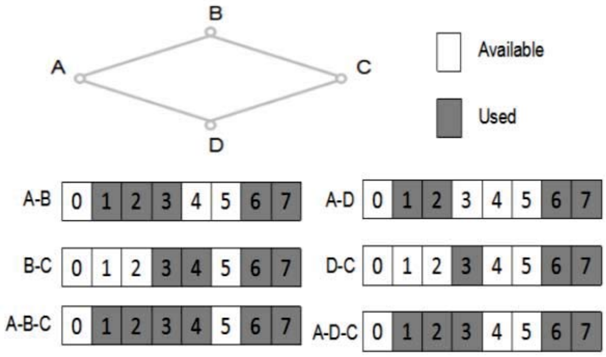

Fig.2. Spectrum contiguity and continuity

Because of real-time nature of dynamic scenario, RSA algorithms in dynamic traffic environment must be simple and fast. Since combined routing and spectrum assignment is an N-P hard problem, heuristic algorithms are proposed. Online RSA algorithms can be classified into two categories depending on whether they tackle the routing and spectrum assignment jointly or separately. The greedy algorithm [14] achieves a suboptimal solution in simple and rapid manner. Auxiliary graphs [15] get the optimal solution with high computational complexity.

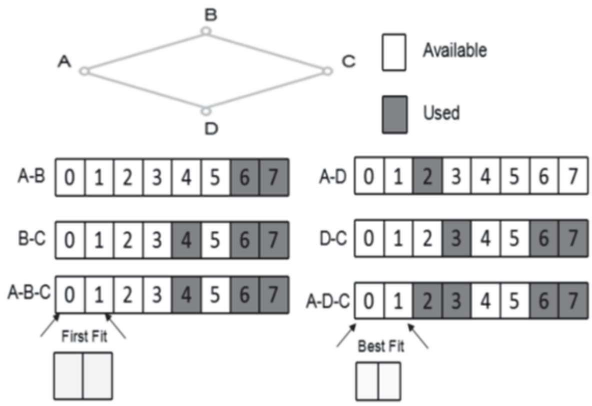

Fig.3. First-fit and best-fit policies

Fig.3 shows the first-fit and best-fit spectrum allocation polices for two frequency slots of request. The most popular algorithm among the two-step algorithms is the *K*-shortest path routing with first-fit allocation [16]. The algorithm finds a set of candidate paths. For each candidate path, it searches a group of available FSs with the lowest index. The first-fit algorithm is considered the best spectrum allocation algorithm because of the lower computational complexity and bandwidth blocking probability. The *K*-shortest path routing with best-fit allocation algorithm tried to allocate connections in order to minimize fragmentation.

III. Dynamic RSA Algorithm to Minimize Fragmentation

In this paper, a connection request is accepted when the spectrum is available along the routed path. The given network is modeled as graph G (V, E, B, D) where V represents the sets of nodes, E is a set of fiber links, each link can accommodates B FSs at most and d (v_i, v_i) denotes distance from the node i to node j. Each FS has the bandwidth of 12.5 GHz and is able to provide a capacity of 12.5 Gbps if modulation format is BPSK. R (*s*, *d*, *c*, *h*) represents connection request with required capacity *c* from source node *s* to the destination node *d* where *h* is the connection holding time. We assume the capacity of request can be translated into the requested number of FSs on the basis of specific modulation level *m*. The candidate paths from source to the destination are determined when the request is arrived with the information. According to the distance of the chosen path, the appropriate number of FSs is computed by modulation format as equation (1).

$$Number\ of\ FSs\ = \frac{R(Gbps)}{m(bit/Hz) * FSwidth(GHz)} + GB \quad (1)$$

The remaining notations are listed as follows:

$\overline{P}^{\,s,d}$: A set of paths from source *s* to the destination *d*

$P_k^{s,d}$: The k^{th} path from sources to the destination *d*

Hop ($P_k^{s,d}$): The number of hops for $P_k^{s,d}$

$B_{k,h}^{s,d}(i,n)$: Cost of the h^{th} block from index i to index *i+n-1* along the path

$B^{u,v}(i,n)$: Cost of the block from index *i* to index *i+n-1* between node u and node *v*

$C^{u,v}(i)$: Cost of *i*th slot between node u and node *v*

$C_R^{u,v}(i+n)$: Cost of right neighboring slot for the $B^{u,v}(i,n)$

$C_L^{u,v}(i-1)$: The cost of left neighboring slot for the $B^{u,v}(i,n)$

H: The number of blocks

K: The number of shortest paths

B_{min}: The minimum cost of the block among the *K* shortest paths

A. Routing algorithm

The *K*-shortest routing algorithm is employed to determine the transmission path for request. In order to find *K*-shortest paths, Yen's algorithm has been used [17]. Dijkstra's shortest path algorithm finds shortest path from source to destination.

B. Fragmentation aware spectrum allocation

The fragmentation divides the spectrum into small spectral segments called subblock. Therefore, it is difficult for the next connection request with large bandwidth to be accepted. This results in increasing blocking probability for the demands with high-data-rate and decreasing the efficiency of spectrum. To combat fragmentation problem, the fragmentation-aware spectrum allocation is proposed in this paper.

Large block is divided into several subblocks according to the request. If a request needs *n* FSs, the available block has *m* FSs and *m-n+1* subblocks. In Fig.4, 6 FSs are available. New arrival requests 2 FSs. Thus, the block can be divided into three subblocks according to the required number of FSs. Each subblock or block can be denoted by B(i, n). B(i, n) indicates the block from index *i* to index *i+n-1*.

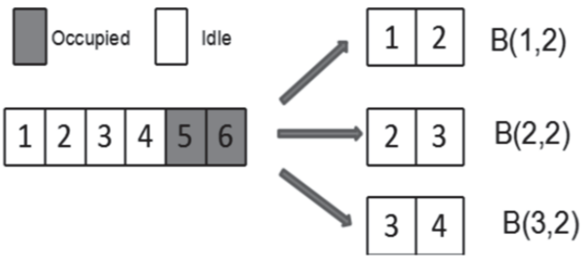

Fig.4. Configuration of sub blocks

When *K*-shortest paths are determined, the block cost along the link and path needs to be calculated to choose a block of spectrum for the request. FS has two states: 0(occupied) or 1(idle).

$$C^{u,v}(i) = \begin{cases} 0\ (Occupied) \\ 1\ (Idle) \end{cases} \quad (2)$$

$$B^{u,v}(i,n) = \begin{cases} C_R^{u,v}(i+n), i = 1 \\ C_R^{u,v}(i+n) + C_L^{u,v}(i-1), 1 < i < N-n+1 \\ C_L^{u,v}(i-1), i = N-n+1 \end{cases} \quad (3)$$

The cost of leftmost block is determined according to the state of right neighboring slot by Eq. (2). Similarly, the cost of rightmost block is determined by the state of left neighboring slot. And the cost of block in the middle depends on the two neighbor slots.

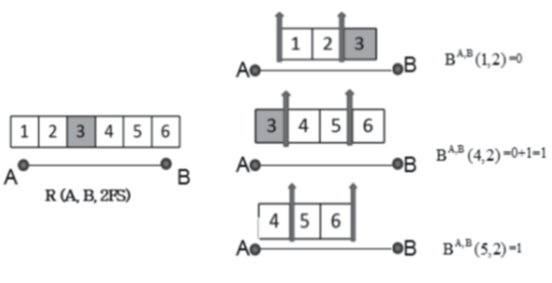

Fig.5. Computation of block cost

All parameters are initialized at beginning phase. The *H* and B_{min} are set as 0 and ∞. Data rate can be translated into the required number of FSs according to the equation (1). If the available blocks for request could be found, the next step is executed. Otherwise, the request is blocked. If the cost is less than B_{min} after computing the cost of current block, the position of FSs is saved with block cost. Finally, if B_{min} is less than infinite, this implies that there is available block for the request, this block is allocated for this request. Otherwise, the request must be rejected. For example, the arriving request needs 2FSs from source A to destination B in Fig.5. For simplicity, it is assumed that there are 6 FSs on single fiber link in this example. It is observed that there are three candidate blocks. The costs of the candidate blocks are calculated according to current states. The costs of the candidate blocks are determined as follows: 0, 1, and 1. Thus, the first block which has minimum value is chosen for this request.

The proposed algorithm is operated similar to best-fit algorithm in the case of single link connection from source to destination. We consider mesh network consisting of four nodes and four links as shown in in Fig.6.

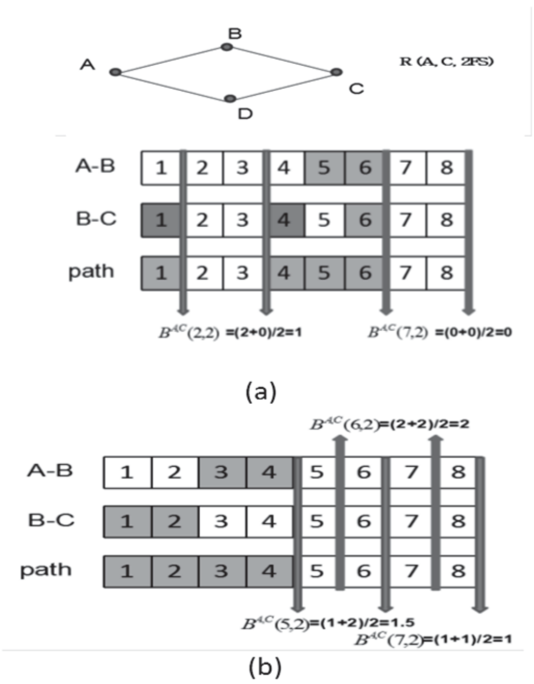

Fig.6. Example of proposed algorithm

The spectral resources on the fiber link are allocated as shown in Fig.6(a). One of blocks is selected randomly in view of best-fit policy as two blocks $B^{A,C}(5, 2)$ and $B^{A,C}(7, 2)$ which are satisfied the requirement of best-fit policy. According to the defined equations (3) and (4), the costs of two blocks are computed to 1 and 0, respectively. Certainly, the $B^{A,C}(7, 2)$ is allocated for the request because of its minimum value. Another advantage of proposed algorithm is observed for following example with the same network and request (A, C, 2FS). Only one candidate block for the request is larger than the request in Fig.6(b). Frequency slots 5 and 6 in low order position are allocated by using best-fit policy. It is clearly seen that a large group of contiguous FSs are separated into two parts after allocation on the link B-C. Thus, it just has ability for serving request with required 2FS. However, the block is divided into three subblocks by proposed algorithm. Each subblock can be candidate for the request. The subblock $B^{A,C}(7, 2)$ is selected to establish lightpath for demand after computation and comparison. In this way there are four contiguous FSs on the link B-C and it has large probability to serve large demand. $B^{A,B}(1,2)$ is chosen due to its minimum cost among candidate blocks.

C. Routing and spectrum allocations

This subsection introduces the complete proposed algorithm through flowchart in Fig.7. At the beginning, the system is initialized. Each FS is assigned different cost on the basis of its state. When a request arrives, the routing function is used to determine the paths for request. After then, the proposed spectrum allocation algorithm assigns frequency slots to the request and updates the state of FSs. If frequency slots are not available for the request, the request is blocked.

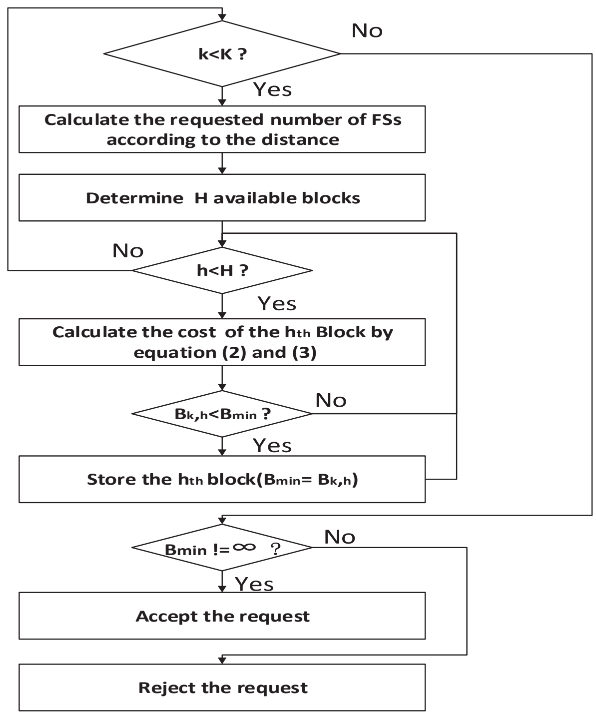

Fig.7. Flowchart of proposed RSA algorithm

IV. PERFORMANCE EVALUATION

A. Assumptions

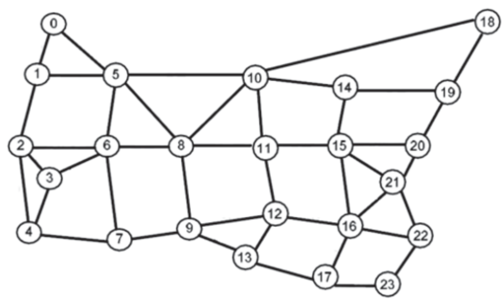

Fig.8. Topology of US network

The proposed algorithm and conventional algorithm are simulated in US network and NSF network. The US network consists of 24 nodes and 43 links shown in Fig.8 and the NSF network consists of 14 nodes and 21 links shown in Fig.9.

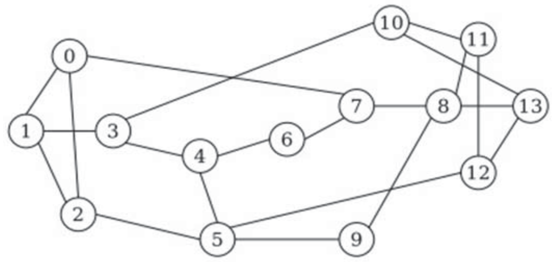

Fig.9. Topology of NSF network

Table II shows the simulation parameters. The k-shortest paths are used and k is regarded as 3 for simulation. We assume each link has one fiber. The bandwidth of each FS and total number of FSs per fiber are considered as 12.5GHz and 300, respectively. Thus, one fiber link supports the capacity of 3.75THz.

TABLE II. SIMULATION PARAMETERS

Parameter	Value
k	3
Number of FSs/fiber	300
FS Bandwidth	12.5GHz
Average HT	50s
Required rate/request	12.5-237.5Gbps
Capacity of FS for BPSK	12.5Gbps

In simulation, 10^4-10^5 connection requests are arrived with Poisson process at rate λ. The holding time is 1/μ which has negative exponential distribution with averages 50 second. Thus, the network load becomes λ/μ. The required capacity of requests is distributed from 12.5Gbps to 237.5Gbps randomly. Each source-destination pair is selected randomly.

The performance of proposed algorithm is evaluated in terms of bandwidth blocking probability, the number of hops and spectrum utilization. The performance metrics are defined as follows:

- Bandwidth blocking probability (*BBP*) is important for evaluating network performance. *B* and *AR* are assumed the set of blocked requests and set of arriving requests. The b_i , indicates the amount of bandwidth for request *i*. The bandwidth blocking probability is defined as Eq. (4)

$$BBP = \frac{\sum_{i \in B} b_i}{\sum_{i \in AR} b_i} \quad (4)$$

- Spectrum utilization (*SU*) is to measure spectrum efficiency. The *ATR* is the set of accepted requests and HT_i is holding time of request *i*. The *SU* is expressed by Eq. (5).

$$SU = \frac{\sum_{i \in ATR} b_i * HT_i}{Total\ spectrum * Simulation\ time} \quad (5)$$

B. Simulation results

Fig.10 shows the performance in terms of the bandwidth blocking probability for KSP-FF, KSP-BF and proposed algorithm KSP-FASA. The blocking probability is increased according to increasing traffic load. The proposed algorithm, KSP-FASA, shows the lowest blocking probability while the KSP-FF has the highest blocking probability among three schemes. The KSP-FASA achieves the 28% to 85% and 10% to 45% savings over FF and BF, respectively in terms of bandwidth blocking probability under U.S. topology. In NSFNET, KSP-FASA achieves the 37% to 90% and 16% to 64% savings over KSP-FF and KSP-BF respectively in Fig.11. Because the proposed algorithm minimizes the fragmentation, the probability to support high-data-rate requests is increased as previous description.

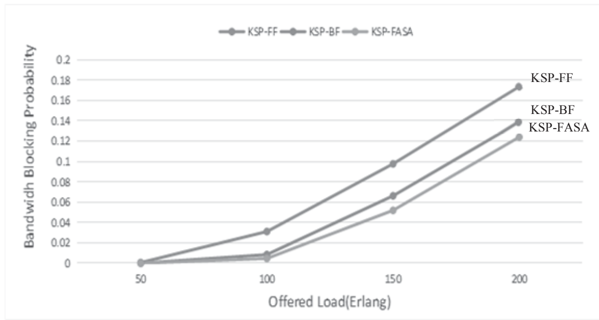

Fig.10. Comparison of BPP in US Network

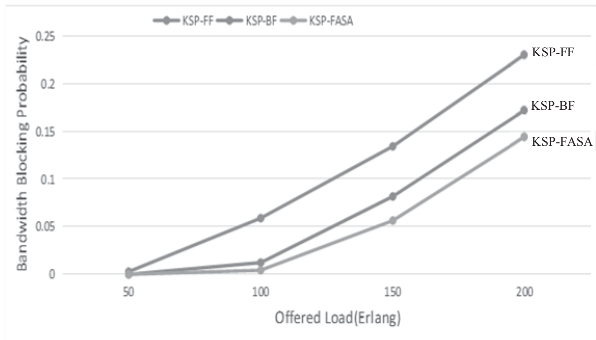

Fig.11. Comparison of BPP in NSF Network

In Fig.12 and Fig.13, KSP-FF algorithm performs the lowest level of spectrum utilization even though the lowest blocking probability is achieved.

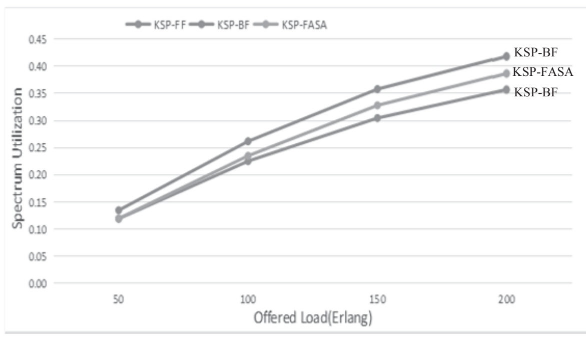

Fig.12. Comparison of SU in US Network

Furthermore, the interesting phenomenon is observed that the KSP-BF algorithm achieves higher spectrum utilization while the proposed algorithm accepts more requests than the KSP-BF algorithm. The simulation results show that the proposed KSP-FASA achieves 8%-12% and 5%-22% spectrum saving comparing to BF algorithm in the US network and NSF network, respectively. Theoretically KSP-BF may use fewer spectrums in case that the number of accepted request for BF is less than that of KSP-FASA.

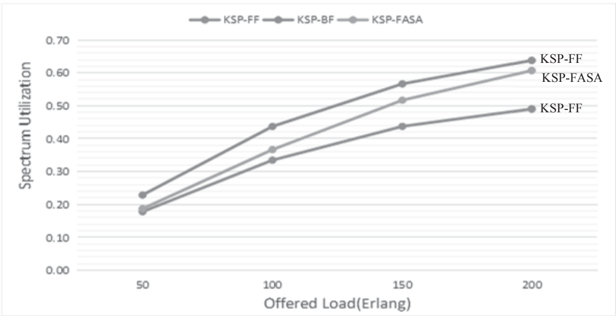

Fig.13. Comparison of SU in NSF Network

In Fig. 14 and Fig. 15, the selected path by KSP-BF has the most number of hops among these algorithms and needs to assign more spectrums to request. Because the KSP-BF always finds the smallest block for request without the hop distance of the path between source and destination, the average number of hop may be increased. The KSP-FASA decreases the blocking probability and improves the spectrum efficiency by reducing fragmentation.

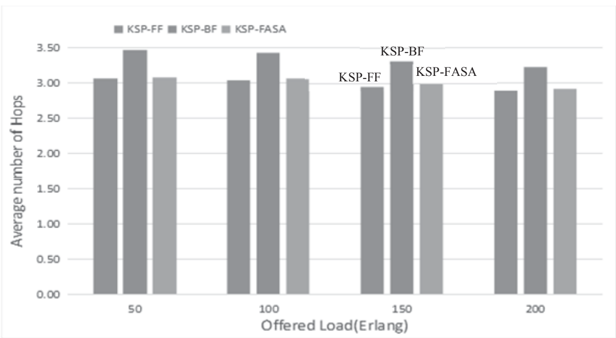

Fig.14. Comparison of hop distance in US network

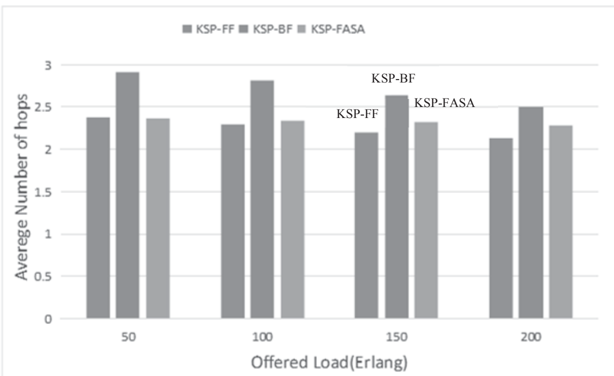

Fig.15.Comparison of hop distance in NSF network

V. CONCLUSION

Routing and spectrum allocation is one of challenging issues in elastic optical networks. The fragmentation with small and noncontiguous spectrum results in inefficient spectrum utilization and increasing high blocking probability. In this paper, we proposed novel routing and spectrum allocation algorithm to minimize the fragmentation in elastic optical networks. We defined two cost functions so as to minimize the fragmentation of spectrum resource.

The performance of the proposed algorithm is evaluated by simulation in US and NSF networks. The proposed algorithm showed higher performance than conventional algorithms in terms of blocking probability and spectrum utilization. The proposed algorithm achieved 28% to 85% and 10% to 45% improvement over KSP-FF and KSP-BF in terms of bandwidth blocking probability under U.S. topology, respectively.

In future, our work will focus on defragmentation in EON. In a dynamic environment, the fragmentation problem cannot be completely eliminated. Therefore, reactive fragmentation-aware RSA algorithms can restore the network's ability to accommodate high-rate and long-path connections.

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