Dynamic Spectrum Assignment Algorithm Based on Fuzzy Logic to Reduce Fragmentation in EONs

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Abstract— Elastic optical networks based on the optical orthogonal frequency-division multiplexing technology have been studied as promising next-generation optical backbone networks with large transport capacity and bandwidth flexibility. A main challenge in the EONs is to reduce spectrum fragmentation that decrease the network performance due to dynamic setting up and tearing down of non-uniform bandwidth requests. It is quite complex problem to solve the spectrum fragmentation. Fuzzy logic system that resembles human inference has been used for decision making for complex problem. In this paper, we propose the dynamic spectrum assignment (SA) algorithm for minimizing the fragmentation based on the fuzzy logic in EONs. To design fuzzy logic control system for the SA algorithm, we define spectrum fragmentation ratio(SFR) and time fragmentation ratio(TFR) for input membership. We also define the weight values of available spectrum blocks as output membership. The spectrum block with the minimum crisp value is selected for the spectrum assignment of connection request. The performance of the proposed algorithm is evaluated in terms of the average bandwidth blocking probability and the spectrum utilization.

Keywords—fuzzy logic control system, elastic optical network, routing and spectrum assignment, RMSA

I. INTRODUCTION

The explosive growth of the internet traffic volume due to the increasing number of connection and high-rate various applications requires efficient and scalable network technology. The Elastic Optical Networks (EONs) based on Optical Orthogonal Frequency-Division Multiplexing (O-OFDM) technology have attracted intensive research interests [1]. The EONs can provide the flexible and variable bandwidth assignment to each connection request with fine spectrum granularity, 6.25 GHz or 12.5 GHz, and achieve higher spectrum utilization by using the technology of O-OFDM [2]. The OFDM can assign an appropriate number of contiguous subcarrier slots based on the required bandwidth of a connection request. In addition, the EONs can support various modulation formats according to the optical impairments [3].

The Routing, Modulation format, and Spectrum Assignment (RMSA) that is similar to the routing and wavelength assignment (RWA) in WDM networks is a crucial task for resource management in EONs [4]. The RMSA problem in the EONs must simultaneously consider the Spectrum-Continuity and the Spectrum-Contiguity constraint. The spectrum contiguity ensures that the allocated spectrum slots to a traffic demand have to be consecutive in spectrum domain. Similarly, the spectrum continuity imposes that the allocated slots must be the same on each link of the selected routing path [5].

One of the main concern is the spectrum fragmentation problem in EONs. The dynamic setting up and tearing down connections of non-uniform bandwidth requests will trigger the spectrum fragmentation problem. The spectrum fragmentation leads to higher blocking probability and reduce the spectrum utilization. To address this issue, dynamic RMSA algorithms have been proposed to reduce the fragmentation. In [6-8], authors proposed RMSA with holding time awareness. A two dimensional resource model with time and spectrum domain has been considered. The spectrum block cost function consist of time and spectrum block was proposed in [8].

The fuzzy logic system has been used as a solution for the decision making for the complex problem. The approach imitates the way of decision making in humans that involves all intermediate possibilities between digital values 0 and 1. The fuzzy logic helps to deal with the uncertainty in engineering. The output of a fuzzy controller is derived from fuzzy inference process of both input data and rule base [9].

In [10-12], routing algorithms based on fuzzy logic system have been proposed for load balancing to reduce the blocking probability in EONs. In order to find the optimal route among candidate routes these algorithms defined some metrics for fuzzy logic, such as fragmentation level, slot index, the number of occupied slots, and relative physical distance. The proposed algorithm has better performance comparing to conventional algorithms. However, only fuzzy logic was used to find optimal route and it was not considered in the phase of the spectrum assignment.

In this paper, we propose the dynamic SA algorithm based on the fuzzy logic control system in the EONs. We design the fuzzy logic control system to define the status of available spectrum blocks based on the spectrum and time fragmentation ratio. We define the spectrum fragmentation and time fragmentation ratio considering the request holding time and the state of slots on a selected route. The performance of the proposed algorithm is compared with conventional methods in terms of average bandwidth blocking probability and the spectrum utilization.

II. Elastic Optical Networks

The EONs based on OFDM consist of bandwidth-variable transponders (BVTs) and bandwidth-variable wavelength cross connects (BV-WXCs), as shown fig. 1. The BV-WXC is used to establish a lightpath by a cross-connection with the appropriate spectrum bandwidth. The BVT is used to tune the bandwidth by adjusting the transmission data rate or modulation level. The high-speed transmission is supported by BVTs with high modulation level for short distance lightpaths. Meanwhile, low modulation level is used to extend the transmission reach. Table I represents the relationship of spectrum efficiency and transmission reach for various modulation formats [3].

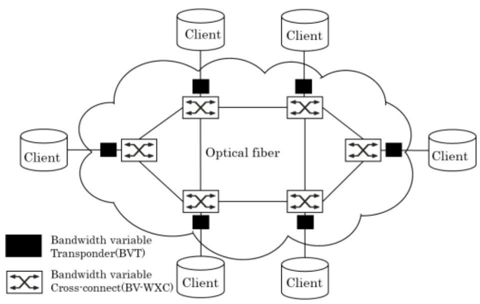


Fig. 1. Elastic optical networks

A. Routing, Modulation and Spectrum Assignment

The EONs can be represented as a graph *G(V, E, D)*, where *V* is a set of nodes, *E* is a set of links, and *D* is a set of the distance between each pair of adjacent nodes. A connection request is denoted as *R(s, d, b, h)*, where *s* and *d* represent the source and destination node, *b* is the required bandwidth, and *h* is the holding time. The required number of slots *n* can be denoted as (1), where *m* is the spectrum efficiency, n_g is the number of guard band slots to avoid signal interference, and *FSwidth* denote the slot width . We assume the *FSwidth* as slot width of 12.5GH.

In EONs the RMSA problem for a request *R(s, d, b, h)* is divided into three sub-problems: *i)* find a route for a source *s* and destination pair, *ii)* select the modulation format considering physical impairments, *iii)* assign the spectrum block for a connection request. The RMSA problem is more complex problem than the RWA problem as it has to simultaneously satisfy the spectrum contiguity and continuity constraints. The spectrum continuity along the links of a given routing path where the same slots must be used in all links of the path. The spectrum contiguity also must be satisfied, which means that assigned spectrum slots must be contiguous in the spectrum.

TABLE I. Modulation Formats

Modulation Level	Spectrum Efficiency (bps/symbol)	Data rate /Subcarrier (Gbps)	Reach (Km)
BPSK	1	12.5	> 2000
QPSK	2	25	<= 2000
QAM	3	37.5	<= 1000
16-QAM	4	50	<= 500

$$n = \left\lceil \frac{b(Gbps)}{m(bps/Hz) \times FSwidth(GHz)} \right\rceil + n_g \qquad (1)$$

B. Fragmentation problem

The spectrum fragmentation, which is similar to the memory fragmentation in computer storage, is the main factor that degrades the performance of the networks. The fragmentation is caused by dynamic the setting up and tearing down of non-uniform bandwidth requests. This spectrum fragmentation leads to higher blocking probability and reduce the spectrum utilization. Examples of the spectrum and time fragmentation is shown in fig. 2 and fig. 3.

We assume a new request *R(A, D, 3, 3)* is arrive, the required number of slots is three, and the holding time is three time units. If a route A-B-C-D is selected in routing phase, then there are two candidate cases for spectrum assignment. When case 1 is selected, slot number S2 of link A-B and B-C, S6 of link C-D are isolated and the three links may lose a chance to accommodate connection requests that has four required slots. If case 2 is selected, it is possible to accommodate connection requests requiring up to four slots at each links. Therefore, we can reduce the spectrum fragmentation according to the spectrum assignment policy.

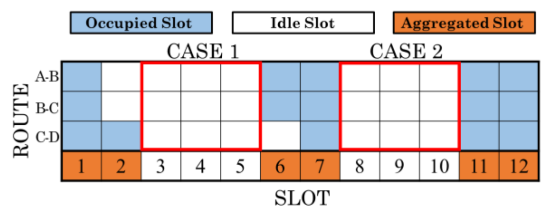


Fig. 2. Spectrum fragmenatation

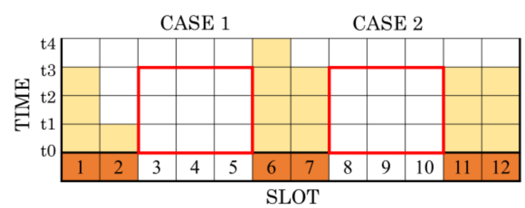


Fig. 3. Time fragmentation

Figure 3 shows an example of the spectrum assignment in view of holding time. The vertical axis represents the holding time of connection requests. At previous example, we assumed that a connection request requires three slots for three time units. If case 1 is selected for the request, the fragmentation will occur at S2 in view of time. Therefore, the holding time should be considered in the fragmentation problem.

III. Dynamic SA based on Fuzzy Logic

In this paper, we propose the SA algorithm based on the fuzzy logic to reduce the spectrum fragmentation. The proposed algorithm only focuses on the phase of the spectrum assignment to select an appropriate spectrum block using the fuzzy logic control system. The fuzzy logic control system define the status of available spectrum blocks based on the spectrum and time fragmentation ratio. The fuzzy logic control system is composed of the following three steps, as shown fig. 4:

1) *Fuzzification:* converts crisp input data into fuzzy data or Membership Functions

2) *Fuzzy Inference Process:* combines membership functions with the control rules to derive the fuzzy output.

3) *Defuzzification:* converts the fuzzy outputs into crisp values.

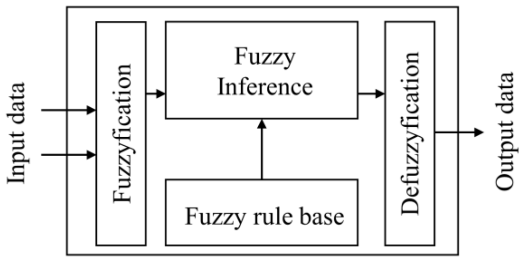


Fig. 4. Fuzzy logic control system

A. *Criterion of fuzzy logic system for SA*

In order to design fuzzy logic control system, we consider two criterions. We use the concept of two dimensional spectrum assignment in our previous work [8] as the criterions for the input membership functions, Spectrum Fragmentation and Time Fragmentation ratio. Each criterion for fuzzy logic system is given in below.

1) *Spectrum Fragmentation Ratio (SFR):* The SFR indicates the degree of spectrum fragmentation in a particular route. Equation (2) and (3) indicate that i^{th} spectrum slot is idle or occupied, and the SFR of the j^{th} spectrum block in route k, respectively.

$$CS_i^l = \begin{cases} 0, & Idle \\ 1, & Occupied \end{cases} \tag{2}$$

$$SFR_j^k = \begin{cases} \frac{(H^k - \sum_{l \in K}^{K} CS_{j+n}^l)}{H^k} & , j = 0 \\ \frac{(H^k - \sum_{l \in K}^{K} CS_{j-1}^l) + (H^k - \sum_{l \in K}^{K} CS_{j+n}^l)}{H^k} & , j > 0 \cap j + n < N \\ \frac{(H^k - \sum_{l \in K}^{K} CS_{j-1}^l)}{H^k} & , j + n = N \end{cases} \tag{3}$$

This value is divided into three cases according to the location of the block, where H^k is the number of hops on the route *k*, *n* is the number of required slots using (1), *N* is the total number of slots in a link. $\sum_{l \in K}^{K} CS_{j-1}^l$ and $\sum_{l \in K}^{K} CS_{j+n}^l$ are the state of aggregated slot for left and right side slots of selected spectrum block, respectively.

2) *Time Fragmentation Ratio (TFR):* The TFR represents the degree of time fragmentation in a particular route.

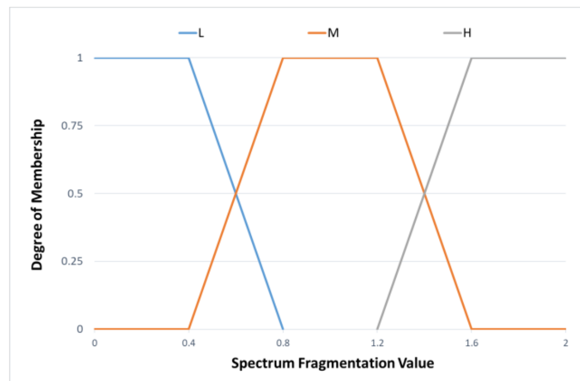
$$GT_j^R = \frac{|t^c + t^h - T_{j+n}^e|}{t^h}, \text{if } GT_j^R > 1 \text{ then } GT_j^R = 1 \tag{4}$$

$$GT_j^L = \frac{|t^c + t^h - T_{j-1}^e|}{t^h}, \text{if } GT_j^L > 1 \text{ then } GT_j^L = 1 \tag{5}$$

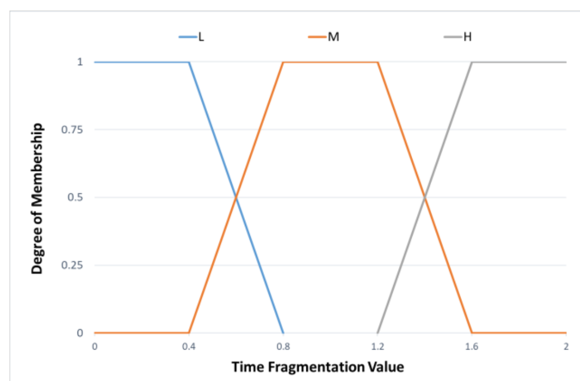
In both (4) and (5), t^c is the current time, T_j^e represents the end time of the corresponding slot, and t^h denotes the required holding time for the request, respectively. All of them do not exceed the maximum of 1. The TFR is determined by (6) according to the location of block based on equations (4) and (5).

$$TFR_j^k = \begin{cases} GT_j^R, & j = 0 \\ GT_j^R + GT_j^L, & j > 0 \cap j + n \\ GT_j^L, & j + n = N \end{cases} \tag{6}$$

Figure 5 show the input membership functions of the SF and TF. The membership functions consist of three trapezoid type fuzzy sets: Low (L), Medium (M), High (H).



(a) Spectrum Fragmentation Ratio



(b) Time Fragmentation Ratio

Fig. 5. Input membership function

B. *Fuzzy Rule Base*

The output of fuzzy logic control system is the crisp value for the condition of available spectrum blocks. The output membership function consists of three triangles and two trapezoid-type fuzzy set: very good (VG), good (G), medium (M), bad (B), very bad (VB), as shown fig. 6. All the membership values will be lies in between 0 to 1.

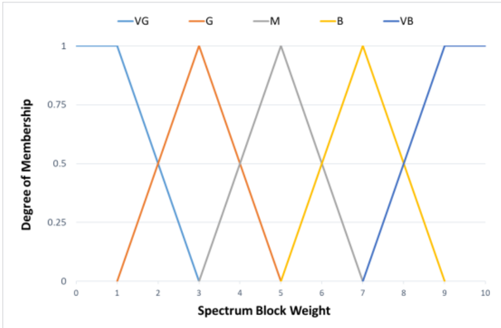


Fig. 6. Output membership function

To define the relationship of the inputs and output, we compose the Mamdani-type fuzzy rule base. The proposed SA algorithm uses nine fuzzy rules, as shown Table II.

TABLE II. FUZZY RULE OF SA

TFR \ SFR	Low	Medium	High
Low	**VG**	**G**	**M**
Medium	**G**	**M**	**B**
High	**M**	**B**	**VB**

Figure 7 shows the flowchart of the proposed algorithm to reduce the spectrum fragmentation problem. At the beginning, the all variables and graph are initialized. When a new connection request arrives, K candidate paths for source and destination node pair using yen's k shortest path algorithm are found. After then, modulation format and required number of slots are selected according to the table 1 and (1). If there are available spectrum blocks on the route, then the spectrum block weight is calculated using fuzzy logic system to assign the spectrum block having the minimum weight. If not, it performs the same operation for next candidate path. After the spectrum assignment for the connection request completes successfully, the variables are updated. If not, the request is blocked.

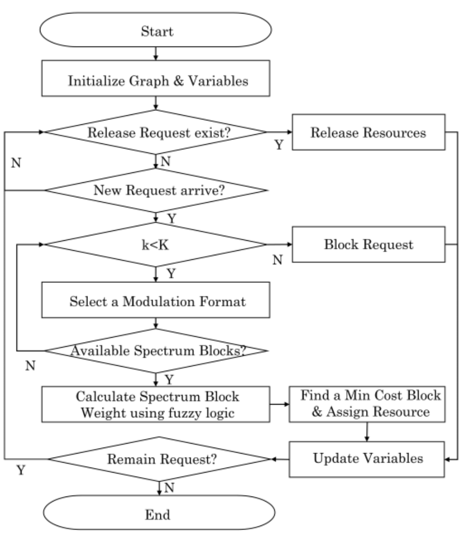


Fig. 7. Flowchart of proposed algorithm

IV. SIMULATION AND RESULT

A. Simulation Environment and Assumptions

To simulate the performance of the proposed algorithm, we set up the simulation in the C ++ development environment with Visual Studio 2017. We use the open source fuzzylite library to implement the fuzzy logic system [13]. NSFNET topology in fig. 8 with 14 nodes and 42 directed links is used. We suppose that each link has 320 spectrum slots with the slot width of 12.5 GHz. We generate 100000 connection requests. The source and the destination node pair is selected according to the uniform distribution, and the required bandwidth is uniformly distributed from 12.5 to 125 Gbps. The modulation format is determined by the distance of the route according to Table 1. We assume the K-value to 5, each connection requests are arrived with Poisson distribution at the average arrival rate λ, and the connection holding time is $1/\mu$, which has exponential distribution with the average 50 unit time. The network load is calculated as λ/μ.

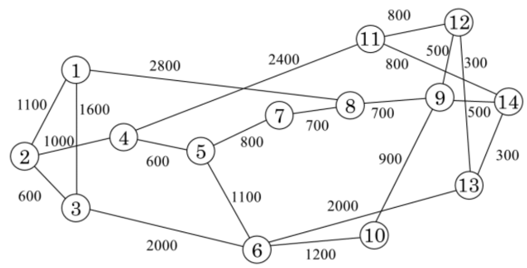


Fig. 8. Network topology (NSFNET)

B. Performance Evaluation

The performance of the proposed algorithm is evaluated in view of average bandwidth blocking probability and the spectrum utilization. The bandwidth blocking probability and spectrum utilization are important performance criterion to evaluate the network performance. The performance of the proposed algorithm is compared with the conventional methods, which use First-Fit and Best-Fit spectrum assignment policies. In order to analyze the effect of the fuzzy logic system and two-dimension policy considering the SFR and TFR criterion, we also compare the proposed algorithm with spectrum assignment policies considering the single spectrum and time fragmentation criterion only.

In fig. 9, we compare the proposed SA algorithm with First-Fit, Best-Fit, SFR, and TFR policies in terms of average bandwidth blocking probability. In this results, it shows that the proposed SA algorithm reduces considerably the bandwidth blocking probability and that it outperforms the conventional First-Fit and Best-Fit policies. Comparing the proposed SA algorithm with the policy applying the single SFR and TFR, the proposed algorithm based on the fuzzy logic system considering two fragmentation criterions can reduce the average bandwidth blocking probability. It implies that our SA algorithm using fuzzy logic system with the spectrum and time fragmentation ratio efficiently allocates the connection requests to the appropriate spectrum blocks that have remain holding time similar with the required holding time and less the spectrum fragmentation.

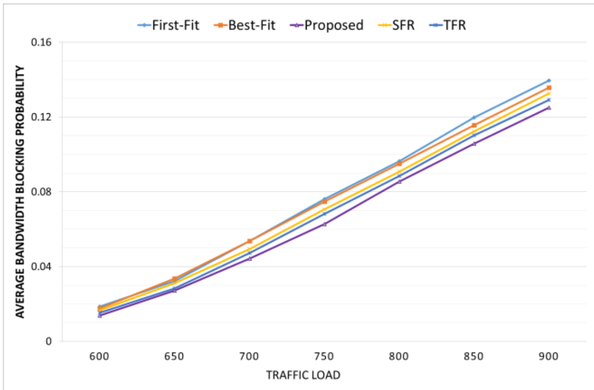


Fig. 9. Average bandwidth blocking probability

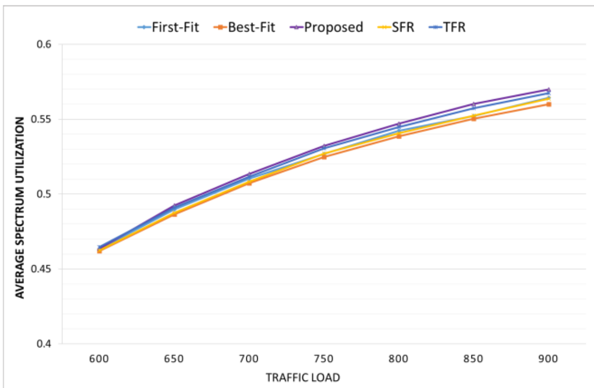


Fig. 10. Average spectrum utilization

Figure 10 presents the average spectrum utilization of the proposed SA algorithm, the conventional First-Fit, Best-Fit, SFR, and TFR policies. It shows that the proposed SA algorithm achieves the highest spectrum utilization under any traffic load. The reason is that proposed algorithm accommodated more connection requests rather than the conventional First-Fit, Best-Fit, SFR, and TFR policies. It presents that the proposed algorithm can efficiently manage the network resource and mitigate the spectrum fragmentation.

V. Conclusion

In elastic optical networks, one of main issues is to mitigate the spectrum fragmentation problem due to the setting up and departure of non-uniform bandwidth requests. The fragmentation results in reducing the network performance in EONs. In this paper, we proposed a spectrum assignment algorithm based on the fuzzy logic to reduce the spectrum fragmentation in EONs. We designed a fuzzy logic control system to define the status of available spectrum blocks based on spectrum and time fragmentation ratio. The spectrum block that has minimum crisp value was allocated for the connection request. The performance of the proposed algorithm was evaluated in terms of the average bandwidth blocking probability and the spectrum utilization. The simulation results showed that the proposed algorithm has better performance comparing to the conventional policies under any traffic load. This implied that the proposed algorithm mitigated the spectrum fragmentation.

Acknowledgment

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