Efficient Planning and Provisioning of Flexible-Grid Optical Networks with Adaptive Genetic Algorithms

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***Abstract*—In this paper, we discuss adaptive genetic algorithms (GA) that can solve the routing, modulation-level, and spectrum assignments (RMSA) for both static and dynamic optical orthogonal frequency-division multiplexing (O-OFDM) networks, with high efficiency. Based on network status and traffic information, the GAs encode the RSMA of lightpaths as genes and optimize them with a process that mimics the natural evolution. Both the crossover and mutation in the GAs operate adaptively according to the fitness of individuals. The simulation results show that compared with several existing algorithms, the adaptive GA achieves better static network planning with more efficient spectrum resource utilization in both the NSFNET and US Backbone topologies. Meanwhile, the GA converges within 80 generations. In dynamic network provisioning, multi-objective optimization is incorporated to improve spectral efficiency and reduce blocking probability simultaneously. For low traffic cases when there is no blocking, the GA focuses on minimizing the maximum number of slots required on any fiber in the network. Otherwise, it tries to minimize the blocking probability when the traffic load is high. The simulation results also indicate that the GA achieves the best provisioning performance in terms of blocking probability.**

***Index Terms*—Optical orthogonal frequency-division multiplexing (O-OFDM), routing, modulation-level, and spectrum assignment (RMSA), adaptive genetic algorithm**

I. Introduction

With the rapid development of various network applications and the soaring of people's desire on information, bandwidth demand is growing continuously in the Internet and greatly accelerates the research and development of flexible and scalable networking technologies. It has been demonstrated that a single optical fiber could support transmission of 20 Tb/s signal over more than 6000 km [1]. In order to utilize this tremendous optical bandwidth efficiently, researchers are still searching for optical technologies for network planning and provisioning [2–23]. Owing to the reason that it can achieve high bandwidth efficiency and sub-wavelength granularity [24], optical orthogonal frequency-division multiplexing (O-OFDM) technology recently has attracted intensive research interests [25–64]. As shown in Fig. 1, the traffic requests are carried by overlapped and orthogonal subcarrier frequency slots, and hence elastic bandwidth allocation can be achieved. Moreover, the modulation-level of each slot can be adaptive to accommodate various transmission reaches [25]. Under this mechanism, a bandwidth variable (BV) O-OFDM transponder [24] can assign just-enough bandwidth to serve the lightpath requests.

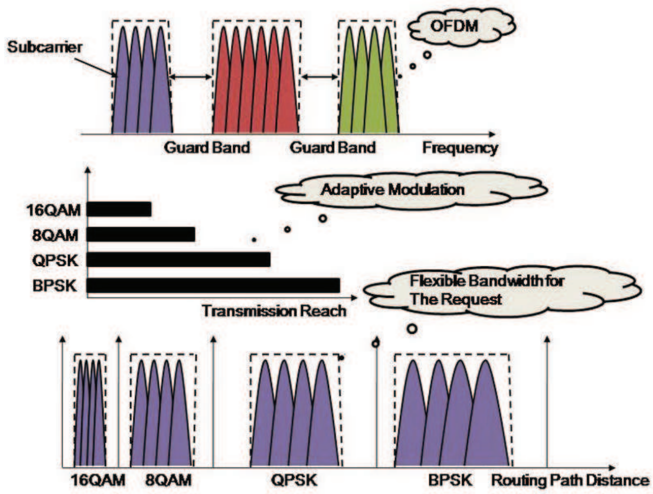

Fig. 1. Flexible bandwidth allocation in O-OFDM systems

The elastic nature of O-OFDM networks calls for more sophisticated network planning and provisioning mechanisms. Besides, the subcarrier slots allocated to each request should be contiguous in the frequency domain, and proper modulation-levels need to be selected to balance the tradeoff between transmission performance and bandwidth efficiency. To solve these problems, effective routing, modulation-level, and spectrum assignment (RMSA) algorithms are required for both network planning and provisioning. In [25], inspired by the wavelength-division multiplexing (WDM) network design with mixed line rates [11], the authors came up with a routing and spectrum assignment (RSA) algorithm based on the combination of shortest path routing and first-fit spectrum assignment. In [49], the authors proposed a bandwidth-efficient and distance-adaptive RMSA by figuring out K shortest paths for each lightpath request and selecting the one with the lowest available contiguous subcarrier slots. For network provisioning, dynamic RMSA algorithms have been discussed in [37] under the spectrum-continuity constraint, since all-optical spectrum converter may not be practically available in the near future.

In this paper, we discuss how to achieve scalable and efficient O-OFDM network planning and provisioning with genetic algorithms (GA). We put together adaptive GA whose key parameters can change their values based on the optimization status. The rest of the paper is organized as follows. Section II formulates RMSA problems for both static network planning and dynamic network provisioning. The designs of the adaptive GA are presented in Section III. In Section IV, we evaluate the performance of the GA for RMSA in several network topologies. Finally, Section VI summarizes the paper.

II. Problem Formulation

A. Design Considerations of Static O-OFDM Network Planning

For the static O-OFDM network planning, all the requests are known a priori. The RMSA problem is to assign routing paths, modulation-levels and frequency slots for all the requests. The physical network topology is $G(V,E)$, where V is the nodes set and E is the fiber links set. The capacity of a slot is related to the modulation-level M. If we define C as the capacity of a slot when $M=1$, then the capacity of a slot is $M \cdot C$ for different modulation-levels. In this work, M can be 1, 2, 3, 4 for BPSK, QPSK, 8 QAM, and 16 QAM, respectively. M is determined by the transmission distance of the routing path. For a lightpath request that needs B data-rate, the number of contiguous slots N we need to assign for it is:

$$N = \lceil \frac{B}{M \cdot C} \rceil + N_g \tag{1}$$

where N_g is a constant number for the slots of the subcarrier guard-bands. In this work, we assume that there is no spectrum conversion available, and hence we must satisfy both the spectrum continuity and spectrum non-overlapping constraints in the network planning.

In static network planning, we assume the bandwidth resource on the fiber links is large enough that no lightpath request is blocked. For certain lightpath request set, when the network planning is finished, we evaluate its performance with a fitness function defined in [37] as

$$F_s = max(f(e)), \forall e \in E \tag{2}$$

where $f(\cdot)$ is the function to return the index of the maximum used slot on a link e in $G(V,E)$. A smaller fitness F_s reflects a more efficient RMSA, as we can allocate a smaller number of slots per fiber link to satisfy the same traffic demands. Therefore, we strive to find the RSMA that can minimize F_s in the network planning.

B. Design Considerations of Dynamic O-OFDM Network Provisioning

For dynamic O-OFDM network provisioning, the RMSA problem focus on how to serve time-variant lightpath requests. Since the occurrences of request blocking may become unavoidable and we have to try our best to minimize the blocking probability. Hence, the fitness function for dynamic network provisioning is designed in [37] as

$$F_d = max(f(e)) + H \cdot \mu(F_b) + F_b, \forall e \in E \tag{3}$$

where H is a large constant for punishing blocking, $\mu(\cdot)$ is a unit step function that $\mu(x)=1$ for $x>0$, otherwise $\mu(x)=0$, and F_b is the number of blocked requests. The objective of the dynamic network provisioning is to minimize F_d at any service provision time. When the traffic load is low and there is no blocking, the fitness function will be the same as that in the static network planning (i.e. Eqn. (2)). For high traffic load, request blocking is considered in F_d.

III. Design of Adaptive Genetic Algorithms for RMSA

GA can obtain solutions of complicated optimization problems by using techniques inspired by the natural evolution, such as inheritance, crossover, selection and mutation. We focus on the details of the adaptive GA for RMSA in this section.

A. Genetic Encoding for RMSA

In GA, genetic encoding means decomposition of the solution space into serval dimensions. Fig. 2 illustrates an example of the genetic encoding procedure for RSMA. We first find out all feasible routing paths for each s-d pair in $G(V,E)$ using a link-disjoint path search (LDPS) algorithm and denote the routing paths with an unique positive R-index to form a routing path table. Secondly, for each pending request LR_i, we figure out the modulation-level $M_i^{(k)}$ and required slot number $N_i^{(k)}$ based on the its capacity and the transmission distance of the routing path $R_{s,d,i}^{(k)}$. To this end, we obtain a gene for RMSA of the request LR_i, $Gene_i^{(k)} = \{R_{s,d,i}^{(k)}, M_i^{(k)}, N_i^{(k)}\}$. For network provisioning, the RMSA of LR_i over $R_{s,d,i}^{(k)}$ may be unavailable due to resource limitation, and we record a request blocking in this case. An individual chromosome that contains numbers of genes can be formed by repeating the above procedures for all pending requests. Then, by combining different individuals, a population can be constructed.

B. Genetic Operations

When the genetic encoding for all individuals in a population is done, we compute their fitness with the functions in Eqn. (2) or Eqn. (3), for static network planning or dynamic network provisioning, respectively. We then utilize Tournament Selection to select pairs of individuals from the current population, based on their fitness values, as parents for crossover. Crossover is a multi-point operation on the gene-level, which means that certain number of genes are selected and swapped at random locations of parents based on a crossover ratio p_c (i.e. the crossover probability of a gene). We take pairs randomly from the parents and apply crossover to them. New offspring individuals are produced with the crossover. We select fittest individuals as the next generation from the whole population pool that includes both parents and

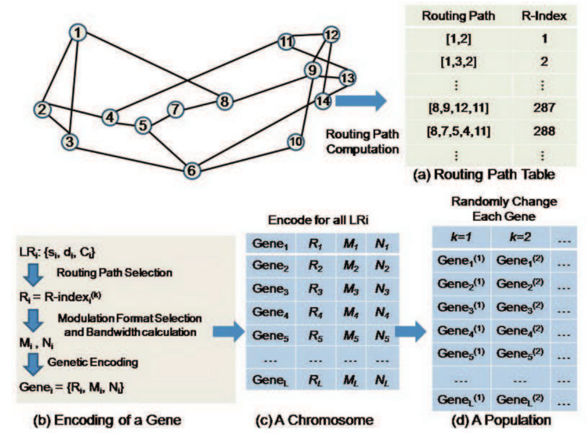

Fig. 2. Genetic encoding for the RMSA problem in an elastic O-OFDM network

offsprings, while keeping the population size as constant. The selected individuals then go through the mutation phase in which certain number of genes are randomly changed based on a mutation ratio p_m. The two key parameters, the crossover ratio p_c and mutation ratio p_m, play vital roles in GA. Here, we adopt an adaptive mechanism to alter them based on the individuals' fitness.

C. Fitness Update and Algorithm Convergence

Note that every time after crossover or mutation we need to assign spectrum for all individuals again to update their fitness. For each individual, the spectrum assignment is performed with the *First-Fit* scheme that use the first available contiguous slots along the path.

One important aspect of a GA is its convergence performance, as shorter convergence time implicates better algorithm design. To qualify the GA's convergence performance, we define a diversity degree as:

$$D_p = \frac{2}{P_{size}(P_{size}-1)} \sum_{k=1}^{P_{size}-1} \sum_{k=k_1+1}^{P_{size}} \frac{d(k_1,k_2)}{L} \quad (4)$$

where $d(k_1, k_2)$ denotes the number of different genes among all L genes between individual k_1 and individual k_2, P_{size} is the size of the population. We claim the GA has converted when D_p becomes lower than a threshold for certain number of generations. Here the empirical value of the threshold is obtained by running a large number of simulations that each involves hundreds of generations.

IV. Performance Evaluations

We conduct our simulations using the NSFNET (with 14 nodes and 22 links) and US Backbone (with 24 nodes and 43 links) topologies. We assume that the bandwidth of each subcarrier slot is a constant as 12.5 GHz, and for the dynamic provisioning, the network is deployed on C-band spectrum that contains 4.75 THz bandwidth, i.e. 358 slots can be accommodated on each optical link. The s-d pairs of the lightpath requests are selected randomly and the required bit-rate is uniformly distributed from 10 Gb/s to 100 Gb/s. The population size of the GA is 50.

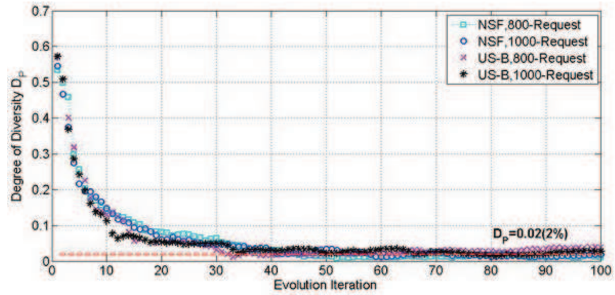

Fig. 3. Convergence performance of the static GA-RMSA for two network topologies

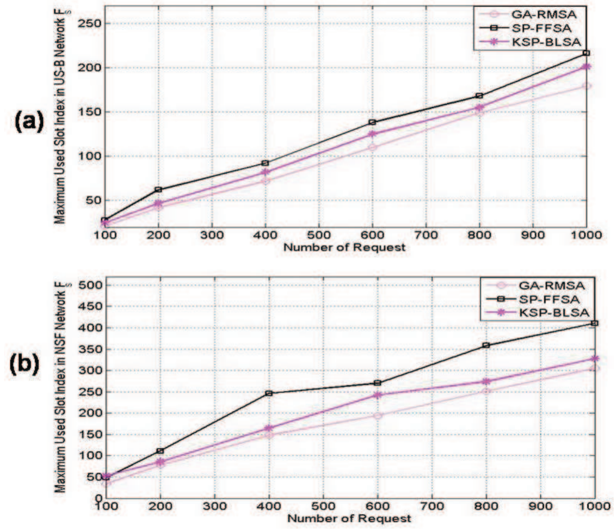

Fig. 4. The comparisons of F_s from three different static RMSA algorithms for (a) US Backbone and (b) NSFNET topologies

A. Static Network Planning with RMSA

For network planning, Fig. 3 depicts the evolutions of D_p with the adaptive GA, for request sets that contain 800 and 1000 lightpath requests. The simulation is performed with the NSFNET and US Backbone topologies. It can be seen that the GA converges within 80 generations for both topologies. Fig. 4 compares the network planning results from the GA based RMSA algorithm to two existing algorithms, the Shortest Path Routing and First-Fit Spectrum Assignment (SP-FFSA), and the K-Shortest Path Routing and Balanced Load Spectrum Assignment (KSP-BLSA). When comparing to the results from the SP-FFSA and KSP-BLSA, we can see that the GA-RMSA reduces the frequency slots up to ∼40%, ∼35% in the NSFNET topology, and ∼32%, ∼16% in the US-B topology, respectively.

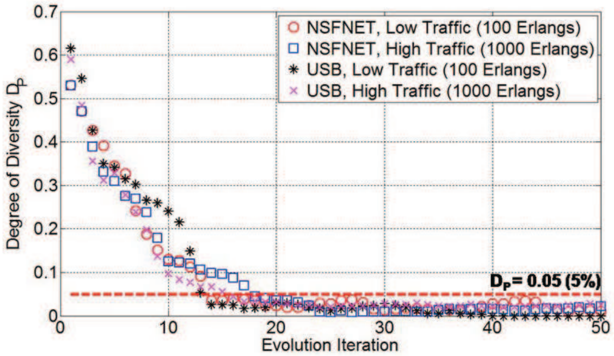

Fig. 5. Convergence performance of the dynamic GA-RMSA for two network topologies

B. Dynamic Network Provisioning with RMSA

For network provisioning, the traffic requests arrives dynamically obeying the Poisson process. We evaluate the convergence performance of the GA with the D_p defined in Eqn. (4), and Fig. 5 shows the results with the NSFNET and US Backbone topologies. If we set the threshold of D_p at 0.05 for 5 generations, we can see that the GA has converged after ~ 25 generations in both topologies. We perform simulations with different traffic loads to show the performance of GA. Fig. 6 and 7 depict the performance comparisons of the GA-RMSA to SP-FFSA and KSP-BLSA, by using the NSFNET topology. Fig. 6 plots the maximum used slot index in the network, at each service provision time. Comparing with SP-FFSA and KSP-BLSA, the GA-RMSA provides the smallest used slot index throughout the simulation for the low traffic case (100 Erlangs), while for the high traffic case (800 Erlangs), the network with the GA-RMSA approaches to the saturation state with the slowest speed. With respect to the blocking probability, Fig. 7 reveals the comparisons of the blocking probability from different dynamic RMSA algorithms in both the NSFNET and US-Backbone topologies. Obviously, the blocking probability from the GA-RMSA is the smallest and has a average reduction of ~20%, compared to those from the SP-FFSA and KSP-BLSA.

V. Conclusion

We discussed adaptive genetic algorithms to solve RMSA for efficient O-OFDM network planning and provisioning. Given the network topology and requests information, we encoded the RMSA of all lightpath requests as genes and optimized them with the GA. In static RMSA for network planning, the GA was proved to produce better solutions than several existing algorithms. In dynamic RMSA for network provisioning, the GA offered an efficient way of serving the dynamic lightpath requests based on the current network status at each service provision time.

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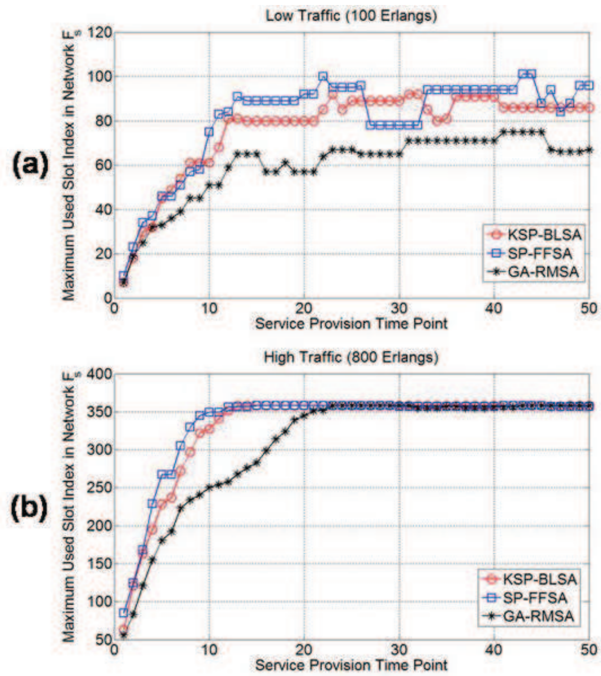

Fig. 6. The evolutions of F_s from three different dynamic RMSA algorithms in NSFNET topology for a) low traffic case (100 Erlangs) and (b) high traffic case (800 Erlangs)

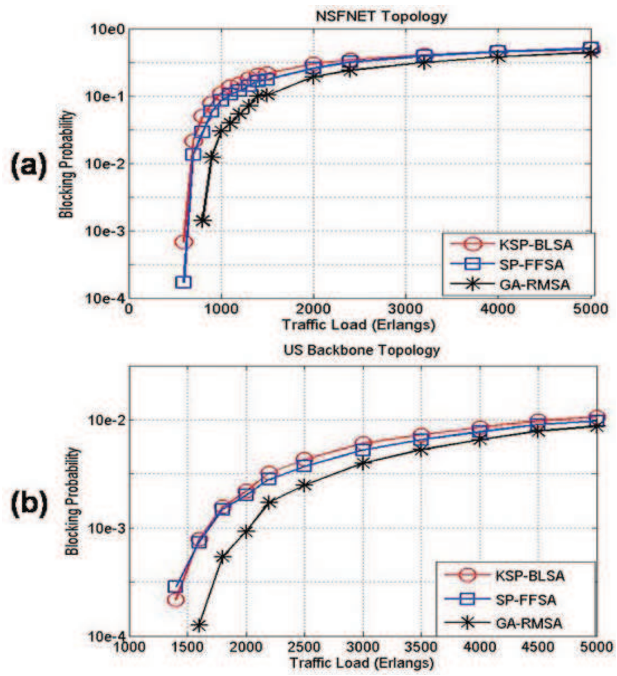

Fig. 7. Blocking probability comparisons for (a) NSFNET and (b) US Backbone topologies

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