Using Genetic Algorithm to Optimize Mixed Placement of 1R/2R/3R Regenerators in Translucent Lightpaths for Energy-Efficient Design

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***Abstract*—We propose an evolutionary approach to efficiently optimize the mixed placements of 1R/2R/3R regenerators in translucent lightpaths. The genetic algorithm encodes the placements of mixed types of regenerators as genes, and incorporates adaptive genetic operators for effective search strategy. We consider both end-to-end signal transmission quality and regeneration energy cost, and design the fitness function for multi-objective optimization. The simulation results show that the proposed approach converges within 50 generations even when the lightpath under investigation is as long as 31 hops. To improve the flexibility of network designs, multiple energy-efficient mixed regenerator placement (MRP) results can be obtained simultaneously.**

***Index Terms*—Genetic algorithm, mixed regenerator placement, energy-efficient optical networks.**

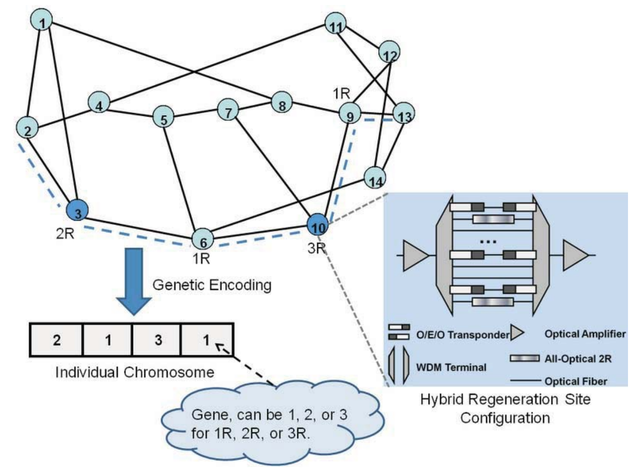

Fig. 1. Genetic encoding of the MRP problem.

I. INTRODUCTION

WHILE the remarkable growth of Internet bandwidth demands have spurred intensive research on efficient optical networking systems, the major technical difficulties are still the physical layer limitations. In opaque networks, optical-electronic-optical (O/E/O) 3R (Re-amplification, Re-shaping, and Re-timing) regenerators suppress signal distortions at every switching node to increase transmission reach. However, since these 3R are usually expensive and power-hungry [1], network operators have to mitigate their network infrastructure from opaque to translucent, for reducing capital expenditures (CAPEX) and operational expenditures (OPEX) [2]. Translucent network design aims to minimize the number of 3R, without compromising transmission performance. Recently, all-optical 2R (Re-amplification and Re-shaping) regenerators have been demonstrated for operation speed at 40 Gb/s and beyond [1], and commercially available devices have been released [3,4]. Compared to O/E/O 3R, these devices are much more energy-efficient, and can achieve wavelength conversion simultaneously with signal regeneration [1,4]. Therefore, they can partially replace 3R in optical networks, and solve the signal quality and wavelength contention issues with a more energy-efficient way. To explore these benefits, we have proposed a translucent lightpath arrangement that involves mixed placement of optical inline amplifiers (1R), all-optical 2R, and O/E/O 3R, for energy saving [5]. However, the mixed regenerator placement (MRP) algorithm in [5] depends on exhaustive search, which will become impractical when the lightpath has a large number ($\geq$ 20) of intermediate nodes for regenerator placements, or there is a need for multiple placement candidates.

In this letter, we propose to optimize the MRP more efficiently with a genetic algorithm (GA). The placements of 1R/2R/3R in a lightpath are encoded as genes. We consider both the end-to-end transmission quality and the regeneration energy cost, and formulate a fitness function for multi-objective optimization. The size of the population is properly selected, and the genetic operators (i.e., selection operator, crossover operator, and mutation operator) are designed as adaptive for fast convergence speed.

II. GENETIC ALGORITHM FOR LIGHTPATH DESIGN

Genetic algorithm is a search strategy that mimics natural evolution [6]. With genetic encoding, a possible solution is represented by a data structure of genes, called individual chromosome. A set of individuals are randomly generated as the initial population P_{init}. Each individual is evaluated with a fitness function, and selection chooses relatively fit individuals as parents for crossover. In crossover, a pair of parents exchange their genes to create offsprings. The individuals may then mutate their genes to increase population diversity. By applying these procedures iteratively, the GA modifies the population consistently, until good solutions have been found. *Algorithm 1* shows the logic flow of our proposed GA.

A. Genetic Encoding and Fitness Function

We consider a hybrid configuration of regeneration site as illustrated in the inset of Fig. 1. When there is no regenerator (2R or 3R) between the WDM terminals, the signal is re-amplified (1R) only with inline fiber amplifiers. We assume

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Algorithm 1 Genetic Algorithm for Optimizing MRP

Input: N-hop Lightpath $L_{s,d}$, Fitness threshold F_{TH}, BER_t, Initial population size M_{init}, Desired solution set size M_{sol}, Maximum number of generations G_{max}
Output: Desired MRP solution set P_{sol}

$\{$Phase I$\}$
$P_{init} \leftarrow \emptyset$;
$P_{sol} \leftarrow \emptyset$;
while $|P_{init}| < M_{init}$ **do**
  generate new individuals with $N-1$ genes randomly;
  kill individuals with apparently low fitness;
  $P_{init} \leftarrow$ new individuals;
end while
$\{$Phase II$\}$
$Generation = 1$;
$P = P_{init}$;
while $|P_{sol}| < M_{sol}$ AND $Generation < G_{max}$ **do**
  if BER-qualified individuals $< 10\%$ **then**
    evaluate P using the fitness function with $\beta = 0$;
  else
    evaluate P using the fitness function with $\beta = 1$;
    $P_{sol} \leftarrow$ individuals with $F_{s,d} < F_{TH}$;
  end if
  $P_{parents} = Select(P)$;
  $P_{offsprings} = Crossover(P_{parents})$;
  $P_{temp} = P_{parents} \cup P_{offsprings}$;
  $P = Select(P_{temp})$;
  $P = Mutate(P)$;
  $Generation = Generation + 1$;
end while

the optical signal is in an on-off keying (OOK) format, and bit-error-rate (BER) is the performance indicator. As illustrated in Fig. 1, for a lightpath $\{2\text{-}3\text{-}6\text{-}10\text{-}9\text{-}13\}$, the signal gets regenerated by a 2R and a 3R at nodes 3 and 10, respectively. The 5-hop lightpath has four intermediate nodes for regenerator placement, and we can encode the MRP of this lightpath as an individual chromosome [2 1 3 1]. Hence, for an arbitrary lightpath $L_{s,d}$ with N hops, the corresponding individuals have $N-1$ genes. Each gene can be 1, 2, or 3, for a placement of 1R, 2R, or 3R at an intermediate node.

When the MRP of a N-hop lightpath $L_{s,d}$ is determined, we can calculate end-to-end $BER_{s,d}$ by estimating the BER evolution hop-by-hop with the model in [5]. The regeneration energy cost P_{Regen} of the lightpath can be calculated by summarizing the energy cost of all 2R and 3R regenerators in it. The BER threshold of a lightpath is BER_t. The fitness function is designed as:

$$F_{s,d} = \alpha \cdot f(BER_{s,d}) + \frac{\beta}{N-1} P_{Regen} \tag{1}$$

where α and β are coefficients for balancing the evolution direction between signal quality and energy cost. Note that α and β can change during evolution. $f(BER_{s,d})$ has a formulation of

$$f(BER_{s,d}) = \{ \begin{array}{ll} log_{10}(BER_{s,d}), & BER_{s,d} < BER_t \\ M, & BER_{s,d} \geq BER_t \end{array} \tag{2}$$

TABLE I
SIMULATION PARAMETERS

Output power per wavelength channel	0 dBm
Fiber loss	0.25 dB/km
PMD parameter	0.1 $ps/\sqrt{km}$
EDFA noise figure	6 dB
EDFA spacing	75 km
Link length between two adjacent intermediate nodes	150 - 450 km
Total number of intermediate nodes	8 - 30
Data rate	40 Gb/s
BER_t, End-to-end BER threshold	10^{-4}
Data sequence for BER estimation	PRBS $2^{31}-1$
M_{init}, Initial population	50
Energy cost per 2R	2 units
Energy cost per 3R	25 units

M is a large positive integer for discouraging the selection of MRP with $BER_{s,d} \geq BER_t$.

B. Initial Population and Population Size

When the intermediate nodes of a lightpath are determined, an initial population is randomly generated with different combinations of MRP along the lightpath. To improve the convergence performance, we implement a filtering process to kill individuals with apparently unfavorable fitness. We choose an appropriate population size (e.g. 50) and keep this size as constant through the evolution.

C. Selection

The selection operator is used for two operations: 1) to select parents from the current generation for crossover, and 2) to select individuals from the union of parents and their offsprings for the next generation. The selection is based on a modified roulette method [6], with the preference to individuals with small $F_{s,d}$. To make sure the BER requirement is first satisfied, we set $\alpha = 2$ and $\beta = 0$ initially. When the percentage of individuals that satisfy $BER_{s,d} < BER_t$ is larger than 10%, we change β to $\beta = 1$ to direct the evolution to prefer energy-efficient solutions.

D. Crossover and Mutation

After the parents are selected, they are sorted from fittest to less fit. We then take pairs in a descending order and make them crossover to get offsprings. The crossover is a multi-point operation on the gene level, with randomly selected locations. To make the crossover adaptive to fitness, the number of locations is proportional to the average value of parents' $F_{s,d}$. When the parents are not yet fit, large portion of genes are exchanged to increase the searching space. Otherwise, good combinations of genes are preserved. After crossover, the mutation possibility of genes is also proportional to an individual's $F_{s,d}$.

III. Performance Evaluation

Table I shows the simulation parameters for the performance evaluation. We assume that the FEC functionality only exists at the end nodes of lightpaths, and set BER_t at 10^{-4}. The energy cost of all-optical 2R and O/E/O 3R are assumed based on the parameters in [1,7].

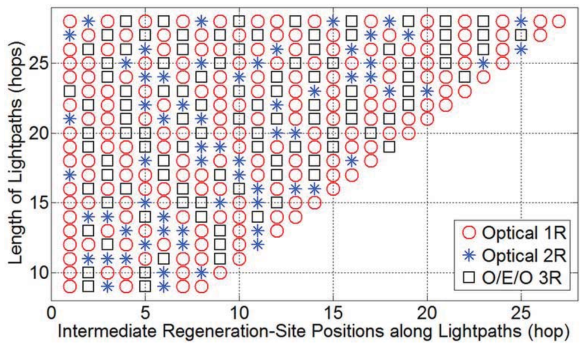

Fig. 2. MRP results for lightpahts with lengths of 9 to 28 hops.

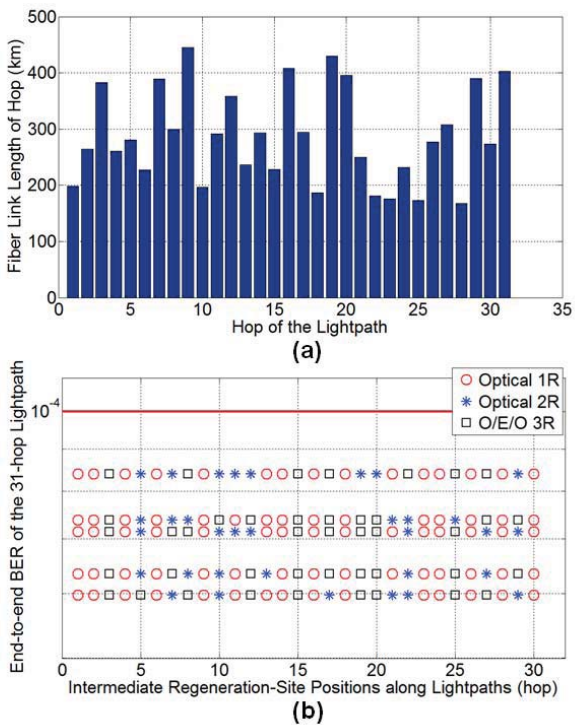

Fig. 3. (a) Link lengths of a 31-hop lightpath, (b) Five optimized MRP results for the lightpath.

We first assume that the fiber link length is identical between the intermediate nodes, as 160 km. Fig. 2 shows the fittest MRP results for lightpaths from 9 to 28 hops. The GA gets these results within 32 generations. The fiber link lengths between two adjacent nodes are then randomly chosen in the range of 150 to 450 km. Fig. 3(a) shows the link lengths of a 31-hop lightpath, and Fig. 3(b) plots five optimized MRP results found by the GA within 50 generations. Fig. 4(a) plots the histograms of the GA's results for the 31-hop lightpath, and we can see that the algorithm converges after 50 generations, where the percentage of individuals with $F_{s,d} < 0$ stabilizes at $\sim 40\%$. Fig. 4(b) shows $F_{s,d}$ of the fittest individual through evolution, and the curve also shows convergence after 50 generations.

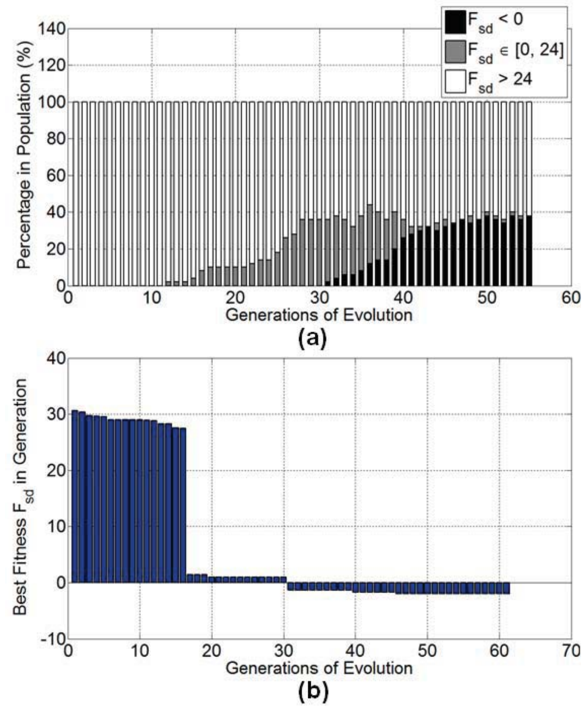

Fig. 4. (a) Histograms of $F_{s,d}$ for MRP individuals of the 31-hop lightpath, (b) Best fitness for generations.

IV. Conclusion

We proposed a genetic algorithm to optimize the placements of 1R/2R/3R regenerators in lightpahts for high energy-efficiency. By considering both the signal quality and regeneration energy cost, we achieved multi-objective optimization with a properly designed fitness function. Simulation results showed that the proposed algorithm converged within 50 generations, and multiple optimized regenerator placements could be obtained simultaneously.

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