Design Energy Efficient Translucent Optical Networks with Joint Routing and Wavelength Assignment and Mixed Regenerator Placement

Weida Zhong, Zuqing Zhu*, Chuanqi Wan
University of Science and Technology of China, Hefei, Anhui 230027, P. R. China, Email: zqzhu@ieee.org
Farid Farahmand
Sonoma State University, Rohnert Park, CA 94928, USA, Email: farid.farahmand@sonoma.edu

Abstract: We propose network design algorithms to improve energy-efficiency of a translucent network with joint optimization of RWA and mixed regenerator placement (MRP). Simulations show that the MRP schemes achieve effective energy-saving and low blocking probability.

OCIS codes: (060.4251) Networks, assignment and routing algorithm; (060.4264) Networks, wavelength assignment

1. Introduction

The objective of translucent optical network design is to minimize the number of optical-electronic-optical (O/E/O) 3R regenerators in optical networking systems without compromising transmission performance [1]. Previous translucent network designs only relied on O/E/O 3R to solve the signal quality and wavelength contention issues [2,3]. However, due to the fact that 3R are relatively power-consuming, it is desired to further reduce their numbers for better energy-efficiency. Recently, all-optical 2R regenerators have been demonstrated for operation speeds at 40 Gb/s and beyond [4], and commercially available devices were released [5,6]. These devices consume much less power [4,6], and can achieve wavelength conversion simultaneously with signal regeneration [4]. Therefore, they may partially replace 3R in networks, and solve the signal quality and wavelength contention issues with a more energy-efficient way. On the other hand, previous works usually assume that there is FEC functionality in 3R and the signal quality gets restored after each 3R [2,3]. However, for those 3R, the FEC itself and the associated DSP can consume more than 20% of the total energy [7]. Due to the cost and energy constraints, some 3R may not have the FEC capability. In our recent work [8], we proposed to include all-optical 2R in translucent networks and utilize mixed regenerator placement (MRP) to reduce the energy consumption of lightpaths. In this paper, we extend our previous work on lightpath design to network design, and propose algorithms that can further improve the energy-efficiency of a translucent network with joint optimization of routing and wavelength assignment (RWA) and MRP. We investigate the performance of the algorithms with simulations using a NSFNET topology and a practical traffic matrix. The results on offline network design show that the proposed algorithms effectively reduce the number of 3R in the network, and achieve a green network design. Online network provisioning is also investigated to evaluate the performance of the network design algorithms, and simulation results illustrate that MRP can decrease the blocking probability with a reduced energy cost.

2. Offline Network Design with Joint RWA and MRP

Fig. 1(a) shows the hybrid configuration of a regeneration site that is considered in this work. When there is no regenerative device between the WDM terminals, the signal is re-amplified (1R) only with optical in-line amplifiers. We assume the optical signal is in an on-off keying (OOK) format. The WDM network topology is $G(V,E)$, where V is the node set, and E is the fiber link set. We define the BER threshold of a lightpath as BER_t, and let $BER_{s,d,k}$ denote the end-to-end BER of the *k-th* lightpath from node *s* to *d*. For an arbitrary lightpath, $BER_{s,d,k}$ is calculated by estimating the BER evolution hop-by-hop with the model in [8]. To minimize energy consumption on FEC, we assume that it only exists in the end nodes of each lightpath, and set BER_t at 1E-4. Note that to satisfy $BER_{s,d,k} < BER_t$, the regenerator placement for each lightpath is not unique [8]. $R2_u$ and $R3_u$ denote the numbers of 2R and 3R at node *u*, and the energy cost per regenerator for 2R and 3R is P_{2R} and P_{3R}. We then define the energy-efficient network design problem as: Given a topology $G(V,E)$, wavelength set *W*, and traffic matrix Λ_{sd}, choose routing path, place regenerators and assign wavelengths for lightpaths to minimize:

$$P_{\mathrm{Regen}} = P_{3R}\sum_{u\in V} R3_u + P_{2R}\sum_{u\in V} R2_u \tag{1}$$

and the transmission performance should be guaranteed:

$$BER_{s,d,k} \le BER_t, \forall s,d \in V, \forall k \tag{2}$$

Meanwhile, the constrains on capacity, flow-conservation, and wavelength-continuity should also be satisfied. To solve this problem, our proposed algorithm first finds *N* shortest routing paths $R_{s,d}^{(1)}, R_{s,d}^{(2)}, ..., R_{s,d}^{(N)}$ for each lightpath request from node *s* to *d*. Based on the length, link characteristics, and BER_t of each path, *M* regenerator placement schemes are then calculated for each path. Here, we consider two scenarios, *mixed placement of 2R and 3R* (2R&3R-MRP) and *3R-only placement* (3R-ORP). Since both 2R and 3R regenerators can achieve wavelength conversion, we only need to consider the wavelength continuity constraint for the segments between them. To minimize the energy cost on regenerators, we use a *maximum transparent segment length* algorithm for wavelength assignment. Specifically, for each segment between regenerators, we try to find a wavelength that is commonly available, and when the wavelength cannot be found, we insert a regenerator for wavelength conversion. For the 2R&3R-MRP scenario, we only insert 2R for wavelength conversion to save energy. When the wavelength assignment and regenerator placement adjustment are finished for each of the *M* schemes, the combination with the lowest energy cost is selected for the path $R_{s,d}^{(i)}$. And then, among the *N* paths, we pick the one with the lowest energy cost for the lightpath request, and commit the selection into the network.

In order to evaluate the performance of the proposed network design algorithm, we perform simulation experiments with a NSFNET network topology as illustrated in Fig. 1(b). We define two types of nodes in the topology, 1) primary nodes (labeled with numbers) at where the lightpaths can start and end, and 2) secondary nodes at where the lightpaths can only pass through. We assume the fiber link length between two adjacent nodes is identical, and Fig. 2(a) shows the simulation parameters. The traffic matrix Λ_{sd} is in Fig. 2(b) [9]. The simulation generates lightpath requests by picking up the source and destination nodes with a probability normalized from Λ_{sd}, and the requests are handled sequentially. Fig. 3(a) shows the number of 3R required for different volumes of lightpath requests in the NSFNET topology. For each data point, we simulate 16 times and average the results for statistical accuracy. It can be seen that the MRP scheme requires much less 3R, comparing to the traditional ORP one. The average number of 3R per request in MRP scheme is ~1.2, while this value of the ORP is ~2.5. Using the values of energy costs in Fig. 2(a) [8], we plot the total energy consumption for the two schemes in Fig. 3(b). It can be seen that the MRP scheme can save up to 50% energy consumption on regeneration.

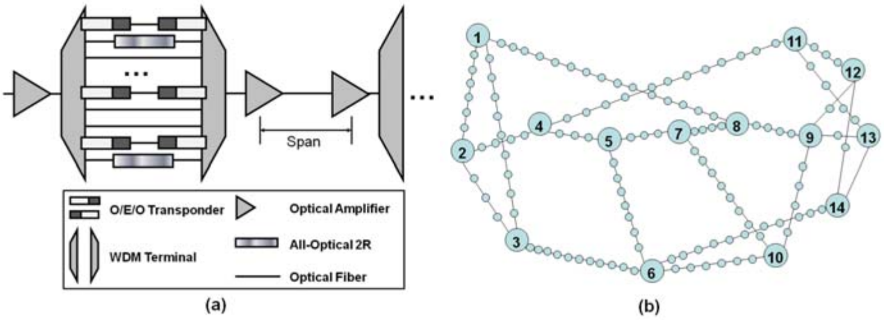
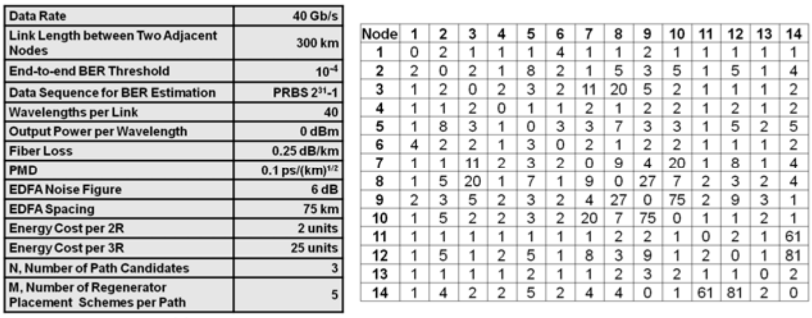


Fig. 1 (a) Hybrid configuration of a regeneration site, (b) NSFNET topology for simulation



Data Rate	40 Gb/s
Link Length between Two Adjacent Nodes	300 km
End-to-end BER Threshold	10^{-4}
Data Sequence for BER Estimation	PRBS 2^{31}-1
Wavelengths per Link	40
Output Power per Wavelength	0 dBm
Fiber Loss	0.25 dB/km
PMD	0.1 ps/(km)$^{1/2}$
EDFA Noise Figure	6 dB
EDFA Spacing	75 km
Energy Cost per 2R	2 units
Energy Cost per 3R	25 units
N, Number of Path Candidates	3
M, Number of Regenerator Placement Schemes per Path	5

(a)

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0	2	1	1	1	4	1	1	2	1	1	1	1	1
2	2	0	2	1	8	2	1	5	3	5	1	5	1	4
3	1	2	0	2	3	2	11	20	5	2	1	1	1	2
4	1	1	2	0	1	1	2	1	2	2	1	2	1	2
5	1	8	3	1	0	3	3	7	3	3	1	5	2	5
6	4	2	2	1	3	0	2	1	2	2	1	1	1	2
7	1	1	11	2	3	2	0	9	4	20	1	8	1	4
8	1	5	20	1	7	1	9	0	27	7	2	3	2	4
9	2	3	5	2	3	2	4	27	0	75	2	9	3	1
10	1	5	2	2	3	2	20	7	75	0	1	1	2	1
11	1	1	1	1	1	1	1	2	2	1	0	2	1	61
12	1	5	1	2	5	1	8	3	9	1	2	0	1	81
13	1	1	1	1	2	1	1	2	3	2	1	1	0	2
14	1	4	2	2	5	2	4	4	0	1	61	81	2	0

(b)

Fig. 2 (a) Simulation parameters, and (b) Traffic matrix in simulation

3. Online Network Provisioning with Joint RWA and Regenerator Allocation

To further evaluate the performance of the proposed network design algorithm, we perform simulations on online network provisioning with the networks being designed. With a desired regeneration energy cost, the regenerators have been placed in the networks according to the algorithms described in the previous section. We then generate lightpath requests based on a Poisson process with rate λ requests/time-unit. The source and destination of a request are randomly chosen based on the probability normalized from Λ_{sd}. The holding time of each lightpath is set according to an exponential distribution with an average of μ time-unit. Therefore, the traffic load can be defined as $\lambda \cdot \mu$ Erlangs. For network provisioning, we also finds N shortest routing paths for each lightpath request. For each of the routing paths, we first allocate regenerators to keep the end-to-end BER below BER_t. Similar to that in network design, the wavelength assignment afterwards tries to maximize transparent segments and minimize regeneration energy cost. During the wavelength assignment, the regenerator allocation may be readjusted when wavelength contention is unavoidable. When the wavelength assignment has been done for all routing paths, we validate their availabilities by verifying wavelength continuity and recalculating the end-to-end BER. The available paths are then sorted based on their lengths and we pick the shortest path to carrier the lightpath request. If there is no available path, the request will be blocked. Fig. 4 shows the simulation results of the network provisioning. For each data point, we simulate 16 times and average the results for statistical accuracy. For each simulation, 10000 lightpath requests are processed. The MRP scheme achieves lower blocking probability when the energy cost on regeneration is fixed. This is due to the reason that 2R in the MRP scheme help solve more signal quality and wavelength contention issues. Therefore, more lightpath requests can be set up.

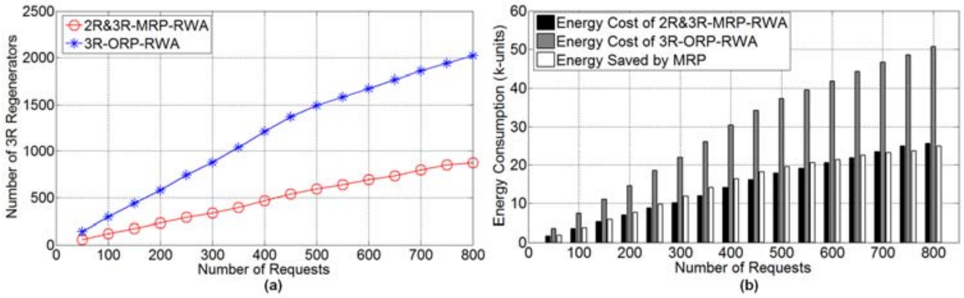


Fig. 3 (a) Comparison of numbers of 3R needed, and (b) Comparison of energy consumption

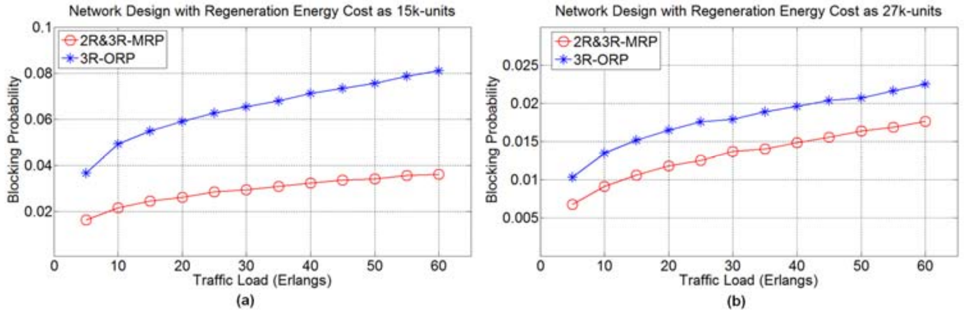


Fig. 4 Blocking probability for networks designed with regeneration energy cost as (a) 15k-units, and (b) 27k-units

4. Summary

We proposed network design algorithms to improve the energy-efficiency of a translucent optical network with joint optimization of routing and wavelength assignment (RWA) and mixed regenerator placement (MRP). Simulation results showed that MRP scheme could save up to 50% energy cost with the help of signal regeneration and wavelength conversion in all-optical 2R regenerators. Moreover, results on online network provisioning demonstrated that networks designed with MRP could achieve lower blocking probability.

5. References

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