Optical Regenerator Placement Strategy to Achieve Green Design of Translucent Optical Networks

Zuqing Zhu
School of Information Sci. & Tech., University of Science and Technology of China, Hefei, Anhui 230027, China
Email: {zqzhu}@ieee.org

***Abstract*—We report a novel optical regenerator placement strategy to achieve green and cost-effective design of optical translucent networks. Instead of treating the BER independently before and after a regenerator, we calculate the BER increment at each regeneration site with the considerations of reshaping nonlinearity and jitter effect. Simulation results demonstrate that the cost and power consumption of a translucent network can be effectively reduced with our proposed scheme.**

***Index Terms*—Optical regeneration, regenerator placement, translucent optical networks, green networks**

I. INTRODUCTION

FIBER transmission and optical switching can lead to noise and jitter accumulations on signals and limit the scalability of optical networks. The deployment of optical regenerators can suppress signal distortions and improve the network scalability. Optical re-amplification (1R) with optical amplifiers compensates for the fiber propagation loss and supplies sufficient optical power beyond the receiver sensitivity. However, the optical amplifiers can degrade the optical-signal-to-noise-ratio (OSNR), which will cause the signal BER to increase exponentially in a chain of optical 1R regenerators [1]. Optical reshaping with a nonlinear transfer function thus becomes necessary in order to prevent the amplifier noise from accumulating. Optical reshaping, together with the re-amplification, provides the optical 2R capability. When the retiming is absent, timing jitter accumulates and eventually imposes the necessity for full optical 3R regeneration with retiming added [2]. Due to the fact that the original overlapping of the noise distribution cannot be removed [3, 4], even an ideal regenerator cannot "correct" BER but can only minimize the BER increment [1] if error-correction coding (FEC) is absent.

Translucent optical networks have been considered as a cost-effective infrastructure, where the end-to-end optical signal quality is guaranteed with a reduced number of optical-electronic-optical (O/E/O) 3R regenerators [5, 6]. During the network-planning phase, most of the previous works treat the signal quality (e.g. bit-error-rate (BER) and Q-factor) independently before and after a 3R regenerator, and only place a 3R at the place where the signal quality is at the borderline [5, 6]. However, the optimal BER of a regenerated signal is the same as that before the regeneration if measured directly after the regenerator [1, 3, 4, 7], as long as the regenerator does not have FEC functionality. Therefore, placing a 3R at where the signal quality is at the borderline may not satisfy the end-to-end BER requirement for a lightpath. A more sophisticated strategy is desired to estimate the BER evolution along a lightpath and to optimize the regenerator placements for network planning.

Another drawback of current translucent network design algorithms is that they rely solely on O/E/O 3R to solve the signal quality and wavelength contention issues. Comparing with O/E/O 3R regenerators, all-optical 2R regenerators usually have the advantages of compact size, relatively low cost, and low power consumption [3, 8]. In this paper, we use a theoretical model to estimate the BER evolution in mixed operations of optical 1R/2R/3R regenerators. Instead of treating the BER independently before and after a regenerator, the model calculated the BER increment at each regeneration site with considerations of reshaping nonlinearity and jitter effect. Based on the model, we propose regenerator placement algorithms that can reduce the cost and power consumption of an optical translucent network.

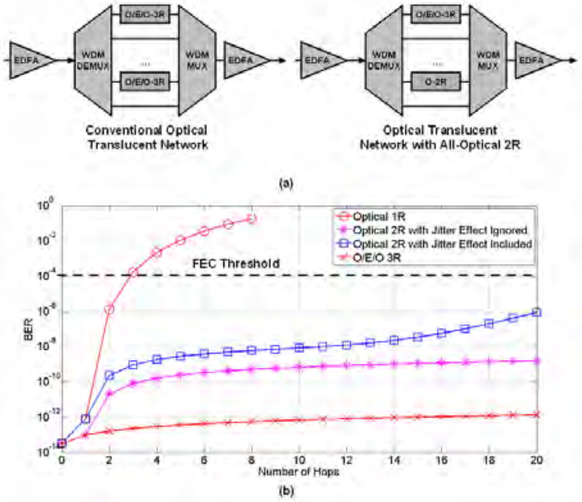

Fig. 1 (a) Configurations of regeneration sites, (b) BER evolutions for cascaded operations of different regenerators

II. THEORETICAL ANALYSIS

Fig. 1(a) shows the configurations of regeneration sites for conventional translucent network and our proposed scheme.

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We replace certain O/E/O 3R regenerators with all-optical 2R regenerators to reduce the cost and power consumption. The nonlinear power transfer function of an all-optical 2R regenerator can be modeled with $\gamma \in [0,1]$ as the degree of the nonlinearity [1, 4]. The BER evolution in mixed operations of optical 1R/2R/3R regenerators can be modeled as:

$$BER(n) = BER(n-1) + f_i(\sigma_{n,0}^2), \begin{cases} \sigma_{n,0}^2 = \sigma_{link,n}^2 + \sigma_{n-1,1}^2 \\ \sigma_{n,1}^2 = \gamma_n^2 \sigma_{n,0}^2 + \sigma_{regen,n}^2 \end{cases} \quad (1)$$

where n represents the number of regeneration sites the signal experienced, $\sigma_{n,0}^2$ is the noise variance right before the regenerator in current site, $\sigma_{n,1}^2$ is the noise variance for retransmission, $\sigma_{link,n}^2$ is the noise variance from the fiber transmission between site $n-1$ and n, $\sigma_{regen,n}^2$ is the noise variance from the current regenerator, γ_n is the reshaping nonlinearity of the regenerator in current site, and $f_i(\sigma_{n,0}^2)$ is the error function to calculate the incremental BER from the current site with *i* as 1, 2, 3 for 1R, 2R and 3R, respectively. When retiming is absent, timing jitter limits the cascadability of optical 1R/2R regenerators in an interesting way [9, 10]. We take jitter effect into consideration and model the error function as [4]:

$$f_i(\sigma_n^2, n) = \begin{cases} \dfrac{1}{4}\sum_{m=1}^{M-1} P_M(m) \cdot Q(\dfrac{E_m(n) - D_n}{\sigma_n}) + \dfrac{3}{4} Q(\dfrac{E_0}{2\sigma_n}), i = 1,2 \\ Q(\dfrac{E_0}{2\sigma_n}), i = 3 \end{cases} \quad (2)$$

where $P_M(m)$ is the possibility of *m* consecutive '0' symbols in a 2^M-1 PRBS sequence, E_0 is the energy of the '1' symbol from the original transmitter or an O/E/O 3R, $E_m(n)$ is the energy of the '1' symbol after the *m* consecutive '0' symbols at hop *n*, and D_n is the regeneration decision level at hop *n*. Fig. 1(b) shows the BER evolutions through a 20-hop lightpath with cascaded operation of different regenerators at each hop. The bit-rate is 40 Gb/s and we assume the noise characteristic $\sigma_{link,n}^2$ is the same for each hop. With the jitter effect considered, the all-optical 2R still outperforms 1R (optical re-amplification only). Therefore, we can replace certain O/E/O 3R with all-optical 2R to achieve a cost-effective solution.

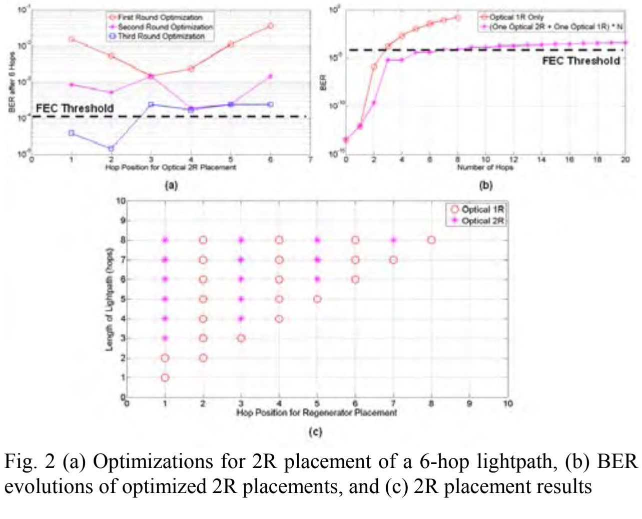

Fig. 2 (a) Optimizations for 2R placement of a 6-hop lightpath, (b) BER evolutions of optimized 2R placements, and (c) 2R placement results

III. MIXED PLACEMENT OF OPTICAL 1R/2R/3R

We assume there is FEC functionality at the edge of the translucent network and set the BER threshold of a lightpath at 1×10^{-4} to accommodate the FEC threshold around 3×10^{-3} and to reserve certain performance margin. We divide the network design algorithm into two steps: 1) all-optical 2R placement and 2) O/E/O 3R placement, and discuss them in this section.

A. Algorithm of All-Optical 2R Placement

For the 2R placement algorithm, we define two parameters: M_{2R} as the maximum number of 2R we can place along the lightpath, and S_{2R} as the minimum spacing of 2R in terms of hops. The 2R placement algorithm targets for minimizing M_{2R} and satisfies S_{2R} and the end-to-end BER requirement. With this algorithm, we perform a case study for a 6-hop lightpath. Fig. 2(a) shows the optimization of the 2R placements in three rounds with $M_{2R} = 3$ and $S_{2R} = 2$. Since the end-to-end BER is less than the threshold after the 2R placements, there is no need to place 3R in the lightpath. The final 2R placements are at hops 1, 3, and 5. We set $M_{2R} = round(hops/2)$ and $S_{2R} = 2$, and the configuration of $(2R + 1R)\times N$ becomes a quick solution for 2R placement. Fig. 2(b) shows the BER evolution. The requirement of 3R can be eliminated when the lightpath length is less than 9 hops. On the other hand, Fig. 1(b) shows that with only 1R, the signal BER exceeds threshold after 3 hops. Thus, all-optical 2R effectively extends the transparent optical reach to three times longer. Fig. 2(c) shows the 2R placements for different lightpath lengths.

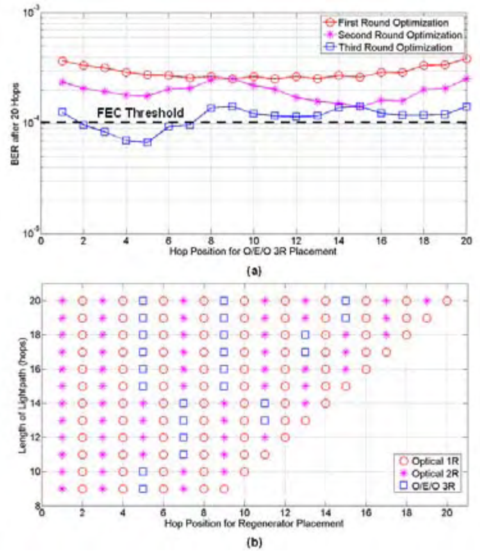

Fig. 3 (a) Optimizations for 3R placement of a 20-hop lightpath, and (b) 2R and 3R placement results

B. Algorithm of O/E/O 3R Placement

The algorithm of 3R placements is similar to that of 2R and it starts to search for the optimal positions of 3R based on the output of 2R placements. Fig. 3(a) shows the optimization of 3R placements for a 20-hop lightpath. The final 3R placements are at hops 5, 9, and 15. Fig. 3(b) shows the 2R and 3R placements for lightpaths with lengths of 9 to 20 hops.

C. Case Study

Up to now, we have been assuming that the link characteristic is identical. To simulate a practical network, we need to consider the situation where the link characteristic is random. Fig. 4(a) shows the link noise characteristic with random generated values. The noise characteristic is normalized with the fixed value we use in Section III.A and III.B. By applying our regenerator placement algorithms, we get the optimized placements as shown in Fig. 4(b). As a reference, Fig. 4(c) shows the placements without all-optical 2R. Our proposed algorithms effectively reduce the number of O/E/O 3R regenerators by using all-optical 2R as replacements. The comparison in Fig. 5(a) illustrates that our proposed scheme reduces the 3R regenerators' number to less than 50% for all of the lightpath lengths. Another benefit from replacing O/E/O 3R with all-optical 2R is energy saving. The power consumption of a 40 Gb/s O/E/O 3R is usually hundreds of Watts (e.g. 250 W [11]) due to high-speed electronics, while that of an all-optical 2R can be calculated as 20 W from DC current injections [11]. Fig. 5(b) shows the power saving achieved by the proposed scheme.

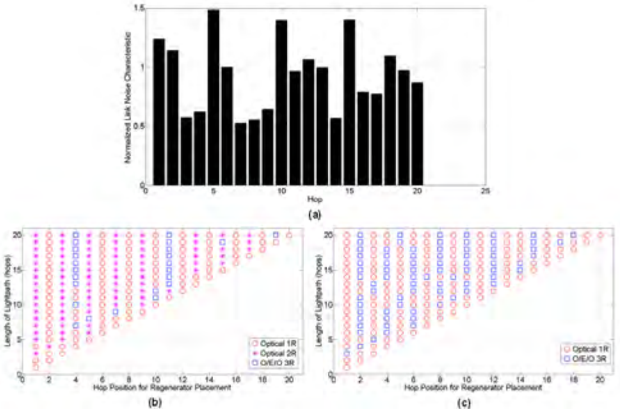

Fig. 4 (a) link noise characteristic with random generated values, (b) 2R and 3R placement results, and (c) 3R placement results without 2R involved

IV. CONCLUSION

In this paper, we reported a more accurate and convincing theoretical model to estimate the BER evolutions in optical translucent networks. Instead of treating the BER independently before and after a regenerator, the model calculated the BER increment at each regeneration site with the considerations of reshaping nonlinearity and jitter effect. Based on this model, we proposed network design algorithms to use mixed operations of optical 1R/2R/3R regenerators and demonstrated that the cost and power consumption of an optical translucent network can be effectively reduced with our proposed scheme. Therefore, green and cost-effective optical translucent networks can be achieved.

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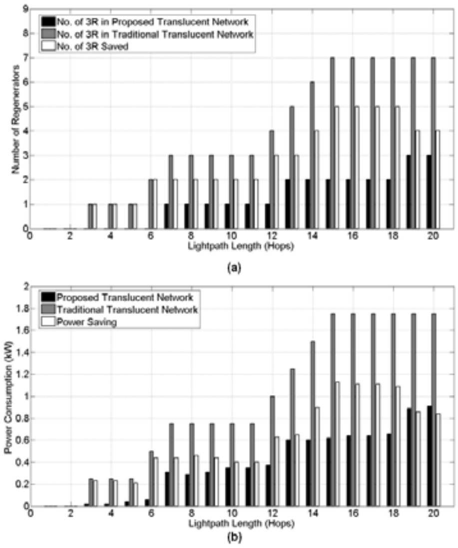

Fig. 5 (a) Comparison of number of O/E/O 3R regenerators needed in the proposed scheme and the conventional optical translucent network, and (b) Comparison of power consumption