Mixed Placement of 1R/2R/3R Regenerators in Translucent Optical Networks to Achieve Green and Cost-Effective Design

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***Abstract*—We develop a theoretical model to estimate the BER evolutions in optical translucent networks in a more accurate way. The model calculates the BER increment at each regeneration site with considerations of reshaping nonlinearity and jitter effect for 40 Gb/s signals. Based on the model, we propose a novel translucent optical network infrastructure that includes all-optical 2R regenerators and uses mixed operation of 1R/2R/3R regenerators for cost and power consumption savings. Simulation results show that our proposed infrastructure reduces the number of O/E/O 3R regenerators to less than 50% and achieves effective power saving.**

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

I. INTRODUCTION

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 [1, 2]. 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 [1, 2]. However, it is known that the optimal BER of a regenerated signal is the same as that before the regeneration if measured directly after the regenerator [3-6], as long as the regenerator does not have error-correction functionality, such as forward-error-correction (FEC). And due to the cost and power restrictions on the systems, some O/E/O 3R regenerators may not have the FEC capability. Therefore, placing such 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 model 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. All-optical 2R regenerators achieve re-amplification and reshaping of optical signal with a nonlinear power transfer function [5, 7, 9, 10]. 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]. Moreover, majority of them achieve 2R with a regenerative all-optical wavelength conversion, and can resolve wavelength contention simultaneously [3, 8].

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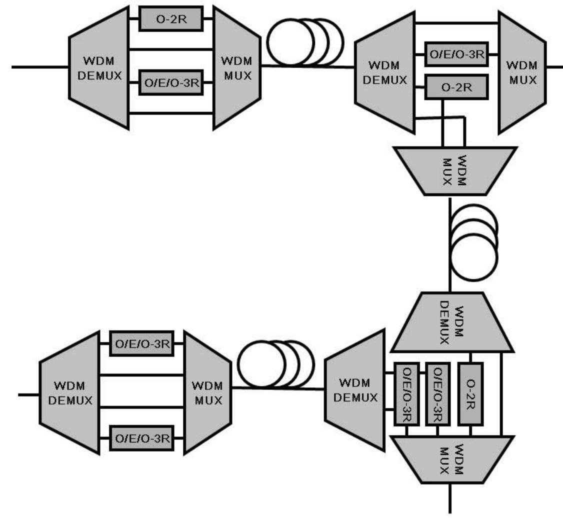

Fig. 1. Configurations of regeneration sites in our proposed translucent optical networks.

In this letter, we report a theoretical model to calculate the BER increment at each regeneration site with considerations of reshaping nonlinearity and jitter effect. With this model, we propose a novel translucent optical network infrastructure with mixed operation of 1R/2R/3R regenerators. Simulation results show that the introduce of all-optical 2R regenerator can effectively reduce the number of O/E/O 3R regenerators in lightpaths, hence achieving significant cost and power savings.

II. THEORETICAL ANALYSIS

Figure 1 shows the configurations of regeneration sites for our proposed scheme. We replace certain O/E/O 3R regenerators with all-optical 2R regenerators to reduce the cost and power consumption. To estimate the signal quality in this scenario, we model the BER evolution in this mixed operations of 1R/2R/3R regenerators as:

$$BER_n = BER_{n-1} + Err(L_{n-1,n}, R_n(\gamma, \sigma^2_{regen}, i)) \quad (1)$$

where BER_n is the signal BER value after the current regenerator, n is the ID of the current regenerator (e.g. the number of the regenerators the signal experienced along the lightpath), $Err(.)$ is the error function to calculate the incremental BER caused by the current regenerator, $L_{n-1,n}$ represents the link characteristics of the fiber link between the current and previous regenerators (such as length, noise, dispersion and etc), $R_n(.)$ represents the characteristics of the current regenerator, $\gamma \in [0, 1]$ is the degree of amplitude regenerative nonlinearity [4, 5], σ^2_{regen} models the noise generated by the

2R Position	1st Round	2nd Round	3rd Round
n = 1	4.47E-2	2.30E-3	1.20E-3
n = 2	1.71E-2	1.30E-3	
n = 3	8.80E-3	1.40E-3	8.00E-4
n = 4	5.00E-3		
n = 5	1.53E-2	1.50E-3	2.42E-5
n = 6	4.86E-2	2.30E-3	2.00E-4
n = 7	1.00E-1	5.00E-3	1.40E-3

Fig. 2. Procedures for optimizing optical 2R placements.

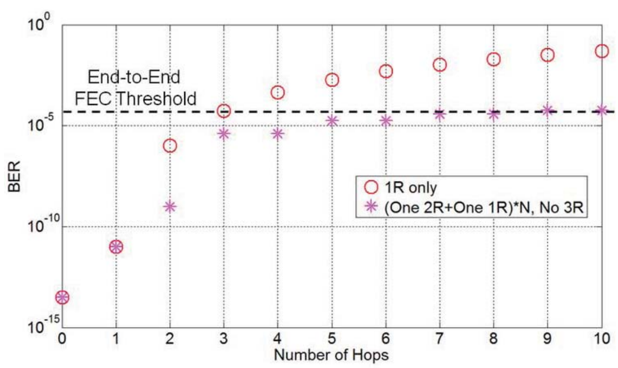

Fig. 3. End-to-end BER for lightpaths with different configurations.

current regenerator, i can be 1, 2, or 3 to distinguish the current regenerator as 1R, 2R or 3R, respectively. In fiber transmission, timing jitter limits the cascadability of 1R/2R/3R regenerators in an interesting way [9, 10]. We take both amplitude noise and jitter effect into consideration and model the error function as:

$$Err(L_{n-1,n}, R_n(\gamma, \sigma^2_{regen}, i)) = \left\{ \begin{array}{ll} \frac{1}{4}\sum_{m=1}^{M-1} P_M(m) Q(E_{m,n}, \sigma_n^2) + \frac{3}{4} Q(E_0, \sigma_n^2), & i = 1, 2 \\ Q(E_0, \sigma_n^2), & i = 3 \end{array} \right. \quad (2)$$

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 an '1' symbol from the original transmitter or an O/E/O 3R, $E_{m,n}$ is the energy of an '1' symbol after m consecutive '0' symbols at current regenerator's output, σ_n^2 represents the total noise on the signal after current regenerator (including the noise from the fiber transmission and the regenerators). Here, the key problem of the model is to accurately calculate $E_{m,n}$. We extend our previous work for 10 Gb/s inputs in [4] to 40 Gb/s. Due to the operation principle of all-optical 2R, the memory effect and its impact on jitter accumulation have been remodeled to accommodate the finite carrier recovery time of the optical device at 40 Gb/s operations.

III. Mixed Placement of 1R/2R/3R

A. Regenerator Placement Algorithms

The network design algorithm is then developed to achieve proper 1R/2R/3R regenerator placements along the lightpaths. The optical 2R placement has to satisfy one restriction: M_{2R} as the maximum number of 2R we can place along the lightpath. The 2R placement algorithm is as follows:

Algorithm 1 All-Optical 2R Placement

Input: Lightpath length, link characteristics, regenerator characteristics, initial BER from the transmitter, and M_{2R}
Output: 2R placements and a flag to tell whether further 3R placements are necessary
Operations:
WHILE (Placed 2R $\leq$ M2R) **AND** (end-to-end BER $>$ threshold)
  Search for the optimal position of current 2R
  Place current 2R
  Calculate end-to-end BER
END
IF end-to-end BER $\leq$ threshold
  Return 2R placements
  Set 3R flag to FALSE
ELSE
  Return 2R placements
  Set 3R flag to TRUE
END

With this algorithm, we perform a case study for a lightpath including 7 regeneration sites. The signal bit-rate is 40 Gb/s and we assume the link characteristics $L_{n-1,n}$ is the same for each hop. We assume that the FEC functionality only exists at the end of each lightpath (e.g. at the edge of the translucent network). Then, the end-to-end BER threshold of a lightpath is set at 1E-4 to accommodate the FEC threshold around 3E-3 and to reserve certain performance margin.

Figure 2 shows the procedures for optimizing the 2R placements in the lightpath. Basically, we place one 2R in the lightpath in each round and stop when the end-to-end BER is below the threshold. The final 2R positions along the lightpath are at hops 2, 4, and 5. 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. Figure 3 plots the end-to-end BER for lightpaths with configurations of 1R only and $(2R+1R)*N$. The requirement of 3R can be eliminated when the lightpath length is less than 9 hops. On the other hand, the end-to-end BER exceeds threshold after 3 hops with 1R only and O/E/O 3R will be required in this case for traditional translucent optical networks. Thus, all-optical 2R effectively extends the transparent optical reach to three times longer.

The algorithm of 3R placements starts to search for the optimal positions of 3R based on the output of 2R placements. Similar to the 2R placement, one 3R is placed in the lightpath in each round to minimize the end-to-end BER until it is below the pre-defined threshold. Figure 4 shows the 1R/2R/3R placements for lightpaths with lengths of 9 to 20 hops.

B. Simulation Results

To emulate a practical network, we run simulations to consider the situation where the link characteristic is random. By applying our regenerator placement algorithms, we get the optimized placements as shown in Fig. 5. The comparison in

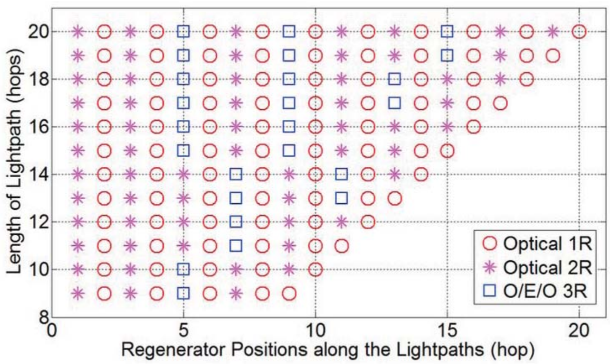

Fig. 4. 1R/2R/3R placements for lightpaths with lengths of 9 to 20 hops.

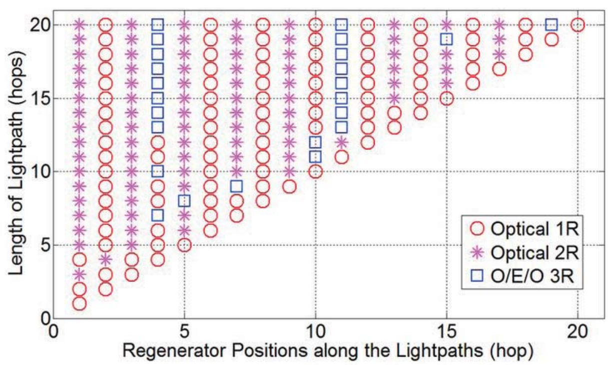

Fig. 5. 1R/2R/3R placements for lightpaths with random lengths.

Table I illustrates that our proposed scheme reduces the 3R regenerators' number to less than 50%. 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 [3, 8]. Table II shows the power saving achieved by the proposed scheme. Note that these regenerator placement algorithms only consider the design of lightpaths, more sophisticated algorithms that can accommodate dynamic routing scheme will be our future work.

IV. Conclusion

In this letter, we developed a more accurate model to estimate the BER evolutions in optical translucent networks. The model calculated the BER increment at each regeneration site with considerations of reshaping nonlinearity and jitter effect for 40 Gb/s signals. Based on this model, we proposed to introduce all-optical 2R regenerators into translucent optical network, and to use mixed operation of 1R/2R/3R regenerators for cost and power savings. Simulation results showed that our proposed infrastructure reduced the number of O/E/O 3R regenerators to less than 50% and achieved effective power saving. Therefore, our proposed scheme achieved green and cost-effective translucent optical network design.

TABLE I
Comparison of number of O/E/O 3R needed in traditional and proposed schemes.

Lightpath Length (hops)	4	8	12	16	20
No. of 3R in Traditional Scheme	1	3	4	7	7
No. of 3R in Proposed Scheme	0	1	1	2	3
No. of 3R Saved	1	2	3	5	4

TABLE II
Comparison of number of O/E/O 3R needed in traditional and proposed schemes.

Lightpath Length (hops)	4	8	12	16	20
Power of Traditional Scheme (kW)	250	290	370	640	910
Power of Proposed Scheme (kW)	20	750	1000	1750	1750
Power Saving (kW)	230	460	630	1110	840

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