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Design Green and Cost-Effective Translucent Optical Networks

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Abstract: We report a network design algorithm to effectively reduce the cost and power consumption of translucent networks by using all-optical 2R regenerators. Simulation results show that the number of O/E/O 3R can be effectively reduced.
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1. Introduction

Translucent optical networks have been considered as a cost-effective infrastructure, where the end-to-end optical signal quality is maintained with a reduced number of optical-electronic-optical (O/E/O) 3R regenerators [1, 2]. Previous works in [1, 2] show that the most important parameter for network planning of translucent networks is the signal quality in terms of bit-error-rate (BER) or Q-factor. These works treat the signal quality independently before and after a 3R regenerator, and only place a 3R in the network where the signal quality is right below the performance threshold. However, it is well known that when there is no forward-error-correction (FEC) functionality in the 3R regenerator, the optimal BER of a regenerated signal is the same as that before the regeneration if measured directly after the regenerator [3]. Thus, placing a 3R at where the signal quality is at the borderline may not satisfy the end-to-end BER requirement for a lightpath. Another drawback of current translucent network designs 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 [3]. Among them, the monolithic integrated semiconductor optical amplified based Mach-Zehnder interferometer (SOA-MZI) is a promising device, for its compact size, relatively low cost, low power consumption and high operation speed up to 40 Gb/s [4]. In addition, it achieves 2R with a regenerative all-optical wavelength conversion, and can resolve wavelength contention simultaneously. In this paper, we report an analytical model to precisely estimate the BER evolution in mixed operation of optical 1R/2R/3R regenerators and then propose a network design algorithm that can optimize the cost and power consumption of a translucent network with the utilization of all-optical 2R regenerators.

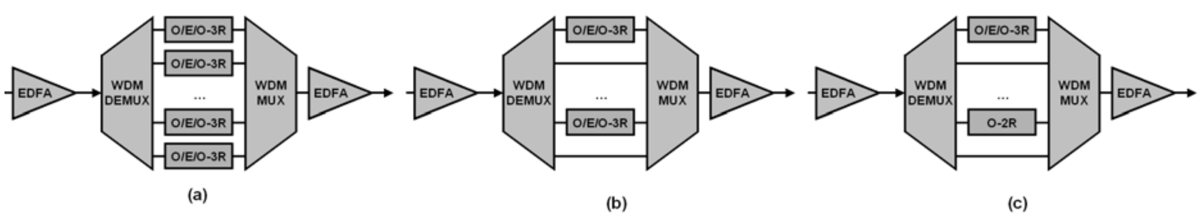

Fig. 1 Configurations of regeneration site in optical networks as (a) opaque, (b) traditional translucent, and (c) translucent with all-optical 2R included, EDFA: Erbium-doped fiber amplifier, O-2R: all-optical 2R regenerator

2. Theoretical Model and Simulation

Fig. 1 shows the configurations of regeneration sites for three types of optical networks. Fig. 1(c) is the configuration we propose to use. It replaces some O/E/O 3R regenerators with all-optical 2R regenerators to reduce the cost and power consumption. The nonlinear power transfer function of the all-optical 2R regenerator can be modeled with $\gamma \in [0,1]$ as the degree of the nonlinearity [5]. γ changes the transfer function from a step function (ideal reshaping) when $\gamma = 0$ to a linear slope (no reshaping) when $\gamma = 1$. We take $\gamma = 0.5$ to model the SOA-MZI based all-optical 2R regenerator in this paper. The following equations can be derived to model the signal quality in mixed operation of optical 1R/2R/3R regenerators:

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

where n represents the number of regeneration sites the signal experienced, $\sigma_{n,0}^2$ is the noise variance of the signal right before the regenerator in current site, $\sigma_{n,1}^2$ is the noise variance of the signal for retransmission, $\sigma_{link,n}^2$ is the noise variance from the fiber-link 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 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. We ignore bandwidth-limitation and pattern-dependence when calculating BER with $f_i(\sigma_{n,0}^2)$. A more sophisticated BER model that considers these effects is available in [3]. We choose γ_n as 1, 0.5, and 0, for optical 1R, 2R, and 3R regenerators, respectively.

Numerical simulation is then performed to investigate the system performance. The data bit-rate is 40 Gb/s, and the initial BER after the transmitter is 3.31×10^{-14}. In the simulation, the fiber link between each hop has the same length of 160 km with in-line amplification and the noise characteristics $\sigma_{link,n}^2$ is the same. The constant $\sigma_{link,n}^2$ is calculated with the channel model in [3]. If we assume that there is FEC functionality at the edge of the translucent network, the BER threshold of a lightpath can be set at 1×10^{-4} to accommodate FEC threshold around 3×10^{-3} and to reserve certain performance margin. Fig. 2 shows the simulation results for the signal BER evolving along with the lightpath lengths (regeneration hops). Fig. 2(a) illustrates the case in traditional translucent networks, where there are only optical amplifiers and O/E/O 3R regenerators. The curve shows that when there are only optical amplifiers (1R), the signal BER can be maintained below threshold when the lightpath length is less than 4 hops, and 3R has to be placed, when the desired lightpath length is more than 3 hops. Fig. 2(b) shows the results for our proposed configuration with all-optical 2R regenerators. With the configuration of $(2R+1R)\times N$, the requirement of 3R can be eliminated when the lightpath length is less than 15 hops. Thus, all-optical 2R effectively extends the transparent optical reach to five times longer. When 3R is involved, the BER is below threshold after 20 hops, with a mixed regeneration configuration of $(3R+2R\times2+1R)\times N$.

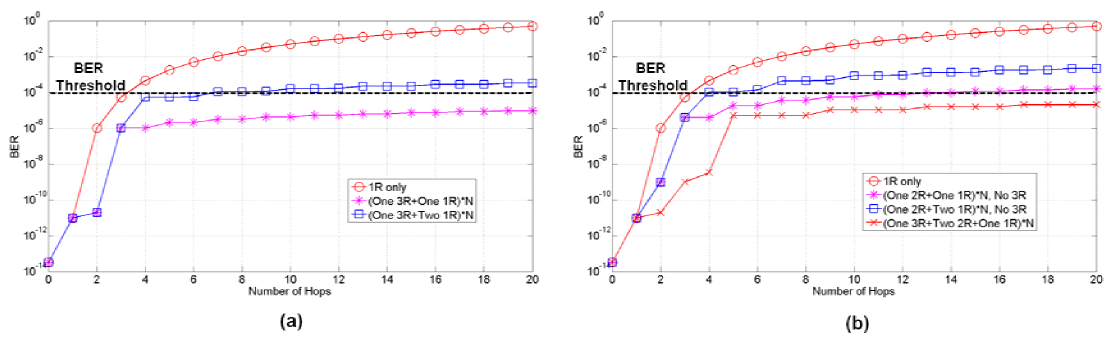

Fig. 2 Simulation results of BER evolving along the fiber links for: (a) Traditional translucent optical networks, (b) Proposed translucent optical networks with all-optical 2R regenerators

3. Network Design Algorithm

With the analytical BER model discussed above, we can describe the translucent network design problem with the following notations and constrains:

1) The network physical topology is $G(V,E)$, where V is a set of nodes, and E is a set of fiber links (u,v) directly connecting node u to node v. The noise characteristic of fiber link (u,v) can be denoted as $\sigma_{u,v}^2$.
2) The traffic matrix is Λ_{sd}, and $L_{s,d}$ is the number of lightpaths from node s to node d. W is a set of wavelengths on the fiber link (u,v).
3) The wavelength connection flag is $f_{s,d}^{(u,v)}(w)$. Its value is 1 if wavelength w is used on link (u,v) for a lightpath from node s to node d; otherwise, it is 0. We have the following constrains:

$$\sum_{s\in V}\sum_{d\in V} f_{s,d}^{(u,v)}(w)\le 1, \forall (u,v)\in E, \forall w\in W \quad (3)$$

$$\sum_{v\in V}\sum_{w\in W} f_{s,d}^{(u,v)}(w) - \sum_{v\in V}\sum_{w\in W} f_{s,d}^{(v,u)}(w) = \begin{cases} L_{s,d}, u = s \\ -L_{s,d}, u = d, \forall s \in V, \forall d \in V \\ 0, otherwise \end{cases} \tag{4}$$

$$\sum_{s\in V}\sum_{d\in V}\sum_{w\in W} f_{s,d}^{(u,v)}(w) \le |W|, \forall (u,v) \in E \tag{5}$$

4) The BER threshold is BER_t, and $BER_{s,d,k}$ denotes the end-to-end BER for the k-th lightpath from node s to node d. $R2_u$ denotes the number of 2R regenerators at node u, and $R3_u$ denotes the number of 3R regenerators. We have the following constrains and objective function:

$$BER_{s,d,k} \le BER_t, \forall s \in V, \forall d \in V, k \in [1, L_{s,d}] \tag{6}$$

$$\min(\sum_{u\in V} R3_u + \rho \sum_{u\in V} R2_u) \tag{7}$$

where ρ is the coefficient to reflect the cost of all-optical 2R related to O/E/O 3R.

We then perform a case study for a lightpath of 20 hops and try to find the optimal placements of 3R regenerators. Simulation condition is the same as that in previous section. The lightpath has already had a configuration of $(2R+1R)\times N$ before 3R placement. The simulation scans the 3R placement from hop 1 to hop 19 and calculates the end-to-end BER at hop 20. Fig. 3(a) shows the simulation results. In the first optimization, we found that the best spot to place the 3R is at hop 10. However, the final BER is still above the threshold and we need to place a second 3R in the lightpath. The second optimization is then performed, and this time we found 4 candidate spots for the second 3R to achieve the minimal BER below the threshold: hop 4, 6, 14, and 16. Thus, we only need two O/E/O 3R regenerators to ensure the signal quality along the lightpath, while in the traditional case we need at least ten 3R regenerators. In addition, we have the flexibility for placing the second 3R at four different spots, and this relieves the network design restrictions when other practical constrains, such as power, space and etc [1], have to be considered. Fig 3(a) also shows that placing the 3R towards the receiver end actually gives the worst end-to-end BER performance, which matches with our theoretical prediction. With the same optimization algorithm, we calculated the number of 3R regenerators needed for lightpath lengths from 160 to 3200 km. Fig. 3(b) shows results for the traditional and our proposed translucent networks. 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 [6]) due to high-speed electronics, while that of an all-optical 2R (in cascaded operation of dual SOA-MZIs) can be as low as 10 W from DC current injections. The Fig. 3(c) shows effective power saving with the proposed scheme.

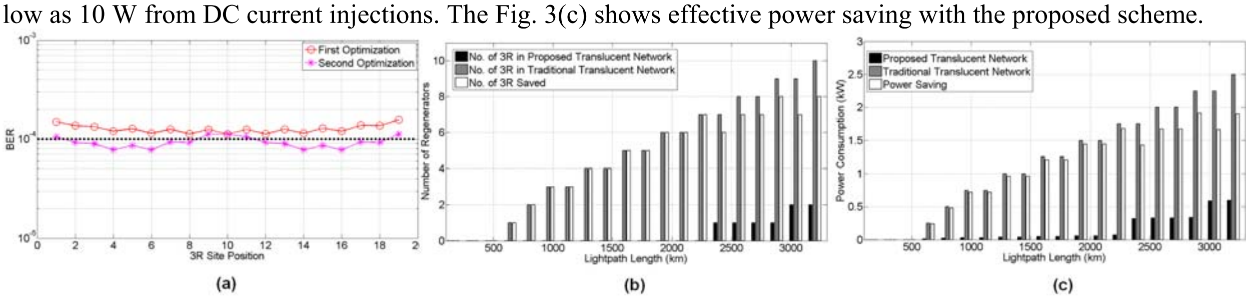

Fig. 3 Simulation results for (a) 3R placement optimization, and (c) Number of 3R regenerators and (b) Power consumption, in traditional and proposed translucent networks

4. Summary

We reported an analytical model to estimate signal BER in mixed operation of optical 1R/2R/3R regenerators. Based on the estimation, we proposed a network design algorithm to effectively reduce the cost and power consumption of a translucent network with all-optical 2R regenerators. Simulation results showed that the algorithm can effectively reduce the number of O/E/O 3R regenerators and thus achieves green and cost-effective optical translucent networks.

5. References

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