Performance Comparison of Dynamic Elastic Optical Networks with Optical Regeneration

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Abstract: We have investigated optical regeneration issues and application in elastic optical networks that are capable of providing dynamically optical paths with flexible bandwidths. We have analyzed the impact of optical regeneration in elastic optical networks and clarified various usage scenarios. We have then evaluated and compared the performance, in terms of the overall blocking probability and the total accommodated traffic volume, of three possible network scenarios with regeneration capability including (i) no regeneration, (ii) 3R regeneration, and (iii) 4R regeneration for practical network topologies. Numerical simulation proved that deployment of optical regeneration devices can exploit elastic optical networking to enhance the network performance for provisioning dynamically bandwidth-flexible lightpath services. It is also demonstrated that using re-modulation function while regenerating optical signals (4R regeneration) can further improve the network performance. However, due to the high cost of optical regeneration devices, especially all-optical ones, and more functional regenerators, the trade-off between the performance enhancement and the necessary number of regenerating devices needs to be carefully considered.

Keywords: *Optical regenerator, routing, modulation format and spectrum assignment, network control algorithm, elastic optical network.*

I. Introduction

Internet traffic is growing at incredible rates, driven by high-performance applications including video on demand, and cloud and grid computing [1, 2] which demand even more ubiquity, mobility, and heterogeneous bandwidths [3, 4], in recent decades. This traffic growth places an importance of extremely large data capacity yet flexible and efficient optical network technologies to support broadband services up to Terabit/s in the near future. To scale to Terabit/s, optical networks based on current WDM technology using fixed ITU-T frequency grid will face serious problems due to the stranded bandwidth provisioning, inefficient spectral utilization, and high cost [5]. Present researches on optical transmission and networking technologies are oriented forward more efficient, flexible, and scalable network solutions. Recently, elastic optical network (EON) utilizing a flexible frequency grid has been proposed as a promising candidate for future ultra-high capacity optical networks [6, 7]. Elastic optical networking technology helps greatly improve the spectral efficiency and flexibility of the network by eliminating stranded spectrum between channels, supporting both sub-channel and super-channel traffic, and therefore allowing flexible bandwidth connections of multiple data rates and modulation formats [6–8]. However, EON is currently facing challenges owing to the lack of architectures and technologies to efficiently support bursty traffic on flexible spectrum.

Elastic optical networks are able to allocate spectrum resources flexibly for handling not only legacy low-bitrate services but also new super-channel services [6]. Although elastic optical networks are also capable of provisioning dynamic bandwidth-flexible and spectrum-efficient end-to-end optical paths while enable an economical scalability of networks adapting to the growing trend and the heterogeneity of bandwidth requirements for Telcos/Internet service providers [7, 8], more sophisticated network design and provision control strategies are required for realizing efficient and robust network operations [7]. As a result, routing and wavelength assignment (RWA) problem of elastic optical networks becomes more complicated and is known as routing and spectrum assignment problem which includes three sub-problems that are routing, modulation format assignment and spectrum allocation [7–9].

Moreover, optical signals suffer from the physical impairments, such as dispersion and noise, etc. which are being accumulated along the optical paths and consequently, cause a limitation on the optical transmission reach [10–12]. Particularly in large optical networks in which optical paths may travel ultra-long distances, the optical impairment impact becomes very critical. Hence, optical regenerators need to be deployed to clear the impairments and improve the optical transmission reach [12, 13].

Among the regenerator realization technologies, all-optical regeneration can potentially offer significant cost savings thanks to less power and size requirement, especially at high-data rates. Employing advanced all-optical regeneration that applies multi-channel packaging can be a disruptive technology to reduce the power and size footprint.

Besides conventional optical regeneration techniques including the signal re-amplifying along with re-shaping (2R), and even/or re-timing (3R), a new elastic optical regenerator, which is Virtualized Elastic Regenerator (VER), has been lately proposed for elastic optical networks [14]. Different from traditional optical regenerators, the developed VER not only offers 3R regeneration functions (re-amplifying, re-shaping and re-timing), but also naturally supports re-modulating function (so called 4R) [15, 16]. In addition, all 3R/4R optical regenerators can also provide the spectrum conversion capability and therefore, the use of optical regenerators can help to avoid spectrum collision efficiently and significantly enhance spectrum resource utilization in elastic optical networks.

In this paper, we investigate optical regeneration issue and its impact on dynamic elastic optical networks with bandwidth flexible optical paths provisioning capability. We also analyze the performance limits of elastic optical transmission system. The network performance, in term of the overall blocking probability and the accommodated traffic volume, has been then evaluated and compared among three typical optical regeneration deploying scenarios that are

(i) no (without) regeneration,
(ii) 3R regeneration, and
(iii) 4R (3R plus Re-modulation) regeneration in two practical network topologies.

Numerical simulation is used to verified the efficiency of using optical regenerators to exploit elastic optical networking and enhance the network performance. It is proved that at least 29.8% (or 45.6%) more traffic volume for NSF (USNET) network can be obtained. Re-modulation feature of elastic regenerators can also further improve the network performance. However, in order to build cost-effective, bandwidth-abundant and flexible optical networks, the balance between the network performance and the required regeneration resource cost should be carefully considered due to costly optical regeneration devices.

II. Optical Regeneration and Its Application in Dynamic Elastic Optical Networks

1. Performance Limits of Long-Haul Elastic Optical Transmission Systems

Unlike traditional WDM networks, elastic optical networks can support one or several modulation formats. Even more, distance-adaptive EONs are able to dynamically assign the modulation format to each lightpath according to its length [9]. Backbone elastic optical networks also consist of long-haul transmission systems which are set up by many spans. The performance of systems is mainly limited by Optical Signal to Noise Ratio (OSNR) parameter.

Optical Signal to Noise Ratio is defined so as to include the nonlinear interference noise as follows [17],

$$\mathrm{OSNR} = \frac{P_{tx}}{P_{\mathrm{ASE}} + P_{\mathrm{NLI}}}, \tag{1}$$

where P_{tx} is the average transmitted power per channel, P_{ASE} is the amplified spontaneous emission (ASE) noise power and P_{NLI} is the nonlinear interference noise power which accounts for the nonlinear effects.

In fact, P_{ASE} is calculated by [18],

$$P_{\mathrm{ASE}} = S_{\mathrm{ASE}} \times B_0, \tag{2}$$

where S_{ASE} is the ASE noise power spectral density (PSD), B_0 is the noise bandwidth. Depending on the amplifiers applied (i.e. Erbium-Doped Fiber Amplifier (EDFA) or distributed amplification like Raman), S_{ASE} is calculated differently.

If EDFA is used, S_{ASE} can be calculated as the following formulation:

$$S_{\mathrm{ASE}} = N_s h\nu(G-1)N_F, \tag{3}$$

where G is the EDFA gain that is equal to the span loss, N_F is the EDFA noise figure, N_s is the number of EDFAs that is equal to the number of spans, h is Planck's constant and, ν is the optical carrier frequency of the signal being amplified.

On the other hand, P_{NLI} is approximated as [19]

$$P_{\mathrm{NLI}} = \left(\frac{2}{3}\right)^3 N_s \gamma^2 P_{tx}^3 L_{\mathrm{eff}} \frac{\log\left(\pi^2 |\beta_2| N_{ch}^2 R_s^2 L_{\mathrm{eff}}\right)}{\pi |\beta_2| R_s^3} B_0, \tag{4}$$

where P_{tx} is the transmitted power, N_{ch} is the number of channels, γ is the fiber nonlinear parameter, β_2 is the fiber dispersion parameter, R_s is the baudrate ($R_s = R_b/\log_2(M)$ with R_b bitrate and M is the modulation order) and L_{eff} is the effective length is given by

$$L_{\mathrm{eff}} = \frac{1 - e^{-\alpha L}}{\alpha}, \tag{5}$$

where L is the span length, α is the fiber loss parameter.

TABLE I
SUMMARY OF TRANSMISSION PARAMETERS

Parameter	Value
Baud rate	12.5 Gbaud
Channel spacing	12.5 GHz
Centered wavelength	1550 nm
Number of channels	80
Modulation	M-QAM
Fiber loss	0.2 dB/km
GVD coefficient	-21.7 ps^2/km
Nonlinear coefficient	1.4 W^{-1}/km
Amplifier noise figure	5 dB

For distributed amplification, the S_{ASE} and P_{NLI} are calculated as follows:

$$S_{\text{ASE}} = 4\alpha h\nu K_T L_{\text{tot}}, \tag{6}$$

$$P_{\text{NLI}} = \left(\frac{2}{3}\right)^3 \gamma^2 P_{tx}^3 L_{\text{tot}} \frac{\log\left(\pi^2|\beta_2|N_{ch}^2 R_s^2 L_{\text{tot}}\right)}{\pi|\beta_2|R_s^3} B_0, \tag{7}$$

where L_{tot} is the total fiber length, K_T is a constant ($K_T \backsimeq 1.13$ for Raman amplification).

Furthermore, system capacity at Nyquist limit is given in the following equation [17, 20]:

$$\frac{C}{B} = \log_2(1 + \text{SNR}) \text{ (bits/s/Hz/pol)}, \tag{8}$$

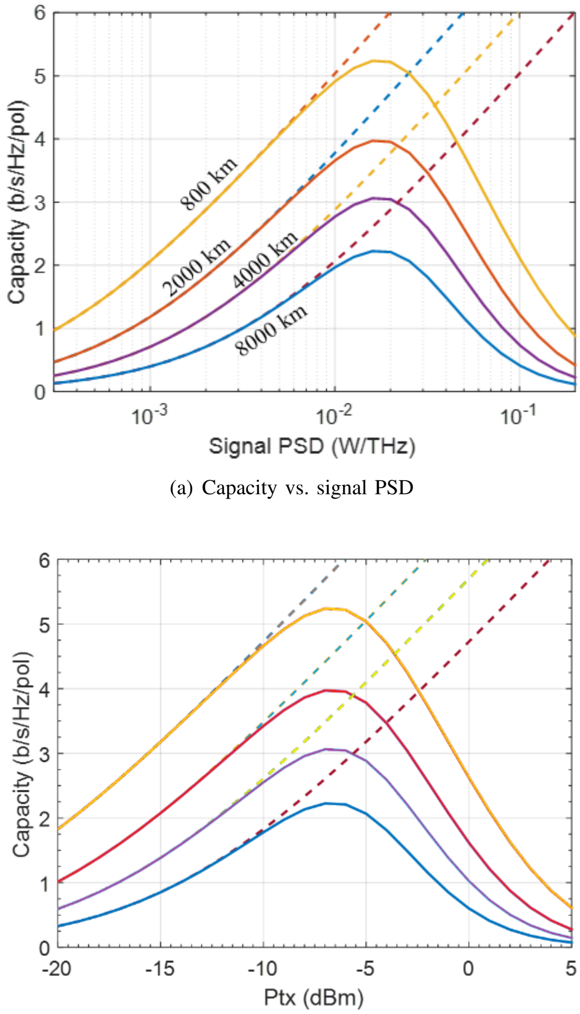
$$\text{SNR} = \frac{2B_0}{R_b}\text{OSNR} = \frac{2B_0}{R_s \log_2 M}\text{OSNR}. \tag{9}$$

And, the bit error rate (BER) for the systems with QPSK and M-QAM (Quadrature Amplitude Modulation) can be estimated respectively as in formulas (10) and (11) [20]:

$$\text{BER} = \frac{1}{2}\text{erfc}(\sqrt{\text{SNR}}), \tag{10}$$

$$\text{BER} = \frac{2\left(1 - \frac{1}{\sqrt{M}}\right)}{\log_2 M}\text{erfc}\left(\sqrt{\frac{3\log_2 M}{2(M-1)}\text{SNR}}\right). \tag{11}$$

In order to estimate the performance limits of an elastic optical transmission system, we assumed values of key parameters as given in Table I. Figure 1 demonstrates the capacity limits per polarization of 16-QAM modulation format (M=16) with respect to the signal PSD and the given transmitted power when the transmission distance is various [20]. Here, the capacity is estimated without and with optical fiber nonlinear effects (shown as dashed and solid graphs). The results confirm that the system capacity is limited due to the nonlinear effects of optical fibers. Consequently, the system performance, in terms of BER, is also strongly depended on the fiber distance and the transmitted power (as shown in Figure 2).



(a) Capacity vs. signal PSD

(b) Capacity vs. signal transmission power

Fig. 1. Information capacity limits per polarization of 16-QAM for linear (dashed line) and nonlinear (solid line) transmission at different transmission distances (L_{span} = 80 km).

On the other hand, the dependence of the system performance, in terms of capacity, BER and the maximum optical reach at BER of 10^{-3}, on the transmission distance and the applied modulation format is shown in Figures 3 and 4 correspondingly. Applying higher-order modulation formats which support higher capacity per spectrum slot and consequently, require less number of spectrum slots. In other words, employing higher-order modulation format can attain higher spectrum efficiency but it suffers from shorter optical transparent reach and as a result, more frequent regeneration and/or more regeneration resources are required. On the other hand, using lower-order modulation formats may cause less spectrum slot capacity and thus, may result in an increment in the required number of spectrum slots. Hence, there exists a trade-off between the system performance and the transmission length/modulation format in elastic optical networks.

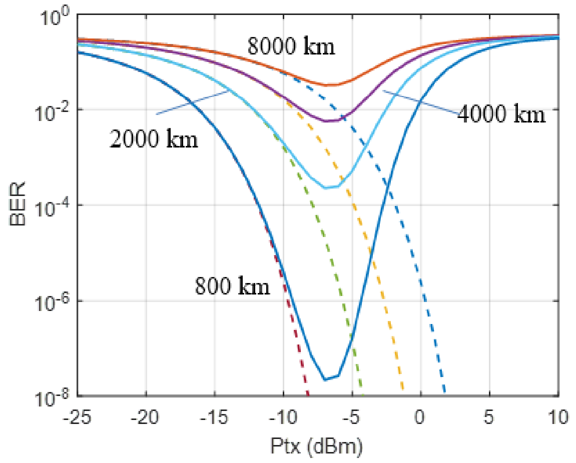
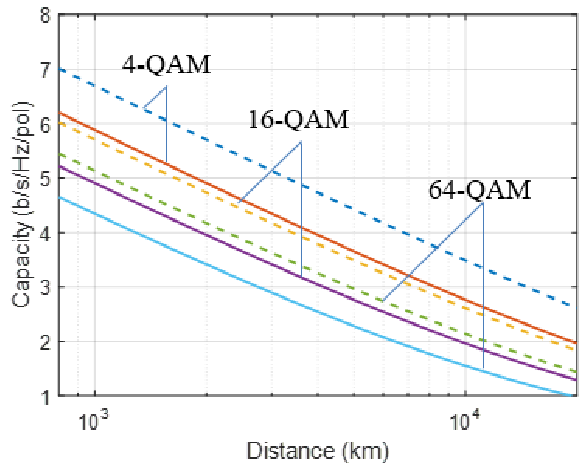
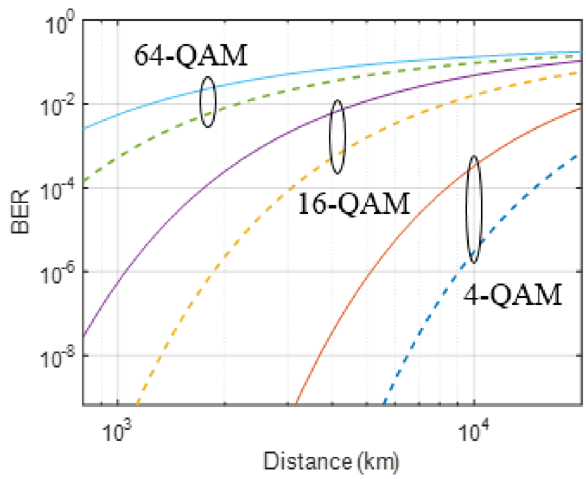


Fig. 2. Performance limits of 16-QAM format for linear (dashed line) and nonlinear (solid line) transmission.



(a) Capacity



(b) BER

Fig. 3. Performance limits vs transmission distance for linear (dashed line) and nonlinear (solid line) transmission schemes at different M-ary (L_{span} = 80 km).

2. Optical Regeneration Issue and Its Application

In general, optical regeneration can be deployed in optical networks to mitigate the accumulation of noises to limit signal degradation and extend the transmission length of optical paths. Optical regenerators are capable of re-amplifying (1R), re-shaping (2R), and even re-timing (3R) the signals and so, called 1R, 2R or 3R regenerators respectively. Among those regenerators, 3R regenerators are required for high-speed and long reach optical paths. Optical regenerator technology for WDM networks is quite mature and it strongly relies on the provided data rate; semiconductor optical amplifier (SOA)-based Mach-Zehnder interferometers have been widely utilized for amplitude modulation to support data rates up to 40 Gbps while ultrafast mechanisms in optical fibers or polarization rotation in SOAs are popularly employed to deal with higher rates such as beyond 40 Gbps [10, 14]. Recently, all-optical 3R (reamplifying, reshaping, and re-timing) regeneration devices can directly handle the optical signal degradation caused by fiber loss, dispersion and the amplified spontaneous emission noise of EDFAs or fiber nonlinearity, and overcome the bandwidth bottleneck of optical–electrical–optical (O/E/O) processing systems.

In addition to conventional regenerators, a new regeneration technology, named virtualized elastic regenerator (VER), that is able to regenerate flexibly and cost-effectively multiple-data-rate optical signals, has been proposed to realize emerging elastic optical networks [14]. VERs are constructed based on spectrum-selective sub-channel regenerators (SSRs) where each SSR is capable of regenerating a sub-channel, i.e., 100 Gbps. A VER includes a set of SSRs and all the incoming optical signals, that need to be regenerated, share the regeneration resource, says SSR pool. By sharing SSRs in the regeneration pool of VER, optical signals with various data rates can be cost-effectively regenerated. Based on the data rate of each incoming optical signal, a number of necessary SSRs is allocated to regenerate the optical signal. In order to provide the spectrum selectivity in VER, optical coherent detection with a wavelength tunable local oscillator (LO) is employed. Along with the multiple-channel and various data rate regeneration capability, a VER is also able to convert modulation format distance-adaptively (also known as re-modulation capability) and hence, it enables saving the spectrum utilization when the transmission distance is sufficiently short enough to use more spectrum-efficient (higher-order) modulation formats. In other words, VERs can provide 4R regeneration function. However, note that VER cost seems to be expensive and relies strongly on the SSR pool size, the number of SSRs [15, 16].

From network point of view, elastic optical networks that are partially with VER-equipped nodes (i.e. recon-

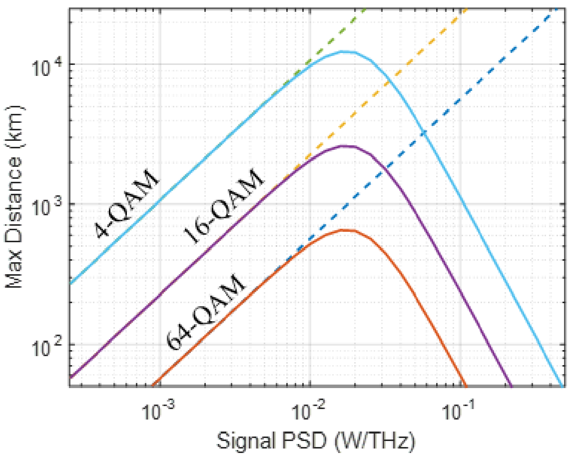


Fig. 4. Transmission distance limits vs signal PSD per channel at BER = 10^{-3} with L_{span} = 80 km for linear (dashed line) and nonlinear (solid line) transmission schemes at different M-ary QAM formats.

figurable optical add-drop multiplexer (ROADMs)/optical cross-connects (OXCs)) are capable of not only providing distance-adaptive and multiple modulation format optical paths, but also offer the optical path regeneration (including 3R and 4R regeneration). Lightpaths can be regenerated with/without being re-modulated only at the nodes that consist of VERs. Furthermore, to establish lightpaths dynamically and effectively in elastic optical networks, routing, modulation and spectrum assignment (RMSA) problem must be solved efficiently. The applied RMSA scheme must be able to overcome the optical reach limit constraint while exploiting distance-adaptive modulation capability of the networks. As discussed in [18], with a given capacity of traffic demand, higher-order modulation formats may offer a spectrum reduction while suffer from an increase in the regeneration utilization frequency and/or necessary regenerator devices. Contrarily, a lower-order modulation format can help to extend the optical reach and so, may reduce the number of necessary regenerator devices but, it may result in less spectrum utilization efficiency. Therefore, employing 4R regeneration with an effective RMSA algorithm enables improving the spectrum usage efficiency while dealing with the spectrum continuity and spectrum consecutiveness constraints in elastic optical networks.

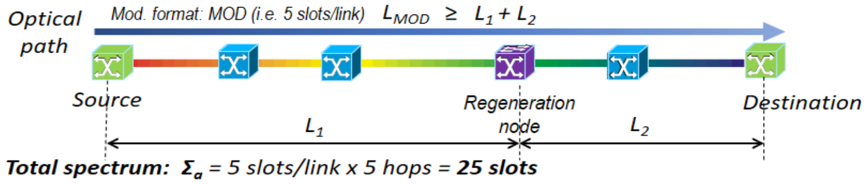
In fact, elastic optical networks can use various types of regenerators (3R or 4R) and low-order modulation formats can be employed to extend the optical reach and avoid the use of regenerators. Figure 5 illustrates the differences among three regeneration applicable elastic optical network scenarios that are a network without using regenerators, 3R and 4R regeneration capable ones. Here, L_{MOD} is the optical reach required if the modulation format, MOD, is used while L_1 and L_2 are the sub-path lengths. The distance adaptive modulation capability can be exploited by using appropriate regenerators to enhance the spectrum utilization efficiency of the networks (the required L_{MOD} is shorter). Obviously, selection of regeneration nodes and modulation format and spectrum assignment strategy are the key for minimizing the network performance.

III. Network Performance Evaluation

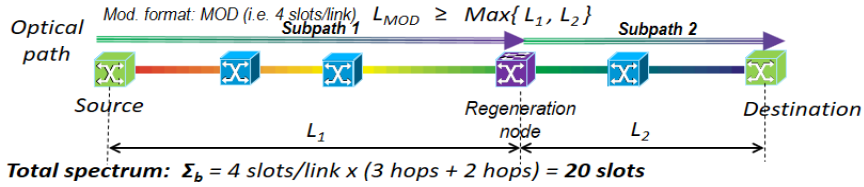
In this section, we evaluate the performances of dynamic elastic optical networks using different optical regeneration techniques including 3R- and 4R-capable regeneration, in term of the overall blocking probability and the accommodated traffic volume. In order to clarify the impact of optical regeneration in dynamic elastic optical networks, the network performances of three regeneration applicable network scenarios including (i) no regeneration, (ii) only 3R regeneration and (iii) fully-capable elastic regeneration (4R) will be tested and compared. For fair comparison, we employ similar RMSA algorithms for those cases. We also use two different RMSA algorithms which are a simple shortest path and first fit algorithm (called First Fit) [21] and the spectrum-least RSA algorithm which has been developed in [22] (denoted as Least Spectrum).

Moreover, two typical network topologies, that are (i) National Science Foundation network (NSF) consisting of 14 nodes and 22 links, and (ii) US backbone network (USNET) including 24 nodes and 43 links (shown in Figure 6) are used for numerical experiments. The regeneration capable node number is assumed to be limited at 4 and 7 for NSF and USNET respectively and each case will be tested with 20 random scenarios. We also use following parameters for the numerical simulation. Each fiber link can carry up to W spectrum slots (W is fixed at 128) and the slot bandwidth is assumed to be 12.5 GHz. The networks can flexibly and dynamically set up and release optical paths (also called lightpaths). Modulation format of each lightpath is distance-adaptively assigned. Lightpath requests arrive sequentially and follow Poisson distribution. Average arrival rate of ligthpaths is λ (requests per time unit). Distribution of lightpath holding time is assumed to be a negative exponential one with the mean hold time of $1/\mu$ (time units). Consequently, the given network traffic load in Erlangs is λ/μ. Here, the capacity, C, of each requested lightpath between node pairs is also randomly assigned between 50 and 100 Gbps following a uniform distribution. The assumed modulation formats are BPSK, QPSK, 8-QAM and 16-QAM. The slot bandwidth and the corresponding transparent reach of BPSK, QPSK, 8-QAM, and 16-QAM optical signals are given in Table II [21, 22].

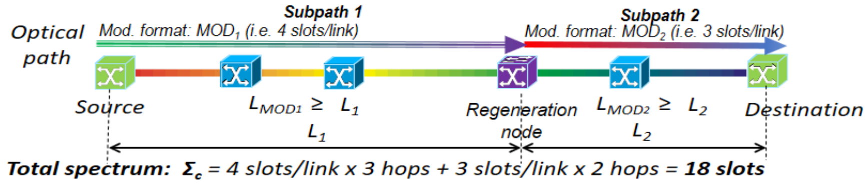
As mentioned above, we evaluate the network performance in three comparative regeneration scenarios of elastic optical networks: (i) without regeneration capability (named



(a) No regeneration scenario

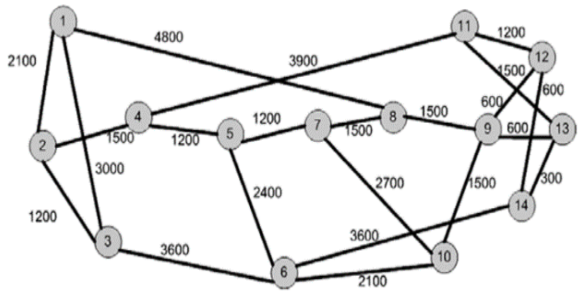


(b) 3R regeneration scenario

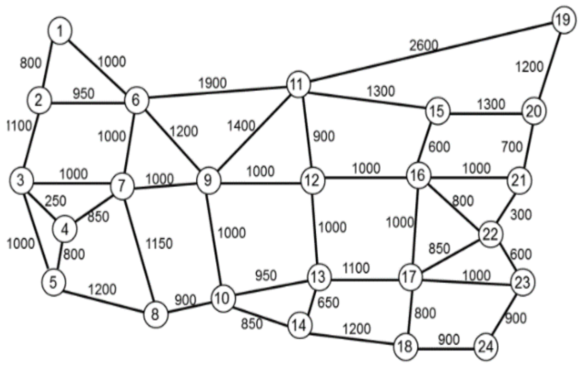


(c) 4R regeneration scenario

Fig. 5. Regeneration network scenario comparison.



(a) NSF



(b) USNET

Fig. 6. Experimental network topologies (NSF and USNET).

No regeneration), (ii) 3R regeneration with two different RSA algorithms including First-fit and Least-spectrum algorithms (so called First fit w/ 3R and Least spectrum w/ 3R correspondingly), and (iii) 4R regeneration also with

TABLE II
SUMMARY OF KEY PARAMETERS

Parameter			Value
Spectrum slot number per link			128
Slot bandwidth			12.5 GHz
Modulation format	BPSK	Slot capacity	12.5 Gbps
		Transparent reach	9600 km
	QPSK	Slot capacity	25 Gbps
		Transparent reach	4800 km
	8-QAM	Slot capacity	37.5 Gbps
		Transparent reach	2400 km
	16-QAM	Slot capacity	50 Gbps
		Transparent reach	1200 km
Capacity of requested lightpaths			50-100 Gbps
Connection mean hold time			1000

First-fit and Least-spectrum RSA algorithms (denoted by First fit w/ 4R and Least spectrum w/ 4R respectively). The performance of the comparative network scenarios, in terms of the blocking probability, is shown severally in Figures 7 and 8 for NSF and USNET network topologies when the traffic load ranges from 100 to 1500 Erlangs. These figures verify that the network scenarios using optical regeneration, i.e. 3R or 4R regeneration, can dramatically decrease the blocking probability in comparison with that without regeneration. That is because implementing optical regeneration can help to resolve the spectrum collision, save the spectrum resources with higher modulation formats and enhance the optical reach to improve the network utilization. Moreover, the results also show that applying

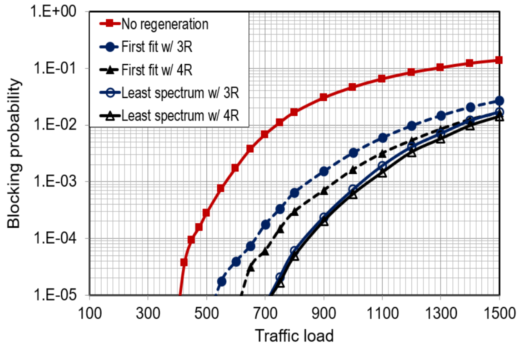


Fig. 7. Blocking probability for NSF network.

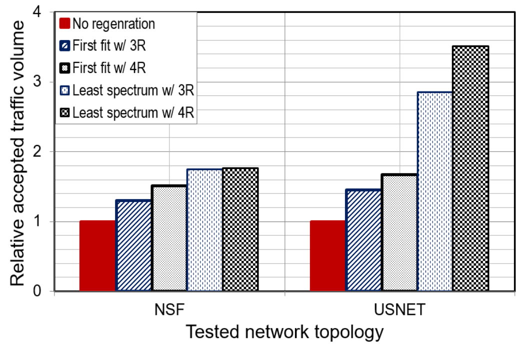


Fig. 9. Accommodated traffic volume comparison.

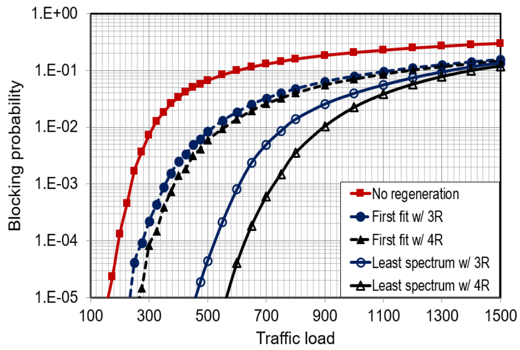


Fig. 8. Blocking probability for USNET network.

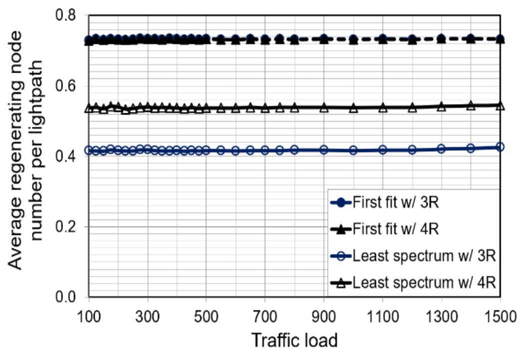


Fig. 10. Average number of regenerating nodes per lightpath for NSF network.

4R regeneration offers better performance than that of 3R regeneration. Such performance improvement is obtained by re-modulating the optical signal into the optimal modulation format for exploiting the distance-adaptive feature of elastic optical networks.

Furthermore, as being verified in Figures 7 and 8, the performance of the networks also strongly depends on the applied RMSA algorithm due to the effect of selecting the regeneration nodes and the modulation format. Optimizing the regenerating node position and assigning suitable modulation formats play an important role to enhance the overall spectrum utilization efficiency. It is confirmed that the effect of optical regeneration is enhanced with larger network. The main reason is that high-order modulation levels can be assigned to shorter lightpaths and consequently, help to lessen the number of spectrum slots required. On the other hand, larger network which contains longer average length of lightpaths requires more regeneration resources, especially for the lightpaths with high-order modulation format due to the transparent reach limitation.

Moreover, Figure 9 demonstrates the comparison of relative accepted traffic volumes among the experimented scenarios, that are No regeneration, First fit w/3R, First fit w/ 4R, Least spectrum w/ 3R and 4R, with the given blocking probability of 10^{-5}. The results obtained by No regeneration is used as the benchmark, so its graph is 1. The figure describes that, with the same network conditions, using optical regeneration provides higher accepted traffic volume thanks to the signal regeneration. We can attain at least 29.8% (45.6%) higher traffic volume with NSF (USNET) network. Implementing more-efficient RSA algorithm (i.e. spectrum least) even can further improve the network performance. However, note that it may results in higher network CAPEX. In fact, we must consider the cost of regeneration devices carefully to satisfy the tradeoff between the CAPEX and the network performance.

We have also estimated the average number of regenerating nodes and that of spectrum slots per lightpath in the experimental network topologies to determine the requirement of necessary regeneration resources. Figures 10 and 11 illustrate the obtained numerical results for NSF topology and Figures 12 and 13 show that of USNET respectively. Because of the use of same regenerating node selection strategy, both First fist w/ 3R and First fit w/ 4R scenarios need almost the same average number of regenerating nodes for each lightpath. However, the number of regenerated spectrum slots is decreased with the use of 4R regeneration thanks to modulate the signals distance-adaptively. The graphs also verify that, with the Least spectrum algorithm, the improvement of the network performance costs more regenerating resources.

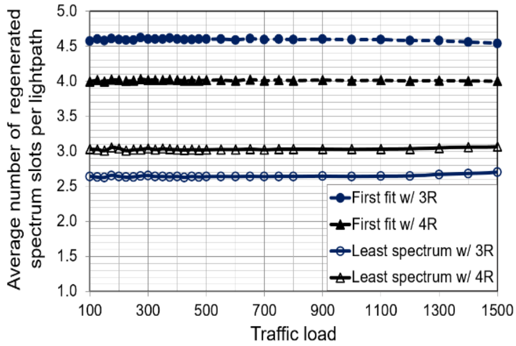


Fig. 11. Average number of regenerated spectrum slots per lightpath for NSF network.

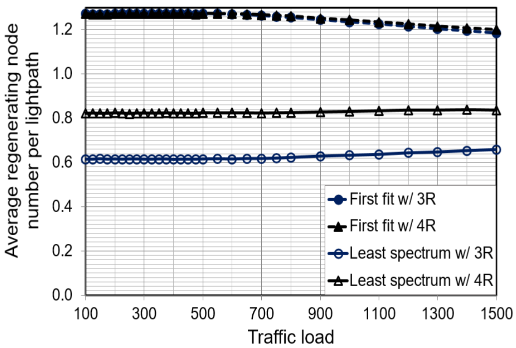


Fig. 12. Average number of regenerating nodes per lightpath for USNET network.

Finally, Figures 14 and 15 illustrate the modulation efficiency, which is the ratio of the average spectrum slot number per established lightpath of each compared scenario to that of No regeneration one, of both NSF and USNET. The spectrum slot number of No regeneration scenario is used as a benchmark and consequently, its normalized value is one. It demonstrates that although First fit strategy offers better modulation efficiency (less ratio) for established lightpaths, it does not consider the spectrum collision an as a result, its performance is poorer than that of Least spectrum strategy.

IV. Conclusion

In this paper, we have investigated the impact of various optical regeneration techniques including 3R and 4R on the performance of dynamic elastic optical networks. We firstly discussed and clarified the differences among optical regenerating usage scenarios without regeneration and with regeneration (both 3R and 4R regeneration). We have, then, evaluated and compared the dynamic elastic optical network performance, in term of the blocking probability and the total accepted traffic volume, etc. for three comparative network scenarios including (i) no regeneration, (ii) with 3R regeneration and (iii) with 4R regeneration capabilities.

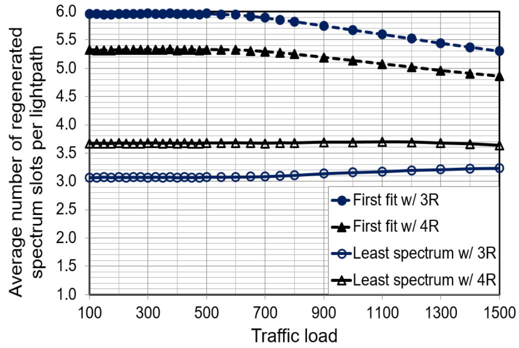


Fig. 13. Average number of regenerated spectrum slots per lightpath for USNET network.

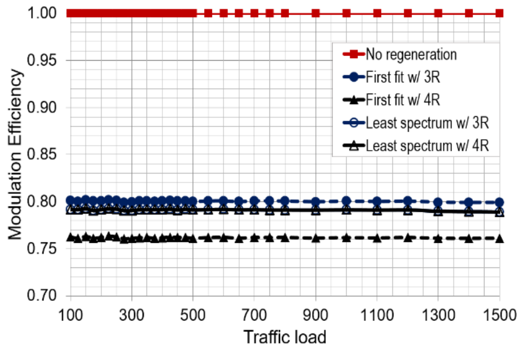


Fig. 14. Modulation efficiency of NSF network.

Numerical simulation results prove that using optical regenerators, especially 4R regenerators, can help to exploit elastic optical networking and enhance the dynamic network performance for provisioning bandwidth-flexible lightpath services. It was demonstrated that at least 29.8% (or 45.6%) more traffic volume can be attained for NSF (USNET) network. However, optical regenerating devices are expensive and hence, the trade-off between the required network performance and the necessary regenerating resource cost should be considered carefully in order to create future cost-effective, spectrum-efficient and bandwidth-flexible optical networks.

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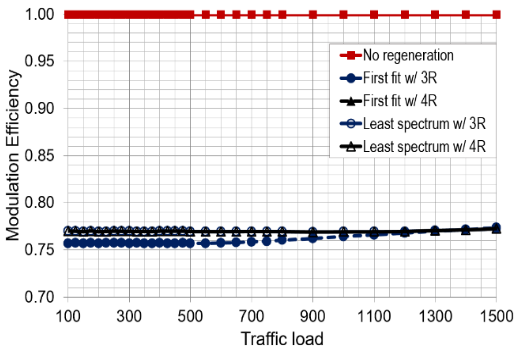

Fig. 15. Modulation efficiency of USNET network.

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