Effect of Reduced Link Margins on C+L band Elastic Optical Networks

Abhijit Mitra, Daniel Semrau, Nishant Gahlawat, Anand Srivastava, Polina Bayvel and Andrew Lord

***Abstract*—Network traffic is growing exponentially which has increased the onus on network operators to expand their network spectral resources beyond the C band. This work explores the effect of operating at reduced Link Margin (LM) over the combined C and L bands. For this purpose we utilize a lightpath Optical Signal to Noise Ratio (OSNR) estimation model which considers Non-Linear Interference (NLI) due to Inter-channel Stimulated Raman Scattering (ISRS) and Amplified Spontaneous Emission (ASE) noise generated by in-line amplifiers while predicting the OSNR. This model is utilized to account for the benefits of operating at reduced LM in the BT-UK, Pan Europe and USA-NSFNET networks. Our results indicate that significant gains in capacity can be achieved by operating at low margins across all the networks. Further, it is concluded that the launch power of network lightpaths should be optimized based upon the network size and operating LM.**

***Index Terms*—C+L band, Link Margin, Non-Linear Interference, Stimulated Raman Scattering**

I. Introduction

THE exponential rise in data traffic growth is due to growth in high-speed wireless and fixed access for consumers, fuelled by the development of innovative applications like video on demand, ultra-HD video conferencing and cloud based services. These services are enablers for the fourth industrial revolution where the seamless flow of data is essential. This high rate of data exchange has put the onus on network operators to increase their network capacity which, for the core part of the network has led to the inception of Elastic Optical Network (EON) technology [1] where a truly re-configurable and dynamic network, maximising spectral efficiency, was envisioned. EON's main objective is to enhance the capacity per lightpath by use of high order PM-m-ary modulation formats, and more efficiently use spectral resources by using finer frequency granularity (FG) of 25 GHz and 12.5 GHz [2].

Manuscript received April 16, 2019.This work was supported in part by the Inspire Faculty Scheme, Department of Science and Technology, New Delhi, India, under Grant DST/INSPIRE/04/2017/000089.

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In recent years, strong research contributions have been made to develop EON. However, the data growth projection still indicates an average internet traffic growth of more than 40% [3]. This has made it incumbent upon network operators to explore additional methods to increase network capacity. One option is to use multi-core fibers or few-mode fibers while an alternative option is to use parallel fibers on some links. In both cases, operators will need to incur additional capital expenditure. An alternative way to avoid the expenditure of laying additional fiber is to explore the entire spectrum range of standard Single Mode Fiber (SMF). SMF has various frequency bands, O,E,S,C and L bands, with networks currently operating in the C band with a net bandwidth of 5 THz. Therefore, as a first step, addition of the L band seems to be a good choice because the attenuation coefficient variation between C and L band is negligible and the in-line Erbium Doped Fiber Amplifier (EDFA) can be tuned to amplify in the L band. The impact of this would be to increase the cumulative bandwidth per optical link from 5 THz to 10 THz. However, the increase in network capacity will come at a cost of incurring higher NLI due to ISRS. Hence, it will limit the optical lightpath's OSNR which is an important figure of merit in EONs.

ISRS is a phase-insensitive power transfer which amplifies lower frequency components and depletes higher frequency components. In C+L band network operation, this process needs to be considered in order to reasonably predict the increase in network capacity. In [4]–[8] attempts have been made to model the ISRS process. However, those works propose analytical expressions in integral form which need to be solved numerically. This makes them unsuitable for optical network analysis where a vast number of NLI calculations must be performed for numerous traffic and routing configurations. Recently, the work in [9] presented a closed form expression to estimate the NLI due to ISRS enabling quasi-instantaneous NLI estimation.

Traditionally, network operators have been operating network lightpaths with built-in LMs to prevent service disruption due to link degradation [10], [11]. LM is an accumulation of Design Margin, Ageing Margin and Fill Margin and the range is between 3 to 6 dB for various networks, including North American backbone networks [12], [13]. Given that the transponders in EONs can be dynamically configured to adapt their modulation formats [14], it is unnecessary to use high LMs for every link in the network, and indeed, setting such a high LM, coupled with the detrimental effect of NLI across C+L band will significantly limit the network capacity. Hence, it is important for a network operator to consider the

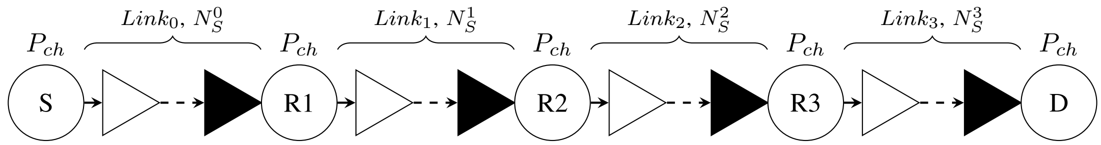

Fig. 1: Multihop path for OSNR estimation

network dimensions and tunability of their transponders before using high LMs on the network lightpaths. It is unlikely that operators will reduce LM all the way to 0 dB. However, in this paper we show the extreme upper bound to show what the maximum benefits of reduced margin might be. In practice, the actual operating margin is still an open question, involving issues such as performance variations which are beyond the scope of this paper.

In this work, the closed form expression [9] is used to derive the OSNR of a network lightpath while utilising the OSNR estimation model. This model is used to study the effect of operating at the OSNR limit in the BT-UK, Pan Europe and USA-NSFNET networks. The frequently used modulation formats for these networks are reported at various LMs. In Section II, the lightpath OSNR estimation model is described. In Section III (A), the benefits of operating at the OSNR limit are reported. Finally, in Section III (B) we highlight that channel launch power needs to be optimized while considering network dimensions and operating LM.

II. OSNR ESTIMATION MODEL

In Fig. 1, a network lightpath connection is shown which travels through multiple intermediate re-configurable optical add-drop multiplexers (ROADMs) and multiple optical links. A uniform channel launch power, P_{ch} is assumed and ROADMs are considered to have an 18 dB loss. The in-line EDFA module not only compensates for the previous span loss but has a gain equalizing effect that compensates for the ISRS gain of various channels to restore the channel power back to P_{ch} across all the active channels in the C+L band [15].

While following Fig. 1, the OSNR of a network lightpath operating at a particular frequency is calculated from Eq. (1):

$$\frac{1}{OSNR(f)} = \sum_{i=0}^{N_L-1} \left(\frac{P^i_{ASE}(f) + P^i_{NLI}(f)}{P_{ch}} \right) + \left(\frac{P^R_{ASE}}{P_{ch}} \right) N_R \tag{1}$$

$P^i_{ASE}(f)$ is the total ASE noise from the in-line EDFAs in the i^{th} optical link. $P^i_{NLI}(f)$ is the nonlinear interference power in the i^{th} optical link. In this work, $P^i_{NLI}(f)$ includes nonlinear mixing terms due to self-phase modulation (SPM) and cross-phase modulation (XPM). Additionally, the impact of ISRS on these nonlinear mixing terms is accounted for. P^R_{ASE} is the ASE noise generated at the ROADM post amplification. N_R is the number of intermediate ROADM nodes traversed by a lightpath. The ASE noise generated by the in-line amplifiers considers the frequency dependent ISRS gain profile across the C+L band. The ISRS gain at frequency

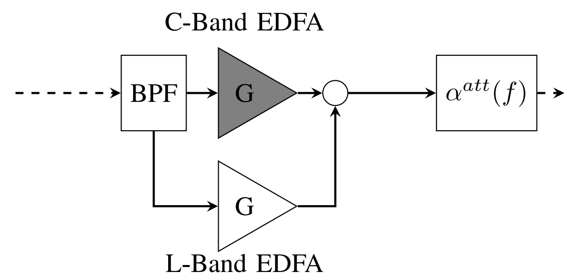

Fig. 2: EDFA Model for C+L band amplification

f, can be approximated from Eq. (2) [4]:

$$\rho(z, f) = \frac{P_{tot} e^{-\alpha z - P_{tot} C_r L_{eff} f}}{\int G_{Tx}(\nu) e^{-P_{tot} C_r L_{eff} \nu} d\nu} \tag{2}$$

P_{tot} is the total signal power across the active channels in the 10 THz spectrum, G_{Tx} power spectral density, C_r is the Raman gain slope, α is the attenuation and L_{eff} is the effective length. Equation (2) assumes negligible variation of the attenuation coefficient and lumped amplification over the optical transmission window.

A. EDFA noise model

The EDFA module in Fig. 2, is modelled as an EDFA with fixed gain G(dB) (linear gain g), followed by a frequency dependent attenuation, $\alpha^{att}(f)$ [15]. The Bandpass Filter (BPF) in Fig. 2 separates the C and L band frequencies. $G(dB)$ restores the lowest signal power reaching the EDFA module back to P_{ch} and the $\alpha^{att}(f)$ block compensates for any additional gain due to ISRS and restores the uniform P_{ch} across all the channels. The ASE noise generated by each EDFA is given by Eq. (3):

$$P^{i_{span}}_{ASE}(f) \approx 2 n_{sp} g(f) h f B_{Ref} \tag{3}$$

In Eq. (3) we have considered separate n_{sp} values for C and L band lightpaths. This paper has fixed the EDFA performances to be 4 dB (n_{sp}=1.25) and 6 dB (n_{sp}=1.99) noise figures (NF) for the C and L band EDFAs respectively, together with a further 0.5 dB loss for the BPF. We assumed that L band performance would inevitably be worse than C band, and also we assumed that the native C band noise figure could be around 4 dB, with monitoring functions being part of the surrounding optics and included in the 0.5 dB coupling loss. Combined C + L band amplifier designs are in their infancy and we fully expect these tentative values to change as the technology develops. Nevertheless, changing EDFA NFs has the effect of directly changing the lightpath ASE-driven OSNRs by the same amount in dB, whilst leaving

TABLE I: System Parameters

Symbol	Parameters	Values
α	Loss [db/km]	0.2
D	Dispersion [ps/nm/km]	17
S	Dispersion Slope [ps/nm^2/km]	0.067
γ	NL coefficient [1/W/km]	1.2
C_r	Raman gain slope [1/W/km/THz]	0.028
C_r·14 THz	Raman gain [1/W/km]	0.4
B_{CH}	Channel Spacing [GHz](FG=50 GHz)	50
B_{CH}	Channel Spacing [GHz](FG=12.5 GHz)	37.5
P_{ch}	Channel Launch Power [dBm]	0, -1.25, -3
N_{CH}	Number of 50 GHz Channels	200
N_{CH}	Number of 37.5 GHz Channels	266
B_{tot}	Optical Bandwidth [THz]	10

the NLI contributions unchanged. Therefore, although the absolute network capacity values will change, the general conclusions of the paper will not change. The fiber attenuation, α has a negligible variation of about 0.01 dB/km across C+L band [16], hence $\alpha = 0.2$ dB/km has been assumed for all lightpaths, h is Planck's constant, B_{ref} is the reference bandwidth and f is the central frequency of the lightpath under consideration. The EDFA modules are symmetrically placed at equal distances in an optical link with a maximum span length of 60 km. The EDFA gain $G(f)$ is frequency dependent such that the power across all the channels is uniformly restored to P_{ch}. $G(f)$ can be calculated from Eq. (4):

$$G(f)(dB) = \begin{cases} \alpha L^i_{span} - \rho(L^i_{span}, f) & \text{positive ISRS gain,} \\ \alpha L^i_{span} & \text{no ISRS gain,} \\ \alpha L^i_{span} + \rho(L^i_{span}, f) & \text{negative ISRS gain} \end{cases} \tag{4}$$

where L^i_{span} is the symmetrical span length of the i^{th} link and $\rho(L^i_{span}, f)$ (dB) is the ISRS gain which is experienced by respective frequency components over L^i_{span}. Given the number of spans, N^i_S in the i^{th} link, the total ASE generated by symmetrically spaced EDFA modules, $P^i_{ASE}(f)$ for the i^{th} link is given by Eq. (5)

$$P^i_{ASE}(f) = N^i_S P^{i_{span}}_{ASE}(f) \tag{5}$$

B. Nonlinear Interference across C+L Band

In this work the ISRS based NLI model has been considered [9]. In a C+L band system the total signal power P_{tot} and power spectrum density $G_{\text{Tx}}(f)$ will have an impact on the ISRS process which has been accounted for in this model. The NLI coefficient for single span in presence of ISRS, $\eta_1(f_z)$ at f_z channel is given by Eq. 6 [4], where $\phi(f_1, f_2, f_z, \zeta)$=$-4\pi^2(f_1 - f_z)(f_2 - f_z)[\beta_2 + \pi\beta_3(f_1 + f_2)]\zeta$. β_2 is the group velocity dispersion (GVD) parameter, β_3 is the linear slope of the GVD parameter [4].

$$\begin{aligned} \eta_1(f_z) = &\frac{B_z}{P_z^3}\frac{16}{27}\gamma^2 \int df_1 \int df_2 G_{\text{Tx}}(f_1)G_{\text{Tx}}(f_2) \\ &.G_{\text{Tx}}(f_1 + f_2 - f_z) \\ &\cdot \left| \int_0^L d\zeta \frac{P_{\text{tot}} e^{-\alpha\zeta - P_{\text{tot}} C_r L_{\text{eff}}(f_1+f_2-f_z)}}{\int G_{\text{Tx}}(\nu) e^{-P_{\text{tot}} C_r L_{\text{eff}} \nu} d\nu} e^{j\phi(f_1, f_2, f_z, \zeta)} \right|^2 \end{aligned} \tag{6}$$

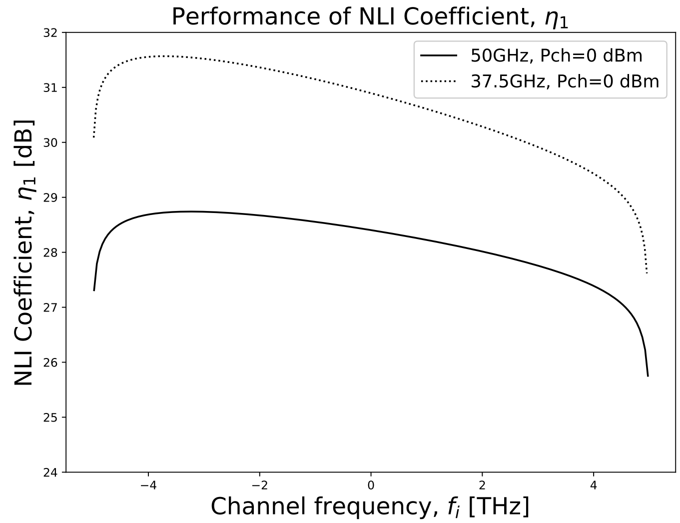

Fig. 3: Single span NLI Coefficient for different channel spacing B_{ch} at P_{ch}=0 dBm with fully occupied 10 THz spectrum

An alternative closed form expression for Eq. (6) has been proposed in [9]. The closed form expression considers the nonlinear perturbations due to XPM and SPM. The $\eta^{(k)}_{\text{XPM}}(f_z)$ in Eq. (7) is the NLI contribution where the k^{th} channel interferes with the z^{th} channel of interest (COI). In Eq. (7), B_z is the COI channel bandwidth and B_k is the channel bandwidth of the k^{th} interfering channel.

$$\begin{aligned} \eta_{\text{XPM}}(f_z) \approx &\frac{32}{27} \sum_{k=1, k\neq z}^{N_{\text{ch}}} \left(\frac{P_k}{P_z}\right)^2 \frac{\gamma^2}{B_k \phi_{z,k} \bar{\alpha}(2\alpha + \bar{\alpha})} \\ &\cdot \left[\frac{T_k - \alpha^2}{\alpha} \text{atan}\left(\frac{\phi_{z,k} B_z}{\alpha}\right) + \frac{A^2 - T_k}{A} \text{ atan}\left(\frac{\phi_{z,k} B_z}{A}\right)\right], \end{aligned} \tag{7}$$

where

$$\phi_{z,k} = 2\pi^2 (f_k - f_z)[\beta_2 + \pi\beta_3(f_z + f_k)] \tag{8}$$

$$T_k = (\alpha + \bar{\alpha} - P_{\text{tot}} C_{\text{r}} f_k)^2 \tag{9}$$

and $A = \alpha + \bar{\alpha}$. $\eta_{\text{SPM}}(f_z)$ represents the SPM process where the z^{th} COI interferes with itself which is given by Eq. (10).

$$\begin{aligned} \eta_{\text{SPM}}(f_z) \approx &\frac{4}{9}\frac{\gamma^2}{B_z^2}\frac{\pi}{\phi_z \bar{\alpha}(2\alpha + \bar{\alpha})} \\ &\cdot \left[\frac{T_z - \alpha^2}{\alpha} \text{asinh}\left(\frac{\phi_z B_z^2}{\pi\alpha}\right) + \frac{A^2 - T_z}{A} \text{asinh}\left(\frac{\phi_z B_z^2}{\pi A}\right)\right], \end{aligned} \tag{10}$$

where

$$\phi_z = \frac{3}{2}\pi^2(\beta_2 + 2\pi\beta_3 f_z) \tag{11}$$

The closed-form approximation has been derived based on a first-order description of ISRS Eq. (2). More details on the key assumptions made to derive Eq. (7-11) can be found in [9]. As

TABLE II: Network Link Dimensions

Network	Min	Max	Avg
BT-UK	2 km	686 km	147 km
Pan Europe	218 km	783 km	486 km
USA NSFNET	282 km	3482 km	1319 km

TABLE III: OSNR Threshold

Modulation	Data Rate (Gbps)	OSNR Threshold
PM-BPSK	50	9 dB
PM-QPSK	100	12 dB
PM-8QAM	150	16 dB
PM-16QAM	200	18.6 dB
PM-32QAM	250	21.6 dB
PM-64QAM	300	24.6 dB

the variation of the attenuation coefficient over the C+L band is neglected, we have that $\bar{\alpha} = \alpha$. The closed form expression of the above total NLI contribution due to $\eta_{XPM}(f_z)$ and $\eta_{SPM}(f_z)$ is given by :

$$\eta_1(f_z) = \eta_{\text{XPM}}(f_z) + \eta_{\text{SPM}}(f_z) \tag{12}$$

The SMF parameters used for $\eta_1(f_z)$ evaluation are listed in Table I. The closed form expression in Eq. (7) and Eq. (10) can approximate NLI coeffiecient with high accuracy for span lengths > 23 km. Smaller link lengths have been set to 23 km (only for the NLI computations) in order to obtain reliable and conservative performance estimates. The GN model will underestimate the performance for short single span transmissions. However, please note that interfering channels, within such short links, mostly originate in other parts of the network and therefore accumulate significant amounts of dispersion. As a result, the performance underestimation of the GN model for single-span transmission is expected to be less than in a pure point-to-point configuration.

The model assumes an incoherent addition of NLI generated across symmetrically spaced spans [9] in an i^{th} link. Following the above process, the NLI coefficient for a single span in every i^{th} link has been calculated and is denoted by $\eta_1^i(f_z)$. Therefore the net NLI for the i^{th} optical link with N_s^i spans will be :

$$P_{NLI}^i(f_z) = P_{ch}^3 N_s^i \eta_1^i(f_z) \tag{13}$$

where P_{ch} is the uniform launch power for active channels in the C+L band. The $P_{NLI}^i(f_z)$ is the $P_{NLI}^i(f)$ of Eq. (1). Equation (13) is used to calculate the NLI for all the intermediate links based upon its current state of spectral occupancy.

The NLI does not only depend upon the P_{tot} but also upon the frequency granularity (FG). For a 28 GBaud system a channel bandwidth, B_{ch} of 50 GHz (FG=50 GHz) and 37.5 GHz (FG=12.5 GHz) is required. Therefore, for B_{ch}=50 GHz there will be 200 channels and using B_{ch}=37.5 GHz we will have 266 channels across the 10 THz spectrum range. Thus, more active interfering channels will give rise to increased NLI as shown in Fig. 3. Therefore, with B_{ch}=37.5 GHz, extra spectral resource may be available at the cost of higher NLI. This effect has been considered in the network simulations. From Fig. 3 and Eq. (2) the NLI and ASE noise experienced by a lightpath is dependent on the ISRS gain experienced by that channel frequency. The gradient of ISRS gain reduces with P_{ch} values. Therefore for lower P_{ch} values, the gradient of ISRS gain is almost negligible which may lead to almost uniform NLI and ASE noise being generated across the C+L band. However, the P_{ch} values should not be reduced significantly such that it has a detrimental effect on the OSNR of a lightpath. The OSNR penalty due to the ROADM filtering effect can be controlled by using using a Wavelength Selective Switch (WSS) with high Super Gaussian (SG) order [17]. Considering the research progress in this field, the results indicated in this paper suggest an upper limit to network capacity with an assumption that SG order can be modified to handle the OSNR penalty associated with the ROADM filtering effect.

III. Effect of Link Margin

In this work, the effect of reducing the LM across three geographically diverse networks BT-UK [9], Pan Europe [18] and USA-NSFNET [19] has been studied with network dimensions as indicated in Table II. For network simulation, traffic matrices of three thousand 100 Gbps demands were considered while selecting source and destination with a uniform distribution. For every new 100 Gbps demand, an attempt is made to carry them over an operational lightpath which has an unused capacity of 100 Gbps and operates between the same source and destination. As an example, if presently a lightpath is operating with PM-64QAM and carrying two 100 Gbps demands, an additional 100 Gbps demand can be allocated over the same lightpath. Similarly, if we have a pair of lightpaths, each having a spare capacity of 50 Gbps while operating at either PM-8QAM or PM-32QAM, then an attempt is made to adjust the 100 Gbps demand over this pair of lightpaths which are operating between the same source and destination and the same route. However, if no empty spectrum is found among the operating lightpaths then a new lightpath request is initiated to the network [14].

Various lightpath modulation formats were assumed, as shown in Table III. For every new lightpath, a single shortest path was found between the demand source and destination and the network OSNR estimation model was used to predict the OSNR of the lightpath. Based upon the predicted OSNR, subsequent modulation formats were allocated to each lightpath as per Table III. A first fit approach was followed to allocate the spectrum for each lightpath while maintaining spectrum continuity and contiguity constraints. After adding a new lightpath, the OSNR of the active lightpaths sharing the same optical link were updated and an attempt made to re-accommodate demands of a degraded lightpath. Simulations were done over 20 random seeds with simulation times of up to 14 hours per seed to reach the end performance results. The average value across the 20 random seeds has been presented in this paper. It was assumed that regeneration was not possible. All demands were carried all-optically from source to destination. Thus, it was necessary to select a modulation format that could accommodate this. The impact of this is discussed in Section III.A

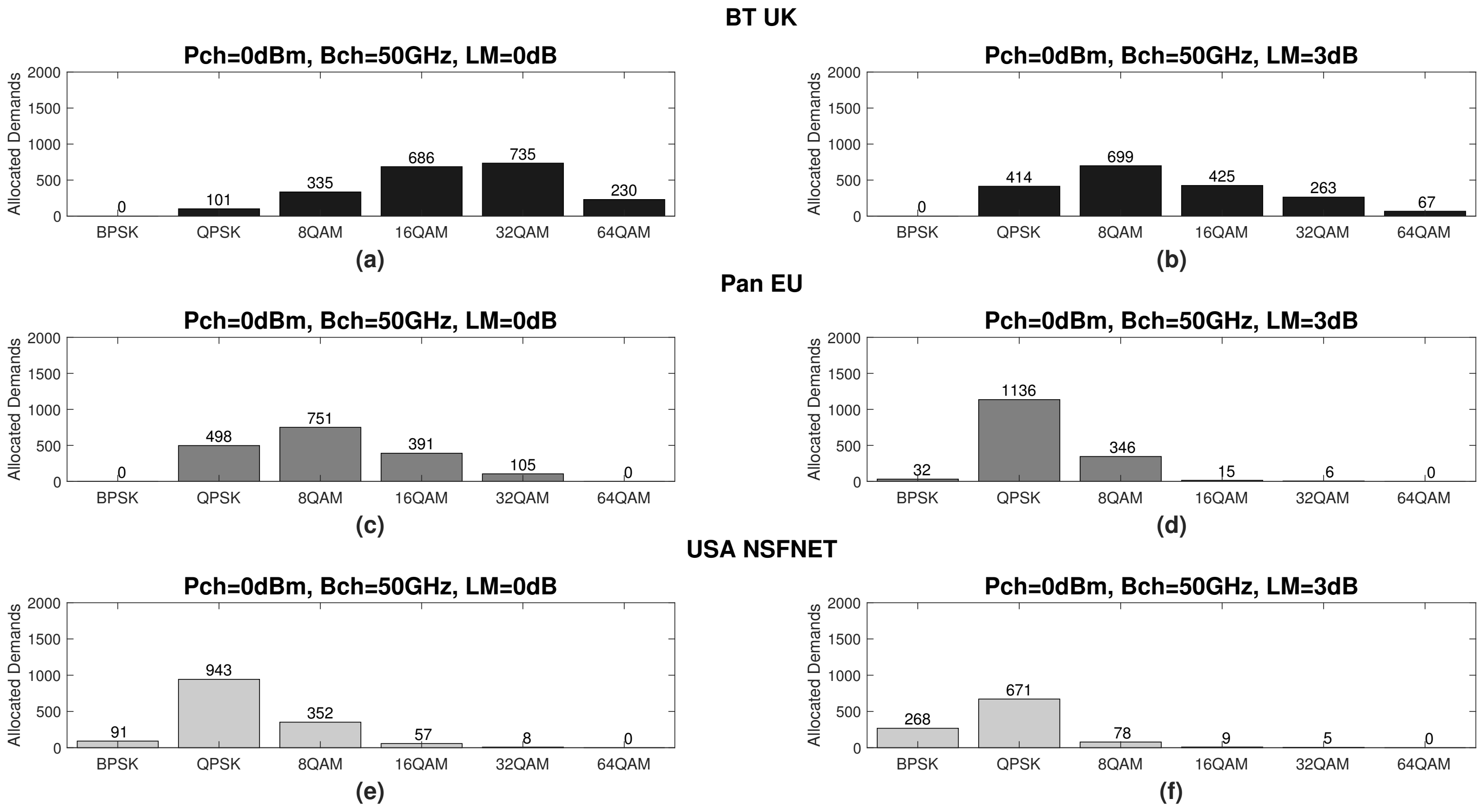

Fig. 4: End performance LM results with B_{ch}=50 GHz

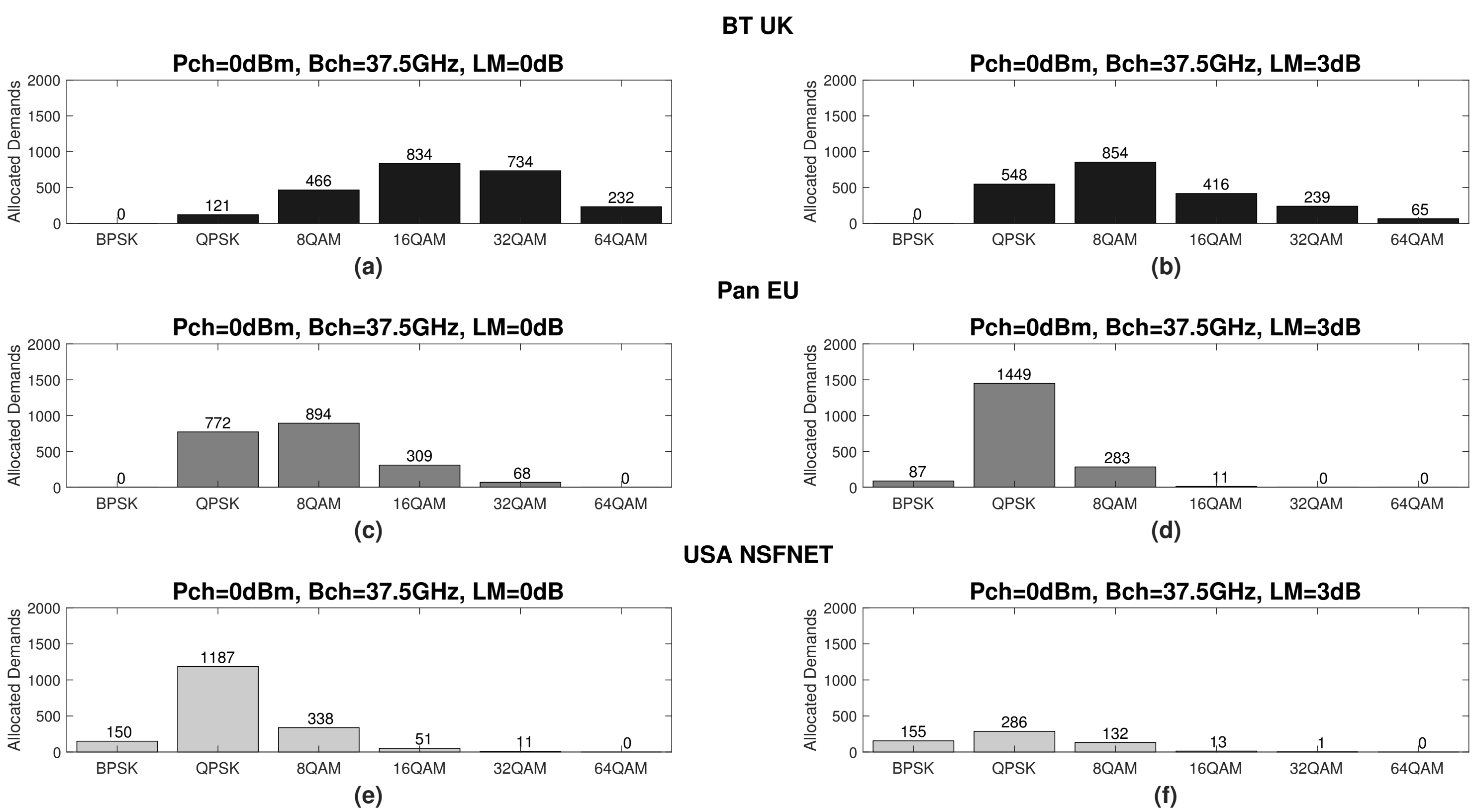

Fig. 5: End performance LM results with B_{ch}=37.5 GHz

TABLE IV: Number of allocated 100 Gbps demands with increasing LM at P_{ch}=0 dBm for 10% blocking performance

	BT-UK		Pan Europe		USA-NSFNET	
B_{ch}	LM=0 dB	LM=3 dB	LM=0 dB	LM=3 dB	LM=0 dB	LM=3 dB
50 GHz	1501	1177	1230	479	526	228
37.5 GHz	2031	1580	1562	711	671	184

TABLE V: Number of allocated 100 Gbps demands with increasing LM at P_{ch}=0 dBm for End performance

	BT-UK		Pan Europe		USA-NSFNET	
B_{ch}	LM=0 dB	LM=3 dB	LM=0 dB	LM=3 dB	LM=0 dB	LM=3 dB
50 GHz	2087	1868	1745	1535	1451	1031
37.5 GHz	2387	2122	2043	1830	1737	587

A. Benefits of operating at lower LM

In Table IV the number of allocated 100 G demands are listed for each B_{ch} and LM, until 10% of demands are blocked. 10% blocking of demands was chosen as a value that is high enough for significant blocking to be seen, which would allow the networks to be sufficiently stressed. However an operator may well choose to upgrade the networks, or certain busy links before this value is reached. In the case of the BT-UK network, a capacity benefit of 27.5% and 28.5% is achieved while operating with B_{ch}=50 GHz and 37.5 GHz at LM=0 dB. However, in the case of Pan Europe the benefit is 156.7% and 119.6% for B_{ch}=50 GHz and 37.5 GHz while operating at LM=0 dB. Similarly in the case of USA-NSFNET network the benefit is 130.7% and 264.6%. We define Fill Factor (FF) as the ratio of utilized spectral resource to the total spectrum resource in the network. The utilized spectral resource is computed by summing up the number of occupied spectrum slots in each fiber link. The FF values indicate how much the network fiber links are filled on average. We can also see this increase in network capacity reflected in the FF of the network while operating at LM=0 dB and 3 dB. In BT-UK the FF is around 0.45 for both B_{ch} and LM values, at 10% blocking. For Pan Europe, the network gets fairly filled at LM=0 dB with FF values of 0.5. However, the FF is lower at LM=3 dB, with values of 0.28 for B_{ch}=50 GHz and 0.31 for B_{ch} =37.5 GHz, reflecting the lower number of lightpaths. In the case of the US nework, at LM=3 dB the FF value is 0.16 for B_{ch}=50 GHz and 0.09 for B_{ch}=37.5 GHz, while for LM=0 dB the FF values for both B_{ch} is around 0.28. These low FF values illustrate the importance of an accurate NLI model, rather than assuming all links in a network are completely full - an assumption which would overestimate the OSNR penalty significantly. However, it should be noted that one reason for the low FF values was the assumption of shortest-path routing, which can lead to premature blocking.

In the case of USA-NSFNET, one of the primary limitations is the large dimension of the network as indicated in Table II. Given the large network dimension of USA NSFNET where the average link length is 1319 km, a lightpath is likely to incur significant ASE noise and NLI due to incoherent addition. The NLI accumulation will be higher while operating with B_{ch}=37.5 GHz which can further detrimentally impact a lighpath's OSNR at high P_{ch}=0 dBm. Under these conditions, at LM=3 dB, we see very few allocated lightpaths. The majority of lightpath requests are blocked due to a lack of sufficient OSNR or they require PM-BPSK. In this work, we consider a PM-BPSK superchannel composed of two contiguous slots to be a single lightpath (lightpaths with higher modulation formats required just one slot). Also note that there is not a one-to-one correspondence between the number of demands and the number of lightpaths because some of the higher order m-ary modulation formats are capable of carrying multiple 100 G demands in one lightpath. PM-BPSK lightpaths are difficult to allocate as they require two slots and even if allocated they degrade the OSNR of previously allocated lightpaths. This may lead to degradation of PM-QPSK to PM-BPSK, which is again difficult to allocate and requires two slots rather than one, and we even see degradation of the already allocated PM-BPSK. Hence at LM=3 dB many lightpath requests get blocked due to the detrimental effect of PM-BPSK allocation. Therefore, in USA-NSFNET an operator should use regenerators while operating with high LM. A simulation study for the USA NSFNET that includes regenerators would be a different piece of work to what is presented here, because the placement algorithms themselves represent a large subject, especially when considering both C and L bands. Because this is far more important for the longer networks, we envisage further work focusing on the optimisation of specifically long-haul networks such as the USA NSFNET, complete with regenerator placement discussions. The Pan Europe network is a medium size network with an average link length of 486 km. It has the potential to support more lightpaths than the USA-NSFNET network, and hence a better FF. Similar is the case for the BT-UK network with average link length of 147 km and a potential for higher QAM lightpaths.

Table V shows the number of allocated 100 G demands for each B_{ch} and LM=0 dB and LM=3 dB at the end of simulation when all 3000 demands requests have been offered to the network. In the paper we refer to this as an End performance of the network. The 3000 demand requests were adequate to fill the network spectrum in order to show the biggest impact of the Raman pumping effect over C+L bands.

The FF for BT-UK increases to 0.6 with the majority of demands allocated over PM-32QAM and PM-16QAM for LM=0 dB and PM-8QAM for LM=3 dB respectively, as shown in Fig. 4 and Fig. 5. Although here the benefit of operating at LM=0 dB is 11.7% for B_{ch}=50 GHz and 12.48% for B_{ch}=37.5 GHz. For Pan Europe, few additional lightpaths could be generated over moderate distances which increases the FF to around 0.67 for both the B_{ch} with the majority

TABLE VI: Number of allocated 100 Gbps demands with reducing P_{ch} at LM=0 dB for End performance

	BT-UK		Pan Europe		USA-NSFNET	
P_{ch}	B_{ch}=50 GHz	B_{ch}=37.5 GHz	B_{ch}=50 GHz	B_{ch}=37.5 GHz	B_{ch}=50 GHz	B_{ch}=37.5 GHz
0 dBm	2087	2387	1745	2043	1451	1737
-1.25 dBm	2145	2468	1782	2101	1628	1944
-3 dBm	2147	2468	1803	2140	1749	2024

TABLE VII: Number of allocated 100 Gbps demands with reducing P_{ch} at LM=3 dB for End performance

	BT-UK		Pan Europe		USA-NSFNET	
P_{ch}	B_{ch}=50 GHz	B_{ch}=37.5 GHz	B_{ch}=50 GHz	B_{ch}=37.5 GHz	B_{ch}=50 GHz	B_{ch}=37.5 GHz
0 dBm	1868	2122	1535	1830	1031	587
-1.25 dBm	1900	2159	1635	1929	1204	1264
-3 dBm	1886	2151	1606	1918	1310	1526

TABLE VIII: Number of allocated 100 Gbps demands with increasing LM at P_{ch}=-1.25 dBm for 10% blocking performance

	BT-UK		Pan Europe		USA-NSFNET	
B_{ch}	LM=0 dB	LM=3 dB	LM=0 dB	LM=3 dB	LM=0 dB	LM=3 dB
50 GHz	1583	1200	1308	1014	830	299
37.5 GHz	2165	1629	1700	1371	1194	320

of demands being allocated at PM-8QAM and PM-QPSK for LM=0 dB and LM=3 dB, as shown in Fig. 4 and Fig. 5. In the case of Pan Europe, the benefit of operating at LM = 0dB is 13.68% and 11.6%. The situation in USA-NSFNET however does not improve in terms of FF and the allocated demands are still low at LM=3 dB. In fact, the USA-NSFNET has less capacity while operating at B_{ch}=37.5 GHz and LM=3 dB with FF of 0.24 which causes this grid to perform worse than that of the grid of B_{ch}=50 GHz which has a FF in the range of 0.6. All the above indicate the existence of high NLI in USA-NSFNET at P_{ch}=0 dBm. Overall, network operators can decide how much blocking they are prepared to accept before upgrading their network. Clearly, the more traffic carried by the network, the more blocking there is likely to be, and then the benefits of reducing the LM will be less in pure % terms. However reducing LM will typically boost the network's capacity as shown in Table V.

B. Effect of launch power on network performance with a given LM

As discussed, the network performance is based upon LM, network dimensions and P_{ch} values. Therefore, given that the ISRS process depends upon the P_{ch}, it is important to explore the capacity benefit for various network sizes while reducing the P_{ch} value for LM=0 dB and LM=3 dB.

From Table VI, the effect of reduction in P_{ch} on network capacity for various networks can be accounted for LM=0 dB. For BT UK network, the NLI is not a dominating factor due to small link length and fewer number of spans. For B_{ch}=50 GHz, as P_{ch} is reduced by 3 dB the allocated demands increase by 2.8%. For 37.5 GHz, the reduction in P_{ch} increases the capacity by marginally 3.3%. In addition, at B_{ch}=37.5 GHz we have no improvement in capacity while reducing the P_{ch} from -1.25 dBm to -3 dBm. For the Pan Europe network a network capacity increase of 3.1% and 4.5% is reported for B_{ch}=50 GHz and B_{ch}=37.5 GHz, as P_{ch} is reduced from 0 dBm to -3 dBm. Here, the reduction in channel power results in slightly higher capacity gain. For USA-NSFNET, the capacity increases significantly by 20% and 16% for B_{ch} of 50 GHz and 37.5 GHz as the P_{ch} is reduced by 3 dB and the network starts operating with lesser NLI and more operational lightpaths.

In Table VII, at LM=3 dB the benefits for smaller networks remain insignificant with reducing the P_{ch}, while in case of larger USA NSFNET the benefit increases significantly up to 3 times due to better FF. This result again advocates the use of slightly lower launch power in larger networks. It should also be noted that when NLI is not significant in a network, then too much reduction in P_{ch} while operating with LM= 3dB can reduce the OSNR of operating lightpaths. This is seen in the case of BT-UK and Pan Europe networks where NLI is fairly limited at P_{ch}=-1.25 dBm and as the P_{ch} is reduced from -1.25 dBm to -3 dBm then there is a slight reduction in allocated demands across both B_{ch}. However, in the case of USA NSFNET there is a continuous growth in network capacity. Similarly, the network capacity at 10% blocking also improves as shown in Table VIII while operating with a lower P_{ch} of -1.25 dBm for all the networks, thereby indicating low ISRS as compared to P_{ch} of 0 dBm for both LM=0 dB and LM=3 dB.

From the above results, it is can be concluded that an operator needs to optimize the channel launch power while operating at a given LM. However, optimising individual channel launch power has shown to be non-convex with a large solution space, making it a non-trivial problem [7].

IV. Conclusion

In this paper, network operations over two LM values of 0 dB and 3 dB have been studied over BT-UK, Pan Europe and USA-NSFNET networks while using a C+L band spectrum. It is shown that operating at LM=0 dB results into higher network capacity. At LM=0 dB for Pan Europe and USA NSFNET achieving PM-8QAM and PM-16QAM is easier as compared to LM=3 dB. This causes fewer lightpath requests compared to LM= 3dB operation thereby contributing to less blocking. It is also seen that the large USA NSFNET is particularly susceptible to high NLI while operating with B_{ch}=37.5 GHz which leads to a large amount of lightpath requests being blocked particularly at LM=3 dB. Reducing P_{ch} controls the NLI due to ISRS and results into more allocated lightpaths in the large USA network.

It should be considered that every network has a different topology. The NLI is dependent upon network dimension and P_{ch} of lightpaths in the network. For smaller networks reducing the P_{ch} does not significantly benefit the network capacity. In addition, too much reduction in P_{ch} in smaller networks can also effect the OSNR of network lightpaths at higher LM. However, larger networks like USA-NSFNET benefit more in terms of network capacity with reduced P_{ch} values. It is seen that P_{ch}=-1.25 dBm results into better network performance across all the network sizes and LM values.

Overall, C+L band systems can bring higher capacity benefits, especially operated at low margin levels. However, given the complex effects of NLI, including Raman, an operator will need to also consider the channel launch power, the network dimensions and the current spectrum occupancy.

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