Effect of Channel Launch Power on Fill Margin in C+L Band Elastic Optical Networks

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

***Abstract*—Increasing traffic in the optical backbone network has made it incumbent upon operators to extend the use of optical spectrum beyond the C-band. In this work we estimate network performance over the C+L band using a physical layer model for estimating the optical signal to noise ratio (OSNR) for lightpaths operating over the C+L band optical spectrum. The model considers nonlinear interference (NLI) due to inter-channel stimulated Raman scattering (ISRS) and the impact of ISRS gain on amplified spontaneous emission (ASE) noise generated by in-line amplifiers while estimating the OSNR. This model is used to account for the capacity benefits associated with OSNR estimation while considering current state of spectral occupancy to account for NLI as compared to the fully-filled, worst-case NLI assumption. OSNR estimation based on current state of spectral occupancy provide higher capacity benefits for smaller networks like the BT-UK while for larger networks like the USA NSFNET the capacity benefit is significantly reduced. Further network capacity benefits of operating over C+L band as compared to C band have been reported. For BT-UK the capacity benefit is more than 100% while for larger networks like USA NSFNET the maximum capacity benefit is 73% with 37.5 GHz of bandwidth until 10% of demands are blocked.**

***Index Terms*—C+L band , Fill Margin, Nonlinear Interference, Stimulated Raman Scattering**

I. Introduction

THE data traffic growth has been catalyzed by rising number of subscribers and new innovative services, such as 4K-ultra-HD video, intensive cloud storage and a rising number of machine-to-machine communications which are fuelling the fourth industrial revolution through 5G. This has lead to an annual increase of network traffic by approximately 40% [1] in numerous regions. This exponential growth and strong projected increase in data consumption has made it incumbent upon network operators to explore innovative ways to increase network capacity. One of the options is to light up new dark fibers; however dark fibers can incur higher lease cost. Another option is to use few-mode fibers or multi-core fibers, but operators will need to incur significant deployment costs which will increase the total capital expenditure. One of the most cost effective and immediate solutions to handle this traffic growth is to explore the entire low loss spectrum range of a standard single mode fiber (SMF). SMF fibers have O, E, S, C and L bands ranging from 1260 nm to 1625 nm wavelength range with varying fiber attenuation from O to L band. Presently most optical fiber systems operate in C band with total bandwidth of 5 THz. As a first step, network operators are considering extension to the L band. This seems to be an optimum choice because the attenuation coefficient variation is negligible across the C+L bands (1530 nm to 1625 nm). In addition, the in-line erbium doped fiber amplifiers (EDFA) technology extends from C to L band, thereby extending the cumulative bandwidth from 5 THz to 10 THz.

However, this increase in network capacity is achieved at a cost of a strongly wavelength dependent OSNR on the optical channels due to ISRS [2]. ISRS results in a power transfer from high to low frequency components within the multiplex of optical signals in the fibre. The process clearly becomes significant in a C+L band communication system. Attempts have been made to model and accurately capture the ISRS process [2]–[6]. Most of the initial works consider a fully occupied spectrum in their study which might not be true for a network, particularly at beginning of life (BOL). Additionally the proposed expressions rely on numerically solving integrals in at least 3 dimensions to compute the ISRS-based NLI in a limited time, which made these models computationally complex and difficult to apply for analysis of an optical network. However, recently the work in [7] presented a closed form expression which is able to predict the NLI per span in real-time and with a minimal 0.1 dB average discrepancy, making it suitable for network studies. In this work, we utilize the closed form expression [7] to derive the OSNR of a network lightpath. Further the derived OSNR expression is used to understand the effect of channel launch power on fill margin (FM) and quantify its benefits on the overall network capacity. In [8] FM was reported in C Band simulations and it was suggested that with optical monitoring technologies it is possible to estimate the NLI based on the present state of spectral occupancy rather than considering the fully filled worst case spectral occupancy. FM is defined as the OSNR gain in dB which is achieved while estimating NLI based on the present state of link spectral occupancy (Dynamic case) rather than NLI based upon fully-filled spectrum (Worst

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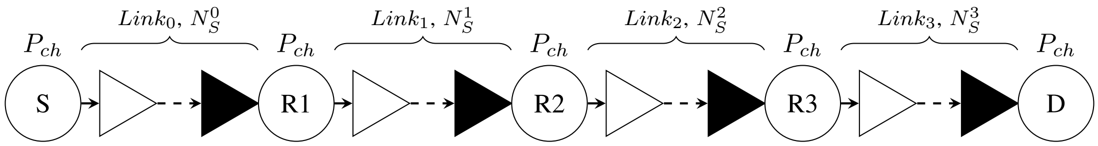

Fig. 1: Multihop path for OSNR Estimation.

case) assumption [8], [9]. For example, while assuming the Worst case , the OSNR of a lighptath may be estimated to support PM-16QAM while in Dynamic case the same lightpath can support PM-64QAM due to lower NLI estimation. In this work, the the regions where FM will be significant over C+L band are explored for BT-UK, Pan Europe and USA-NSFNET networks. The modulation sweet spot for the three networks is reported for various uniform launch power levels. Finally, expected growth in the network capacity while moving from C band to C+L band for all three networks has been shown. The paper has been organised as follows. In Section II the lightpath OSNR estimation model is proposed. In Section III, the results for significant FM regions over various networks are discussed . In section IV, the paper is concluded while comparing the capacity benefits of operating over C+L bands.

II. OSNR ESTIMATION MODEL FOR C+L BAND TRANSMISSION

In Fig. 1, a multi-hop lightpath connection is shown where it traverses through multiple intermediate re-configurable optical add-drop multiplexers (ROADM) and multiple optical links. Every optical channel is launched with power, P_{ch} and every intermediate EDFA module not only compensates for its previous span loss but also normalizes the ISRS gain effect via a gain equalizing process as shown in Fig. 2. Thus, the EDFA module restores the uniform launch power of P_{ch} across all the channels in the C+L band spectrum. The ROADMs are modelled as a span of 18 dB loss with an EDFA module compensating for this loss.

The total OSNR is calculated from (1):

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

$P_{ASE}^i(f)$ is the total ASE noise from the in-line EDFAs in the i^{th} optical link. $P_{NLI}^i(f)$ is the cumulative NLI due to ISRS in the i^{th} optical link.An incoherent NLI accumulation has been assumed in this work. P_{ASE}^R is the ASE noise generated at the ROADM post amplification. N_R is the number of intermediate ROADM nodes traversed by a lightpath. N_L is the number of intermediate links traversed by a lightpath. The ASE noise generated by the in-line amplifiers takes into consideration the frequency dependent ISRS gain profile across the C+L band. The ISRS gain at frequency f that can be approximated from (2) [3]:

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

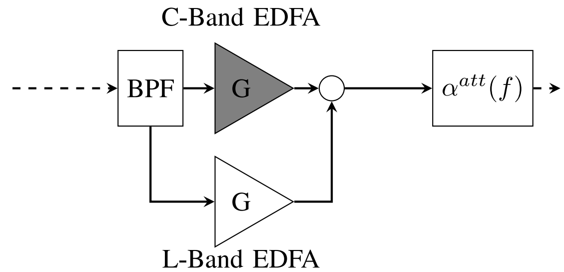

Fig. 2: EDFA Model for C+L Band Amplification.

where C_r is the Raman gain slope and L_{eff} is the effective length. P_{tot} is the total signal power which depends upon the number of active channels in the 10 THz spectrum. G_{Tx} is the launch power distribution across the optical channel bandwidth.

A. Estimation of ASE Noise from EDFA

The EDFA module is modelled with fixed gain G[dB] (linear gain g) and followed by a frequency dependent attenuation, $\alpha^{att}(f)$. The ASE noise generated by each EDFA is given by (3):

$$P_{ASE}^{i_{span}}(f) = 2n_{sp}(g-1)hfB_{Ref} \quad (3)$$

In (3) we have considered separate n_{sp} for C and L Band lightpaths. For C Band, n_{sp} of 1.25 equivalent to noise figure (NF) of 4 dB and L Band n_{sp} of 1.99 equivalent to NF of 6 dB have been considered respectively. The fiber attenuation variation, is assumed to be negligible across the C+L band and assumed to be $\alpha = 0.20$ dB/km for all lightpaths [3]. The EDFA modules are symmetrically placed with a maximum span length of 60km. As the ASE generated by each EDFA passes through the $\alpha^{att}(f)$ module, it will be scaled based upon the frequency dependent attenuation profile that will restore the P_{ch} power across all the channels. With the above system parameters and assumption that $g >>$1, (3) can be written as:

$$P_{ASE}^{i_{span}}(f) \approx 2n_{sp}g(f)hfB_{Ref} \quad (4)$$

where

$$g(f) = g\alpha^{att}(f) \quad (5)$$

Therefore, the net overall gain, $g(f)$ of the EDFA module not only needs to account for the power loss due to attenuation in the fiber span but also needs to consider the power transfer due to ISRS.

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]	50, 37.5
P_{ch}	Channel Launch Power [dBm]	-5.25, -3, -1.5, 0.75
B_{tot}	Optical Bandwidth [THz]	10

During the ISRS process, the higher frequency lightpath will experience an additional loss where the magnitude of this ISRS loss will be primarily dependant upon the spectral occupancy as indicated in (2). Hence the uniform gain G[dB] should be able to restore the lowest signal power reaching the EDFA module back to P_{ch}. The highest signal power loss due to ISRS process is denoted by $\rho_{hf}^{i_{span}}$[dB] and L_{span}^i the span length of the i^{th} link, then G[dB] can be written as:

$$G[dB] = \alpha L_{span}^i + \rho_{hf}^{i_{span}} \tag{6}$$

This gain will restore the lowest signal power belonging to the highest frequency component back to the launch power value of P_{ch}. The attenuation profile of $\alpha^{att}(f)$ will compensate for any additional gain that is experienced by the low frequency lightpaths and will negate the effect of $\rho_{hf}^{i_{span}}$ to restore the uniform launch power of P_{ch} for all the channels.

Hence the overall gain $G(f)$[dB] (linear $g(f)$) for the EDFA module which will affect the ASE generation in (4) is given by:

$$G(f)[dB] = \begin{cases} \alpha L_{span}^i - \rho^{i_{span}}(f) & \text{positive ISRS Gain at f,} \\ \alpha L_{span}^i & \text{no ISRS gain at f,} \\ \alpha L_{span}^i + \rho^{i_{span}}(f) & \text{negative ISRS Gain at f} \end{cases} \tag{7}$$

Given the number of spans, N_S^i in the i^{th} link, the total ASE generated by symmetrically spaced EDFA modules, P_{ASE}^i for the i^{th} link is given by:

$$P_{ASE}^i(f) = N_S^i P_{ASE}^{i_{span}}(f) \tag{8}$$

B. Nonlinear Interference accross C+L Band

The NLI is calculated based upon the ISRS GN model [7] which accounts for the ISRS. The NLI coefficient for a single span, $\eta_1(f_z)$ at f_z channel is a function of P_{tot} and $G_{Tx}(f)$, given by [3]:

$$\eta_1(f_z) = \frac{B_z}{P_{ch}^3}\frac{16}{27}\gamma^2 \int df_1 \int df_2 G_{\text{Tx}}(f_1) G_{\text{Tx}}(f_2)$$
$$.G_{\text{Tx}}(f_1+f_2-f_z)$$
$$\cdot \left| \int_0^L d\zeta \frac{P_{\text{tot}} e^{-\alpha\zeta - P_{\text{tot}} C_r L_{\text{eff}}(f_1+f_2-f_z)}}{\int G_{\text{Tx}}(\nu) e^{P_{\text{tot}} C_r L_{\text{eff}} \nu} d\nu} e^{j\phi(f_1,f_2,f_3,\zeta)} \right|^2 \tag{9}$$

In [7] a closed form expression in (9) was proposed while assuming that nonlinear perturbations are only based upon XPM and SPM. $\eta_{XPM}^k(f_z)$ is the NLI contribution due to XPM where the k^{th} channel interferes with the z^{th} channel of interest (COI). $\eta_{XPM}(f_z)$ is then the summation over all $\eta_{XPM}^k(f_z)$ contributions, $\eta_{SPM}(f_z)$ SPM accounts for NLI where the z^{th} COI interferes with itself. The total contribution across all the active interfering channel is given by:

$$\eta_1(f_z) = \eta_{XPM}(f_z) + \eta_{SPM}(f_z) \tag{10}$$

The closed form expressions of the above total NLI contribution due to $\eta_{XPM}(f_z)$ and $\eta_{SPM}(f_z)$ [7] is given by :

$$\eta_{\text{XPM}}(f_z) \approx \frac{32}{27} \sum_{k=1, k\neq z}^{N_{\text{ch}}} \left(\frac{P_k}{P_{ch}}\right)^2 \frac{\gamma^2}{B_k \phi_{z,k} \bar{\alpha}(2\alpha+\bar{\alpha})}$$
$$\cdot \left[\frac{T_k - \alpha^2}{\alpha} \text{atan}\left(\frac{\phi_{z,k} B_z}{\alpha}\right) + \frac{A^2 - T_k}{A} \text{atan}\left(\frac{\phi_{z,k} B_z}{A}\right) \right], \tag{11}$$

where

$$\phi_{z,k} = 2\pi^2 (f_k - f_z)\left[\beta_2 + \pi\beta_3 (f_z + f_k)\right] \tag{12}$$

$$T_k = (\alpha + \bar{\alpha} - P_{\text{tot}} C_{\text{r}} f_k)^2 \tag{13}$$

and $A = \alpha + \bar{\alpha}$. $\eta_{\text{SPM}}(f_z)$ represents the SPM process which is given :

$$\eta_{\text{SPM}}(f_z) \approx \frac{4}{9}\frac{\gamma^2}{B_z^2}\frac{\pi}{\phi_z \bar{\alpha}(2\alpha+\bar{\alpha})}$$
$$\cdot \left[\frac{T_z - \alpha^2}{a} \text{asinh}\left(\frac{\phi_z B_z^2}{\pi a}\right) + \frac{A^2 - T_z}{A} \text{asinh}\left(\frac{\phi_z B_z^2}{\pi A}\right) \right], \tag{14}$$

where

$$\phi_z = \frac{3}{2}\pi^2 (\beta_2 + 2\pi\beta_3 f_z) \tag{15}$$

As the variation of the attenuation coefficient over the C+L band is neglected, we have that $\bar{\alpha} = \alpha$. The reader is referred to [7], for more details about the use of $\bar{\alpha}$.

The single mode fiber parameters which have been used to evaluate the $\eta_1(f_z)$ are mentioned in Table I. In this work,

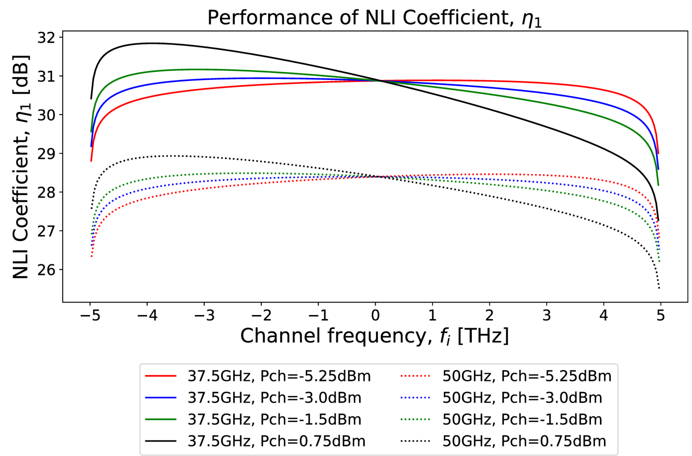

Fig. 3: NLI Coefficient for different channel spacing and various launch powers for fully filled C+L band.

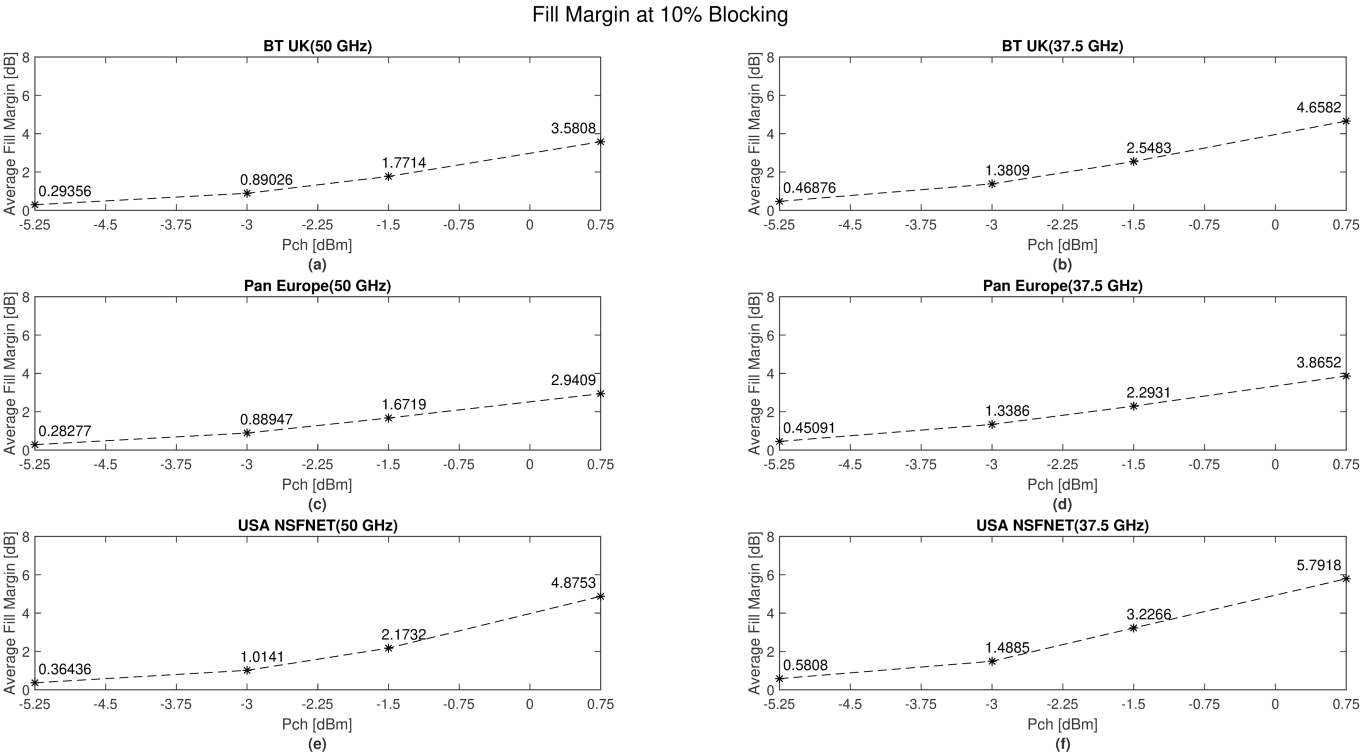

Fig. 4: Performance of Average Fill Margin with increasing P_{ch} for BT-UK, Pan Europe and USA NSFNET network.

TABLE II: Total Launch Powers for Different Channel BW

P_{ch}	P_{tot} (BW=50 GHz)	P_{tot} (BW=37.5GHz)
-5.25 dBm,	17.76 dBm	19 dBm
-3 dBm,	20.01 dBm	21.24 dBm
-1.5 dBm,	21.5 dBm	22.7 dBm
0.75 dBm,	23.7 dBm	25 dBm

we assume that the NLI is accumulated incoherently across multiple spans. Given that the spans are symmetrical, the net NLI for the i^{th} optical link is :

$$P^i_{NLI}(f_z) = P^3_{ch} N^i_s \eta_1(f_z) \qquad (16)$$

The $P^i_{NLI}(f_z)$ is the $P^i_{NLI}(f)$ of (1). Eq. (16) is used to calculate the NLI for all the intermediate links based upon their current state of spectral occupancy.

Fig. 3 shows that the NLI increases upon reducing the frequency granularity (FG). Based on Table I, since we have 266 channels of bandwidth (BW)=37.5 GHz, the NLI in this case will be higher due to the larger number of interfering channels which also increases the P_{tot} value for a given P_{ch} as shown in Table II. Further it can be seen in Fig. 3, that for a given BW, if the P_{ch} is reduced significantly then the slope of the ISRS gradient reduces, thereby indicating a reduction in NLI due to ISRS across the channels. This model can estimate the NLI based upon the current state of spectrum occupancy which gives us the OSNR of the lightpath in the dynamic case. Therefore, it is highly useful for studying the impact of FM on network capacity over C+L bands. In this work, uniform P_{ch} has been considered rather than optimising individual channel launch powers as this is non-trivial, with a large solution space, which may be infeasible for real networks [5].

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

TABLE IV: 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

III. Effect of Channel launch power on Fill Margin

In C+L Band operation, the NLI due to ISRS can become a significant limitation to attain high network capacity and assuming a worst case NLI for OSNR prediction can significantly limit the network performance. This section explores the benefit of predicting the NLI based upon the current spectrum occupancy at various P_{ch} values over three geographically diverse networks, namely BT-UK [10], Pan Europe [10] and USA NSFNET network [11]. The network dimensions for each network has been mentioned in Table IV. The average FM is reported in Fig.4 and OSNR prediction using current spectrum occupancy is referred to as the Dynamic case in Fig. 5 to

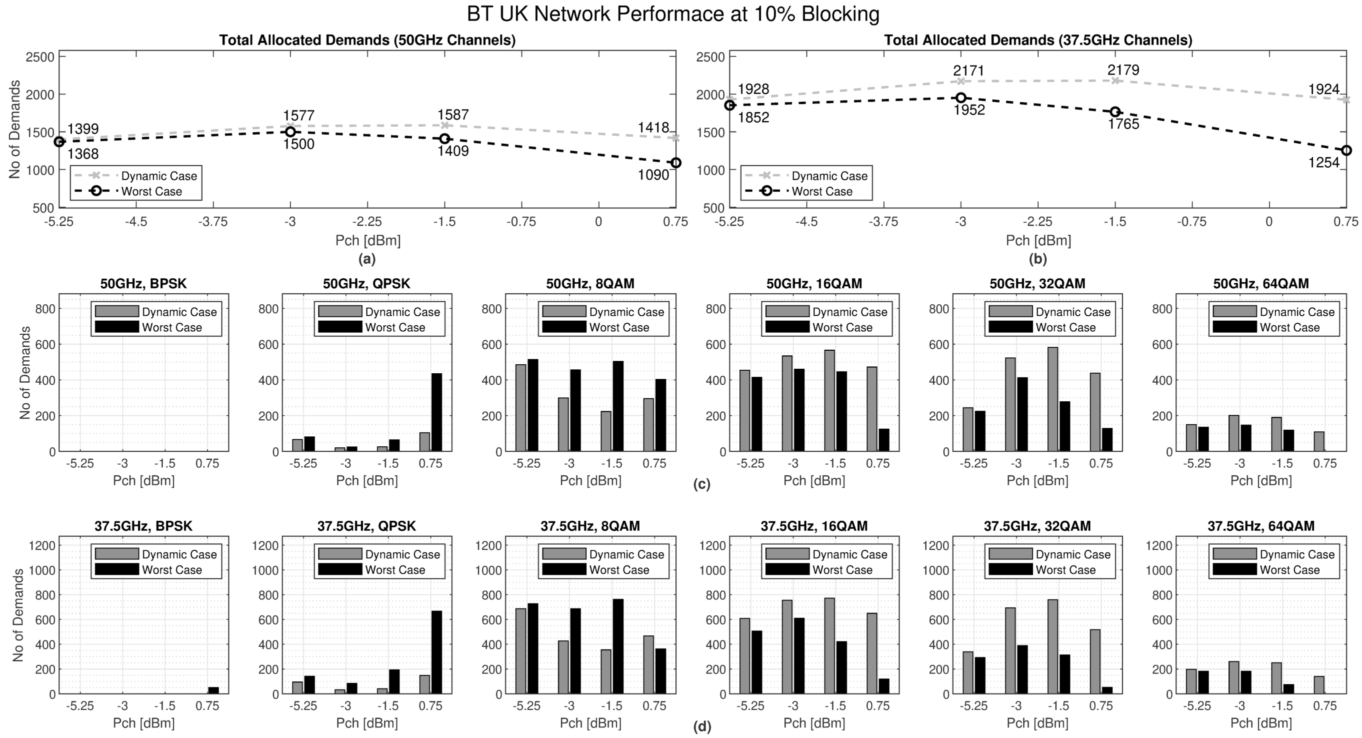

Fig. 5: Performance with Dynamic and Worst Case NLI Assumption for BT-UK.

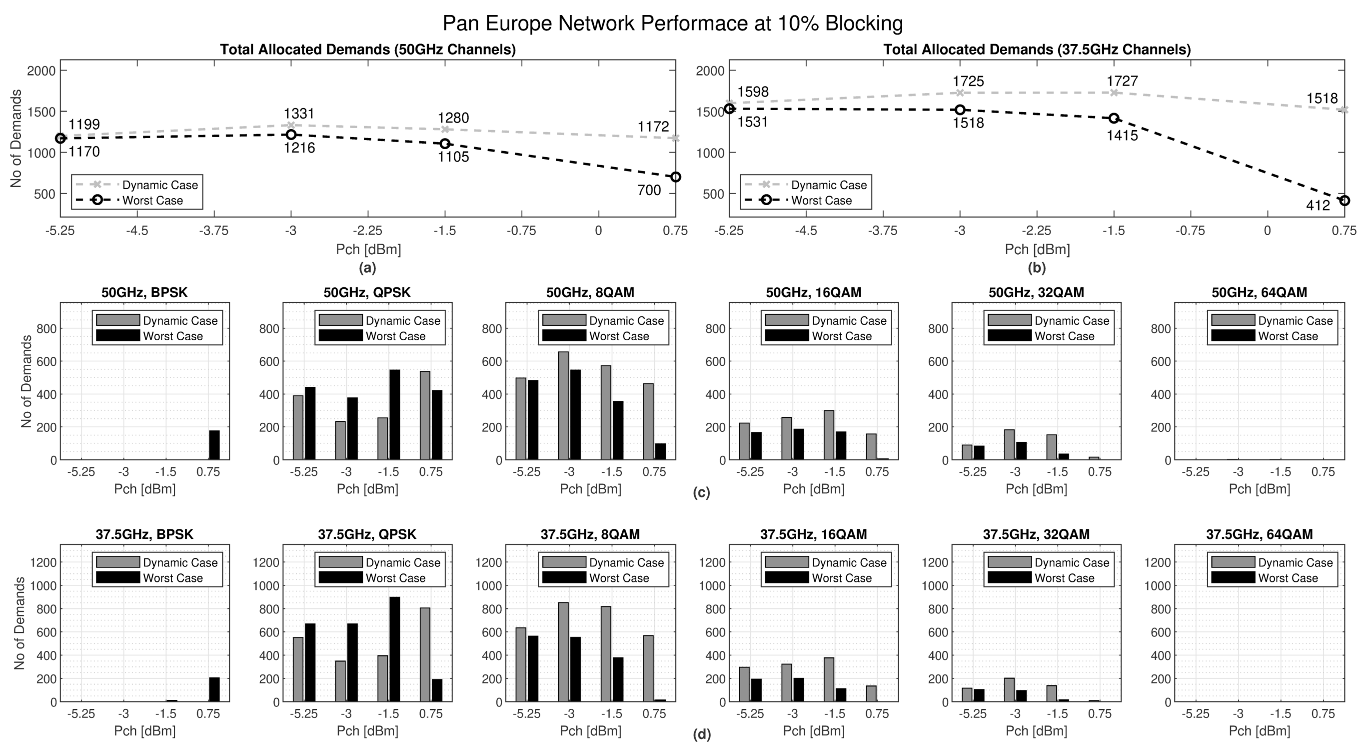

Fig. 6: Performance with Dynamic and Worst Case NLI Assumption for Pan Europe.

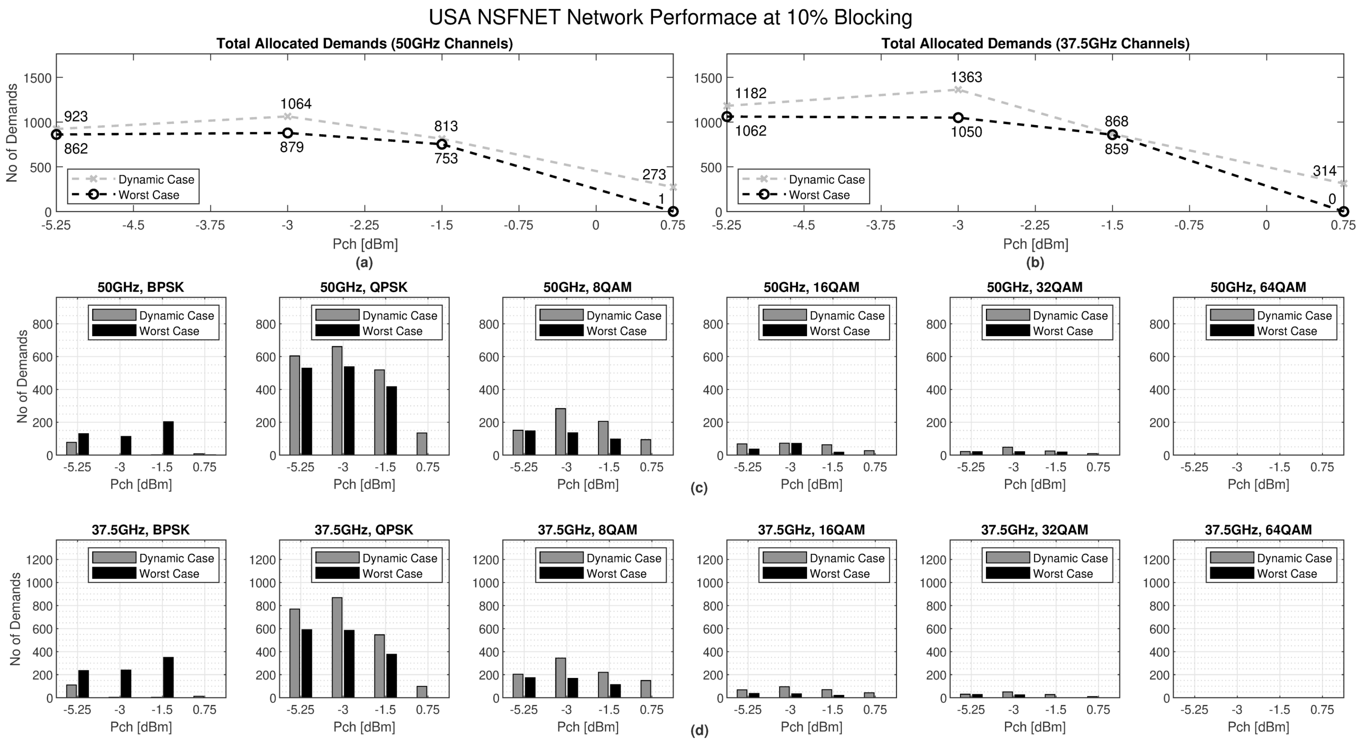

Fig. 7: Performance with Dynamic and Worst Case NLI Assumption for USA NSFNET.

Fig. 7, while the Worst case assumes a fully occupied C+L band spectrum.

For every network a traffic matrix of three thousand 100 Gbps demands have been considered while selecting the source and destination with uniform distribution where on an average equal proportion of 100 Gbps demands are generated between the source and destination.A uniform traffic matrix has been added in order to ensure that entire network is equally stressed thereby enabling a fair way to focus on the broader question of C+L band spectrum performance across all the networks. The demand size of 100 Gbps is driven by the P-Router clients and original 100G coherent optical transport technology, where traffic in core network is added in granularity of 100 Gbps. The generation of high number of demands is useful in comparing the performance of networks with different geographical sizes. This helps in stressing the network spectral resources and allows us to highlight the detrimental effects of NLI based on ISRS over various geographies. At first, an attempt is made to cater for every new 100 Gbps demand over an existing 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 new 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 new 100 Gbps demand over this pair of lightpaths which are operating between the same source and destination and the same route.

In case no such lightpath is found, then a request is put to the network to allocate a new lightpath. For every new lightpath request, a single shortest path is found and the OSNR estimation model is used to determine the modulation format which a lightpath can support based on Table III. The OSNR values in Table III are indicative for BER of 10^{-3} and symbol rate of 28 to 32 GBaud [12], [13]. The true OSNR values depend upon the modulation formats and channel spacing [13]. If the channels are spaced at the baud rate then there will be a significant OSNR threshold penalty associated with each modulation format [13].For PM-BPSK we have assumed the Nyquist WDM Superchannel approach where each PM-BPSK Superchannel lightpath is made of two contigously spaced subcarriers [13]. A first fit spectrum allocation approach has been followed while maintaining the spectrum continuity and contiguity constraints. After a new lightpath is added, the OSNR of the active lightpaths are also updated. An attempt is made to re-accommodate any 100 Gbps demand which cannot be accommodated in a degraded lightpath into other existing lightpaths. If no extra capacity is found in the existing lightpath then a new lightpath is generated to accommodate this extra 100 Gbps demand. The computation time to update the OSNR of active lightpaths becomes time intensive as the network spectrum gets utilized. However, as this is part of physical process the effect of ISRS of on the active lightpaths should be considered.

All the results presented have been estimated at 10% blocking probability. The value of 10% blocking of demands is significant enough for stressing the networks thereby resulting into significant blocking. However, an operator can upgrade the network before this high value of blocking is reached. The results in this work are repeated heuristically over different P_{ch} values. Average results over 30 seeds for every heuristic step has been presented in this work for each network scenario. In this paper we fix the baud rate, and flex the throughput with a combination of adapting the modulation format and adding multiple channels. Including additional baud rate flexibility is also possible but we prefer not to include another degree of transponder freedom in this paper so that we can focus on the broader question of C + L band performance. Fig. 5- Fig.7 show only the number of allocated demands. OSNR penalty due to ROADM filtering effect can be controlled by using WSS with high Super Gaussian (SG) order [14]. 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.

One of the advantages of the dynamic case is to achieve higher OSNR. This is quantified by the average FM shown in Fig. 4 at different P_{ch} values. The primary reason for such a behaviour is that the gradient of the ISRS slope will also reduce as P_{ch} reduces, which is evident in Fig. 3. In Fig. 3 at low Pch=-5.25 dBm the gradient of ISRS is almost zero, indicating minimal NLI due to ISRS. This reduction in the FM at lower P_{ch} values is immediately reflected in the network performance shown in Fig. 5 to Fig. 7 for the BT-UK, Pan Europe and USA network where the gap between the Dynamic and Worst case plots is narrow, particularly at lower P_{ch} values. Therefore, the capacity gain of FM is greater for higher P_{ch} values.

Further, in Fig. 4 it is clearly seen that while operating at BW=37.5 GHz the FM values are higher. At high P_{ch}=0.75 dBm, the average FM gain is in the range of 3.8 dB to 5.8 dB. This effect is also reflected in Fig. 5 to Fig. 7 where in BT-UK the capacity benefit at P_{ch}=0.75 dBm and BW=37.5 GHz in the Dynamic case is 53% and for Pan Europe it is 268%. In the case of USA NSFNET with a fully filled Worst case assumption, the estimated OSNR always falls short of 9 dB and none of the lightpaths could be established at high P_{ch}=0.75 dBm. Comparatively, with the Dynamic case assumption, still a higher number of demands are allocated. For the USA network, more demands are allocated as P_{ch} is reduced due to reduction in NLI. Therefore, while operating with a FG = 12.5 GHz and 37.5 GHz channel bandwidth, the Dynamic case OSNR prediction is able to provide a superior capacity benefit. The NLI estimation based on the Dynamic case will be less than estimation for the Worst Case Scenario which leads to better OSNR prediction.

As discussed earlier, one of the key motivations to estimate OSNR in the dynamic case is the benefit in terms of network capacity by using higher order modulation (HOM) formats. In this work, the HOM performance is referred to as the joint sum of the number of demands allocated over PM-16QAM, PM-32QAM and PM-64QAM as these modulation formats can support more than two 100 Gbps demands per lightpath while lower order modulation (LOM) performance is considered over PM-BPSK to PM-8QAM. As seen in Fig. 5(c), in BT-UK at BW=50 GHz about 75% of the demands are allocated over HOM in the Dynamic case while 53% of demands are allocated over HOM in the Worst case. In Fig. 5(d), in BT-UK at BW=37.5 GHz about 72% of the demands are allocated over HOM in the Dynamic case compared to 46% over HOM in the Worst case. Therefore, the Dynamic case provides a significant performance gain at both BW=50 GHz and 37.5 GHz. For Pan Europe, as seen in Fig. 6(c), at BW=50 GHz, about 28% of demands are allocated over HOM in the Dynamic case while in the Worst case about 17% of demands are allocated over HOM. In Fig. 6(c), at BW=37.5 GHz, about 24% of demands are allocated over HOM in the Dynamic case as compared to 14% over HOM in the Worst case. Therefore, the benefit of operating with Dynamic case is reduced for Pan Europe. In case of USA-NSFNET, as seen in Fig. 7(c), at BW=50 GHz, only 11% of demands are allocated over HOM in the Dynamic case while just 7% of demands are allocated over HOM in the Worst case. In Fig. 7(d), at BW=37.5 GHz, about 11% of demands are allocated over HOM in the Dynamic case while it is just 6% of demands for the Worst case. Therefore, the benefits of operating with the Dynamic case are marginal. This progressive decrease in the capacity benefit is expected, as with increasing geographical size, more demands are allocated over LOM lightpaths due to longer link lengths.

It is desirable to decrease the P_{ch} values to reduce the effect of NLI on the OSNR of a lightpath. However, P_{ch} should not be reduced to an extent that the OSNR of lightpaths starts to degrade due to insufficient signal power and consequently the lightpaths fails to achieve the OSNR threshold for HOMs. In BT-UK, the peak performance is at P_{ch}=-1.5 dBm while in the case of Pan Europe and USA NSFNET the peak performance is at a lower P_{ch}=-3 dBm for the Dynamic case. Reducing the P_{ch} lower than this value causes fewer allocated demands. This trend is seen across the modulation graphs of Fig. 5, Fig. 6 and Fig. 7, where number of allocated demands in HOM reduces when the P_{ch} reduces below the prescribed optimum value.

For the USA network it is seen that at P_{ch}=-1.5 dBm the difference between the network performance of the Dynamic case and the Worst case is marginal for both BW of 50 GHz and especially at FG=37.5 GHz. This is due to a higher spectrum fragmentation with the first fit approach, particularly while using BW=37.5 GHz. Assuming the worst case, 819 generated lightpaths are allocated while in Dynamic case 782 generated lightpaths have been allocated. The Worst case has more generated lightpaths because the OSNR of previously generated lightpaths are not affected by newly generated lightpaths, while in the Dynamic case the OSNR of an existing lightpath may degrade to the point of failure or to operate at PM-BPSK leading to spectrum fragmentation. For example, a PM-QPSK lightpath may degrade down to PM-BPSK which will need two slots of 37.5 GHz to support the same 100 Gbps demand. Finding two contiguous slots while maintaining spectrum continuity can be harder which often leads to a demand being blocked. Thus the degradation of a lightpath's OSNR to PM-BPSK can contribute to spectrum fragmentation in Dynamic case, which in a larger network like the USA NSFNET can limit the performance across C+L bands for some P_{ch} values. This has been simulated in the paper, however optimal spectral filling to minimize

TABLE V: Capacity Benefits with BW=37.5 GHz at 10% Blocking

Network	P_{ch} (dBm)	No. of Demands (C Band)	No. of Demands (C+L Band)	% Growth
BT-UK	-5.25	976	1928	97.5%
	-3	1061	2171	104.6%
	-1.5	1017	2179	114.2%
	0.75	814	1924	136.3%
Pan-Eu	-5.25	874	1598	82.8%
	-3	935	1725	84.4%
	-1.5	848	1727	103.6%
	0.75	700	1518	116.8%
USA NSFNET	-5.25	778	1182	51.9%
	-3	784	1363	73.8%
	-1.5	729	868	19.1%
	0.75	211	314	48.8%

TABLE VI: Capacity Benefits with BW=50 GHz at 10% Blocking

Network	P_{ch} (dBm)	No. of Demands (C Band)	No. of Demands (C+L Band)	% Growth
BT-UK	-5.25	684	1399	104.5%
	-3	744	1577	111.9%
	-1.5	717	1587	121.3%
	0.75	597	1418	137.5%
Pan-Eu	-5.25	642	1199	86.7%
	-3	671	1331	98.3%
	-1.5	621	1280	106.1%
	0.75	534	1172	119.4%
USA NSFNET	-5.25	563	923	63.9%
	-3	590	1064	80.3%
	-1.5	535	813	51.9%
	0.75	189	273	44.4%

fragmentation is a separate large subject and will be a different piece of work. At P_{ch}=-1.5 dBm and at B_{ch}=50 GHz we have 692, 236 and 50 HOM lightpaths while for B_{ch}=37.5 GHz 879, 265 and 55 HOM Lightpaths in the BT-UK, Pan Europe and USA NSFNET networks for Dynamic case. In worst case scenario extremely low number of HOM lightpaths. For B_{ch}=50 GHz we have 446,110 and 20 HOM lightpaths and for B_{ch}=37.5 GHz we have 419, 68 and 11 HOM lightpaths . It should be considred that with B_{ch}=37.5 GHz and worst case prediction the net Ptot in the fiber will be more thereby causing higher NLI due to ISRS.

IV. Capacity Benefits of using C+L Band Optical Spectrum

As discussed in the previous section and in [10], larger networks do not have the high inherent OSNR benefit as compared to smaller networks such as BT-UK. Also, given that the network traffic is exponentially increasing, it will be of interest to observe the capacity benefits while operating using both C+L bands as compared to C band.

For C band transmission, the effect of ISRS is negligible. In C band, there will be 100 channels of BW=50 GHz or 133 channels of BW=37.5 GHz. Across all the networks, for higher power levels, reduction in P_{ch} leads to better performance due to reduction in NLI.. For all three networks, at P_{ch}=-3 dBm, the maximum number of demands are allocated over C band. However, reducing P_{ch} any further causes reduction in the OSNR due to less signal power which leads to lesser number of allocated demands; this can be seen in Table V and Table VI as P_{ch} is reduced from -3 dBm to -5.25 dBm.

In Table V and Table VI it is seen that the smaller BT-UK network has a higher percentage growth while operating over C+L band. Comparatively, the percentage growth in network capacity for larger Pan Europe and USA networks is limited by high NLI due to higher number of interfering channels and longer link lengths. In addition, for BW=37.5 GHz the percentage growth is slightly less, particularly for larger networks such as the USA where higher NLI is incurred due to a greater number of active channels for BW=37.5 GHz

It will be of interest to consider the percentage growth at optimum power levels where the network capacity is a maximum for C+L bands. In case of BT-UK at P_{ch}=-1.5 dBm, a capacity growth of 114% and 121% is reported for BW=37.5 GHz and BW=50 GHz respectively. For larger networks, at P_{ch}=-3 dBm a maximum number of demands are allocated. In Pan Europe, at this P_{ch} value, the growth is around 104% and 106% respectively for BW=37.5 GHz and BW=50 GHz while in case of USA the growth reduces to 73% and 80%. The high percentage growth, while adding an L band is because it provides more routing options for generation of lightpaths; particularly HOM lightpaths in small and medium size networks.

V. Conclusion

In this work, it is shown that the capacity benefits of estimating NLI over the Dynamic case depends upon the geographical size of a network. In smaller networks this benefit is higher because a higher number of lightpaths can operate on HOMs for the Dynamic case. However, for larger networks like the USA, the benefits of operating network lightpaths with Dynamic NLI estimation are marginal and for certain P_{ch} values network fragmentation can lead to lower capacity benefits than the Worst case. Ultimately, the benefits of having higher FM will only be useful if it accounts for higher network capacity and this benefit will depend upon the network size and channel launch power. Finally, the capacity benefits of operating with C+L band instead of C band have been reported. The percentage growth of allocated demands reduces as network size increases due to increasing link lengths and high NLI. For BT-UK, at optimum P_{ch}=-1.5 dBm the growth in allocated demands is more than 100% while for larger networks like USA NSFNSET the percentage growth reduces to 73% at P_{ch}=-3 dBm and BW=37.5 GHz.

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