Capacity Benefits of Operation Over C+L Band Elastic Optical Network in the Indian Network Scenario

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***Abstract*—Introduction of high data rate services has increased the traffic load on the backhaul network. In order to cater more demands, the operators are looking for solutions to minimize spectral wastage and to extend their network operations beyond the C-band, especially for inter-city networks. This paper highlights the advantages of operating over C+L band as compared to operations over C band in a large Indian network. The physical model factors in the non-linear interference (NLI) due to inter-channel stimulated Raman scattering (ISRS) and amplified spontaneous emission (ASE) noise while estimating the optical signal to noise ratio (OSNR) of a network lightpath. The OSNR estimation model can dynamically account for the NLI as compared to the conventional worst case assumption. The capacity benefits for the Indian network over the C+L band for channel power -1.5 dBm are about 108.67% for channel bandwidth 50 GHz and 103.98% for channel bandwidth 37.5 GHz until 10% of the demands are blocked.**

***Index Terms*—C+L band, Elastic Optical Networks, Link Margin**

I. INTRODUCTION

Broadband telecom services have proven to be one of the essential drivers of economic growth in the world, including India. The introduction of ultra high definition (UHD) video and cloud based services are increasing the data traffic per capita [1]. Further, rising number of users and the advancement of variety of 5G services is powering the fourth industrial revolution. India being one of the fastest growing economy in the world is investing heavily to upgrade its telecom infrastructure that has to handle the growing number of mobile broadband subscribers. To sustain such an overwhelming growth, the Government of India is investing heavily into fibre based telecom infrastructures, like the National Optical Fibre Network (NOFN) project.

Due to the introduction of high data rate services the effective traffic load on the metro and the inter-city core network is expected to substantially increase. Presently these networks use Dense Wavelength Division Multiplexing (DWDM) technology which operates on fixed channel bandwidth of 50 GHz and provides a data rate of up to 100 Gbps. However, given the long fiber links in larger geographies like India, the data rate per lightpath will not be adequate to cater the increasing demands due to a lower OSNR. Therefore, in order to address the exponential rise in data traffic, the core network operators need additional spectral resource to support higher number of lightpaths.

One option is to utilize the dark fibres, but this can lead to higher lease cost and not all links have multiple fibers. Alternatively, a cost effective and efficient solution will be to explore the entire spectrum range available to a standard single mode fibre (SMF). SMF fibres have bands ranging from 1260 nm to 1625 nm, namely O, E, S, C and L bands. The fibre attenuation coefficient varies in all of the bands. Presently the backbone networks works on the C-Band (5 THz bandwidth), which may prove to be a bottleneck to sustain the future broadband growth, especially considering the low OSNR in larger networks . The C+L Band (10 THz bandwidth) shows very little variation in the attenuation coefficient of about 0.01 dB/km [2]. Additionally, the in-line erbium doped fibre amplifier (EDFA) technology can be extended from C to L band. This makes the C+L band suitable for long distance optical communication in larger geography while providing a

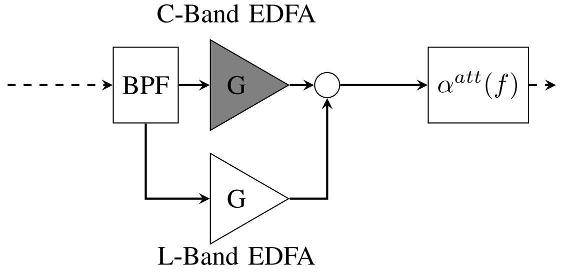

Fig. 1. EDFA Model for C+L band Amplification

large spectral resource to the network operator.

However, for C+L band operation, the effect of ISRS must be taken into account. ISRS is a non-linear process which amplifies the lower frequency components at the expense of higher frequency components. Hence this increase in network spectral resource is achieved at the cost of incurring higher NLI due to ISRS. The ISRS process has been modeled in previous works [3]. The proposed expressions were computationally complex and were difficult for network analysis. A closed form expression for the same was reported in [4] which was able to derive the network OSNR in real-time with an average discrepancy of 0.1 dB. In this work, we have utilized the closed form expression [4]–[6] to approximate the OSNR for a light path and analyze the capacity benefits while operating over C+L bands as compared to C band in the Indian backbone network.

In optical networks, operators use link margin (LM) as a precaution to link degradation and operate lightpaths at lower order modulation formats than at their true potential due to the lack of information about optical link parameters. [7]. However, using superior optical monitoring technologies, which are now available, and adaptive EON transponders, it is possible to estimate the NLI based on the present state of the spectral occupancy rather than fully occupied worst case assumption. This information would help the operators to operate the lightpaths with a lower LM and higher OSNR.

This paper investigates the benefits of operating the Indian backbone optical network across the C+L band as compared to the operation on the C band. In section II the noise model [5], [6] is briefly described which is used to approximate the lightpath OSNR while considering the NLI and ASE impairments. In section III, the benefits of operating the Indian network over C+L band with dynamic NLI prediction has been highlighted. In section IV the work is concluded by comparing the C band and C+L band network capacity for the Indian backbone network.

II. OSNR ESTIMATION MODEL

An optical lightpath traverses through multiple ROADMs and optical links. The OSNR of an optical lightpath can be estimated by (1) [5], [6]:

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

In (1) P_{ch} is the launch power of an optical channel, $P^i_{ASE}(f)$ is the total ASE noise of the inline EDFAs of the i^{th} link. $P^i_{NLI}(f)$ is the NLI noise due to ISRS in the i^{th} link. P^R_{ASE} is the ASE noise of ROADMs. N_R is the number of intermediate ROADMs in the lightpath and N_L is the number of intermediate links in the lightpath [5], [6].

A. ISRS Gain

The ISRS gain $\rho(z,f)$ at a given frequency f is (2) [5], [6]-

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

In (2) P_{tot} is the total launch power across all the active channels. C_r is the Raman gain slope and L_{eff} is the effective length. G_{Tx} is the launch power spectrum density across the optical channel bandwidth.

B. Calculating the ASE noise

In this model, the EDFA amplification has been considered as per Fig. 1. The spontaneous emission factor, n_{sp} for C Band EDFA is 1.25 and n_{sp} for L Band EDFA is 1.99, which gives noise figures of 4dB and 6dB respectively [5], [6]. Considering, the fiber attenuation coefficient variation is negligible across C+L Band, the attenuation coefficient, α = 0.20 dB/km has been considered. Assuming g >>1, the ASE noise in a single span can be given as [5], [6]:

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

Here $g(f)$ is the linear gain corresponding to $G(f)$[dB], which can be written as [5], [6]:

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

In the model, the EDFA's $G(dB)$ restores the lowest signal power reaching the EDFA module back to P_{ch} and $\alpha^{att}(f)$ block compensates for any additional gain due to ISRS and restores the uniform P_{ch} across all the channels. As the $\alpha^{att}(f)$ block has a frequency dependent attenuation profile hence the equivalent gain, $G(f)$[dB] of the module depends on channel frequency. L^i_{span} is the length of the span of the i^{th} link. As the amplifiers are considered being placed at equal spans in the i^{th} link, the net P^i_{ASE} for the i^{th} link is (5) [5], [6]

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

where N^i_S is the number of spans in the i^{th} link.

TABLE I
SYSTEM PARAMETERS FOR C+L BAND

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=50GHz)	50
B_{CH}	Channel Spacing [GHz](FG=12.5GHz)	37.5
P_{ch}	Channel Launch Power [dBm]	-5.25, -3, -1.5, 0.75
N_{CH}	Number of 50GHz Channels	200
N_{CH}	Number of 37.5GHz Channels	266
B_{tot}	Optical Bandwidth over C+L Band [THz]	10

C. *Calculating the NLI noise*

Earlier, NLI was calculated using the GN model. Using the closed form approximation NLI can be estimated with low complexity [4]. NLI caused in a lightpath is contributed by the cross channel interference due to cross phase modulation (XPM) and self phase modulation (SPM). The XPM which is denoted by the $\eta_{XPM}(f_z)$ and the interference of a channel with itself is due to SPM, which is denoted by the $\eta_{SPM}(f_z)$.The NLI coefficient for a single span $\eta_1(f_z)$ at f_z is shown in (6) [4]:

$$\eta_1(f_z) = \eta_{XPM}(f_z) + \eta_{SPM}(f_z) \tag{6}$$

The closed form approximations of $\eta_{XPM}(f_z)$ and $\eta_{SPM}(f_z)$ given above can be further written as:

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

where

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

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

and $A = \alpha + \bar{\alpha}$. $\eta_{\text{SPM}}(f_z)$ represents the SPM process [4] which is estimated by:

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

where

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

If the spans are of same length, the total NLI of the i$^{\text{th}}$ link while assuming incoherent addition is (12):

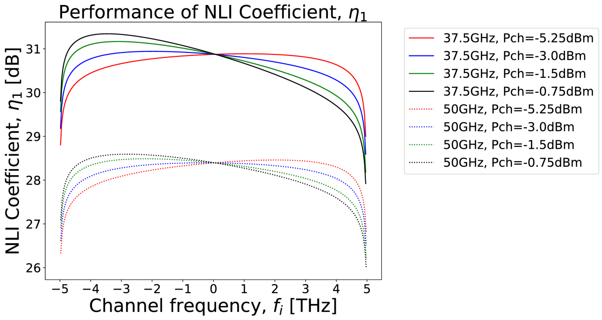

Fig. 2. NLI Coefficient for different channel spacing and various launch powers for fully filled C+L band.

TABLE II
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

$$P^i_{NLI}(f_z) = P^3_{ch} N^i_s \eta_1(f_z) \tag{12}$$

III. CAPACITY BENEFITS ASSOCIATED TO DYNAMIC C+L BAND OPERATION IN THE INDIAN NETWORK

In the previous works NLI was calculated by assuming the worst case (fully filled spectrum) which should not be the case anymore given the availability of superior monitoring equipment. Hence, it is important for a network operator to estimate the link OSNR based upon the present state of spectral occupancy. The closed-form expressions in (6), (7) and (10) [4] are used to calculate the NLI from the ISRS effect based upon the present state of spectral occupancy (dynamic case) and thereby allowing the operators to operate the lightpaths closer to their OSNR limit. The benefit of the OSNR estimation in dynamic case compared to the worst case can be quantified as fill margin (FM) [6]. This section will be highlighting the benefits of having a high FM margin and how it translates into overall capacity benefit in context of the large Indian Network.

For simulation, multiple random traffic matrices of three thousand 100 Gbps demands are considered while selecting the source and destination with uniform distribution. Then, an attempt is made to serve every new 100 Gbps demand over an existing lightpath which has the capacity to serve a 100 Gbps demand and operates between the same source and destination. The modulation format to be used is estimated from (1) and determined from Table II [8]. In an event when

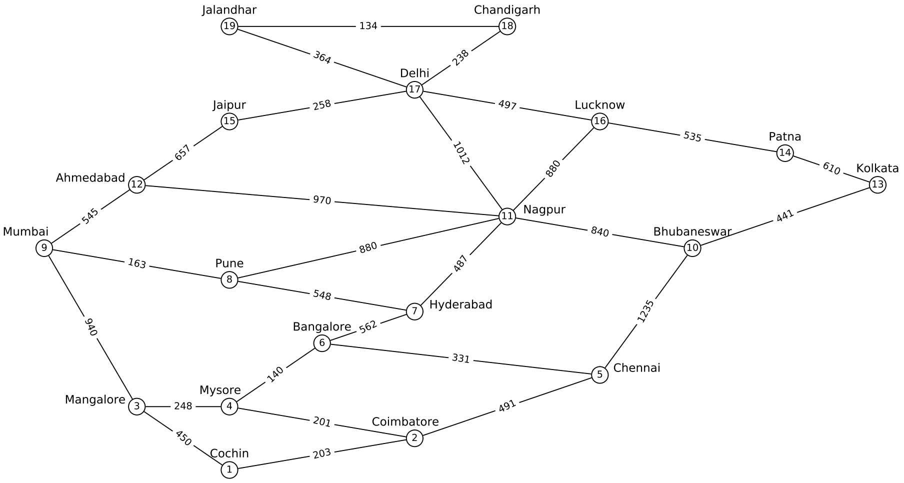

Fig. 3. Indian Network Topology

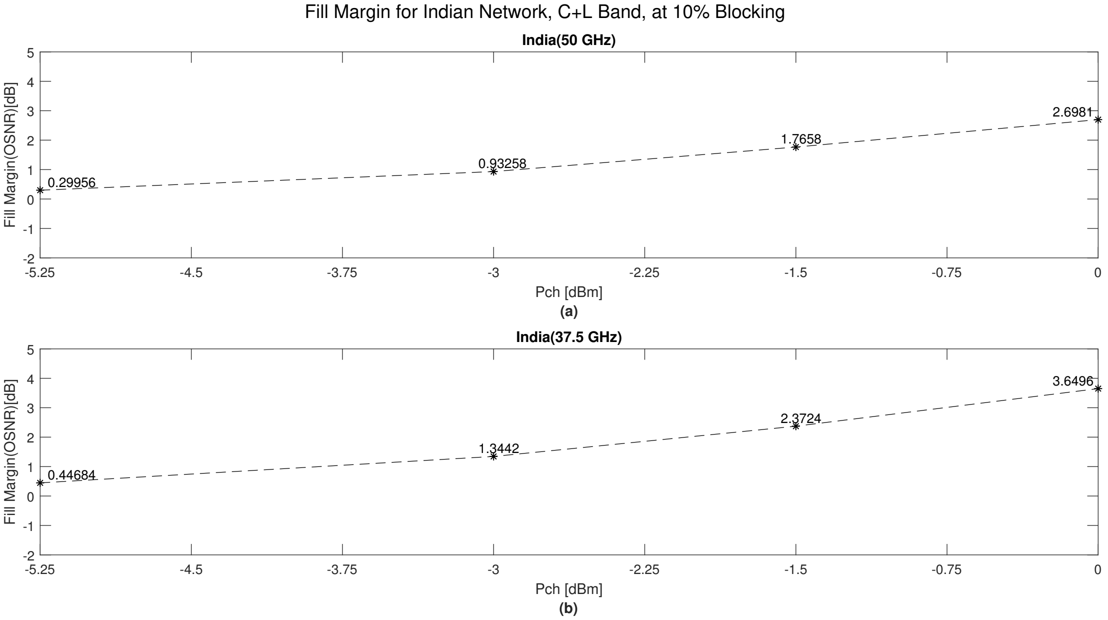

Fig. 4. Performance of Average Fill Margin with increasing P_{ch} for India network.

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. While maintaining the spectrum continuity and contiguity constraint, a first-fit spectrum allocation approach has been followed. After a new lightpath is added, the OSNR of the active lightpaths are also updated and a similar attempt is made to re-accommodate the 100 Gbps demands of any degraded lightpath. In this paper the average results across all the random seeds are presented and the capacity benefits are evaluated at 10% blocking probability. In this work, the above results are based upon the Indian network topology [9].

One of the benefits of estimating NLI over the dynamic case is to have a higher OSNR, hence a higher FM. It can be seen in Fig. 4 that as the channel launch power; Pch is reduced, the average FM across the simulated lightpaths also decreases. From Fig. 2 it can be seen that as the P_{ch} values are reduced the gradient of NLI due to ISRS also keeps on decreasing, thereby causing the reduction in FM. The benefit of high FM immediately translates into higher network capacity as can be seen in Fig. 6. Further, in Fig. 4, it can be seen that FM values for B_{ch}=37.5 GHz are much higher than B_{ch}=50 GHz which shows that in case of EON with FG=12.5 GHz, a NLI estimation over dynamic case has a significant impact on the light path's OSNR. As an example at Pch = -1.5 dBm, the FM is 1.76 dB and 2.37 dB for B_{ch}=

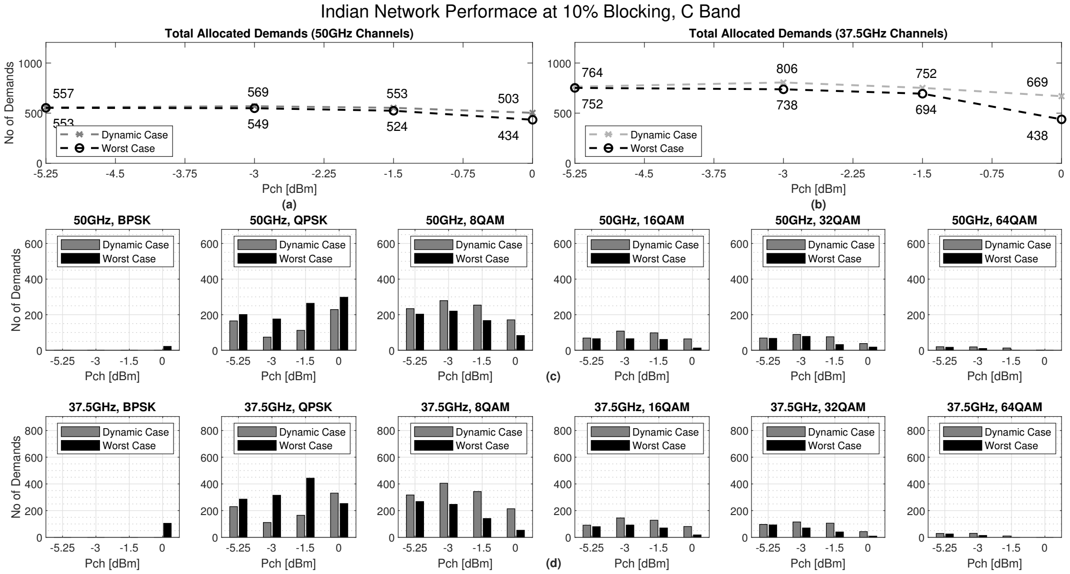

Fig. 5. Performance with Dynamic and Worst Case NLI Assumption for Indian network over C band .

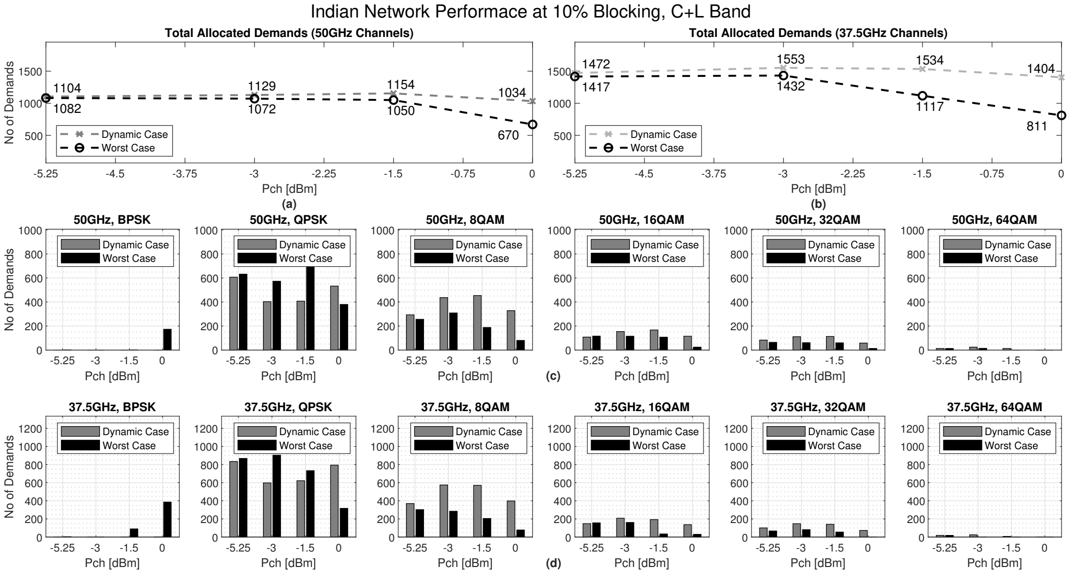

Fig. 6. Performance with Dynamic and Worst Case NLI Assumption for Indian network over C+L band.

50 GHz and 37.5 GHz respectively. Another important point to consider while comparing C and C+L band operation is the role of ISRS. As shown in Fig. 5 and Fig. 6 the ISRS is not a dominating factor in C band and hence the worst case and dynamic case predictions are almost similar for lower powers in the 50 GHz grid. However for EON and consequently C+L band the dynamic case predictions become important to estimate the true potential capacity of the network.

One of the main reasons of using the dynamic case is to get a higher OSNR, which can support higher order modulation (HOM) formats so that the network can benefit from their higher capacity. In this work, PM-8QAM,PM-16QAM, PM-32QAM and PM-64QAM modulation formats are referred to as the HOM formats, because they can support more than one 100 Gbps demands per lightpath. Similarly, PM-BPSK and PM-QPSK formats are referred to as lower order modulation (LOM) formats. As it can be observed in Fig. 6(c), in the C+L band and FG = 50 GHz, where about 65% of the demands are allocated over HOM formats in the dynamic case, as compared to 33% of the demands allocated over HOM formats in the

TABLE III
CAPACITY BENEFITS OF C+L BAND OVER C BAND AT 10% BLOCKING

Channel Bandwidth (GHz)	P_{ch} (dBm)	No. of Demands (C Band)	No. of Demands (C+L Band)	% Growth
50	-5.25	557	1104	98.20%
50	-3	569	1129	98.41%
50	-1.5	553	1154	108.67%
50	0	503	1034	105.56%
37.5	-5.25	764	1472	92.67%
37.5	-3	806	1553	92.67%
37.5	-1.5	752	1534	103.98%
37.5	0	669	1404	109.86%

worst case. A similar trend can be observed in Fig. 6(d), in the C+L band and FG = 37.5 GHz, where 62% of the demands are allocated over HOM formats [6] in the dynamic case for an Indian backbone network. Therefore, higher demand allocation in the dynamic case is due to higher utilization of HOM formats .

It can be observed from Fig. 6, where as Pch decreases the number of demands increase. This can be explained from the fact that P_{NLI} and ISRS depends upon channel launch power. Although, this makes it desirable for a lightpath to have a lower Pch in C+L band, however, it shouldn't be too small such that it degrades the OSNR due to lack of signal power. From Fig. 5 and Fig. 6, it can be seen that Pch between - 3dBm and -1.5 dBm is an optimum region for most signals in the Indian network, where a peak in the allocated demands can be seen. A further reduction in the Pch reduces the OSNR of majority of lightpaths leading to fewer allocated demands.

From Table III it can be observed that C+L band operations can provide higher network capacity as compared to C band operation in the Indian network scenario. The capacity gain are in range of 98.41% and 108.67% in between Pch of - 3 dBm to -1.5 dBm while operating with B_{ch}=50 GHz. Similar capacity gain of 92.6% and 103.98% is reported for B_{ch}=37.5 GHz at the operating range of P_{ch} of -3 dBm to -1.5 dBm respectively.

From Fig. 5 and Fig. 6 it is seen that using C+L band can provide higher proportion of allocated lightpaths for both, B_{ch}=50 GHz and 37.5 GHz while limiting our launch power in the range of -3 dBm to -1.5 dBm for large Indian network. Therefore, this will be helpful to sustain the broadband traffic growth of the inter-city core network because operations in C band with low order QAM (QPSK or 8QAM) will rapidly exhaust the C band spectral resource in near future.

IV. CONCLUSION

In this paper the benefits and operation of a long haul Indian Backbone network has been analyzed while operating over C+L band. A comprehensive OSNR estimation model has been used to predict the OSNR of optical lightpaths while considering the ASE and NLI noise impairments due to ISRS. The noise model has been used to categorically describe the capacity benefits associated to dynamic NLI prediction in the Indian network. The results indicate that capacity benefits associated are significant in C+L band operation due to significant presence of ISRS. Further, these benefits are significant at high launch power of 0 dBm and particularly at B_{ch}=37.5 GHz. From the results it is desirable to control the P_{ch} as clearly the higher spectral resource of C+L band comes at a cost of incurring higher NLI due to ISRS. However, care must be taken not to significantly reduce the P_{ch} value as this may lead to degradation of lightpath OSNR due to lack of channel power. For Indian network a suitable region of operation for P_{ch} is in between -3 dBm and -1.5 dBm. Therefore an operator should optimize his channel launch power based upon the network dimensions while operating over C+L band. Finally, operating over C+L band can increase the network capacity of the inter-city Indian network by around 100% while compared to operation over C band at suitable channel launch power levels of -3 dBm to -1.5 dBm. Thereby indicating a promising technology to sustain the exponentially growing broadband traffic in the Indian network.

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