# Migration from C to C+L Band

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NetLab Group Meeting

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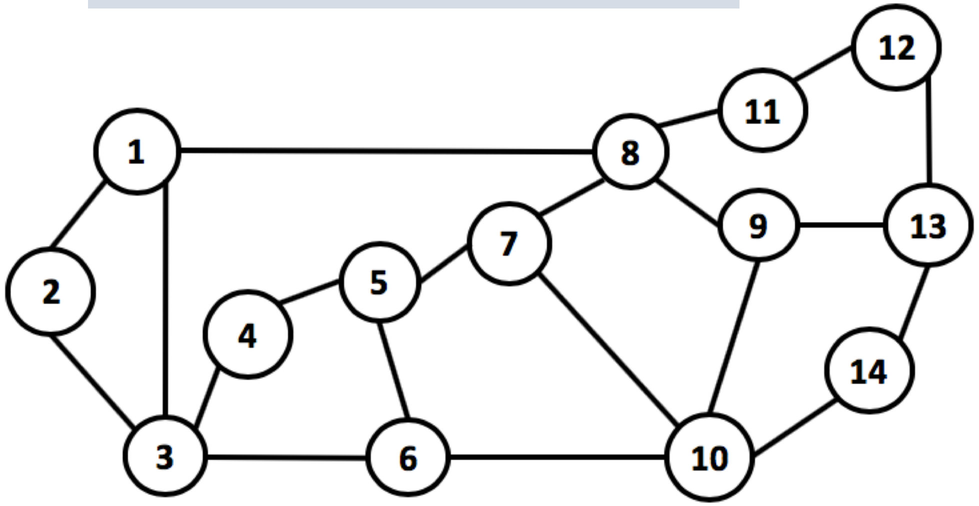
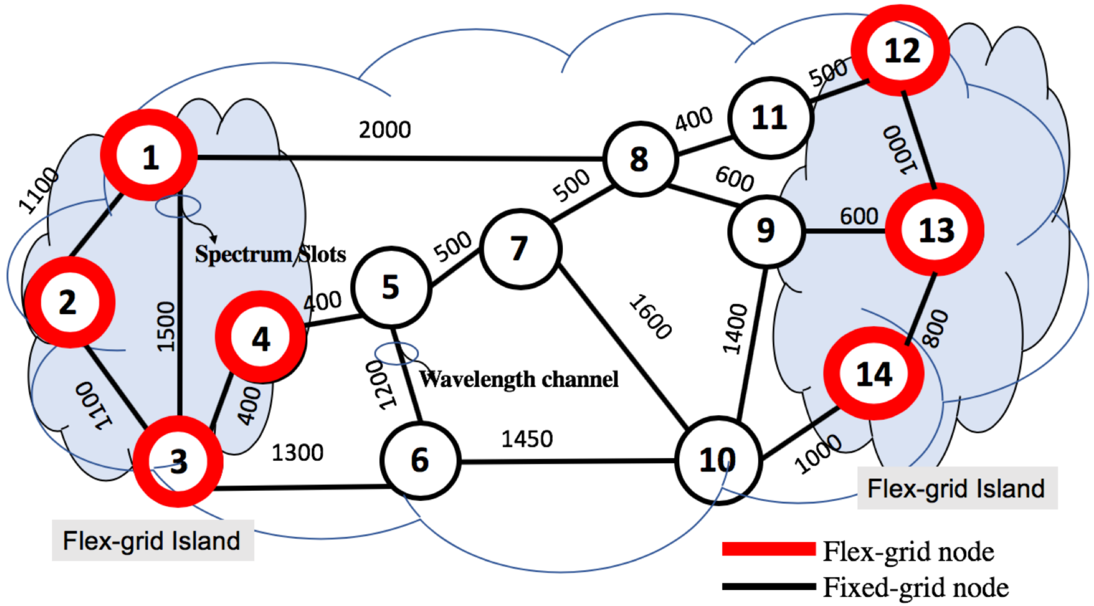
# Migration from C to C+L Band

**Capacity Enhancement**




Migration to Elastic Optical Network




What else can be done to increase network capacity?

*Increase the spectrum from C (5 THz) to C+L (10 THz) band*

# Migration from C to C+L Band

## C + L Benefits:

1. Attenuation co-efficient variation is negligible
2. Inline EDFA can be tuned to amplify L band

## C + L Drawbacks:

1. Higher nonlinear interference (NLI) due to inter-channel raman scattering (ISRS)
2. Limited OSNR

| Name | O | E | S | C | L |
|---|---|---|---|---|---|
| Wavelength range (nm) | 1260-1360 | 1360-1460 | 1460-1530 | 1530-1565 | 1565-1625 |
| C-band system | | | | 35 nm | |
| C+L-band system | | | | 95 nm | |
| Average fiber loss [dB/km] | 0.36 | 0.28 | 0.22 | 0.18 | |
| Multi-band | 365 nm | | | | |

Fig. 1. Low loss transmission bands of single mode fiber.

A. Napoli et al., "Perspectives of Multi-band Optical Communication Systems," *Proc., Opto-Electronics and Communications Conference (OECC)*, June 2018.

# Biased Traffic Matrix

- Probability Mass Functions based on Gravitational Model

| | Seattle | Palo Alto | San Diego | Salt Lake City | Boulder | Houston | Lincoln | Champaign | Pittsburgh | Atlanta | Ann Arbor | Ithaca | Princeton | College Pk |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Seattle | 0 | 0.1119041 | 0.1667369 | 0.1688483 | 0.07299 | 0.0571824 | 0.0387771 | 0.0202173 | 0.0173859 | 0.0168271 | 0.0150814 | 0.0128297 | 0.0112556 | 0.0090996 |
| Palo Alto | 0.0501523 | 0 | 0.1228368 | 0.0215922 | 0.0081419 | 0.0086807 | 0.0042797 | 0.0020199 | 0.0017312 | 0.0018189 | 0.0014932 | 0.0012841 | 0.0011286 | 0.0011204 |
| San Diego | 0.4499745 | 0.7396726 | 0 | 0.4560375 | 0.2251454 | 0.2955089 | 0.0964943 | 0.0486641 | 0.041364 | 0.0548508 | 0.032564 | 0.0277 | 0.0267506 | 0.0199513 |
| Salt Lake City | 0.1453278 | 0.0414671 | 0.1454442 | 0 | 0.1498184 | 0.0446563 | 0.0437538 | 0.0142163 | 0.0101714 | 0.0103808 | 0.009486 | 0.0071115 | 0.0060602 | 0.0045821 |
| Boulder | 0.0310477 | 0.0077276 | 0.0354873 | 0.0740421 | 0 | 0.0426997 | 0.0698774 | 0.013794 | 0.008301 | 0.0092446 | 0.0083327 | 0.0054529 | 0.0046617 | 0.0036234 |
| Houston | 0.2262866 | 0.0766491 | 0.4333221 | 0.2053181 | 0.3972422 | 0 | 0.503979 | 0.3516066 | 0.2205135 | 0.6595924 | 0.1740787 | 0.1290303 | 0.1291979 | 0.1120006 |
| Lincoln | 0.0082568 | 0.0020333 | 0.0076134 | 0.0108243 | 0.0349789 | 0.0271176 | 0 | 0.0234675 | 0.0083831 | 0.0083355 | 0.0102101 | 0.0048557 | 0.0038594 | 0.0031026 |
| Champaign | 0.0101981 | 0.0022735 | 0.009096 | 0.0083317 | 0.0163577 | 0.0448185 | 0.0555941 | 0 | 0.0651589 | 0.0409409 | 0.0931172 | 0.0224431 | 0.0196852 | 0.0178543 |
| Pittsburgh | 0.0259945 | 0.0057754 | 0.0229166 | 0.017669 | 0.0291775 | 0.0833148 | 0.0588642 | 0.1931349 | 0 | 0.125633 | 0.497588 | 0.4941719 | 0.4099824 | 0.5464622 |
| Atlanta | 0.0347024 | 0.00837 | 0.0419158 | 0.0248731 | 0.0448202 | 0.34374 | 0.0807326 | 0.1673833 | 0.1732891 | 0 | 0.1168517 | 0.083452 | 0.0992755 | 0.1091033 |
| Ann Arbor | 0.0116129 | 0.0025654 | 0.0092914 | 0.0084865 | 0.0150841 | 0.0338725 | 0.0369226 | 0.1421449 | 0.256262 | 0.0436297 | 0 | 0.0730482 | 0.0459805 | 0.0443776 |
| Ithaca | 0.0021865 | 0.0004883 | 0.0017493 | 0.0014082 | 0.0021848 | 0.0055569 | 0.0038865 | 0.0075828 | 0.0563294 | 0.0068965 | 0.0161679 | 0 | 0.0920536 | 0.0312159 |
| Princeton | 0.0018979 | 0.0004246 | 0.0016714 | 0.0011872 | 0.0018479 | 0.005505 | 0.0030562 | 0.0065803 | 0.0462362 | 0.0081169 | 0.0100688 | 0.0910754 | 0 | 0.0975067 |
| College Pk | 0.0023621 | 0.000649 | 0.0019191 | 0.0013819 | 0.0022112 | 0.0073468 | 0.0037823 | 0.009188 | 0.0948744 | 0.0137328 | 0.0149602 | 0.0475453 | 0.1501088 | 0 |

# Questions to be Answered

- Which links should be migrated to C+L?
- When to migrate?
- How many links should be migrated?
- How to handle the non-linear interference generated by additional spectrum?

# Inter-Channel Stimulated Raman Scattering (ISRS)

- *Power transfer between high-frequency optical signal to low-frequency optical signal sharing the same fiber that amplifies low-frequency signals and depletes higher-frequency ones*

ISRS gain at frequency f,

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

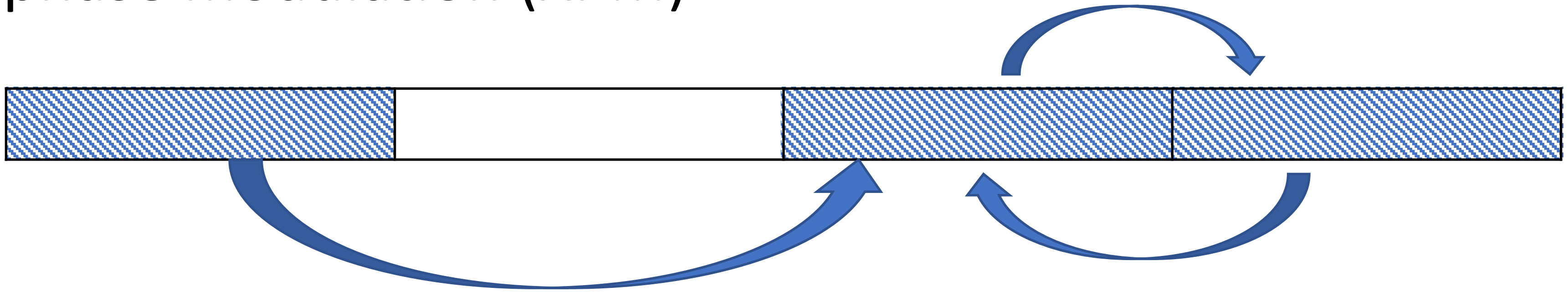
$P_{tot}$ is the total signal power, $G_{Tx}$ is the power spectral density, $C_r$ is the Raman gain slope, $\alpha$ is the attenuation, $L_{eff}$ is the effective length

A. Mitra, D. Semrau, N. Gahlawat, A. Srivastava, P. Bayvel, and A. Lord, "Effect of reduced link margins on C + L band elastic optical networks," *J. Opt. Communication Networks,* vol. 11, no. 10, pp. C86-C93, Sept. 2019.

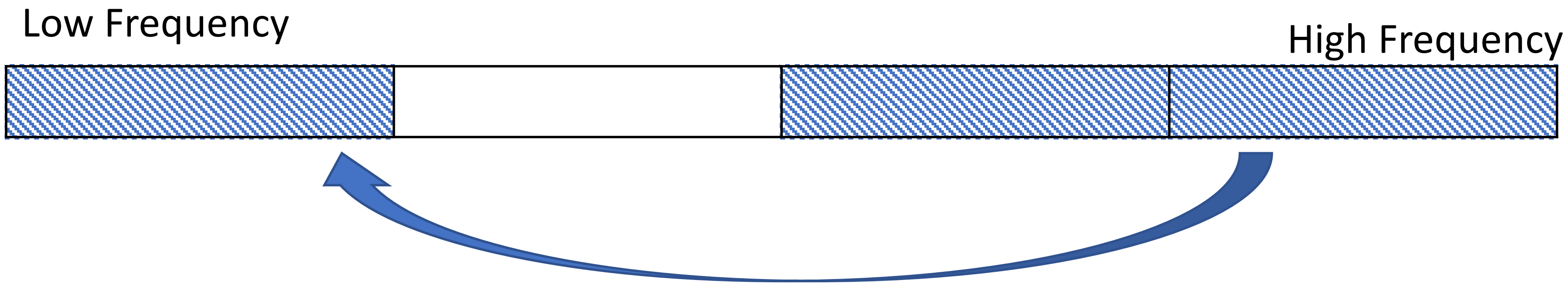
# Nonlinear interference (NLI)

- Self phase modulation (SPM)

- Cross phase modulation (XPM)



- ISRS



# Link Margin (LM)

*Link Margin in optical networks is the difference between the quality metric of a signal (OSNR, BER), and the threshold value above which it can be recovered error-free*

- Important for error-free performance and commitment on SLA
- Determined using conservative data for beginning-of-life (BOL) and end-of-life (EOL) performance
- Conservative assumptions (High LM) reduces overall network capacity and efficiency
- It further limits network capacity adding to NLI of C+L

*Solution: live network data and traffic forecasting for accurate dynamic margin requirement*

# Proposed OSNR Estimation Model

- Multiple ROADMs, optical links and EDFA
- In line EDFA compensates for previous span loss + compensates ISRS gain
- Amplified spontaneous emission (ASE) : noise from EDFA and ROADM
- NLI: self-phase modulation + cross-phase modulation + ISRS gain

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

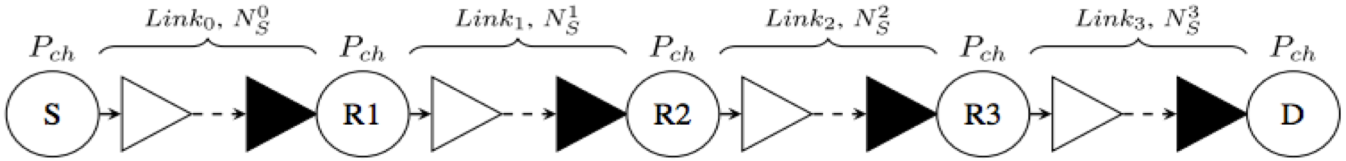



**Fig. 1.** Multihop path for OSNR estimation.

A. Mitra, D. Semrau, N. Gahlawat, A. Srivastava, P. Bayvel, and A. Lord, "Effect of reduced link margins on C + L band elastic optical networks," *J. Opt. Communication Networks,* vol. 11, no. 10, pp. C86-C93, Sept. 2019.

# Proposed EDFA Noise Model

- Fixed gain + frequency-dependent attenuation
- BPF separates C and L frequencies

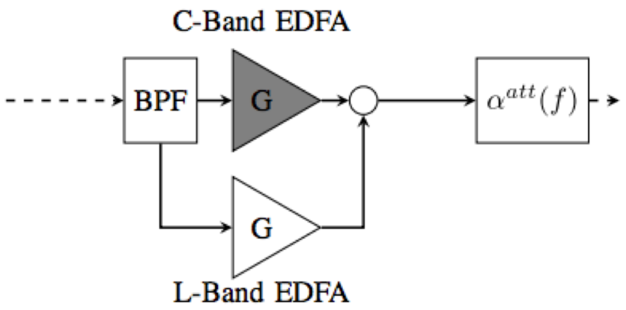



**Fig. 2.** EDFA model for C + L band amplification.


A. Mitra, D. Semrau, N. Gahlawat, A. Srivastava, P. Bayvel, and A. Lord, "Effect of reduced link margins on C + L band elastic optical networks," *J. Opt. Communication Networks,* vol. 11, no. 10, pp. C86-C93, Sept. 2019.

# Lightpath Provisioning Method

- Effect of reducing LM is observed across geographically diverse networks:

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 |

- 3000, 100 Gbps demands are considered, selecting source and destination with uniform distribution
- For every new 100 Gbps demand, goal is to carry it over an operational lightpath that has an unused capacity of 100 Gbps between same source and destination

A. Mitra, D. Semrau, N. Gahlawat, A. Srivastava, P. Bayvel, and A. Lord, "Effect of reduced link margins on C + L band elastic optical networks," *J. Opt. Communication Networks,* vol. 11, no. 10, pp. C86-C93, Sept. 2019.

# Lightpath Provisioning Method

Before allocating a 100 Gbps demand,

- Single shortest path is found
- Network OSNR estimation model is used to predict OSNR of the lightpath
- Modulation formats selected based on calculated OSNR & OSNR threshold
- After new lightpath allocation, OSNRs of active lightpaths sharing same link are updated
- An attempt is made to re-accommodate demands of any degraded lightpath

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 |

PM-QPSK = 25 (symbol/sec) * 2 (bit/symbol) *2 (polarization) = 100 Gbps
PM-16QAM = 25 * 4 * 2 = 200 Gbps
PM-BPSK = 25 * 1 * 2 = 50 Gbps
PM-32QAM = 25 * 5 * 2 = 250 Gbps
PM-64QAM = 25 * 6 * 2 = 300 Gbps



A. Mitra, D. Semrau, N. Gahlawat, A. Srivastava, P. Bayvel, and A. Lord, "Effect of reduced link margins on C + L band elastic optical networks," *J. Opt. Communication Networks,* vol. 11, no. 10, pp. C86-C93, Sept. 2019.

# Benefit of Operating at Lower LM

- Number of allocated 100 Gbps demands are listed for each $B_{ch}$ and LM until 10% of demands are blocked for high signal power.
- Capacity Benefits of reducing LM:
  - BT-UK, 27.5 & 28.5%
  - Pan Europe, 156.7 & 119.6%
  - USA-NSFNET, 130.7 & 264.6%

**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 |

- Large dimension of the network is the limitation of USA-NSFNET.

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# Benefit of Operating at Lower LM

- Avg link length of USA-NSFNET is 1319 km
- Significant ASE noise and NLI is experienced
- NLI is higher for 37.5 GHz channels and high transmit power
- Majority of lightpath requests are blocked due to lack of sufficient OSNR
- Or, they require PM-BPSK, which needs two contiguous slots to be a single lightpath
- If they are allocated they degrade OSNR of other active lightpaths

*Solution for larger networks can be adding regenerators!*


A. Mitra, D. Semrau, N. Gahlawat, A. Srivastava, P. Bayvel, and A. Lord, "Effect of reduced link margins on C + L band elastic optical networks," *J. Opt. Communication Networks,* vol. 11, no. 10, pp. C86-C93, Sept. 2019.

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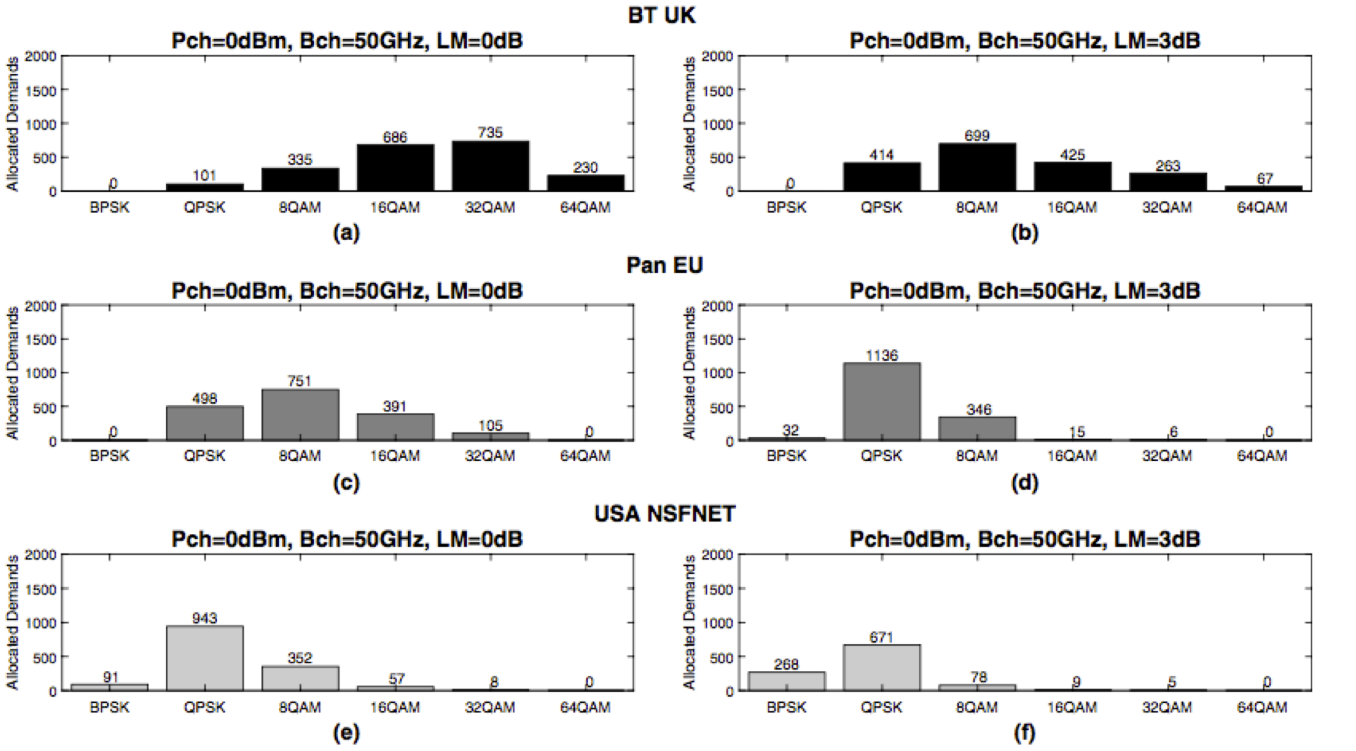

End performance LM results with $B_{ch} = 50$ GHz.

- The more the traffic carried by the network, the more blocking there is likely to be, then the benefit of reducing LM will be less visible.
- However, reducing LM will typically boost the network capacity.

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# Effect of Launch Power on Network Performance with a Given LM

- ISRS process depends upon the transmit power $P_{ch}$

**Table 6. Number of Allocated 100 Gbps Demands with Decreasing $P_{ch}$ 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 |

For USA-NSFNET, capacity increases by 20% and 16% for 50 and 37.5 GHz respectively as $P_{ch}$ is reduced by 3 dB. Network starts operating with lesser NLI and more operational lightpath.

When NLI is not high (in smaller networks), decreasing $P_{ch}$ too much can reduce OSNR of operating lightpaths

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# Summary

- Lower LM results in higher capacity
- The more the active channels the more NLI is generated
- NLI depends upon network dimension and launch power
- For smaller network reducing launch power does not significantly benefit the network capacity unlike larger ones
- Overall, C+L band system brings higher capacity benefits at low margins, given the complex effects of NLI
- Operators need to consider launch power, network dimensions, and current spectrum occupancy.

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# Questions to be Answered

- Which links should be migrated to C+L?
- When to migrate?
- How many links should be migrated?
- How to handle the non-linear interference generated by additional spectrum?
- Given the traffic matrix, NLI model, network dimension, current spectrum occupancy, find where on the network a migration from C band to C+L band can be obtained.