Capacity Crunch Solution

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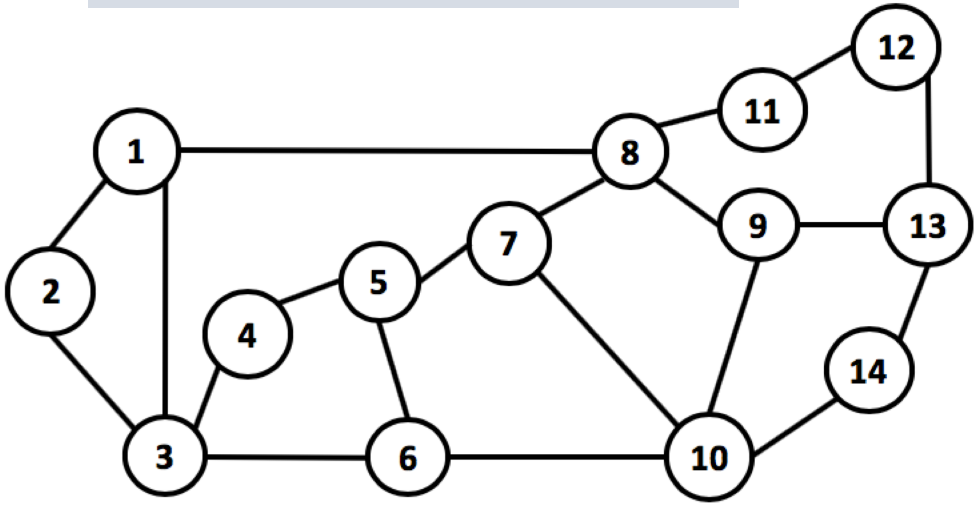
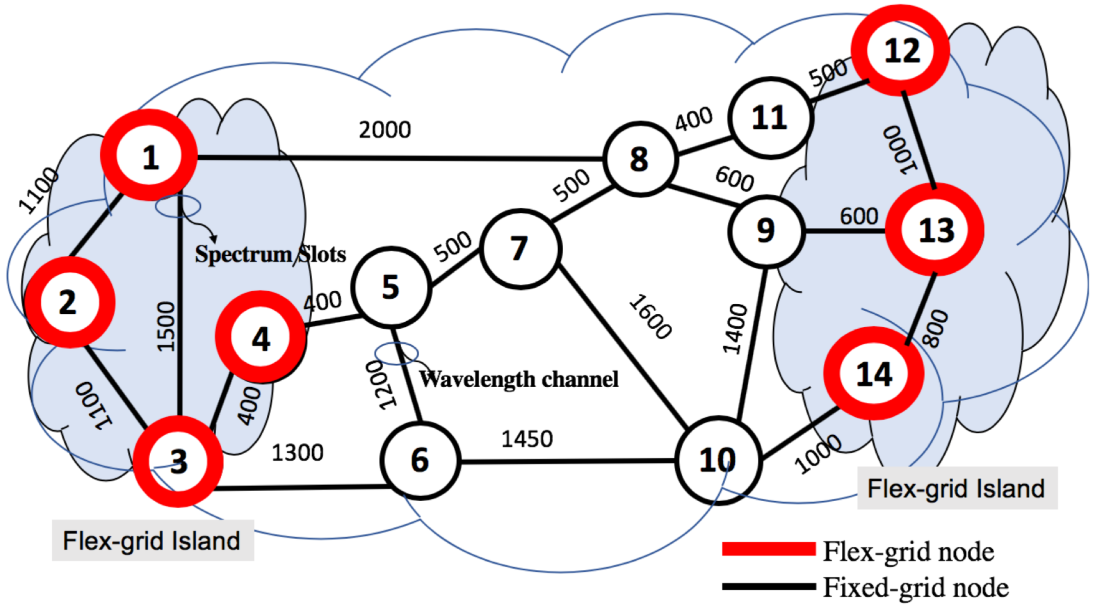
Migration from C to C+L Band

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.

Things We do not Know yet

- Which links should be migrated to C+L?
- When to migrate?
- How many links should be migrated at a time?
- 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,

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

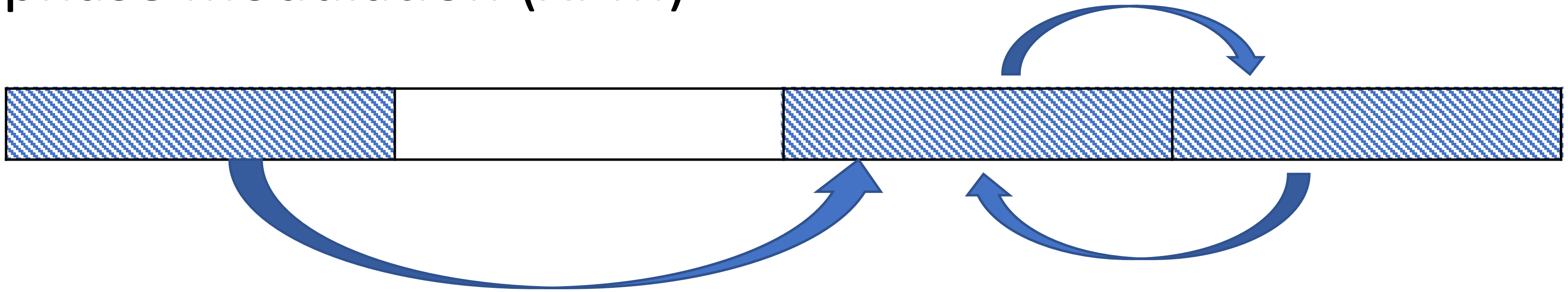
P_{tot} is the total signal power, G_{Tx} is the power spectral density, C_r is the Raman gain slope, α is the attenuation, L_{eff} is the effective length

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.

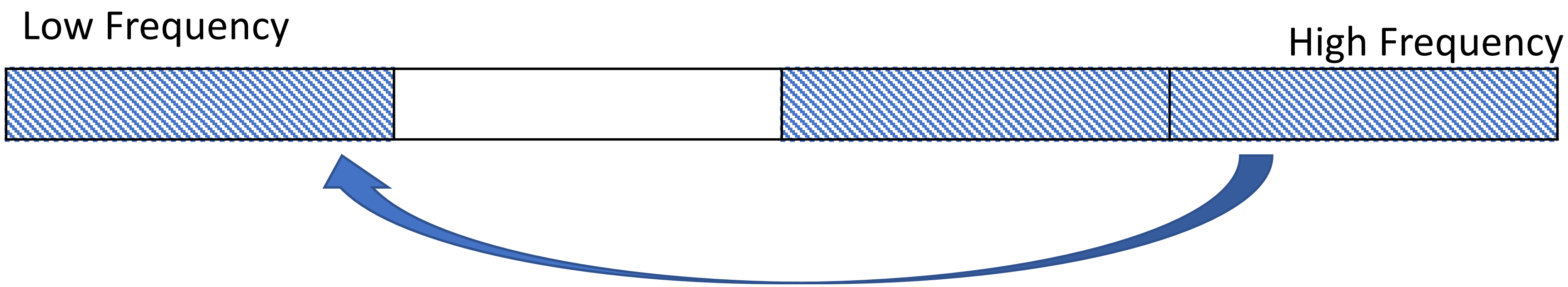
Nonlinear interference (NLI)

- 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

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.

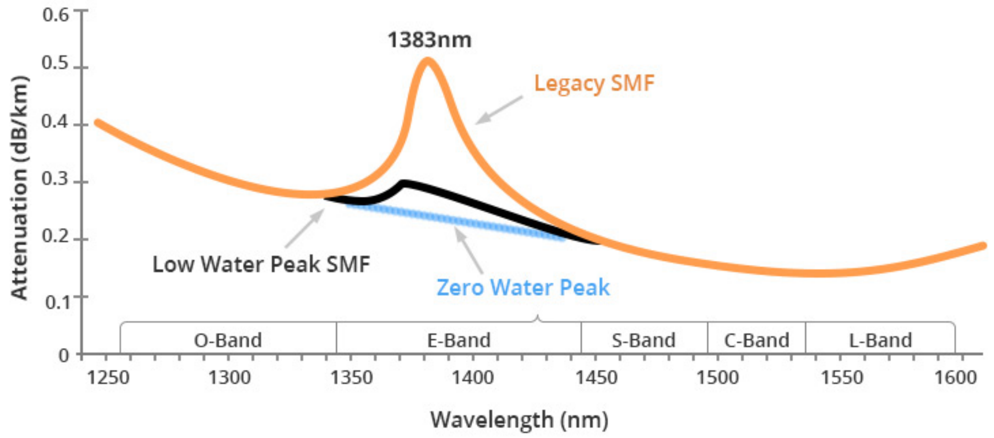
Summary

- 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.

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.

Motivation

- ITU-G.652D: most deployed optical fiber worldwide
- Wide low-loss window with negligible water absorption peak



- Multi-band systems exploit this characteristic to increase transmission capacity
- In this work, optical degradation (signal-to-noise) on different bands, resulting from successive channel upgrades until the complete low-loss window is occupied

Image: https://community.fs.com/blog/what-kind-of-single-mode-fiber-should-you-choose.html

Paper Review

- A. Ferrari, A. Napoli, J. K. Fischer, N. Costa, J. Pedro, N. Sambo, E. Pincemin, B. S. Krombholz, and V. Curri, "Upgrade Capacity Scenarios Enabled by Multi-band Optical Systems," *Proc., International Conference on Transparent Optical Networks (ICTON)*, July, 2019.

Network Capacity Crunch Solutions

Mitigate limitations arising in physical layer:

(a) Utilization of high spectral efficiency techniques, better DSP, stronger FEC, etc

(b) Lighting up new, possibly dark fibers

(c) Deploy novel multi-core or multi -mode fibers

(d) Usage of the entire low-loss spectrum of single mode fibers through a multiband (MB) approach

Name	O	E	S	C	L
Wavelength range (nm)	1260-1360	1360-1460	1460-1530	1530-1565	1565-1625
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Shannon's Capacity Equation

Shannon's capacity equation,

$$C = B \times log_2(1 + SNR)$$

1. (a) leads to a logarithmic improvement of the capacity C
2. (b)–(d) increase the term B. In other words, spatial or frequency multiplexing or a combination of them is the only approach achieving a substantial increase of fiber capacity

Methodology: Systematic Upgrade

- Starting from C-band up to complete occupation of low-loss spectrum (U→O-band)
- 80 new channels are added to the system each time
- Calculate SNR (SNR) and maximum achievable bit-rate R_b per band at different stages of the system upgrade

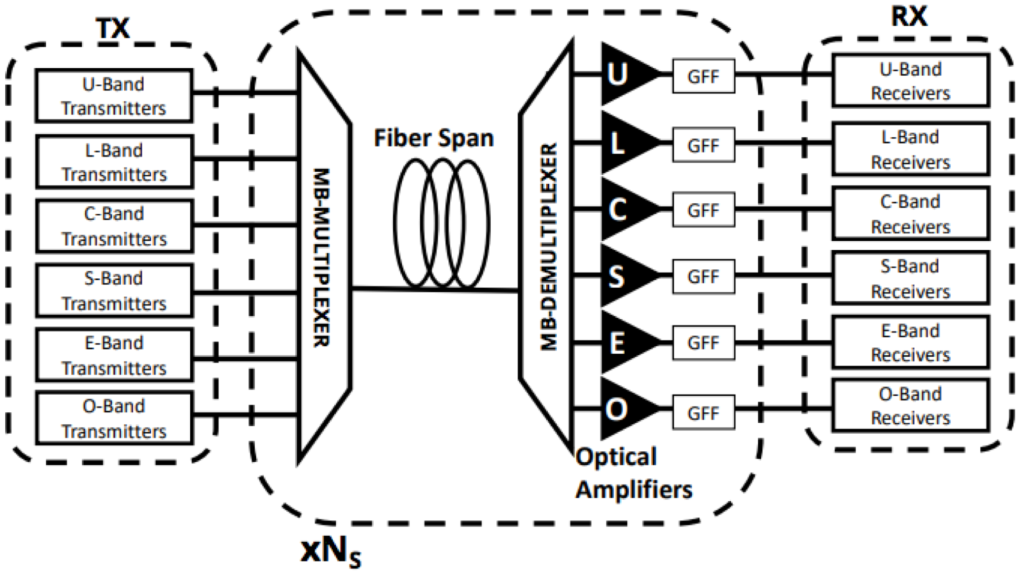


Fig. 1: Simplified block diagram of an optical MB transmission system.

Simulation Setup

- MB transmission bench with {U, L, C, S, E, O}-band transmitters
- 50 GHz spaced polarization multiplexed M-quadrature amplitude modulation (PM-M-QAM) symbol rate R_s= 32 Gbaud
- 2 nm guard-band
- Praseodymium doped fibre amplifier(DFA): O-band, Bismuth DFA: E, Thulium DFA: S, Erbium DFA: C & L and lumped Raman amplification (LRA): U
- Transmission system composed of 5 spans, where each fiber span is a 75 km long ITU-G.652D
- At receiver side, the bands are de-multiplexed, amplified, optically equalized (gain flattening filter (GFF)) and demodulated

Upgrade Scenarios

- Case 1 is benchmark (starting point), C-band only, with 80 channels
- From this case onward successive channels are added to the transmission system (with a step of 80 channels) until entire low-loss spectrum is occupied

Parameters / Band	0	E	S	C	L	U
Wavelength range [nm]	1260–1360	1360–1460	1460–1530	1530–1565	1565–1625	1625–1675
Central frequency [THz]	229.07	212.79	200.65	193.89	188.07	181.86
Amplifier type	PDFA [4]	BDFA [5]	TDFA [6]	EDFA	EDFA	LRA [7]
Noise figure [dB]	7	6	7	5.5	6	6
γ [1/W/km]	1.6	1.5	1.4	1.3	1.28	1.23
Upgrade scenarios						
Case 1	–	–	–	80	–	–
Case 2	–	–	183	80	137	–
Case 3	–	52	183	80	137	108
Case 4	156	296	183	80	137	108

320

160

400

Table 1: Considered parameters per-band and number of per-band channels for each upgrade scenario.

Result 1

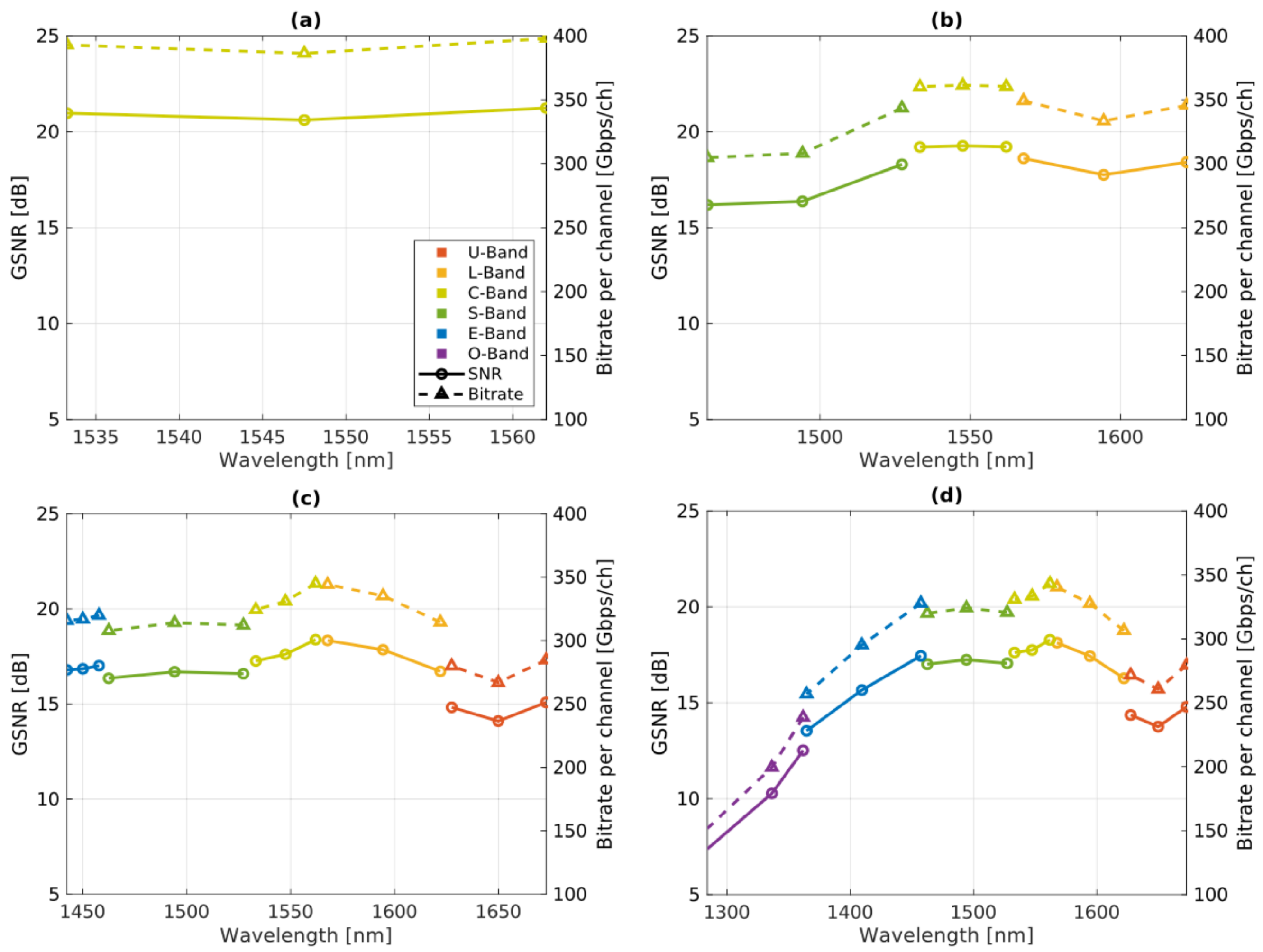


Fig. 2: GSNR (solid line) and per channel bit-rate (dashed line) after transmission along 375 km of ITU-G.652D optical fiber considering 80 C-band channels (a), 400 S+C+L channels (b), 560 E+S+C+L+U channels (c) and 960 O+E+S+C+L+U channels (d).

Result 1

- *Case 1-case 4*, GSNR for C-band decreases by ~4 dB & bit-rate by ~70 Gbps
- Edge bands show worse performance than middle ones
- For small-wavelength channels, worse performance results from strong optical power depletion induced by SRS (stimulated raman scattering)
- High-wavelength channels suffer from high SRS pumping, consequently, being transmitted with an high optical power, above optimum. So, optical performance is limited by NLI
- Middle channels are impacted by both SRS pumping and SRS depletion where both counteract each other.

Power transfer between small-wavelength signal to high-wavelength signal sharing same fiber that amplifies high-wavelength signals and depletes low-wavelength ones

Conclusion

- Total capacity of a point-to-point link may increase by up to ~8 times in case the complete 48 THz low-loss spectrum is exploited
- However, the average transceiver spectral efficiency decreases by up to ~25% in this case
- C-band represents just a small part of the capacity in the fiber
- Sophisticated techniques are needed to efficiently plan the line system

Motivation

- *L-band deployments with minimal up-front cost*
- *Add L-band capacity only when it is actually needed due to C-band exhaustion*
- *Avoid operational complexity and impact to existing services*
- *Maximizing the performance and agility of the overall C+L system*

Ciena

- With the 6500 Reconfigurable Line System (RLS), network operators deploy, day 1, C&L-band optimized equipment that uses integrated channelized Amplified Spontaneous Emission (ASE) loading to ensure maximum fiber capacity, optimal system performance and guaranteed in-service upgrade

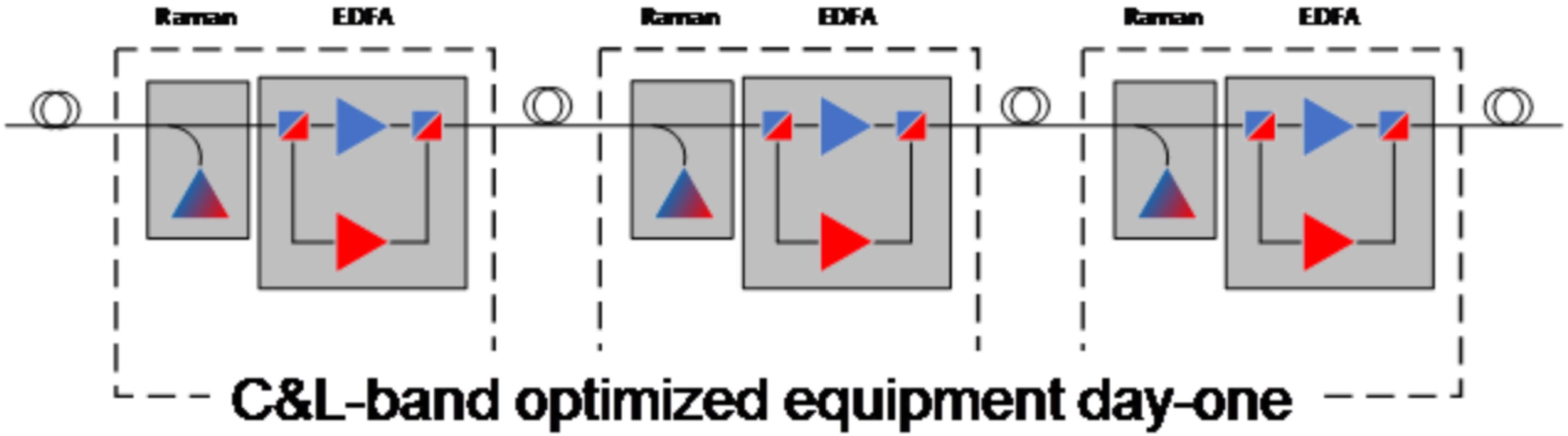
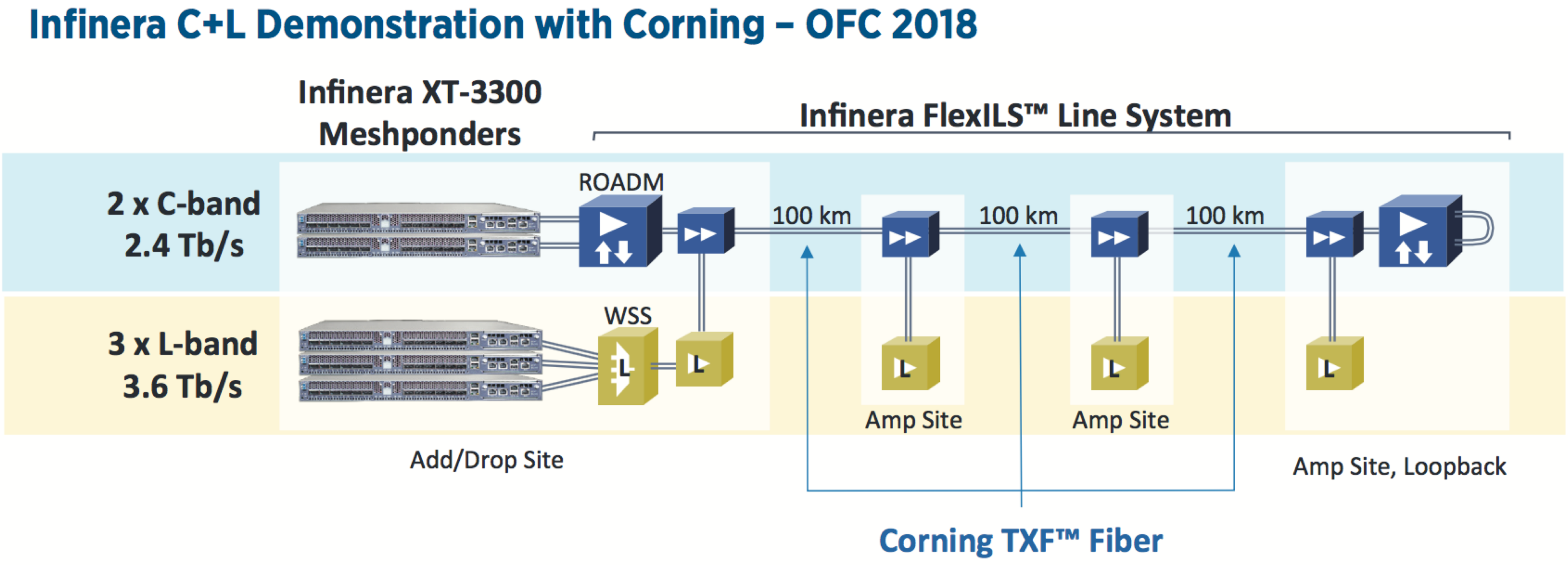


Fig. Ciena's integrated C + L band upgrade solution

https://www.ciena.com/insights/articles/The-benefits-of-an-integrated-CL-band-photonic-line-system.html

Infinera

Corning and Infinera demonstrate 55 Tb/s capable transmission equipment operating in C+L bands across 600 km of G.654.E compliant ultra-low-loss, large effective area fiber



https://www.corning.com/media/worldwide/coc/documents/Fiber/R_OFC_Infinera-2018.pdf

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.