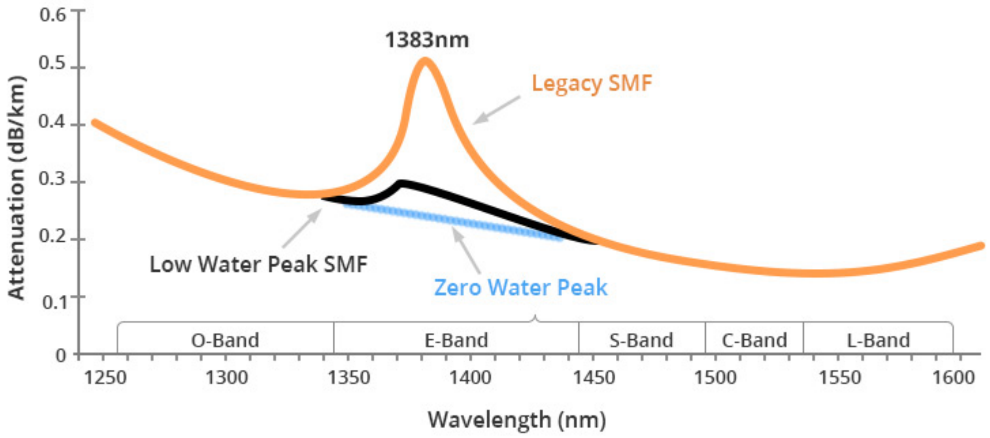
Capacity Upgrade Through Multi-band Optical Systems

Tanjila Ahmed
NetLab Group Meeting
Friday, November 15, 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
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.

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

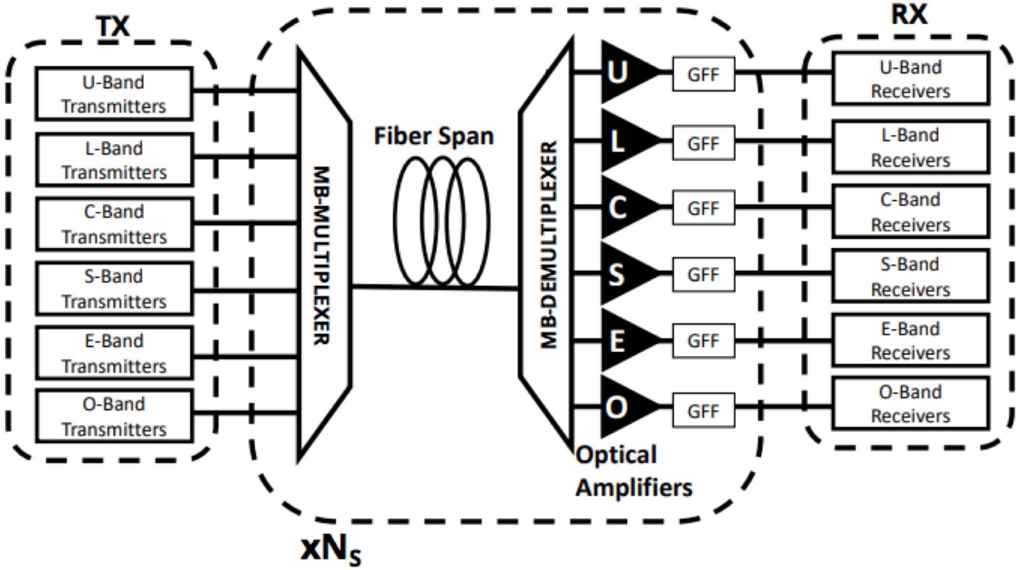


Fig. 1: Simplified block diagram of an optical MB transmission system.

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.

Analytic Model

$$\text{GSNR} = \frac{P_S}{P_{ASE} + P_{NLI}}$$

Where P_s is the signal power, P_{ASE} is the amplified spontaneous emission (ASE) noise introduced by amplifiers and P_{NLI} is the equivalent nonlinear interference (NLI) power

Achievable capacity is computed assuming a flexible transceiver capable to completely exploit the available SNR

Result 1

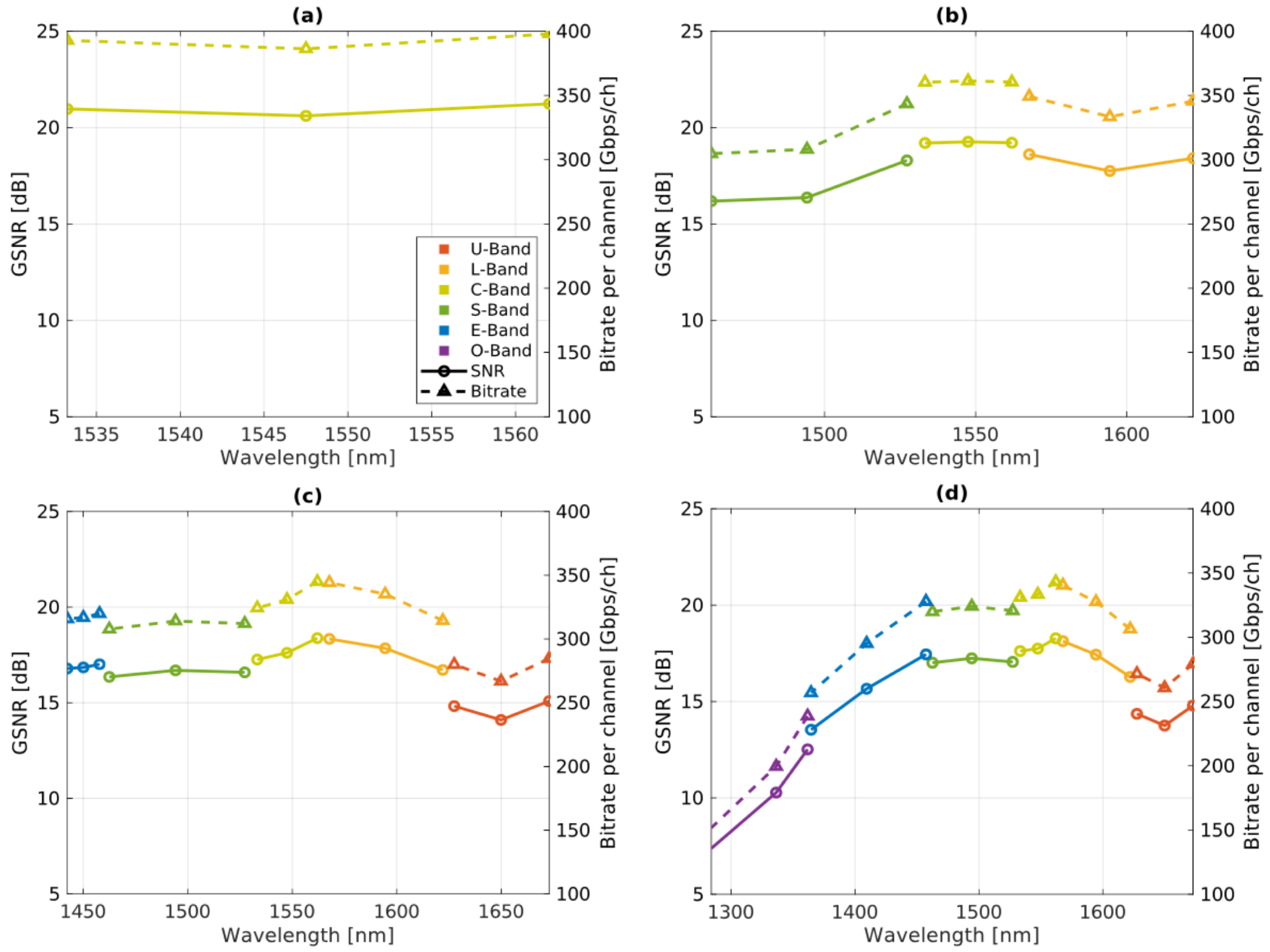


Fig. 2: GSNR (solid line) and per channel bit-rate (dashed line) after transmission along 375 km of ITU-G.652D optical fiber considering 80 C-band channels (a), 400 S+C+L channels (b), 560 E+S+C+L+U channels (c) and 960 O+E+S+C+L+U channels (d).

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

Result 2

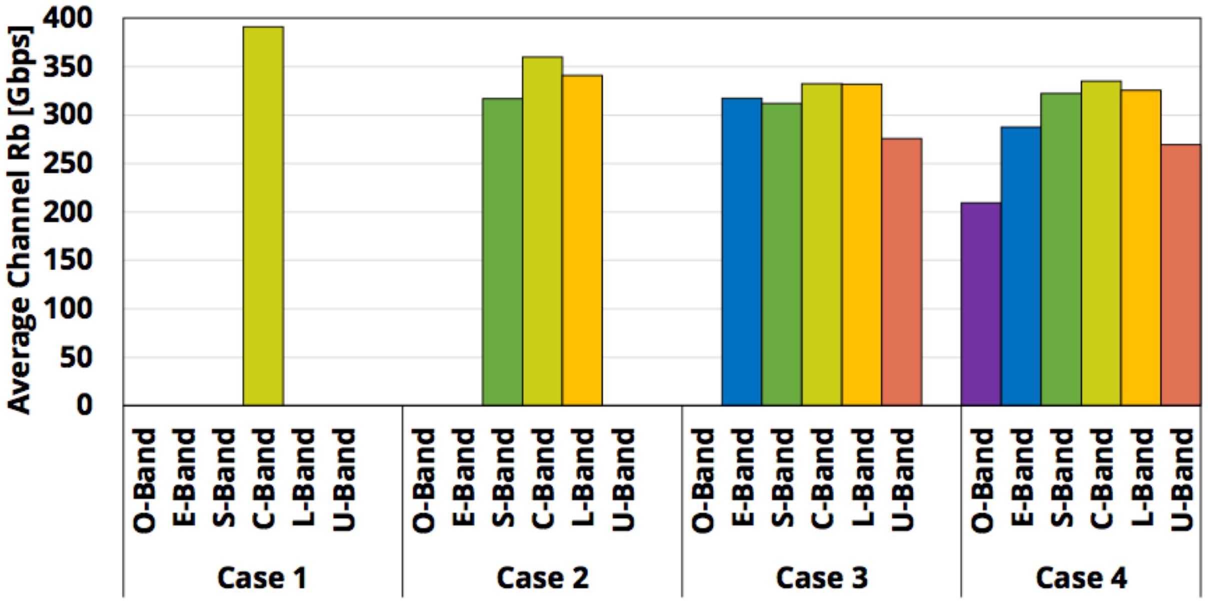


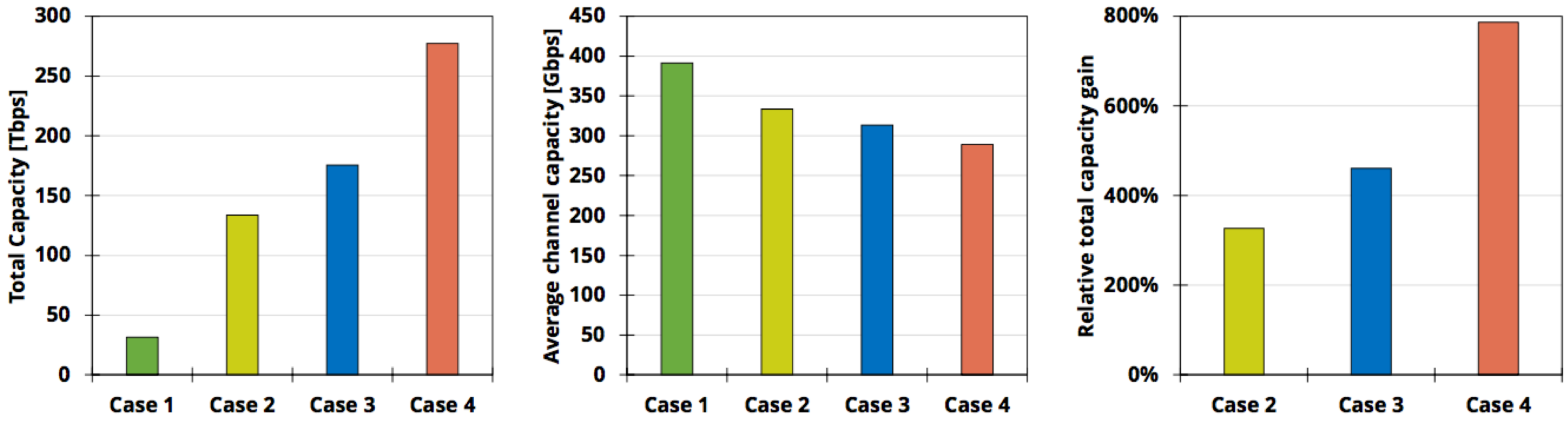
Fig. 3: Average channel bit-rate R_b per band for each considered upgrade case.

Average bit-rate per transceiver for each band and all cases. S- & L-band show performance similar to C-band having an average bit-rate per channel just ∼10% lower than the one in C-band. While O-, E- and U-band present larger penalties with respect to the C-band: 17%, 14% and 20% respectively.

This is due to the large fiber attenuation coefficient α(λ), the large amplifier noise figure and the SRS which both largely decrease the GSNR.

Case 1	–	–	–	80	–	–
Case 2	–	–	183	80	137	–
Case 3	–	52	183	80	137	108
Case 4	156	296	183	80	137	108

Result 3



(a) (b) (c)

Fig. 4: Total capacity (a), average capacity per transceiver (b) and relative total capacity improvement with respect to *case 1* (c) for each scenario.

Fig. 4a reports total system capacity versus considered upgrade cases showing that *case 2* increases available capacity by 100 Tbps, while *case 3* leads to only 40 Tbps of additional traffic. Finally, *case 4* increases total capacity by an additional 100 Tbps

Results 3

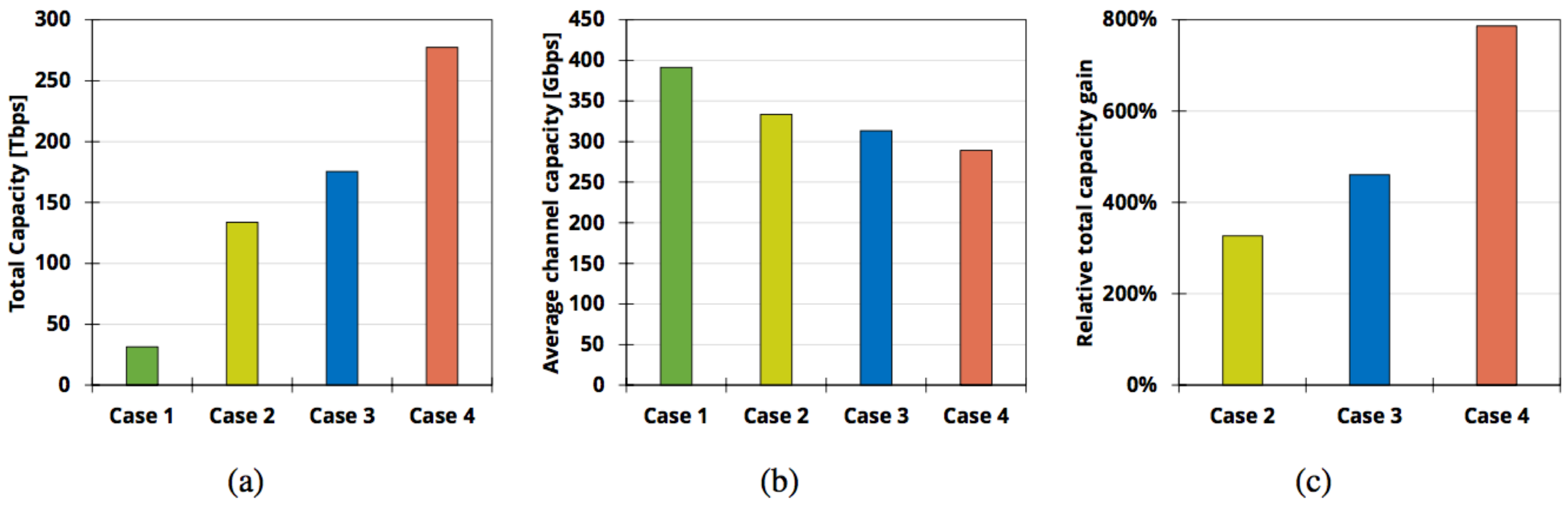


Fig. 4: Total capacity (a), average capacity per transceiver (b) and relative total capacity improvement with respect to *case 1* (c) for each scenario.

- Fig. 4b shows average bit-rate per transceiver and Fig. 4c reports the relative total capacity gain with respect to *case 1*. Moving from 80 C-band to 400 L+C+S band channels, total capacity increases by 320%. However, number of channels is 5 (400/80) times higher, which corresponds to a decrease of 15% of the average capacity per channel

Results 3

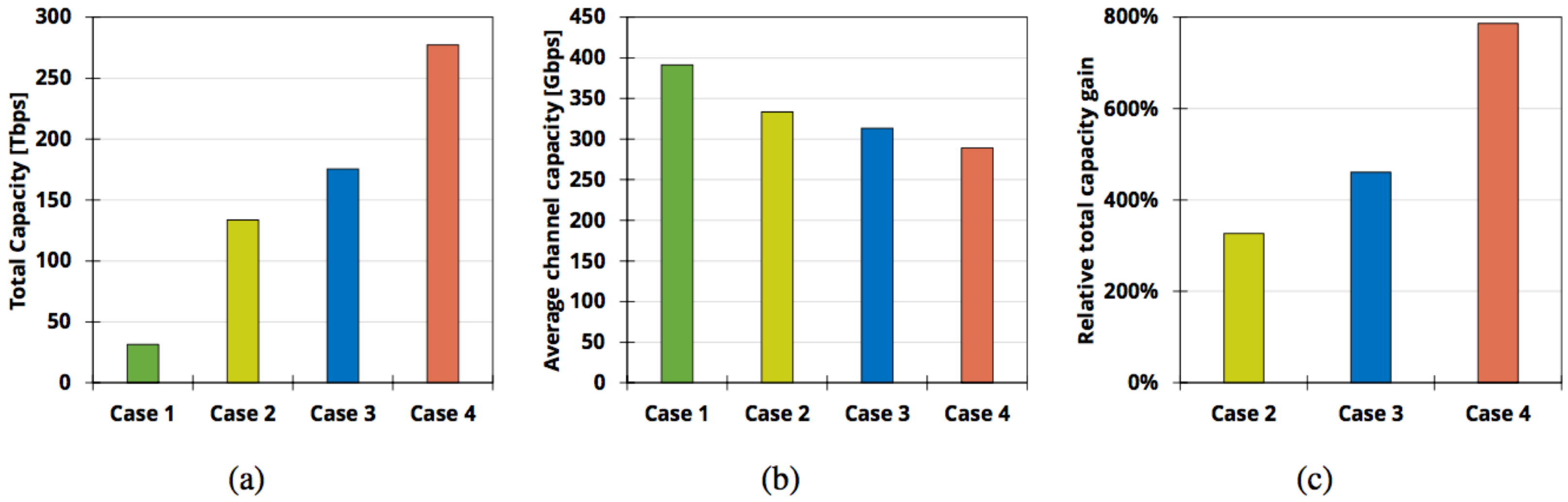


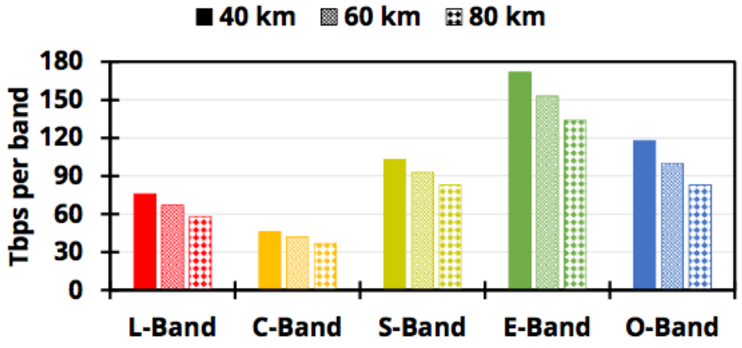
Fig. 4: Total capacity (a), average capacity per transceiver (b) and relative total capacity improvement with respect to *case 1* (c) for each scenario.

- For 560 channels on *case 3*, capacity increases by 460%, but at the cost of an average transceiver capacity reduction of 20% (C-band)
- For 48 THz bandwidth (*case 4*), the total capacity grows by 780% (C-band). However, 12 (960/80) times more transceivers are required, which corresponds to a decrease of the average capacity per transceiver of 26%

Results 4

Table 1: Per-band system parameters.

Band/Wavelength Range (nm)	L (1565-1625)	C (1530-1565)	S (1460-1530)	E (1360-1460)	O (1260-1360)
Number of channels	136	82	182	295	237



- C-band provides a low per band capacity for its narrow bandwidth
- Per band capacity over distance, a higher negative slope is observed for S-, E- and O-bands when compared with the L- and C-bands
- O-band is severely degraded by signal depletion

A. Ferrari *et al*., "Multi-Band Optical Systems to Enable Ultra-High Speed Transmissions," *Proc., Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC)*, June 2019.

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