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Upgrade Capacity Scenarios Enabled by Multi-band Optical Systems

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Abstract: The ITU-G.652D is the most deployed optical fiber worldwide and presents a wide low-loss window with negligible water absorption peak. Multi-band systems exploit this characteristic to increase the transmission capacity. In this work, we show the optical degradation in terms of generalized signal-to-noise ratio, on different bands, resulting from successive channel upgrades until the complete low-loss window is occupied.

1. Introduction

Over the last decade, several user-based applications contributed to increase greatly the bandwidth demand that optical fibers transport around the globe. Traffic forecasts highlight how this trend is likely to continue for the years to come. Moreover, new technologies might further fuel it, thus leading to a possible capacity crunch [1]. Several options have been considered to mitigate the limitations arising in the physical layer [2,3]: (a) utilization of high spectral efficiency techniques, better DSP, stronger FEC, etc.; (b) lighting up new, possibly dark, fibers; (c) deploy novel multi-core / -mode fibers; and finally (d) enabling the usage of the entire low-loss spectrum of single mode fibers through a multi-band (MB) approach. The options (a) and (b) are available commercially; (c) is within the research phase and neither fibers nor transponders have been deployed; (d) is partially available (transmission over C+L-band is commercially available, while the full set of components required for transmission over the remaining bands does not exist yet.

If we put all this in the context of Shannon's capacity equation ($\mathrm{C} = \mathrm{B} \times \log_2(1+\mathrm{SNR})$), we would immediately recognize that (a) leads to a logarithmic improvement of the capacity C since it aims at increasing the signal-to-noise-ratio (SNR), while (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. In this invited contribution, we will focus on (d) by considering upgrade scenarios from C-band up to the complete occupation of the low-loss spectrum of an optical fiber, i.e., from U→O-band. More precisely, we will investigate the scenario of a systematic upgrade, where 80 new channels are added to the system each time. The results report the performance, assesses by the generalized SNR (GSNR) and maximum achievable bit-rate R_b per band at the different stages of the system upgrade.

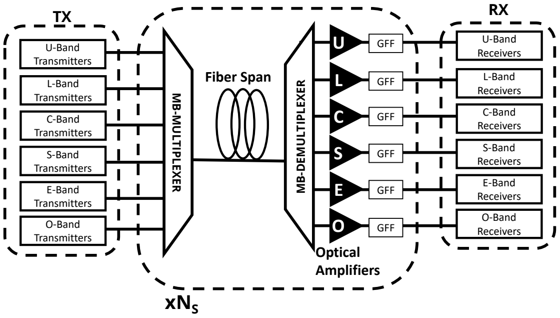

Fig. 1: Simplified block diagram of an optical MB transmission system.

2. Simulation setup and considered upgrade scenarios

Simulation setup: Fig. 1 illustrates the system considered throughout this work. It is composed of a MB transmission bench with {U, L, C, S, E, O}-band transmitters. We considered 50 GHz spaced polarization multiplexed M-quadrature

amplitude modulation (PM-M-QAM) signals with root raised cosine shaping (roll-off ρ = 0.15) and symbol rate R_s = 32 Gbaud. After being multiplexed, all channels are launched into the fiber. A 2 nm guard-band between adjacent bands is assumed. At the receiver side, the bands are de-multiplexed, amplified, optically equalized (via a gain flattening filter (GFF)) and finally demodulated. We assume lumped amplifiers: Praseodymium doped fibre amplifier(DFA) in O-band [4], Bismuth DFA in E-band [5], Thulium DFA in S-band [6], Erbium DFA in C- and L-bands and lumped Raman amplification (LRA) in U-band [7]. The noise figure are: (7, 6, 7, 5.5, 6 and 6) dB for $\{$O, E, S, C, L, U$\}$-band amplifiers, respectively. The wavelength ranges and other per-band parameters are reported in Table 1. The transmission system consists in a periodical link composed of 5 spans, where each fiber span is a 75 km long ITU-G.652D.
Upgrade scenarios: The considered system upgrade scenarios are listed in the last four rows of Table 1, resembling a typical pay-as-you-grow approach. *Case 1* is the benchmark (and starting point), consisting in the C-band only transmission, with a total of 80 channels. From this case onward, we consider different upgrade options, where successive channels are added to the transmission system (with a step of 80 channels) until the entire low-loss spectrum is occupied (*case 4*).

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

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

3. Employed Analytic Model

The key parameter for the optical quality of transmission (QoT) of a path in the network is the GSNR evaluated as $\mathrm{GSNR} = \mathrm{P_S}/(\mathrm{P_{ASE}} + \mathrm{P_{NLI}})$. Where P_S is the signal power, $\mathrm{P_{ASE}}$ is the amplified spontaneous emission (ASE) noise introduced by amplifiers and $\mathrm{P_{NLI}}$ is the equivalent nonlinear interference (NLI) power. The NLI is evaluated using the generalized Gaussian noise (GGN) model [8]. The GGN model takes into account the frequency dependence of the fiber loss $\alpha(\lambda)$, the dispersion $D(\lambda)$ and the stimulated Raman scattering (SRS). The local-optimization global-optimization (LOGO) approach [9] is employed to optimize the launched power. Finally, the achievable capacity is computed assuming a flexible transceiver capable to completely exploit the available SNR.

4. Results and discussions

Fig. 2(a) – (d) report the results for the cases 1 to 4 as described in Table 1. All figures show on the left y-axis the GSNR [dB] and on the right one the bit-rate per channel in [Gbps]. Fig. 2 shows that, when moving from *case 1* to *case 4*, the GSNR for the middle channel in the C-band decreases by $\sim$4 dB and the bit-rate by $\sim$70 Gbps. Additionally, the bands at the edge of the transmission spectrum show, in general, worse performance then the ones in the middle. For the small wavelength channels, the worse performance results from strong optical power depletion induced by SRS. In this case, the channels operate below the optimum LOGO optical power after transmission and, therefore, are mostly affected by ASE noise disturbance. On the opposite side of the low-loss spectrum, high wavelength channels suffer from high SRS pumping, consequently, being transmitted with an high optical power, above the optimum one. As a result, the optical performance is mainly limited by NLI. The channels in the middle of the spectrum are impacted by both SRS pumping and SRS depletion where the two effects counteract each other. Consequently, the channels in the middle of the WDM comb keep their power values close to the optimum value estimated by the LOGO.
Fig. 3 reports the average bit-rate per transceiver for each band and all cases. In each scenario, S- and L-band show performance similar to C-band having an average bit-rate per channel just $\sim$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

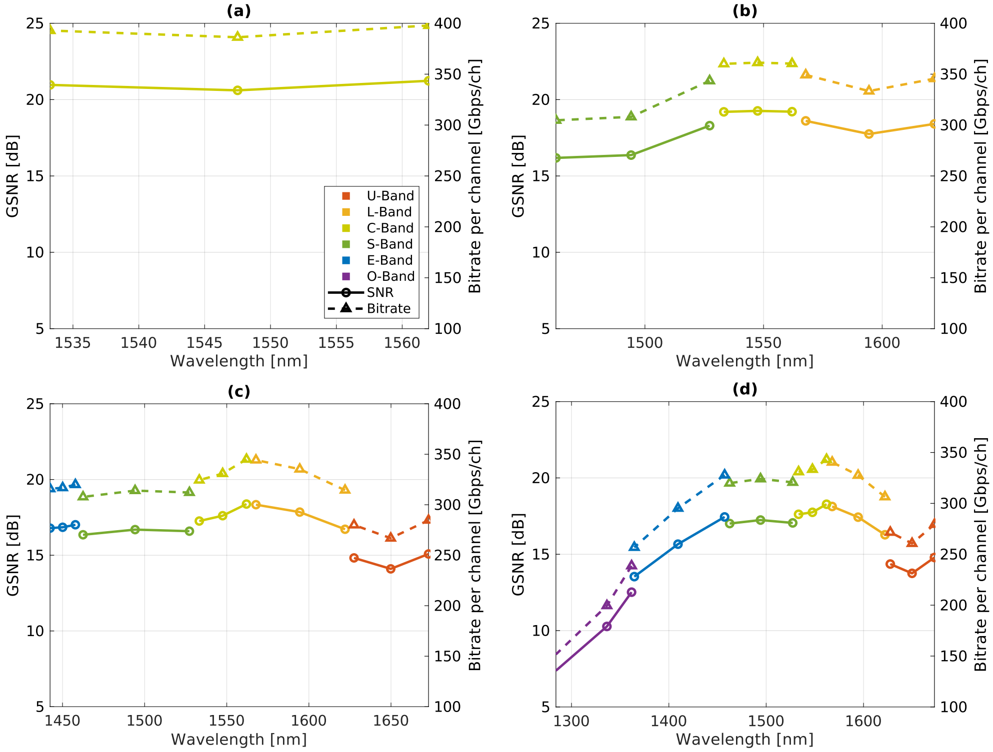

Fig. 2: GSNR (solid line) and per channel bit-rate (dashed line) after transmission along 375 km of ITU-G.652D optical fiber considering 80 C-band channels (a), 400 S+C+L channels (b), 560 E+S+C+L+U channels (c) and 960 O+E+S+C+L+U channels (d).

the large fiber attenuation coefficient $\alpha(\lambda)$, the large amplifier noise figure and the SRS which both largely decrease the GSNR.

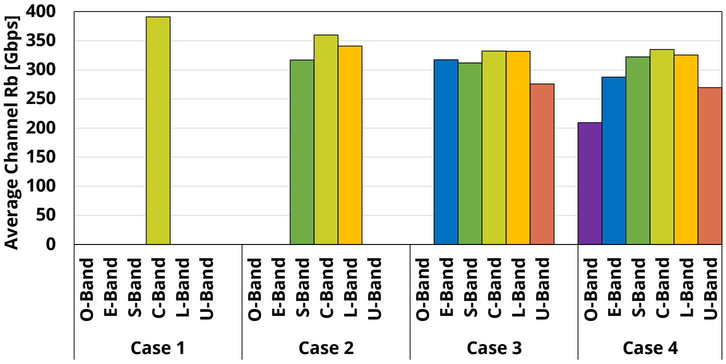

Fig. 3: Average channel bit-rate R_b per band for each considered upgrade case.

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

Fig. 4b(b) shows the average bit-rate per transceiver and Fig. 4c(c) reports the relative total capacity gain with respect to *case 1*. Moving from 80 C-band only channels to 400 L+C+S band channels, the total capacity increases by 320%. However, the number of channels is 5 times higher, which corresponds to a decrease of 15% of the average capacity per channel. Then, when 560 channels are turned on (*case 3*), the capacity increases by 460%, but at the cost of an average transceiver capacity reduction of 20% with respect to the C-band system only (*case 1*). Finally, when considering the full 48 THz bandwidth (*case 4*), the total capacity grows by 780% with respect to the C-band only case. However, 12 times more transceivers are required, which corresponds to a decrease of the average capacity per transceiver of 26%.

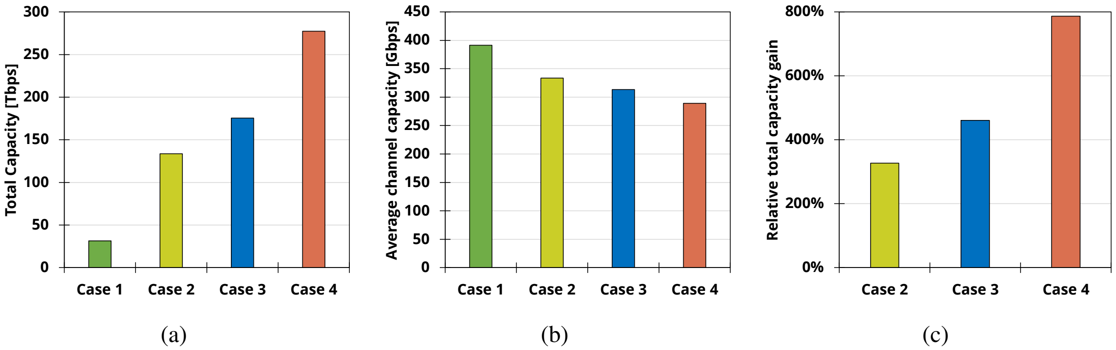

Fig. 4: Total capacity (a), average capacity per transceiver (b) and relative total capacity improvement with respect to *case 1* (c) for each scenario.

5. Conclusions

A comprehensive investigation of the capacity of a multiband line system was performed. It was shown that the 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.

6. Acknowledgement

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