Ultra-Wideband High-Capacity Transmission Systems: Challenges and Opportunities

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Abstract. We compare the capacity of S+C+L systems to C+L and C systems, highlighting the importance of power control techniques for ultra-wideband systems. We also review the benefits of pre-emphasis when maximizing the transmission distance under the constraint of fix bitrate per channel.

Introduction

The evolution in optical broadband amplification motivated the interest of extending wavelength division multiplexed (WDM) systems beyond the conventional spectral window of C-band (from 4.8 THz to 6 THz), representing an attractive solution to overcome the increasing traffic growth while better exploiting deployed fiber resources.

More than two decades after the first ultra-wide band (UWB), long distance standard single-mode fiber (SSMF), 1 Tbit/s transmission [1]-[2], C+L band systems (from 9.6 THz to 12 THz) are now a mature solution, commercially exploited for long-haul transmissions [3].

Simultaneously, since the pioneering triple-band demonstration of 10.92-Tbit/s over two fiber spans (117 km) [4], many research efforts were dedicated to enhance the multi-terabit-capacity of S+C+L transmissions [5]-[8]. Recent capacity achievements of 200.5 Tbit/s over two 100 km pure-silica-core fibers (PSCF) [9], 157 Tbit/s tested over field-deployed 120 km SSMF [10] and real-time capacity of 112.8 Tbit/s across 101 km of large-core low-loss fiber [11] are proof of the growing relevance of UWB S+C+L transmission systems.

While bandwidth extension improves the system capacity, challenges such as fiber propagation impairments, optical amplification and ecosystem maturity cast doubt on the benefits of multi-band systems compared to the deployment of independent C-band parallel fibers. In this paper, we analyze how capacity scales with bandwidth and the importance of power pre-emphasis to fully exploit the throughput of UWB systems. Additionally, we present the benefits of different pre-emphasis for more realistic cases without much granularity on the channel bitrate. Finally, we discuss one of the biggest challenges of UWB systems: the trade-off between capacity gain and cost factor.

Fiber systems beyond C-band

The effectiveness of UWB system design relies on propagation models accounting for wavelength dependent effects such as fiber loss; chromatic dispersion and inter-channel stimulated Raman scattering (ISRS). Current advances in closed-form ISRS GN model enable accurate and fast power optimization techniques based on the maximization of quality of transmission (QoT) [12]-[14]. Based on the system model described in [15], and considering a similar approach to [16], next we assess the capacity gain with regard to bandwidth when uniform and optimized power distribution are launched.

The transmission link consists on an optical multiplexing section (OMS) with 5x80 km SSMF spans, transmitting 140 Gbaud channels spaced by 150 GHz. We progressively transmit 40, 80 and 120 PCS64QAM channels within C, C+L and S+C+L bands, assuming a total of 18 THz of bandwidth for the triple-band transmission. The proposed study case is based on the system parameters from the S+C+L experiment reported in [17], aiming to investigate performance in extended scenarios with more and longer spans. The back-to-back penalty (SNR_{TRX}) of each band considers the experimental characterization presented in [9] and is set to 22 dB for all the bands. The link is assumed to use lumped amplifiers with no ripple, having the following noise figures: 5 dB for C band and 6 dB for both L and S band. Multiplexers and demultiplexers with 1 dB and 2 dB insertion loss, respectively, are used at each amplification stage.

Tab.1: Per-band amplifier output power with (a) optimized pre-emphasis and (b) uniform channel launch power profile

	a) Pre-emphasis (dBm)			b) Uniform (dBm)		
C	21.8			21.3		
C+L	22.7	19.3		20.8	20.8	
S+C+L	24.5	20.9	16.3	19.8	19.8	19.8

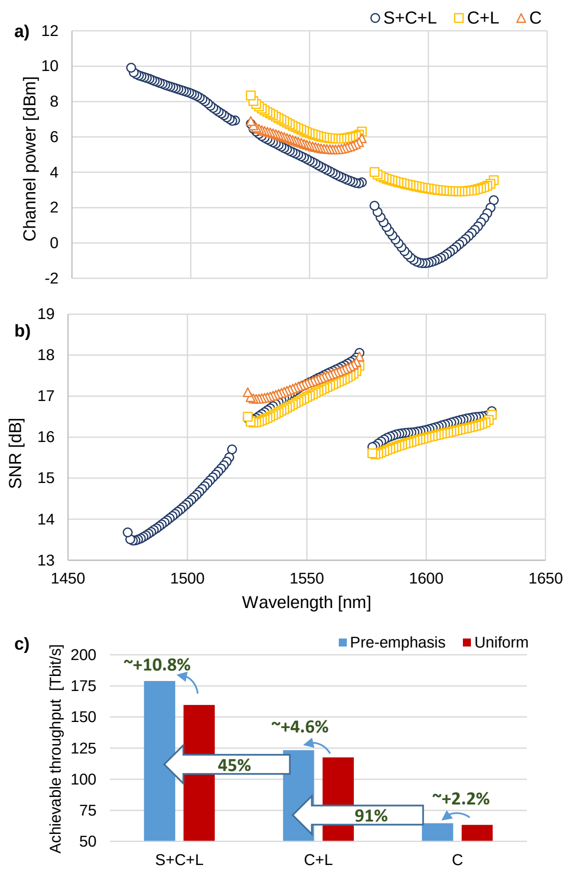

Fig. 1: (a) Booster channel power and (b) estimated SNR for optimized pre-emphasis when transmitting in C (triangles), C+L (square) and S+C+L (circles). (c) Achievable throughput when transmitting uniform power spectrum (red) and optimized pre-emphasis (blue) in C, C+L and S+C+L systems.

We first perform a per channel power optimization using the ASE-NL heuristic, which aims to have twice amplified spontaneous emission (ASE) noise than Kerr nonlinear noise (NL) [15], to compare the capacity benefits of optimized pre-emphasis versus the equivalent optimal uniform power profile.

Table 1 presents the per-band total output power predicted by the algorithm and the uniform power spectrum that maximizes the total Shannon capacity. We observe that for C and C+L transmissions, the pre-emphasis requires 0.5 dB higher total power than when launching uniform power spectra. However, this difference increases to 2 dB for the S+C+L configuration.

The resulting optimized pre-emphasis for the three transmission scenarios are presented in Figure 1(a). Notably, the power distribution suggested by the algorithm increases the power allocated in the bands with shorter wavelengths in order to cope with the higher fiber losses and the ISRS power transferred to the neighboring channels. Figure 1 (b) plots the estimated signal-to-noise ratio (SNR) for each configuration, showing that we slightly reduce the performance of C band when adding L-band, but S-band improves the SNR of the larger wavelengths of C-band due to ISRS as well as the performance in the L-band.

Moreover, Figure 1(c) quantifies the throughput increase with respect to bandwidth, showing that we almost double the capacity when we move from C to C+L band. When adding the S band, the increase is 45%, which is also close to the 50% bandwidth increase. Additionally, for all the scenarios, capacity is higher when using power pre-emphasis, being more relevant with larger bandwidth. With S+C+L system, the use of power optimization is providing more that 10% capacity increase, highlighting the importance of power pre-emphasis in ultra-wide systems.

S+C+L equalization and system design

The total capacity for the S+C+L transmission when all the channels are optimized is 178.9 Tbit/s. Although pre-emphasis enables this high-throughput performance, the large SNR difference incurred by S-band could be challenging for longer distance demonstrations.

Therefore, we propose two supplementary equalization techniques, based on the ASE-NL heuristic, suitable for different transmission scenarios. Intra-band equalization, aims to optimize the worst channel per-band, targeting to have a flat SNR for each band; and inter-band equalization, optimizing the worst channel in the entire system. These alternative pre-emphasis have a lot of potential in realistic transmission scenarios, limited to fixed bit-rate transponders at each band or in the entire system.

Figure 2 shows the per- band booster power allocation for each equalization, having for all the cases a clear unbalance between S-band and the other bands. Particularly, for the inter-band equalization the power gap between S and C-band is ~6 dB. Furthermore, in terms of power efficiency, the newly proposed methods reduce the total output power required at the booster. Next, we analyze the performance of each equalization technique. Figure 3(a) presents the resultant SNR after propagation in one OMS. Circular markers plot the achieved SNR with uniform (red) and optimized pre-emphasis (blue)

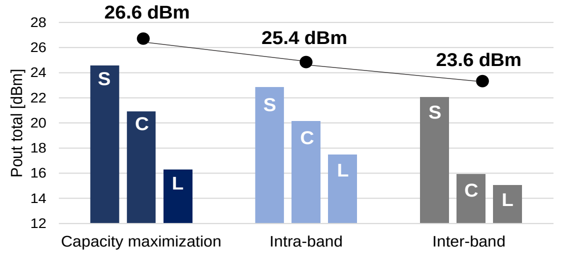

Fig. 2: Per-band and total booster output power (bold) of each equalization technique.

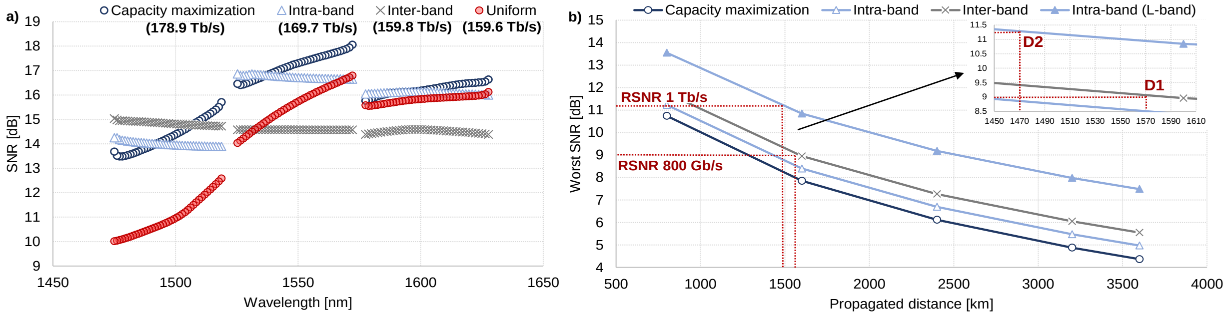

Fig. 3: (a) System performance for different pre-emphasis (unfilled markers) or uniform (filled marker) launch power profiles. (b) Achievable transmission distance for the channel with worst SNR for each equalization technique. D1 is the distance reached by 3x40 channels transmitted at 800 Gbit/s. D2 is the achievable distance of 2x40 channels with 1 Tbit/s and 40 channels at 800 Gbit/s.

discussed in the previous section. We observe that launching uniform power spectra provides the worst SNR (10 dB) and the lowest total capacity. Then, when we maximize capacity, we improve the worst channel SNR to 13.4 dB. Intra-band equalization (triangular markers) provides 0.4 dB SNR gain in the worst channel, achieving flat SNR per-band at the cost of 2% Shannon capacity loss. Finally, inter-band equalization (cross markers) improves the worst channel by 0.9 dB, achieving flat SNR per-band at expenses of 7% of Shannon capacity. Overall, the intra- and inter-band equalization techniques improve the channel with worst SNR at expense of all other channel degradation.

Next, we simulate the transmission along several OMS to study the performance with respect to distance. We plot in Figure 3(b) the channel with worst SNR and the estimated required SNR (RSNR), based on recent demonstrations using transceivers operating at data rates of 800 Gbit/s and 1 Tbit/s [18]. These RSNR estimations will frame the potential of the intra- and inter-band equalization. 9 dB and 11.3 dB of RSNR are estimated for bit-rates of 800 Gbit/s and 1 Tbit/s, respectively. Therefore, as shown in the inset of Figure 3(b), thanks to the inter-band equalization, the transmission of 120 channels (80 at each band) with 800 Gbit/s along 1570 km (D1) is possible, transmitting along 300 km more than with capacity maximization pre-emphasis.

To exploit the benefits of intra-band equalization, we assume different bit-rates per-band. Therefore, Figure 3(b) includes the performance of the worst channel in L-band, the band with lower SNR after the S-band. For this case, we transmit 80 channels (40 channels in C plus 40 channels in L-band) at 1 Tbit/s plus 40 channels (S-band) with 800 Gbit/s, up to 1470 km (D2).

Discussion

Even though, the industry adoption of C+L systems had settled the dilemma between ecosystem maturity and economic viability for UWB systems, the additional costs required to support S+C+L bands endangers the deployment of the technology.

It is expected higher costs for the S-band amplifiers (e.g. TDFA), than current erbium-doped amplifiers (EDFA) that can be designed to work on either C or L bands. The use of semiconductor optical amplifiers (SOA) for S-band amplification could reduce the cost difference, but its performance has not been demonstrated yet apart from ASE generation. These factors become even more daunting when by adding 6 THz in the S-band, the capacity gain is less than 50%, as presented in this study case and requires thorough pre-emphasis optimization which could not be so realistic in an actual network. System performance could be improved by Raman amplification, but the cost of high power pump lasers should be considered.

Also, for UWB transmissions, system failure of one band (amplifier lost), will severely affect the other bands by ISRS, requiring solutions to contain the impact of power variations in system performance.

Conclusion

We have presented the importance of equalization techniques to boost performance of S+C+L systems in different scenarios (fixed/flexible bit-rates, maximized capacity or long-haul transmissions). Up to 45% capacity improvement can be achieved with these techniques, turning the biggest challenge for S-band its expected higher cost than adding another fiber with C and/or L band. However, they are an attractive solution when fibers are scarce or the deployment of new fibers is unfeasible (fiber leasing).

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