OPTICAL DESIGNS FOR GREATER POWER EFFICIENCY

Alexei Pilipetskii, Dmitri Foursa, Maxim Bolshtyansky, Georg Mohs, and Neal S. Bergano
(TE Connectivity SubCom)
Email: apilipetskii@subcom.com

TE Connectivity SubCom, 250 Industrial Way West, Eatontown, NJ, 07724, USA.

Abstract: One of the significant limitations in the long-haul undersea systems is the ability to deliver power to the optical amplifiers due to the power feeding from the shore ends thus capping the achievable optical power. The expected growth in undersea capacity requires new solutions for powering problem. The paper will examine approaches that include SDM to optimize the use of available optical power and discuss experimental capacity results.

1. INTRODUCTION

The capacity demand is expected to keep increasing exponentially over time. Transmission of tens of Tb/s per fibre requires higher output power for optical amplifiers. Attaining these high optical power levels in long-haul undersea systems is problematic, since the ability to deliver power to the optical amplifiers is limited due to the maximum voltage that can be applied to a cable from the shore ends [1]. The straightforward approach for solving this problem by increasing the maximum cable voltage is associated with significant cost and reliability risks. Thus finding more efficient ways of using the optical power becomes imperative.

Improvement of overall power efficiency of a transmission system depends on electrical power delivery and optical power utilization [1]. In this paper we discuss the ways to use optical power in a more efficient manner which means how to transmit more information having overall optical power limitations. We present results of the transmission capacity demonstrations in C and extended C+L bands from the perspective of the achieved capacity vs. optical power. Special consideration is given to Space Division Multiplexing (SDM) as the method to scale transmission capacity up while keeping power constrains. We show that the use of SDM can also result in further power efficiency improvement by effectively mitigating nonlinear penalties and discuss the scaling of the capacity with power, bandwidth and index of space multiplexing. Optimization of power efficiency and capacity in turn requires optimization of transmission spectral efficiency and the search for the new power efficient modulation formats. The overall task of capacity increase and power efficiency improvement is considered as complex multi-dimensional problem with many aspects.

2. SINGLE-MODE FIBRE CAPACITY DEMONSTRATIONS AND OPTICAL POWER

In order to understand the optical power efficiency achieved in the recent long-haul transmission experiments in single mode fibres [2-4] let us analyze the optical power required to demonstrate the capacity. In [2] the capacity of 30 Tb/s was achieved in the full C band transmission at 6.1 bit/s/Hz spectral efficiency (SE) over transatlantic distance with ~20 dBm of EDFA output power set to near optimum from nonlinear operation point of view. Subsequent experiment expanding the bandwidth to C+L bands improved transmitted capacity to 44.1 Tb/s over longer transpacific distance of 9,100 km with approximately the same optical power [3]. Further boost in the EDFA optical output by ~66 % to 22.2 dBm resulted in only ~ 10% capacity increase [4]. In all experiments the capacity was maximized by the choice of modulation formats with appropriate spectral efficiency.

Based on these results the following observations can be made: a) it is possible to increase capacity with similar total optical power by spreading the optical power over wider bandwidth. This is equivalent to spreading the power over more fibre cores or space dimensions and suggests higher capacity for SDM systems with equivalent total signal output power, b) a choice of modulation format with appropriate spectral efficiency is required for optimizing system power efficiency, and c) operation at optimal system nonlinear point is not the most optimal power utilization from the standpoint of achievable capacity under power limitation condition.

3. SYSTEM DESIGN AND OPTICAL POWER OPTIMIZATION

One of the metrics of optical power efficiency can be defined as a product of total capacity by transmission distance divided by the sum of output powers of amplifiers in the system. Optical power efficiency metrics for two different values

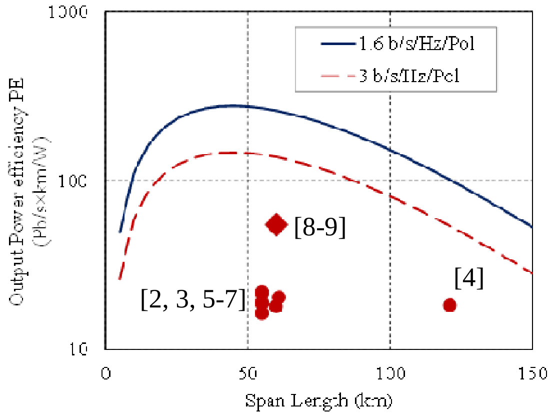

Figure 2: Power efficiency for an ideal 10,000 km system.

of spectral efficiency are shown in Fig. 2 as function of repeater spacing under the assumption of an ideal 3 dB amplifier noise figure. It demonstrates that repeater spacing of about 50 km provides the highest power efficiency. For comparison, the power efficiencies achieved in recent transmission demonstrations [2-9] are also shown. The experiment [8, 9] that aims specifically at the power efficiency improvement is discussed in more detail below.

Improvement to the optical power efficiency can come from the use of modulation formats with the high receiver sensitivity. The example of eight dimensional coded 8D-APSK modulation format with spectral efficiency equivalent of QPSK and ~0.8 dB better receiver sensitivity is shown in Fig. 3.

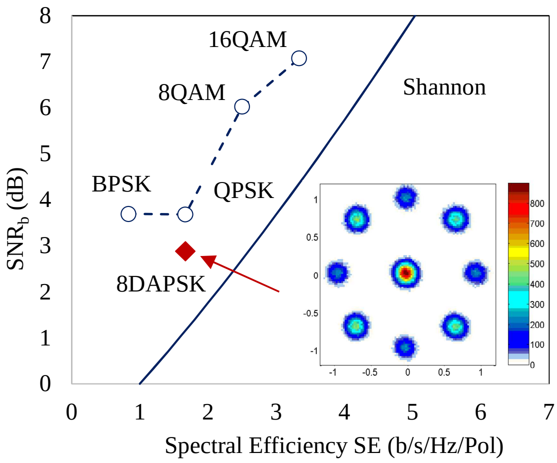

Figure 3: Comparison of 8D-APSK with regular QAM formats. Constellation shows non-equal probability of points.

Operating transmission system in a linear regime by proper choice of repeater output power is another way of power efficiency improvement. The most efficient value of power is well below that for which the maximum fibre capacity is achieved in a nonlinear regime. In the experiment [8] the power efficiency is optimized by operating amplifiers at low output power.

The improvement in power efficiency can also come from the adjustment of the amplifier bandwidth. The bandwidth optimization can eliminate the need in gain equalization filter (GEF) in every repeater resulting in reduction of the average repeater output loss.

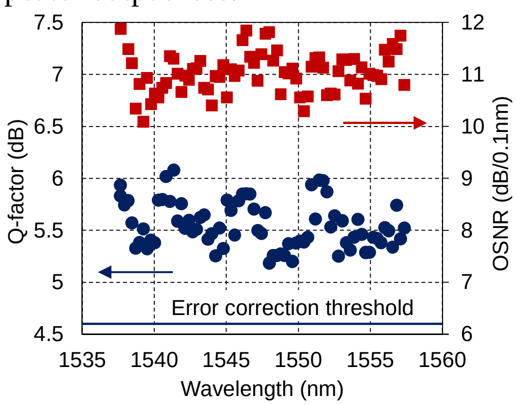

Figure 4: Performance and OSNR after 9,750 km distance.

Power efficient transmission with low loss 60 km fibres spans, power efficient modulation format and bandwidth optimized EDFA's with gain flattening performed on a block of 10 amplifiers has been demonstrated in [8]. Not more than 45 mW of pump power per EDFA is required in transmission of 8.12 Tb/s over 9750 km (Fig. 4). The transmission testbed operates in the linear regime and demonstrates the highest recorded power efficiency of 54.8 (Pb/s)*(km/W) [9].

4. SDM AND POWER EFFICIENCY

The ideas discussed above can be separately applied for power efficiency and capacity improvements in optical transmission systems. The highest capacity improvement can be achieved by applying all of them using space division multiplexing (SDM) concept. This follows from the consideration of the fundamental Shannon limit which shows that higher SE comes at the cost of increasingly growing SNR (Fig. 5). For example, doubling polarization multiplexed SE from 2 to 4 b/s/Hz would require ~ 4.8 dB increase in SNR and the required power, while another factor of 2x (from SE=4 to SE=8) requires ~7 dB further increase in SNR and power.

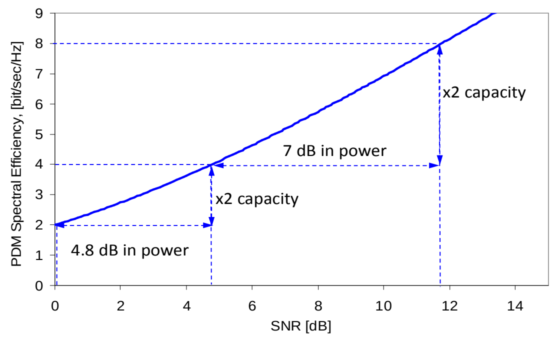

Figure 5: Theoretical spectral efficiency.

Consequently the total power increase of 11.8 dB improves SE from 2 b/s/Hz by only 4 times. Moreover, the optical signal power increase in the fibre will entail the increase in nonlinear penalty.

Alternatively, following the SDM approach, this 11.8 dB total power increase can be divided, for example, between 15 parallel space dimensions (cores, fibres), each carrying the initial SE of 2 b/s/Hz. The total SE in this case would be 30 b/s/Hz as opposed to 8 b/s/Hz single dimension estimation that does not consider nonlinearities.

5. MULTICORE FIBRE EXPERIMENT

The demonstration of high capacity, power efficient SDM transmission has been carried out using multicore fibre (MCF) [10]. In this work, the transmission path is based on 46 km 12-core fibre spool with fan-in and fan out devices. The average loss of all 12 cores with 110 μm^2 effective area that includes fan-in fan out devises is 9.7 dB. The power efficiency is maximized through reduction of the power and nonlinearities in the fibre by using large number of space dimensions (fibre cores) and the use of single-stage EDFAs with ~22 nm bandwidth. The width and the location of the operating bandwidth is optimized for the maximum power efficiency and gain flatness and to avoid using GFFs in each amplifier.

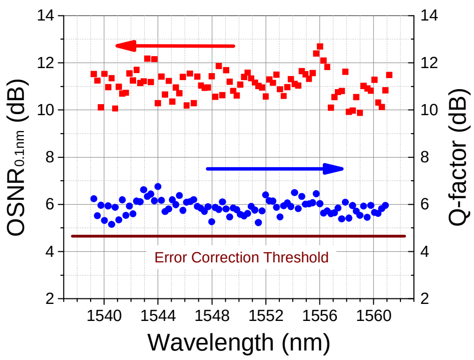

Figure 6: OSNR and Q-factors for the single spatial dimension after 14,350 km.

A total transmission capacity of 105.1 TB/s has been demonstrated using 12-core fibre and power efficient 8D-APSK [8] modulation format. Fig. 6 shows performance measured for 82 channels in a single core. The total pump power used by 12 EDFAs in the transmission loop setup does not exceed the rating of a single pump laser diode with 800 mW rating.

6. CONCLUSION

Ability to deliver electrical power to optical amplifiers is a limiting factor in long-haul undersea optical cables. This limitation requires efficient ways of using optical power. Space Division Multiplexing in conjunction with optimization of the modulation schemes, repeater spacing and amplifier design is shown as a promising direction.

7. REFERENCES

[1] T. Frish, S. Desbruslais ‘Electrical Power, A Potential Limit To Cable Capacity’, ‘SubOptic2013’.

[2] M. Mazurczyk et al., ‘30 Tb/s transmission over 6,630 km using 16QAM signals at 6.1 bits/s/Hz spectral efficiency,’ ECOC, Th.3.C.2. Amsterdam, 2012.

[3] D. G. Foursa, et al., ‘44.1 Tb/s transmission over 9,100 km using coded modulation based on 16QAM signals at 4.9 bits/s/Hz spectral efficiency,’ ECOC, PD3E1, London, 2013.

[4] J.–X. Cai et al., ‘Transmission over 9,100 km with a Capacity of 49.3 Tb/s Using Variable Spectral Efficiency 16QAM Based Coded Modulation,’ OFC, Th5B.4, Los Angeles, CA, 2014.

[5] H. Zhang, et al., ‘200 Gb/s and Dual Wavelength 400 Gb/s Transmission over Transpacific Distance at 6.0 bits/s/Hz Spectral Efficiency,’ OFC, PDP5A.6, Anaheim, CA 2013.

[6] D. Qian, et al., ‘30Tb/s C-and L-bands Bidirectional Transmission over 10,181 km with 121 km Span Length,’ Optics Express, vol. 21, no. 12, pp. 14244-14250, 2013.

[7] S. Zhang, et al., '40×117.6 Gb/s PDM-16QAM OFDM Transmission over 10,181 km with Soft-Decision LDPC Coding and Nonlinearity Compensation,' OFC, PDP5C.4, Los Angeles, CA 2012.
[8] H. Zhang et al., 'Power-Efficient 100 Gb/s Transmission over Transoceanic Distance Using 8-Dimensional Coded Modulation', ECOC, Th.2.2.1, Valencia (Spain) 2015.
[9] H. Zhang et al., 'Power-Efficient 100 Gb/s Transmission over Transoceanic System', accepted for publication in Journal of Lightwave Technology, 2015.
[10] A. Turukhin et al., '105.1 Tb/s Power-Efficient Transmission over 14,350 km using a 12-Core Fiber', to be published OFC, Th4C.1, Anaheim, (CA) 2016.

