On the Road to 1-Pbps systems: Experimental Demonstration of an Energy Efficient 500-Tbps Transatlantic Cable with 200-µm Outer Diameter Fibers

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Abstract: We experimentally emulate an energy efficient 500-Tbps subsea cable with 24 fiber pairs of 200-µm outer diameter Pure Silica Core Fiber and then we draw projections to assess how to achieve a 1-Pbps submarine cable for distances from 3000 to 12000 km.

1. Introduction

In the past, the subsea community has done a huge effort developing new technologies such as pump farming that allowed optical amplifiers to share electrical pumps maximizing the energy efficiency of repeaters [1]. These techniques have permitted to significantly increase the number of fibers inside a submarine cable following a Spatial Division Multiplexing (SDM) paradigm. High-capacity repeated submarine cables are now designed using up to 16-24 fiber pairs (FP) [2]. The effort has clearly paid off and transatlantic submarine cables carry now ~80 times more capacity than 20 years ago [3]. Indeed, more recently field trials done in transatlantic submarine cables approach net throughputs around 300 Tbps [4]. However, the continuous increase in traffic demand will push these systems to go up and up in terms of delivered capacity and the 1-Pbps cable is the next step.

In order to achieve the 1-Pbps cable, new fiber types have been introduced in the submarine designs with only 200-µm outer diameter, instead of the conventional 250-µm. With this reduced coating size, the potential fiber pair count of submarine cables can be increased around 50% without impacting the cable size. But the solution to reach the 1-Pbps cable is not as straightforward as keeping going with the increase of fiber pair count because it would lead us to new unexplored limits. For instance, reducing even more the fiber size would compromise fiber mechanical reliability or cause an important increase of microbending losses as studied in [5]. Another solution to exploit the SDM paradigm consists in the use of Multicore Fibers (MCF). The idea behind this technology consists in pushing to the limit the number of cores deployed in a submarine cable, and 2 uncoupled core MCF or 4 coupled core MCF have already been proposed for submarine cables. On the other hand, the number of optical amplifiers in a submarine repeater has been multiplied by 4 in this period [3-4] and it will forcibly lead us to experience power constraints, specifically for long-haul systems that must be considered for capacity predictions.

In this paper, the 200-µm outer diameter PSCF is experimentally tested at 6279 km using probabilistically shaped (PS) modulation formats to approach the Shannon limit and maximize the total Achievable Information Rate (AIR). A transmission of ~650 Tbps with 24 FP is assessed at the Nonlinear Threshold (NLT) of the fiber and then, the total output power (TOP) per fiber is reduced below the NLT to 12.5 dBm targeting a net throughput of 500 Tbps. This last configuration is x2.5 more energy efficient than previous one. Then, this experiment is used to validate the model presented in [6]. In the last part, we use this prediction model to study how a 1-Pbps cable can be achieved covering all the ranges going from regional systems around 3000 km to transpacific distances up to 12000 km.

2. Experimental demonstration of an energy efficient 500-Tbps transatlantic cable and model validation

The transmission setup is depicted in Fig.1a). At the transmitter side three modulated channels are combined with ASE noise occupying a total bandwidth of 38 nm. Channels are modulated with 74 GBd Dual Polarization PS-16QAM spaced by 75 GHz. The entropy selected to this experiment is 3.8 bps which is the value that reduces the gap to Shannon around the G-SNR values estimated for this experiment. An 897 km recirculating loop has been used to obtain a transmission of 6279 km (7 loops) composed of 15 spans of ~60 km of 200-µm outer diameter Pure Silica Core Fiber (PSCF) with an attenuation of 0.15 dB/km, 21 ps/nm·km of chromatic dispersion and an effective area of 112 µm^2 at 1550 nm. Total capacity is calculated after FEC and extrapolated emulating a 24-FP cable. FEC code rate is adapted to maximize the transmission throughput. We started the transmission with a TOP of 17.3 dBm which is the estimated NLT of the system. Then different transmissions have been replicated at lower TOP to increase the energy efficiency of the 24 FP system targeting 500 Tbps. Fig.1b) shows in orange dots the capacity obtained for different TOP values. Fig.1c) shows the power efficiency (PE) per fiber pair obtained by dividing the total capacity per FP by the corresponding TOP in mW. 12.5 dBm is the lowest TOP that ensures a 500 Tbps transmission corresponding to a PE of 1.21 Tbps/mW, whereas the PE at NLT was around 0.49 Tbps/mW. PE has been improved by 2.5x when descending the TOP to 12.5 dBm. If optical pump power is considered, taking the definition of PE in [7], this value has been doubled from 0.20 Tbps/W to 0.40 Tbps/W. Besides in Fig.1b-c), predicted values by the model presented in [6] are shown in blue. We observe a good match which permits to validate this model for future capacity predictions.

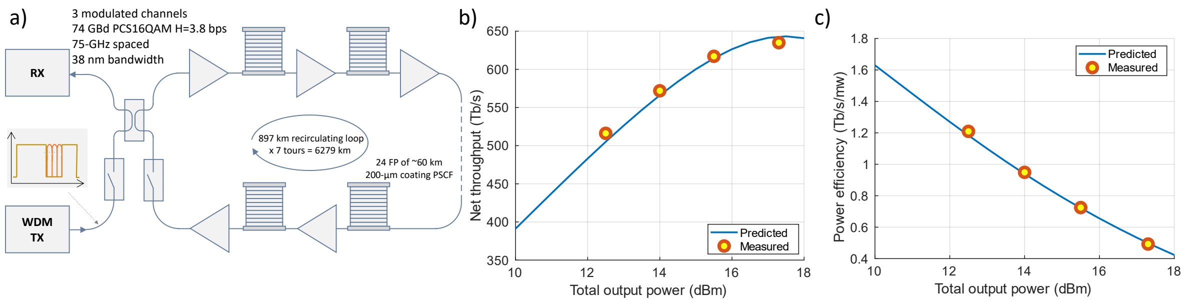

Fig. 1. Experimental setup in a), predicted and measured Achievable Information Rate in b) and predicted and measured power efficiency in c) both at 6279 km as a function of the total output power

3. Capacity predictions: defining the road to the 1-Pbps submarine cable

In this section we use the aforementioned model to imagine new scenarios at different submarine distances. Fig.2 shows the total AIR that can be obtained for different number FP as a function of the TOP at four different distances from 3000 up to 12000 km, which covers almost all possible scenarios for repeated submarine systems. In Fig.2, we highlighted the case with 24 FP that is the limit for current submarine cables with 200-µm outer diameter fibers.

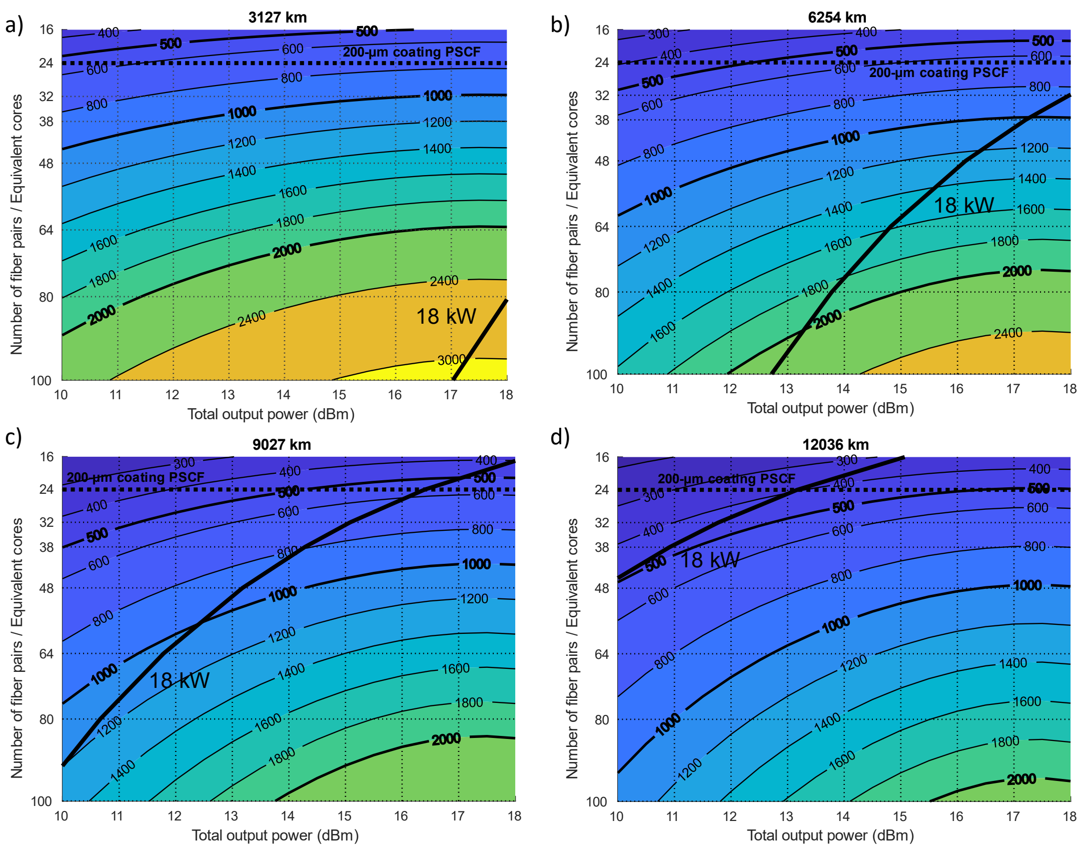

Fig. 2. Predicted Achievable Information and power limitation for a Power Feed Equipment that delivers 18 kW (with 1 Ω/km and 1A) for a) 3127 km, b) 6254 km, c) 9027 km and d) 12036 km

Fig. 2 also shows the predicted maximum TOP at which we can operate the system for a PFE of 18 kW considering a cable resistivity of 1 Ω/km and a line current of 1A. All the values that fall at the right side of this curve cannot be reached because of power limitations. These curves are extremely useful to imagine how future 500 Tbps and 1 Pbps systems may resemble. In Fig. 3, the required number of fiber pairs is represented as a function of the power delivered by the PFE (still assuming 1 Ω/km resistivity) for two different AIR targets i.e., 500 Tbps in a) and 1 Pbps in b). We observe that specifically for long distances, where the system suffers more from power constraints, upgrading the technology of PFE can significantly relieve the required number of FPs to target a certain AIR.

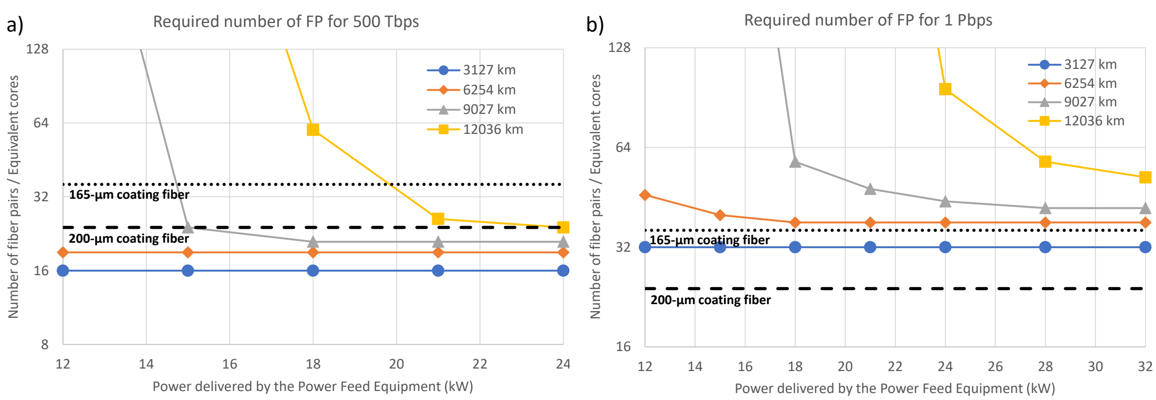

Fig. 3. Required number of fiber pairs for 500 Tbps in a) and 1 Pbps in b) at 3127, 6254, 9027 and 12036 km

4. Discussion

We observe that at least 38 FP (or equivalent cores) are required to obtain the 1-Pbps transatlantic cable. There are several technologies to make it possible. One of them consists for instance in using multicore fibers. With this technology, the number of equivalent cores will be potentially increased up to 48 if the 2 uncoupled core MCF is used. An increase of similar order of magnitude could be achieved if the L band is included in transmission. On the other hand, reducing still more the fiber size would permit to increase the fiber count in the cable. In [4], the adoption of a 165-µm fiber is studied. With this fiber type, 36 FP would be imaginable without the need of increase the cable size. This scenario would approach significantly to the 1-Pbps cable for transatlantic distances. However, reaching the 1-Pbps following this path seems extremely difficult because of technical challenges to be faced in the fiber development. On the other hand, power limitations will occur if we try to go beyond 1 Pbps. Eventually, an increase in the cable size will also permit increase the number of fiber pairs to ~38 without the need of reducing the fiber size. 1-Pbps cable scenarios for 9000 and 12000 km still seem very far away because both they are very power constrained and require at least 50 FP.

5. Conclusion

In this paper an energy efficient 500-Tbps transatlantic submarine cable has been experimentally emulated with 24 fiber pairs of 200-µm outer diameter PSCF (110 μm^2 of effective area). Total output power has been optimized to maximize the power efficiency at this given target capacity. It has permitted to double the energy efficiency with respect to the one obtained at the nonlinear threshold of the fiber. Then this result is projected to see how 500 Tbps and 1 Pbps can achieved for different distances from 3000 up to 12000 km. For transatlantic distances, we observed that at least 38 FP (or equivalent cores) are required to obtain the 1-Pbps cable and then we discuss how this value can be achieved by using technologies such as multicore, C+L, reducing fiber coating size or increasing the cable size.

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