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TO THE BEACH AND BEYOND
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PUMP FARMING AS ENABLING FACTOR TO INCREASE SUBSEA CABLE CAPACITY

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Abstract: Long distance submarine transmission systems face the challenge of accommodating exponential traffic growth while maintaining simplicity and cost efficiency. Current cable designs are contemplating 200-300 Tb/s cable capacity with the most popular routes already pushing for 1 Pb/s cable capacity in the near future.

The traditional approach of maximizing the capacity per fiber by increasing the repeater's total output power (beyond 20dBm) and by using larger and larger effective area (150µm²) fibers is limited by the electrical power availability (current Power Feed Equipment (PFE) can deliver power around ~18kW) and may not be economically sustainable. Instead, to cope with future traffic trends and to prepare this fundamental infrastructure for the challenges of the coming years, a disrupting paradigm called SDM1 - the first step of Space Division Multiplexing (SDM) - is proposed. The SDM1 concept is focused on total cable capacity rather than fiber capacity. Therefore, the number of Fiber Pairs (FPs) becomes a parameter and can be optimized. This concept is a promising solution to approach the Shannon limit (maximum transmission efficiency, increased capacity) while optimizing the total cost.

In this paper, various SDM1 designs for different target performances (OSNR, GOSNR, Capacity) and different fiber types will be studied to find the right cable design for the target cable performance at different cable lengths, including trans-Atlantic and trans-Pacific.

One result of the optimization is the introduction of the "pump farming" concept. It consists of sharing the X repeater pumps (X>2) other Y FPs (Y>1) while, in current repeater scheme, pumps are dedicated to one single FP. This can improve the cable reliability, bringing increased cable capacity and improve overall resource efficiency.

1. INTRODUCTION

Surprisingly, 2018 has been the Space Division Multiplexing (SDM) year for submarine cable. One will tell you that SDM is quite simple: you just need to use the "MORE" philosophy where more Fibre Pairs (FPs) will automatically mean more capacity. This approach is quite logical after 5 years of the "MORE" philosophy applied to repeaters (Total Optical Power beyond 20 dBm) and fibre (effective area of 110 then 130 and finally 150µm²). Nevertheless, a key parameter is usually forgotten when using this approach: the available power (usually 18kW). Indeed, it should be shared among the FPs. Consequently, the SDM solution using non-premium products allows us to increase the capacity and reduce the cost per bit.

In this paper, we will first introduce the optical and electrical formulas showing that the PFE and Optical Signal to Noise Ratio (OSNR) are strongly linked. In the second paragraph, we will study the optical and electrical products needed to reach an OSNR of 17dB/0,1nm for 120 channels and 8-12-16 FPs and we will also vary the distances from 6 000 km to 9 000 km and 12 000 km.

The impact of the effective area of the fibre will be considered.

Finally, a 9 000 km SDM use case will be presented where we will compare 8FP with 150µm² vs 10FPs with 110µm² and 12FPs with 80µm² in terms of products needed.

2. OPTICAL AND ELECTRICAL FORMULAS

Studies have already been made to maximize capacity of submarine cable by considering the power limitations [1-5].

The three key parameters to design and deduce the products needed for a submarine cable are: OSNR, GOSNR and the drop voltage split between repeaters and the cable. The classic OSNR formula will be used to calculate it (1). A small modification is applied to take into account the droop effect considering that optical power is shared between signal and noise.

$$\mathrm{OSNR} = P(I) - Gain - NF - N_{dB} + 58 \qquad (1)$$

where:

- P(I) : power per channel which is I (current of the PFE) dependent
- Gain of the repeater
- NF: Noise Figure of the amplifier
- N_{dB}: number of repeaters in dB
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The GOSNR is calculated using the GN model [6,7], taking into account the "signal droop" effect as well as impairments from spontaneous guided acoustic-wave Brillouin scattering (GAWBS) [8] and also fine tuning linked to experimental results.

Finally, the link between optical and electrical will be given by the following formula:

$$V_{PFE}=V_{Cable}+V_{Repeaters} \qquad (2)$$

where:

- V_{PFE} : is the voltage of the PFE (typically 15kV)
- V_{Cable}=R.I.Distance: is the drop voltage induced by the cable. R(ohm/km) is the resistivity per km of the conductor, I(A) the current of the PFE, Distance(km) is the electrical distance of the cable
- $V_{Repeaters}$ = N.$V_{1Repeater}$: is the drop voltage induced by the N repeaters along the cable (drop voltage of BUs and ROADMs can generally be neglected)

The numbers of repeaters will have an impact on the OSNR and GOSNR of the cable and the current I of the PFE as well since it will impact the drop voltage of the cable and the TOP of the repeater.

3. RESULTS FOR A STANDARD DESIGN

In this paragraph, in order to illustrate the behaviour of the optical part (OSNR, GOSNR, TOP needed) and the electrical part (Resistivity needed) a standard design has been studied. Consequently, a high OSNR has been considered (OSNR=17 dB/0,1nm) with a high level of nonlinearities (OSNR-GOSNR=2,5dB) for different distances (6 000, 9 000 and 12 000 km) with 8 FPs. We then varied the level of nonlinearities by increasing the number of repeaters and reducing the TOP needed since for all simulations the OSNR is kept constant.

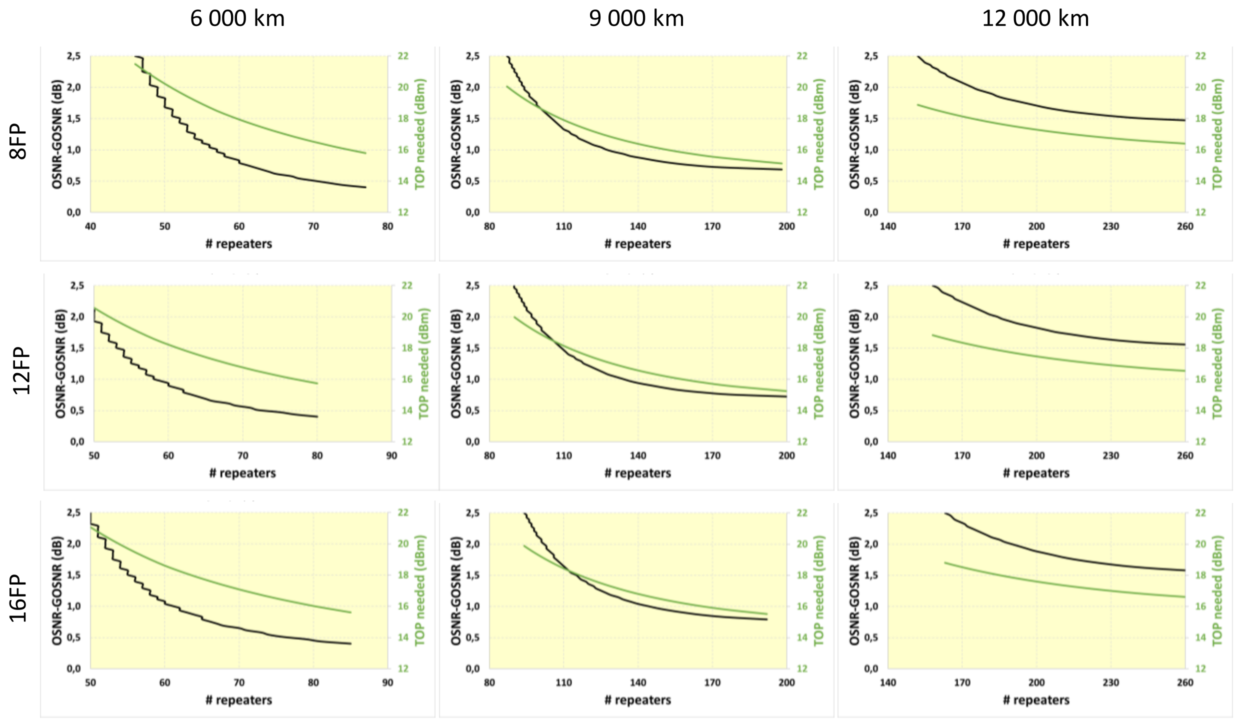

Fig. 1: Evolution of OSNR-GOSNR and TOP needed vs the number of repeaters for a design OSNR of 17dB/0,1nm (120 ch) and 150µm² effective area fiber.

Fig. 1 shows the evolution of the nonlinearities via the OSNR-GOSNR parameter and the associated TOP vs the number of repeaters to reach an OSNR of 17dB/0,1nm. In Fig. 1, as a first step, the same fibre has been used with an effective area of 150µm².

On the optical side, if we consider the distance of 6 000 km (upper left corner of Fig. 1) and 8FPs, we see that by increasing the number of repeaters the OSNR- GOSNR decreases and that the TOP also decreases. When we increase the number of FPs (upper left corner to lower left corner) from 8 to 12FPs and 16FPs using the “MORE” philosophy, the optical behaviour does not change much. A small variation of the parameters can be observed since we considered the increase of the fibre attenuation with the increase of the number of FPs in the cable.

Finally, as we increase the distance, we can observe that the impact on the OSNR-GOSNR of an increase of the number of repeaters is flatter.

In Fig. 2, to complete the optical analysis completed in Fig. 1, we study the evolution of the cable resistivity needed in all cases described on Fig. 1. This brings an electrical-optical analysis and allows us to know which products should be used to reach a target that we can define in term of distance or level of nonlinearities. For all cases, we consider the type of repeater with different level of pumps farming. The blue curves are related to standard repeaters with 4 pumps dedicated to 1FP (4P/1FP), so without farming. Red curves are dedicated to a repeater with a first level of farming where 4 pumps are dedicated to 2FPs (4P/2FP) and finally for the grey curves we push the level of farming one step further and consider a repeater with 4 pumps dedicated to 4FPs (4P/4FP).

If we consider a 6 000 km system with 8FPs, we can find that the solution with the highest resistivity (so lower cost cable) is the one without farming (4P/1FP). When we apply the “MORE” philosophy by increasing the number of FPs, we see competition between 4P/1FP and 4P/2FPs. For 16FPs, the first level of pump farming will be slightly better. But, as soon as we increase the number of repeaters, we see that the cable resistivity

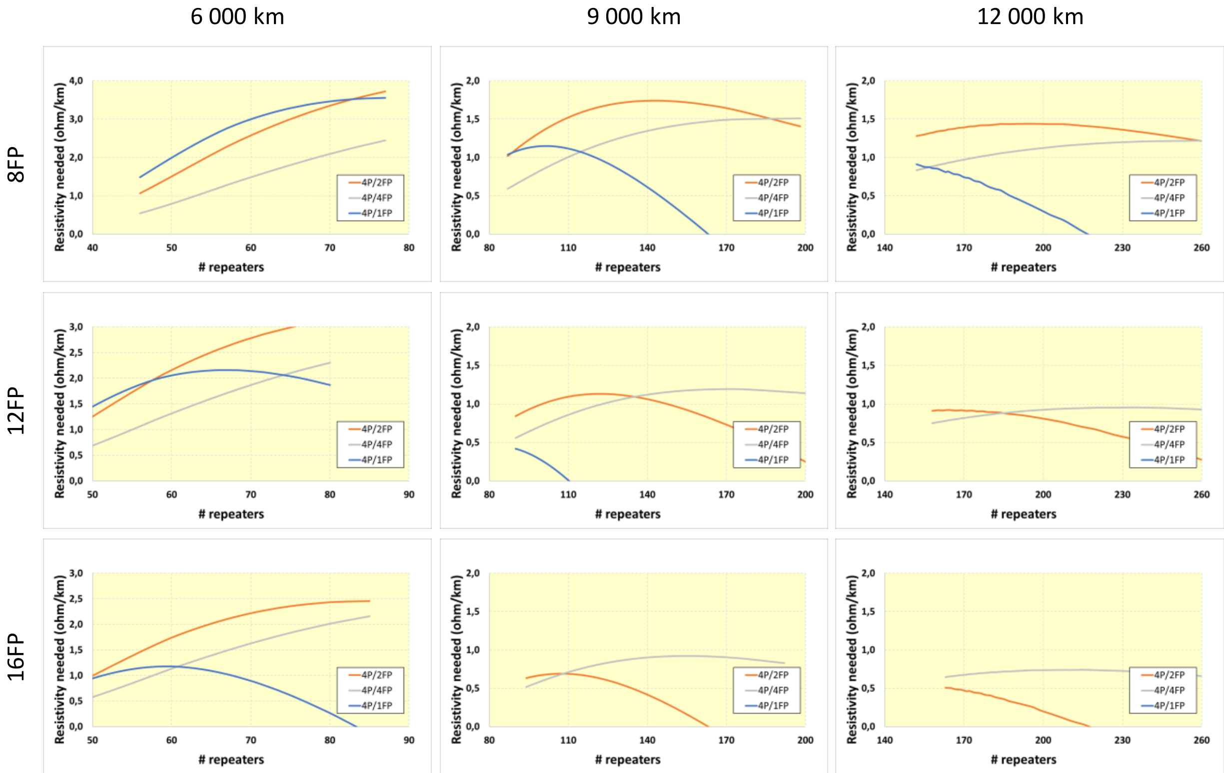

Fig. 2: Evolution of the resistivity needed vs the number of repeaters for different distances, various number of FPs and 150µm² fibre.

increases rapidly. For example, for 16 FPs, when we increase the number of repeaters by 30% (50 to 65) we double the cable resistivity needed (1 to 2 ohm/km). This leads to a huge saving on the cable conductor cost.

When we increase the distance from 6 km to 9 and 12 km for 16FPs, we see that farming is mandatory, since we do not have any solution without farming. Instead of farming solutions, we could have also chosen to reduce the number of pumps by going to 2 (equivalent to 4P/2FP) or 1 (equivalent to 4P/4FPs) pump per FPs, but for reliability reasons the farming solution is preferred. Indeed, it is not manageable to have only one pump per FP in case of failure. Finally, we see that for long distances (12 000 km, for example) and 16 FPs, we need a cable resistivity below 1 ohm/km.

A first conclusion is that, no matter the distance, it is mandatory to use pump farming when we increase the number of FPs to increase the capacity while maintaining the electrical power constant and increasing the reliability.

To analyse the impact of the fibre on top of the simulations done in Fig. 2, we considered the 6 000 km distance and simulated the 3 cases already used for the number of FPs (8, 12 and 16FPs). In this work, we consider three fibre types. The first fibre has ultra-low attenuation and very large effective area, the second one has an effective area which is a little bit lower and an attenuation slightly higher. Finally, the last one has an effective area equivalent to terrestrial fibres (80µm²), but with an attenuation that remains in the typical submarine range.

Parameter	**150µm²**	**110µm²**	**80 µm²**
Attenuation (dB/km)	0.151	0.154	0.162
A_{eff} (µm²)	150	110	82
Dispersion (ps/nm/km)	21	20,7	17

Table 1: Fiber parameters.

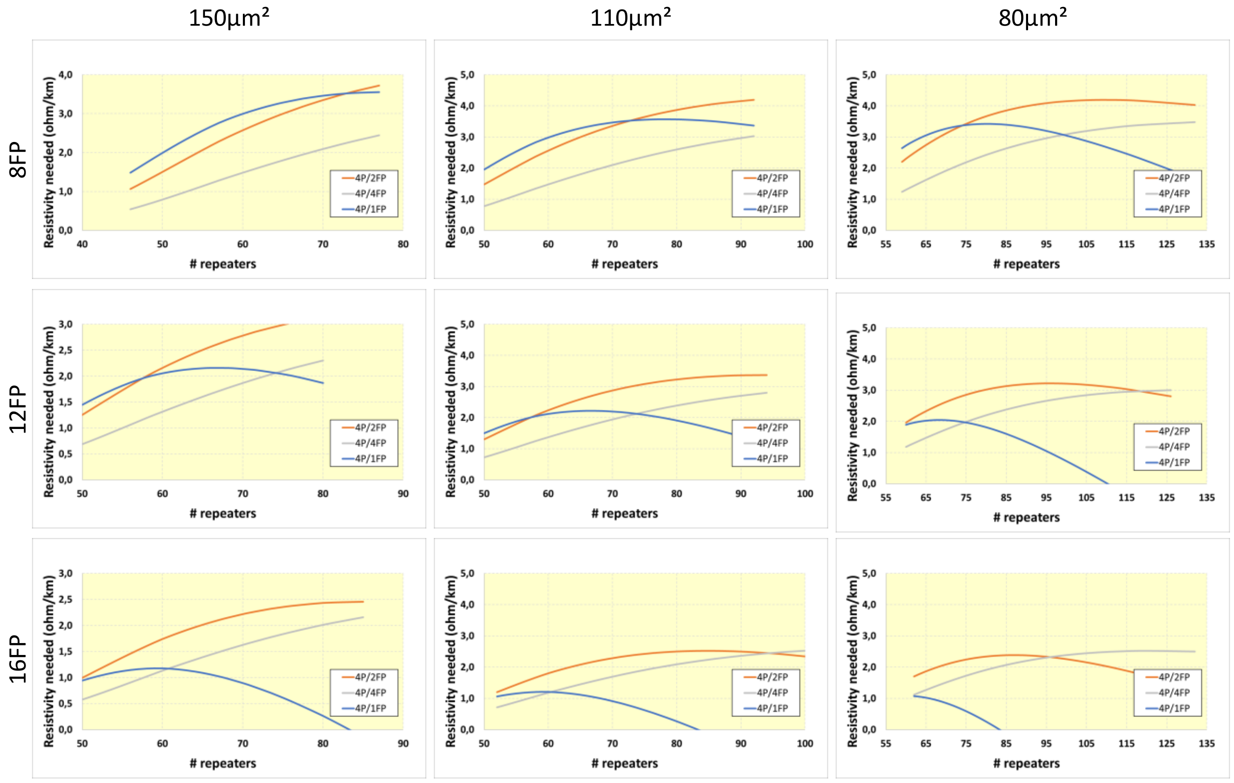

Fig. 3: Evolution of the resistivity needed vs the number of repeaters for different fibers, various number of FPs and 6 000 km.

Fig. 3 summarizes the results obtained while varying the fibres. Obviously, as lower effective area fibre can handle less optical power due to nonlinearities, it reinforces the use of pump farming. Indeed, we see that, most of the time, the red and grey curves need a higher resistivity when pumps farming is used and that the classical repeater scheme with 4P on 1 FP is almost useless.
For 6 000 km and a fix cable resistivity of 3 ohm/km (Fig. 3), it is possible to find a solution with all fibres by slightly varying the number of repeaters (60 for 150µm²/8FP 65 for 80µm²/8FP). For sure, a higher level of NLE can be expected with 80µm², inducing a lower capacity, but probably a lower cost per bit.

By analysing Fig. 2 and Fig. 3 we observe 2 phenomena. The first one is that, as soon as the number of FPs and/or the distance increase, the pump farming is mandatory to find a solution (cable resistivity above 0). As pump farming means lower TOP, we see that solutions can also be found with non-premium fibre.

Therefore, in the final part of the paper let's study the solutions to have ¼ Petabit/s cable using SDM.

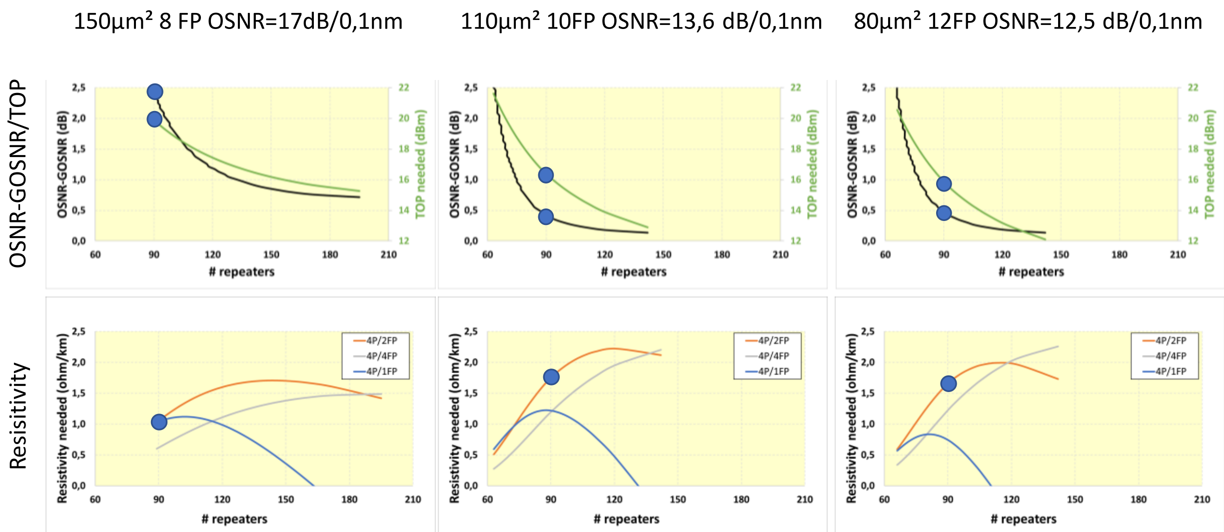

Fig. 4: Evolution of the resistivity needed and OSNR-GOSNR vs the number of repeaters for different fibres, various OSNR and different number of FPs for 9 000km and a Shannon capacity around ¼ Pb/s.

4. SDM RESULTS

In this last part, we study different solutions and the associated products to reach a ¼ Petabits cable.

We compare in Fig. 4 a classical design of 8FP/ 150µm² / OSNR=17dB/0,1nm / OSNR-GOSNR=2,5dB with a design of 110µm²/10FP and 80µm²/12FP.

As a starting point, if we compare the two designs with 150µm² and 110µm² we see (blue dots) that in both cases we can have a solution with 90 repeaters using pump farming (4P/2FPs). So, the repeater cost is the same and the fibre cost is also the same, if we consider that the 110µm² fibre is cheaper by 20% with respect to the 150µm². As long as the 110µm² is more than 20% cheaper we save money on the fibre part. Finally, if we consider the cable electrical resistivity, the 110µm² needs a cable 70% more resistant than the 150µm². Consequently, from an economic point of view, for 9 000 km the solution with 110µm² is more interesting. When we push one step beyond the use of low effective area fibre, we see that with 12FPs/80µm² and 90 repeaters 4P/2FPs we have the same cable resistivity as for the 110µm². So, no saving can be expected on the repeater side. The only saving should come from the 80µm² cost where the cost per km should be minimum 33% lower than the 150µm² at this distance of 9 000 km.

SDM design is a clever association of products (repeaters, conductor, fibre) that should be combined efficiently to find the best design leading to the highest capacity with the lowest cost.

5. CONCLUSIONS

In this paper, we analysed a standard design and then compared it to a SDM one using a ¼ Petabit/s cable case.

For the standard design, we clearly saw that the "more" philosophy applied to the number of FPs is not enough to increase the cable capacity, when the electrical power provided by the PFE is kept constant. For long distance systems, classical repeater without pumps farming has no solution. Therefore, the introduction of pump farming is mandatory to continue to increase the capacity.

To diversify the solutions, alternatives to standard design have been proposed that were named SDM (ASN solution is branded "SDM1 by ASN"). These solutions, for the same Shannon cable capacity, showed that cost savings can be made on the resistivity of the conductor and the fibre itself by using lower effective area fibres.

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