THE CHALLENGE OF VERY HIGH CABLE CAPACITY: PDM-8QAM, THE BOOSTER FOR TRANS-ATLANTIC DISTANCE AND OSNR$_{WET}$, THE PARAMETER TO EVALUATE CABLE CAPABILITIES

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Abstract: In this paper we review the parameters which allow the capacity of a cable to be increased. Advanced coherent modulation formats bring higher capacity per channel but require a high OSNR. As there are many ways to obtain this high OSNR in the cable, how can one solution be differentiated from another? An OSNR$_{WET}$ parameter is proposed to help in this technical decision. A case study of a 6 600 km link is used to illustrate the capacity dilemma both experimentally and by simulations.

1. INTRODUCTION

The constant need to increase the capacity of submarine networks can be satisfied with the use of coherent transponder technology combined with a suitable cable design. On one hand, the transponders bring more complex coherent modulation formats (from BPSK to 16 QAM via 8QAM and the standard QPSK) allowing a higher capacity per channel. On the other hand, the cable has a number of fibre pairs that can be increased up to certain limits while housing fibres with a huge effective area and very low losses. Additionally the trend in the last generations of well known EDFA is for larger usable bandwidth and increased output power in repeaters, also contributing to quest for increased capacity.

In order to evaluate the performance of such cable, the OSNR$_{ASE}$ will be the first parameter we will think about. In this paper we will propose a new parameter called OSNR$_{WET}$ in order to better characterize the cable performance and its upgradability.

2. MAXIMUM CAPACITY

The dilemma facing submarine transmission is how to maximize capacity on a fixed distance across the oceans. Currently 3 parameters are used to calculate the cable capacity.

The first is the number of fibre pairs (FP) that a cable can manage. We can currently find contracted cables with 6 to 8 FP.

The second parameter is the bandwidth of the amplifiers. The usable bandwidth in the C-band has been extended from 32nm to 36nm. Even 40nm on long distances is considered in the near future. Further increases will lead to C+L band solutions that may reach up to 70nm.

The third parameter is linked to the transponder itself, the modulation formats and the channel spacing that will be used. In the past the fourth parameter would have been the FEC because it was de-correlated from the modulation formats but nowadays the trend is to correlate modulation formats and FEC. As a consequence, it is often linked to the advanced modulation formats.

To summarize this paragraph with a formula, we can write:

Cable Capacity= #FP x OB x SE (1)

where

FP: Fibre pairs

OB: Optical Bandwidth (GHz)

SE: Spectral Efficiency (Gb/s/GHz)

The spectral efficiency in Gb/s/GHz is directly linked to the modulation formats, the FEC and the channel spacing.
In the following section we focus on the modulation formats and how to increase the capacity for a fixed distance.

3. MODULATION FORMATS

All recently laid cables and those cables to be laid in the foreseeable future use one single optical fibre type compared to previous generation cables which used two (or even three) types and an optimised dispersion map (+D/-D or NZDSF: Non-Zero Dispersion Shifted Fibre). This single fibre type is a very high chromatic dispersion fibre (>20ps/nm.km, called +D or coherent fibre) with effective areas beyond 110µm². Using one single fibre type is possible thanks to the introduction of smart coherent transponders. Indeed these coherent transponders provide the capability to fully compensate the linear phenomenon of chromatic dispersion beyond 300ns/nm. In addition to this, they can generate many complex coherent modulation formats with constellations which have only 2 symbols (for BPSK: Binary Phase Shift Keying) up to 16 symbols (for 16 QAM: Quaternary Amplitude Modulation).

Finally it is also possible to generate 2 signals on orthogonal polarisations and to use PDM (Polarisation Division Multiplexing) to multiply the spectral efficiency by a factor of 2. Knowing the channel spacing, it is possible to calculate the spectral efficiency for coherent modulation formats this way:
SE = PDM x # bits/symbol x BaudRate / Channel Spacing (2)

where

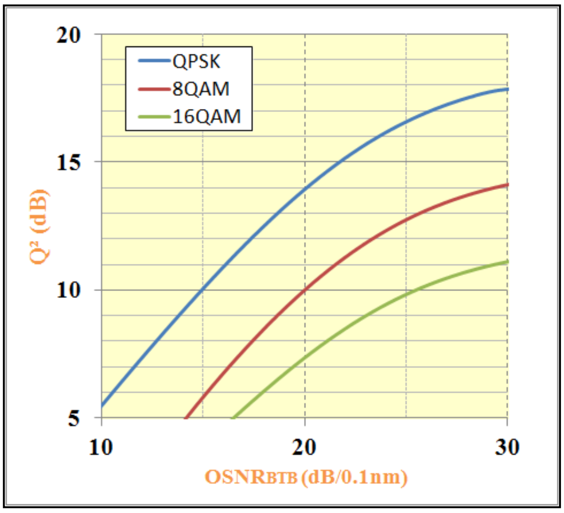
PDM = 2, knowing that 2 polarizations exist

 # bits per symbol could be 2, 3 or 4

BaudRate in GBd lying in between 30 and 40GBd

Channel Spacing is between 33 and 50GHz

The submarine market selected mainly PDM-QPSK (Quaternary Phase Shift Keying), PDM-8QAM and PDM-16QAM for the most recent cables laid and also for those to be laid soon considering the distance to cross the oceans which is typically around 3 000km, 6 500km or around 15 000km. Indeed the selection of the modulation formats is a trade-off between reach and capacity. As we have seen, capacity is increased by using the modulation format transporting a higher number of bits per symbol at a given baudrate. The reach is directly linked to the OSNR (Optical Signal to Noise Ratio) which we characterize in back-to-back and call it $OSNR_{BTB}$. As a consequence a very simple way to differentiate formats is to plot the Q^2 (Quality) factor versus the $OSNR_{BTB}$. In Graph 1, the Q^2 vs $OSNR_{BTB}$ curves are plotted for the three modulation formats with 2 (QPSK), 3 (8QAM) and 4 (16QAM) bits per symbol respectively. Theoretical transponders are considered with a 31 GBd baudrate (25GBd of data and 25% of FEC). A Q^2 floor has been considered in the three cases in order to make the transponders more real.



Graph 1: Q^2 vs $OSNR_{BTB}$ for QPSK, 8QAM and 16QAM

Regardless of the $OSNR_{BTB}$, the best Q^2 can be obtained with QPSK then 8QAM and finally 16QAM. Usually these are compared using a delta in OSNR for a targeted Q^2 value. In Table 1, the results of such a comparison is given for a Q^2= 7dB.

Modulation Format	Capacity per wavelength (Gb/s)	Delta OSNR (dB)
QPSK	100	Reference
8QAM	150	-4.7 dB
16QAM	200	-7.9 dB

Table 1: Comparison of coherent modulation formats

$OSNR_{BTB}$ is very useful to characterize the transponders in back to back and we see that the higher the OSNR the higher the number of bits per symbol we can have at a given baudrate and so the higher the capacity.

However in submarine systems, signals are transmitted across oceans via amplified lines so $OSNR_{BTB}$ is no longer the key parameter but should be replaced by the $OSNR_{ASE}$ (related to noise from the amplifiers spread along the line). $OSNR_{BTB}$ and $OSNR_{ASE}$ have exactly the same impact on the Q^2 factor, they just have a different naming due to the way noise is generated. In the next section, we will see how to link $OSNR_{ASE}$ to a fixed distance.

4. $OSNR_{ASE}$ vs. # SPANS AND OP

$OSNR_{ASE}$ is a relevant parameter to characterize the submarine cable if nonlinearity does not come into play. Indeed it is a parameter that can be easily calculated (see (3) below) with accuracy precision and it also has the advantage that it can be measured and written as a commissioning parameter within a contract.

$$OSNR_{ASE} = OP - SL \quad NbRep - NF + 58 \quad (3)$$

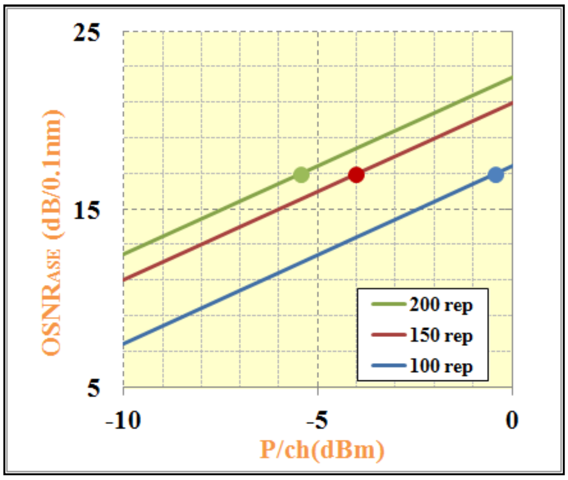
where

OP is the average output power per channel of an amplifier in dBm

SL is the span losses in dB

NbRep is the number of repeaters in dB

NF is the Noise Figure of the amplifier in dB



Graph 2: $OSNR_{ASE}$ vs. P/ch for 3 cases

In Graph 2, the variation of the $OSNR_{ASE}$ for a 10 000km submarine link is plotted for different numbers of repeaters (100, 150 and 200) versus the power per channel. It can be seen that for the same $OSNR_{ASE}$ many solutions can be found. As an example dots are shown on each curve with an OSNRASE=17dB/0.1nm. One solution could be to use a high number of repeaters (green curve: 200 repeaters) combined with a low power per channel (~-5.5dBm) while another one could be to select a low number of repeaters (blue curve: 100 repeaters) and in this case to go for a higher power per channel (-0.5dBm). By considering only the OSNRASE, technically speaking there is no differentiator for selection of one solution with respect to another one.

Let's now introduce a new parameter that will help us decide between the different solutions available. We call it OSNRWET.

5. OSNRWET

Once the number of repeaters is fixed we would like to increase the power per channel to have a higher OSNRASE. Nevertheless in this case we will have to face the effects of nonlinearities that will occur in the fibre and the degradation of the performance linked to them. This is demonstrated in the simulations below based on a fibre with an effective area of 150µm².

Poggiolini [1] and Bononi [2] showed that these nonlinear effects can be considered as an AWGN (Additive White Gaussian Noise).As a consequence, in order to take into account both noise sources (OSNRASE coming from amplifiers and OSNRNLE from nonlinear effects) we propose a parameter called OSNRWET that will allow the performance of the line to be evaluated considering all degradations.

$$\frac{1}{OSNR_{WET}} = \frac{1}{OSNR_{ASE}} + \frac{1}{OSNR_{NLE}} \quad (4)$$

where:

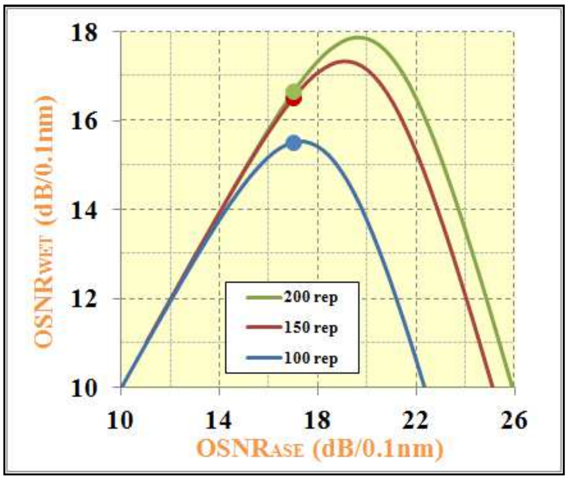
$$\frac{1}{OSNRNLE} = NbRepLin.K.OPlin^2 \quad (5)$$

where

K: constant linked to the configuration

NbRepLin is the number of repeaters in linear

OPlin is the average output power per channel of an amplifier in linear



Graph 3: OSNRWET vs. OSNRASE for 3 cases

In Graph 3, OSNRWET vs. OSNRASE is plotted for a 10 000 km submarine link (fixed distance) for the 3 cases considered previously. It can be seen that OSNRWET varies as a bell curve where nonlinearities are low on the left side so OSNRWET=OSNRASE, while on the right side nonlinearities are strong leading to a sharp reduction of OSNRWET, with an optimum area in the centre. However, regardless of the value of OSNRASE , the higher the number of repeaters the higher the value of OSNRWET. While previously, considering OSNRASE, there were no technical differentiators to select a solution, but with the OSNRWET parameter, a solution with a higher number of repeaters would be preferred.

The dots plotted on Graph 3 indicate an OSNRASE of 17dB/0.1nm (same value taken previously on Graph 2). Considering the curve with 100 repeaters, a gain of +1dB OSNRWET can be obtained with 150 repeaters and +1.2 dB with 200 repeaters. If we now compare the maximum OSNRWET for each solution, the case with 200 repeaters will outperform the one with

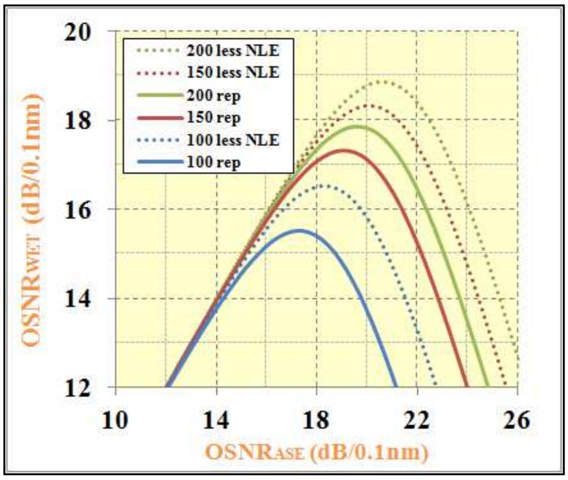
150 repeaters by 0.5dB and the case with 100 repeaters by 2.3dB. Looking at the increase in repeaters the intuitive trade-off could be the 150 repeaters solution. Indeed by increasing the number of repeaters by 50 (from 100 to 150) an increase of 1.8dB in $OSNR_{WET}$ would be obtained, while a smaller increase of 0.5dB in $OSNR_{WET}$ would be obtained by a further increase of 50 repeaters (from 150 to 200).
Graph 3 has been plotted for a 150µm² effective area fibre and a channel spacing of 40GHz. Different scenarios could be investigated for example, reducing the channel spacing to 36.36GHz (increase of the SE by 10%), or reducing the nonlinearities by using compensating techniques, but in all cases the difference between the solutions will be of the same order of magnitude. Graph 4 compares the results of Graph 3 with the results obtained by considering a reduction of the nonlinear effects by a factor of 2.
We still find the same differences as seen as previously: +1dB for 150 vs. 100 repeaters and +1.2dB for 200 vs. 100 repeaters. So even by considering a reduction of nonlinear effects by a factor 2, the case of 100 repeaters case still has an $OSNR_{WET}$ which is below the optimum of the 150 repeater case.
The differences found on the $OSNR_{WET}$ parameter are the same that could be found on the Q^2 factor (see 7 below).
Indeed

$$Q^2 = M.OSNR_{WET} \quad (6)$$

where M is a constant

Deriving the above formula, we obtain:

$$dQ^2\,(dB) = dOSNR_{WET}(dB) \quad (7)$$



Graph 4: Impact of the reduction of nonlinearities by a factor of 2

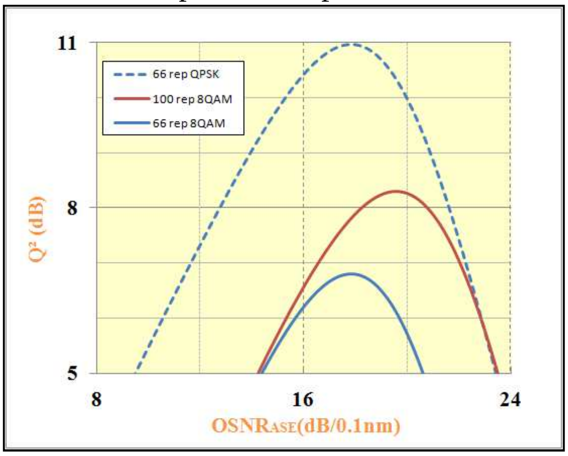
In the previous paragraphs we studied the Q^2 versus $OSNR_{BTB}$, and then considered $OSNR_{ASE}$ and $OSNR_{WET}$. Let's now combine the results coming from the WET part and the DRY part meaning the transponder.

6. OSNRWET, MODULATION FORMATS AND EXPERIMENT

Considering the objective of achieving the maximum capacity on a transatlantic distance (6,600km), how can $OSNR_{WET}$ and the modulation formats we studied help us select a solution?

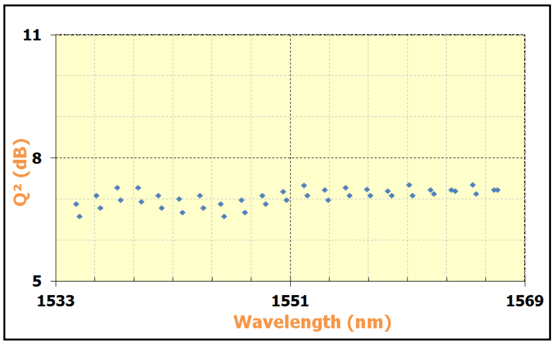
We've seen previously that we have a difference of roughly 4.7dB OSNR difference in back-to-back between PDM-QPSK and PDM-8QAM (Table 1) and that the higher the number of repeaters the better for the $OSNR_{WET}$. Let's now combine these two pieces of information on a single graph.

On Graph 5, a distance of 6,600km is considered. Curves are plotted for Q^2 factor versus $OSNR_{ASE}$ (which can, be measured) for 66 repeaters (plain blue curve and dotted blue curve) and 100 repeaters (plain red curve). For 66 repeaters, PDM-QPSK has a Q² factor 4.2dB higher than PDM-8-QAM which is roughly the value found with $OSNR_{BTB}$. However the absolute Q² factor value of PDM-8QAM is very close to the FEC limit and would not give enough margins. Thus it would be mandatory to switch to QPSK and lose 33% of capacity. If we now consider the Q² factor value of the PDM-8QAM curve (plain red curve) with 100 repeaters, we can see that the PDM-8QAM result is better by 1.5dB with respect to the other PDM-8QAM with 66 repeaters, roughly the value found on the $OSNR_{WET}$ when we compared the optimum.



Graph 5: Q² factor vs. $OSNR_{ASE}$ for 66 repeaters (PDM-QPSK, PDM-8QAM) and 100 repeaters (PDM-8QAM)

To consolidate, the trend given by the simulation, an 18.6 Tb/s capacity record experiment has been performed on 6,600km 100% coherent submarine fibre using PDM-8QAM and a channel spacing of 33GHz with a Q² factor of 7dB. This Q² factor is better than the theoretical one simulated for 66 repeaters.



Graph 6: PDM-8QAM Q² factor for 6 600 km and 33GHz channel spacing

As a consequence, it is easier to increase the capacity on a cable with a higher number of repeaters.

The higher the $OSNR_{WET}$ the better the cable will be. In other words we can conclude that by the sole use of $OSNR_{WET}$ it is possible to evaluate the performance of the WET part of the system.

7. 10,000 km PDM-8QAM record experiment

We also report a trial on a straight line test bed to evaluate a real time PDM-8QAM performance over 10,000 km. The lab experiment is composed of 10,000km second-generation coherent submarine fibre (CSF 2) with spans of 9.3dB. An average Q² factor of 6.5dB was measured. The result is better than the quasi theoretical 31GBd transponder which has a Q² factor found for 100 repeaters.

8. CONCLUSION

In this paper, the different ways to enhance the capacity of a cable have been reviewed. Besides adding FP and/or extending the optical bandwidth of amplifiers, one way is to use advanced modulation formats with a higher number of bits per symbol. But the higher the number of bits per symbol the higher the required $OSNR_{ASE}$. To reach this $OSNR_{ASE}$, we have seen that many ways can be used: low number of repeaters combined with high output power or high number of repeaters and low output power.

In order to differentiate the solutions, nonlinearities should be considered leading to the definition of a new parameter that should be defined: $OSNR_{WET}$. It seems to be a relevant parameter to characterize the cable capability to provide its best without considering the transponders. We compared for a distance of 6 600km two solutions and showed via simulations, which have been confirmed by an experiment, that PDM-8QAM is the best modulation format to provide the highest capacity at this distance.

We concluded the paper with a breakthrough record of data transmission over a distance of 10,000 km using real time processing PDM-8QAM giving a hint on the capacity of cables in the near future.

9. REFERENCES

[1] P. Poggiolini, A simple and effective closed-form GN model correction formula accounting for signal non-Gaussian distribution, Journal of Lightwave Technology, Vol. 33, issue 2, pp459-473

[2] A. Bononi, Modeling nonlinearity in coherent transmissions with dominant intrachannel-four-wave-mixing, Optics Express, Vol. 20, No. 7 / 26 March 2012

