Design of Submarine "Open" cables

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Abstract: Digital coherent receiver and GN model moved submarine transmission systems into the era of "open cables". This new paradigm leads to consider new parameters to design and characterize open submarine systems independently of the terminal equipment.
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1. Introduction

The evolution of transmitters and receivers during the last 20 years has led to dramatic change in the fiber infrastructure. Dispersion Shifted Fiber (DSF) was used for the first optically repeated systems, and then Non-Zero DSF (NZDSF) was selected to allow WDM transmission. Then a limited number of cables, targeting ultra-long reach and wide optical amplification, took advantage of the benefits of +D/-D systems having almost constant dispersion properties over the whole amplification bandwidth. Digital coherent receiver technology has canceled the need for complex in-line fiber mapping and allowed the use of high chromatic dispersion fiber. The purpose of this paper is to present the main design rules applied to submarine "Open" cables using the new technologies (coherent transponders, +D systems) [1].

2. Key parameters for a Submarine Open cable

a) $OSNR_{ASE}$: the upper bound limit

The $OSNR_{ASE}$ has always been used in submarine as a parameter to be measured on field in addition to the Q² factor. It is also a parameter that appears in the first line of the power budget table from the ITU recommendation [2]. The classical formula used to calculate it is: $OSNR_{ASE} = TOP\text{-}NbCh\text{-}G\text{-}N\text{-}NF\text{+}58$ (TOP: Total Output Power; NbCh: number of channel in dB; G: Gain; N: number of spans in dB; NF: noise figure of the repeaters). We can extend this formula by removing the NbCh parameter since it is linked to the Submarine Line Terminal Equipment and not to the wet part by considering equation Eq. 1. Based on this new parameter we can easily calculate the upper bound limit for the capacity using the well-known Shannon formula Eq. 2.

$$OSNR_{ASE\_TOT}(dB/0.1nm) = TOP - G - N - NF + 58$$

Eq. 1

$$C_{upper\ bound} = 2.B.\log_2\left[1+\frac{Bref}{B}.OSNR_{ASE\_TOT}\right]$$

Eq.2

where B is the total bandwidth of the repeater.

In the frame of "open" cable the $OSNR_{ASE}$ is a design parameter but also a commissioning parameter. The targeted $OSNR_{ASE}$ value can be achieved by combination of repeater count and TOP value. On Figure 1, several combinations are presented for an $OSNR_{ASE\_TOT}$ of 38.8dB/0.1nm (18dB/0.1nm for 120ch). We vary the TOP from 16 to almost 23 dBm and calculate the number of repeaters needed and the corresponding gain for a distance of 13 000 km and a fibre losses of 0.156dB/km.

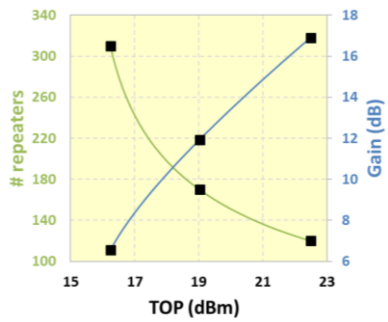

Figure 1: Solutions to reach an $OSNR_{ASE\_TOT}$ of 38.8d/0.1nm for a distance of 13 000 km with 0.156dB/km fibre losses

38.8dB/0.1nm	TOP (dBm)	# rep	Gain (dB)
High TOP	22.5	120	16.9
Medium TOP	19.0	170	11.9
Low TOP	16.2	310	6.5

Table 1: 3 solutions to reach an $OSNR_{TOT}$ of 38.8dB/0.1nm on 13 000km (square on Figure 1)

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Using the $OSNR_{ASE\_TOT}$ only there is no way to differentiate between the 3 solutions selected on Figure 1. A new parameter has been introduced beginning of the 2010's in order to better evaluate the performance.

b) GOSNR: the lower bound limit

The GN model [3] coupled with coherent was a revolution for the submarine design. Indeed, the fact that we can add in a very simple manner the noise coming from ASE (Amplified Spontaneous) and the noise coming nonlinearities (NLE) ease the submarine design (Eq. 3). A new parameter has been created and called GOSNR.

$$\frac{1}{GOSNR} = \frac{1}{OSNR_{ASE}} + \frac{1}{OSNR_{NLE}} \quad \text{Eq. 3} \qquad \text{where: } \frac{1}{OSNR_{NLE}} = N.B_{NL}.P^2 \text{ and } OSNR_{ASE} = \frac{P.K_{58}}{N.G.NF}$$

In order to find the best technical solution using GOSNR, it is possible to calculate the derivative vs TOP (Figure 2) and also the one vs the number of repeaters (Figure 3). The optimum GOSNR is given in Eq. 4 [4] and 5. We can see that the optimum in term of power is not linked to the distance but to the gain of the amplifier and the nonlinear coefficient (B_{NL}) while the optimum in term of gain is a constant value.

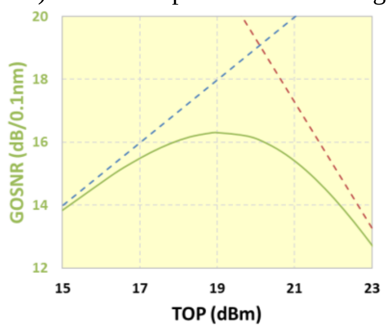

Figure 2: GOSNR vs TOP for 170 repeaters

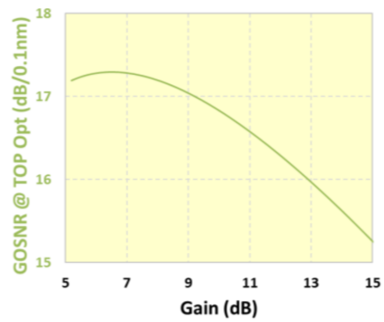

Figure 3: GOSNR vs Gain @ Optimal TOP

$$GOSNR^{OptPower} = \frac{2}{3} OSNR^{Opt}{}_{ASE} \quad \text{Eq. 4}$$

where

$$OSNR^{Opt}{}_{ASE} = \frac{P^{Opt}.K_{58}}{NF.G.N} \text{ and } P^{Opt} = \left[\frac{G.NF}{2.B_{NL}.K_{58}}\right]^{1/3}$$

$$Gain^{Opt} = e^{\frac{3}{2}} \quad \text{Eq. 5}$$

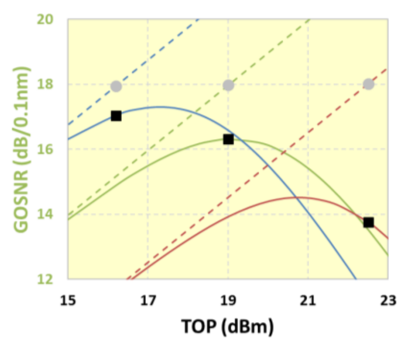

Figure 4: Comparison of High (Red), Medium (Green) and Low TOP (Blue) using GOSNR

If we come back to the 3 possible solutions with High, Medium and Low TOP described in Table 1, it is now possible to differentiate it using the GOSNR. On Figure 4, we can see that all solutions, considering ASE only, have the same performance (grey dots) but when NLE comes into play (black square) the solution with the lower TOP is the best one. If we now consider the number of repeaters as a cost parameter, a reduction of 140 repeaters (-45%) when we go from Low TOP to Medium TOP solution seems to be a good tradeoff since the GOSNR loss is only 0.6dB (2T according to Shannon formula for a 40nm bandwidth repeater). If we go one step further with the cost aspect, the High TOP solution will save 190 repeaters (-62%) with a GOSNR loss of 2.4dB (7.2T loss). We can define a lower bound capacity using Eq. 6.

$$C_{lower\ bound} = 2.B.\log_2\left[1 + \frac{Bref}{B}.GOSNR_{TOT}\right] \quad \text{Eq. 6 where} \quad GOSNR_{TOT} = GOSNR + 10.Log(NbCh)$$

As GOSNR can't be measured by its own as a performance parameter, we will see in the next paragraph how to link it with the Q² factor.

c) From GOSNR to Q² factor:

The addition of noises can also be applied to the whole system and not only to the nonlinear effects. Therefore, we can define a total $OSNR_{TOT}$ for a submarine link as indicated on Figure 5 and in Eq.7. If we consider in the transceiver a terminal based on PDM-QPSK coherent modulation, the Q² factor and the $OSNR_{TOT}$ can be linked using Eq. 8 and Eq. 9 which lead to Eq. 10 [5].

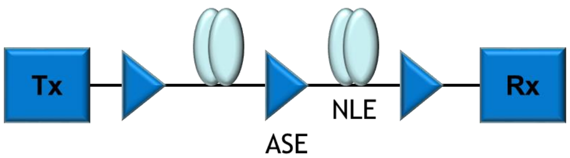

Figure 5: Scheme of a submarine line

$$\frac{1}{OSNR_{TOT}} = \frac{1}{OSNR_{Tx}} + \frac{1}{GOSNR} + \frac{1}{OSNR_{Rx}}$$

Eq. 7: $OSNR_{TOT}$ definition

$$BER = \frac{1}{2} erfc\sqrt{\frac{Q^2}{2}} \quad \text{Eq. 8}$$

$$BER = \frac{1}{2} erfc\sqrt{\eta . \frac{OSNR_{TOT}}{2}} \quad \text{Eq. 9}$$

$$\boxed{Q^2 = \eta . OSNR_{TOT}} \quad \text{Eq. 10}$$

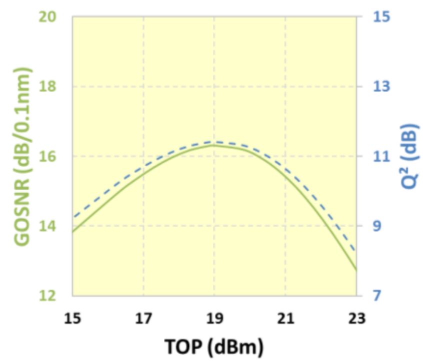

Figure 6: Comparison of GOSNR and Q² factor for PDM-QPSK with eta=-4.2dB and $OSNR_{Tx\_Rx}$=24dB/0.1nm

As GOSNR and Q² factor are really closed (Figure 6), it could be very interesting to extend the ITU recommendation G.977 to an Open Budget Table (OBT) that can be used to commission submarine cable and also to use a $GOSNR_{TOT}$ the same we proposed in Eq. 1 an $OSNR_{ASE\_TOT}$. An example is given in Table 2.

Item	Description	(dB/0.1nm)
A	BOL $OSNR_{ASE}$ at full loading	18.0
Item		Q² (dB)
1	Back-to-back Q² at BOL $OSNR_{ASE}$	12.8
2	Propagation impairments	1.4
3	Other Impairments	1.1
4	Margin for Q² time variations	0.1
5	BOL segment Q²	10.2

Item		$GOSNR_{TOT}$ (dB)
1	BOL $OSNR_{ASE\_TOT}$	38.8
2	Propagation impairments	1.7
3	Other Impairments	1.3
4	Margin for GOSNR time variations	0.1
5	BOL segment GOSNR	35.7

Table 2: ITU G977 Power Budget Table (left) and Open Budget Table (Right) with $GOSNR_{TOT}$

5. Conclusion

In this paper, we first considered the design based on $OSNR_{TOT}$ only. To differentiate the multiple $OSNR_{TOT}$ based solutions, we combined $OSNR_{ASE}$ with GN modelling and then moved to a design based on GOSNR which allows defining optimum TOP and Gain. This optimum in term of repeater count can also be challenged according to economic criteria as shown in the study case: 170 repeaters vs 310 for a 2T capacity loss.
During the conference, we will open the discussion considering design optimization of cable capacity instead of fiber capacity only. In addition, we will present a procedure to measure GOSNR in the field.

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