Q MEASUREMENTS SOMETIMES MISLEADING?

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Abstract: Upgraded submarine cable systems operating at high line-rates often experience significant non-linearity. This means that the difference between measured Q and the minimum required Q is no longer a precise measure of the margin available for ageing, repair and operation. In this paper we describe both theoretical and practical assessments of this issue, show that the difference can be quite significant and discuss how practical measurements of margin could be made.

1. INTRODUCTION

A key requirement of an optical power budget is that it must contain margins to cover the possibility of fibre ageing, repairs and amplifier pump failures. All of these reduce the signal power and therefore will reduce the Optical Signal to Noise Ratio (OSNR). In a system with significant non-linearity, however, reductions in signal power will also reduce the non-linear propagation impairments. This effect can be quite significant in systems which have been upgraded to higher line rates because the power per carrier is higher than that envisaged in the original design. The move from 10G per wavelength to 100G, for example, has been accompanied by significant improvements in detection and FEC, but these do not add up to the 10dB increase that would be needed to avoid increasing the power per wavelength. As a result, upgrades often result in higher power per wavelength than was envisaged in the original design.

Conventional power budgets assess "ageing and repair" margins by calculating the OSNR penalty that would result from the anticipated ageing and repairs and do not consider how non-linearity might affect this margin [1]. This is clearly a safe way to set a margin, but it will over-estimate what is required in systems where non-linearity is significant. While "safe" estimates represent good engineering practice, it is also important to avoid requirements which are excessive. In a worst case these might cause the rejection of a solution which would function after repairs and ageing effects.

2. LINEAR OSNR

Linear OSNR can be calculated from the amplifier noise figure and bandwidth, combined with fibre losses and number of amplifiers. In the event of increased fibre loss (due to ageing/repair) or amplifier pump failure a number of amplifiers will experience a reduced signal. Assuming that there are N amplifiers producing noise N_a, then the total noise is:

$$N_{tot} = N\,N_a \tag{1}$$

Assume M amplifiers have extra loss L (dB) and that amplifier control circuitry increases the gain to compensate for the loss

$$N_{tot'} = (N - M)N_a + 10^{(0.1L)} M N_a \tag{2}$$

The fractional increase is:

$$\frac{N_{tot'}}{N_{tot}} = 1 + \left(10^{(0.1L)} - 1\right)\frac{M}{N} \tag{3}$$

Equation 3 can be extended to determine a repair/ageing margin which includes different losses such as fibre ageing, repeater pump failure, shallow and deep water repair. In a linear system it would be correct to assume that the impairment budget should include just this amount of margin to cover such changes. However, in a non-linear system the situation is somewhat different. Repairs, ageing and pump failures all reduce the power in the fibre and thus the impact of non-linearity. The following diagram shows three different cases.

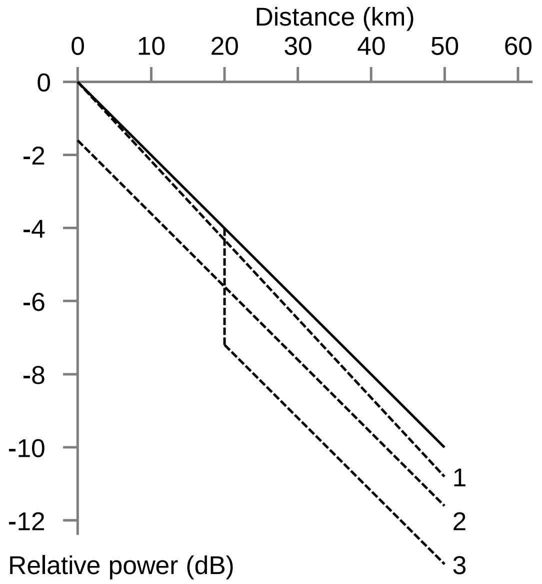

Figure 1. Power vs. distance

1. Ageing at 0.005 dB/km, the "industry standard" figure for 25 years of operation
2. Amplifier power reduced by 1.3 dB This would be typical of a single pump failure in an amplifier with 4 pumps
3. A 3 dB repair at 20 km, typical of the allocation for repairs in water deeper than 1000 metres – smaller values are used for shallower water

Ageing, while apparently the smallest effect, remains important because, if systematic, it has the potential to affect every repeater section, although it should be noted that there is little experimental data regarding the magnitude of ageing effects. Pump failures and deep water repairs should only affect a relatively small number of sections, but a pump failure will clearly affect the power over the entire repeater section and will therefore reduce non-linear impairments. In the case of a repair, the impact on non-linear impairments will depend on the position of the repair; if it were to be close to the amplifier input then the power in the fibre would be unaffected and the simple OSNR calculation would be essentially correct.

3. SYSTEM EXPERIENCE

For a number of reasons it is difficult to do ageing/repair experiments on operational systems, but Xtera was fortunate to be given an opportunity to assess the impact of power variations. During a field trial of 100G transmission Xtera was able to do tests on a system with repeaters where the amplifier output power could be changed using the supervisory system. This gave the opportunity to measure the effect of reducing the power from its normal value by 1 dB. The results are summarised below:

Wavelength (nm)	Measured Q (dB)		ΔQ
	Normal	–1 dB	
1546.1	8.0	7.8	**–0.2**
1552.5	7.7	8.3	+0.6
1559.0	8.0	8.1	+0.1

The results show clearly the impact of non-linearity, which had been observed when determining the power levels needed for optimal operation. Instead of observing an Q reduction of 1 dB – the linear prediction – the worst change was only 0.2 dB, while at several wavelengths the Q value improved.

4. SYSTEM SIMULATIONS

Due to practical limitations, a significant part of the work was done using optical transmission simulation software VPI™. This has a good track record, but like all such software is dependent on the accuracy of input parameters. However, even if the ultimate precision of results is open to question, comparisons with test results from field measurements show that simulations are reasonable models of the real world. On this basis a number of simulations were done to explore the impact of fibre ageing, repairs and pump failures on systems which might be expected to experience non-linear impairments.

According to [2] a significant number of the submarine cables are based on 2nd generation (Gen2) designs i.e. submarine cables with a dispersion map using mainly Non-Zero Dispersion Shifted Fibre (NZDSF) with occasional spans of Single-Mode Fibre (SMF) to compensate the chromatic dispersion. Hence, the simulation was carried out for a generic link model of a Gen2 cable system of length ~5700km.

The simulated system consisted of around 80 repeaters with the nominal span length set to ~70 km. PM-DPSK (polarization multiplexed differential phase shift keying) 40Gb/s transmitter was employed to investigate the system transmission performance at the start (SOL) and end of life (EOL). The optical transmitters' wavelengths ranged from 1550nm to 1560nm with 0.4nm channel separation. The dispersion map was formed by approximately ten dispersion blocks. Each dispersion block consisted of seven NZDSF spans and one SMF span. The system zero dispersion wavelength was 1555.75nm. For the EOL system model, the following repair losses were added to the system:

- Fibre ageing - increase in fibre loss by 0.005dB/km
- Shallow water repairs: 0.5dB loss every 20km to the first and last 500km of the system
- Pump failure: 1.25dB loss to the output of every 20th repeater
- Deep water repair: 3dB loss every 1000km

Repair / fault	No of spans affected
Shallow water	15
Deep water	4
Pump failure	4

For a test channel power of -5dBm, the simulated OSNR was 5.1dB/nm and 4.1dB/nm for the SOL and EOL system, respectively. This is in agreement with the linear calculation from equation (3 and also quite typical of a system of this length [3]. To evaluate the transmission performance of both SOL and EOL system, the launch power per channel was varied between -9dBm and 0dBm and the simulated Q-values are shown in Figure 2 for a test wavelength of 1559.79nm. In the linear region, the Q vs. power shows 1dB Q penalty for EOL as expected from the 1dB drop in the OSNR for the EOL system. However, in the non-linear region (power level above -3dBm) there is improvement in the Q value for the EOL system due to the reduced non-linear impact as a result of reduced signal power (ageing + repair loss) in some spans.

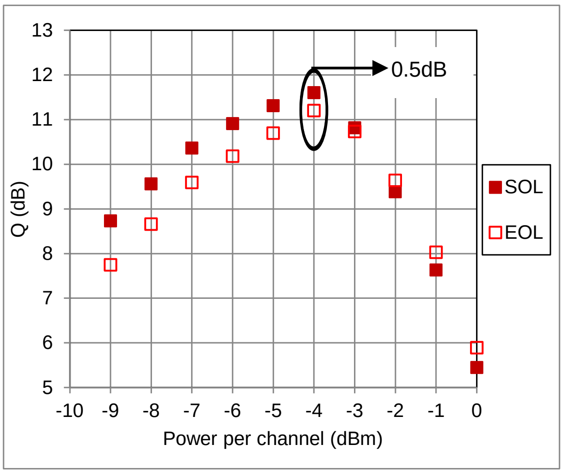

Figure 2 Q vs. per channel power for SOL and EOL system

Figure 3 shows the difference in Q (ΔQ) between the EOL and SOL vs. channel power. At a channel power of -4dBm, the EOL Q degradation is only 0.5dB instead of 1dB Q one would predict from a conventional power budget EOL margin evaluation.

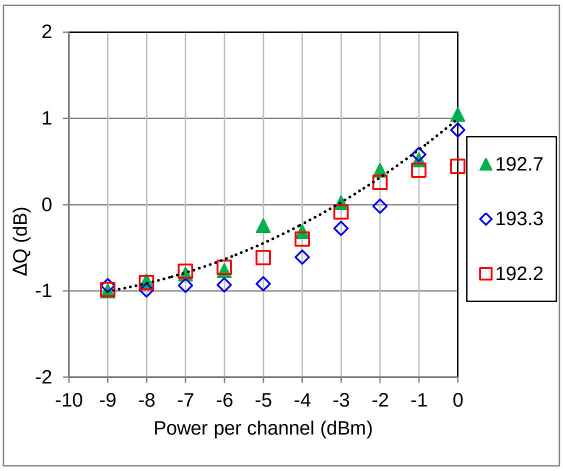

Figure 3 Simulated ΔQ values between the SOL and EOL system

5. MEASURING MARGIN

From the simulation work presented in Section 4, it is clear that it is possible to have a system with a relatively small apparent Q margin which nevertheless has a larger tolerance to the degradations caused by aging and repairs. If the Q measured at SOL is not an accurate measure of the margin to OSNR degradations caused by ageing and repairs then a method to measure this margin at SOL, and thus the system robustness, would be very useful.

Clearly, in general, it is not possible to reduce the repeater output power and it could be argued that this would be representative only of pump failures. However, it is possible to sweep the power of an individual test channel in a comb of wavelengths and measure the OSNR and Q impact on that test channel alone. Could this be a reasonable approximation to the real ageing and repair effects? Figure 4 shows such measurement made at 40GB/s on a system with characteristics similar to those modelled in Section 4.

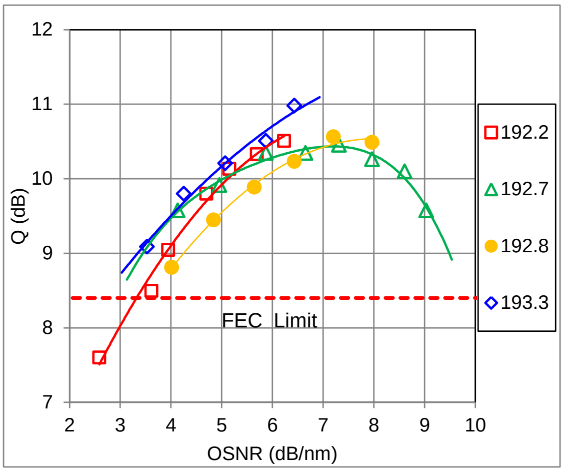

Figure 4 Q vs. OSNR for individual test channel

It can be noticed that the Q vs. OSNR in Figure 4 shows the same type of relationship as in Figure 2. Although the curves vary somewhat we see that around Q=10dB, a realistic operating point, the general trend is that an OSNR reduction of 1dB would produce a Q change of 0.4-0.8dB, consistent with the results of the earlier simulation.

A possible way of performing a test of margin is illustrated Figure 5.

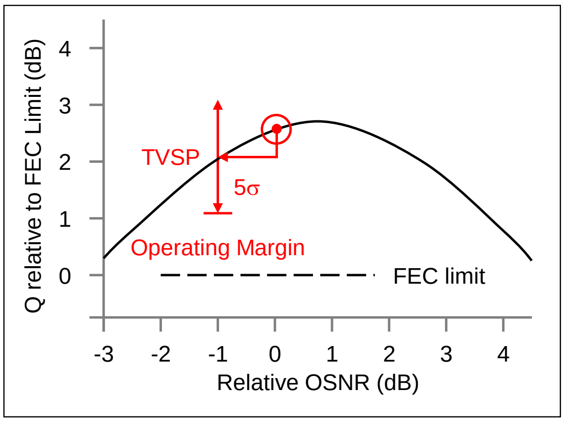

Figure 5: Possible margin verification

Starting from the proposed operating point the power (and thus the OSNR) of the channel under test is reduced by the desired ageing, repair and fault margin and the system Q measured over a period of time. During this Time Varying System Performance (TVSP) will produce fluctuations in the measured Q and the average minus 5 sigma should be calculated to cover worst case conditions. The difference between this value and the FEC limit is then a measure of the expected EOL operating margin. The process is shown schematically in

6. DISCUSSION

A key question is whether reducing the power of a single channel and measuring the Q change represents a fair approximation to the effects of all the potential ageing and repair effects?

A pump failure at EOL will reduce the power in a full span, but repairs will typically affect only a part of a span and would thus have a small impact on non-linear effects. Accordingly, it could be suggested that this test exaggerates the reduction of non-linear effects. However, in a real system ageing, repairs and pump failures will reduce the power of all wavelengths, which in turn would mean that non-linear cross-talk would also be reduced, suggesting that measuring a single channel might under-estimate the real effect of repairs, ageing and pump failures. To a degree these two factors will counteract each other and most of the measurements support it. However, so far the range of systems examined is limited and further work will be needed to determine how effective this type of measurement could be in other non-linear systems.

7. CONCLUSION

In this paper we have shown how the reduction in signal power from fibre ageing, repairs and pump failure also reduces the effect of non-linear impairments on the system Q. This means that using the apparent Q margin will give a quite pessimistic assessment of the margin for ageing and repairs.

Simulations of a non-linear system show that the Q reduction for the EOL is only 0.5dB at the optimum channel power instead of 1dB Q reduction expected from linear prediction. The simulation results are supported by field measurements on the target system. In addition, during a 100G transmission field trial where it was possible to reduce the output of submerged amplifiers the Q actually increased for some channels.

A possible practical measurement technique for assessment of ageing and repair margin is described, but it will require further investigation to check that it applies to other systems.

8. ACKNOWLEDGMENT

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9. REFERENCES

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