MARGINS ON SUBMARINE SYSTEMS

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Abstract: During the adjudication phase of all submarine systems, transmission margin is a key input from the suppliers that affects the system's cost. Margin is at crossroad of many fields (e.g. design methodology, repeater quality, technologies within the WDM terminal) and is regularly monitored by cable owners during their system's lifetime.

1. INTRODUCTION

Given their complexity and scale, repeated submarine networks are usually expensive to deploy. The repeater spacing is a key parameter since it determines to a large extent the contribution of the wet equipment to the overall system cost. The repeater spacing - or count - depends on three mutually dependent factors: i) the design of the submerged plant (e.g. end-to-end distance, repeater features, fibre type), ii) the dry plant features (capacity required, channel bit rate or modulation format) and iii) the assumptions used to derive the End Of Life (EOL) penalties affecting the system. Depending on choices, the margin management hence the system cost may differ significantly. Same applies when systems are upgraded: while the submerged plant is already set, suppliers and cable owners usually examine the benefits of updating ii) and iii). Whatever the context is - cable deployment or upgrade - the final objective is always to find the best compromise between system cost and maximum capacity achievable. This all depends on how margins are set and used. This paper proposes a short insight of the optical Power Budgets and reviews all margins associated to the BOL (Beginning Of Life) and EOL conditions. Then margin management is discussed and we propose some thoughts about the lessons learnt from the past design and implementation of 10 Gbit/s systems.

2. BASICS ON POWER BUDGETS

The Power Budget tables are proposed by the suppliers, discussed with Purchasers and included in the Contract. They guarantee that the design meets the required line performances over the system life. They relate to point-to-point sections fully loaded and are based on the Quality factor In practice the Q factor is nowadays computed from the pre-FEC error ratio.

The Power Budgets are defined at two different points in time. The BOL describes the system when it is turned into service whilst the EOL condition refers to the system performances after several years of wet plant operation (25 years typically). The consideration of the system ageing has direct influence on its initial design and EOL provisions are required (channel Optical Signal to Noise Ratio is reduced and the gain spectrum shape is affected with time). In this paper, the term "margin" refers to unreasonable/unallocated provisions or assumptions in the Power Budget calculations.

2.1 STRUCTURE OF THE POWER BUDGETS

The Power Budgets tables are generally read from the top (Mean Q factor) to the bottom (Commissioning limit). The "Mean Q factor" reflects the system performance limited by ASE noise only. All the transmission/SLTE penalties are then subtracted to get the System Q value (or Segment Q).

In practice, the tables could be read up or down. A template is provided in ITU G.977. The FEC limit ensures the minimum BER performance defined in the ITU-T Recommendations G.826 and/or G.828. The addition of the required EOL provisions defines the commissioning limit, which is the minimum Q factor to demonstrate on site for all channels before system Ready For Provisional Acceptance date. As illustrated in Figure 1, EOL provisions are twofold: provisions for system ageing and Purchaser's provision (further developed in section 4).

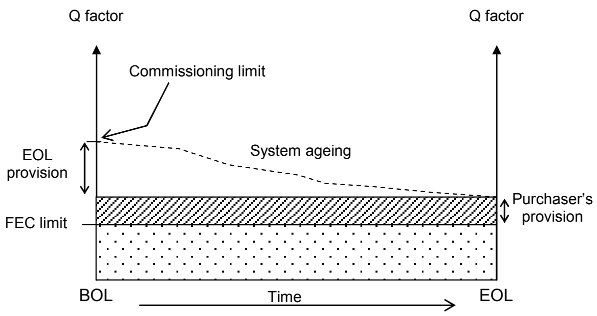

Figure 1 Main parameters from the Power Budgets. The dash line means that no linear assumption can be made on failure/cable cut occurrences over time.

2.2 PROVISION MANAGEMENT

The goal of the system design is to set the adequate EOL provisions to allow Q factor fluctuations and system ageing, while minimizing system cost. It is well observable that the first 10 Gbit/s WDM systems were conservative for various reasons: (1) design practices, (2) incomplete knowledge of the transmission effects [1], (3) provision for unexpected manufacturing problems and (4) accuracy of the simulation tools. This has lead to some "over-engineering" which in turn allowed operators either to upgrade their systems well beyond the maximum designed capacity [2] or to modify their network topology [1]. On the other hand, these systems were more expensive that they should have been because equipment quantities were larger. The next three sections review both parts of the Power Budgets (top and bottom) and identify areas where further optimization is feasible.

3. MEAN Q FACTOR AND PENALTIES

Two types of design practices are to be distinguished: assumptions about the system behaviour and equipment quality.

Almost all transmission penalties are slightly over estimated in the power budgets even if it should recognized that no supplier can take unreasonable risks in their design approach, which could be at Purchasers expense.

A transmission effect which remains unclear relates to the supervisory impairment. Both types of wet plant monitoring (active or passive) are assumed to affect the Q factor of all channels in the range of 0,2 dB typically. However no supplier is able to demonstrate this penalty on a system because it is too low to be measured. Hence the suggestion to evaluate more carefully this penalty or even to remove it from the Power Budgets.

Another area of challenge resides in the assessment of the Time Varying System Performances penalty. The well-known "5 sigma" rule is frequently applied during field trials and the resulting value is a common input to the Power Budgets. This rule is also used during the commissioning for all channels: each average Q factor is reduced by five times the standard deviation to account for performance fluctuations. The difference between the Q factor obtained and the FEC Q limit gives the operational margin. One may wonder why the 5 sigma rule was never modified through the years. It could be interesting to investigate the design implications of adopting a 4 sigma rule for example, as widely assumed for terrestrial systems (3×10^{-5} outage probability). First order, this would relax the line design by sigma dB and still would capture 99,99% of the fluctuations. The corresponding outage would be around 16 minutes per year. Also, at 40 Gbit/s, the traditional allocation rule and assumption of Gaussian shaped distributions will probably be refined to account accurately for the time varying effects [3].

About equipment quality and manufacturing provisions, a telling example may be the comparison on metrics between the repeaters manufactured against their specifications. It is always noticed that the actual individual performances are significantly better than what is assumed in the Power Budgets. Figure 2 represents the gap observed between the statistical average and the contractual Noise Figure for three different 10G systems and three different suppliers. It is roughly 1dB in all three cases.

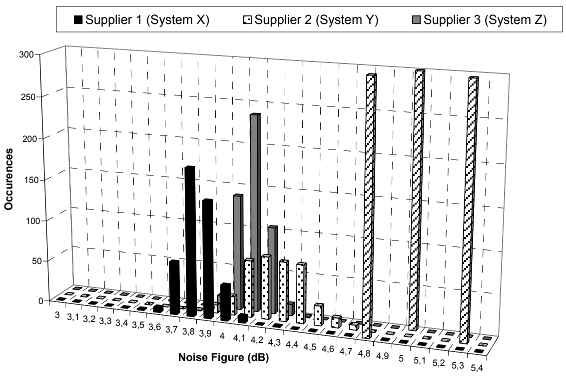

Figure 2 Comparison between Power Budget assumption and noise figure measured during the repeater tests in the factories

For well-established suppliers, the manufacturing issues mainly come from the dry plant transponders.

Lastly, simulation tools were intensively used for designing the first 10 Gbit/s systems. To a large extent this allowed the suppliers to identify and fine-tune the critical parameters and to better understand the propagation effects. However, due to the increase of systems complexity and difficulties to simulate them fully, many operators now require representative test beds for accepting the design proposed by the suppliers. Laboratory experiment increase the level of similarity with the system to deploy/upgrade and this represents a first accurate opportunity to review the expected margin.

4. EOL PROVISION

4.1 SYSTEM AGEING

Depending on assumptions and rules-of-thumb adopted, the computation of the required provisions may create significant equipment quantities variation amongst suppliers.

Material ageing: this contribution to the system ageing mainly regards the fibre ageing even if some suppliers also include component ageing/failure (leads to extra loss or noise figure degradation). It is widely accepted that the fibre ageing translate to an increase of cable loss over time due to hydrogen scattering and radiation effects. However depending on suppliers the corresponding penalty varies from 1 mdB/km to 5 mdB/km. In practice, very few papers were published to examine the real impact of material ageing on span loss variation and system performances. This appears to be a form of copy/paste from the first 10 Gbit/s projects and investigations from system suppliers and cable manufacturers is now required. In 2004, it was measured on a transatlantic cable a uniform increase of the fiber loss by about 1 mdB/km after three years of service [4]. This was based on calculations from the induced spectrum tilt. The supplier argued that ageing occurred within the first few years and then stabilized. More recently, the span loss of a fibre pair of another transatlantic system was analyzed during four years and showed a slight … decrease in loss of 0,8 mdB/km [5]! In both cases the loss variation was found negligible and material ageing could probably be removed or at least reduced from the Power Budgets.

Cable cuts: the provision for cable faults (submarine/land portions) is the major source of EOL penalties even if their prediction cannot be based on any scientific analysis. External aggressions are random in nature and rule-of-thumb based on experience can only be applied. On the submerged plant, the extra losses due to cable repairs come from the addition of cable and optical splices along the transmission path.

Two different approaches exist to calculate the impact of deep water repairs (>1000m depth) on OSNR: i) the average actual water depth is considered using the Route Position List data or ii) a lumped loss is assumed. The latter assumption is generally applied for the shallow water and the land cable repairs as well. Both approaches are comparable for the deep water repairs since the number of such repairs is low.

However, the frequency of repairs is of paramount importance, especially in shallow waters where the cable is more likely to be damaged than in deep waters. A concrete example if provided in Table 1. The cable owners' records should be constantly considered when finalizing the cable route to estimate the cable cut probability. Sharing this information should reduce the expected number of cable cuts to realistic figures without jeopardizing the system over time. This approach is already in place for estimating the cable quantities/characteristics to be stored in the maintenance depots. Obviously it is only valid for places where a few cables were laid. In [6] it has already been observed a major decrease in shallow water faults due to better armoring or burying practices. Investigations on the real impact on performances after repair(s) are also mandatory.

<u>Repeater pumps failure</u>: repeaters are expected to operate for 25 years and each submarine system is designed to survive several laser pump failures, provided they are in line with the predictions. These failures lead to additional noise into the system due to repeaters output power drop and their occurrence probability is based on individual FIT value. The actual impact on OSNR is generally limited because pump redundancy increases the repeaters reliability and repeaters are working in gain compression regime. The influence of a single pump failure on the Q performances is often impossible to estimate with the latest systems because pumps are fed into series. The improvement of the pump reliability does not lead to provision saving.

4.2 PURCHASER'S PROVISION

Until recently, all Invitation To Tenders (ITT) included a 1 dB Purchaser's margin in the Technical Specifications. Even if this value was somewhat empiric, this ensured contractually that systems would be able to accommodate a certain level of unexpected issues. This volunteered "over design" is always Purchaser's responsibility and can lead to a non-negligible amount of additional repeaters to lay. On the other hand, provided extra bandwidth is available or channel spacing can be reduced, this contingency can also be utilized to upgrade systems beyond the capacity they were designed for. Given the current cost of transponders there is no debate this approach is cost-effective in the middle term even if investment is increased.

5. NUMERICAL EXAMPLES AND DISCUSSION

Hereunder is a table highlighting the influence of the individual provisions optimization on the repeater count. The system simulated is 5000 km long (69 repeaters, 1360 km of shallow water), designed for 68 channels at 10 Gbit/s OOK channels.

This table shows that reasonable optimizations could lead to ~20% reduction of the repeater count, still with 1 dB EOL margin.

It should be noted that all three contributions to EOL penalties were treated individually but in theory, all of them are combined and penalties cannot be strictly added linearly. Also the OSNR/Mean Q factor relationship differs amongst all suppliers. For a given wet plant, a significant variation in Mean Q factor is observed depending on the formula used (e.g. ASE noise accumulation, consideration for the dry amplifiers or the channel modulation format).

Reduction of NF by 1 dB No supervisory impairment	6 repeaters saved
Material ageing	5 mdB/km → 0 mdB/km 2 repeaters saved
Pump failures	50 FIT → 25 FIT 0,1 dB OSNR gain only
Cable cuts in shallow waters	1 rep/10km → 1 rep/100km 5 repeaters saved
Purchaser's provision (optional)	1 dB → 0,5 dB 2 repeaters saved

Table 1 Influence of provisions against repeater count

All provisions other than EOL and Purchaser's provisions are underlined during the segment commissioning phase. It would appear normal and fair that the suppliers re-issue the contractual Power Budgets and commit on the extra margin observed. At the same time, they should be encouraged to propose options on how to utilize it (e.g. how to implement more capacity, how to decrease the cost of the dry plant).

It is worth noting that when a system is upgraded beyond its contractual final capacity, the total EOL provision is frequently revised. Most of the time, this revision is disconnected from any maintenance records and does not mean that the pump failure/cable cut probabilities or ageing has changed.

Lastly, as noted in Section 2.1, the FEC Q limit is a key parameter since the lower it is, the lower the commissioning limit is too. It currently exists roughly 1,5 dB difference between the most and the least efficient chips used in the industry. The latest techniques (e.g. soft decision and iterative decoding with Turbo or LDPC codes [7] should allow all suppliers to reduce the number of repeaters required.

Based on the above, we believe that some lessons should be learnt from the design of the first 10 Gbit/s systems to pave the way to new systems. It is evident that extra provision means extra capital that could be saved by cable owners, even if massive upgrades make legacy systems more profitable than expected. It is questionable that design rules will change but many areas could be improved to deliver more cost-effective systems still with appropriate provisions over their entire lifetime. This is particularly true knowing that i) the Purchaser's margin is still available if desired and ii) enabling dry technologies are often likely to increase the spectral efficiency or at least relax the submerged plant constraint.

6. CONCLUSION

The concepts of provision and margin were reviewed. Several types of provisions were differentiated and some ideas were shared on how to improve the Power Budgets and decrease accordingly the system cost. It is suggested that the over-design observed on the first 10 Gbit/s systems could be avoided for next systems, provided suppliers revise some of their practices. The introduction of imminent 40 Gbit/s systems is an excellent opportunity to rethink the Power Budgets structure and content. The need for less conservative approach in predictions and efforts in R&D are mandatory.

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