ADAPTING THE C&A PROCESS FOR COHERENT TECHNOLOGY

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Abstract: Power budgets have been a successful tool to reflect the performance expectations for 10G upgrades. When applied to 100G technology, it can be difficult to communicate performance expectations in power budgets since the original recommendations diverge from reality. This often impacts vendor selection and the acceptance process. This paper presents proposed improvements to submarine performance budgeting, and highlights areas of the acceptance process which would be affected by these changes, in order to facilitate upgrades at 100 Gb/s and beyond.

1. THE UPGRADE MARKET

Submarine cable systems evolved from a single channel per fiber pair (FP) in 1990, operating at sub-Gb/s bit rates, to systems which were capable of 64 x 10 Gb/s per FP by 2002. For example, in the northern trans-Atlantic market, 15 new cables (which are still in service) were deployed with increasing optical bandwidth to meet these increasing design capacities. Using public information and applying typical vendor technology, we estimate that the 15 cables provide a total trans-Atlantic optical bandwidth in excess of 100 THz.
In this period, the lit capacity of all trans-Atlantic cables terminating in the USA grew from 2 Gb/s to 3.3 Tb/s in 2002 [1]. The growth rate has since decreased; the lit capacity was ~13 Tb/s by the end of 2010, and it is forecasted to grow to ~23 Tb/s by the end of 2013. In other words, the trans-Atlantic cables would reach a spectral efficiency of ~0.23 b/s/Hz by the end of 2013. This demand could be met with 10G technology operating on a ~50 GHz grid.
During the past 10 years, transponder technology has evolved at a rapid pace. The key technology enabler has been the FEC improvement. Figure 1 shows the evolution of the FEC limit with time; hard FEC reached ist best performance by 2006; subsequent improvements originate solely from the recent application of soft FEC in 100G products. The red data points show the FEC limit of soft FEC products, where we assume that the FEC limit will approach 5 dB in 2013, which will enable 100G technology on the longest cables.

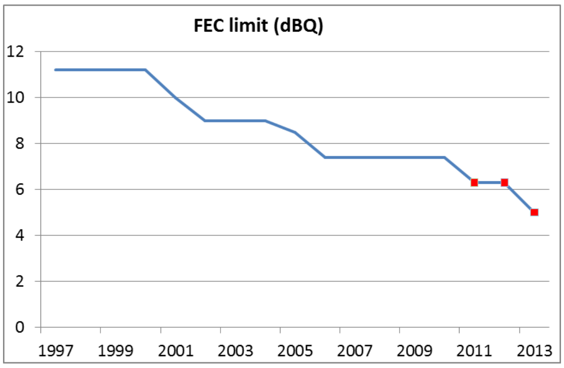

Figure 1: Evolution of the FEC limit

In the trans-Atlantic market, most, if not all, systems are expected to be upgradable with 100G DP-BPSK or more spectrally efficient products. With initial channel spacing at 100 GHz, the existing trans-Atlantic cables would be capable of supporting 1 b/s/Hz. Further terminal improvements are expected to increase to spectral efficiency to >2 b/s/Hz by 2015-2016, which would imply that the lit trans-Atlantic capacity could grow by a factor of 10 (as compared to the end of 2013) via terminal upgrades. As the average annual lit-capacity growth during past years was typically 20%, the owners will continue to focus on upgrades of existing systems with digital coherent technology for many more years to come. Hence, it is imperative that we correctly understand the performance expectation of coherent technology on legacy systems.

2. THE CONVENTIONAL PBT

The conventional power budget table (PBT) is described in [2], and an example is shown in Table 1. It starts with the mean Q value from a simple OSNR calculation. Next impairments and the time-varying system performance (TSVP) are subtracted to obtain a Line Q. The Segment Q is obtained via $1/Q^2$ summation of line and terminal equipment back-to-back (B2B) Q. The B2B Q of traditional 10G technology was large (e.g. 24 dB), and its net impact on the Segment Q was negligible (e.g. the Segment Q was typically 0.1 dB lower than the Line Q).

	Parameter	SOL Q in dB	EOL Q in dB
1	Mean Q value		
1.1	Prop. Impairments		
1.2-9	Other impairments		
2	TSVP		
3	Line Q		
4	Specified B2B Q		
5	Segment Q		
6	Q limit after FEC		
7-9	Margins		
10	Commissioning limit		

Table 1: Conventional PBT

The difference between Segment Q and FEC limit (line 6) constitutes margins for repair/ageing, and customer and vendor margin (lines 7-9). The customer margin is typically 1 dBQ for new cables, but it could be reduced for terminal upgrades if the submarine plant experiences no unexpected degradation. Figure 2 shows two typical PBT line items (1 and 4) quoted by 7 different vendors for 3 different (but similar) system upgrades.

All vendors had received the same transmission details and all proposed 100 Gb/s DP-QPSK digital coherent technology. The relevant segments had no particular issues. The figure illustrates two very common, and very concerning trends: (1) the spread of line item 1, which is derived from OSNR, can be as large as 5 dB even when there is no clear correlation with a difference in implemented modulation format or expected optimal launch power, and (2) for similar modem technologies, a 10 dB spread in receiver performance is suggested. The spread in predictions could originate from 1) unclear or inaccurate transmission performance data provided by the owners, 2) product differences, 3) how vendors allocate the 100G modem performance in the conventional PBT, etc. The magnitude of the spread suggests a combination of these is most probable.

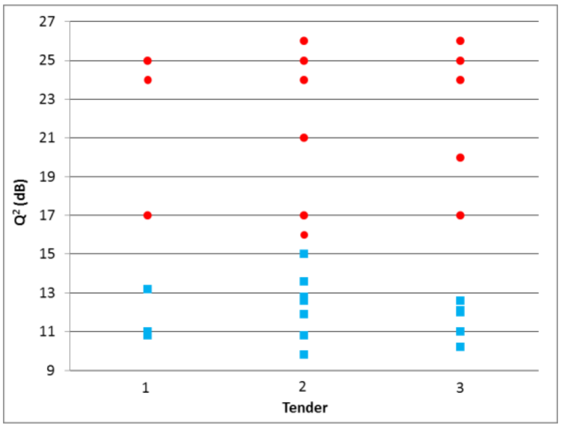

Figure 2: Spread (in dBQ) of PBT elements such as line 1 (blue) and line 4 (red) for 3 different tenders (marked as 1-3)

3. THE "COHERENT PBT"

The conventional PBT assumes a more or less "linear" OSNR to Q relationship, which originates from the high B2B Q. Hence, terminal ageing has a negligible impact on the delivered Q. With increased bit rates and associated increased noise bandwidths, this is no longer the case. Therefore, the existing approach is no longer meaningful. For example, if a 100G transponder or modem would be tested at very large OSNR, this may not provide an accurate prediction of how the modem would perform in the OSNR range of interest applicable to submarine cables. It is more interesting to understand the modem characteristics for the relevant range of system OSNR.

	Parameter	SOL Q in dB
0	OSNR (in dB/0.1 nm) at -5 dBm channel power and known tilt	16
1	B2B Q for line 0 (Q_{simple})	9.0
1.1	Propagation Impairments	1.4
1.5	Mean PDL penalty	0.4
1.8	Supervisory impairment	0.1
1.9	Manufacturing impairment	0.2
2	TSVP	0.2
5	Segment Q	6.7
6	Q limit after FEC	5
7.1	Cable repair & ageing	0.5
7.2	Repeater ageing	0.1
7.3	Impact of future tilt (x dB)	0.2
7.4	Modem ageing	0.2
8	Segment margin	0.7
8.1	Customer margin	0.5
8.2	Unallocated	0.2
10	Commissioning limit	6.5

Table 2: Simplified PBT for coherent terminals

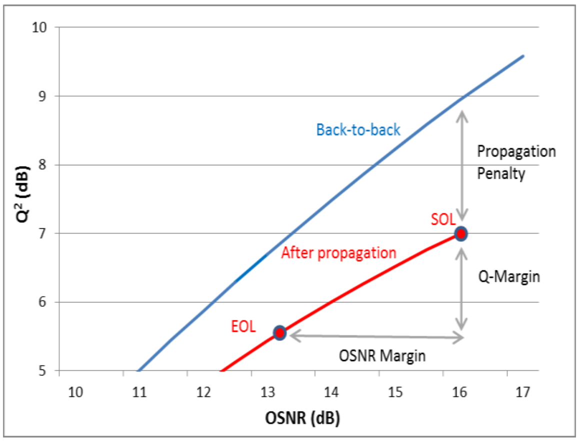

Figure 3: Noise-loaded Q-OSNR curves for a hypothetical modem with a FEC limit of 5 dB. The EOL prediction reflects the FEC limit (line 6 in Table 2) plus the EOL margin (line 9)

A more intuitive approach to modelling the behaviour of coherent technology is outlined as follows, and is illustrated in Table 2 and Figure 3 [3]:

1. The customer provides line 0 in Table 2.
2. The modem's B2B OSNR vs. Q is measured or simulated under noise-loading conditions (Figure 3, blue line). All modem impairments must be included. The Q is derived from the pre-FEC BER. This can be performed in the laboratory or factory for each modem. Repeated tests for different modems provide a measure of manufacture variability and impairment (Table 2, line 1.9). If this information originates from simulation, supporting measurements should be included in a technical evaluation.
3. At the OSNR of the real system given in line 0, the B2B test result provides an estimate of the Q_{simple} (Table 2, line 1). This is used as a reference to calculate performance penalties.
4. When the modem is connected to the line, in a laboratory test bed, or in propagation simulation, the difference between the measured or simulated Q and Q_{simple} is the propagation impairment, including PDL. This is indicated with the "propagation penalties" in Figure 3, or displayed by line 1.1+1.5 in Table 2. PDL can either be measured directly by the coherent modem, or it is known from repeater factory acceptance tests; hence, the penalty associated with PDL can be separated from the propagation impairments.
5. A noise-loading measurement or simulation of Q vs. OSNR after propagation provides an estimate of remaining Q and OSNR margin (~1.7 dBQ in this example).

These measurements can be conducted throughout the available bandwidth, but it would be most relevant at the wavelength which shows the lowest Q (as this is the basis for a PBT).

This approach has the advantage that the PBT now lists measurable parameters, which can be readily verified. It also allows coherent vendors to include accurate receiver models in back-to-back and propagated simulation. This is important, as the performance of a coherent receiver can change depending on statistics of the propagated signal.

Repair and ageing represent OSNR penalties. These can be converted to Q penalties using the red line in Figure 3, where each subsequent penalty follows the red line until the EOL point is reached. For this example, it is assumed that EOL conditions occur at the FEC limit (line 6) plus the Segment margin (line 8).

4. PBT DISCUSSION

Some cables have been affected by a larger than expected number of faults and repairs, or are affected by unforeseen submarine plant reliability problems [4]. It is important that the OSNR and any possible gain tilt are recorded or can be deduced, so these items can be communicated during the tendering stage.

The PBT in Table 2 includes two new items, lines 7.3 and 7.4. Some cables have a repair policy, e.g. via the inclusion of repair repeaters, which can cause the accumulation of gain tilt. Although Table 2 shows this as a normal penalty, in reality, nonlinear effects would cause additional propagation impairment for channels where the gain is increased. If penalties become large, then such penalties reduce the effective transmission bandwidth.

In the conventional PBT, modem aging is reflected by the EOL B2B Q. In the past, this had little impact on the Segment Q. However, as bit rates increase, associated penalties become more important. The impact on modem aging penalties requires addressing in a new PBT format since a larger modem aging penalty is expected at 100 Gb/s. Although there is presently no standardized methodology to estimate this impact, it will be necessary to develop this, and include a credible allocation in the PBT.

The presented test methodology of noise loading is effective in laboratory or factory test environments, or when upgrading a dark FP. This may not be appropriate when an upgrade is being commissioned on a line with legacy traffic-carrying channels. In addition, as more spectrally efficient products become available, it will become increasingly difficult to conduct accurate OSNR measurements in a realistic WDM environment under relevant loading conditions. Future alternative approaches may allow the indirect derivation of OSNR margin, e.g. via digital noise loading of modems [3]. However, until such techniques are available, it will be necessary to derive performance objectives in the laboratory for relevant loading conditions, and next correlate these to required commissioning limits for any particular upgrade.

The red line in Figure 3 shows significant curvature, i.e. a ~1 dBQ margin corresponds to an OSNR margin of ~1.8 dB in this example. Hence, if repair or EOL margins are stated in dBQ in tender requirements, while such margins are typically intended to protect against OSNR penalties, then this could greatly overestimate the margin that is actually needed. As future products will allow flexible tuning of channel density vs. margin, overstated margins could unnecessarily decrease the design capacities.

5. POWER CONSIDERATIONS

In general, coherent technology shows the best performance at lower launch power than legacy 10G equipment. For narrow-band systems, the sum of all channels' optimum powers is typically less than the repeater output power. Some vendors submit tenders without addressing this difference.

There are two ways to overcome this difference: Reduction of repeater output power (if possible) or the addition of idler channels (both). In the latter case, idler channels would typically need to consume at least half of the repeater output power. Some present idler products are configured such that a single failure could remove all idler power from the line. In this case, following a failure, and during the MTTR, all channels experience an additional Q penalty. Rather than a channel independence test, it would be more valuable to characterize the impact of an idler failure on the traffic channels, where the Q reduction should be smaller than the Segment margin (line 8 in Table 2).

When the repeater output power is reduced, then it is important to consider under what conditions (some) repeaters return to their default setting, e.g. if a shunt fault develops. During such event, an additional transmission penalty occurs. Characterization tests at nominal and modified repeater output power will provide an estimate of the upper limit of this penalty.

6. CONCLUSIONS

We described how a few key measurements can lead to an easy to understand and verifiable PBT, so margin expectations for different vendors can be compared reliably. The easiest case is the PBT of a fully loaded line or e.g. an upgrade on a dark FP. If this is not the case, or when the performance of more spectrally efficient equipment needs to be characterized, then it may be necessary to derive commissioning limits via laboratory demonstrations of full loading versus loading with legacy channels. We highlight that modem ageing needs more study, e.g. on how to standardize derivation of relevant penalties for different vendors. Lastly, different commissioning tests may be needed to understand what additional penalties may be encountered due to terminal equipment and wet-plant faults.

7. REFERENCES

[1] FCC capacity utilization reports: http://transition.fcc.gov/ib/pd/pf/csmanual.html .

[2] ITU-T Recommendation G.977 (Annex A).

[3] J. Gaudette et al, "Using Coherent Technology for Simple, Accurate Performance Budgeting", SubOptic 2013.

[4] M. André, "How about technical skills within the submarine industry", SubOptic 2013.

