USING COHERENT TECHNOLOGY FOR SIMPLE, ACCURATE PERFORMANCE BUDGETING

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Abstract: Coherent technology, powered by advanced Digital Signal Processing (DSP), provides access to a rich set of information on the optical field. Despite this, current practices in performance budgeting and system acceptance focus only on the pre-FEC bit error ratio, translated to dBQ^2, and ignore the set of measures offered by coherent technology. In this paper, we discuss how coherent technology with advanced DSP can measure, in real-time, necessary components to derive performance budgets. We demonstrate a working example using commercially available 100 Gb/s coherent DP-QPSK modems with high gain soft FEC.

1 INTRODUCTION

Submarine performance budgets are based on Q-factor. However, the measurement of Q-factor alone is insufficient for verification of performance. One must also know the Q to OSNR relationship for a given propagation condition. This relationship determines how the pre-FEC bit error ratio (BER) changes according to performance penalties that are manifested as OSNR degradations. An example of this is cable aging and repair activity that degrades delivered OSNR. In a laboratory environment, it is acceptable to directly measure the Q to OSNR relationship through noise loading experiments. On an in-service cable system, this approach can disrupt traffic bearing channels, and should be avoided.

The new generation of coherent technology offers insight into propagation conditions, including the Q to OSNR relationship. With a single Q and OSNR measurement at commissioning, all elements in the Submarine Power Budget Table (PBT) can be approximated through understanding of the electrical signal-to-noise ratio (SNR). The electrical SNR is defined as the signal-to-noise ratio measured by the coherent receiver at the decision stage of the receiver:

$$SNR = \frac{A^2}{\sigma^2}$$

Here, A^2 is the average of the squared distance of the signal constellation points from the origin, and σ^2 is the noise variance around each point [1]. Using a coherent receiver, a variety of methods can be used to measure or estimate the electrical SNR. One method known as Error Vector Magnitude (EVM) estimation measures SNR directly from the received constellation [2]. Alternatively, if the equation to calculate Q-factor as a function of SNR is known, this equation could be used to calculate the electrical SNR after propagation.

2 RELATIONSHIP OF SNR AND Q

The BER for 100 Gb/s DP-QPSK with coherent detection can be defined as a function of electrical SNR [1,3].

$$BER = 0.5 erfc\left(\sqrt{EC \cdot SNR / 2}\right) \tag{1}$$

EC is an eye closure factor that accounts for degradations due to waveform distortions caused by modem implementation imperfections. In this paper, we focus on 100 Gb/s DP-QPSK, but the method can be extended to other dual-polarized modulation formats with coherent detection. The SNR term can be expanded as follows to separate contributions from ASE, modem implementation, and propagation penalties.

$$\frac{1}{SNR} = \frac{B_e}{B_o \cdot OSNR_{ASE}} + \frac{1}{SNR_{MODEM}} + \frac{1}{SNR_{PROPAGATION}} \tag{2}$$

Here, B_o is the optical bandwidth used for the OSNR measurement (e.g. 12.57 GHz for 0.1 nm resolution bandwidth) and B_e is the double-sided, noise equivalent bandwidth. The term SNR_{MODEM} is the maximum Q^2 of the coherent modem determined by noise-like implementation penalties. The $SNR_{PROPAGATION}$ term is the maximum achievable Q^2 after propagation, ignoring OSNR and modem distortions, and usually includes contributions from fiber nonlinearities, PDL, and filter penalties.

To convert BER to Q-factor, the following operation is performed.

$$Q = \sqrt{2} \cdot erfcinv[2 \cdot BER] \tag{3}$$

Through expansion and substitution, the Q is defined as a function of OSNR, modem imperfections, and propagation penalties.

$$Q^2 = \frac{EC}{\frac{B_e}{B_o \cdot OSNR_{ASE}} + \frac{1}{SNR_{MODEM}} + \frac{1}{SNR_{PROPAGATION}}} \tag{4}$$

Alignment of Equation (4) with a back-to-back (B2B) noise loading experiment for a commercially available 100G DP-QPSK modem is shown in Figure 1.

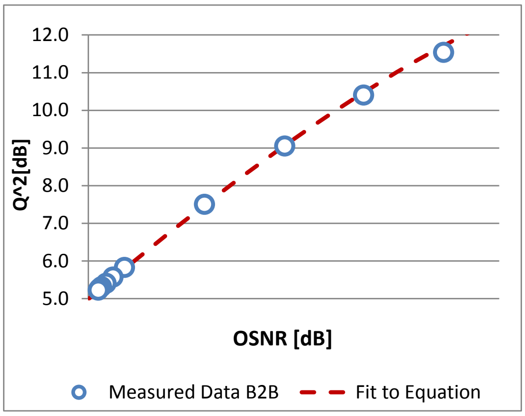

Figure 1. Back-to-back noise loading

Curvature of the Q to OSNR relationship is observed in the back-to-back case. This curvature is caused by finite values of SNR_{MODEM}. At 100 Gb/s and beyond, this contribution is significant, and impacts the optical performance in the OSNR range of interest for Submarine cables.

2.1 Calculation of Modem Penalties

The modem penalties can be derived before commissioning through back-to-back noise loading. A schematic of a typical noise loading experiment is given in Figure 2.

EC and SNR_{MODEM} values can be determined for a modem by fitting the measured noise loading data to the theoretical equation describing the coherent modem performance given in Equation (4). The propagation component of the SNR is infinite, since there is no fibre propagation. The outcome of the back-to-back noise loading experiment, and the line-up with the theoretical equation describing modem performance is given in Figure 1. This exercise can be performed during factory assembly, at factory acceptance, or in the field before commissioning.

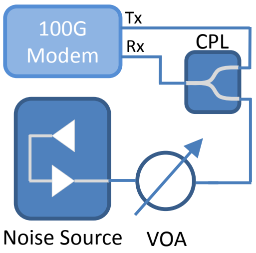

Figure 2. Back-to-back noise loading experiment

2.2 Propagation Component of the SNR

The propagation component of the SNR can be approximated directly through EVM or similar techniques, or calculated using Equation (4).

When using calculation, EC, SNR_{MODEM}, OSNR, and Q must be known for the modem under test. To this end, the modem penalties should be derived through back-to-back noise loading, while the Q-factor and OSNR must be measured for the given propagation condition. This information can be substituted into Equation (4) and the propagation component of SNR can be calculated.

The EVM approach has the following advantages: (1) real-time constellation and SNR monitoring, and (2) potential elimination of the need to measure OSNR. For the example presented in the following section, we assume EVM is not available and focus on SNR calculation.

3 GENERATING A PBT FROM FIELD MEASUREMENTS

Using theoretical calculation, an example of a full PBT derivation from field measurements is considered. In this example, a commercially available 100 Gb/s DP-QPSK modem was examined in back-to-back conditions and over a 5,000 km dispersion managed test-bed featuring Corning Submarine Vascasde™ LEAF and LS fibre types. The schematic of the 5,000 km test is given in Figure 3. The test wavelength was 1537.00 nm. For the 5,000 km test, the spectrum was filled with 70x 100 Gb/s DP-QPSK channels with 50 GHz channel spacing.

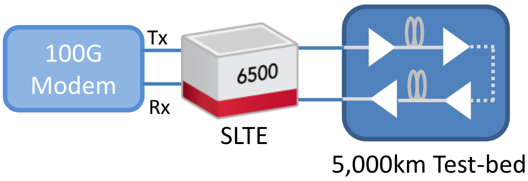

Figure 3. Schematic of the 5,000 km test-bed

In order to facilitate this example, a simplified PBT is considered in Table 1. This format adheres to the suggested improvements given in [4] where penalties are derived with respect to measured back-to-back performance.

100G DP-QPSK over 5,000km		
Item	Description	SOL [dBQ]
0	OSNR [dB/0.1nm] at -7 dBm launch power per channel	13.81
1	Measured Back-to-back Q-factor at OSNR in Line 0	8.30
1.1	Propagation impairments	1.10
1.5	Mean PDL penalty	0.20
1.8	Supervisory impairment	0.00
1.9	Manufacturing impairment	0.00
2	Q time variations (5 sigma)	0.05
5	Segment Q	6.95
6	FEC Limit	5.20
7	Repair and Aging	0.62
8	Extra Margin	1.13

Table 1. Example Power Budget Table as calculated by the coherent modem

Manufacturing and supervisory impairments are not propagation specific, and thus are known for a specific modem or supervisory technology. For simplification, these will be set to zero in the example PBT.

With the modem propagating over the 5,000 km system, a power hunt and pre-dispersion sweep were performed to optimize the Q-factor. After optimization, a single Q and OSNR measurement was performed. The Q-factor was derived from the pre-FEC BER measurement, while the OSNR was measured using an OSA. The measured OSNR is listed as item 0 in the example PBT. The measured back-to-back Q-factor at the OSNR listed in line 0 is given in line 1 as a reference for penalty allocation.

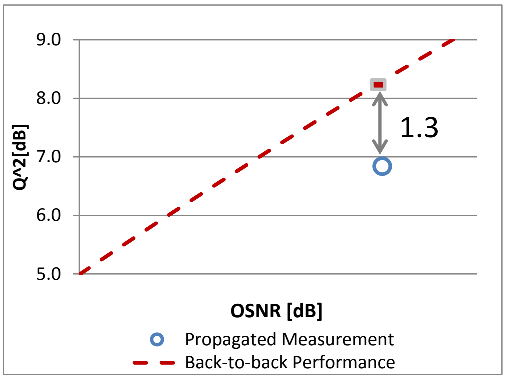

Figure 4. Determining the propagation penalty

To extract the propagation penalty, the difference between line 1 and the measured Q-factor after propagation is calculated. Both values are taken at the OSNR listed in line 0. An example of the extraction is given in Figure 4.

The propagation impairment includes contributions from fibre nonlinearities, as well as polarization dependant loss (PDL), assuming chromatic dispersion (CD) and polarization mode dispersion (PMD) are compensated by the coherent receiver without penalty. Separation of PDL from nonlinear penalties gives more insight into cable health, since high PDL could indicate cable defects. The coherent modem is capable of measuring the PDL distribution of the submarine cable, and PDL penalties can be allocated accordingly. An example of the PDL statistics captured by the coherent modem is shown in Figure 5a.

The coherent modem has the ability to analyse system stability and allocate a time-varying system penalty (TVSP) by monitoring Q-factor at any specified interval for the duration of stability analysis. An example is shown in Figure 5b. In this example, the Q-factor was measured every 10 seconds for a 7-day stability test. Results of the PDL and TVSP testing are given in Table 1. TVSP is subtracted from the measured Q-factor after propagation to generate a worst-case Q-factor, represented as Segment Q in Table 1.

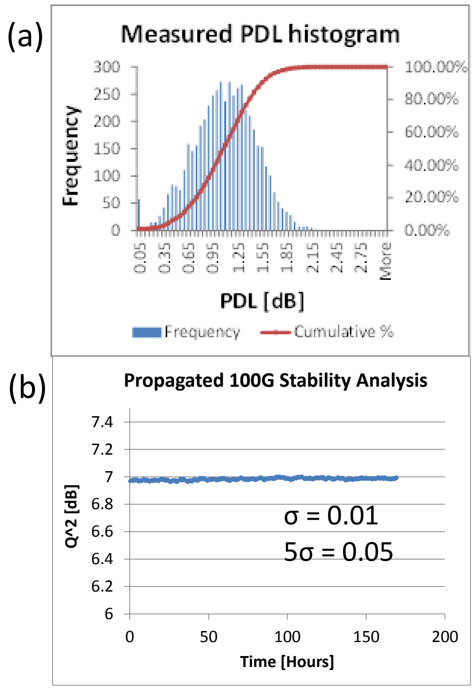

Figure 5. (a) PDL histogram and (b) TVSP measured by the coherent receiver at 5,000 km

To understand the impact of cable repair and aging on performance, the Q to OSNR relationship must be extracted. The primary impact of cable aging is an OSNR degradation that is converted to a Q penalty via the Q to OSNR relationship.

The OSNR in Equation (4) can be varied to calculate the impact on Q-factor. On the laboratory test-bed, OSNR was varied by noise loading the propagated signal at

5,000 km to test the equation for Q. Results are shown in Figure 6.

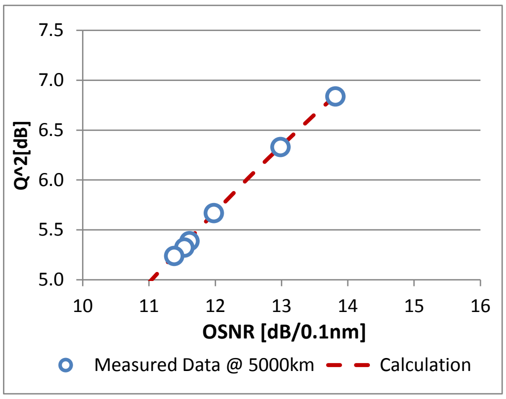

Figure 6. Comparison of theoretical calculation to measured data after 5,000 km of propagation

Continuing the previous example and assuming a cable repair and aging allocation of 1 dB OSNR, the Q penalty was calculated. An example of this procedure is given in Figure 7. As shown in Table 1, a 0.62 dBQ penalty results from 1 dB of OSNR degradation.

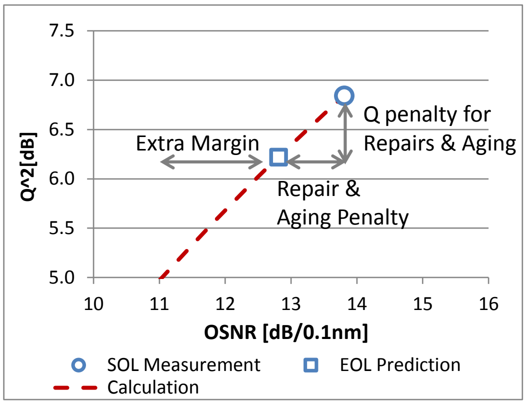

Figure 7. Determining Q penalty for OSNR degradation cause by repair and aging

4 CONCLUSION

A PBT format is proposed whose elements are obtained in real-time by means of coherent modem technology and monitored through network management software. Future coherent modems will provide direct measurement of the SNR, potentially avoiding the need for OSNR measurement – a necessary requirement on systems with high spectral efficiency and grid-less technology. These improvements could enable simple system acceptance, with potential for standardization across supplier technology.

5 REFERENCES

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