Power budget line parameters evaluation on a system having reached its maximum capacity

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Abstract: The evaluation of the submarine line Power Budget parameters, primarily the line impairment together with the time varying system performances is presented and analyzed along with the vendor Power Budget parameters. This evaluation is performed on an existing submarine system having reached its maximum transmission capacity. The Power Budget parameters are defined in ITU-T recommendation G.977 [1].

1 INTRODUCTION

A submarine link Power Budget calculation (hereafter referred as PB) is an essential process through which, several elements of the system are defined. The PB calculations results in the following: maximum transmission capacity knowing the line bandwidth, end to end quality of service, end of life transmission margin, maintenance margin for repair, failure and aging, Optical Signal to Noise Ratio ("OSNR") calculations from which the repeater count is determined and several other elements are factored-in such as fiber attenuation, amplifier characteristics. Submarine line impairments are also presented in a PB and the opportunity of having a system having reached its maximum PB capacity was taken to corroborate the vendor provided PB line impairment with the values derived from the actual segment performances.

Vendors can be reluctant in providing detail calculations, often proprietary, of the relationship between the OSNR and Q. Published equations are found to express the relationship between these values, [2] [3], the OSNR relationships are not adapted to the vendor equipment specificities such as receiver sensitivity, and transmitter characteristics.

Impairments values are equally difficult to evaluate and confirm from the vendors PB. Operators are too often left with "work around methods" in order to evaluate the accuracy of the vendor PB parameter values predictions which consist in performing Trials on the most stringent segment and Maximum capacity tests. Even going through these tests, long term time varying factors and aging cannot be adequately measured.

While performing several trials with vendors in order to evaluate the maximum capacity of this system, they mainly consisted in an attempt to simulate the maximum capacity by modulating a few wavelengths ("waves"), swept across the spectrum while the remaining waves on the line bandwidth were un-modulated CW carriers (referred to as Carrier Waves "CW") or simply with no loading at all. It is interesting to note that trial results on this particular system were very different between vendors which justify furthermore the investigation on power budget calculations. Having the system equipped to maximum capacity with all the waves modulated present a great opportunity for PB parameters evaluation.

2 POWER BUDGET PARAMETERS EVALUATION: TEST SET-UP

Measurements performed for this article were on a 1355km two-fiber pair generation 2 system installed in 1997. It formed the “segment 5” of the GlobeNet network also formally known as BUS-1. Fiber pair 1 transmitting from Bermuda receiving in New Jersey was selected for this test. This system was originally design to support 2 x 2.5 Gb/s per fiber pair but had reached a maximum capacity of 600Gb/s per fiber pair which consisted of 13 x 40Gb/s plus 4 x 20Gb/s waves or the equivalent of 15 x 40Gb/s waves.

3 TOTAL LINE IMPAIRMENTS CALCULATIONS

The main objective is first to evaluate these impairments as a whole. From the standard PB table, the total line impairments are calculated by subtracting the PB Line Q and Time Varying System Performance (TVSP) to the Mean Q as follow [1]:

$$Impairments = Mean\ Q - Q_{Line} - TVSP$$

Equation 1: Impairments derivation

and the line Q is defined as:

$$Q_{line} = \sqrt{\left(\frac{1}{Q_{Seg}^2} - \frac{1}{Q_{TTE}^2}\right)^{-1}}$$

Equation 2: Line Q

In order to obtain the most accurate value for the impairments, each parameter in equation 1 and 2 will be derived in the following sections.

Step 1: The Mean Q is derived from the line concatenated OSNR. The OSNR is calculated for each span of the line and can be approximated by the following formula [2] (eq. 9.23):

$$OSNR = P_{out} - L - NF - 10\log(h\vartheta v_r)$$

Equation 3: One span OSNR approximation

P_{out} is amplifiers output power per channel, L is the span loss, NF is the noise figure, h is the Planck’s constant, υ is the optical frequency in Hz, v_r is the reference bandwidth in Hz. The signal level and noise level are carefully determined from the contribution of each element and a simplification is shown in table 1. The actual process is quite complex taking into account additional factors not listed here.

Line Element	Fibre Length km	Fibre Loss dB/km	EDFA	EDFA out dBm	EDFA NF dB	Fixed Loss dB	…	Cumulative Length km	OSNR dB/nm
							…	0.0	
Fibre	25.9	0.206		0	0	0.5	…	25.9	
EDFA	0.0	0	1	5.5	6.5	0	…	25.9	
Fibre	81.6	0.206		0	0	0.5	…	107.5	
EDFA	0.0	0	2	5.5	6.5	0	…	107.5	
Fibre	84.0	0.206		0	0	0.5	…	191.5	
EDFA	0.0	0	3	5.5	6.5	0	…	191.5	
Fibre	81.7	0.206		0	0	0	…	273.2	
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	
Fibre	83.0	0.206		0	0	0	…	1328.5	
EDFA	0.0	0	17	5.5	6.5	0	…	1328.5	
Fibre	26.6	0.206		0	0	0	…	1355.1	
EDFA	0.0	0		5.5	6.5	0	…	1355.1	**6.13**

Table 1: S5 OSNR concatenation

In order to obtain the most accurate Mean Q, the OSNR table was adjusted or “actualized” to represent the system condition at the time of testing as follow:

- The transmit OSNR on the worst wave set to the field measured value and entered in the table.
- Each cable span was adjusted to the as built and post repair fiber length and EDFA positions.
- Degradation due to pump failures was set to the actual EDFA status: no failures were observed from the passive line monitoring equipment.
- Shallow and deep-water repair loss of 0.5 dB and 3 dB respectively are added to the losses as per the actual submarine line repairs history (3 shallow, no deep water).

- Fiber aging: the industry standard of 0.005 dB/km for the life of the system was applied to each cable span and adjusted to the system age.
- Various other factors are adjusted such as EDFA saturation effects, EDFA filters.

The OSNR obtained was then translated into Q and used as the PB Mean Q. The relation between OSNR and Q is derived from factory back-to-back measurement. The "actualized" Mean Q calculated is 13.4 dB. It is therefore representative of the submarine line but without the impairments.

Second step: Line Q derivation is performed using equation 2. The Terminal equipment back to back Q was measured by the vendor and the value adjusted to the system age.

The Q value for the segment (Q_{seg}) is calculated by first selecting the worst performing wavelength for which we measured a worst BER before FEC over a 41 days period of 4.5E-4.

This BER is then translated into a Segment Q value of 10.4 dB (PB line 5) [2] (eq. 9.16). From equation 2 and the vendor Q_{TTE} value, a 11.5 dB Line Q value is obtained.

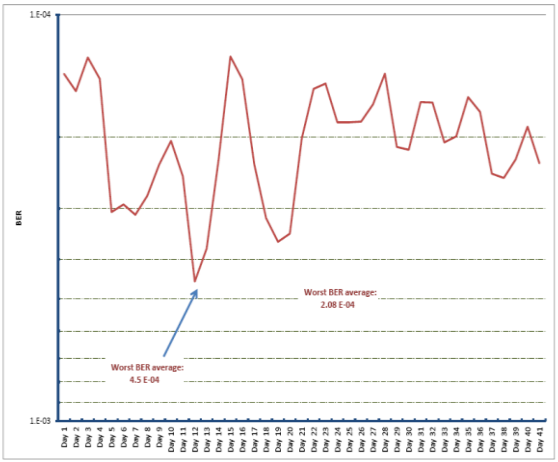

Figure 1: BER monitoring over a period of 41 days

Third step TVSP derivation. As per figure 1, the worst BER observed during the 41 days monitoring period was 4.5 E-4 while the worst 24hrs average BER for that period was 2.0E-4. This corresponds to a Q variation of <u>0.5 dB</u>.

Last step: Total line impairment calculation.

As per equation 1:

Impairments = 13.4 – 11.5 – 0.5 = **1.4 dB**

4 INDIVIDUAL LINE IMPAIRMENTS EVALUATION

This consists in breaking down the line impairments into some of its composite elements in an attempt to quantify some of

PB Line	Line description	Vendor Derivation	Vendor Sum	Vendor Value	Jointly	GlobeNet Value	GlobeNet Sum	GlobeNet Derivation	
0	Calculated OSNR	Actualized vendor OSNR			6.1			Actualized vendor OSNR	dB/nm
1	Mean Q (derived from line 0)	Vendor Q_OSNR formula			13.4			Vendor Q_OSNR formula	dB
1.1	Propagation impairments			1.4					dB
1.2	Gain Flatness impairments			0.1					dB
1.3	Non-optimal pre-emp. impairment			0.1					dB
1.4	Wavelength tolerance impairment		2.7	0.2			1.4		dB
1.5-7	Mean polarisation penalties			0.3					dB
1.8	Supervisory impairment			0.2					dB
1.9	Manufact. / Environ. impairment			0.4					dB
2	Time varying system performance	5 sigma rule		1.5		0.5		Long term field measured	dB
3	Line Q Value (Qline)	Line 1 -(Line 1.1 to 1.9) - Line 2		9.2		11.5		1/Qline2= 1/Qseg2-1/Qtte2	dB
4	TTE Q value (back to back) (Qtte)	Vendor Qtte (BOL+EOL)/2		24.3		24.3		Vendor Qtte (BOL+EOL)/2	dB
5	Segment Q value (Qseg)	$1/Qseg^2=1/Qline^2+1/Qtte^2$		8.6		10.4		Formula (ref. [3]) with line 5.1	dB
5.1	Seg. Q BER w/o FEC from line 5	Formula (ref [3]) with line 5		3.50E-03		4.50E-04		Long term field measured	

Table 2: Power budget adjusted to the 15years system. GlobeNet and Vendor derived parameters.

them and to compare their value against vendor PB proposed value.

4.1 Propagation impairments

Propagation impairments includes the impact of chromatic dispersion, phase modulation, nonlinear effects such as Self Phase Modulation (SPM), Cross Phase Modulation (XPM), Four Wave Mixing (FWM), stimulated Brillouin and Raman Scattering, as well as jitter.

It is assumed that the chromatic dispersion was sufficiently compensated which can be justified by the fact that each channel was electronically compensated in real time.

The test performed to measure the importance of these impairments consisted in monitoring the worst performing wavelength corresponding to a BER of 2.0E-4 after FEC, named hereafter test wave 11. While the BER on this wave was monitored, the remaining spectrum wavelengths were set to CW wave and added one at the time on the line without changing any output power as per table 3.

# Ch	Active channels	Relative Power /ch (dB)	Test Ch 11 BER	State	Pass/ Fail
1	11	12.3	1.00E-08	stable	
2	10, 11	9.3	5.30E-10	stable	
3	10, 11, 12	7.5	2.70E-06	stable	
4	9, 10, 11, 12	6.3	LOF	unstable	
5	9, 10, 11, 12, 13	5.3	LOF	unstable	
6	8, 9, 10, 11, 12, 13	4.5	LOF	unstable	
7	8 ,9, 10, 11, 12, 13, 14	3.9	LOF	unstable	
8	7, 8, 9, 10, 11, 12, 13, 14	3.3	LOF	unstable	
9	7, 8, 9, 10, 11, 12, 13, 14, 15	2.8	1E-4 to 2E-5	unstable	
10	6, 7, 8, 9, 10, 11, 12, 13, 14, 15	2.3	1E-5 to 6E-6	unstable	
11	6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16	1.9	4.00E-05	unstable	
12	5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16	1.5	3.60E-05	stale	
13	5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17	1.2	1.00E-05	stable	
14	4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17	0.8	6.70E-05	stable	
15	3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17	0.5	8.00E-05	stable	
16	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13,14, 15, 16, 17	0.3	7.90E-05	stable	
17	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13,14, 15, 16, 17	0	1.00E-04	stable	

Table 3: BER on test wave will other CW channels are added

As per [2] section 9.7.3, "A multi-span high-speed transmission system with complete dispersion compensation is affected by non-linear optical phenomena, particularly SPM in single-channel systems, XPM and FWM in multichannel systems. These non-linear phenomena are due to the fiber Kerr effect and their influence increases with the optical input power. As a consequence, the system performance can be strongly degraded by such non-linear effects, if the fiber input optical power is very high."

The results from table 3 below seem to corroborate the quote from [2] section 9.7.3, as follow:

For a very low channel count, 1, 2 and 3, the Self Phase Modulation is the dominant factor. The OSNR is very high and the BER very good. There is no or insignificant inter-channel crosstalk due to imperfect demultiplexing and cross phase modulation or Four Wave Mixing due to the fiber Kerr effect.

For a channel count 4 to 11, the test wave 11 performances strongly degraded. The high power per channel and the increase in channel count indicate that XPM and FWM were likely dominant.

With a channel count higher than 11, the performance are good and stable. The reduction of the power per channel likely decreased the effect of XPM and FWM.

Q Allocation for this factor is made in section 4.7 once other impairments parameters are evaluated.

4.2 Gain flatness and non-optimal pre-emphasis

We combined the effect of gain flatness and non-optimal pre-emphasis since they both result is a variation of performances across the spectrum.

The Q standard variation calculated across the spectrum is 0.35 dB. This variation should be near 0 if there would be no wavelength specific dependences. However, this value needs to be reduces since it also captures effect that would be wavelength specifics such as FWM, or combined with the propagation impairments.

Wave:	1	2	3	4	5	6	7	8	9
OSNR:	14.17	13.94	14.66	15.47	16.14	10.63	15.24	15.29	15.3
BER:	8.8E-05	5.4E-05	3.4E-05	4.1E-05	7.5E-05	3.0E-05	5.7E-05	4.9E-05	5.8E-05
Q:	11.48	11.76	12	11.91	11.57	12.07	11.73	11.81	11.72
Wave:	10	11	12	13	14	15	16	17	
OSNR:	15.66	12.87	12.29	15.14	11.68	15	12.14	14.86	
BER:	5.4E-05	2.0E-04	3.8E-05	2.0E-04	5.5E-05	1.6E-05	1.0E-04	3.3E-05	
Q:	11.76	10.98	11.95	10.98	11.75	12.38	11.41	12.02	
Q StdDev:	0.35								

Table 4: Q variation across the spectrum

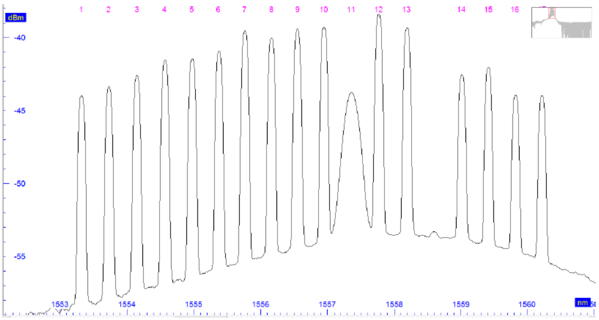

Figure 2: Receive spectrum test wave 11 with other waves CW

4.3 Wavelength tolerance

Each wavelength needs to be perfectly matched to the filtering, chromatic dispersion compensation and the position of adjacent channels. The installed terminal equipment was monitoring performances in real time and provided continuous adjustments to a number of these parameters to minimize the resulting impairment. For this reason the impairment allocation can be kept very low and 0.1 dB was allocated. No other specific derivations were made.

4.4 Polarization impairments

This group of impairments is made of Polarization Mode Dispersion (PMD) Polarization Dependent Loss (PDL) and Polarization Dependent Gain (PDG)

PMD is a statistical average of the Differential Group Delay (DGD) [3] as represented in figure 4:

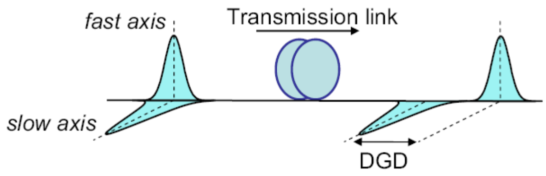

Figure 3: Differential Group Delay represented by a difference in travelling velocity between the horizontal and vertical polarization

We observed considerable variations in the system BER by physically disturbing a 40 Gb/s receiver line fiber. Since PMD is random, and changes both along the optical fiber and over time, the variation over time should be captured in the TVSP under section 4.7 and the variation along the fiber in this section.

The PMD measured on fp1 was very low with an average of 0.8 ps which correspond to a near zero Q degradation [4].

PDL mainly occurs in in-line optical components, such as isolators and couplers. It results in a change of the optical power in the transmission link. With the polarization scrambler connected to the line and monitoring the receive end with a spectrum analyzer in “overlap” mode, a maximum variation of the line gain profile of 0.1 dB was observed which correspond to a Q variation of less than 0.1 dB for the system receive average OSNR.

PDG is caused by polarization hole burning occurs when there is significant amount of the total signal power launched in a single polarization state. In this case the 40G waves used dual polarization modulation so the PDG impairment should be negligible.

4.5 Supervisory impairment

Because the supervisory wavelength is out of band on this system, impairments are considered negligeable. We monitored the best and worst average BER with the supervisory equipment ON and OFF for 14 and 41 days respectively with no significant changes in BER.

4.6 Manufacturing and environmental impairment

This impairment covers for manufacturing tolerances or changes in environmental condition. This impairment could have been evaluated by measuring the test wave performance while different boards are installed under identical conditions. This was not performed at the time of testing. However, experience of several years operating the different terminal equipment shows that performance may degrade to a maximum half a decade when a board is replaced. This represents a Q variation of 0.2 dB which will be used.

4.7 Impairment value allocation

This is a summary of the process followed under section in the order of certainty:

Supervisory impairment was the most certain to determine.

PMD was measured and **PDL** observed.

Manufacturing impairment is based on several years of field experience.

A minimum allocation of 0.1 dB for the **wavelength tolerance impairment** was set for imperfect filtering and chromatic dispersion correction.

Propagation, gain flatness and non-optimal pre-emphasis impairment were allocated a value since FWM effect is likely found in the way the Gain flatness and pre-emphasis impairment was determined.

Time Varying System Performance was derived in section 3 corresponding to a Q variation of 0.5 dB while the vendor had allocated 1.5 dB which might be a high.

Line	Description	Value	Sum	Derivation	
1.1	Propagation impairments	0.9	1.4		dB
1.2	Gain Flatness impairments			BER across spectrum	dB
1.3	Non-optimal pre-emp. impairment			contains FWM	dB
1.4	Wavelength tolerance impairment	0.1		estimated	dB
1.5-7	Mean polarisation penalties	0.2		PDL 0.1, PMD 0.1	dB
1.8	Supervisory impairment	0.0		measured	dB
1.9	Manufact. / Environ. impairment	0.2		Operation experience	dB
2	Time varying system performances	0.5	measured		dB

Table 5: Impairments allocation

5 CONCLUSION

A method has been presented to derive the PB impairments on a system with actual maximum PB capacity. An analytical break down of the line impairments showed also that only a subset of these impairments can be measured in the field with basic testing equipment.

We found that the PB line 1.1 to 1.9 impairments could be 1.3 dB lower than the vendor allocation which may seem prudent and reasonable in term of design.

GlobeNet had a great benefit, by carefully implementing new technology from a vendor that could extend the capacity on this system 120 fold over the initial design capacity, thus practically extending this system life and the adequacy of the network overall with extra impairment margin!

6 REFERENCES

[1] ITU-T G.977, 2004

[2] ITU-T Series G, Supplement 39, 2006

[3] Robust optical transmission systems: modulation and equalization / by Dirk van den Borne. Eindhoven: Technische Universiteit Eindhoven, 2008.

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