High Capacity Optical Link Budgeting for Next Generation Modems

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Abstract: Optical systems in undersea communication networks contain a variety of unique power dependent and power independent noise contributions such as fibre nonlinearity and modem implementation noise respectively. However, coherent optical modems inherently contain dynamic noise mitigation features built into the transmit and receive circuitry resulting in signal quality improvement depending on the parameters of the link. With performance metrics such as the bit-error-rate (BER) or Q, the sources of noise contributions are indistinguishable due to this propagation dependent modem implementation. Power budgets are thus formulated such that the Q factor is bound to an OSNR, creating a series of complex relationships at beginning-of-life (BOL) and at end-of-life (EOL) for each client rate. Next generation modems add a significant challenge to these relationships because of the growing permutations in features such as finer choices in client rates, nonlinear compensation, sub-carrier multiplexing, and variable forward-error correction engines. This paper deconstructs the conventional approach to optical power budgeting and introduces the Signal-to-Noise Ratio (SNR) as a fundamental metric for budgeting with next generation modems. We show how SNR-based budgeting simplifies noise segregation, improves performance margin estimation, and demonstrates a vendor-agnostic approach to measurable performance indicators of a cable.

1. INTRODUCTION

In recent years the undersea communication industry has seen significant capacity implemented using positive dispersion fibres [1]. Compounded with advanced modulation formats in coherent modems, these systems are moving closer to the Shannon limit [2]. Conventional capacity estimations using the power budget tables (PBT) described in ITU-T G.977 were suitable for early generation coherent modems due to the limited modulation formats. Such uncompensated link designs are adequately modelled by a Q vs OSNR mapping [3]. However, coherent modems are diversifying in features including probabilistic constellation shaping (PCS), frequency division multiplexing (FDM), digital nonlinear compensation (DNC), 25Gbps-50Gbps client rate granularity, rate dependent forward error correction (FEC) engines, and variable baud rates, introducing new levels of system agility for significant capacity gains [4]. In-band gain or power variations on an undersea cable can therefore easily be compensated by this array of features [5]. Consequently, this leads to an enormous family of Q vs OSNR relationships for each feature combination and power budgets would need to be formulated for the worst-case wavelength of each feature set.

Part of the complexity in the set of Q vs OSNR relationships stems from the origin of the Q-factor and its explicit relationship to the bit-error rate (BER):

$$Q = \sqrt{2}\,\mathrm{erfcinv}(2 \cdot BER) \quad \{1\}$$

The BER is related to the SNR through the DP-QPSK definition under the assumptions that each symbol is equiprobable and Gray coded:

$$BER = \frac{1}{2}\text{erfc}\left(\sqrt{\frac{SNR}{2}}\right) \qquad \{2\}$$

Substituting the BER from Equation {2} into Equation {1} produces a clear relationship between Q and SNR:

$$Q = \sqrt{SNR} \qquad \{3\}$$

This numeric formulism is extended to coherent modems with uniform n-PSK and n-QAM modulations in ITU-T G.Supl. 41 through an eye-closure (EC) distortion factor such that:

$$Q = \sqrt{EC \cdot SNR} \quad \{4\}$$

Advanced transmission systems no longer satisfy this relationship; their modulation schemes and coding dictionaries exhibit a complex BER to SNR relationship through fitting of the coefficients A and B:

$$Q = \sqrt{2}\,\text{erfcinv}[2BER] \qquad \{5\}$$

where BER is defined by:

$$BER = \sum_{k=1}^{N} A(k)\text{erfc}\left(\sqrt{|B(k)| \cdot SNR}\right) \qquad \{6\}$$

For an arbitrary next generation modem at one FDM, and no DNC, an example of the Q vs OSNR back-to-back curves required to perform a power budget is shown in Figure 1.

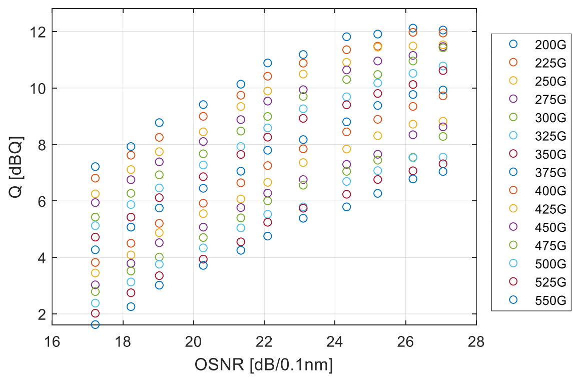

Figure 1. Family of Q vs OSNR curves for Q-based budgeting.

For a modem offering *b*-baud rates, *f*-FDMs, *n*-NLC features, and *c*-Client rates, this equates to $b \times f \times n \times c$ number of back-to-back curves. The computation complexity is further exacerbated when manufacturing variances, aging, FEC limits and customer margins are required as defined in the current approach for PBTs. These permutations become unmanageable for planning, field trials, and deployment commissioning.

We propose an approach at power budgeting where the electrical and optical noises in a system are treated as additive. Impairments for each element are thus represented directly by a noise and a variance.

2. METHOD

In undersea links that are representative of a zero mean Gaussian noise environment [6]-[7] the total optical or electrical noises σ^2 are additive:

$$\sigma^2 = \sigma_{ase}^2 + \sigma_{nl}^2 + \sigma_{imp}^2 \qquad \{7\}$$

Where σ_{ase}^2, σ_{nl}^2, and σ_{imp}^2 are the noise contributions from ASE, nonlinearity, and other impairments respectively. Examples of 'other impairments' include, but are not limited to, modem noise, PMD, chromatic dispersion, etc. At a reference signal power P_r, Equation {7} can be rewritten in SNR, where:

$$\sigma^2 = \frac{P_r}{SNR(P_r)} \qquad \{8\}$$

$$\sigma_{ase}^2 = \frac{P_r}{SNR_{ase}(P_r)} \qquad \{9\}$$

$$\sigma_{nl}^2 = \frac{P_r}{SNR_{nl}(P_r)} \qquad \{10\}$$

Leading to:

$$\frac{1}{SNR(P_r)} = \frac{1}{SNR_{ase}(P_r)} + \frac{1}{SNR_{nl}(P_r)} + \frac{1}{SNR_{imp}} \qquad \{11\}$$

However, when a coherent modem reports SNR, the total noise contribution is scaled by a distortion term δ associated with modem implementation. In a back-to-back configuration the total SNR takes the form:

$$\frac{1}{eSNR} = \delta\left(\frac{1}{SNR_{ase}} + \frac{1}{SNR_m}\right) \qquad \{12\}$$

where SNR_m is the modem implementation noise and $eSNR$ symbolises the electrical signal-to-noise ratio reported by the modem. For simplicity the reference power P_r is assumed to be 0dBm and the modem implementation is assumed to be power independent.

Using Equations {5}, {6}, and {12}, Figure 1 can be recast in eSNR space as shown in Figure 2. The OSNR is converted to SNR_{ase} using the relation:

$$\frac{1}{OSNR} = \frac{B_o}{B_e SNR_{ase}} \qquad \{13\}$$

Where B_o is the reference optical noise bandwidth (12.5GHz), and B_e is the double-sided electrical bandwidth of the modem (70GHz in this example).

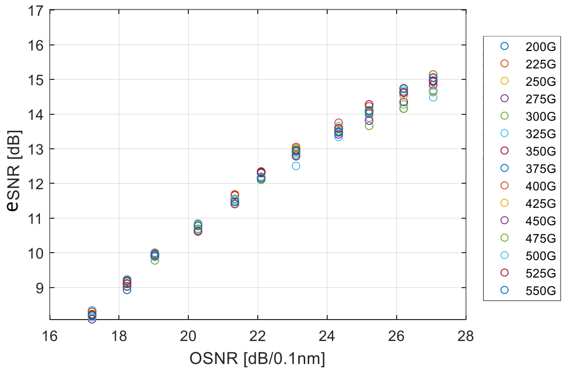

Figure 2.eSNR vs OSNR curves for SNR-based budgeting.

This dramatic simplification where all client rates show a unified relationship is owed to the common noise shared between all client rates. Conventional Q-based power budgeting may be performed from this eSNR curve if a Q (or BER) to eSNR relationship has also been calculated. Thus, cable and terminal impairments may be budgeted in a top-down approach where the eSNR vs OSNR relationships are recomputed after propagation impairments, other impairments, Q time variations, and end of life (EOL) impairments. The result provides a commissioning limit based on eSNR. This eSNR encompasses all noise contributions of the SLTE and cable system:

$$\frac{1}{eSNR} = \delta\left(\frac{1}{SNR_{ase}} + \frac{1}{SNR_m} + \sum_{i=0}^{n}\frac{1}{SNR_i}\right) \quad \{14\}$$

where SNR_i is the sum of implementation impairments due to Submarine Line Terminal Equipment (SLTE) noise, fibre nonlinearity, dispersion, polarization effects, and DWDM filter penalties.

Using the described PBT methodology we look at the consequences of using eSNR in a Q-based budget and further propose an entirely SNR-based budget for high capacity complex transmission technologies.

3. RESULTS AND DISCUSSION

Q-Based Budgeting with eSNR

It has been shown that the eSNR provides the simplest representation for high feature set modems. When applying conventional Q-based budgeting, several components can affect the eSNR commissioning limit; Figure 3 illustrates the process of Q budgeting from a back-to-back eSNR curve. In this figure, the following steps are performed:

(1) The ASE contribution to the line is the beginning of life (BOL) reference.
(2) From this reference the curve is recomputed after the propagation impairment (fibre nonlinearity) is accounted for. This is required as fibre nonlinearity is a noise distortion and hence applied in the SNR domain.
(3) Other Impairments of the PBT manifest themselves as only a linear Q impairment, causing the linear offset. This causes an excess penalty across the entire SNR_{ase} range, whereas Equation {14} suggests a

dependence of impairments relative to an SNR_{ase} value.

(4) Cable repair and aging impairments are manifested as an additional OSNR degradation on the derated curve. This aging impairment is performed after the contribution of the transponder terminal equipment (TTE) thereby aging both TTE and cable. TTE aging is again compounded over the cable aging impairment.

(5) The FEC limit is stated as the limit to error free operation.

(6) Extra and Customer margins are allocated above this FEC limit. These margins do not represent the net system margin (NSM) as it is referenced at an SNR_{ase} close to the FEC limit of the TTE.

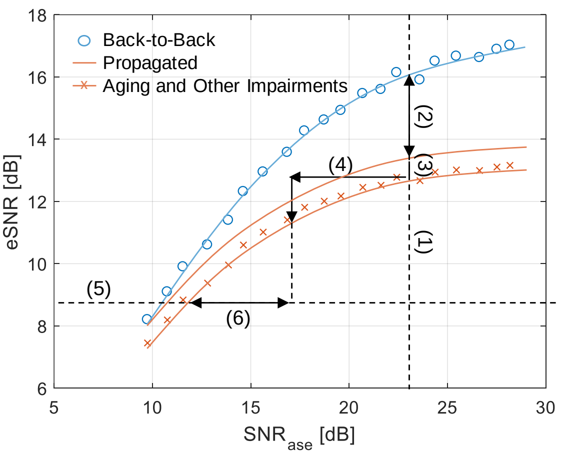

Figure 3. Q-based budgeting applied in the SNR domain.

Without significant manipulation to the Q budget, the current order of operations constrains the capacity limit for next generation modems by over allocating impairments in multiple categories. Furthermore, with modem technologies advancing at an accelerated cadence, the 25 year EOL ITU-T G.977 budget requirements contrive redundant margins thus contributing to the capacity limitations of the cable system.

SNR-Based Budgeting

The objective in SNR budgeting is to achieve an NSM that is a direct indication of how much total margin exists on a commissioned system. The NSM is defined as the difference between the channel's delivered SNR_{ase} and the required SNR_{ase} ($RSNR_p$) to maintain a specified BER at the forward error correction (FEC) limit after propagation [8]:

$$NSM = SNR_{ase} - RSNR_p \qquad \{15\}$$

An accurate budget should be designed such that:

a. Cable penalties and TTE penalties are independent
b. TTE penalties should be transparent across all feature sets such as client rates
c. TTE tolerances should be independent to the system impairments
d. Margins should be expressed as the total system margin or NSM
e. Commissioning should be agnostic of TTE loading and features.

The SNR budget proposed utilises a bottom-up approach. It begins with the modem's back-to-back $RSNR$ and applies penalties of the SLTE and line to reach the propagated $RSNR_p$ as shown in Figure 4.

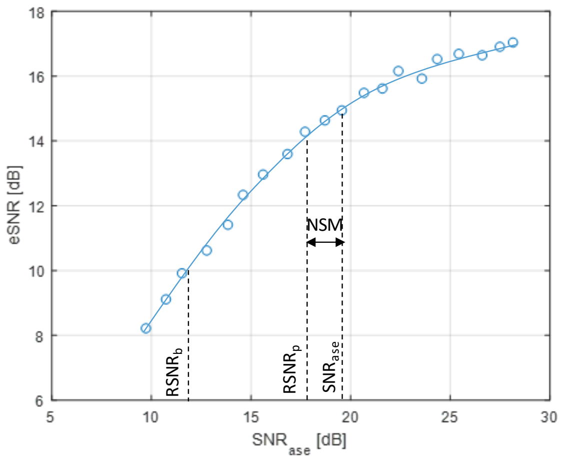

Figure 4. Illustration of bottom-up approach in SNR budgeting.

These provide the fundamental parameters to determine the NSM and hence the expected performance over a specified cable lifetime. Table 1 shows the proposed approach to SNR-based budgeting. The table is sub-divided into sections that can be specified by the cable vendor, modem vendor, and operator/customer independently. The line descriptions are as follows:

Line 1.1: Specifies the BOL ASE OSNR expressed as an SNR. A tolerance is included to account for the SNR profile across the band, equalization, and/or manufacturing variance.

Line 1.2: Is the signal droop impairment of Line 1.1. A tolerance may be applied if necessary.

Line 1.3: Any impairments due to filters, amplifiers, couplers, etc. in the chosen SLTE(s). The tolerance may also include manufacturing and/or aging impairments if necessary.

		Penalty SNR [dB]	**Tolerance SNR [dB]**
	Wet-Plant		
1.1	Line ASE	*A*	*a*
1.2	Droop	*B*	*b*
1.3	SLTE ASE	*C*	*c*
1.4	Repair and Aging Margin	*RA*	
1.5	Wet-Plant Target SNR_{ase}	SNR_{ase}	
	TTE+SLTE		
2.1	TTE RSNR	*D*	*d*
2.2	Nonlinearity	*E*	*e*
2.3	Dispersion	*F*	*f*
2.4	Polarization Effects	*G*	*g*
2.5	DWDM/Filter Effects	*H*	*h*
2.6	Other Impairments	*I*	*i*
2.7	System RSNR	$RSNR_p$	
	Margin		
3.1	Customer Margin	*CM*	
3.2	Net System Margin	*NSM*	

Table 1. Proposed SNR-based optical budget table

Line 1.4: The repair and aging (*RA*) corresponds to the repair guidelines set out in ITU-T G.Sup.41 for shallow and deep water repairs.

Line 1.5: The final delivered ASE SNR after budgeting for Lines 1.2 to 1.4. It is given by:

$$SNR_{ase} = \left[\frac{1}{RA} + \sum_{z=A+a}^{C+c} \frac{1}{z}\right]^{-1} \qquad \{16\}$$

Line 2.1: Specifies the back-to-back RSNR of the modem. The tolerances may include manufacturing and/or aging impairments depending on the state of the technology.

Line 2.2: An analogy to the propagation impairments of conventional Q-based budgeting. It represents the SNR due to fibre nonlinearity.

Line 2.3: Dispersion related penalties such as transmit pre-compensation, receive post-compensation, or the laser linewidth interaction with link dispersion.

Line 2.4: Polarization effects may include any impairments such as PMD and PDL.

Line 2.5: DWDM/Filter effects are commonly associated with flexible grid systems and inter-channel cross-talk penalties and should include the impact of wavelength tolerance

Line 2.6: Other impairments related to all unspecified penalties.

Line 2.7: The System RSNR ($RSNR_p$) is the summation of all noise penalties referenced to the TTE RSNR:

$$RSNR_p = \left[\frac{1}{D+d} - \sum_{z=E+e}^{I+i} \frac{1}{z}\right]^{-1} \qquad \{17\}$$

Line 3.1: Additional SNR margin a customer may request for system operation (CM).

Line 3.2: The NSM is the difference between Line 1.5, Line 2.7, and Line 3.1. That is,

$$NSM = SNR_{ase} - \left[\frac{1}{D+d} - \sum_{z=E+e}^{I+i} \frac{1}{z}\right]^{-1} \qquad \{18\}$$

Trans-Pacific SNR Budget Example

A recent field trial of an offline capture and compute evaluation platform was used to test the NSM concept. The evaluation platform was a 71GBd, four FDM, and PCS encoded transmitter with line rates tuneable in increments of 25Gbps of client capacity. The transmitter was coupled into an 8400km dispersion uncompensated trans-Pacific cable followed by an offline receiver. Figure 5 captures the measured Q margin at each client rate. 400G was the highest client rate that was able to perform error free.

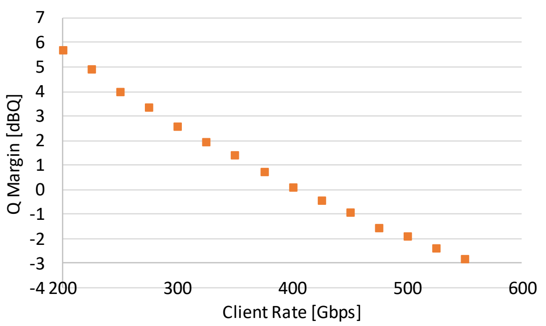

Figure 5. Measurements of Q margin from an 8400km field trial.

An SNR-based budget was formulated and the TTE RSNR varied for each client rate. The SNR penalties in the table remain the same since the noise contributions of the cable system do not change. Table 2 shows the static parameters of the SNR budget through a range of client rates. For each client rate, the TTE RSNR, total system $RSNR_p$ and NSM values are calculated. SNR values of 100dB indicate no penalty or an absence of that item.

Trans-Pacific Field Trial		**Penalty SNR [dB]**	**Tolerance SNR [dB]**
	Wet-Plant		
1.1	Line ASE	*12.87*	*0.00*
1.2	Droop	*30.00*	*0.00*
1.3	SLTE ASE	*100.00*	*0.00*
1.4	Repair and Aging Margin	*100.00*	
1.5	Wet-Plant Target SNR_{ase}	*12.79*	
	TTE		
2.1	TTE RSNR	*[…]*	*0.00*
2.2	Nonlinearity	*22.00*	*0.00*
2.3	Dispersion	*24.50*	*0.00*
2.4	Polarization Effects	*23.60*	*0.00*
2.5	DWDM/Filter Effects	*26.10*	*0.00*
2.6	Other Impairments	*100.00*	*0.00*
2.7	System RSNR	[…]	
	Margin		
3.1	Customer Margin	*0.00*	
3.2	Net System Margin	[…]	

Table 2. SNR budget of a trans-Pacific cable system.

The NSM as a function of client rates is illustrated in Figure 6, where the budget correctly predicts that 400G contains positive margin and thus able to run error free.

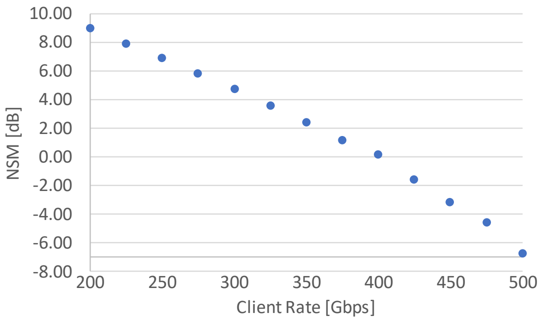

Figure 6. Net system margin budget of a trans-Pacific cable system.

SNR Commissioning

Commissioning an SNR budgeted system is non-trivial due to the complex conversion from the System RSNR to a noise-*unloaded* equivalent. The bottom-up approach is a methodology at establishing the performance limit for a particular TTE technology. If the NSM is positive, the chosen TTE will run error free. However, commissioning based on noise-unloaded BOL performance was a concept introduced in Q-based budgeting to demonstrate confidence over complex cable systems such as legacy dispersion managed links. Dispersion uncompensated cables lend themselves to easier deployment conditions and capacity predictions as margin is the primary indicator of TTE suitability.

Many approaches exist for commissioning a system based on eSNR. For example, the NSM may be demonstrated through receiver optical noise loading to establish the $RSNR_p$. Alternatively, it can be shown that the difference in the TTE reported eSNR at a given SNR_{ase} is greater than the impairments listed in Table 1, that is:

$$\frac{1}{\delta \cdot eSNR} - \frac{1}{SNR_{ase}} - \frac{1}{SNR_m} \geq \sum_{z=D+d}^{I+i} \frac{1}{z} \quad \{19\}$$

The topic of commissioning is still under further study as industry requirements would drive how commercial liability is prescribed.

4. CONCLUSION

SNR based budgeting introduces a simplification of noise representation for advanced transmission technologies with a wide range of features. In contrast to Q-based budgeting, the SNR approach demonstrates an accurate representation of system margin and isn't subject to excess noise allocations that can adversely affect system capacity.

5. REFERENCES

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