ULTIMATE CAPACITY OF OPEN CABLE PROJECTS

Dmitriy Kovsh, Lee Richardson, Maxim Bolshtyansky, Alexei Pilipetskii (SubCom)
Email: dkovsh@subcom.com

SubCom, 250 Industrial Way West, Eatontown, NJ, 07724 USA.

Abstract: Customers of Open Cable systems want a projection of total system capacity in the years after commissioning. However, with the continuing advances in coherent technology, new undersea systems will likely support higher total capacity than the estimates provided during the project bid stage. It will therefore be beneficial to establish a common methodology for quoting future capacity.

While linear and nonlinear Shannon Capacity can be easily evaluated using key parameters of the transmission path, it is preferred to quote more realistic capacity values that in fact can be achieved with future transponders. In this paper we propose several practical rules for estimating future system capacity. We demonstrate tradeoffs between available margins as documented in Performance Budget Tables and capacity, taking advantage of the variable Spectral Efficiency (SE) feature of modern coherent modems.

We also propose a means to derive total capacity based on implementation penalties relative to the Shannon limit, and on the Nonlinearity Compensation (NLC) capabilities that can be expected at time of deployment. Since the assumptions made for both values during the design process can be documented, the resulting assumptions of total capacity become more transparent, thus facilitating adjudication of a given design solution.

1. INTRODUCTION

Traditionally, the contracted performance of a new undersea cable has been characterized by a Commissioning Limit Q-factor for a modem that is expected to be used during the system commissioning. A Power Budget Table (PBT) provides calculations of this value, starting from the Optical Signal-to-Noise value (OSNR) and the modem back-to-back performance. The inclusion of various implementation and environmental margins allocated by the system supplier then provides Beginning-Of-Life (BOL) and End-Of-Life (EOL) Q values for the worst channel within the available data band. System capacity is evaluated based on the number of data channels.

With the rapid developments in coherent modem technology and competition among modem vendors, it has become beneficial to instead contract new projects as “Open Cables,” without a commitment to any particular vendor or generation of Submarine Light Termination Equipment (SLTE). This allows Purchasers to delay SLTE selection until system commissioning. A new method is therefore required to characterize cable performance. Estimation of future system capacity is still a challenge for open cables, as this is a critical value for customers to make a business case for their new project.

2. SYSTEM CHARACTERIZATION

Industry progress has been made in the definition of a “modem-independent” performance metric for dispersion-uncompensated Open Cable systems by introducing a concept of Generalized OSNR (G-OSNR) that incorporates both linear and nonlinear noise contributions to performance. The most generic description is as follows [1]:

$$SNR = \frac{P_{sig}}{P_{ASE}+P_{NL}}, \quad (1)$$

The P_{ASE} and P_{NL} terms are the linear and nonlinear noise, and P_{sig} is optical power of a data channel. If SNR is computed for a given number of carriers and scaled to 0.1nm resolution bandwidth, it is referred to as G-OSNR, so that it can be compared to OSNR to evaluate the amount of nonlinearity on the fiber pair [2]. For example, a customer may require that the difference between OSNR and G-OSNR not exceed a specific value.

The nonlinear noise contribution, P_{NL}, can be approximated based on the GN Theory, assuming a Gaussian distribution of both signal and noise [3]. For Nyquist channel loading, this leads to a closed-term expression. It is proposed that experimental validation of G-OSNR be executed using a well-characterized modem (e.g. PM QPSK) as G-OSNR "test equipment" [4].

While G-OSNR provides a performance metric for developing Open Cable Performance Budgets, it does not by itself offer a view on achievable system capacity. An upper limit of fiber capacity can be estimated from the Shannon formula based on signal to noise ratio (SNR) of a transmission channel with Additive White Gaussian Noise (AWGN) [5]:

$$C = 2 \cdot BW \cdot log_2(1 + SNR), \qquad (2)$$

This value is referred to as "Linear Shannon Capacity" or "Nonlinear Shannon Capacity," depending on whether the SNR includes only linear (ASE) noise or both linear and nonlinear terms. This value is useful, but typically overestimates the eventual practical system capacity.

In this paper, we show how to "bridge" this Shannon Capacity to a more realistic capacity available from achievable modems. We will include additional penalties of the transmission path and the modem, with supporting margins that can be budgeted via Open Cable and/or traditional Performance Budget Tables. This allows us to quote a "practical capacity" of an Open Cable project, with documented assumptions on modem performance and allocated margins.

3. OPEN CABLE SNR (G-OSNR)

For simplicity of tracking additional terms, we can re-write equation (1) as follows:

$$\frac{1}{SNR} = \frac{1}{OSNR_{ASE}} + NSR_{NL}, \qquad (3)$$

The $OSNR_{ASE}$ term here is linear OSNR of a transmission path, and NSR_{NL} is the ratio of nonlinear noise and signal powers.

An additional noise contribution should be added to include Guided Acoustic Wave Brillion Scattering (GAWBS) [6], where the γ_{GAWBS} term is a function of system length and fiber affective area.

$$\frac{1}{SNR} = \frac{\alpha}{OSNR_{ASE}} + \gamma_{GAWBS} + NSR_{NL} \qquad (4)$$

We have also introduced a margin term α that can represent various margins related to cable implementation (Manufacturing Margin, Equalization Margin, Ageing and Repairs).

Open Cable Performance Budgets that reflect Commissioning values of OSNR and G-OSNR can be provided based on (4).

4. MODEM SNR

To unify the characterization of open cables, the definition of the term NSR_{NL} must be agreed on. It can be defined based on the white Gaussian noise as NSR_{NL}^{GN}, following the GN theory [3]. As mentioned above, it can alternatively be referenced to a well-characterized modulation format that does not depend on vendor implementation, e.g. PM QPSK, NSR_{NL}^{QPSK}. Both definitions are related, and the scaling factor between the two has weak dependence on system parameters:

$$NSR_{NL}^{ref} = NSR_{NL}^{QPSK} = f_m \cdot NSR_{NL}^{GN}, \qquad (5)$$

As G-OSNR is currently measured using QPSK modems as test equipment, going forward in this paper we will use QPSK as a reference modulation format.

Modems that can offer mitigation or partial compensation of nonlinear impairments will lead to a reduced value of NSR_{NL} that can be captured via a scaling factor, f_{NLC}, that defines the capabilities of nonlinearity compensation (NLC) compared to the reference modulation scheme:

$$NSR_{NL}^{modem} = f_{NLC} \cdot NSR_{NL}^{ref}, \qquad (6)$$

To demonstrate the difference between nonlinear terms computed for a given modem to that based on GN theory, please see Figure 1 below.

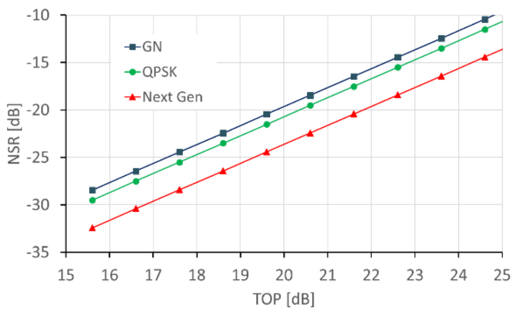

Figure 1. Comparison of NSR computed from GN theory, for a reference modem, and for next-gen modem with NLC.

To optimize the design of a new system, the dependence of performance on repeater output power is considered. Utilizing maximum available repeater Total Output Power (TOP) will allow stretched repeater spacing and therefore reduced system cost.

For an Open Cable, it is important to agree upon a specification for the expected NLC strength when designing a new system. Figure 2 shows how SNR varies with repeater TOP based on the assumptions on NSR_{NL} term used in the equations (3) and (6).

The performance derived using GN theory has slightly lower SNR and lower peak TOP than is expected for realistic modulation formats. The NLC of next-gen modems, shifts the peak performance to even higher values of TOP, impacting the design.

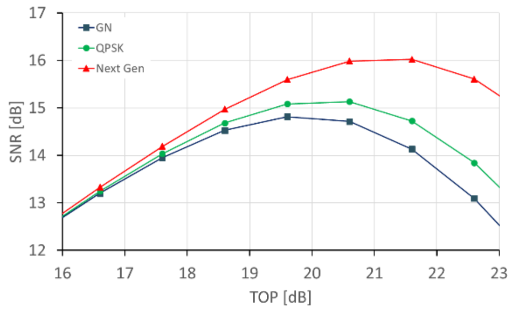

Figure 2. Comparison of SNR computed from GN theory, for a reference modem, and for next-gen modem with NLC.

If the system capacity is to be evaluated based on SNR, it is important to include back-to-back performance characteristics of the next-gen modem. To do that, we introduce two additional terms:

$$\frac{1}{SNRe} = \frac{\delta}{OSNR} + \frac{1}{OSNR_{imp}} \qquad (7)$$

Here $OSNR_{imp}$ captures the additional noise impairment introduced by the modem. The δ term accounts for the lower back-to-back performance of the modem compared to what was assumed in deriving Shannon Capacity.

As the SNR of (7) is now tied to a modem, we refer to it as SNR Effective or “SNRe” to differentiate it from the cable SNR discussed previously. Modem providers can extract δ and $OSNR_{imp}$ from back-to-back measurements or predict these values for their next generation equipment.

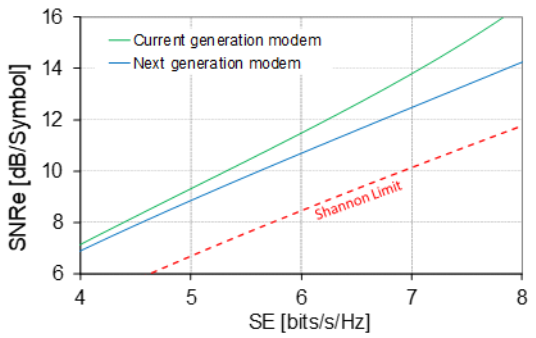

Figure 3. Effective SNR (SNRe) for a modem with current and next generation specifications.

An example of modem performance relative to Shannon can be seen in Figure 3, with δ = 2.05 dB and $OSNR_{imp}$ = 26 dB/0.1 nm. This plot includes the modem modulation/coding format and the error correction scheme. It also includes the physical implementations of the modem that behave similar to a noise floor.

5. SYSTEM CAPACITY

Now we can evaluate the total system capacity with an assumed set of next-gen modem characteristics using the following formula:

$$C = 2\sum_i BW_i \cdot log_2(1 + SNR_e^i), \quad (8)$$

The summation in (8) is over all the channels in the data band, although performance across the band may vary due to non-ideal gain shape or wavelength dependence of modem parameters.

The SNRe of each channel can be approximated by (3) - (7) and written as

$$\frac{1}{SNRe} = \frac{\delta \cdot \alpha}{OSNR_{ASE}} + \gamma_{GAWBS} + f_{NLC} \cdot f_m \cdot NSR_{NL}^{GN} + \frac{1}{OSNR_{imp}} \quad (9)$$

The coefficients α, γ_{GAWBS} and NSR_{NL}^{GN} are characteristics of the Open Cable and provided by the undersea system designer.

The parameters δ, $f_{NLC} \cdot f_m$ and $OSNR_{imp}$ are defined by the modem provider.

As an example, Table 1 lists fiber capacity values for an example 10,000km link designed with full C-band EDFAs. First four rows show capacity values computed using Equation (8), while the last two derived from the conventional PBT.

Linear Shannon Capacity	39.1
Nonlinear Shannon Capacity	30.2
Calculated Capacity (Next Generation Modem Specification)	28.6
Calculated Capacity (Current Generation Modem Specifications)	23.1
Budgeted BOL Capacity (Current Generation Modem specifications)	19.4
Budgeted EOL Capacity (Current Generation Modem Specifications)	17.2

Table 1. Example of Design Capacities projected for a 10,000km C-band link, given in Tbps units.

The wet plant supplier and modem provider parameters used in the calculations of Table 1 are given in Table 2. The accuracy of the modem parameters at the time of undersea system design will depend on the development status of the equipment.

Cable	$OSNR_{ASE}$	17.6 dB
	α	0.4 dB
	γ_{GAWBS}	-26.5 dB
	NSR_{NL}^{GN}	-17.7 dB
Modem (current/ next-gen)	δ	2/2.05 dB
	$f_{NLC} \cdot f_m$	0.67/0.32
	$OSNR_{imp}$	23.8/26 dB

Table 2: Parameters for the capacity predictions in Table 1

6. DISCUSSION

The presented methodology for including SNR contributions due to the Open Cable transmission path and the customer-specified

SLTE assumptions into capacity calculations offers several advantages:

- The performance budgets can be constructed for Open Cable in terms of OSNR / G-OSNR, and then "bridged" to a Q-factor budget via SNR.
- The capacity predictions provided by different modem vendors can be compared on the same "Open Cable" design.
- The performance impairments due to the Open Cable transmission path and the modem technology can be directly compared in terms of Capacity or total SNR degradation.

Measurement techniques must be qualified to validate performance at system commissioning. As discussed, deriving Open Cable SNR or G-OSNR from measurements with 100G QPSK modems as test equipment provides a practical approach. It is feasible to relate modem parameters to the reference modulation scheme. This will simplify calculations of the factor f_m in the equation (9) and offer a reference modem for system characterization.

7. PERFORMANCE BUDGETS FOR OPEN CABLE SYSTEMS

The submarine industry has long accepted the standard (ITU-T G.977) Q-based Power Budget Table (PBT) to characterize system performance. Calculations of commissioning OSNR can be added to justify value of Line A in the standard PBT [7].

This traditional approach however does not allow for a full optimization of Open Cable system designs to reach maximum fiber pair capacity. It supports design optimization based only on performance of available modems. Additionally, the capacity is computed based on the worst performing channel Q, under the assumption of loading with uniform Spectral Efficiency across the data band.

To better optimize system capacity based on the anticipated modem characteristics, it would instead be beneficial to compile the budget in terms of SNR as shown in Table 3. If modem parameters are not known, the SNR column of OC-PBT can be compiled using P_{NL} computed from "modem agnostic" equations of the GN theory or a known modulation scheme (QPSK). This OC-PBT based on a currently available modem can then be used by the customer to generate a PBT for a particular next-gen modem using a "bridge" calculation.

The methodology defined in this paper entirely eliminates the need for Q-based PBT in the design characterization of Open Cable Projects as long as next-gen modem parameters are documented and can be used in calculations of the SNR column of OC-PBT as shown in Table 3.

	OSNR	SNR
Design OSNR/SNR		
Signal Droop		
ROADM(s) Impairment		
Impairment due to Terrestrial Extension(s)		
Nominal OSNR/SNR		
GAWBS		
Manufacturing Margin		
Flat Launch Average		
Equalization Margin		
Equalized Average		
Worst Case		

Table 3. Open Cable Performance Budget Table (OC-PBT), in dB/dBm units.

8. AVERAGE VS. WORST CASE

Modern day modems that offer variable spectral efficiency can be configured for optimum performance in each part of the band, so that the overall capacity estimated by (8) follows the average SNR of transmission path rather than the value in the worst performing part of the band. Uniform spectral efficiency is not required across the spectrum band.

While it is important to characterize the performance across the data band to determine modem set points, it is less important in calculations of total FP capacity of an Open Cable. Long chains of EDFAs will not respond to changes of channel transmit power in a linear fashion due to Spectral Hole Burning. Hence pre-emphasizing part of the band to improve its performance may lead to lowering average SNR across the band. Optimizing worst-case channel(s) performance may not be beneficial when maximizing total fiber pair capacity is the goal.

9. COMPARING IMPAIRMENTS

Currently implementation impairments allocated for wet-plant are tracked as OSNR degradations while modem imperfections are expressed in PBT as Q-penalties. With the proposed approach allocation of performance margins and tracking of performance penalties via SNR simplifies comparison of the impacts of wet-plant and dry-plant imperfections on the overall cable capacity. For example, the penalty caused by gain shape deviations can be illustrated in terms of cable SNR as shown in Figure 4.
The two curves capture how much the average SNR is impacted by gain error as expressed in gain tilt, defined as linear fit to the end-to-end gain shape. The calculation is for a typical transpacific link with full C-band EDFAs and designed to operate near the peak performance point in terms of repeater Total Optical Power (TOP).

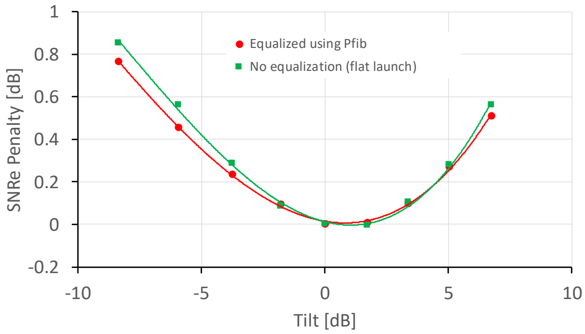

Figure 4. Comparison of SNRe penalty versus gain tilt/error with and without transmit spectrum equalization

One can see that measurements of SNRe penalty made with a uniform launch spectrum ("flat launch") and measurements made with pre-emphasis adjusted for equal sum of transmit and receive power for all channels ("Pfib") are nearly identical in terms of the measured penalty on average SNR. Also, gain tilts within a ± 5dB range lead to modest SNR penalties of less than 0.5dB.

The SNR penalties of a modem can be estimated by partitioning factor δ in Equation (9) into the "nominal" value that represents theoretical performance of a given modulation scheme and then added margins (implementation, manufacturing, etc.). SNR margin allocated for the SLTE can also be derived from the existent PBT table using back-to-back curves.

Whether a particular SNR penalty comes from the cable or the modem, we can also translate this value to the capacity degradation as defined by Equation (8). For instance, 0.5dB of SNR penalty translates to about 4% of capacity degradation.

10. CONCLUSIONS

We have proposed a methodology for the estimation of system capacity based on Effective SNR (SNRe) as calculated from cable and modem characteristics. This allows Purchasers to simplify the adjudication process between system suppliers by expressing all impairments in terms of SNR and achievable capacity, with clearly stated assumptions for all parameters.

11. REFERENCES

[1] O. V. Sinkin et al., "Effective signal to noise ratio performance metric for dispersion-uncompensated links," in 2015 European Conference on Optical Communication (ECOC), 2015

[2] E. Grellier, et al, "Quality parameter for coherent transmissions with Gaussian-distributed nonlinear noise," Vol. 19, No. 13, OPTICS EXPRESS

[3] P. Poggiolini, "The GN Model of Non-Linear Propagation in Uncompensated Coherent Optical Systems," J. Lightwave Technology, vol. 30, no. 24, Dec. 2012

[4] P. Pecci et al, "Experimental characterization of submarine "open cable" using Gaussian-Noise model and OSNRWET parameter," OFC2017, M2E.4

[5] C.E. Shannon, "Communications in the Presence of Noise," 1949, Proc. of IEEE

[6] M.A. Bolshtyansky et al "Impact of Spontaneous Guided Acoustic-Wave Brillouin Scattering on Long-haul Transmission," in Proc. Optical Fiber Communication Conference (OFC), March 2018, M4B.3.

[7] ITU-T G.977

