THE SUBSEA FIBER AS A SHANNON CHANNEL

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Abstract: The Q-budget table (ITU-T G.977), detailing the margin breakdown for modulated channels, has long been used to characterize transmission performance of subsea cables. However, the emergence of coherent detection and Digital Signal Processing (DSP) capabilities have enabled a wide range of modulation schemes featuring various bit rate, FEC encoding, constellation and spectral shaping, non-linear effect mitigation, leading to a transponder-dependent fiber transmission capacity. Combined with the recent industry trend to deploy "open" cables, a new method is required to characterize subsea fiber performance independently of the transponder type.

1. INTRODUCTION

Historically, the definition and characterization of transmission performance for optical subsea links has been based on power budget tables, where the metric for channel performance was the Q-factor as prescribed by ITU-T standards G-976 and G-977 [1-2-3].

The advent of transponders based on polarization multiplexed, multilevel modulation formats with DSP-enabled coherent receivers completely changed the industry approach to coupling of wet plant designs and SLTE. DSP-enabled coherent transponders offered unprecedented flexibility in SLTE operations, putting many different modulation formats, symbol rates, FEC and thus line rates within a single box.

Decoupling of the wetplant and SLTE for design testing and cable operation, now referred to as "Open Cable" design [1], has become fundamental f to exploit the notably faster update cycles of SLTE, allowing the same wetplant to be used with many generations of SLTE. The overall business benefit of this decoupling is a more efficient equipment utilization and a lower total cost of ownership. Considering the design and operational aspects, cable designers need to be able to assess wetplant performance and capacity independently from a particular modem technology, so that Q-factor based performance assessment is clearly unfeasible. A standardized, measurable metric assessing cable performance and potential to estimate the transmission capacity is mandatory.

2. DEFINING GSNR: A NEW PERFORMANCE METRIC

In dispersion uncompensated transmission scenarios, it has been extensively shown that fiber propagation impairments caused by the interplay of loss, chromatic dispersion and Kerr nonlinearity can be approximated as an additive white Gaussian noise (AWGN) or disturbance on any single frequency, named nonlinear interference (NLI)[1-2], also in presence of Stimulated Raman Scattering

[3]. As all major propagation impairments, i.e. amplified spontaneous emission (ASE) noise, and NLI can be modeled as Gaussian disturbances, a unique metric in the form of a signal-to-noise ratio (SNR) can be used to assess the performance of each channel. This metric has been defined as effective or Generalized SNR (GSNR) and is the ratio between the power of useful signal, divided by the sum of the powers of all noise sources - such as ASE and NLI - evaluated in the signal bandwidth.

$$\frac{1}{GSNR} = \frac{1}{SNRase} + \frac{1}{SNRnle}$$

Note that any propagation impairment that can be modeled as Gaussian noise can be properly included in the definition of GSNR. All noise sources associated to GSNR measurement equipment (e.g. electrical noise, implementations and other non-idealities) should not be included in the definition of GSNR.

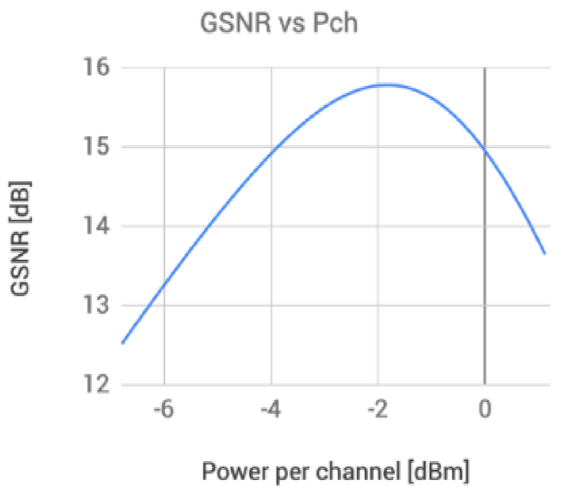
There is no dependence to eye-opening in GSNR, as there is for Q-factor. There is, however, a hidden dependence associated with symbol rate and the grid spacing of the channels. As current transponders rely on root raised cosine pulse shaping, independently from the selected modulation format or transmission technique, and in subsea systems it is desirable to pack channels as tightly as possible, one can consider typical loading scenarios as a reference for performance assessment (e.g. 32 GBaud signals over 37.5GHz WDM grid), or assume Nyquist spaced full loading for worst case performance estimation.
The sections that follow discuss recommendations for how to model GSNR, how to measure it, and how it may be used for capacity estimation.

3. ESTIMATION ACCURACY

As ASE and NLI noise represent the two main contributions in the definition of GSNR, it is fundamental to understand the impact of estimation accuracy of each of these quantities over the overall GSNR estimation. The nonlinear nature of fiber propagation implies that the nonlinear SNR decreases linearly with the cube of the transmitted power into the fiber, whereas the linear one increases in a linear relation with it. Depending on signal power level, either linear or nonlinear noise will represent the dominant source of impairment, and that an optimum power level exists. Power optimization theory for GSNR [1-2] states that, under the assumption of uniform channel loading, flat launch power and flat linear SNR vs frequency, the GSNR of the center channel is maximized when the ASE noise power is twice as much as the NLI noise power, i.e. the nonlinear SNR is 3 dB higher than the linear SNR, and the resulting nonlinear penalty amounts to 1.76 dB. Hence, at optimal power, propagation impairments are mainly linear in nature, therefore the accuracy of GSNR estimations in this regime largely depends the accurate characterization of linear noise sources.

Recall that over the last 2 years, cable designs have trended toward more linear operating regimes rather than for GSNR maximization (i.e. optimal power), to improve the power efficiency of the cable design while scaling cable capacity via SDM (Spatial Division Multiplexing) solutions. Therefore, the difference between ASE and NLI noise will be larger with respect to designs at or above the optimal power level, and there is less impact of an estimation error on the nonlinear SNR.

This concept is demonstrated in Figure 1 where a fixed 0.1 dB error on linear SNR, and a varying relative error on nonlinear SNR in the range of 0.5 to 2 dB are assumed (Fig. 1). The relative error over the GSNR is then represented as a function of the power per channel. For all power levels below the optimal power (-2 dBm), which correspond to the design region of interest for next generation open cables, an error on the nonlinear noise estimation of up to 1 dB, results in GSNR errors less than 0.3 dB. Once again, the highest return on investment to ensure overall GSNR accuracy is achieved by ensuring low error in the modeling and measurement of the linear noise sources.



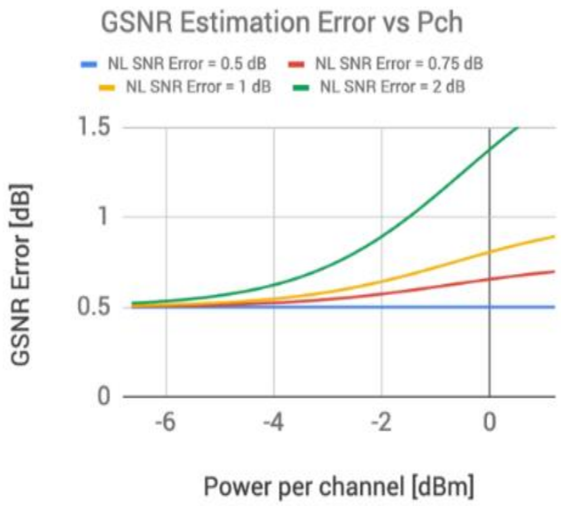


Fig. 1: GSNR error vs power per channel. Typical levels for 120 chs on current subsea designs vary from -5 to -2 dBm/ch.

4. MODELING GSNR

To model propagation impairments in subsea optical links, one needs to accurately model each equivalent noise source. The amplifier ASE noise is modeled as AWGN with a power spectral density given by:

$$Gase(f) = hf[G(f)F(f) - 1]$$

Where h is the Plank constant, f the optical frequency, G the amplifier gain, and F the noise figure. Note that this definition is slightly modified in case of noise droop, i.e. when amplifiers operating in saturations are clamping the total noise.

Modeling NLI, on the other hand, is more complex and relies on time consuming numerical simulations. Analytical models are preferred for estimations of propagation impairments, with the assumption that the Gaussian Noise (GN) model is valid [1].
Aside from linear and nonlinear effects, a relevant phenomenon for optical systems with amplifiers operated at saturation is signal droop. This effect induces a linear SNR penalty due to amplifier gain amplifying both the noise generated in previous spans and the useful signal. As total amplifier output power is constant in subsea systems, noise accumulation progressively erodes the power of the useful signal, causing an additional penalty. Droop needs to be modeled when considering long links (100s spans) and low GSNR regimes (<8 dB).

5. MEASURING GSNR

The GSNR can be used to model optical performance of a subsea system. A reliable measurement approach is required to compare system performance to design expectations for acceptance of an open cable, and for characterization of system performance at any time in the cable lifetime. To measure GSNR, both SNR_{ASE} and SNR_{NLI} need to be measured, recalling that accuracy in linear noise characterization is the most critical to overall GSNR accuracy.

6. SNR_{ASE} MEASUREMENT

SNR_{ASE} measurement is a well understood and fairly accurate process. It is a direct measurement that can be done via a commercial OSA. Various methodologies can be employed for noise measurement, for example, by probing the out-of-band noise power in between channels using appropriately spaced probes, or alternatively, at the center frequency of a specific probe while the probe is removed. Generally accepted accuracy when performed properly is roughly 0.1 dB.

It is important to note, however, that ASE noise level is not independent from the transmitted WDM signal. It is a function of the amplifier operating point, which in turn depends on the spectral loading injected at the input of the amplifier. As such, loading conditions should be carefully selected to align with the desired conditions for characterization. It is recommended that these conditions align with the most likely conditions under which the transponder of choice will be deployed. For example, a flat Tx profile of evenly spaced loading channels may be desired for simplicity. Alternatively, an equalized profile may be used, with power-based or OSNR-based equalization.

Most notably, for accurate GSNR measurement, it is critical that the spectral loading and pre-emphasis be identical for the SNR_{ASE} and SNR_{NLI} measurements for the overall result to be meaningful.

7. SNR_{NLI} MEASUREMENT

Unfortunately, while NLI can be conveniently modeled as noise, it cannot currently be directly probed in a manner in which the measured result is not influenced by the characteristics of the probe itself. This is due to the relevant noise power occupying the same frequency as the signal, precluding the use of an instrument such as an OSA. As such, an indirect form of measurement is needed. In the application range of the GN model, the currently recommended tool for this measurement is a transponder. The directly measurable quantity, the pre-FEC BER (or Q-factor) can be used to infer SNR_{TOT} by using a transponder (or pair of transponders) previously characterized under ASE noise only. This is the so-called inverse B2B (back to back) method (Fig. 2). SNR_{TOT} includes GSNR, but in addition to transponder-specific contributions, reflected in the equation below.

$$SNRtot = \left[\frac{1}{GSNR} + \frac{1}{SNRmodem}\right]^{-1}$$

$$= \left[\frac{1}{SNRase} + \frac{1}{SNRnle} + \frac{1}{SNRmodem}\right]^{-1} \quad (1)$$

The additional SNR_{MODEM} noise contributions will be highly dependent on the interplay of transponder's specific DSP implementations and propagation impairments (e.g. CD penalty). This being said, SNR_{MODEM} needs to be accounted for to obtain an accurate GSNR measurement.

This dependency opens up many questions around the characteristics of the transponder to be used. Recalling that the GSNR error sensitivity is lowest to the NLI measurement, and even less so in highly linear regimes, with careful consideration of the properties of the transponder and the application space, a reasonably accurate measurement can be produced.

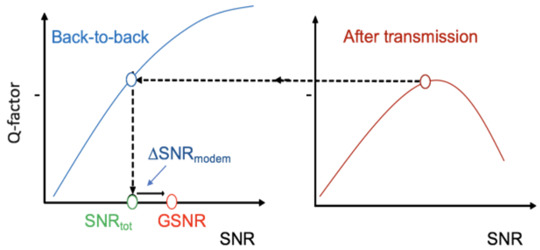


Fig. 2: B2B inverse method

Considerations of high importance are discussed below.

- Impact of modulation format of the channel under test (CUT) on NLI generation: To create operating conditions as close as possible to those used to model NLI, the impact of modulation format dependency on NLI generation should be minimized. We suggest the adoption of PM-QPSK for its maturity, general availability and reach performance. A single PM-QPSK channel for GSNR measurement surrounded by ASE shaped noise to mimic interfering channels can be used. However, the filter applied to ASE channels need to be steep enough to avoid any linear crosstalk in the CUT (Channel Under Test). Alternatively, a single PM-QPSK channel on either side of the CUT can be used.

- Channel loading: The denser the channel loading considered, the larger the total generated NLI power. Introducing a guard band around the CUT would allow for proper characterization of the nonlinear noise, following GN modeling assumptions. We suggest to adopt typical channel loading (e.g. 32 Gbaud/37.5 GHz grid), or to replicate as much as possible typical loading conditions of the system during its lifetime.

- Transponder non-idealities and advanced features to avoid: Among the features to be avoided is worth citing all forms of NL compensation and mitigation techniques (e.g. multidimensional modulation formats, digital subcarrier multiplexing with symbol rates < 10 Gb).

Among the non-idealities of a transponder used for GSNR measurement that need to be well characterized to compensate for SNR_{MODEM} that are worth citing:

- Dependency of B2B vs temperature and frequency

- Q-vs-SNR_{ASE} roll-off to determine the range of validity for accurate use in the inverse B2B method. Different modulation formats should be used if the cable performances are out of range.

- Chromatic dispersion, PMD, and other DSP-related penalties.

Many of these would not represent a concern if a standardized measurement tool were made generally available.

8. HIGH LEVEL MEASUREMENT METHODOLOGY FOR GSNR

For each frequency (or set of N frequencies):

1. Load full spectrum with CUT + ASE noise (or N-1 side channels)
2. Measure SNR_{ASE} with an OSA
3. Center the CUT at frequency f_i
4. Measure Q of the channel at frequency f_i
5. Apply the inverse B2B method to obtain SNR_{TOT}
6. Estimate SNR_{MODEM} (e.g. subtract CD penalty)
7. Compute GSNR with Eq. 1

The number of spectral locations to characterize can be strategically selected based on the SNR_{ASE} profile which can be easily obtained for all frequencies.

As with any practical measurement, some degree of error exists. While the goal is always to minimize such an error, understanding its impact on capacity estimation is fundamental to set an acceptable risk tolerance. For example, a GSNR error of +/- 0.5 dB would result in a fiber capacity uncertainty of the order 8% in the GSNR range of interest for current cable designs (7dB to 13dB).

9. GSNR CAPACITY EVALUATION

In its seminal work, Shannon demonstrate that the capacity of an AWGN channel is given by:

$$C = B\log_2(1 + SNR)$$

where SNR represents the signal to noise ratio of the power of the useful signal divided by the power of the WGN impairing it. As the fiber channel is an AWGN channel if we ignore NLI, we can determine the ultimate fiber capacity as:

$$Cs = \int 2\log_2(1 + SNRase(f))df$$

Assuming for simplicity constant SNR_{ASE} vs f we can write:

$$Cs = 2B\log_2(1 + SNRase)$$

Such ultimate fiber capacity could be achievable if nonlinear effects are ignored. Such operation is not feasible as of today, nor foreseeable in the near future. This being said, under the assumption that NLI noise can be modeled as AWGN, we can determine a generalized capacity given by:

$$Cgen = 2B\log_2(1 + GSNR)$$

This corresponds to the capacity that could be ultimately be achieved with an ideal transponder, i.e. a transponder without implementation penalties and zero coding gap in the absence of nonlinear compensation techniques.
To obtain the capacity that can be achieved with a given transponder under the assumption of zero margin, the previous equation becomes:

$$Cmodem = f(GSNR)$$

where f(GSNR) maps SNR to capacity uniquely for any given transponder based on its characteristics (modulation format, symbol rate, FEC, etc.). These three metrics can be used to determine achievable capacity e (Fig. 3) both theoretically and practically, at any time, both at the fiber level and at the channel level. Fig.3 shows fiber pair capacity under assumption of constant GSNR across the spectrum. Spectral dependence of GSNR is accounted for by averaging GSNR across the whole spectrum to map GSNR into the whole fiber pair capacity. Averaging of GSNR in the part of the spectrum permits estimation of capacity in the selected part of the spectrum.

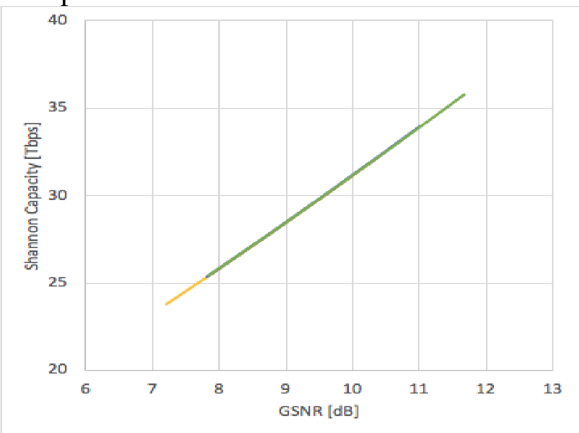


Fig. 3: Fiber Pair Capacity vs GSNR

Given the ever-increasing traffic scaling trends, we believe it is now more appropriate to perform capacity estimations at the fiber level. This has the main benefit of reducing exposure to GSNR variability vs frequency which allows for simpler negotiations in capacity splitting in consortium cables. Delineating ownership at the fiber pair level removes the burden of attempting to equitably allocate portions of optical spectrum whose value is not uniform in frequency, nor static over the cable lifetime. In this sense, fiber can be seen as the new wavelength.

10. CONCLUSION

In this paper, we discussed the definition of GSNR, its modeling and how to measure it, highlighting its domain of validity in modern D+ open cables. We discussed how GSNR can be used for cable acceptance and [9] for characterization of wet plant performance at any time. Finally, we described how to use this metric for capacity estimation purposes both theoretically and practically, finally advocating for capacity evaluation at the fiber level.

The authors believe that GSNR should be the reference metric for designing, accepting and assessing capacity of D+ subsea cables as designed today and in the foreseeable future. Therefore, we consider its adoption highly beneficial to the subsea industry as a whole.

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