Subsea Open Cables: A Practical Perspective on the Guidelines and Gotchas

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A Brief Introduction to the Working Group, our Mission, and the Intent of this White Paper:

This white paper is a collaborative work, written and discussed by the authors and contributors listed.

It is intended as a means to share with the broader industry some collectively agreed ideas and recommendations on Open Cables, from a broad representation of industry experts with varying perspectives and practical experience in designing and building Open Cables. It attempts to lay a foundation upon which standardization via official standards bodies can build on and progress.

It is by no means comprehensive, nor set in stone, as the topics covered are highly nuanced, and the industry and core technologies are constantly evolving, and will no doubt continue to do so. It instead attempts to provide a practical perspective on some key technical topics, as agreed and understood to the best of our knowledge today, that will empower new entrants to the Subsea Open Cable movement to confidently embrace the ideas and reap the benefits made available by doing so.

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Why Open Cables? A Brief History

The Road to Open Cables

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]. This approach was originally derived for intensity modulation formats with direct detection (IMDD) systems, as the Q-factor could be directly related to the eye diagram of the received signal [1]. In this context, the total transmission capacity of an optical cable was estimated using a simplified performance budget accounting for factors such as the linear noise accumulation, the channel spacing, total system operating bandwidth and various other calculated or simulated penalties. Such a simplified approach was acceptable as systems were designed end-to-end, optimizing the wetplant (i.e. its dispersion maps) for the specific SLTE to be deployed. This unified end-to-end design was an ideal approach at the time, under the assumption that the wetplant and SLTE would be provided by the same supplier over the system lifetime. [4]

The advent of transponders based on polarization multiplexed, multilevel modulation formats with DSP-enabled coherent receivers completely changed the industry approach to coupling of wetplant and SLTE. DSP-enabled coherent transponders offered unprecedented flexibility in SLTE operations, offering electronic chromatic dispersion (CD) and polarization mode dispersion (PMD) compensation, and putting many different modulation formats, symbol rates, FEC and thus line rates within a single box. At its inception, the market availability and performance of coherent transponders for use on dispersion managed wetplant were widely varying and offered significant capacity improvements over the IMDD transponders originally designed for. As such, it was often highly beneficial to replace the originally installed SLTE, leading to the emergence of the “upgrade market”, and the first step toward wetplant and SLTE disaggregation in the industry, or “Open Cables”. [4]

An arguably more significant side effect of these new coherent transponders in the path towards Open Cables, with the newly offered ability to digitally compensate CD, was the enablement of significant wet plant design simplification via removal of inline dispersion management [13,14]. This wetplant design shift laid the foundation for new modem-independent performance metrics, by significant simplification of the modeling of fiber propagation impairments, and the ability to reasonably de-couple the wetplant and transponder noise contributions.

Discussing the Benefits of Open Cables

The benefits of Open Cables have been touted extensively in the industry. One often highlighted benefit is the enablement of independent vendor selection for wet plant and SLTE, allowing best of breed utilization on two very critical pieces of the subsea network. [6,7]

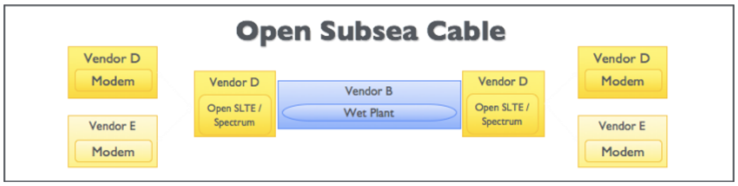


Figure 1. An Open Subsea Cable.

Since SLTE technology cycles are typically faster than a Submarine cable build cycle, and chip generations are inherently staggered in timing across multiple DSP vendors, this independent selection allows absolute maximization of cable capacity at the time of cable RFS.

Just as critically, Open Cables enable the use of preferred SLTE vendors, which is essential operationally when considering a global subsea & terrestrial mesh network. Yet this model still supports wet plant selection from any vendor, something not as easily done in the traditional turnkey models. As such, Open Subsea Cables enable Open Networks on a global scale.

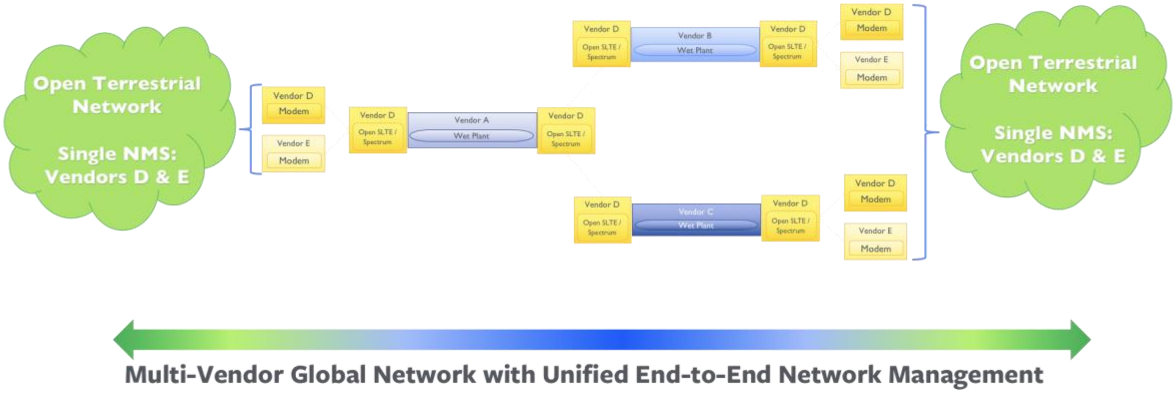


Figure 2. Open Cables to Open Networks.

Open Cables Giving Rise to New Challenges

The Open Cable model also presents a new challenge, where now a means to quantify the wetplant performance independently of a specific SLTE or modem technology is needed. A traditional turnkey capacity specification is no longer of great use, as it is firmly tied to one specific modem vendor technology and indicates very little about the relative performance potential of different wetplant designs offered by different vendors, making comparison during an ITT process difficult.

Capacity potential of a specific wetplant design must also now be viewed as a moving target, in that it is variable in time due to its inherent tie to SLTE vendor technology and their associated generational release dates. Thus, the capacity that can be delivered by a particular wet plant design, is both highly dependent on the SLTE technology choice and the time at which the cable goes RFS.

Furthermore, beyond cable RFS, the ongoing monitoring of the performance and effects of aging and maintenance on any subsea cable throughout its operational lifetime is also of great importance. Monitoring the health and performance of a subsea cable with a single SLTE and its associated performance metrics may be very useful while that SLTE technology is deployed, but that data is not easily carried over nor related to the unique performance metrics of the next generation of SLTE technology that may replace it.

This leads to the logical conclusion that one or more performance metrics are needed that are immutable with respect to SLTE technology and time.

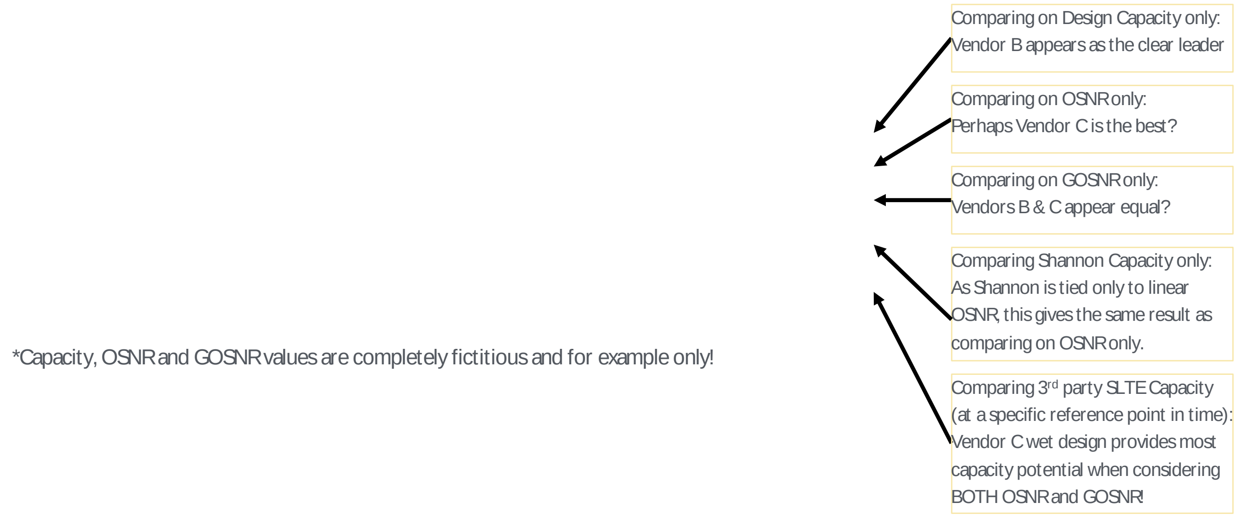
It has been proposed within the industry that OSNR and GSNR are the key metrics that can be used to comprehensively describe the optical performance of a particular wetplant design, assuming a modern-day D+ fiber design [4]. It is important to note that this proposal suggests that both OSNR and GSNR are required, together, to fully describe the optical performance, and that neither metric in isolation will provide a complete picture. More details on OSNR and GSNR are provided in the sections that follow, beginning with their definitions in “Introduction of OSNR and GSNR as Paired Metrics”.

OSNR has many good attributes as a performance metric – it is well understood and straightforward to calculate, define and measure in a repeatable way by any vendor. It is also the primary contributor to the overall optical performance levels (i.e. noise) in modern day D+ subsea designs, particularly as SDM design strategies become more prevalent. However, it is very important to understand that the same OSNR can be achieved with many different wet plant designs, all with varying degrees of nonlinearity, resulting in differing capacity potentials at a given point in time with a given SLTE technology (noting that this variance decreases in SDM designs). These variances and the relative contributions of linear and nonlinear noise are discussed in more detail in this document in “

Discussing the Impact of Errors ”.

Similarly, GSNR is also not all-telling in isolation, as it does not capture potential benefits from SLTE technologies with nonlinear mitigation or compensation techniques. For example, two wetplant designs with the same GSNR will not necessarily give the same capacity potential, even with the same modem. If one wetplant design has the same GSNR, but a higher OSNR, one can deduce that design has higher nonlinearity, which may, perhaps counterintuitively, present opportunity for higher performance gains from a modem with appropriately matched nonlinear compensation techniques.

The key conclusion is thus that the combination of both OSNR and GSNR is required for a comprehensive understanding of optical performance on a D+ design, enabling accurate and comparable 3rd party SLTE capacity estimates. A fictitious example of three optical designs and the various ways to compare them is provided below to illustrate these nuances.



Comparing on Design Capacity only: Vendor B appears as the clear leader

Comparing on OSNR only: Perhaps Vendor C is the best?

Comparing on GOSNR only: Vendors B & C appear equal?

Comparing Shannon Capacity only: As Shannon is tied only to linear OSNR, this gives the same result as comparing on OSNR only.

Comparing 3rd party SLTE Capacity (at a specific reference point in time): Vendor C wet design provides most capacity potential when considering BOTH OSNR and GOSNR!

*Capacity, OSNR and GOSNR values are completely fictitious and for example only!

Figure 3. Comparing Wetplant Designs.

Key Takeaways:

- *Open Cables have many benefits, including capacity maximization at system RFS, and allowing independent best of breed selection for both wetplant and SLTE technologies*
- *New wetplant performance metrics are required that are fully independent from SLTE*
    - *Comparing wetplant designs based on traditional turnkey capacity can be highly misleading*
    - *Ongoing monitoring of wetplant performance over the system lifetime must have continuity and meaning regardless of SLTE technology used*
- *OSNR and GSNR, when considered together, can give a clear picture of the optical performance of a subsea system, offer a fair comparison between different wetplant designs, and enable 3rd party SLTE capacity estimation*

Introduction of OSNR and GSNR as Paired Metrics

In order to properly discuss the nuances of OSNR and GSNR in relation to designing an Open Cable, we must first define each metric with consistency and clarity. This section will introduce the definitions, the variations that exist and what is included or excluded for each, such that the language used to describe these important concepts is well understood.

OSNR Definitions and Conversion into $\mathrm{SNR}_{\mathrm{ASE}}$

In subsea optical transmission, OSNR is the Optical Signal to Noise Ratio, describing the relative noise introduced by the repeaters along the subsea line, as a result of Amplified Spontaneous Emission (ASE), also known as $\mathrm{OSNR}_{\mathrm{ASE}}$. However, OSNR is not an absolute value, and is highly dependent on the conditions under which it is defined. There are a number of OSNR values that are often used in Open Cable designs, such as Design OSNR, Nominal OSNR and Commissioning OSNR.

It is important to note that OSNR, when defined in its most commonly used units of dB/0.1nm, is highly dependent on the reference channel count, or more accurately, the signal power contained within the defined channel width. For simplification, it is common (for historical reasons) to use 120 channels as a reference, however any channel count could be used, as long as it is consistently used. In fact, defining OSNR as a pure ratio in units of dB, also known as SNR (or $\mathrm{SNR}_{\mathrm{ASE}}$), eliminates this potential area of confusion when dealing with variable baud rates and channel counts, and is discussed later in this section.

OSNR is also variable with frequency across the available optical bandwidth. As such, using OSNR as an average value is helpful in simplifying discussions. A Worst Case OSNR, or the lower bound, of all the channels can also be defined.

The Design OSNR (average) is calculated using the classical formula:
$\mathrm{OSNR}_{\mathrm{Design}}=58+P_{\mathrm{TOP}}-N_{\mathrm{Ch}}-G-NF-N_R$ (average, per channel, in dB/0.1nm)
where:

58 is a constant related to the central wavelength of the spectrum
P_{TOP} is the EDFA output power within the repeater in dBm
N_{Ch} is the number of channels in dB
G is repeater gain in dB
NF is the noise figure of the repeater in dB
N_R is the number of repeaters in dB

The Design OSNR has the advantage to be very simple to calculate based on high level system specifications but does not take into account all the impairments that will be present in a practical system. As such, a second OSNR value is often quoted, called the Nominal OSNR (average). This OSNR is based on the Design OSNR, beyond which any path ROADM penalties are added, and the droop is considered.

$\mathrm{OSNR}_{\mathrm{Nominal}}=\mathrm{OSNR}_{\mathrm{Design}}-\mathrm{ROADM\_Penalties}-\mathrm{Droop}_{\mathrm{ASE}}$ (average in dB)

Under ideal conditions, $OSNR_{Nominal}$ should represent a field measurable quantity. However, due to real-world non-idealities and variations, some additional margins are generally considered. These margins account for effects such as variations in fiber loss from expectations, or variability in repeater TOP from nominal, as examples. As a consequence, a Commissioning OSNR is defined. System acceptance is then defined around the specified Commissioning OSNRs, typically considering average and worst case.

$OSNR_{Commissioning}$=$OSNR_{Nominal}$-Manufacturing_Margins (average in dB)

Finally, the Worst Case Commissioning OSNR is also defined. During commissioning and acceptance, each channel individually should be above this Worst Case $OSNR_{Commissioning}$.

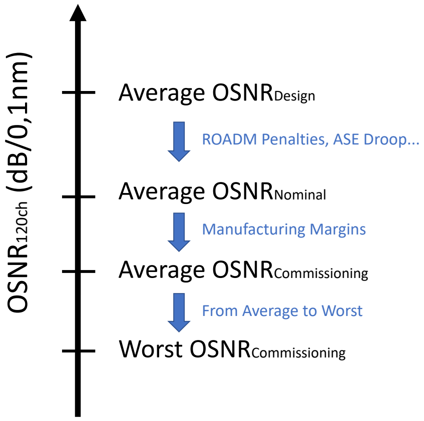


Figure 4. OSNR Definitions.

As previously discussed, defining OSNR with respect to 120 channels is somewhat arbitrary and historically based, due to the advent of Open Cables at a time when 37.5GHz channel spacing and 4.5 THz repeater bandwidths were most common (allowing 120 channels). With the advent of variable baud rate transponders, a more logical reference may be to define OSNR (dB/0.1nm) as SNR_{ASE} (dB), removing any dependency on a specific channel count or spacing. OSNR can be very simply converted into SNR_{ASE} by using the following conversion:

SNR_{ASE} (dB) = OSNR(dB/0.1nm) – 10*LOG_{10}(SignalBandwidth_GHz / 12.5 GHz)

Here, the reference bandwidth is equal to 12.5GHz since the OSNR is usually given for 0.1nm, or 12.5GHz at ~1550nm, and the Signal Bandwidth is the spectral width within which the channel under test is defined. If we take a 37.5 GHz spacing, which is a classical spacing for a ~30-35GBd transponder, the SNR_{ASE} will be 10*LOG_{10}(37.5/12.5) or ~4.8dB lower than the OSNR.

There is an additional benefit to using SNR, as defined here within the full signal bandwidth, from a transmission performance assessment perspective, as it more accurately represents the noise that a coherent receiver will be presented with. [17] In this case, the relationship between baud rate and channel spacing must also be accounted for.

The previous set of key OSNR values could then be re-cast in a baud rate and channel spacing independent SNR-based manner, as below.

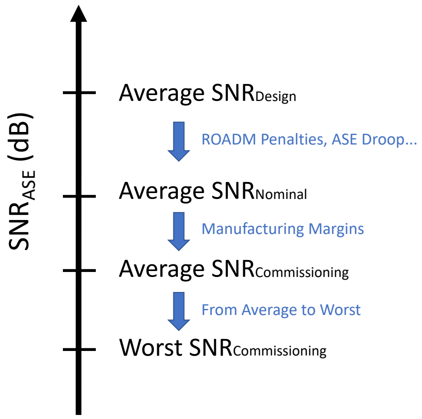


Figure 5. SNR$_{ASE}$ Definitions.

GOSNR Definitions and Conversion into GSNR

As discussed previously, Open Cable systems requires a performance metric for assessing the optical performance of the wetplant which is as independent as possible of the SLTE modem. It is prudent to recall that the contents of this section are specifically defined within the bounds of a modern day D+ wetplant design application space.

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]. As all major propagation impairments, i.e. ASE 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 optical performance potential of a particular defined channel within a specific wetplant design. This metric has been defined as effective or Generalized OSNR (GOSNR).

Per the previous section, it is desirable to define these metrics in a channel width and baud rate independent fashion, and as such Generalized SNR (GSNR) is introduced and defined as 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 wholly in the signal bandwidth.

GSNR is thus defined (in linear units) as: [4]

$$\frac{1}{GSNR} = \frac{1}{SNR_{ASE}} + \frac{1}{SNR_{NLI}}$$

where:

- SNR$_{ASE}$ is the channel width independent OSNR previously defined
- SNR$_{NLI}$ is the noise coming from the nonlinear interference

Note, for simplicity, we are focusing in the effects of fiber nonlinearity in the characterization of open submarine cables. However, other propagation impairments can be included in this formalism. In particular, GAWBS, which can be well modelled in SNR terms and it depends of the fiber type and transmission distance. As discussed in the previous section, calculating SNR_{ASE} is relatively straightforward. Modeling SNR_{NLI}, on the other hand, is more complex and relies on time consuming numerical simulations or approximated analytical models. Analytical models are often favored for their limited numerical complexity that allows quick estimations of propagation impairments. One of the most used analytical models to achieve this, is the Gaussian Noise (GN) model [1]. Additional details on the conditions required to utilize this model, and the relative accuracy can be found in [4], within which it is recommended that the GN model be used in order to model the SNR_{NLI} in subsea optical links, specifically ([10], Eq. 11).

Like OSNR, GSNR carries with it the same variability with frequency in an optical spectrum, and thus is typically defined as an average value, bounded upward by a worst case value. GSNR will also be impacted by additional real-world manufacturing variances that cannot be fully predicted by advance simulation, such as repeater tilt and gain deviations during manufacturing and system deployment, introducing additional nonlinear noise contributions, and thus impacting the GSNR that may be measured at system commissioning.

Logically the, like OSNR, a range of GOSNR values are also defined: Theoretical GSNR, Commissioning GSNR, Worst Case GSNR. During commissioning and acceptance, the average value of measured channels should be above the $GSNR_{Commissioning}$ (average), and each channel individually should be above the Worst Case $GSNR_{Commissioning}$. More discussion and proposed guidelines for Commissioning & Acceptance of Open Cables is given later in this document.

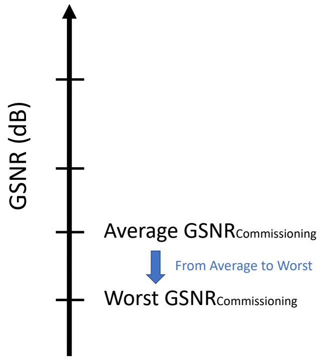


Figure 6. GSNR Definitions.

Key Takeaways:

- *It is desirable, with the prevalence of variable baud rate modem technologies, to define OSNR and GOSNR (as they are most commonly known) in a baud rate and channel spacing independent manner, giving rise to their replacement by SNR_{ASE} and GSNR, respectively.*
- *GSNR represents the total sum of all linear (SNR_{ASE}) and nonlinear (SNR_{NLI}) noise in a given optical design, and is valid only in modern D+ cable designs (dispersion uncompensated)*
- *A range of SNR_{ASE} and GSNR values should be defined to reflect both the theoretical calculations and practical considerations of a subsea system, such as Design SNRs, Average Commissioning SNRs, and Worst Case Commissioning SNRs.*

Measuring our Defined Metrics

SNR_{ASE} and GSNR Measurement Introduction

A performance metric is only as useful and accurate as its practical measurement allows it to be. This section will explain the methodology to measure the GSNR of a fiber-optic line, as per the definitions provided in the previous section.

As a reminder, GSNR is a signal to noise ratio magnitude where the noise includes ASE from amplifiers and Noise from fiber nonlinearities, such as SPM, XPM and FWM. This formalism is valid as long as these noises can be regarded as Gaussian distributed. This is the case in modern fiber-optic transmission line designs, due to the large pulse spreading induced by large chromatic dispersion and represents the target application space for this discussion.

SNR_{ASE} can be obtained using well calibrated Optical Spectrum Analyzers (OSAs) that accurately measure the optical power in a given bandwidth. The typical procedure for measurement is well understood with generally accepted accuracy, when performed properly, to be within roughly 0.1 dB in error.

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 and controlled 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.

Most notably, for accurate GSNR measurement, it is critical that the spectral loading and pre-emphasis conditions chosen are identical for both the SNR_{ASE} and SNR_{NLI} measurements, in order for the combined result to be meaningful [4].

The value of SNR_{NLI} is related to the power of the nonlinear products generated in a given reference bandwidth and is not straightforward to measure directly. However, it is possible to indirectly measure its effect with a well characterized digital coherent transponder, but this method requires careful consideration and de-coupling of impairments introduced by the measurement tool. For example, propagation associated penalties such as CD, PMD and PDL penalties will be associated with the test instrument (coherent modem) and will vary depending on the modem technology or vendor used.

As such, we define a new parameter, SNR_{TOT}, that captures these additional penalties. SNR_{TOT}, like SNR_{ASE}, is a directly measurable parameter.

SNR_{TOT} is thus defined (in linear units) as:

$$\frac{1}{SNR_{TOT}} = \frac{1}{SNR_{ASE}} + \frac{1}{SNR_{NLI}} + \frac{1}{SNR_{MODEM}}$$

Or:

$$\frac{1}{SNR_{TOT}} = \frac{1}{GSNR} + \frac{1}{SNR_{MODEM}}$$

where:

- GSNR, SNR_{ASE} and SNR_{NLI} are as previously defined
- SNR_{MODEM} is the additional noise arising from the specific modem technology used

In this paper, the method suggested to determine the GSNR is the Inverse Back-to-Back ($BtoB^{-1}$) method [8,9,11], which is based on the dependency of a transponder BER (Q-value) on fiber nonlinearities that create a Gaussian-like distribution of the constellation points in the IQ space. A conceptual diagram of the method is provided below and will be discussed in more detail in the coming text.

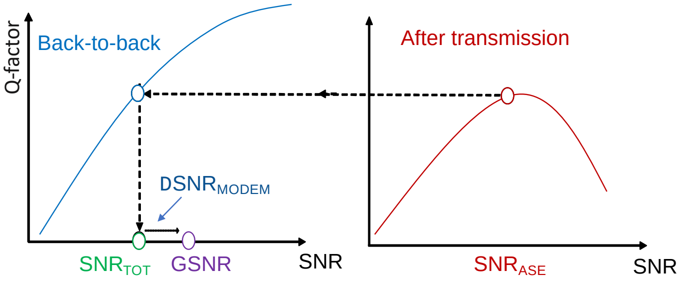


Figure 7. GSNR measurement concept using a coherent modem.

Recently, some alternate methods have been proposed based either on evaluation of spectral broadening of a channel after transmission [16] or measuring some noise correlations on within the channel bandwidth [15]. It is not yet clear whether proposed methods can achieve sufficient accuracy. This leaves us with the indirect measurement method using coherent transponder performance, as the best option at this time.

GSNR Measurement Principle

In this section, a method is introduced to measure the GSNR of a transmission line. This procedure is based on two fundamental ideas or conditions:

1- The transmission line can be well modeled by the Gaussian noise model
2- Digital coherent transponders show a predictable dependency of BER with fiber nonlinearity

If these two conditions are met, the $BtoB^{-1}$ method is used to estimate the GSNR of a transmission line. This method converts the Q-value of a transponder after transmission into SNR_{ASE} (or OSNR) terms, by using the back-to-back SNR_{ASE} sensitivity of the transponder as the conversion function.

The first step to measure the GSNR is, therefore, to obtain the conversion function. SNR_{ASE} has been traditionally used to characterize the performance of transponders. Typically, a transponder is connected back-to-back (i.e. TX-to-RX) with a Gaussian noise source in between and adjacent channel loading to account for typical filtering and inter-channel interference penalties. This is shown in Figure 8.

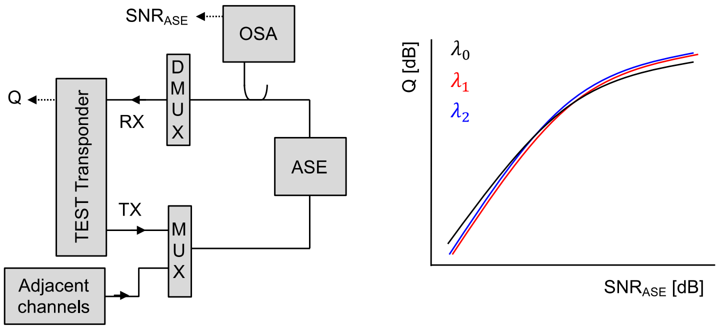


Figure 8: Diagram of the SNR$_{ASE}$ sensitivity characterization of a transponder.

This is typically referred to as the OSNR (or SNR$_{ASE}$) sensitivity of a transponder and it provides a curve where the Q-value (or BER) is plotted as a function of the SNR$_{ASE}$ at the receiver. In general, the SNR$_{ASE}$ sensitivity is frequency dependent, so the test transponder should be characterized at the frequencies relevant to the GSNR measurement.

Considering the Gaussian nature of the main noise sources in fiber-optic transmission, one can use the SNR$_{ASE}$ sensitivity of a transponder to estimate the GSNR of a transmission line. This is illustrated in the Figure 9, where the main principle of the BtoB^{-1} method is shown.

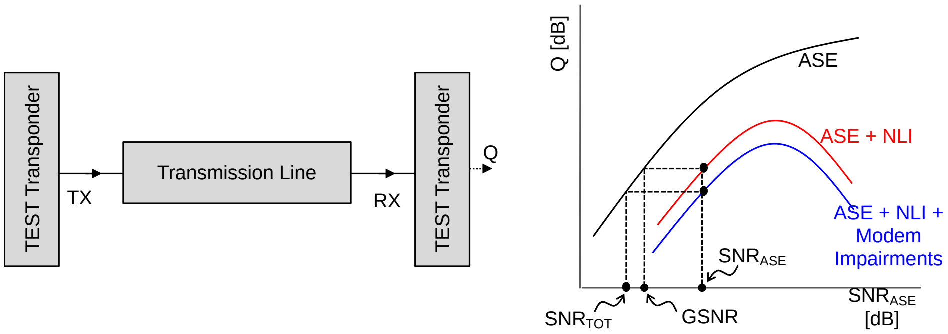


Figure 9: Diagram of GSNR measurement using the BtoB^{-1} method.

By using a set of test transponders, previously characterized by their combined TX-RX OSNR sensitivity, the Q-value is obtained after transmission. This Q-value “contains” the effects of fiber nonlinearity in the degradation of the constellation points of the modulation. Therefore, the value of SNR$_{TOT}$ can be obtained by applying the following equation,

$$SNR_{TOT} = \mathrm{BtoB}^{-1}(Q)$$

Where BtoB^{-1} is the inverse function of the OSNR sensitivity of the TX-RX test transponders, shown in the Figure 8. The GSNR value can be obtained by subtracting the contribution of $\mathrm{SNR}_{\mathrm{MODEM}}$ as shown below:

$$GSNR^{-1} = SNR_{TOT}^{-1} - SNR_{MODEM}^{-1}$$

This measurement should be done in various different spectral locations to obtain a view of the GSNR as a function of the frequency and subsequently estimate the fiber capacity over the usable bandwidth.

GSNR Measurement Procedure

This section will explain the proposed measurement procedures for this method, and some characteristics of the measurement apparatus.

Measurement Conditions: Input and Output Spectra

One of the targets of GSNR measurement is to obtain estimates of the total achievable capacity that can be supported by the transmission line. For that, measurements must be conducted across the usable bandwidth. In general, due to the frequency dependency of amplifier noise figure, scattering effects, gain shape and tilt, among others, optical signals experience frequency-dependent power and OSNR variations as they propagate along the fiber. This relationship with frequency also varies notably with different input power profiles, due to the power limited nature of the subsea repeater, and the frequency-dependent nature of spectral hole burning (SHB). Thus, $\mathrm{SNR}_{\mathrm{ASE}}$ and GSNR will always vary across an optical spectrum and as a consequence of the aforementioned dependencies, the input power profile must be very carefully taken into account in any $\mathrm{SNR}_{\mathrm{ASE}}$ or GSNR measurement.

It is generally agreed today that populating the entire spectrum with test transponders to conduct the GSNR measurement is impractical. It is proposed to use a minimum of 3 test transponders and ASE as dummy lights for the remainder of the optical spectrum. The ASE dummy lights could be continuous or channelized. The advantage of channelized dummy lights is that they can also be used to measure the $\mathrm{SNR}_{\mathrm{ASE}}$.

The test transponder and the adjacent channels are tuned across the usable bandwidth to sample and obtain a view of the frequency dependency of the GSNR. Figure 10 shows the measurement configuration for GSNR measurement.

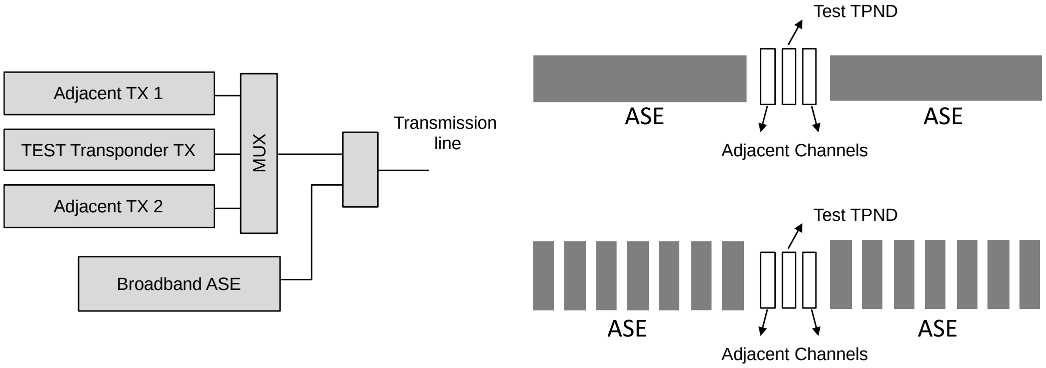


Figure 10: Configuration of the GSNR measurement at the transmitter with continuous or channelized dummy lights.

Three typical configurations may be of interest for GSNR measurements, namely: Flat transmitter power (FLAT), SNR-equalized power (SNREQ) and fiber-power equalized (PFIB). These configurations are schematically shown in Figure 11. These configurations are achieved by adjusting the channel pre-emphasis of the channels. For example, for Flat transmitter power, the channel pre-emphasis is set to equalize the power spectral density at the transmitter (i.e. Same density for dummy light and test channels). In other cases, the pre-emphasis value is adjusted depending on the received power or OSNR (SNR_{ASE}).

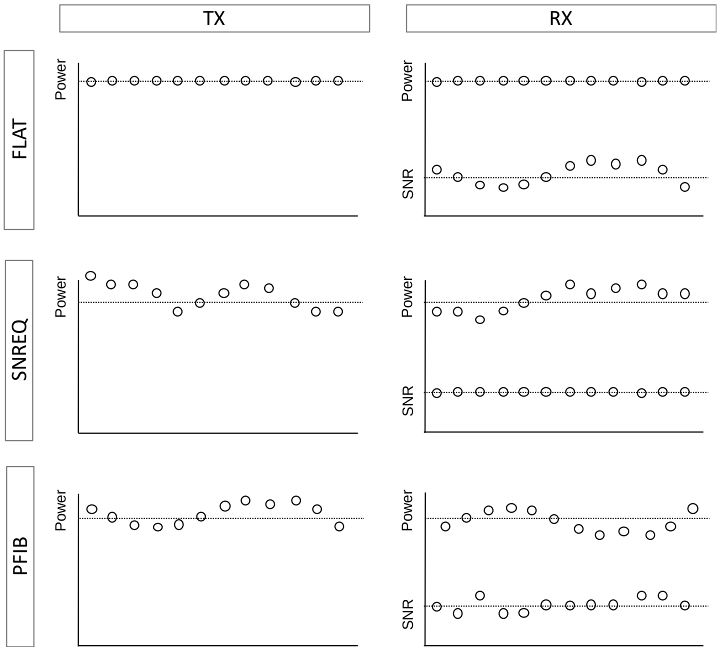


Figure 11: Pre-emphasis settings for GSNR measurement. Arbitrary shapes are shown.

In the case of FLAT equalization input spectrum is flat, where the power is equal at every wavelength. In the case of SNREQ power of each wavelength at the transmitter is adjusted to achieve a uniform SNR across the received bandwidth. Finally, the PFIB equalization consists in equalizing the sum of transmitter and receiver power. FLAT equalization is useful to determine the gain and tilt characteristics of the line and would theoretically be the optimum in the absence of any of the frequency dependencies noted previously. SNREQ equalizes the linear part of the GSNR whereas PFIB attempts to take into account the nonlinear contribution as well as the linear contribution to GSNR.

It is worth noting that we are not attempting to equalize the GSNR, as such equalization may not result in the maximum fiber capacity if, for example, NLC techniques are implemented in the transponder. These three equalization profiles can be used to characterize the fiber transmission line, however, depending on the design and the GSNR wavelength dependency, it may not be necessary to conduct the measurement in all the three configurations. A detailed discussion on the impact of pre-emphasis based equalization strategies on capacity is done in [5].

Test Transponder

The desired test transponder for the GSNR measurement must be able provide stable and accurate results over a wide range of transmission lines. The following are some generally agreed recommendations for standard specifications of a GSNR test transponder:

1. *Modulation format:* dual polarization QPSK and dual polarization 16QAM
2. *Carrier Baud-Rate:* 30-45 GBaud
3. *Carrier spacing for adjacent channels:* ~1.1 x Baud-Rate
4. S*pectral shaping:* RRC with ~0.1 roll-off
5. *Chromatic Dispersion Compensation:*
    5.1 Performed at the receiver
    5.2 CDC range within 1dB penalty: >400ns/nm
6. *Nonlinearity compensation:* Disabled
7. *DSP:* Typical methods for carrier phase recovery, polarization DEMUX and cycle slip protection.

In order to minimize measurement errors, it is desirable to operate in the non-saturated regime of the $BtoB^{-1}$ curve. To avoid this, two approaches are discussed. The first utilizes two modulation formats and is illustrated in Figure 12. This example illustrates a large GSNR measurement range can be obtained by using QPSK and 16QAM, both operating in their respective non-saturated regimes.

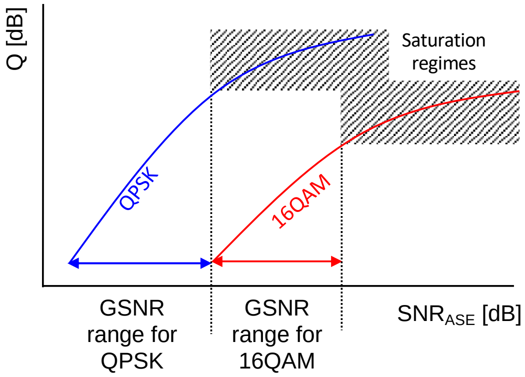


Figure 12. Expansion of the GSNR measurement range by using multiple modulation formats operating at the non-saturated regime.

The saturation characteristics depend of the transponder design and FEC characteristics, but typical 100G QPSK in the 32-34 Gbaud range can be used for a GSNR measurement range of [6dB-17dB], approximately. 16QAM can be used for GSNR values exceeding 16dB. For lower GSNR ranges, QPSK cards with higher FEC overheads could be used, or some other alternative may need to be discussed at that time.

Another potential solution to avoid the saturation regime of the BtoB curve is to load ASE noise at the receiver. This is shown in Figure 13, where a source of ASE is located between the transmission line and the receiver to shift the Q value away from the saturation regime.

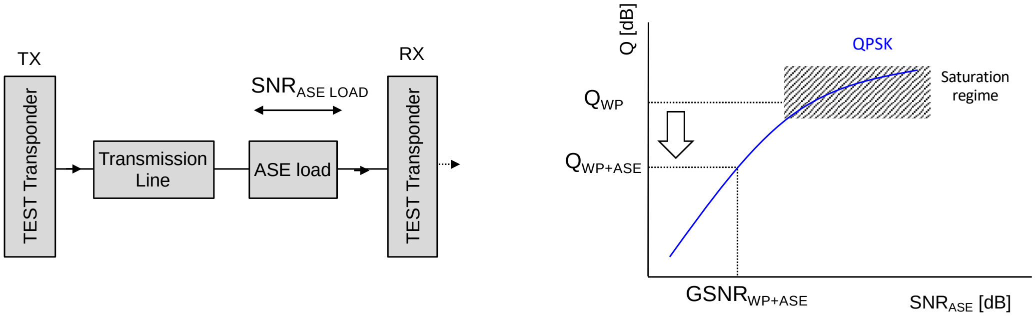


Figure 13. Expansion of the GSNR measurement range by using ASE loading at the receiver.

In this case, the wet-plant SNR$_{TOT}$ is obtained by subtracting the SNR contribution of the loaded ASE.

Estimation of Transponder Impairments

It is important to understand and separate transponder-dependent contributions to the GSNR, especially in wet-plant commissioning applications. Perhaps the most straightforward example is the

CDC penalty, which greatly depends on the effective filter size implemented in the transponder DSP. In order to understand and separate this contribution, it is important to characterize the performance of the test transponder as a function of the chromatic dispersion. For that, it is convenient to obtain the SNR penalty caused by chromatic dispersion. This penalty can be relative to the SNR_{ASE} value of the test transponder at the FEC limit, which is a typical procedure to determine performance penalties. Then, it can be converted to RX noise and subsequently subtracted to the GSNR measurement as a contribution of SNR_{MODEM}.

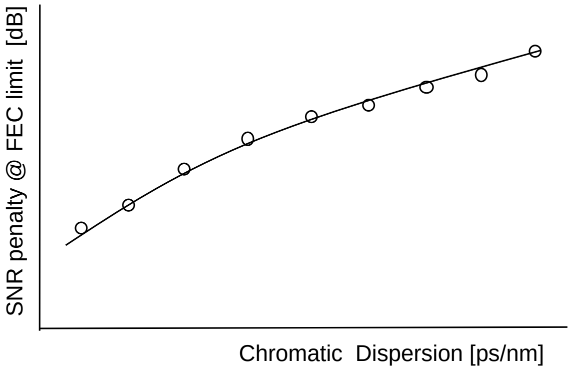


Figure 14. SNR penalty caused by the compensation of chromatic dispersion in the transponder DSP.

Another approach to estimate the transponder penalties is experimentally isolating the contribution of fiber nonlinearity. For that, the Q-performance can be obtained as a function of the channel pre-emphasis under propagated conditions. This Q-variation is only caused by fiber Kerr effect, and it can be modelled by the GN model. By comparing the experimental values with the model, the contributions of fiber nonlinearity and transponder penalties can be separated using a minimum-square fitting. For that, let us define the magnitude $SNR_{NL\text{-}TOT}$, which includes the contribution of fiber nonlinearity and the transmission impairments that are transponder dependent. This magnitude can be experimentally obtained by the following equation, as a function of the channel Pre-emphasis (PE):

$$SNR_{NL\_TOT\_EXP}^{-1}(PE) = SNR_{TOT}^{-1}(PE) - SNR_{ASE}^{-1}(PE)$$

Where SNR_{TOT} and SNR_{ASE} are the parameters defined previously and are both measured experimentally. Alternatively, the same magnitude can be calculated from the following expression:

$$SNR_{NL\_TOT\_THE}^{-1}(PE) = SNR_{NLI+GAWBS}^{-1}(PE) + SNR_{MODEM}^{-1}$$

Where $SNR_{NLI+GAWBS}$ can be obtained from the GN model by emulating the transmitted waveform and using the nominal measured data of the *as-laid* wet plant, such as (number of spans, repeater total output power, fiber attenuation, span loss, effective area, fiber dispersion, etc…). This term also includes the contribution of GAWBS, which is predictable from the transmission distance and the fiber effective area.

Note that the contribution SNR_{MODEM} is assumed to be independent of the power pre-emphasis, accounting for transmission impairments such as CD, PMD and PDL penalties.

In practice, it is difficult to vary the repeater output power and therefore it is common practice to vary the power of only a few channels with the channel under test at the center of them. Since this calculation needs to model the pre-emphasis of only a few channels while keeping the total power constant, the full integration of the GN is required for the channel under test, as follows:

$$P_{NLI} \propto \iint_{-\infty}^{+\infty} G_{wdm}(f_1, PE) \times G_{wdm}(f_2, PE) \times G_{wdm}(f_1 + f_2 - 0, PE) \times \rho \times \chi \; df_1 df_2$$

Where PE denotes the pre-emphasis of the measured channel. More details of this and the parameters therein can be found in [12]. The spectral density function G_{wdm} is defined to match the experimental conditions of the measurement. An example is shown in the Figure 15.

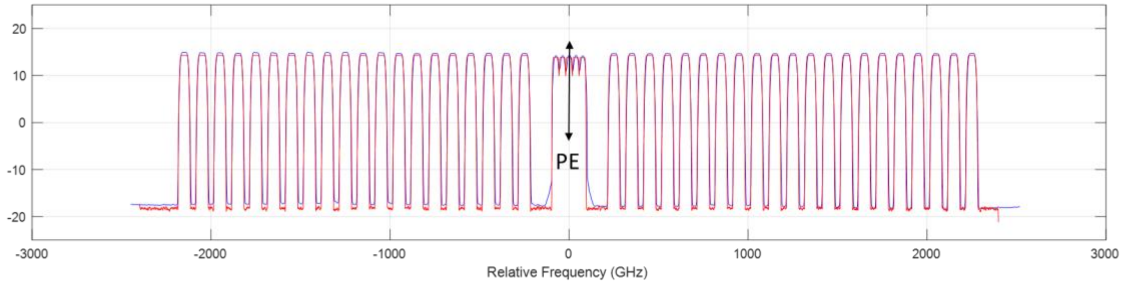


Figure 15. Example of the WDM configuration to calculate P_{NLI} as a function of the channel pre-emphasis. In blue, the experimental spectrum, in orange, the mathematical representation.

Once the theoretical value, SNR_{NLI} is obtained, both expressions, $SNR_{NL\_TOT\_EXP}$ and $SNR_{NL\_TOT\_THE}$ are compared and the value of SNR_{MODEM} is obtained to best fit both curves as a function of the channel pre-emphasis. Figure 16 shows an example of this fitting obtained experimentally in a ~7000km straight-line transmission test with 34Gbaud-QSPK real-time DSP channels. The agreement is very good for a wide range of channel pre-emphasis.

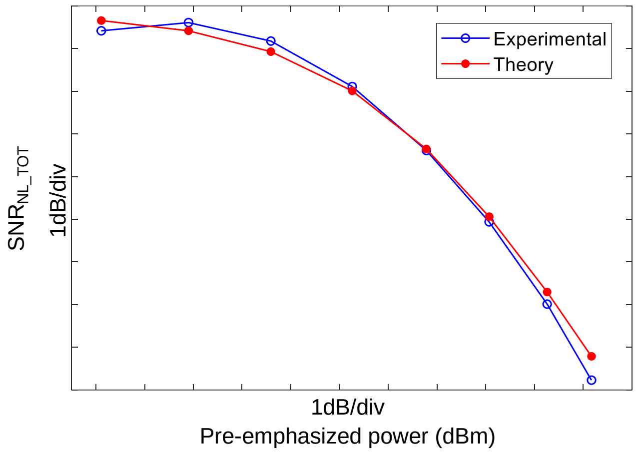


Figure 16. Example of the fitting between $SNR_{NL\_TOT\_EXP}$ *and* $SNR_{NL\_TOT\_THE}$ *after minimum square fitting with the single parameter optimization of* SNR_{MODEM}*..*

Key Takeaways:

- *SNR_{ASE} and GSNR must be measured under identical pre-emphasis conditions for the combined results to be meaningful. Various pre-emphasis options exist.*
- *SNR_{ASE} can be directly measured with an OSA and has a straightforward and well understood measurement procedure with a high degree of accuracy.*
- *GSNR can be measured indirectly with a coherent transponder utilizing the $BtoB^{-1}$ method to measure SNR_{TOT}, from which GSNR can be inferred*
  - *The modem specific penalties introduced by the coherent transponder for effects like CD, PMD and PDL must be considered and removed for accurate GSNR calculation and modem-independent open cable characterization.*
  - *These penalties can be simulated or experimentally derived via the methods proposed.*
- *Opportunity for a universally calibrated 3rd party GSNR test set exists and would eliminate the vendor specific dependency of the removal of these penalties.*

Discussing the Impact of Errors

As with any real-world measurement under non-ideal conditions, there will be a margin of error that will exist and must be considered. The goal is not to eliminate errors, though minimizing them is of course desired, but rather to understand the impact of the magnitude of these errors on what is important. For a subsea cable, generally what matters most is the achievable capacity, so this section will discuss how different magnitudes in error of calculation or measurement of OSNR and GSNR (among other factors) can impact the potential capacity, and arguably more importantly, by how much.

The Relative Impact of SNR_{ASE} and SNR_{NLI} on GSNR

Let us first begin with a discussion on the impact of errors on measured SNR_{ASE} and SNR_{NLI}, and their respective impact on GSNR, and thus subsequent capacity estimation, considering the aforementioned relationship where:

$$\frac{1}{GSNR} = \frac{1}{SNR_{ASE}} + \frac{1}{SNR_{NLI}}$$

The nonlinear nature of fiber propagation implies that the SNR_{NLI} decreases linearly with the cube of the transmitted power into the fiber, whereas SNR_{ASE} increases in a linear relation with it. These two opposing trends imply that depending on the power level of the signal, either linear or nonlinear noise will represent the dominant source of impairment, and that an optimum power level exists [4].

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. Hence, at optimal power, propagation impairments are mainly linear in nature, therefore the accuracy of GSNR estimations in this regime is dominated by the accurate characterization of linear noise sources [4].

In addition to this, it should be considered that the recent trend of designing cables toward even more linear operating regimes rather than for GSNR maximization (i.e. optimal power) has emerged as a solution to improve the power efficiency of the cable design while scaling cable capacity via what is commonly referred to as SDM (Spatial Division Multiplexing) solutions. As such, the difference between ASE and NLI noise will be even larger in these new SDM designs with respect to designs at or above the optimal power level. Accordingly, the effect of an estimation error on the SNR_{NLI} on SDM designs would be notably less.

This concept is demonstrated in Figure 17 where a fixed 0.1 dB error on SNR_{ASE}, and a varying relative error on SNR_{NLI} in the range of 0.5 to 2 dB are assumed. 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 for this particular example), which correspond to the design region of interest for next generation open cables, an error on the SNR_{NLI} 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 SNR_{ASE} [4].

As linear noise dominates propagation impairments, even a large estimation error in SNR_{NLI} (e.g. 2 dB green curve) results in less than 1 dB GSNR error. GSNR error could thus be kept well below 1 dB, as indicated in the figure below [4].

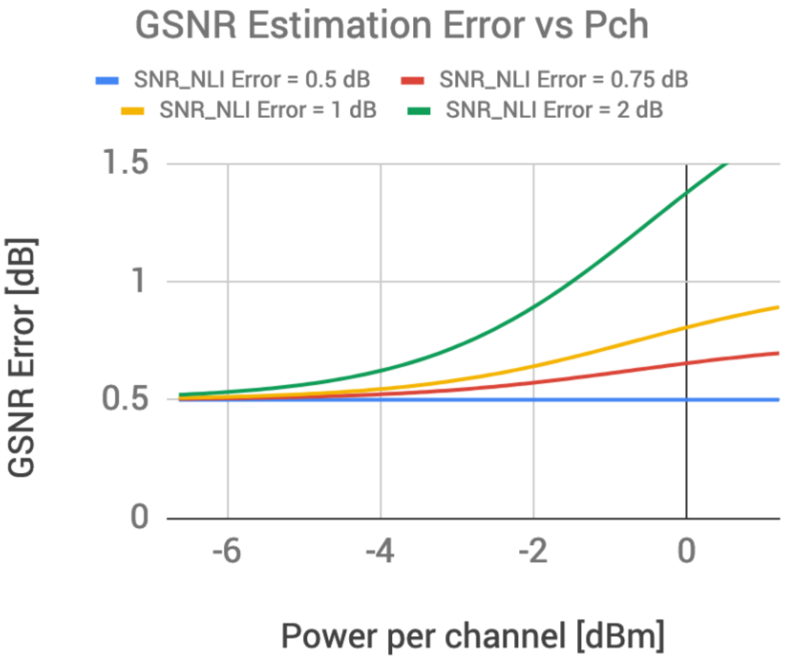


Figure 17. GSNR estimation error vs power per channel. Typical per channel power levels for an example fill of 120 channels vary from -5 to -2 dBm in typical current generation subsea designs.

The Impact of SNR_{MODEM} and GSNR on Capacity Estimation

Now, as discussed, since GSNR is not a directly measurable metric, we must consider the errors that may be introduced through the previously proposed measurement methodology, where a coherent modem is used, and its corresponding noise contributions are subsequently removed. Definitions are provided for QPSK-specific modems with requirements also stated for higher order modulations. The analysis is extended to model the impact of propagation dependent modem implementations that exist in all coherent modems. This impact is expressed as both a variance in the GSNR and cable capacity.

The following discusses the potential errors that may be introduced by modem noise contributions (SNR_{MODEM}), and its impact on GSNR, and thus capacity estimation, per the relationship below:

$$\frac{1}{SNR_{TOT}} = \frac{1}{GSNR} + \frac{1}{SNR_{MODEM}}$$

Formulation of QPSK-based GSNR

For the purposes of this discussion, the definition of SNR_{MODEM} is expanded in more detail to encompass all known noise contributions:

$$1/SNR_{MODEM} \;=\; 1/SNR_m + \sum_{i=0}^{4} 1/SNR_i$$

Where, SNR_m is the link independent (i.e. back to back) modem implementation noise, and SNR_i is the sum of the four main link dependent modem penalties:

1. PDL: Coherent modems have the ability to compensate for Polarization Dependent Loss (PDL), however a Q or SNR penalty is associated with this compensation. The penalty varies as a function of PDL, thus the impairment is link dependent.
2. CDC: Chromatic Dispersion Compensation (CDC) in coherent modems is implemented by a DSP filter. Filters have an implementation noise that is not accounted for in a back-to-back measurement. This filter noise has a Q or SNR penalty that is dependent on the total dispersion of a link.
3. Laser linewidth dispersion interaction: Laser linewidth is a measure of phase noise or phase ‘stability’ in the transmit laser. A coherent receiver needs to maintain a constant tracking of the transmit phase to successfully perform symbol recovery. The larger the linewidth, the larger the phase noise. In the frequency domain, dispersion is a frequency dependent phase profile applied to a channel’s signal. If this phase profile is applied to a noisy laser (i.e. broad linewidth), the dispersion ‘fluctuates’ which manifests itself as temporal jitter in the receiver. This jitter causes a Q or SNR penalty that is dependent on the total link dispersion and the laser used in the modem.
4. Wavelength tolerance: Examples of wavelength tolerance include (but are not limited to) the number of filters used in a cable system causing clipping of a channel’s spectrum, flexible grid cross-talk penalties (linear or nonlinear), and/or penalties associated with laser frequency drifts.

Note that where QPSK is chosen to be the modulation format of choice, SNR_{TOT} is conveniently related to Q, where $Q^2 = SNR_{TOT}$, in linear units. For most other modulation formats, the Q to SNR relationship is highly complex and, in many cases, does not exist. Hence, Q is replaced with SNR.

Measurement Overview

As mentioned, the implementation noises of the modem and link coupling is added when coherent modems are used. Using the previously introduced equations, it can be shown that:

$$1/GSNR \;=\; 1/SNR_{TOT} - 1/SNR_m - \sum_{i=0}^{4} 1/SNR_i$$

This concept was explained in previous sections, and an updated illustrative diagram is provided below to include Q_b (Q in B2B) and Q_p (Q after propagation).

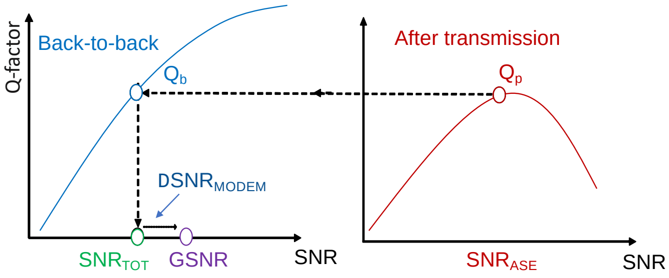


Figure 18. Updated Diagram of B2B-1 Method to include Q_b and Q_p.

Hence the linear SNR used at B2B (i.e. SNR_{TOT}) is scaled by the implementation noises of the modem and link coupling. Fortunately, over a large range of (dispersion uncompensated) undersea link designs, the individual link-dependent implementations noises (i = 1,2,3, & 4) are approximately bound to the range of 23-35 dB. That is, either PDL, CDC, laser linewidth, and wavelength tolerance will each have an SNR penalty within 23-35 dB regardless of coherent modem design.

As discussed in the previous section, in highly linear D+ cable designs, and even more so in SDM designs, $SNR_{NLI} << SNR_{ASE}$, such that the net impact on GSNR is comparatively low, and largely dominated by SNR_{ASE}. The SNR range being discussed here for modem implementation penalties contributing to SNR_{MODEM} is similarly low with respect to both SNR_{ASE} and SNR_{NLI}.

Using this maximum range, a Monte-Carlo simulation can be written for GSNR where the four modem-link implementation noises are distributed between 23-35 dB, in order to bound the practical limits on the impact of these penalties.

Measurement Error in GSNR of Multi-Vendor/Generation Technology

In the above formalism, it is important to emphasize that the modem-link impairments are specific to a modem technology and vendor. The estimated values of these impairments are predominantly simulated (with or without lab verification). Since GSNR is measured through simplified approximations, we can gauge the error in its measurement by Monte-Carlo simulations when SNR_{TOT} is measured using different coherent technologies or vendors:

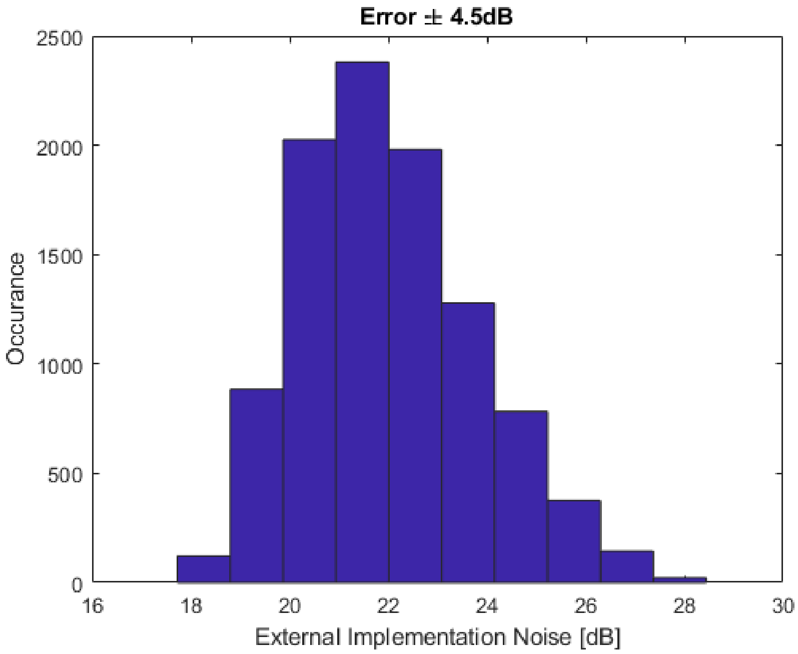


Figure 19. Histogram showing net effect of link-dependent modem penalties ($\sum_{i=0}^{4} 1/SNR_i$) on SNR_{TOT}.

The above figure is a histogram of $\sum_{i=0}^{4} 1/SNR_i$ where each impairment is distributed between 23-35 dB. A 22 dB combined mean is suggested with a 5-sigma error of 4.5 dB.

This indicates that the SNR_{MODEM} contributions to measurements made with any one modem generation or vendor technology, can vary by a maximum of 4.5 dB relative to any another generation or vendor technology, when the extremes in possible modem implementation penalties are considered.

Thus, it is critical that the modem impairments be well characterized and understood, such that they can be properly removed, and an accurate GSNR value can be obtained. Alternatively, this variability is not a concern if GSNR measurements use a coherent technology that serves as a universal reference for all GSNR measurements.

Errors in Capacity Statements of Multi-Vendor/Generation Technology

Using the GSNR of a cable system to calculate capacity of a single fiber at 0 dB margin, with no quantization in line rates considered can be done by assuming:

$$C = 2Blog_2(1 + \Gamma SNR_{TOT})$$

Where,

B is the signal bandwidth

Γ is the coding gap of the modem being used

And,

$$1/SNR_{TOT} = 1/GSNR + 1/SNR_{MODEM}$$

Assuming a SNR_m of ~18dB, and the distribution of $\sum_{i=0}^{4} 1/SNR_i$ in Figure 19, we will examine some theoretical and practical cable system designs and the impact of different modem implementations on capacity.

First, let us consider two theoretical designs, where:

High performance: SNR_{ASE} = 18dB and SNR_{NLI} = 18dB
Low performance: SNR_{ASE} = 14dB and SNR_{NLI} = 14dB

For the high performance case, the error in the capacity is the highest, due to the larger relative noise impact of the SNR_{MODEM} penalties with respect to the combined SNR_{ASE} and SNR_{NLI} (or GSNR):

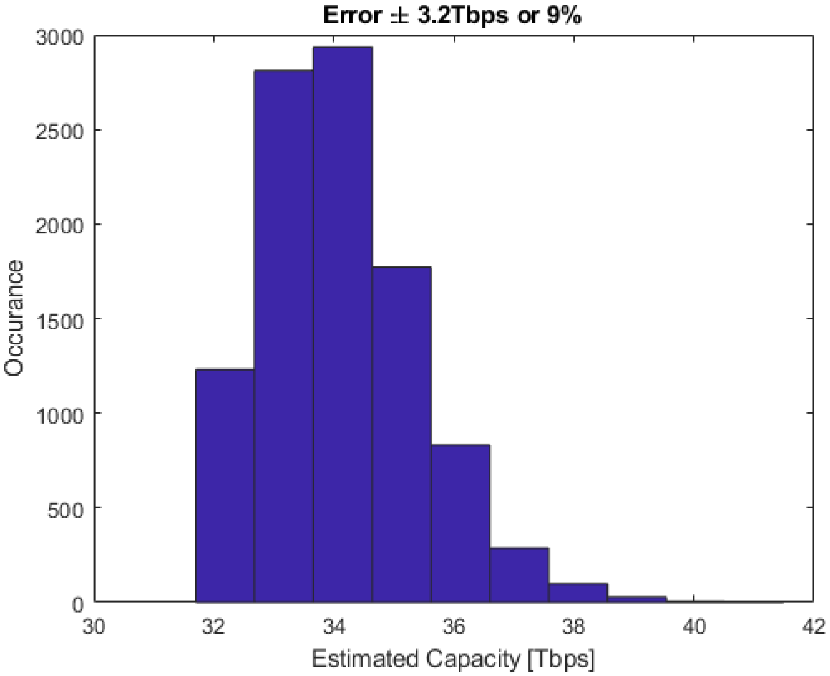


Figure 20. Capacity estimation error on a high performance subsea design.

For the low performance case, the error in the capacity is the lowest, due to the much smaller relative noise impact of the SNR_{MODEM} penalties with respect to the combined SNR_{ASE} and SNR_{NLI} (or GSNR):

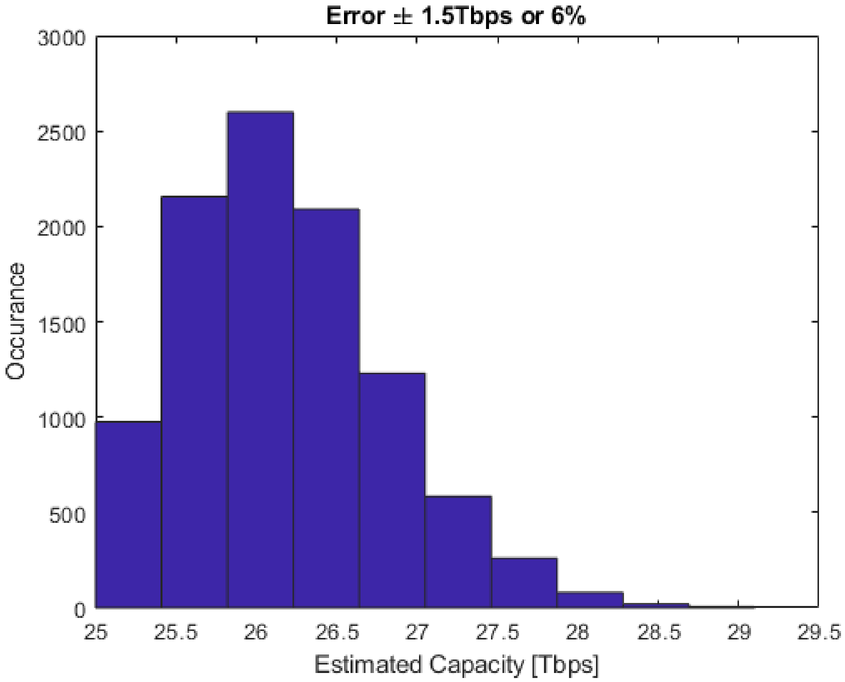


Figure 21. Capacity estimation error on a low performance subsea design.

In order to provide a more practical perspective of the extremes that may be seen in today's cable designs, we have also considered two additional cases. The first is representative of a high OSNR, high TOP design, where the cable TOP is designed to be slightly in the nonlinear regime. The second, is a low OSNR, low SDM design, where the cable TOP is designed to be well into the linear regime.

The SNRs considered for these cases are:

High OSNR, High TOP Design: SNR_{ASE} = 18 dB and SNR_{NLI} = 20 dB
Low OSNR, SDM Design: SNR_{ASE} = 8 dB and SNR_{NLI} = 15 dB

Similar to our indicative theoretical examples, for the high SNR case, the error in the capacity is the highest, due to the larger relative noise impact of the SNR_{MODEM} penalties with respect to the combined SNR_{ASE} and SNR_{NLI} (or GSNR):

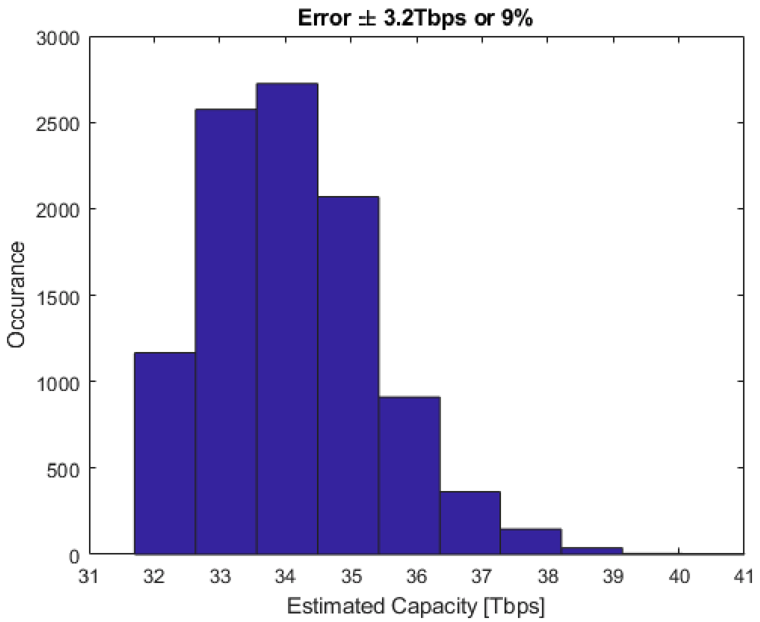


Figure 22. Capacity estimation error on a high OSNR, high TOP subsea design.

And as expected, for the low SNR SDM case, the error in the capacity is extremely low, primarily due to the significantly smaller relative noise impact of the SNR_{MODEM} penalties with respect to the combined SNR_{ASE} and SNR_{NLI} (or GSNR):

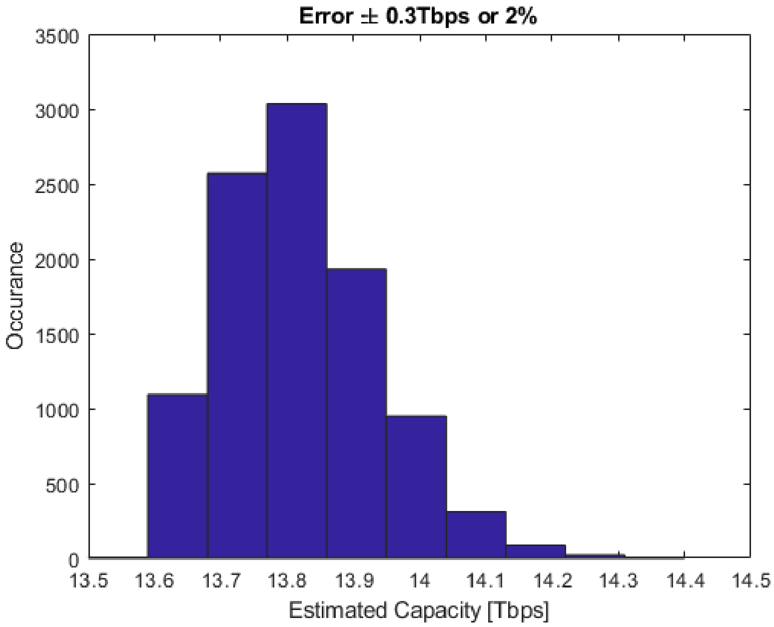


Figure 23. Capacity estimation error on a low OSNR, SDM subsea design.

Capacity Errors on non-QPSK modems

It is worth noting that the total SNR can be expanded to include a critical modem distortion factor, ϵ.

$$1/SNR_{TOT} = \epsilon(1/SNR_{ASE} + 1/SNR_{NLI} + 1/SNR_{MODEM})$$

It is generally accepted that standard QPSK modems, like those that are being proposed for use as a GSNR measurement tool, have ϵ=1, hence this factor is not typically considered in the definitions within this document, nor the referenced documentation.

However, more complex modern modems do not have $\epsilon = 1$. If the GSNR were to be measured with a QPSK modem ($\epsilon = 1$), the GSNR for a non-QPSK modem would need to be linearly scaled per the following relationship:

$$C = 2Blog_2(1 + \Gamma(\epsilon/GSNR + \epsilon/SNR_{MODEM})^{-1})$$

ϵ can vary between 0.1 and 1 and in the absence of proper characterization of ϵ, capacity estimation could vary between $\log_2(1+1)$ and $\log_2(1+0.1)$, resulting in an 86.2% error. As such, per previous guidance, QPSK modems are recommended for the characterization of GSNR.

Errors in PoP-to-PoP System Designs

It is important to note that the model proposed herein can break down for PoP-to-PoP system designs, particularly if the fiber type changes, as ϵ also changes as a function of propagation, particularly in high phase noise environments (such as terrestrial networks and dispersion compensated cables).

Modem Capacity Quantization and the Impact on Risk

The previous sections discussed the impact of errors on GSNR and capacity estimation, considering zero quantization. However, practical modems offer fixed line rates, and if a delivered subsea cable misses its SNR target, and that SNR target crosses below the performance threshold of the expected line rate, the achievable capacity of the system will be impacted.

First, let us set a baseline using Shannon, where quantization is not considered. The Shannon Capacity impact of errors on SNR are small. In the SNR range of a typical modern day subsea design, a 1dB error in SNR represents <10% capacity delta per fiber pair. Now, let us consider the impact with practical modem considerations.

With first generation ~30-35 Gbaud coherent modems, offering 50G line rate steps via 100G QPSK, 150G 8QAM or 200G 16QAM modulations only, the stakes were very high. Let us assume a standard 4.5 THz repeater bandwidth, supporting 120 channels at 37.5GHz spacing. A system designed with a particular set of target SNRs with the intent to support 150G 8QAM would have a design capacity of 18 Tb/s (120 x 150 Gb/s). If the margins considered on the design were low, and the cable under delivered the SNR enough to drop the supported line rate to 100G QPSK only, the new achievable capacity is reduced to 12Tb/s (120 x 100 Gb/s). This represents a 33% drop in cable capacity in this particular example.

More generically speaking, if a system supports 120 channels, and the data rate step size is 50 Gb/s, the per fiber capacity exposure to a large enough SNR miss to cause a change in data rate, is 120 x 50 Gb/s, or 6 Tb/s. This magnitude of risk would more than likely be considered commercially unacceptable for almost any cable owner.

However, the advent of high baud, multi-rate modems significantly reduces the impact of data rate quantization on the achievable capacity, by offering more fixed line rates with smaller SNR step sizes between each rate. The higher the baud rate, the smaller the SNR step size, as the cardinality delta in constellations used for a fixed delta in aggregate line rate decreases.

For example, let us consider the same 4.5 THz repeater bandwidth, but with a ~90 Gbaud coherent modem, supporting 45 channels at 100GHz spacing. If this modem also offers 50 Gb/s line rate steps, one could calculate that the capacity risk is only 45 x 50 Gb/s, or 2.25 Tb/s. Depending on the base capacity target, this could represent 10% fiber capacity risk (on a ~20 Tb/s design), or upwards of a 20% fiber capacity risk (on a ~10 Tb/s design).

The diagram below illustrates the example discussed above. Note the modem considered is a fictitious multi-baud rate modem, where there is no performance delta between the baud rates offered, and as such the example isolates for only the impact of baud rate and capacity quantization.

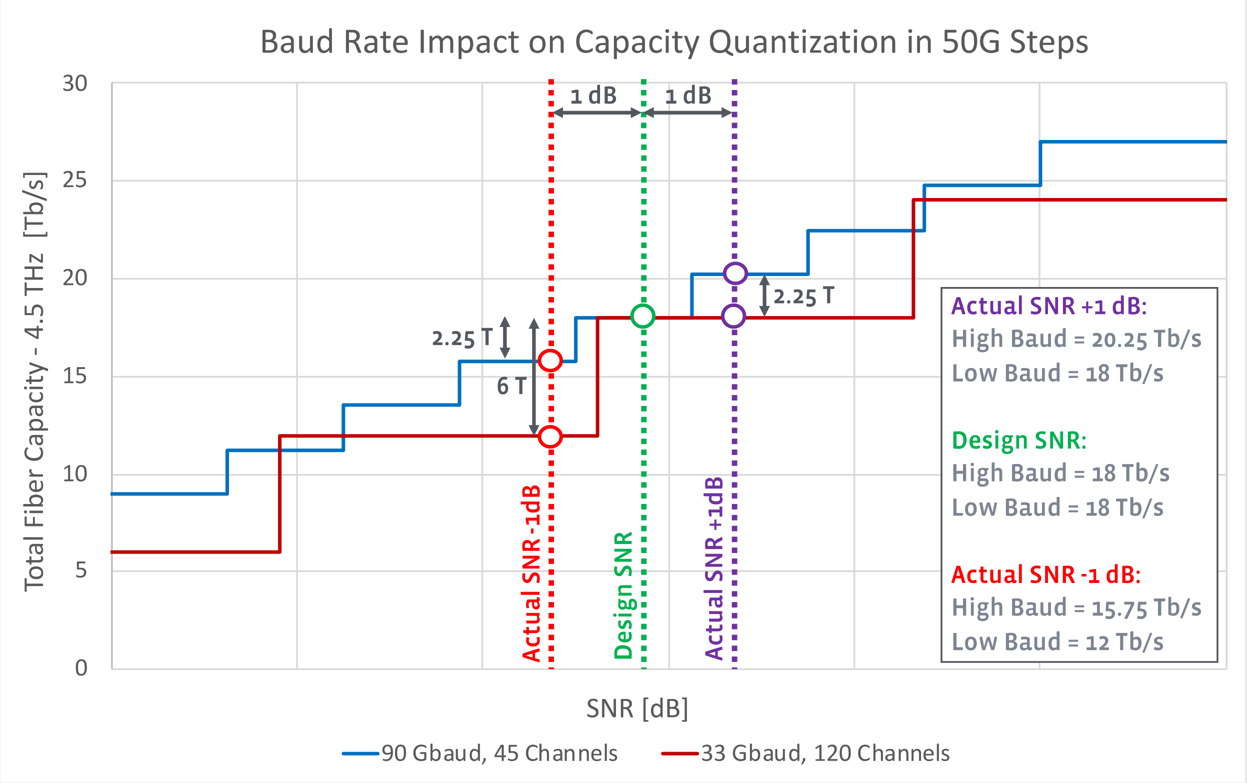


Figure 24. Example of the impact of baud rate and data rate quantization on fiber capacity with changes in SNR.

Should coherent modems push the baud rates of next generation modems even higher, say to ~120-130Gbaud, such that a 4.5 THz subsea fiber might support 30 channels at 150GHz spacing, the same 50 Gb/s line rate granularity further reduces the fiber capacity risk to 30 x 50 Gb/s, or 1.5 Tb/s.

These estimates of course also assume the whole optical spectrum misses the SNR expectation. An additional benefit to high baud, multi-rate modems, is the ability to adjust for SNR variability with frequency. This allows for the mitigation of an under delivered SNR in one part of the optical spectrum, and/or the extraction of additional value from an over delivered SNR in another part of the optical spectrum. Given the lower SNR step sizes between data rates, even a 1-2 dB upside in SNR in parts of the optical spectrum could allow the use of higher data rates, turning the aforementioned risks into noteworthy potential upsides.

Key Takeaways:

- *Due to the highly linear nature of uncompensated D+ subsea cable designs, the accuracy of GSNR is largely dominated by the SNR_{ASE} (or OSNR) contribution*
    - *Recap from last section: SNR_{ASE} can be directly measured with an OSA and has a well understood measurement procedure with a high degree of accuracy.*
- *The impact of errors in SNR_{NLI} (the more challenging contribution to measure), is significantly smaller, and continues to decrease with the trend towards SDM designs*
    - *Even a significant error of up to 2dB on SNR_{NLI} will result in <1 dB of error in GSNR*
- *The impact of errors in SNR_{MODEM} is also significantly smaller, particularly on low SNR_{ASE} systems, and only arises due to incorrect estimation of modem penalties.*
    - *Errors in SNR_{MODEM} estimation on a high OSNR, high TOP system design could yield up to 9% capacity error, not considering margin or quantization.*
    - *Errors in SNR_{MODEM} estimation on a low OSNR, SDM system design drops significantly, to ~2% capacity error, not considering margin or quantization.*
- *High baud, multi rate modems, with small required SNR deltas between available data rates, even further mitigate the risks of SNR_{ASE} or GSNR misses, and even offer opportunity for capacity upside through data rate optimization across the optical spectrum.*
    - *A data rate miss from a first generation ~30-35 Gbaud modem could cost 6 Tb/s in total fiber capacity.*
    - *A data rate miss from a modern day ~90 Gbaud modem could cost at most 2.25 Tb/s in total fiber capacity, but is also more easily mitigated by data rate mixing in different parts of the optical spectrum with higher and lower SNRs.*

Considering the Architecture of Open Cables

ITU Standardization Work

The ITU-T G.971 recommendation is attempting to create a generic reference model for the physical layer applications to ensure common terminology when discussing an open cable. This reference model incorporates details including definition of the optical coupling junction, PFE connections, and the wet plant maintenance coupling. A high-level view of this is shown in below.

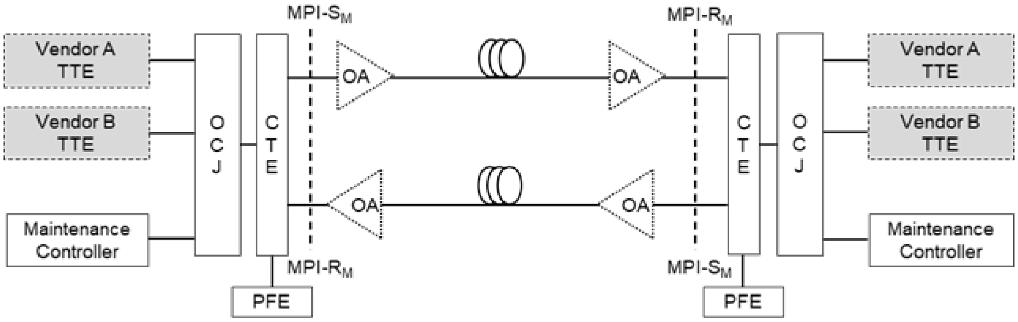


Figure 25. Open Cable Reference Model.

Where:
TTE: Terminal Transmission Equipment
OCJ: Optical Coupling Junction
CTE: Cable Terminating Equipment
MPI-RM: Multichannel receive main path interface reference point
MPI-SM: Multichannel source main path interface reference point
IPI SM: Interoperable reference point on the optical terminal just before the optical coupling junction
IPI-RM interoperable reference point on the optical terminal just after the optical coupling junction

The Optical Coupling Junction may be an active or passive device depending on the solution being used to achieve the coupling. Depending on the solution selected the OCJ can be supplied by either the wet plant vendor or a 3rd party SLTE vendor.

Regardless of the option selected, ensuring interoperability of wet plant and 3rd party SLTE is fundamental. It is critical to be particularly cognizant of what active components are being placed in between the SLTE and the wet plant, and that no limitations, excess losses or requirements for pads are unnecessarily introduced. Some potential options of how an OCJ could be implemented are shown in the figure below.

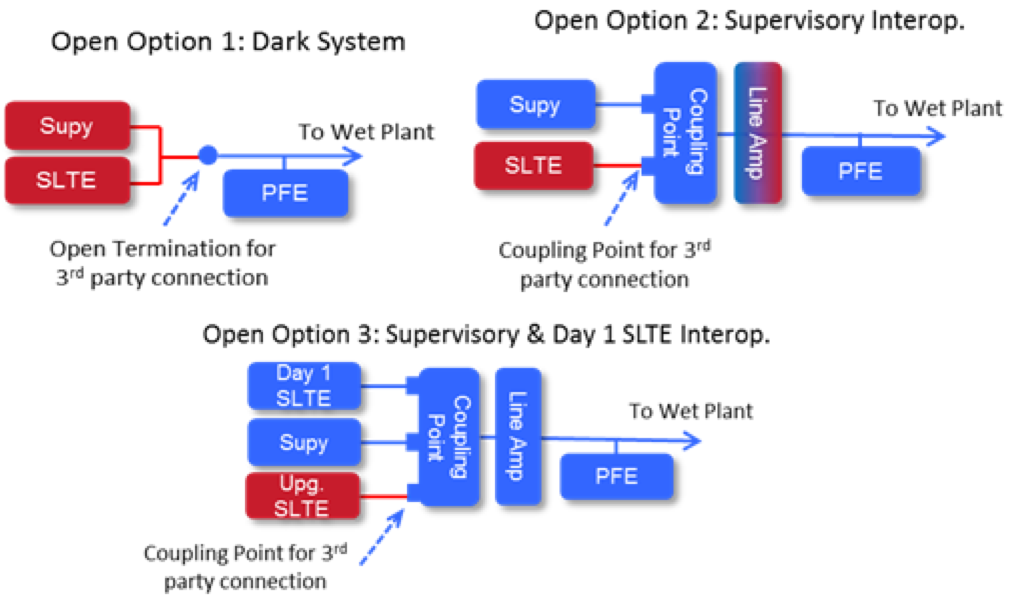


Figure 26. Potential Coupling Strategies.

Coupling Considerations

Regardless of the SLTE chosen for initial day 1 capacity, it is critical that the OCJ have an open coupling port available. Typically, a 50/50 (3dB) coupler with monitor ports for the combined signal has been specified in the past, however other coupling ratios may be supported. Many wet plant designs have lower loss shore spans, in part to accommodate additional losses at the terminal station. If numerous coupling losses are expected in the OCJ for multiple SLTEs, it is important that this be understood.

As some SLTE photonic designs use Total Output Power (TOP) controlled amplifiers, a simple 50/50 coupler may not provide all of the functionality required to ensure additional SLTEs can be coupled if multiple generations of SLTE are installed. Wavelength Selective Switch (WSS) based solutions for the OCJ are becoming common from both wetplant and upgrade vendors to provide seamless integration of additional SLTEs, as foreign wavelength support solutions have advanced significantly in their capabilities and automation, primarily drive by spectrums sharing applications. As such, a single fiber pair owner may even choose to employ a spectrum sharing solution for their own use, with the goal of multi-vendor wavelength support.

Depending on what stage within a cable lifetime an activity is being done (i.e. a dark system or an upgrade to existing capacity), SNR_{ASE} and GSNR characterization needs be done accordingly either on a wet plant only (with or without an OCJ that might be a permanent fixture) or with dry line amplifiers (and any other relevant in-line equipment) included. In the first case, an SLTE provider would need to account for any line amplifiers to be added with SLTE, in the second case, the SNR_{ASE} and GSNR needs to account for any already existing in-line equipment, such as dry amplifiers.

Supervisory Considerations

Wet plant supervisory and control equipment may be provided by the wet plant supplier or by the upgrade supplier, if a solution is available. It is generally recommended that supervisory be provided by the wet plant vendor, assuming the wet plant vendor supplies a supervisory solution that does not require the use of any specific SLTE equipment or modems. In addition, the supervisory solution should have a modern Northbound Interface (NBI) that can be integrated into external NMS solutions to provide a monitoring option for the end to end services, including modems, dry plant and wet plant. For example, Representational State Transfer (REST) Application Programming Interfaces (APIs) could be used for management and control (HTTP/1.1), web sockets for autonomous event notification and data descriptions in JavaScript Object Notation (JSON) or eXtensible Markup Language (XML) format.

As optional items, wet plant providers have also offered solutions that provide support for wet plant power management and spectrum sharing as an integrated offering to the submarine cable. The intent of these solutions is to allow the purchaser to have the ability of monitor and control the wet plant in the absence of modems. When using these types of solutions, it is important to ensure that they do not result in any limitations on how the 3rd party modems operate on the wet plant. For example, solutions that provide power management and/or spectrum sharing must allow the spectrum owner to view the spectrum they have been assigned as a virtual fiber pair and not force the modems to operate on a specific grid or channel width. The operational impact also needs to be considered, when the fiber pair (or spectrum) owner is adding new channels, control of ASE idlers needs to be via the same NMS and not a complex multi system process.

Key considerations for supervisory solutions on Open Cable Systems:

1. SLTE Independence
    a. Interoperability with wet plant monitoring and control of all active submerged components (repeaters, BUs, equalizers).
    b. Solution operation over a spectrum that can be both partially and fully occupied by 3rd party SLTE waves and power management – understand requirements for minimum percentage of spectral occupancy by wet plant supplier waves or power management for proper operation of supervisory system (if any)
    c. Non-conditional wet plant warranty – wet plant vendor supervisory system is not required day 1 or in the future.
        i. In the case of wet plants with active supervisory, confirming all critical information for all active submerged components is the responsibility of the system purchaser and is provided in full at or before Ready for Service (RFS) (e.g. repeater addresses, calibration constants, available control settings, OADM BU passbands, ROADM control mechanisms, and any other relevant details to enable 3rd party control and monitoring if necessary).
        ii. Ensure that at system commissioning, full wet plant scan results by either passive and/or active supervisory systems are documented and provided.
2. Northbound Interfaces
    a. All supervisory systems have northbound interfaces. For network future-proofing, Open APIs should be available for integration into a Software-Defined Networking (SDN) controlled virtualized network.

Key Takeaways:

- *There are a number of Open Cable architectures that can be employed, depending on the Purchasers preferences*
- *It is critical that the measurement demarcation points for OSNR and GSNR are clearly defined, and the contributions from any included dry equipment be explicitly considered and called out in the calculations*
- *Open APIs can significantly simplify the operational handling of equipment from multiple vendors in an Open Cable environment*

What to Ask for in an Open Cable ITT

One of the biggest barriers to designing one’s first Open Cable, is knowing what to ask for in the ITT. With OSNR and GSNR as new Open Cable performance metrics, the next logical question is how to correlate these with a target capacity for the system. This section discusses the Open Cable ITT process, and recommendations on navigating the challenges.

Why Traditional Capacity-based ITTs are no Longer Sufficient

Traditional ITTs were most commonly specified with a Design Capacity and an associated EOL Q margin, often on the order of 1 dB with respect to the modem FEC limit, after considering ITU recommended 25-year repair and aging allocations. Suppliers would prepare an optical power budget, including the SOL Q and EOL Q to meet these specifications and propose a commissioning limit with respect to the Q factor of that particular Supplier’s modem technology. The minimum Q and TVSP would be collected and verified during commissioning to prove design capacity.

Two fundamental concepts need to be understood to help make clear why the traditional capacity-based ITT is no longer optimal.

First, due to the TOP limited nature of subsea systems, optical performance (i.e. OSNR/GSNR/Shannon Capacity) are capped, at their maximum, Day 1. There is no reasonable means to increase any of these parameters for a given subsea system over time. Thus, optical performance of the wet system can be considered as fixed, with a relatively predictable decrease over system lifetime.

Second, as discussed in length in the “Open Cables Giving Rise to New Challenges” section of the document, capacity potential of a particular wetplant design, for a fixed level of optical performance (i.e. OSNR / GSNR), must be viewed as a moving target, and in recent years, a highly variable one, with rapid changes in modem technology and features driving significant capacity improvements over design capacities.

With these concepts in mind, one can grasp the magnitude of the need for consistency in defining the wet plant optical performance.

This concept is visualized in the figures below. Both figures illustrate an evolution of capacity over time, with some broad assumptions around the available coherent technology and corresponding capacity on a subsea design in a given year, where the OSNR and GSNR remains constant, and only improvements from SLTE technology are considered.

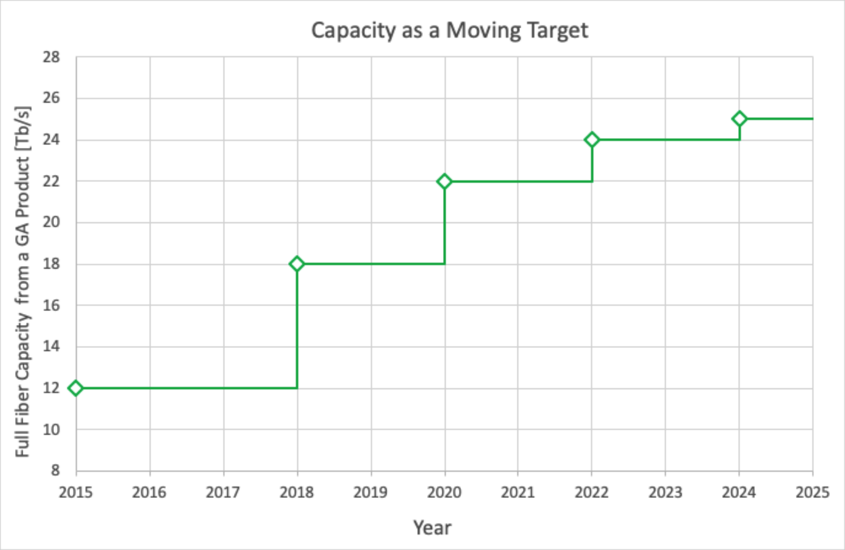


Figure 27. Example of capacity evolution with time. Capacity values are not specific to any particular cable or SLTE, but rather selected for illustrative purposes.

The following figure expands the visualization further to demonstrate the strong dependency achievable capacity for a fixed optical design can have when two vendors with varied technology release timing are present in the market. Additional vendors would of course add additional data points on their own unique timelines.

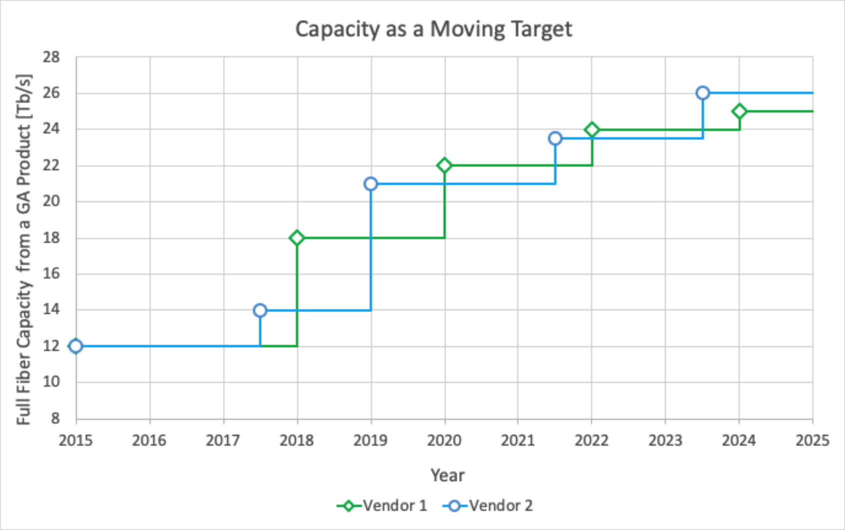


Figure 28. Example of capacity evolution with time when multiple SLTE vendors are considered. Capacity values are not specific to any particular cable or SLTE, but rather selected for illustrative purposes.

Note that the absolute values in both figures are generally irrelevant and would shift both vertically and horizontally depending on the cable design and SLTE technology considered. The capacity values are intended only to illustrate the variability observed with time, the leap frogging that commonly occurs in the SLTE space, and the capacity growth compression being observed as SLTE technology approaches Shannon.

How Open Cables Can Overcome the Traditional ITT Limitations

As just stated, there is a clear need for consistency in defining wet plant optical performance, without direct ties to a particular vendor or generation of modem technology. The evolution towards Open Cables intends to address exactly this need. Open Cables does not mean that capacity is not considered, nor that capacity is not still the foundational target of design. It is rather the disaggregation of capacity from wet plant optical performance, such that the time variability, and fundamentally the supplier variability, of capacity can be accounted for.

As such, one of the fundamental building blocks of setting optical performance design targets for an Open Cable design, is an understanding of the relationship between optical performance and capacity potential from a selection of vendors' current and next generation modems. This is greatly aided by a close working relationship with the modem vendor community.

Setting Capacity Targets and Assessing Individual Risk Tolerance

For any Open Cable, it remains essential that the Purchaser understands the **minimum capacity** that they need to achieve, and their risk tolerance to achieving this target, or missing the target by X Tb/s at a certain point in time. (See the Section "Modem Capacity Quantization and the Impact on Risk" for a discussion on assessing the magnitude of X). This allows the Purchaser to peg their optical design, to a generation of modem that is available within a certain time frame ahead of cable RFS.

For example, a highly risk-adverse Purchaser could choose to fix the optical design such that the minimum capacity is guaranteed to be met by current generation modem technology. In this scenario, all capacity improvements that are expected by modem technology available at cable RFS can be treated as upside. However, since higher optical performance in the wet plant essentially always drives higher system cost, this all but ensures the Purchaser will be paying more than necessary to achieve their minimum capacity target.

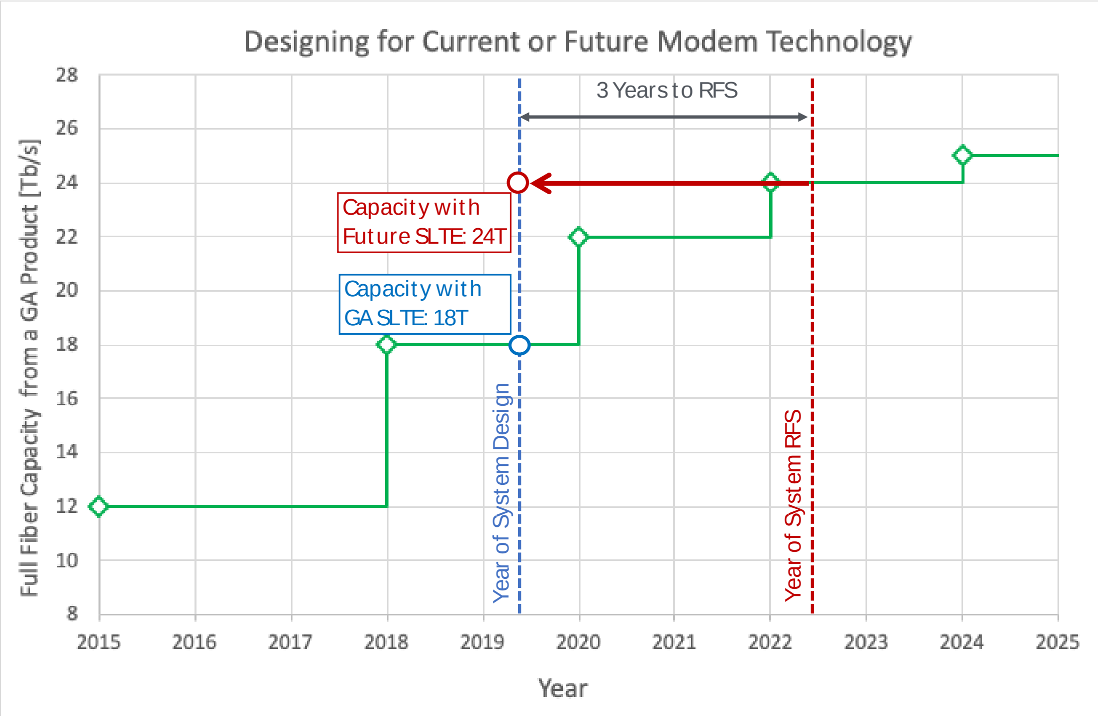


Figure 29. Illustration of a subsea cable design (solid green line), with a particular OSNR and GSNR, aligned to deliver the target minimum capacity using SLTE available at time of System Design, without considering future SLTE potential.

Alternatively, a Purchaser could choose to fix the optical design such that the minimum capacity is expected to be achieved by a generation of modem technology expected to be available a certain number of months prior to cable RFS date. Of course, there is risk that the full fiber capacity is not available at the time of RFS if future technology predictions and timing of SLTE are not met. In this case, the Purchaser will have to absorb the capacity drop. With a healthy staggering of SLTE release dates from multiple vendors, this risk should be lower than depicted in the single vendor example. It should also be considered that while full fiber capacity may not be achievable Day 1, if the Purchaser only plans to fill, say, 10% of the fiber Day 1, the exposure remains minimal.

The following figure illustrates the case where the optical design is fixed such that the minimum capacity required should be fulfilled by the SLTE technology available at RFS.

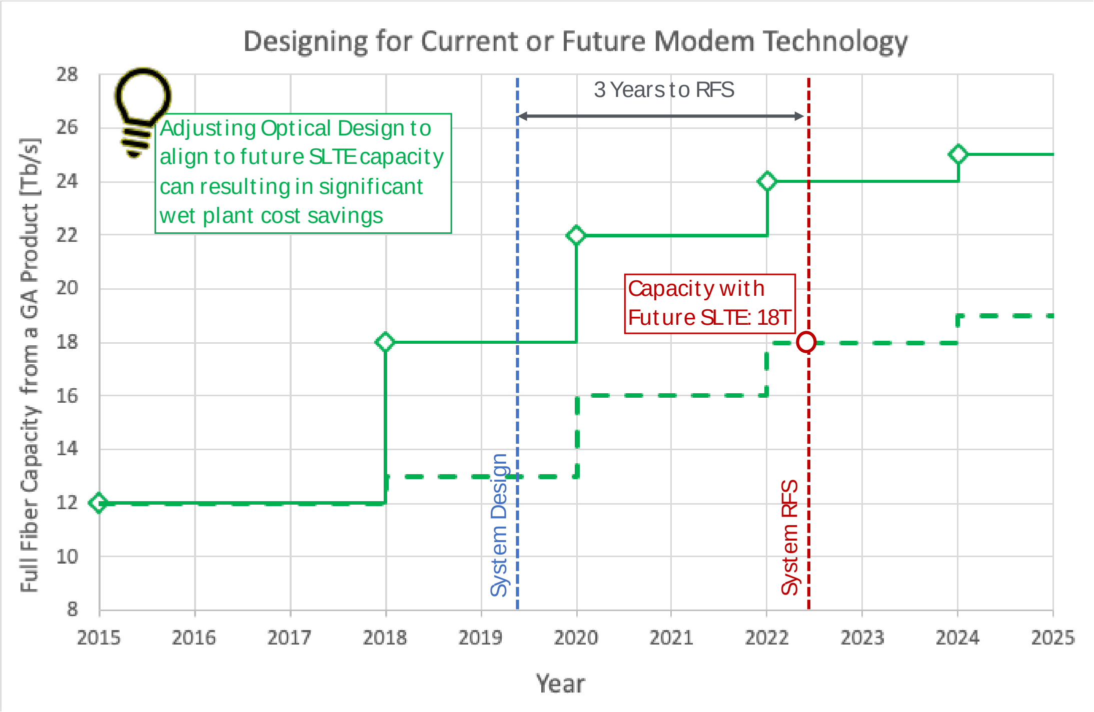


Figure 30. Illustration of a second optical design (dotted green line), with a lower OSNR and GSNR, aligned to deliver the target minimum capacity using future SLTE. The lowering of OSNR and GSNR requirements represents a significant cost savings in wet plant.

One important distinction, and a significant risk reducer to the Purchaser, is that the difference between "current" and "future" generation modem capacity is much lower than would have been seen in recent years and is only continuing to compress with time. This was also discussed in the previous section but is worth re-iterating and can be clearly seen in the capacity growth compression with time shown in the figure above.

Modem technology has pushed closer and closer to Shannon and is approaching a plateau in the performance improvements that can be made for a reasonably proportional level of investment. The current subsea industry design trend of SDM, which pushes optical performance even further into the linear regime, is only limiting the space in which modem technology can improve more, as innovative techniques such as nonlinear compensation have little to no benefit. Therefore, the risk (or cost) of assuming a future (or current) generation of modem technology as a basis for an optical design is reduced, by the sheer reduction in the delta between the two.

Setting Wet Plant Optical Performance Design Targets

Once the Purchaser has determined their minimum capacity target, and generation of modem technology, or time window, to which they would like to peg this capacity to, according to their risk tolerance, the target optical performance specifications for the wet plant can be set.

As previously mentioned, a good working relationship with the modem vendor community significantly aides in this selection of optical performance targets. For example, prior to releasing a cable system ITT, the Purchasers should probe the modem vendor community on current and next generation technologies, performance, and timing to understand the capacity potential at a given point in time. Modem vendors can guide on OSNR and GSNR ranges to achieve a minimum capacity target. Beyond the specified OSNR and GSNR, certain modem specific penalties (SNR_{modem}) would need to be considered by the modem vendor, such as the expected CD of the system, PDL, PMD and aging or other modem specific penalties.

Ideally, modem vendors would provide this in the form of an SNR based power budget, not a traditional Q/OSNR based power budget table. Until this becomes standard, a traditional Q-based power budget table can still be used to assess modem capacity for a given OSNR / GSNR target range.

It is essential, in this model, that the scope and understanding of what is included in the OSNR and GSNR values (i.e. minimum vs average, photonic demarcation points, dry plant contributions, manufacturing margins, etc) are well defined. Recommendations for defining industry standards on most of these are provided throughout in this text.

It is also important to consider the scope of the capacity metric being considered. Total cable capacity targets versus fiber pair capacity targets may result in different cable design economics, particularly with the recent advances in SDM and pump sharing for overall cable capacity optimizations. Even in joint builds, where different Purchasers may have different consumption potential for capacity, SDM has proven more economical than maximizing capacity on a per fiber pair basis only. Nonetheless, it can be beneficial to request multiple design options, with varying numbers of fiber pairs and degrees of pump power sharing, in order to achieve and explore the most economically optimized design options.

If we assume, for simplicity, the minimum capacity, at a point in time, is set on a per FP basis, the performance specifications can be set as a minimum average OSNR, and minimum average GSNR to be achieved across the optical bandwidth per FP. The Purchaser may wish to request a range of targets, +/- 1-2 dB around their planned design, for explorative purposes. This allows a better understanding of cost-performance (and therefore capacity) trade-offs.

In the current industry landscape, wet plant vendors are still offering either in-house modems, or 3rd party modems via partnerships. In this model, the Purchaser can also request a capacity estimation from the wet plant vendor, using either their current or next generation offerings, with an option to purchase as part of a turn-key delivery.

In a true Open Cable environment, traditional full capacity testing by the wet plant vendor, using their in-house modem technology, should only be exercised if the Purchaser plans to deploy said technology. Otherwise, a full capacity test result, with a modem that will not be deployed, is relatively meaningless, and the commissioning efforts would be better spent focusing on the optical performance metrics discussed here. More detailed recommendations on commissioning and acceptance are offered in the sections that follow. However, it may be the case that due to the commercial models driving the cable build, if a capacity guarantee is required, full capacity testing with modem technology offered by the wet plant supplier may still be desired.

Key Takeaways:

- *Traditional ITTs were specified with a Design Capacity and Q targets that were directly tied to one particular vendor's modem technology.*
- *Open Cable ITTs can be specified with OSNR and GSNR in a way that uniquely describes the optical performance of the wet plant, with no ties to a specific modem technology.*
- *OSNR and GSNR based Open Cable ITTs do not mean that capacity is not still the primary target of the cable build, it simply provides a means to consider the capacity offered by the many available variants and generations of modem technology*
    - *Capacity potential of a particular optical design is a moving target with time, with each release of a new modem technology from a new vendor raising the capacity bar*
- *Purchasers of an Open Cable need to understand their minimum capacity, and assess the risk-cost trade-off they are willing to take:*
    - *Lowest risk, Higher Cost Cable: Design OSNR and GSNR targets to align to the minimum capacity, as achievable by a modem technology available now. This can be lab verified in early Design Reviews.*
    - *Higher risk, Lower Cost Cable: Design OSNR and GSNR targets to align to the minimum capacity expected to be achieved by modem technology expected to be available at the time of cable RFS.*
    - *Middle Ground: Design OSNR and GSNR targets to align to some date in between System Design and System RFS.*
- *As modem technology pushes ever closer to the Shannon Limit, and wet plant designs move further into the linear design regime, the capacity delta between "current" and "future" modems will continue to shrink, further minimizing risk.*

Specifying, Commissioning & Accepting an Open Cable

Data Differences Before & After RFS

A key area for consideration in Open Cables is what parameters are important to specify prior to system manufacture during the ITT and design phase, and what parameters can and should be measured at system acceptance. There is a significant difference between the level of detail that can reasonably be provided during system design versus at system acceptance.

For example, at system design, it is common to specify an average and/or worst case commissioning OSNR under a given set(s) of pre-emphasis conditions. At commissioning, however, a detailed profile of OSNR versus frequency would be expected to be measured and provided, even if it is only the average value of the collected data that is utilized as acceptance criteria.

Hence, there are key distinctions that must be made between:

1. Design specifications used to describe the system,
2. Commissioning parameters used to accept the system,
3. Data that should be collected at acceptance for deeper understanding of system performance.

Design Specifications & Acceptance Criteria

There are many optical specifications that Purchasers may consider relevant in their decision making during the design phase, that cannot be directly measured at system commissioning. Effective area of fiber, for example, can only be inferred by a measurement of nonlinear noise, which can be calculated via GSNR measurements, as discussed previously. Other critical design parameters, such as fiber loss, repeater noise figure, per repeater gain profile, etc, cannot be directly measured via end-to-end system commissioning, but are each one of a number of parameters that contribute to the measurable parameters, such as OSNR and GSNR.

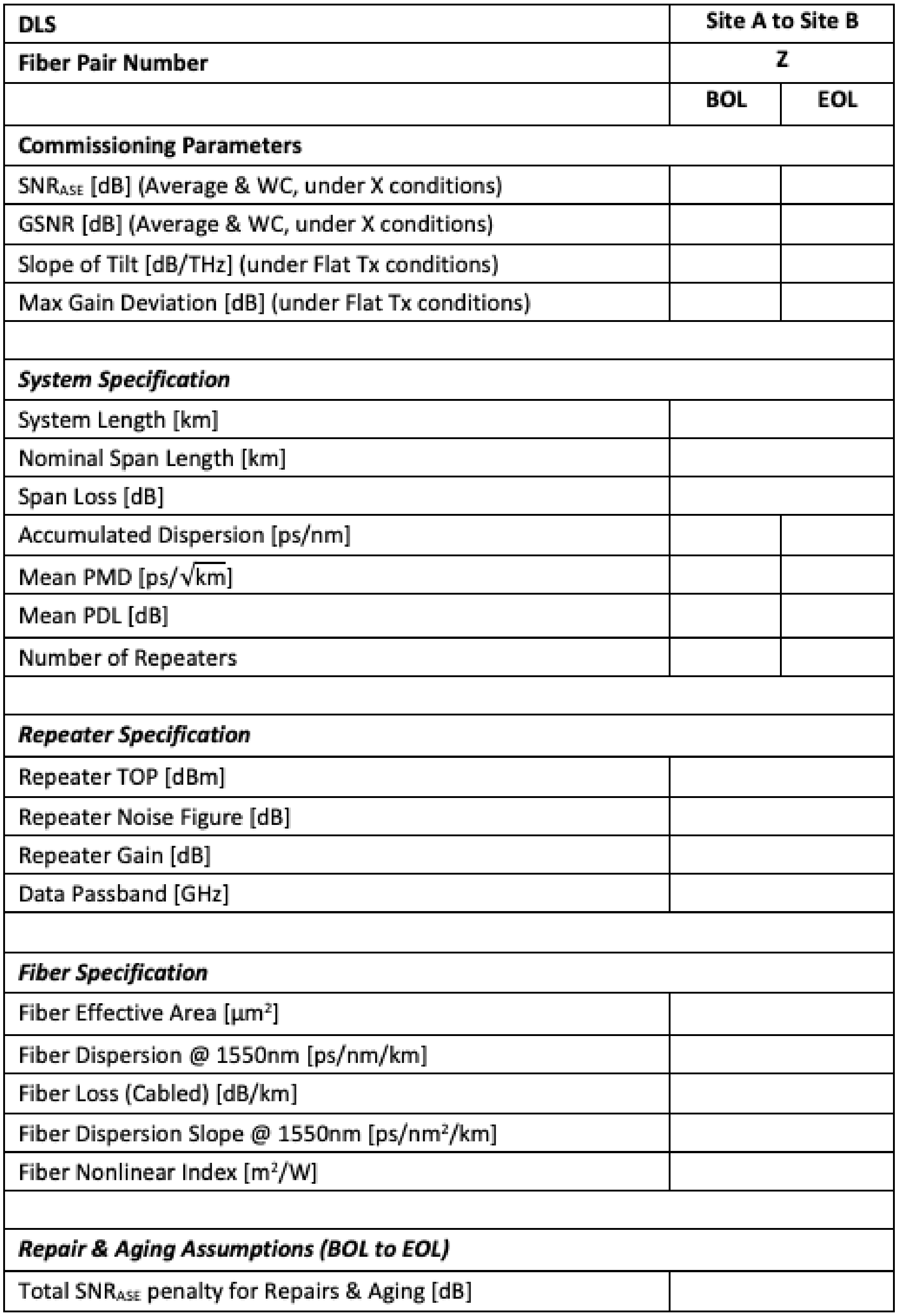
Key Parameter Table

As such, a set of optical parameters that describe the key parameters that contribute to overall optical performance should be specified and agreed during the system design phase. This set of parameters is often requested and provided in the form of a “Key Parameter Table”. A particularly important use for these parameters, is that they should provide, at a minimum, the key values required for a 3rd party SLTE provider to accurately model and estimate the system capacity with a particular generation of modem technology that may appropriately intercept the system RFS date.

One may question if OSNR and GSNR alone could be sufficient for capacity estimation. We must recall that different modem generations from different vendors will have varied responses and limitations to factors such as PDL, PMD, CD, etc (Recall the previously defined SNR_{MODEM} term). As such, more information is required for a complete picture.

Figure 31 is a suggested set of parameters that can be used to fully describe a system’s optical performance in advance of system manufacture. It is important to note that many systems will have multiple DLS of varying levels of end to end performance, and perhaps even different fiber types, or variations from fiber pair to fiber pair on the same DLS due to differing numbers of BUs or ROADMs. It is common to build the design around the worst case fiber pair on the worst case DLS, but in some cases, more options may be requested for contrast and understanding.

One particularly challenging aspect of any ITT process is what should the Purchasers specify, versus what should be opened up to the Suppliers to propose. It is important not to stifle creativity and innovation with overly stringent design criteria. One recommendation would be for the Purchasers to specify only the “Commissioning Parameters” listed below, and to do so with “minimum” or “maximum” guidelines, and as much context as possible to the Purchasers design goals, so as not to limit the Supplier freedom to use their expertise to optimize a design. The table below could then be used as a template for Supplier responses to allow Purchasers to assess the system within their individual proposals.



DLS	**Site A to Site B**	
Fiber Pair Number	**Z**	
	BOL	**EOL**
Commissioning Parameters		
SNR_{ASE} [dB] (Average & WC, under X conditions)		
GSNR [dB] (Average & WC, under X conditions)		
Slope of Tilt [dB/THz] (under Flat Tx conditions)		
Max Gain Deviation [dB] (under Flat Tx conditions)		
System Specification		
System Length [km]		
Nominal Span Length [km]		
Span Loss [dB]		
Accumulated Dispersion [ps/nm]		
Mean PMD [ps/$\sqrt{km}$]		
Mean PDL [dB]		
Number of Repeaters		
Repeater Specification		
Repeater TOP [dBm]		
Repeater Noise Figure [dB]		
Repeater Gain [dB]		
Data Passband [GHz]		
Fiber Specification		
Fiber Effective Area [μm^2]		
Fiber Dispersion @ 1550nm [ps/nm/km]		
Fiber Loss (Cabled) [dB/km]		
Fiber Dispersion Slope @ 1550nm [ps/nm^2/km]		
Fiber Nonlinear Index [m^2/W]		
Repair & Aging Assumptions (BOL to EOL)		
Total SNR_{ASE} penalty for Repairs & Aging [dB]		

Figure 31. A Recommended Key Parameter Table.

Commissioning Parameters

A subset of the parameters within the Key Parameter Table should be agreed upon and explicitly designated as the commissioning parameters that will be used for system acceptance. The conditions and methods for measurement should also be defined.

As discussed, due to a wide range of largely unpredictable factors and variances that contribute to the frequency dependency of parameters like OSNR (or SNR_{ASE}) and GSNR, it is common for commissioning parameters to be defined as a set of average and worst case values within the defined usable data bandwidth of the repeater.

A typical set of Commissioning Parameters may include:
1- Commissioning OSNR (average & worst case under X conditions)
2- Commissioning GSNR (average & worst case, under X conditions)
3- Slope of Tilt [dB/THz] & Gain Deviation [dB]

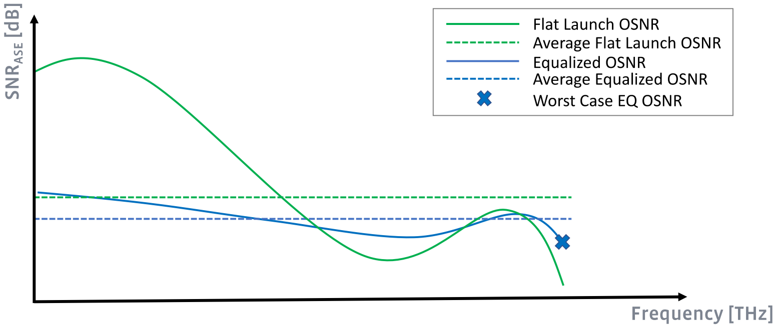


Figure 32. Illustration of flat and equalized OSNR profiles.

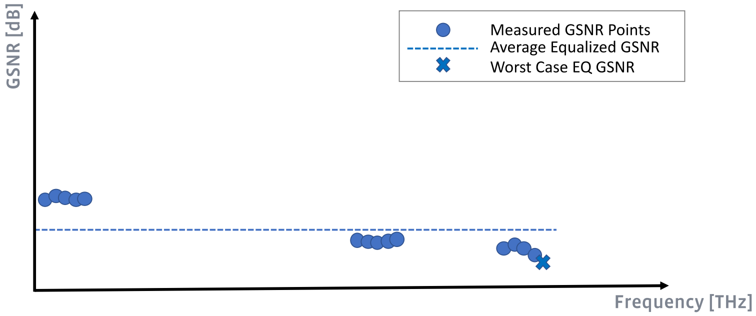


Figure 33. Illustration of GSNR measurement points for an Equalized profile.

In the absence of an automated GSNR measurement to capture a full sampling of the optical spectrum, it is currently common practice for GSNR to be probed at select spectral locations. Due to the unpredictable nature of the exact SNR_{ASE} versus frequency of any given fiber, it would be prudent to select the exact test locations based on the results of the SNR_{ASE} testing.

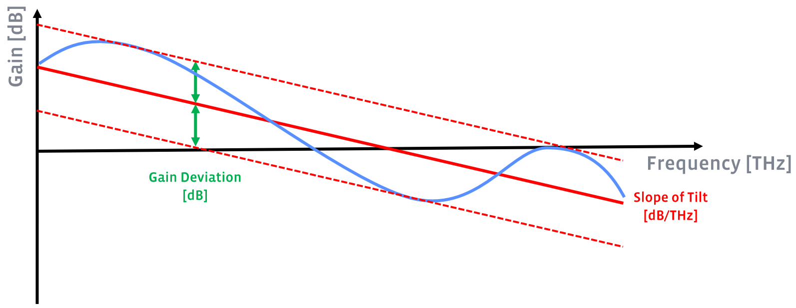


Figure 34. Illustration of Slope of Tilt and Gain Deviation.

It is worth noting that gain shape and tilt change and evolve throughout a subsea system on a per span basis. As such, Slope of Tilt and Gain Deviation are somewhat hindered by the limited ability to measure these parameters on a per span basis and are often only captured at the Tx and Rx. This results in significant uncertainty in whether the Rx spectral snapshot is fully representative of the conditions of propagation over many, sometimes hundreds, of spans.

However, the combination of detailed OSNR and GSNR profiles, better capture the aggregate effect of the variations in tilt across all individual spans, without being tied to the single gain shape profile captured at the output of the final span, providing a very good indicator of system behavior.

Commissioning & Acceptance Testing

Conditions of Commissioning

Note that the conditions of commissioning should be clearly specified in advance, as both OSNR and GSNR vary with frequency depending on the pre-emphasis conditions. A number of conditions for measurement are common, all with their own advantages and disadvantages, including:

1. Flat Launch, whereby the Tx power profile is “flat” within a reasonable range, typically +/- 0.5dB
    a. These conditions are the most accurately repeatable, as a flat Tx profile is easily re-created by any vendor at any time.
    b. This option best represents the natural response of the system, with the minimum possible impact from spectral hole burning effects due to the lack of varied pre-emphasis.
    c. SNR_{ASE}, gain and tilt are most commonly defined under these conditions.
    d. GSNR can also be defined under these conditions, however, since GSNR is often reliant on a BER measurement from a modem, the use of these conditions for GSNR measurement is predicated on the assumption that the modem that will be used to measure it will have sufficient margin for the system in question.
2. Rx OSNR Equalized, where the Rx OSNR is equalized within a reasonable range, typically +/1 dB.
    a. These conditions are difficult to repeat from vendor to vendor, as different equalization algorithms may be used. While the +/- 1dB may be respected, the channel to channel pre-emphasis will likely vary.

    b. These conditions are effective at ensuring that GSNR can be measured for all wavelengths if the system margin is low for the modem in use, as there will be less channel to channel variability in BER measurements.
    c. This method is currently the most difficult to implement operationally in an automated fashion, thus can be quite time consuming to perform.
3. Pfib Equalized, where the average channel power (simply defined as the average of the Tx and Rx powers only) is equalized within a reasonable range, typically +/-0.5 dB
    a. These conditions are difficult to repeat exactly from vendor to vendor, as different equalization algorithms may be used. While the +/- 0.5 dB may be respected, the channel to channel pre-emphasis will likely vary.
    b. These conditions are effective at ensuring that GSNR can be measured for all wavelengths if the system margin is low for the modem in use, as there will be less channel to channel variability in BER measurements.
    c. This method is more easily implemented operationally in an automated fashion than the Rx OSNR Equalized method, thus can be used as a means to minimize testing over Rx OSNR Equalization.

A detailed discussion on the relationship between equalization methodology and capacity maximization, see the SubOptic 2019 publication [5].

Commissioning Tests

With the commissioning parameters and test conditions clearly determined, a suite of commissioning tests should be agreed. While the suite of tests may be very similar for any Open Cable, the number of DLS and FPs on which each test is performed may vary widely depending on the cable system architecture. With SDM designs driving higher fiber pair cables, and WSS ROADMs enabling more complex architectures, the number of DLS, FPs and landings can become quite high, making the detailed characterization of the entire system impractical.
In particular, while certain OSNR testing can be done quite rapidly, GSNR measurement can be quite time consuming without automated techniques. The current GSNR testing techniques generally require a portable kit that requires specialized field technicians to operate them and perform the measurements. This is limiting to the practicality in testing GSNR on every FP and every DLS, particularly in geographic regions or countries in which shipping and importation are lengthy processes. However, if a 3rd party GSNR test set were made available, enabling automation, this reduction in testing may not be necessary.

Given that in a typical subsea system, the trunk is common, and typically represents a significant portion of any DLS, it is reasonable to perform the majority of OSNR and GSNR testing on the trunk DLS and perform a reduce set of tests on the remainder of the system. This ensures that the bulk of the fiber propagation is captured on the most challenging segment(s). On modern day subsea D+ designs, in particular those following the SDM design philosophy, the vast majority of the nonlinear penalty will be captured on the trunk. It would be extraordinarily difficult to insert excessive nonlinear penalties on a branch segment only, making it very low risk to rely on the OSNR measurement of these DLSs alone.

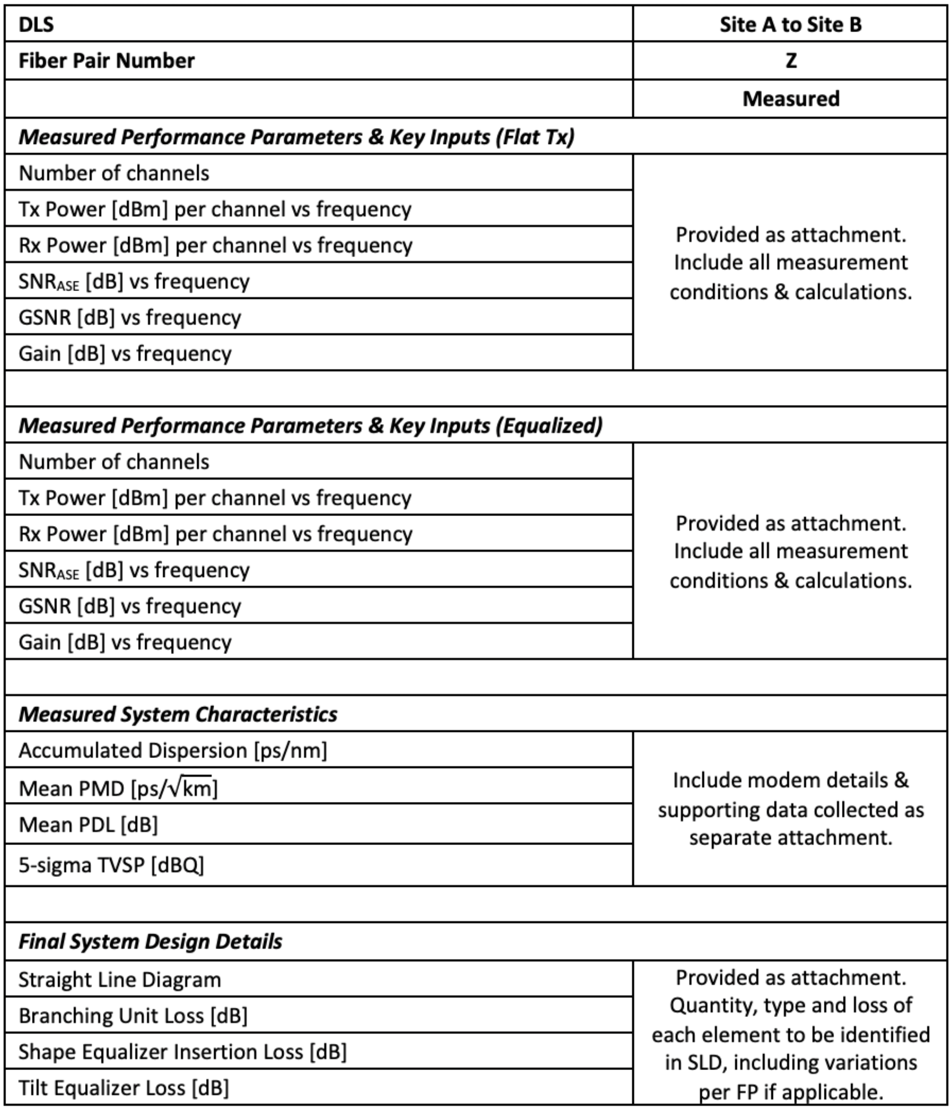
A suite of commissioning tests, including a minimum recommendation on how many FPs and DLSs on which to perform them, is suggested below. These are solely focused on optical performance characterization, and are intended to be in addition to other common cable tests, such as BU switching, COTDR testing, supervisory & control functions, etc.

1- Simple OSNR Characterization, Flat Tx
    a. Characterized on all FPs and DLSs, as measured via the standard Open Cable Interface. This test will provide indications on which FPs are worst case, and if any outlier cases exist that warrant additional more detailed testing.
2- Commissioning OSNRs, GSNRs, Gain, Slope of Tilt
    a. Characterized on a select number of specified FPs and DLSs, under agreed equalization conditions (e.g. Flat or Equalized), as measured by the GSNR measurement toolkit.
3- Stability & Traffic Continuity Testing
    a. Performed on a select number of specified FPs and DLSs, to validate error free traffic carrying capabilities and to characterize statistical parameters such a PMD, PDL, and TVSP via the GSNR measurement toolkit.

Commissioning Data to be Collected

As discussed in the previous section, the final commissioning of a system will reveal significantly more detail than can be defined in advance, in particular with respect to frequency dependence of parameters like OSNR and GSNR. As such, there is value in understanding the level of detail that is desired for a 3rd party SLTE vendor to model, with a higher degree of accuracy, the capacity potential of a system. Additionally, more detailed information is critical in ongoing monitoring of a system, for the identification of system changes as a result of aging, failures, or repairs, to enable informed decisions on system maintenance.

The additional recommended information, beyond what is specified in the Key Parameter Table, that should be collected at system commissioning for the purposes of improving accuracy of system modeling and for use in ongoing system monitoring, are summarized below.



DLS	**Site A to Site B**
Fiber Pair Number	**Z**
	Measured
Measured Performance Parameters & Key Inputs (Flat Tx)	
Number of channels	Provided as attachment. Include all measurement conditions & calculations.
Tx Power [dBm] per channel vs frequency	
Rx Power [dBm] per channel vs frequency	
SNR_{ASE} [dB] vs frequency	
GSNR [dB] vs frequency	
Gain [dB] vs frequency	
Measured Performance Parameters & Key Inputs (Equalized)	
Number of channels	Provided as attachment. Include all measurement conditions & calculations.
Tx Power [dBm] per channel vs frequency	
Rx Power [dBm] per channel vs frequency	
SNR_{ASE} [dB] vs frequency	
GSNR [dB] vs frequency	
Gain [dB] vs frequency	
Measured System Characteristics	
Accumulated Dispersion [ps/nm]	Include modem details & supporting data collected as separate attachment.
Mean PMD [ps/$\sqrt{km}$]	
Mean PDL [dB]	
5-sigma TVSP [dBQ]	
Final System Design Details	
Straight Line Diagram	Provided as attachment. Quantity, type and loss of each element to be identified in SLD, including variations per FP if applicable.
Branching Unit Loss [dB]	
Shape Equalizer Insertion Loss [dB]	
Tilt Equalizer Loss [dB]	

Figure 35. Data to be Collected at System Commissioning.

Note that multiple conditions are specified for OSNR, GSNR and Gain parameters. This is largely as a means to capture the system response to pre-emphasis and spectral hole burning. These characteristics can only be captured with channel powers included in the reference. OSNR itself is only useful when tied to a set of channel power conditions. Since the gain profile at the output of every repeater is not available, this is the best means to peer inside what is largely a black box. For example, a well behaved system will have an OSNR profile highly correlated to the average channel power under flat launch conditions. A system suffering from high variability in tilt throughout system propagation may not be as highly correlated, and this will be evident from the measured data.

This range of measurement conditions are especially useful for capacity estimation purposes, whereby a 3rd party SLTE vendor can see the range of OSNRs and GSNRs that may be achievable via pre-emphasis, enabling them to determine the best conditions to extract the maximum capacity possible from the system.

Additional information may be desired to be collected based on specific system features, such as guard bands introduced by WSS ROADMs in various configurations, for example. These should be addressed on a case by case basis.

There are also certain system characteristics that are still most easily measured by a modem today, such as accumulated CD, PMD, PDL and TVSP. Some of which require a statistical distribution of data to calculate, thus necessitating a soak. A 3rd party test measurement tool could also be used for characterizing these elements.

Key Takeaways:

- *There are important distinctions between the level of detail that can be specified at System Design, versus what can be collected at System Commissioning.*
- *System Design often specifies high level, average and/or worst case system parameters, typically defined within a Key Parameter Table*
    - *Only a subset of these key parameters may actually be measurable, but are all useful for capacity estimation by 3rd party modem vendors*
    - *Typical Open Cable commissioning targets include Average and/or Worst Case OSNR and GSNR, Slope of Tilt and Gain Deviation.*
- *System Commissioning can collect detailed data on the frequency and pre-emphasis dependence of OSNR and GSNR, which is highly valuable for accurate 3rd party capacity modeling, and baselining system performance to aide in ongoing monitoring and maintenance decisions*
    - *Equalization conditions for OSNR and GSNR should be clearly defined*
    - *Flat Tx OSNR testing should be tested on every FP and every DLS*
    - *Testing GSNR on every FP and every DLS can be time prohibitive in complex systems with many branches and landings. In such cases, a subset of FPs and DLSs can be selected.*
    - *An automatable 3rd party GSNR test kit could significantly increase the number of GSNR tests that can be performed in a reasonable time at system commissioning.*
    - *An error-free stability test should still be performed to characterize statistical characteristics of the system performance, such as TVSP, PMD and PDL.*

Spectrum Sharing. How does GSNR vs Frequency Help?

The Old Adage: Not All Spectrum is Created Equal

As discussed in the previous section, both OSNR and GSNR vary across the optical spectrum. The precise relationship and variability across the spectrum are highly dependent on the range of components and conditions solidified in the final manufactured system and are nearly impossible to predict at System Design with any precision. This is why commissioning parameters and key parameters are typically specified as average and/or worst case values with respect to frequency, and certain manufacturing margins are considered to cover the unknowns. Recalling, of course, that the OSNR and GSNR variances with frequency, and response profiles to pre-emphasis, can be characterized in great detail at system commissioning, this uncertainty primarily exists pre-RFS.

However, this lack of resolution of performance versus frequency during System Design and Manufacturing presents a significant commercial challenge to Purchasers who may wish to share, buy or sell spectrum. Specifically, different parts of the optical spectrum will have inherently different capacity potentials, and therefore difference values, and will not be known with accuracy until RFS. This inequity with respect to spectral location is further amplified by high baud, variable rate modems, as smaller and smaller deltas in SNR can be capitalized upon to gain more capacity. And to complicate things further, the relative performance across the spectrum will change with time as the subsea system ages.

It is very important to understand that this is an unavoidable feature of subsea cables, whether spectrum sharing is being considered or not, and whether the cable is an open cable or not. Performance will always vary across the optical spectrum, regardless of whether capacity, Q, OSNR or GSNR are used to define it.

Strategies for Sharing Spectrum Equitably

With this understanding, we can explore some potential strategies to address these challenges. GSNR can be extremely helpful in establishing the relative value of the parts of the bandwidth, or rather, their relative capacity potential.

In the ideal case of flat system gain, spectrum sharing would be quite straightforward, and the recommendation would be to simply have the same power spectral density across the bandwidth at the system input. The relative value of the band will be determined by GSNR or respective potential capacity (based on GSNR).

The practical (but more complex) case of variable performance with frequency is much more realistic to consider. In this environment, an equalization strategy may be needed. The merits of various equalization methods are discussed in previous sections, and at length in [5], but one recommended method may be to use Pfib equalization. This would approximately equalize nonlinear penalties to GSNR across the bandwidth.

Alternatively, another strategy for equitable spectrum sharing could be to determine a pre-emphasis profile that equalizes the GSNR across the optical spectrum. This will roughly equalize the achievable capacity in equally sized slices of spectrum, regardless of spectral location. This of course does not consider potential benefits of modems with nonlinear compensation algorithms, which could take advantage of more nonlinear portions (lower SNR_{NLI}) of the spectrum with the same GSNR. This would most likely be a minimal to negligible benefit on an SDM cable design.

However, it should be considered, that depending on the system characteristics, and due to the wavelength dependency of spectral hole burning, attempts to fully equalize GSNR across the bandwidth may in fact result in total capacity loss through the fiber, while not leading to notable improvement of lower performing parts of the bandwidth. In this fashion, the total capacity is sacrificed for simplicity in spectrum division. This might be an acceptable trade-off to some Purchasers.

This could be avoided with a more complex division of spectrum that is in proportion to the GSNR frequency dependence, where it is assumed that achievable capacity is proportional to $GSNR_{dB}$ integrated across a particular bandwidth.

Operationally, to employ either of these spectrum value equalization strategies, it would be critical to utilize a single spectrum sharing solution capable of automatically managing a very specific power spectral density profile across the full spectrum for all owners. This profile would need to be automatically maintained as various spectrum owners make upgrades to their respective sub-bands, such that the initially provisioned ASE idler pre-emphasis is properly transferred to any newly added traffic wavelengths of any spectral occupancy and continues to respect the agreed conditions of all spectrum owners. Spectrum owners would have little freedom to adjust the pre-emphasis of their own channels, as it would violate the agreed conditions.

As mentioned, any equalized profile will only remain equalized for a period of time, pursuant to the effects of system aging that will result in changes in the system gain profile over time. Thus, considerations would need to be given to if / when a shared spectrum might be re-equalized, and the impact of such an activity to all parties.

One limitation that should be acknowledged in this suggestion is that it may not be possible to easily measure GSNR on an in-service fiber pair, especially if its bandwidth is heavily loaded. Multiple owners may have multiple vendors' equipment installed across the bandwidth. However, if GSNR can be measured then it may be possible to adjust bandwidth allocations over time. Alternatively, if bandwidth allocations stay the same then the pre-emphasis could be adjusted so that any GSNR loss due to aging is similar across the bandwidth. However, as previously noted, spectral hole burning will impose some limitations on the ability to fully execute on this potential strategy. [18]

Spectrum Sharing and Trending Towards SDM

One useful industry trend that may help Purchasers with lower bandwidth demands than what a typical fiber pair today offers, is the trend towards SDM designs, where the number of fiber pairs is going up, and the per fiber capacity is going down. More importantly, the cost per bit and cost per fiber pair is going down substantially in this new model, significantly lowering the barrier to entry on full fiber pair ownership.

Key Takeaways:

- *The performance of a subsea fiber varies with frequency. This is true irrespective of whether the performance is defined by capacity, Q, OSNR or GSNR, and whether the cable is Open or not.*
- *A well characterized GSNR vs frequency at different pre-emphasis profiles can be performed at system commissioning and used to assess the relative value of the optical spectrum.*
- *The potential for changes in the relative value of the optical spectrum over time with system aging should be considered and strategies on when and how to address should be agreed.*
- *Purchasers will need to assess the trade-offs between simplicity of equitably dividing spectrum and maximization of overall fiber capacity.*

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