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# Capacity Prediction from Commissioning Parameters of Subsea Open Cables

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***Abstract*** *We numerically assess the impact of the transceiver modes and of non-public line parameters on the capacity estimation of submarine open cables. We show that throughput can be predicted within 4% when the system operates close to the optimal power. ©2022 The Author(s)*

## Introduction

Over the last decade, submarine systems have evolved from turnkey systems into an open cable approach, so that submarine line termination equipment (SLTE) and wet plant sections from different suppliers can be independently chosen and be interconnected [1]-[3]. This approach allows maximizing capacity with the latest SLTE technology as soon as cable is commissioned. However, it requires SLTE-independent metrics describing wet plant performance [4] [5] to enable end to end capacity estimation by a third party.

In the last years, the OSNR (optical signal-to-noise ratio) and GSNR (generalized signal-to-noise ratio) have been adopted by the industry to characterize open cables [6]. Estimating capacity from those metrics has become critical. It has been shown in the literature that with simple assumptions on the SLTE (and thus the transceiver) technology, the GSNR measure can be converted into capacity with an adapted Shannon formula [7]-[9]. However, to the best of our knowledge, while it is of high interest to accurately bound the achievable capacity and avoid wasting resources, performance prediction at cable upgrade with transceiver-dependent conversion of measured GSNR into capacity has never been investigated.

This paper aims to present a methodology to evaluate the achievable capacity of open cables from GSNR and OSNR for specific transceiver modes. We also investigate for the first time the related uncertainty due to the unawareness of line parameters for specific modulation formats.

## Background and objectives

When a new submarine cable is installed or at upgrades, third parties (different than cable owner and vendor) such as traditional telecom operators and SLTE vendors must estimate the capacity they can provide to their clients. For this, the cable owner shares some end-to-end parameters, such as commissioning measurements of GSNR, OSNR, transmission reach and cumulated chromatic dispersion, without disclosing details of the infrastructure. GSNR accounts for the total noise contributions of the wet plant, and OSNR accounts for the amplified spontaneous emission (ASE) [1].

Two challenges emerge. First, commissioning measurements are conducted following ITU recommendations [10], in a reference configuration (REF), typically using 3 test channels modulated at a given symbol rate with QPSK or 16QAM, without terminal nonlinearity compensation (NLC), and the remaining optical spectrum is loaded with ASE noise. Nevertheless, when the network is operated, this configuration changes into an effective configuration (EFF), where all channels over the bandwidth may be modulated differently. As nonlinear interferences are format and symbol rate dependent, the configuration change results in different performance and a different $\mathrm{GSNR}_{\mathrm{EFF}}$. Here we investigated the impact of different dual-pol. transceiver modes, varying the modulation formats, the symbol rates, and the intra-channel NLC efficiency.

Secondly, $\mathrm{GSNR}_{\mathrm{EFF}}$ estimations per transceiver mode are impacted by the lack of knowledge of non-disclosed line parameters, mainly span length and fiber attenuation.

In this paper, we first quantify the nonlinear SNR deviation from the reference to the effective configurations for several modulation formats for a nominal cable design. Then, we compute the resulting $\mathrm{GSNR}$ deviation. Finally, we investigate the impact of the non-disclosed information on the $\mathrm{GSNR}_{\mathrm{EFF}}$ estimation, and we infer an upper bound of the corresponding capacity uncertainty.

## Methodology to assess open cable $\mathbf{GSNR}_{\mathbf{EFF}}$

It is known that Gaussian-like modulation formats suffer more from nonlinear interference than others [4] and thus, their GSNR is degraded. To quantify the impact of the modulation format on $\mathrm{GSNR}_{\mathrm{EFF}}$, we estimated, with the eGN model [11], the nonlinear SNR ($\mathrm{SNR}_{\mathrm{NL}}$) in the reference and effective configurations. For this investigation, the transmission line is 7000km

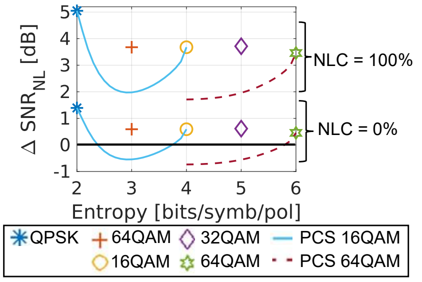
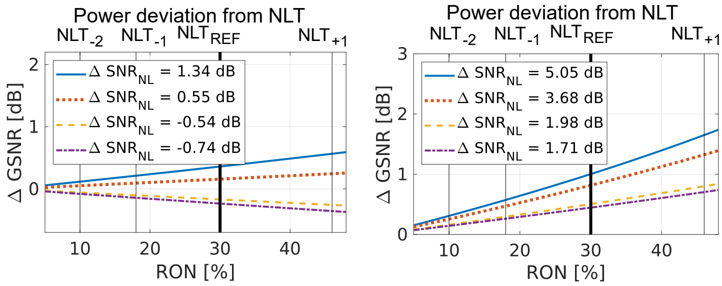



**Fig. 1:** $\Delta\mathrm{SNR}_{\mathrm{NL}}$ between reference and effective configurations for different formats vs. formats entropy with and without NLC.




(a) without NLC (b) with NLC

**Fig. 2:** $\Delta\mathrm{GSNR}$ vs. $\mathrm{RON}$ for four $\Delta\mathrm{SNR}_{\mathrm{NL}}$. The $\mathrm{RON}$ corresponding to the system NLT in the REF configuration is indicated with a thick black line.

long, composed of 70 km spans with 0.16 dB/km attenuation. There are 61 channels with a symbol rate of 69.4 Gbd and spacing of 75 GHz. We only consider central channel performance, as it is representative enough of the averaged performance over C-band. Fig. 1 depicts the deviation of $\mathrm{SNR}_{\mathrm{NL}}$ ($\Delta\mathrm{SNR}_{\mathrm{NL}}$) between the reference (three QPSK channels surrounded by Gaussian channels) to the effective configuration for various modulation formats vs. entropy (H), i.e., the average number of bits per symbol per polarization (bits/symb/pol). Regarding the propagation without NLC, we observe that the $\mathrm{SNR}_{\mathrm{NL,REF}}$ is in-between the extreme cases. $\mathrm{SNR}_{\mathrm{NL}}$ deviations range from -0.76dB (PCS 64QAM, H=4) to +1.3dB (pure QPSK). In presence of NLC, $\Delta\mathrm{SNR}_{\mathrm{NL}}$ is always positive, reaching up to 5 dB.

In this study, for sake of simplicity, we neglect signal droop [12]. Thus, the link GSNR can be derived from [13] as:

$$\frac{1}{\mathrm{GSNR}_{\mathrm{REF}}} = \frac{1}{\mathrm{SNR}_{\mathrm{ASE}}} + \frac{1}{\mathrm{SNR}_{\mathrm{GAWBS}}} + \frac{1}{\mathrm{SNR}_{\mathrm{NL,REF}}}$$

where $\mathrm{SNR}_{\mathrm{GAWBS}}$ accounts for guided acoustic wave Brillouin scattering (GAWBS) [14],[15]. All SNRs are expressed in the symbol rate band. At commissioning, we can measure $\mathrm{GSNR}_{\mathrm{REF}}$ and $\mathrm{SNR}_{\mathrm{ASE}}$, and $\mathrm{SNR}_{\mathrm{GAWBS}}$ can be estimated from the total length and the effective area of the fiber [14]. Assuming that such parameters are known, we can estimate $\mathrm{SNR}_{\mathrm{NL,REF}}$. We introduce the ratio of nonlinearity (RON) which is the ratio of the estimated nonlinear distortion over the total cable noise variances at commissioning.

$$\mathrm{RON} \triangleq \frac{\text{Nonlinear noise variance}}{\text{Cable noise variance}} = \frac{\mathrm{GSNR}_{\mathrm{REF}}}{\mathrm{SNR}_{\mathrm{NL,REF}}} \quad (1)$$

The deviation from $\mathrm{GSNR}_{\mathrm{REF}}$ to $\mathrm{GSNR}_{\mathrm{EFF}}$, denoted as $\Delta\mathrm{GSNR}$, can be derived from the $\mathrm{RON}$ and the format-dependent $\Delta\mathrm{SNR}_{\mathrm{NL}}$, following:

$$\frac{1}{\Delta\mathrm{GSNR}} \triangleq \frac{\mathrm{GSNR}_{\mathrm{REF}}}{\mathrm{GSNR}_{\mathrm{EFF}}} = (1-\mathrm{RON}) + \frac{\mathrm{RON}}{\Delta\mathrm{SNR}_{\mathrm{NL}}} \quad (2)$$

Fig. 2 depicts the evolution of $\Delta\mathrm{GSNR}$ with $\mathrm{RON}$ for different $\Delta\mathrm{SNR}_{\mathrm{NL}}$ (corresponding to QPSK, 16QAM, PCS 16QAM with H=3 and PCS 64QAM, with H=4) without (a) and with NLC (b). Black vertical lines indicate typical $\mathrm{RON}$ values corresponding to specific launch power levels with respect to system nonlinear threshold (NLT) in the commissioning (REF) configuration, with nonlinear noise being half ASE noise at NLT [16], and assuming that GAWBS typically amounts to 10% of cable noise at this NLT [15]. Before submarine systems moved to a spatial division multiplexing (SDM) paradigm, they were usually operated close to the NLT, and up to 1 dB above for anticipation of NLC. Today's SDM systems are operated below the NLT [17]. We observe that $\Delta\mathrm{GSNR}$ increases with $\mathrm{RON}$ and $\Delta\mathrm{SNR}_{\mathrm{NL}}$. Without NLC, $\Delta\mathrm{GSNR}$ is always below 1 dB. With NLC, it is higher and reaches up to 2.5 dB.

In summary, a third party can estimate the $\mathrm{RON}$ from commissioning measurements, accurately predict $\Delta\mathrm{SNR}_{\mathrm{NL}}$ for different transceiver modes from simulations if line parameters are known and derive the effective GSNR values. Eventually, GSNR can be converted into achievable information rate (AIR) using per transceiver mode calibrated conversion laws (as an SLTE vendor would do) or generic laws, such as an adapted Shannon formula:

$$AIR = 2 \cdot B \cdot \log_2\left(1 + \frac{\left(GSNR_{EFF}^{-1} + SNR_{TRX}^{-1}\right)^{-1}}{Pen}\right)\eta, \quad (3)$$

where $B$ is the bandwidth, η the filling ratio and $SNR_{TRX}$, and $Pen$ account for transceiver noise, gap to Shannon and end of life margins.

## Impact of the non-public parameters

We investigate how varying fiber attenuation and span length impacts $\Delta\mathrm{SNR}_{\mathrm{NL}}$ and thus might add uncertainty to the GSNR and AIR prediction. For this investigation, we start with a 4.5 THz-wide, 7000 km transmission line, with various symbol rates and a fill-in ratio of 92% (symbol rate over channel spacing ratio).

Fig. 3 shows $\Delta\mathrm{SNR}_{\mathrm{NL}}$ for the PCS formats vs. entropy. For readability, we only plot the results with NLC. We display four sets of curves corresponding to four symbol rates, from top to bottom: 300, 130, 69.4, and 30 GBd.

For 30 GBd, in addition to the PCS formats; we show the x-QAM formats with markers. For all rates and entropies, we show the max and min deviations (with different colors at 30GBd) due to:

- attenuation, with fixed span length (green),
- span length, with fixed attenuation (blue),
- best/worst span length/attenuation mix (red)

The highest $\Delta\mathrm{SNR}_{\mathrm{NL}}$ are obtained at highest symbol rate (reaching 8 dB). However, the highest excursion of $\Delta\mathrm{SNR}_{\mathrm{NL}}$ due to unknown line parameter is obtained at 30 GBd for QPSK with 2.5 dB between the best- and the worst-case for an average $\Delta\mathrm{SNR}_{\mathrm{NL}}$ of 4.7 dB. For the PCS formats, the excursion is lower and, at 30 GBd, reaches a minimum for PCS 64QAM with H=4, where the excursion is 0.3 dB. These possible excursions of $\Delta\mathrm{SNR}_{\mathrm{NL}}$ quantify the impact of lack of knowledge of system parameters.

We also investigated different total link lengths (3500, 7000, and 10500 km) and observed a slight increase of $\Delta\mathrm{SNR}_{\mathrm{NL}}$ excursions with distance, but with variations below 0.05 dB.

From Fig. 3 to Fig. 4, we focused on the best- and worst-case $\Delta\mathrm{SNR}_{\mathrm{NL}}$ at 300Gbd, yielding the highest average values, and we converted the $\Delta\mathrm{SNR}_{\mathrm{NL}}$ values for the same selection of formats as Fig. 2 into curves of $\Delta\mathrm{GSNR}$ vs $\mathrm{RON}$, in presence and absence of NLC. The uncertainty resulting from the missing information is the excursion between the best- and worst-case curves. We observe the highest excursion on $\Delta\mathrm{GSNR}$ for QPSK at NLT+1, with NLC: 0.4 dB between 1.7 and 2.1 dB.

From such curves, one can derive the corresponding excursion of AIRs due to unknown parameters. Fig. 5 depicts the highest $\Delta\mathrm{GSNR}$ excursions (difference between best- and worst-case $\Delta\mathrm{GSNR}$) obtained over all the investigated distances and symbol rates, as a function of $\mathrm{RON}$ (with less than 0.05 dB discrepancies, it corresponds to the 30 GBd, 10500 km case). For sake of representativity, we restricted the analysis to two formats (16QAM and PCS 16QAM, H=3), with and without NLC: the previous PCS 64QAM exhibits lower excursions than the chosen PCS 16QAM, and the $\Delta\mathrm{GSNR}$ excursion of the QPSK format are artificially high, since QPSK is of interest only for the longest links, thus designed with very low span lengths. The right axis reports the maximum relative uncertainty on AIR resulting from the $\Delta\mathrm{GSNR}$ excursion. For this, we define two $\mathrm{GSNR}_{\mathrm{EFF}}$ distant by the $\Delta\mathrm{GSNR}$ excursion around a GSNR of 8dB (pessimistic target even for typical transpacific links); then we computed the relative AIR deviations from (3) using a 3 dB penalty and $\mathrm{SNR}_{\mathrm{TRX,dB}}$ = 18.5 dB.

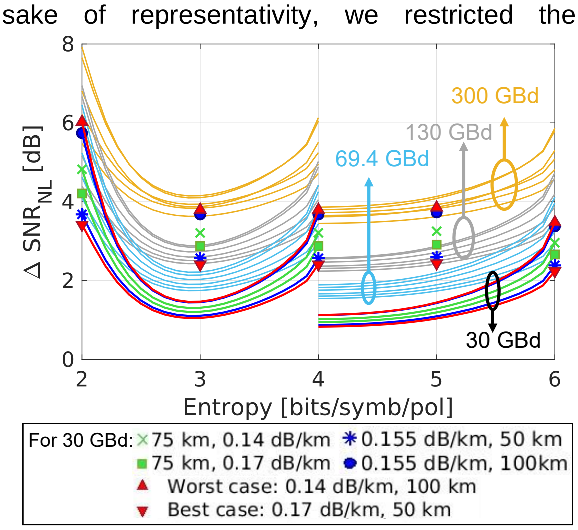



**Fig. 3:** $\Delta\mathrm{SNR}_{\mathrm{NL}}$ vs. modulation formats entropy for six combinations of line parameters for transmission with symbol rates 30, 69.4, 130 and 300 GBd, 7000 km.

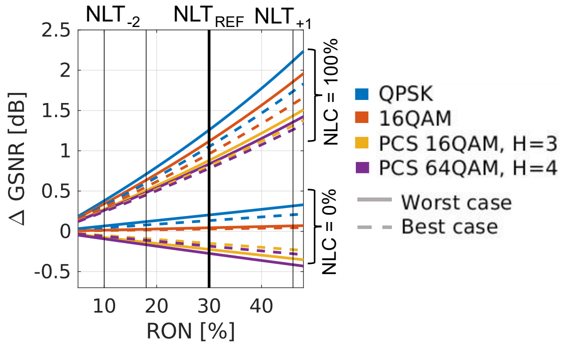



**Fig. 4:** $\Delta\mathrm{GSNR}$ vs. $\mathrm{RON}$ for the worst (–) and best (- -) $\Delta\mathrm{SNR}_{\mathrm{NL}}$ of four modulation formats, with and without NLC, at 300GBd, 7000 km

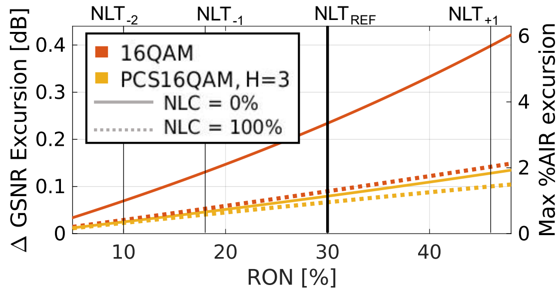



**Fig. 5:** Left: excursion between the worst and best $\Delta\mathrm{GSNR}$ vs. $\mathrm{RON}$ for two modulation formats, with (-) and without (o) NLC, at symbol rate and total length giving the highest $\Delta\mathrm{GSNR}$ excursion. Right: corresponding relative impact on AIR estimation for GSNR > 8 dB.

Using 16QAM operating at NLT+1 with NLC, we observe a 6% uncertainty (±3%) on the AIR. At NLT and below (SDM), this uncertainty is below 3.5%. Without NLC, the maximum uncertainty for 16QAM is lower than 2% at NLT.

To get a full picture, one should consider the uncertainties related to $\mathrm{RON}$ estimation, that we leave for the future: for instance, an effective area within [80;150] µm², leads to a 4% excursion on the $\mathrm{RON}$, thus to 1% more uncertainty on AIR.

## Conclusions

We investigate how effective GSNR may depart from commissioning conditions for various modulation formats and its impact on achievable capacity estimates by a third party, particularly with partial knowledge of line parameters.

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