Improving Capacity Predictions for Subsea Open Cables Employing Modern Coherent Transceivers

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Abstract *We study the effects of modern transceiver technologies such as probabilistic constellation shaping, symbol interleaving, and fiber nonlinearity compensation on subsea cable capacities and describe how their effects can be included in the subsea open cable standard to improve capacity predictions. ©2022 The Author(s)*

Introduction

Over the past 25 years, subsea communication systems have undergone several evolutionary cycles owing to various technological improvements in the optical and electronic domains [1]. Today, state-of-the-art trans-Atlantic cable systems equipped with space division multiplexing (SDM) technology can support >300 Tbps traffic capacity [2].

Over its 25-year typical operational life, a cable can undergo several capacity upgrades; exploiting transceiver improvements. A capacity upgrade on a subsea cable may involve multiple field trials through different submarine line terminal equipment (SLTE) vendors. The process is time-consuming and expensive. To alleviate these concerns, the subsea open cable standard was introduced [3]. It leverages the fact that modern subsea cables deploy dispersion uncompensated (D+) fiber and the effects of optical signal propagation in such systems can be analytically estimated using the Gaussian Noise (GN) model [4]. The standard describes how to measure SNR and GSNR for a subsea cable to design, optimize and characterize the cable independently of the transceiver technology. SLTE vendors are then directed to use these metrics in combination with the known characteristics of their own transceivers to predict achievable cable capacity post-deployment.

While the GN model can largely account for the effects of nonlinear propagation in optical fiber, it is unable to account for several commonly used signalling techniques found in high performance modern transceivers. In this work, we describe three such techniques and their impact on subsea capacities. Additionally, we demonstrate how their effects can be included in the open cable capacity computations to improve performance predictions.

Capacity Prediction in Subsea Open Cables

The subsea open cable standard [3] describes the capacity of a cable system as

$$\mathrm{C}_{\mathrm{modem}} = 2\chi \sum_{i}^{N_{FP}} \sum_{\forall j} \mathrm{B_j} \log_2 \left(1 + \frac{SNR_{TOT\ i,j}}{\eta M}\right) \quad (1)$$

where the factor 2 comes from the two polarizations, χ is the spectral occupancy factor, N_{FP} is the number of fiber pairs in the cable system, $SNR_{TOT\ i,j}$ is the SNR of the j^{th} channel in the i^{th} fiber pair, B_j is the bandwidth of the j^{th} channel, η is the gap-to-Shannon capacity owing to non-ideal characteristics of the transceiver (e.g. complexity constrained FEC), and M is the system margin specified by the cable operator.

SNR_{TOT} can be expressed as

$$\frac{1}{SNR_{TOT}} = \frac{1}{GSNR} + \frac{1}{SNR_m} + \frac{1}{SNR_i} \quad (2)$$

where, $GSNR$ is the generalized signal-to-noise ratio and comprises the noise contributions from ASE, GAWBS [5], and fiber nonlinearity, SNR_m is the back-to-back implementation noise from the coherent modem, and SNR_i includes the noise caused by the modem due to propagation specific effects such as chromatic dispersion (CD), polarization effects, wavelength tolerance penalties and equalization enhanced phase noise (EEPN) [6].

To ensure that the SLTE's performance does not impact the assessment of the subsea cable system, the open cable standard describes a systematic method with a few fixed configurations to measure the cable's GSNR. For brevity, we will not describe the methodology here (see Sec. III in [3]) but instead describe key constraints within the methodology where modern transceiver technologies can significantly affect capacity predictions. These include the use of QPSK and/or 16QAM as the choice of modulation for cable characterization, and the requirement to disable nonlinear compensation circuits when measuring GSNR and predicting capacities.

Method

The assumed transmission link for this study consists of 110 × 60 km EDFA-amplified spans with the following parameters: 0.156 dB/km attenuation, 20.9 ps/(nm-km) dispersion at 1550 nm wavelength, 0.07 ps/nm^2 dispersion slope, 0.57 /(W-km) nonlinearity parameter, and 4.5 dB amplifier noise figure. This choice of parameters is intentionally chosen to mimic the MAREA subsea cable system [7].

Investigated modulation formats include Gaussian, QPSK, uniform 16 and 64QAM, and probabilistically shaped (PS)-64QAM. For PS-64QAM, the signal was generated using a constant composition distribution matcher (CCDM) with a word length of 1024 and a constellation entropy of 8.25 bit/(2 polarizations); a reasonable target entropy for the given link parameters.

For numerical simulations, we employed signals with 8 digital subcarriers with each subcarrier consisting of 2^{16} symbols (64 PS codewords). Wherever interleaving was applied, the generated symbols were randomly permuted within the interleaving block length. CD compensation was split evenly between the transmitter and receiver. The transmitted signal was root raised cosine pulse shaped with a 1/16 roll-off; with a corresponding matched filter applied at the receiver. 11 wavelengths at 64 GBaud (8 x 8 GBaud subcarriers) were transmitted using a 70 GHz frequency grid, and the fiber was modelled using an adaptive step-size split step Fourier method. For analytical computations, we use the ISRS GN model that accounts for modulation format dependence through excess kurtosis [8].

Effects of Modern Transceiver Technologies

Probabilistically shaped constellations are commonly being deployed in modern subsea cable systems owing to their ability to operate closer to the Shannon limit and provide fine granularity in spectral efficiency. Nonetheless, the open cable standard requires the use of QPSK or 16QAM when computing a cable system's GSNR. These lower order modulation formats provide optimistic GSNRs which can overestimate a cable system's operating capacity, Fig. 1. In case of the MAREA system, our analysis indicates that the GSNR deteriorates by ~0.2 dB when moving from QPSK to uniform 64QAM and by ~0.5 dB when moving from QPSK to Gaussian modulation format.

Based on the employed spectral efficiency, the performance of PS-64QAM would lie between 64QAM and Gaussian modulation format resulting in 0.2-0.5 dB degradation. This

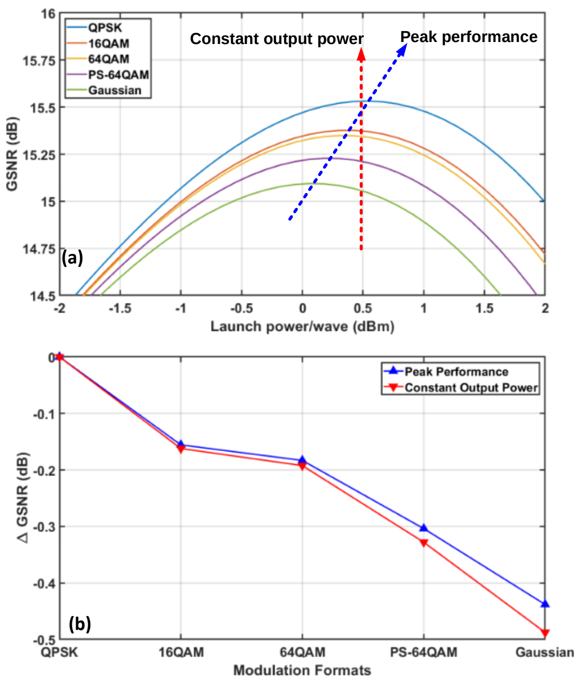

Fig. 1: Analytical models: (a) GSNR vs launch power for various modulation formats. (b) GSNR degradation associated with various modulation formats. Peak performance refers to GSNR degradation at the peak of the GSNR vs launch power. Constant output power is the GSNR degradation at a fixed launch power of 0.5 dBm per wave.

degradation is slightly worse for subsea cable systems as they operate at constant output power, Fig. 1(b). To accurately obtain the effects on GSNR from various modulation formats, one needs to compute the excess kurtosis associated with the modulation format [9] and then include it in the GN model.

Symbol interleaving is another commonly employed technology in modern transceivers to combat the effects of burst errors. By interleaving symbols at the transmitter and deinterleaving them at the receiver, burst errors incurred during transmission get interspersed across different FEC and PS blocks allowing for improved error correction. However, such interleaving changes the timescale of PS imposed average power constraint. Therefore, in the presence of fiber nonlinearity, these modified distributions can lead to performance degradation for PS-formats [9].

To understand the effects of symbol interleaving on transmission performance, we chose the ratio of the symbol interleaving block length to that of the CCDM block length as our figure of merit. Figure 2(a) shows the variation of GSNR for various launch powers and interleaving length ratios. When the interleaving length is smaller than the CCDM block length, the signal sees a marginal performance improvement which we attribute to the preservation of the distribution's average power within the CCDM

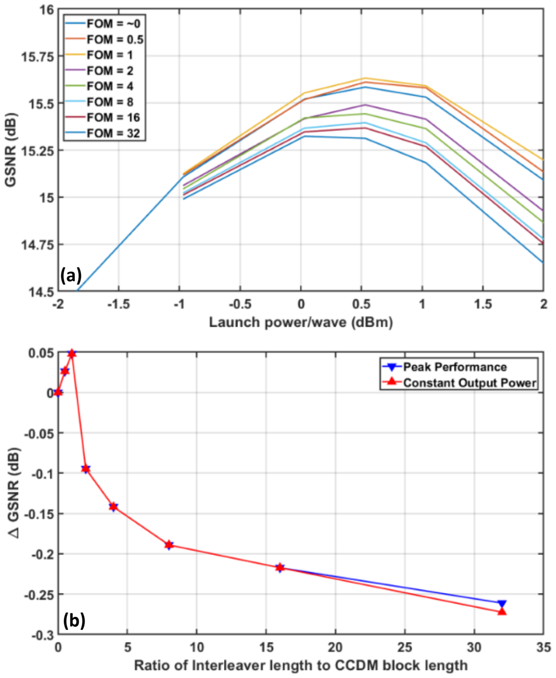

Fig. 2: Simulations: (a) GSNR vs launch power for various interleaving block length ratios. (b) GSNR degradation associated with various interleaving ratios.

block length while reducing average power variations within the timescale of the interleaving. However, when the interleaving block length exceeds the CCDM block length, the performance begins to steadily degrade. For modern transceivers, these penalties can be ~0.25 dB in GSNR, Fig. 2(b). Once again, the degradations are slightly worse for subsea systems that operate at constant output power. Since the current open cable standard employs QPSK or 16QAM to measure GSNR, this performance penalty needs to be included when predicting cable capacities where PS formats would be deployed.

Finally, with the advancement of DSP algorithms and ASIC technology, low complexity nonlinear compensation (NLC) circuits are being widely deployed in subsea cable systems to compensate for fiber nonlinearities. Current generation optical transceivers can provide up to 1 dB nonlinear interference (NLI) gains through both intrinsic methods (e.g., nonlinearity tolerant modulation formats) and extrinsic methods (e.g., adaptive equalizers). These NLC circuits can significantly improve cable GSNRs, Fig. 3, and associated cable capacities.

Discussions

To account for the effects of modern transceiver technologies in the open cable standard, we propose the following modification to SNR_{TOT} for Eqn. 1,

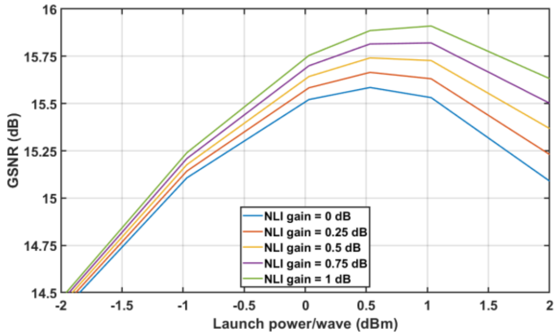

Fig. 3: GSNR vs launch power for the MAREA system with various nonlinear interference (NLI) gains.

$$\frac{1}{SNR_{TOT}} = \frac{1}{SNR_{LIN}} + \frac{\alpha}{SNR_{NL}} + \frac{1}{SNR_m} + \frac{1}{SNR_i} \quad (3)$$

where SNR_{LIN} accounts for the noise contributions from ASE and GAWBS, SNR_{NL} accounts for the noise from fiber nonlinearity, α accounts for the degradations from using PS formats and symbol interleaving, and enhancement from using NLC circuits.

Using appropriate parameters in Eqn. 2 and substituting it in Eqn. 1, we obtained a capacity of 30.74 Tbps per fiber pair on the MAREA cable systems. Accounting for the degradations from probabilistic shaping (0.33 dB, Fig. 1, analytically derived penalty) and symbol interleaving (0.27 dB, Fig. 2, correction determined by simulations) reduces the capacity to 29.22 Tbps (α = 1.5). Finally, adding the performance enhancements from the NLC circuits (1 dB NLI gain, Fig. 3) increases the prediction to 30.04 Tbps (α = 0.79). The field trial on the MAREA cable system demonstrated a per fiber pair capacity of 30.01 Tbps capacity [7]. Properly accounting for the effects of modern transceiver technologies allowed us to accurately compute MAREA cable's capacities while still following the framework of subsea open cable standard.

Conclusions

We discussed the effects of modern transceiver technologies on link GSNR and demonstrated how probabilistic shaping and symbol interleaving can degrade GSNR by ~0.75 dB while realistic nonlinear compensation algorithms can improve GSNR by ~0.25 dB. We discussed how these inaccuracies in GSNR could lead to inaccuracies in capacity predications for cable upgrades; in our example, an error of >2%. Additionally, we demonstrated how these effects can be easily included in the subsea open cable standard to accurately predict cable capacities (<0.1% capacity error). We anticipate that future refinement of windowed kurtosis methods described in [9] could be used to fully determine α without the need for numerical simulations.

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