PERFORMANCE OF OPEN CABLE: FROM MODELING TO WIDE SCALE EXPERIMENTAL ASSESSMENT

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Abstract: In the frame of submarine open cables we investigate the relevance of possibly agreed performance prediction models between vendors and customers. We first review wide-spread models accounting for main propagation effects: amplifier noise, fiber nonlinearities, Guided Acoustic Wave Brillouin Scattering, imperfect mitigation of Chromatic Dispersion. Then we propose a Generalized Droop framework to accurately aggregate the impairments in the context of low-SNR, SDM-like, submarine cables. Eventually, we experimentally assess the accuracy of candidate models through a wide-scale parametric study: we investigate no less than 100 configurations of distances (up to 16 000km), baud rates (from 31 to 69Gbaud), modulations (QPSK, 8QAM, Probabilistic Constellation Shaping), channel spacings and repeater output powers. The best model ensures errors in average Q^2 factor (over C-band) better than 0.2dB.

1. INTRODUCTION

Over the past few years, submarine systems have drastically evolved. The advent of coherent technologies has enabled versatile, software-defined, transceivers to become adaptive to transmission lines. Consequently, submarine systems have gradually moved from end-to-end systems to interconnected systems of open cables and transponders where different vendors can provide best in class technologies as soon as they emerge. In order to efficiently design a submarine cable or propose capacity on existing cables, it becomes necessary for vendors and customers to converge on accurate, agreed models and metrics to predict end-to-end performance. The need for accuracy is enhanced by the ongoing evolution of subsea systems towards low SNR, Spatial-Division Multiplexed (SDM) solutions [1][2][3]. Global optimization of cable capacity, power consumption and cost lead to new system trade-offs with adapted repeater pump sharing, cable conductor and fiber count / type (more fibers, lower-effective area).

In this paper, we perform a wide-scale experimental assessment of the accuracy of simple existing performance prediction models (closed-form expressions) and particularly stress the necessary adaptation of those models to the constraints of submarine systems. First, we review usual models that capture main signal impairments (Amplified Spontaneous Emission [4], nonlinear noise [5], as well as non-power dependent impairments such as GAWBS [6] or EEPN [7]). Then we revisit those models in the light of submarine constraints imposed by fixed power repeaters as in [8]. Such constraints become detrimental when operating cables at low SNR values. This is typically the case for transoceanic distances and/or for power-optimized multi-fiber SDM cables. To that end we propose a new model to simply aggregate the different impairment sources. Then we experimentally assess the accuracy of various performance prediction models through a wide-scale parametric study: using SDM_1-compatible [1], 110µm²-CSF based, 34 and 36nm full WDM testbeds, we investigate more than 100 configurations of distance (up to 16,000km), repeater output power, format (QPSK, 8QAM, Probabilistic

Constellation Shaping), symbol rate (from 31 to 69Gbaud), and channel spacing.

2. USUAL MODELS TO PREDICT QUALITY OF TRANSMISSION

This section reviews the main causes of signal impairment in coherent optical systems along with widespread models simply predicting the accumulation of these impairments. Based on the assumption that those impairments can be modelled as Additive Gaussian Noises, a Quality of Transmission Estimator (QoT) is proposed.

2.1. Transceiver model

In order to separate transceiver limitations from sources of impairments stemming from the line, we usually rely on back-to-back measures linking transceiver-dependent QoT (it could be BER, Q^2 factor, electrical SNR, xGMI) to optical SNR, assuming Amplified Spontaneous Emission (ASE) noise from amplifier as the sole source of degradation.

$$QoT = f_{btb}(OSNR_{ASE}) \qquad (1)$$

After propagation, we expect noise sources stemming from different physical phenomena (amplifier noise, nonlinear Kerr effect, GAWBS, Chromatic Dispersion partial mitigation) to aggregate so that the QoT depends on the aggregate OSNR.

$$QoT = f_{btb}(OSNR_{ASE+NLE+GAWBS+CD}) \quad (2)$$

We depict hereafter how the different contributions can be assessed and aggregated

2.2. Theoretical degradation of $OSNR_{ASE}$

ASE noise generated by the cascade of optical amplifiers is the main source of impairments. Knowing amplifier input powers and noise figures, the OSNR contributions of each amplifier k, $OSNR_{ASE,k}$, can be derived and easily combined after N amplifiers into

$$\frac{1}{OSNR_{ASE,1\to N}} = \sum_{k=1}^{N} \frac{1}{OSNR_{ASE,k}} \qquad (3)$$

With identical amplifiers compensating for span loss we get (in absence of signal droop):

$$OSNR_{ASE,theo,1\to N} = \frac{OSNR_{ASE,1}}{N} \quad (4)$$

2.3. Nonlinear noise model

In today's coherent systems, signal distortions induced by nonlinear Kerr effect can be modelled as an Additive Gaussian Noise [10][11]. Perturbative models [5]are particularly adapted to rapidly predict the characteristics of this Gaussian Noise (GN) and some closed-form expressions of the nonlinear noise variance are even possible, among which [5]:

- Nyquist channel spacing (flat spectrum) Incoherent GN model,
- Arbitrary spacing Incoherent GN model,
- Coherent GN model, accounting for faster than distance growth of variance.

An equivalent OSNR can then be derived from the nonlinear noise variance estimation and the total optical power, by accounting for signal depletion [9][12].
Further refinements are possible to account for modulation format (eGN models), but closed form expressions are less obvious.

2.4. Guided Acoustic Wave Brillouin Scattering

Beside ASE and nonlinear noises, an acousto-optic effect, referred to as GAWBS (Guided Acoustic Wave Brillouin Scattering) has recently been shown to significantly impact system performance [6]. It is modelled as an additive noise, the variance of which is proportional to total optical power and distance and is a decreasing function of fiber effective area. A model description as well as a small signal characterization are described in [6], enabling to predict an equivalent OSNR term in practical systems.

2.5. Chromatic dispersion mitigation

Commercial coherent transceivers have the capability to mitigate the Chromatic Dispersion (CD) accumulated along the line, thanks to efficient Digital Signal Processing. However, residual noise may remain after compensation because of ASIC limitations (e.g. duration of implemented compensation filter) or laser linewidth limitations (causing Equalization Enhanced Phase Noise, EEPN [7]). Numerical simulations (or models) aware of ASIC implementation and actual laser linewidth generally enable to predict equivalent SNR terms in practical cases.

2.6. Simple aggregation model

The usual way to aggregate impairments is derived from the sum of the inverse (O)SNRs associated to the different physical effects [5]

$$\frac{1}{OSNR_{total}} = \sum_{effects} \frac{1}{OSNR_{effect}} \qquad (5)$$

The aggregate OSNR can then be used into Eq. 2 to compute a QoT estimate.

3. ADAPTATION TO LOW SNR, SUBMARINE OPEN CABLES

This section is devoted to the adaptation of the previous models to accurately predict performance in low SNR submarine cables

3.1. Generalized droop in repeaters

When crossing identical spans and repeaters with fixed total output power, ASE noise gradually grows at the expense of signal power [3][4]. Accurate OSNR calculation requires to account for actual signal power at each amplifier [3][4]. In first order, it is also possible to use theoretical Eq. (4) provided assuming an average signal droop equal to half the theoretical ASE power [8]

$$OSNR_{ch.spacing}^{1st\,order} = OSNR_{theo,ch.spacing} - \frac{1}{2} \qquad (6)$$

This estimate accounting for signal and ASE droop is accurate within 0.1dB for OSNR above 2.3dB in channel spacing band (or 7.1dB$_{0.1nm}$ assuming 37.5GHz spacing). The OSNR limit is 9dB lower than with simpler estimates that neglect (Eq. 4) or overlook droop, as illustrated by Figure 1.
Coming back to exact calculations, we could change perspectives and consider that each amplifier converts a fraction of total output power into additional noise. Conversely the remaining fraction is devoted to the "attenuation" or droop of the input signal. This attenuation is $\frac{P_{total}}{P_{signal}} = 1 + \frac{1}{SNR}$. After several amplifiers, it becomes:

$$1 + \frac{1}{SNR_{ASE,1\to N}} = \prod_{k=1}^{N}\left(1 + \frac{1}{SNR_{ASE,k}}\right) \qquad (7)$$

Such a model, accounting for signal and noise droop in the context of addition of noise at fixed total power, is referred to as Generalized Droop [8].

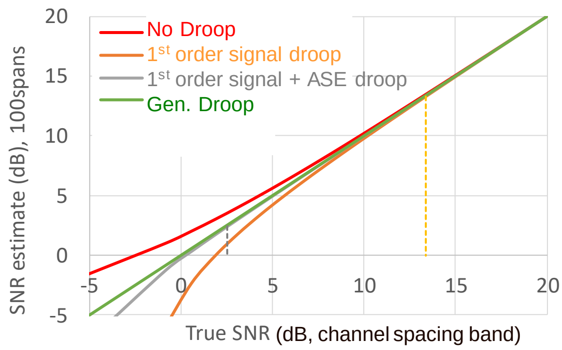

Figure 1: SNR$_{ASE}$ estimations vs exact SNR computation, after a cascade of 100 repeaters. Exact SNR corresponds to Generalized Droop model, [4] and [3] (Eq. A4); "No Droop" corresponds to theoretical OSNR in Eq. 4; "1st order signal droop" corresponds to [3] (Eq. 4), and "1st order signal +ASE droop" to Eq. 6.

3.2. Impact on SDM theoretical optimum

Using this generalized-droop-aware OSNR model to compute the **theoretical SDM optimum** between capacity and number of fibers in submarine cables constrained by electrical power (as in [3]) leads to very simple optima:

- **0dB electrical SNR per fiber/core** with
- **1b/symbol/polar.** spectral efficiency,

in absence of additional penalty. In presence of other penalties, the OSNR target should increase by half the penalty (in dB scale). In addition, should we notice that a reduction of fibers by a factor of two with respect to this optimum would only reduce capacity by

10%, it is likely that **OSNR** targets for practical future SDM systems should always remain higher than **3dB** per fiber/core in receiver band (1.6b/symbol).

3.3. Generalized droop to aggregate other sources of impairments

The Generalized Droop model to aggregate ASE along repeaters with constant total power could be applied to aggregate other sources of impairments in low-SNR operations that may appear in SDM undersea systems: in any case total power remains constant. It even seems to be the case to aggregate nonlinear and ASE noises as numerically shown in [8]:

$$1+\frac{1}{SNR_{NL+ASE}} = \left(1+\frac{1}{SNR_{NL}}\right)\left(1+\frac{1}{SNR_{ASE}}\right) \quad (8)$$

Here, SNR_{ASE} and SNR_{NL} refer to the isolated impacts of ASE or nonlinearities, and SNR terms are expressed in channel bandwidth. As for the repeater cascade, the classic Eq (5) formula overlooks additional signal and noise droop in presence of both sources of impairments. The derived aggregated SNR thus overestimates system performance, as illustrated by Figure 2 (AWGN raw curve). Conversely, a signal-droop aware adaptation of Eq (5) consisting in summing the inverses of the 1+SNR terms (AWGN SD curve) would lead to performance underestimation, while the Generalized Droop model correctly aggregates nonlinear and amplifier noises.

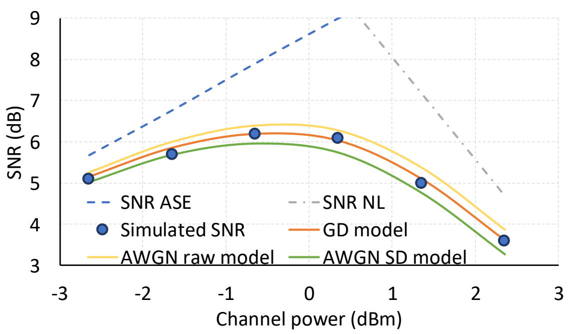

Figure 2: numerically simulated combination of SNRASE and SNRNLE, for 34Gbd QPSK link [8].

Using classical Eq. 5 leads to overestimation of the aggregate SNR by 0.2dB at SNR=6dB ($10.8dB_{0.1nm}$ assuming 37.5GHz channel grid), and by almost 0.5dB at SNR=3dB.

4. EXPERIMENTAL SET-UP

In order to test the accuracy of those models we run a myriad of experiments using both real-time and offline transceivers on transmission testbeds based on 110 μm^2 Coherent Submarine Fiber (CSF), typical of SDM_1 systems [1]. We first performed a parametric study using ASN commercial transceivers on a same 36nm recirculating loop composed of 78km-long spans, over distances ranging from 1,522 to 12,176 km and with repeater output powers varied between 16 and 20dBm. We investigated different combinations of symbol rates and channel spacings (31Gbaud and 33.3GHz, 34Gbaud and 37.5 or 50GHz). Signals were modulated using root-raised-cosine pulses of 0.1 or 0.2 roll-off factor with QPSK and 8QAM. The number of WDM channels was adapted to fill the 36nm C-band as in [13].
We also tested the performance of offline transceivers on another 34nm-wide testbed (55km-long spans) over distances from 8,102 to 16,203km, with repeater output power set to 16dBm. We varied transceiver symbol rate and channel spacing combinations (34Gbaud and 37.5GHz, 45Gbaud and 50GHz, 69Gbaud and 75GHz), and modulation format: QPSK and Truncated Probabilistic Constellation Shaping TPCS-64QAM (3.7 bit/symbol entropy). Signals were modulated with root-raised-cosine filters using a 0.01 roll-off factor. They were generated and received following the same procedure as in [13]. Again the number of WDM channels was adapted to fill the amplifier band. To receive the signal, we used Tektronix's DPS77002SX 70GHz real-time oscilloscope.

5. RESULT ANALYSIS

For each configuration, average OSNR and Q^2 factors were measured (SNR for TPCS), and Q^2 measurements were compared to different performance prediction models, with increased degree of complexity:

- Model 1 assumes a flat spectrum incoherent GN model without signal depletion, combined with $OSNR_{ASE}$ using the sum of inverse SNRs (Eq. 5).
- Model 2 uses the channel-spacing aware incoherent GN model
- Model 3 uses the coherent GN model with signal depletion
- Model 4 introduces GAWBS
- Model 5 uses Generalized Droop to aggregate ASE, NL effects and GAWBS
- Model 6 introduces CD mitigation limitations from ASIC provider simulations and laser characterizations.

Starting with the parametric study with real-time transceivers, Figure 3 depicts for each model the mean Q^2 factor estimation error per distance (whatever format, spacing, power). For the most basic models, the mean error in "Predicted vs measured Q^2" increases with distance: this is the signature of missing signal impairments in models.

The evolution to the coherent GN model associated with signal depletion (model 3), and GAWBS (model 4) have the highest impact on accuracy, but the mean Q^2 error reaches 0.25dB at long reach. This residual error is halved when using the Generalized Droop aggregation model, and almost zeroed when accounting for chromatic dispersion limitations, leading to an unbiased estimator.

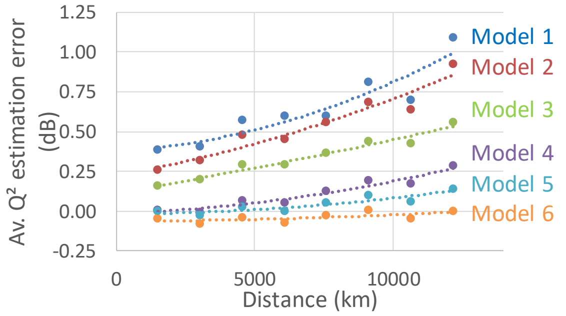

Figure 3: Average Q^2 factor estimation error (whatever format, spacing, power) vs distance on 36nm loop test-bed, with XWAV transceivers

Beyond the mean Q^2 error per distance, the standard deviation appeared almost constant from model 3 to better models, gradually moving from 0.2 to 0.1dB whatever reach.

To fully assess the level of uncertainty of Model 6, Figure 4 represents the Q^2 factor error for the 100+ configurations described in section 4, including offline and real-time tribs modulated between 31 and 69Gbaud, even with TPCS at 16,203km: the error remains within ± 0.25dB after 2000km.

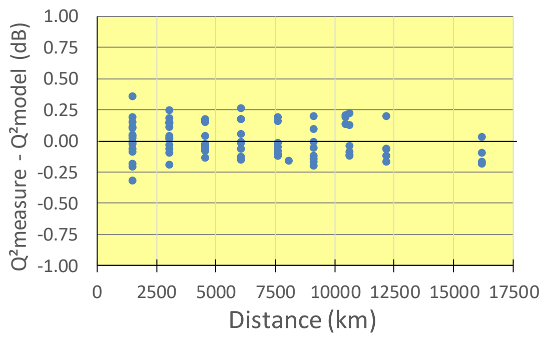

Figure 4: Q^2 factor error versus distance, for all configurations described in section 4.

6. CONCLUSION

We investigated candidate performance prediction models that could be shared by vendors and customers to efficiently build open submarine systems. To that end, we proposed a Generalized Droop concept to extend the domain of validity of widespread models to low-SNR regimes typical of SDM systems. Then we experimentally performed a wide-scale parametric study including different modulation formats, symbol rates, spacings, distances, real-time and offline transponders. The best model can predict average Q^2factor with 0.25dB accuracy.

Acknowledgements

We were kindly supported by Tektronix

7. REFERENCES

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