Analysis of 34 to 101GBaud submarine transmissions and performance prediction models

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Abstract: We analyze more than 100 subsea experiments with various configurations of rates, modulations, powers, reach and show a format and rate agnostic, accurate QoT prediction tool. We particularly show the impact of signal droop and the connection between GAWBS models based on spectral measurements and system impact.

OCIS codes: (060.2330) Fiber optics communications; (060.1660) Coherent communications

1. Introduction

Over the past few years, submarine systems have evolved into interconnections of open cables and terminal equipment, leveraging software defined coherent transceivers. To efficiently design or upgrade a submarine cable, it has become necessary for vendors and customers to converge on accurate, agreed models and metrics to predict and measure cable performance [1,2,11]. In [3] we experimentally investigated the accuracy of simple, public, performance prediction models, through a wide-scale parametric study including more than hundred configurations of modulation formats (PDM-QPSK, 8QAM, PCS), symbol rates (from 31 to 69Gbaud), channel spacings, real-time and offline transponders over distances ranging from 1500 to 16 000km of CSF1 (110µm²) fiber, typical of SDM systems. We demonstrated +/-0.25dB Q^2 accuracy beyond 2000km assuming back to back characterizations of transceiver tolerance to Gaussian noise, measurement of $OSNR_{ASE}$ and a combination of models: a coherent GN model [4] for Kerr effect, a model for Guided Acoustic Wave Brillouin Scattering (GAWBS) [5-7], a model for imperfect chromatic dispersion compensation (due to EEPN [8] and ASIC limitations), signal depletion in the nonlinear noise SNR estimate [4], and a Generalized Droop (GD) model to aggregate all sources of noise instead of an AWGN model [9,10].

In this paper, we carry out a deep analysis of the experiments and of the role of the different physical effects beside to nonlinearities and ASE. We particularly highlight the role of signal and noise droop at long reach / low SNR along with the presence of an additional noise term, the variance of which is proportional to total power and to the inverse of distance and coincides with extrapolations from spectrum measurements of GAWBS achieved in [5,6]. Eventually, we extend the panel of experiments to 101 Gbaud modulations and stress the impact of baud rate and modulation.

2. Detailed choice of the Quality of Transmission (QoT) model

Our QoT estimator (here Q^2 factor) assumes back to back characterizations of transceivers tolerance to a Gaussian noise, and a propagation medium characterized by a Gaussian noise, as a combination of Gaussian-noise like contributions of different propagation effects, each modeled by an effective noise variance or O-SNR. Next, OSNR, resp. SNR refers to noise integration in 0.1nm, resp. channel band. We do not focus the well-known ASE contribution to the SNR, which accumulation laws are well known, even with constant output power subsea repeaters [9,10].

To account for nonlinear induced noise variance, we rely on a channel-spacing aware closed-form expression of the coherent GN model (Eq. 39, and section VI.C in [12]) rather than the incoherent version that do not match our experiments [3]. Should we model GAWBS, we use the model in [5]: the effective noise variance is proportional to the ratio of total power times distance over fiber effective area to the power of 1.3, with an experimentally calibrated proportionality coefficient obtained from spectral measurements and equal to -32dB after 1000km (-32dB/Mm) for a reference 150µm² fiber type; this figure is fully consistent with the -40dB measured after 160km fiber by [6]. For typical 110µm² CSF fiber, we would therefore expect -30.1dB/Mm.

Beside the transceiver tolerance to a Gaussian noise characterized in back to back, one should account for the imperfect mitigation of chromatic dispersion by the coherent transceivers: one limitation stems from the interplay between laser linewidth and digital chromatic dispersion compensation (causing EEPN [8]), and the other from ASIC limitations when performing chromatic dispersion mitigation (in terms of resolution, or duration of the implemented compensation filter). We studied EEPN both theoretically and experimentally [13,14] and concluded that W. Shieh's model predicting EEPN equivalent noise could be used with a small reduction induced by the receiver Carrier Phase Estimation, CPE (by typically 10 to 50% depending on the CPE averaging window), and that a typical effective laser linewidth was in the range of 5-10kHz for external cavity lasers (ECL), far from the usual 100kHz specifications. As a result, we did not observe any system impact when replacing the ECL by sub-kHz linewidth lasers in 34 to 95Gbaud experiments [13]. Here we assumed a 5kHz laser linewidth local oscillator, making EEPN negligible. Beside EEPN, we modelled the imperfect dispersion mitigation of real time transceivers as an effective noise variance growing exponentially with the cumulated dispersion to compensate, in agreement with numerical simulations from our ASIC provider. For each of those effects, we converted the noise variance estimates into SNR estimates by accounting for signal depletion and combined them into a total SNR estimate either based on an Additive Gaussian Noise Model or on a Generalized Droop (GD) model (autoregressive process) [9,10] to account for the fixed total power constraint. The latter model is particularly suitable for SDM-like, low SNR applications [11]. Next, the GSNR (Generalized SNR) corresponds to the aggregation of ASE, nonlinear and GAWBS (unless explicitly overlooked) effects, thus represents the line-induced impairments, while dispersion related impairments are associated to the transceivers. As a result, a GSNR measurement is obtained while converting the measured Q² factor into an effective SNR (by inverting the back to back Q² = f(SNR) curve), from which the impact of chromatic dispersion related SNR contributions can be removed.

3. Experimental set-up

To test the accuracy of those models we run a myriad of full WDM experiments using both real-time and offline transceivers on transmission testbeds based on 110 µm^2 Coherent Submarine Fiber (CSF) as described in [3]. 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. 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) as detailed in [3]. Eventually, we tested 101Gbaud PDM-QPSK modulations (with offline receiver) on the 36 nm recirculating loop with 110GHz channel spacing, 3 powers and 3 distances in similar conditions as [2]. Electrical pre-emphasis is used to compensate the distortion added by the electrical driver. No optical pre-emphasis was applied to reach 101 GBaud. For each configuration, average OSNR and Q² factors were measured (SNR for TPCS), and GSNR values were derived. In the following, we compare GSNR values to emphasize the differences between predictions and measurements, without masking them with transceiver noise.

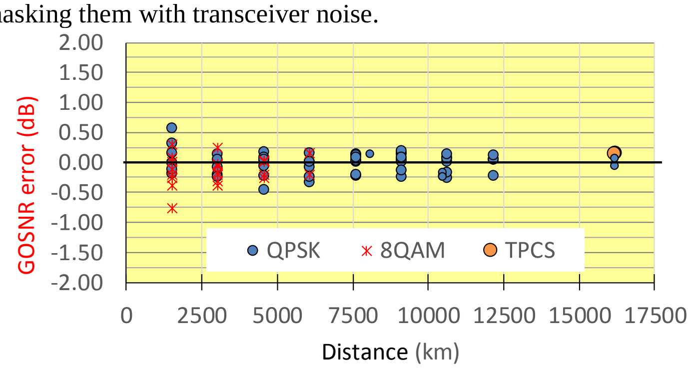

Figure 1-Left: GSNR error with real-time experiments when using the full model with Generalized Droop. Each point corresponds to a different configuration of format, spacing… Blue / orange discs correspond to QPSK / TPCS 64, Red stars to 8QAM modulations.

4. Physical analysis of the parametric study at 31/34Gbaud

We first analyze the 78 transmission experiments described in [3], including 31/34Gbaud real-time transceivers. In [3] we showed that the agreement between average Q² measurements and predictions remained within +/-0.25dB beyond 2000km when combining the GD model to the abovementioned models. It results in a GSNR prediction accuracy better than +/- 0.4dB as shown in Fig.1. To get more insight on the impact of the different propagation effects, and particularly why GAWBS and signal droop are particularly relevant, we show in Fig 2-3 the evolution of the inverse GSNR error, in linear scale, i.e. $1/GSNR_{measured} - 1/GSNR_{predicted}$: positive values represent a residual relative noise power that would overlooked by models. Starting the investigation with the measured ASE and predicted nonlinear terms, combined with the AWGN model, Figure 2-left depicts the residual noise power with distance. The red solid line corresponds to the average values per distance, while the black solid line corresponds to the linear approximation at short reach. Beside ASE and GN model, we observe a positive residual noise, increasing supra-linearly with distance (or low SNR), in average. GSNR estimation errors can reach 1dB.

By accounting for signal depletion in the GN model [4] and GD model (Fig. 2 right), this residual noise is reduced by 34% in average at long reach (60% of the impact stems from GD model). This average residual crosstalk (red curve) is almost proportional to distance, equal to -34.6dB in 0.1nm after 1000km (or -30.2dB in receiver bandwidth). We modelled that phenomenon as an extra-noise the variance of which is proportional to total power divided by distance, with a fitted proportionality coefficient (along with another one on top of the GN model prediction) to minimize Q^2 / GSNR errors: we converged to the same -30.2dB/Mm optimum, with a <2% correction factor on the nonlinear noise estimate. This is perfectly in line with the abovementioned calibrated GAWBS model based on spectral measurements. When accounting for this extra noise that we can associate with GAWBS, the residual noise is reduced by 90% in average at long reach, leading to an unbiased estimator (as shown in Fig 3 left and Fig 1).

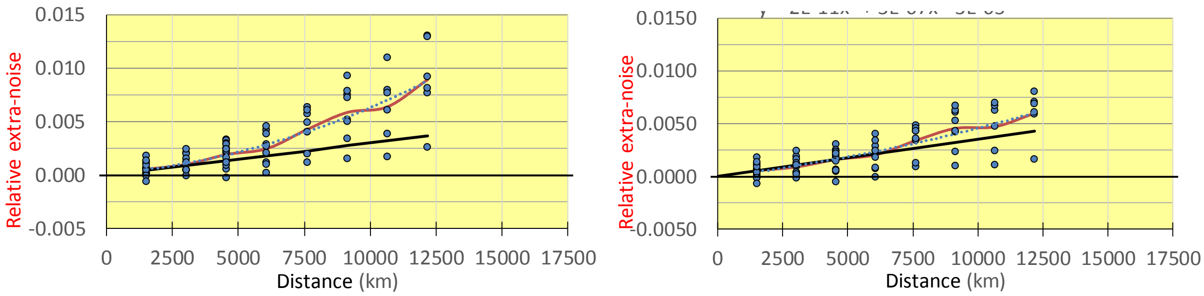

Figure 2: Residual relative noise power vs distance, with ASE and NL model only (left), and with depletion/droop models (right)

Eventually, Fig. 1 confirms that a same format-agnostic model accurately predicts the performance of QPSK, 8QAM or TPCS. Similarly, Fig 3-right depicts the Q^2 error as a function of baud rate with the additional 101 Gbaud QPSK transmissions, showing that the model accuracy (±0.25dB Q, ± 0.35dB GSNR) is not affected by baud rate.

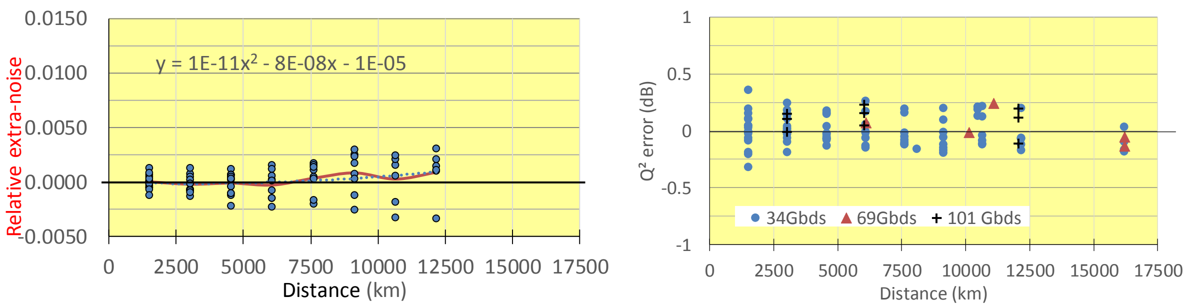

Figure 3: Left: Residual relative noise power vs distance, with all models at 31/34Gbaud. Right: GSNR error and baud rate

6. Conclusion

Based on multirate (31-101Gbaud) and multiformat experiments (QPSK, 8QAM, TPCS), we demonstrated for the first time the connection between spectral measurements of GAWBS and system impact, and showed the impact of signal and noise droop at long reach. We also demonstrated accurate QoT prediction whatever format or baud rate.

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