Experimental Assessment of Capacity Prediction from G-SNR measurements for Submarine Systems

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Abstract: We experimentally assessed that total net throughput of submarine cables can be predicted from G-SNR measurements with inaccuracy <3% when the system is operated close or below the nonlinear threshold using probabilistic constellation shaping modulation formats. © 2022 The Author(s)

1. Introduction

In the last years, a new metric referred to as Generalized Signal-to-Noise Ratio (G-SNR) has been popularized in the optical transmission community and is now standardized to characterize open submarine links and enable disaggregated architectures and designs of optical cables and transceivers [1-3]. G-SNR "characterizes the total noise contributions of the link due to linear noise and fiber nonlinearity", free of "all transponder distortion and implementation noise". It assumes that all signal impairments occurring along the transmission can be modelled as additive white Gaussian noise, which is a fair approximation even for fiber non-linearities in highly dispersed, long-haul submarine links. The "standard" G-SNR [3] is measured with a minimum of three "dual polarization quaternary phase shift keying (QPSK) or 16-quadrature amplitude modulation" test transponders without "nonlinearity compensation" and amplified stimulated emission (ASE) "for the remainder of the spectrum". It is expected to barely depend on modulation format, even though recent Gaussian-like, Probabilistic Constellation Shaping (PCS) techniques approaching the Shannon limit suffer from more non-linear noise [4] and may see a reduced "effective" G-SNR. On the other hand, powering constraints in current high capacity submarine links have led to highly parallel structures leveraging Spatial Division Multiplexing (SDM): the available powering at repeater level is shared between tens of fibers in order to maximize the overall cable capacity, leading to systems operated at low power per fiber, below the "nonlinear threshold" (NLT) corresponding to maximum fiber capacity and former submarine designs. This leads to a lower proportion of nonlinear noise and reduces the modulation dependence of G-SNR. Therefore, current SDM submarine systems operate in a favourable environment to be characterized with G-SNR measurements. We took advantage of this fact in [5-6] to evaluate the G-SNR of an SDM-representative straight-line testbed for different modulation formats with either real-time or offline transceivers, demonstrating average G-SNR variations within 0.3dB. Despite appearing as a relevant metric to characterize a submarine system, G-SNR does not express the total capacity or Achievable Information Rate (AIR) that a system could carry after future transceiver upgrades.

In this paper we introduce a method to predict the total achievable capacity of SDM open submarine cables for any desired modulation format: this method only requires the standard G-SNR measurements obtained with 69 GBd DP-QPSK following the recommendations in [1-3] and the spectral efficiency deduced from the back-to-back characterization of the selected modulation format in the transceiver under test, before or after a real error correction implementation. We experimentally validate this method using highly spectral efficient modulation formats based on PCS techniques that may be the option chosen by next generation transceivers to achieve maximum capacity even though capacity estimation is a priori more challenging with such formats since they experience much more nonlinear noise than DP-QPSK. We also demonstrate that this method is adapted to predict cable capacity even when emulating transceivers at different symbol rates and bandwidth occupancies. Finally, we fit the key parameters to be introduced in the transceiver-aware adapted Shannon formula [2, eq.21] based on back-to-back characterizations of our PCS transponders at different entropies and realistic FEC choices. Then we extrapolate from the measured standard G-SNR the total AIR that can be reached, in absence of nonlinearity compensation, with 3% discrepancy between predicted and experimental results, over three straight-lines of 2 254, 5 390 and 10 819 km lengths, operated close to the NLT.

2. Experimental set-up

The transmitter and receiver measurement setup is represented in fig.1a). Channels under test were coupled with loading noise to emulate a transmission of 4.2-THz optical bandwidth. Noise loading was generated with an amplified stimulated emission (ASE) noise source and equalized with a wavelength selective switch (WSS). Three modulated channels were used of which only the central one (λ_2) is measured. The other two (λ_1 and λ_3) were introduced to approach real system conditions, and particularly cross-talks induced by neighbour channels. For the system G-SNR characterization, the modulated channels were composed of three independent real-time DP-QPSK transceivers modulated at 69 GBd with a channel spacing of 75 GHz according to the standard procedure explained in [1-3]. For capacity validation, the modulated channels were composed of independent offline coherent transponders driven by a dedicated digital-to-analog convertor (DAC) to emulate next generation transceivers which will use PCS techniques. We considered the following modulation formats: 49GBd/69GBd DP-PCS16QAM and DP-PCS64QAM, shaped by a root-raised-cosine filter with 0.01 roll-off factor. To perform a characterization across the full C-band, the test channels were swept along the band considering a 50-GHz/75-GHz grid respectively, which corresponds to 84/56 channels over the system bandwidth. As depicted in fig.1b), three different straight-lines of 2 254, 5 390 and 10 819 km were considered. At each distance, modulation format and entropy were selected to maximize GMI based on SNR measurements. The lines consisted of several 56km-long spans of Pure Silica Core Fiber with 110 µm² effective area. We amplified the signal using 4.2 THz-wide C-band EDFAs operated at 16.5 dBm average output power to approach a real SDM operating point configuration. According to our estimations this is 0.5 dB below the NLT.

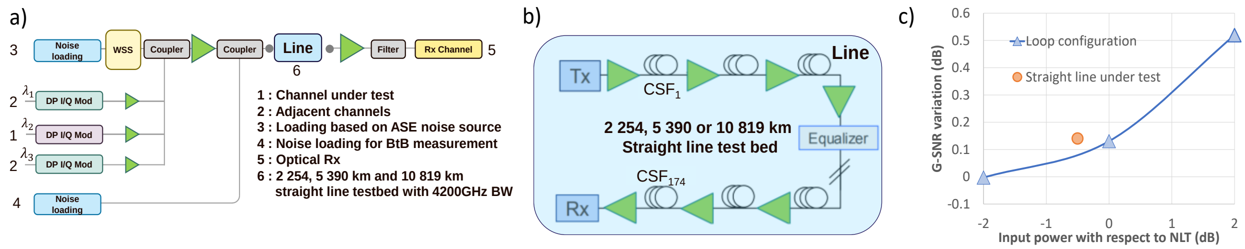

Fig. 1. Transmitter and receiver setup in a), straight-line configuration for transmission experiments in b) and G-SNR variation between DP-QPSK and DP-PCS16QAM at ~10 000 km for the straight line under test and in a loop configuration in c)

3. Domain of G-SNR measurement validity

Before addressing the problem of total capacity estimation, we need to define the domain of G-SNR measurement validity, i.e. the operating regime where the G-SNR is weakly impacted by the modulation format, thus ensuring an accurate estimation of the total AIR. For that purpose, we compared the G-SNR measured with DP-QPSK and DP-PCS16QAM modulation schemes that exhibit different tolerance to nonlinearities. We used a circulating loop to test different span input powers ranging from 14 to 18 dBm (16 dBm being the system NLT) in flat spectrum conditions. Fig.1c) shows the measured G-SNR difference between the two modulation formats as a function of normalized span input power. At low input powers both modulation formats show similar G-SNR values. Then, when the span input power is increased, fiber nonlinear effects arise, penalizing the PCS format as expected in [4], with up to 0.6 dB difference for a span input power 2 dB above the NLT and less than 0.2dB at NLT. The same measurement has been also performed over the 10 819 km straight-line confirming the results obtained in the recirculating loop, which permitted us to be confident that in this setup, the G-SNR format dependence is lower than 0.2 dB, leading to a capacity misprediction around 2% when using the classical Shannon formula. Such a weak impact can be attributed to the choice of Gaussian ASE-based loading around the test transponders, already emulating the worst cases of inter-channel nonlinear noise, thus making G-SNR measurements robust and future-proof. Next, we focus on standard G-SNRs.

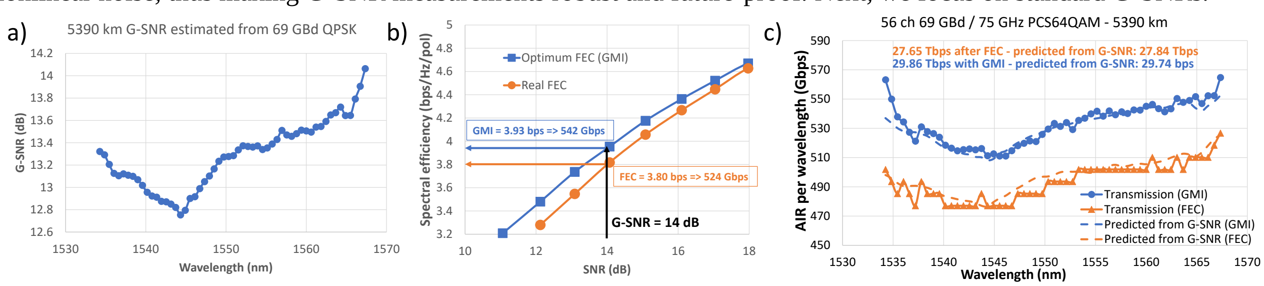

Fig. 2. Estimated G-SNR from the real-time transceiver at 69 GBd QPSK with GMI and after FEC at 5 390 km in a), back-to-back characterization of the offline transceiver at 69 GBd PCS64QAM H=5.4 bps in b) and measured and predicted AIR with GMI and after FEC at 5 390 km in c)

4. AIR prediction with 69 GBd PCS-64QAM H=5.4 bps over 5 390 km

The total AIR prediction is performed in two steps. In a first step, we perform a G-SNR measurement to characterize the line under test according to the standard procedure depicted in [1-3] based on real-time t 69 GBd QPSK modulated and 75-GHz spaced transponders and their WDM back-to-back performances. Fig.2a) shows as example the measured G-SNR of the 5390 km straight-line versus wavelength. All the G-SNR shown in this paper are expressed within the channel spacing. In a second step, we perform a back-to-back measurement of the transceiver performance for all wavelengths with modulation format contemplated for the total AIR estimation. Fig.2b) shows the back-to-back performance measurement with the transceiver configured at 69 GBd PCS-64QAM H=5.4 bps, which is the modulation format which maximizes the GMI at this distance. Two types of performance measurements are represented in fig.2b): the Generalized Mutual Information (GMI) which gives the capacity using ideal error correction and the Spectral Efficiency (SE) which gives the capacity when a real FEC is implemented. In this paper, the adaptative multirate FEC introduced in [7] is used to simulate the impact of a real FEC testing a total of 25 codes with rates ranging from 0.67 to 0.91. Then, AIR per wavelength is calculated with the following formula: AIR = $2_{pol} * SE * R$, where R is the symbol rate and SE the spectral efficiency per wavelength is obtained by projecting the line G-SNR to the wavelength back-to-back curve. Finally, the total AIR is obtained by adding the AIR of all the wavelengths. Fig.2c) shows in dashed lines the predicted channel AIR which is compared with the real values (solid line with dots) obtained after experimental transmission. For this example, GMI based AIR was estimated at 29.7 Tbps and measured at 29.9 Tbps (which represents an error of 0.4%) and a total AIR after a real FEC implementation was estimated at 27.8 Tbps and measured at 27.6 Tbps (which represents an error of 0.7%).

5. AIR prediction with 49 GBd PCS-16QAM/64QAM at any length

We also investigated the filling ratio impact. Indeed, one possibility to increase the total AIR consists in increasing the bandwidth occupancy of the system, but according to [2, fig.2], it could have an impact in G-SNR estimation that would compromise the accuracy of our capacity predictions. To test this potential impact, we considered a higher filling ratio, i.e. 49 GBd PCS-64QAM 50-GHz spaced (98% with respect to 92% previously), to check if AIR can also be extrapolated to this configuration. Fig.3a) shows predicted AIR with this new filling ratio interpolated directly from the G-SNR measurement at 69 GBd reaching similar accuracies than with previous cases. Hence, following capacity prediction assessment is given using this higher filling ratio. Eventually we tested our method at different distances. Fig.3b) shows the measured (dots) and predicted (lines) AIR values for three different straight-lines lengths: 2 254 km, 5 390 km and 10 819 km, using their respective estimated G-SNR values with the standard procedure [1-3] and back-to-back measurements for the transceiver under test. Modulation formats have been adapted for each case to maximize capacity thus leading to PCS64QAM H=5.95 bps, PCS64QAM H=5.4 bps and PCS16QAM H=3.77 bps respectively. In order to extrapolate this method to any distance, we used the Shannon capacity formula depicted in [2, eq. 21]. The parameters that depend on modem implementation: the equivalent modem SNR_m and the modem penalty η, were adjusted from total predicted AIR values in fig.3b) at the three distances. We found: SNR_m=18.5 dB and η=2 dB. Fig.3c) shows the estimated capacity formula (blue line) we obtained. It is compared with the capacities measured experimentally (in dots) at the three distances under test. With this formula, the AIR can be predicted, in absence of nonlinearity compensation, for any system length with a maximum uncertainty of 3%. We eventually plotted as a reference the Shannon limit (red line), which considers an ideal modem implementation and capacity formula estimated from predictions but considering a typical margin of 1 dB (green line).

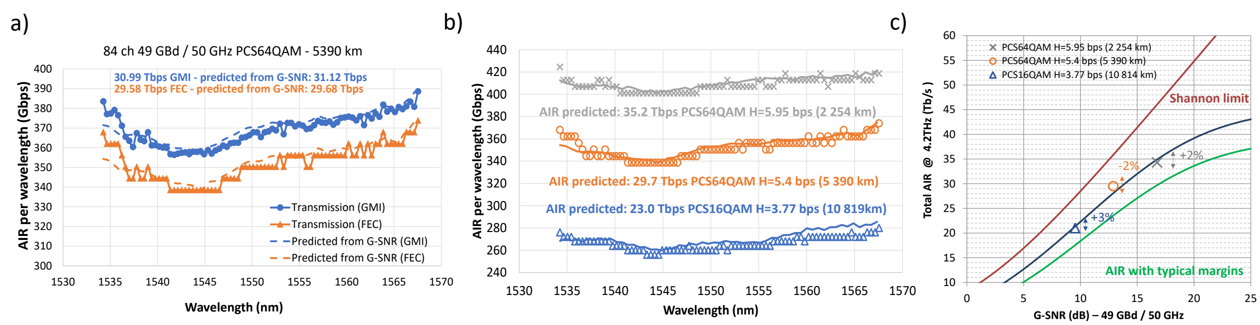

Fig. 3. Measured and predicted AIR for 49 GBd PCS-64QAM with GMI and after FEC at 5 390 km in a), after FEC at 2 254, 5 390 and 10 819 km in b) and total measured AIR after FEC at 2 254, 5 390 and 10 819 km compared with prediction in c)

6. Conclusions

We introduce and experimentally assess a method to predict the total AIR of an open SDM submarine cable. This method relies on the standard G-SNR measurement done with 69 GBd DP-QPSK signals and the back-to-back performance of another modulation format / transceiver. We experimentally validated this method by comparing the predicted AIR values with the measured values over three different straight lines (2 254, 5 390 and 10 819 km) with a prediction accuracy below 3%. We demonstrate that total AIR of a submarine system can be estimated with high accuracy even with highly spectral efficient formats such as PCS when operating around the NLT or below.

7. References

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