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# GNPy Experimental Validation for Nyquist Subcarriers Flexible Transmission up to 800 G

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**Abstract:** We test the performance of Nyquist subcarriers flexible transponders up to 800 Gbit/s over a 20×80-km optical link operated at full WDM spectral load, obtaining excellent accuracy in GSNR and optimal power predictions using GNPy.

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## 1. Introduction

Transparent optical networking based on wavelength-division multiplexing (WDM) of dual-polarization coherent optical technologies is fast expanding from core networks and submarine cables to metro networks. Thanks to silicon photonics technologies [1], integrated coherent transceivers are evolving from fix rate and fix spectral occupation to flexible rate and spectral occupation according to the flex-grid WDM to optimize the spectral efficiency [2, 3]. Flexibility in rate can be obtained using shaped or time-hybrid constellations, or exploiting Nyquist subcarriers. The latter enables a further degree of freedom by optimizing the order of the modulation format individually for each subcarrier [4].

Consequently, operators are progressively managing diversified optical infrastructures possibly including multi-vendor optical domains and mixed transponder solutions [5] sharing the spectrum according to the flex-grid WDM. To manage such a complex scenario, the operators need the capability to rely on a trustable digital twin of the WDM optical transport layer to enable an optimal network planning, and management of both optical data and control plane [6]. The industry consortium Telecom InfraProject promotes open solutions for networking, and within the open optical packet activities supports the development of the GNPy open-source project for a vendor-neutral abstraction of WDM optical transport [7]. The core of GNPy is the quality-of-transmission estimator (QoT-E) that predicts transmission performance using the generalized signal-to-noise ratio (GSNR) as a metric and back-to-back characterization as transponder model, for optical planning, optical control and optical path computation [8]. GNPy has been extensively tested with excellent results in green- and brown-field scenarios for fix-grid WDM [9]. Recently, experimental tests have confirmed the accuracy in flex-grid scenarios with single carrier transceivers and shaped constellations for a bit rate up to 200 Gbit/s, and symbol rate up to 44 Gbaud [10]. In this work, we present for the first time an experimental validation of GNPy predictions for Nyquist subcarrier transponders at bit rate up to 800 Gbit/s and symbol rate up to 96 Gbaud, operated at full flex-grid WDM spectral load on the C-band. Transmission experiments were performed at the Orange Labs on a 20×80 km optical link. Results show an excellent accuracy of GNPy computation, both in predicting performance and optimal power per channel, confirming its reliability in abstracting the optical transport also in flex-grid mixed-technologies scenarios up to 800 Gbit/s per wavelength. Additionally, GNPy provides a reliable estimation of the maximum reach for the different bit rates under investigation. In this article, all the results are expressed by means of SNR variations,  $\Delta$ SNR, with respect to an unrevealed reference in order to avoid any disclosure issues.

## 2. Experimental Setup

The experiment performed in this work was carried out at Orange laboratories in Lannion, France. A detailed schematic of the optical line system (OLS) under investigation is given in Fig 1a. The OLS consists of 20×80 km spans of ITU-T G.652 fiber that are characterized by mean losses of 16.6 dB. After each fiber span, a JDSU WRA 200 erbium doped fiber amplifier (EDFA) has been used to fully recover the fiber loss, operating in a constant gain mode. All EDFAs operate with a -1 dB tilt (expressed in dB per wavelength) in order to compensate for the stimulated Raman scattering (SRS) effect. As shown in Fig 1a, after both the 6<sup>th</sup> and 13<sup>th</sup> spans, dynamic gain equalizers (DGEs) have been used to equalize the spectrum by compensating for both the amplification ripples and the residual tilt introduced by the SRS. A total of 42 channels have been considered within this experimental framework. These channels have been organized in a flexible WDM grid with a minimum division of

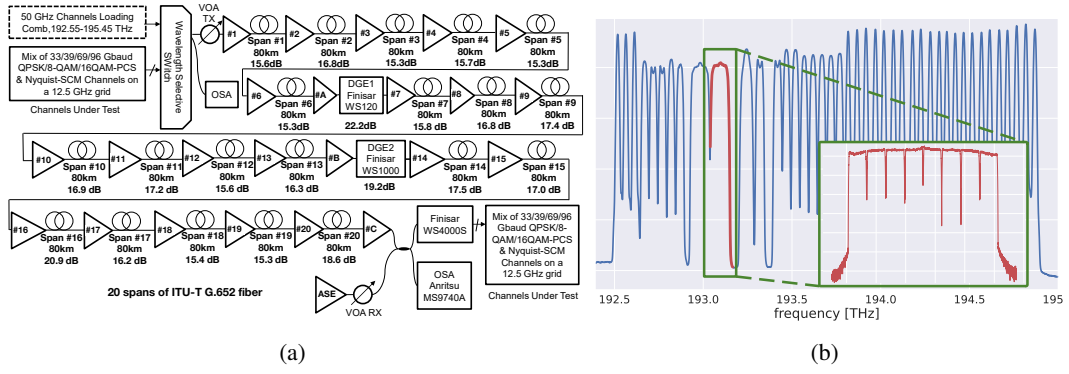


Fig. 1: (a) Schematic of the setup, (b) 800 Gbit/s - 96 Gbaud spectrum of the channel under test.

$\Delta f$ [THz]	192.55-192.65	192.7-192.9	193.013-193.125	193.275	193.35-193.55	193.6-193.8	193.85-194.9
$N_{ch}$	3	5	2	1	4	5	22
$R_b$ [Gbit/s]	100	100	up to 800	200	200	100	100
$R_s$ [GBaud]	28	33	91/96 *	69	39	33	28
$M$	QPSK	QPSK	64-QAM PCS **	QPSK	16-QAM PCS	QPSK	QPSK

Table 1: Detail description of the transmitted spectrum. The spectrum is subdivided in terms of the occupied frequency interval,  $\Delta f$ , the number of channels,  $N_{ch}$ , the bit rate,  $R_b$ , the symbol rate,  $R_s$ , and the modulation format,  $M$ .

\* it is an aggregated baud rate of the 8 sub channels working up to 12 GBaud individually.

\*\* the individual modulation scheme per sub-channel were not recorded.

6.25 GHz located between 192.55 THz and 194.9 THz within the C-band; a detailed description of the spectrum is reported in Table 1. The channel under test (CUT), centred at 193.125 THz, has been transmitted with bit rates,  $R_b$ , from 400 up to 800 Gbit/s, with step of 100 Gbit/s. The CUT consist of 8 Nyquist subcarriers multiplexed (SCM), each working at 64-QAM Probabilistic Constellation Shaping (PCS) and a data baud rate up to 12 Gbaud. This yields an equivalent total channel bandwidth,  $B_c$ , up to 96 GHz. An example of the transmitted signal measured by a MS9740B Anritsu optical spectrum analyzer (OSA) is shown in Fig. 1b. In order to analyze the QoT of this experiment, the CUT signal has been demultiplexed using a Finisar WaveShaper 4000S and received at different distances along the entire OLS. For each  $R_s$ , a back-to-back characterization have been performed varying the attenuation of a variable optical attenuator (VOA) in front of an amplified spontaneous emission (ASE) noise source. This procedure provides an indirect estimation of the GSNR given the resulting bit-error-ratio measured at the transponder [9]. Additionally, the CUT OSNR have been measured turning off the CUT itself and evaluating the noise floor with the OSA. The  $SNR_{NL}$  has been evaluated as a subtractive estimate of the measured GSNR and OSNR.

### 3. Measurements and Validation

In this extensive experimental campaign, we collect the measured GSNR and OSNR, evaluated over the entire  $B_c$ , of the CUT operated at 400 up to 800 Gbit/s. In particular, the transmitted signal has been received at different distances along the entire OLS, depending on the  $R_b$ , between 6 and 20 crossed spans, which correspond to 480 up to 1600 km. For each  $R_b$  and receiving distance, the launch power at the input of the OLS has been varied in order to obtain an estimation of the optimal power. In this work, different launch power values are expressed as

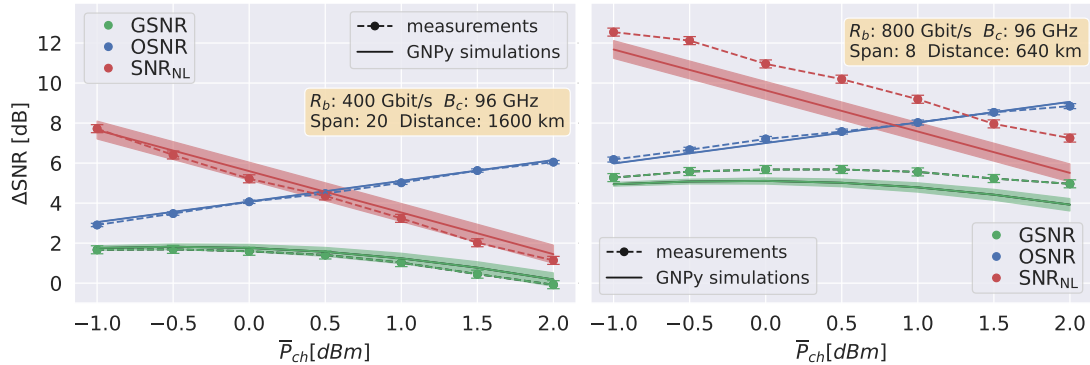


Fig. 2: Power sweeps for two selected bit rates. The shaded area surrounding the solid lines represents the variation of the GSNR and  $SNR_{NL}$  predictions varying the connector loss within a 0.5 dB range.

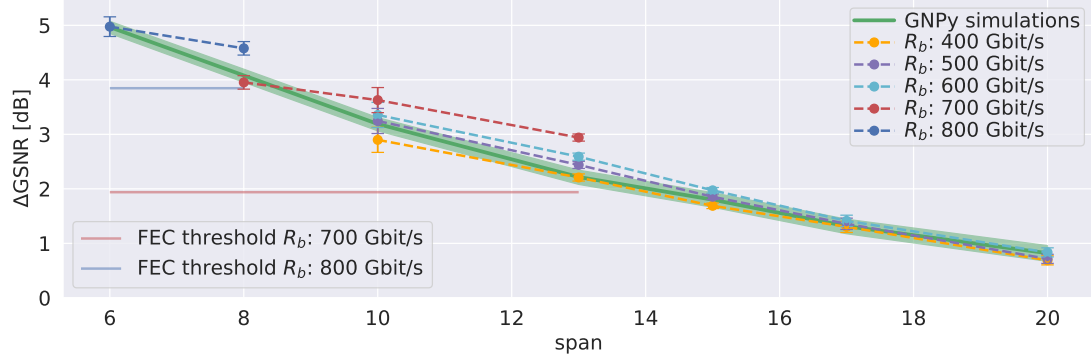


Fig. 3: Measured and simulated GSNR at different receiving distances for all the investigated bit rates. The FEC thresholds of the  $R_b$  lower than 700 Gbit are not shown in the figure as they are not significant being lower than the minimum GSNR reached after 20 spans of transmission.

the *equivalent* power per channel,  $\bar{P}_{ch}$ , defined as the total power divided by the number of channels in the WDM comb; this quantity does not match with the actual power per channel as the transmitted spectrum has been set at constant power spectral density, *i.e.*, larger channels have higher powers.

In this work, the Nyquist subcarrier CUT has been simulated in GNPpy as a single carrier with a symbol rate equivalent to the total CUT  $B_c$ . Furthermore, the input connector loss at each fiber span has been set equal to a reference value of 0.25 dB, and all the simulations have been repeated varying this value between 0.00 and 0.50 dB in order to obtain an estimation of the interval of confidence of the GNPpy predictions.

In Fig. 2, measurements and GNPpy predictions are compared for the 400 and 800 Gbit/s transmission, at the 20-th and 8-th span, respectively. It can be observed that the GNPpy functions as a reliable QoT estimator for the investigated system for all the  $\bar{P}_{ch}$  values, providing an adequate prediction of the GSNR and, in particular, of both its components, the OSNR and the  $SNR_{NL}$ , allowing an accurate prediction of the optimal power. The larger error obtained in the  $R_s = 800$  Gbit/s case is due to a non-negligible difference between the actual and nominal CUT power at the specific  $R_s$  and span. It is worth to highlight that this discrepancy is not generated by an inaccuracy of the simulation but it rather provides an estimation of the system QoT fluctuations due to spectrum variations occurring in distinct measurements, mainly due to the equalization procedures. This behaviour can be further observed in Fig. 3, where the GSNR predictions and measurements are compared for all the considered  $R_s$  and receiving spans, for a fixed value of  $\bar{P}_{ch} = -0.5$  dBm. Theoretically, all the GSNR measurements should lie on the same curve, span-by-span, as this quantity does not depend on the symbol rate nor the modulation format. On the contrary, these measurements vary in a range of 1 dB depending on the  $R_b$  and the receiving span; this range is completely compatible with the error observed in the GNPpy predictions.

In general, Fig. 3 shows an excellent accuracy and reliability of GNPpy in simulating the QoT along the entire OLS and for all the investigated  $R_s$ , also providing a precise prediction of the maximum reach for the distinct  $R_s$ .

#### 4. Conclusion

In this work we experimentally validate the GNPpy accuracy for a cutting-edge transmission scenario of a flex-rate, flex-grid spectrum including Nyquist subcarriers flexible transponders up to 800 Gbit/s and symbol rate up to 96 Gbaud. The precise results obtained using GNPpy allows a reliable estimation of the system QoT enabling an optimized power management and a trustworthy evaluation of specific modulation format feasibility for different distances.

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