gnpy Documentation

Release 0.1

Telecom InfraProject - OOPT PSE Group

May 17, 2019

Contents

gnpy is an open-source, community-developed library for building route planning and optimization tools in real-world mesh optical networks.

gnpy is:

- a sponsored project of the OOPT/PSE working group of the Telecom Infra Project.
- fully community-driven, fully open source library
- driven by a consortium of operators, vendors, and academic researchers
- intended for rapid development of production-grade route planning tools
- easily extensible to include custom network elements
- performant to the scale of real-world mesh optical networks

CHAPTER 1

Documentation

The following pages are meant to describe specific implementation details and modeling assumptions behind gnpy.

1.1 The QoT estimation in the PSE framework of TIP-OOPT

1.1.1 QoT-E including ASE noise and NLI accumulation

The operations of PSE simulative framework are based on the capability to estimate the QoT of one or more channels operating lightpaths over a given network route. For backbone transport networks, we can suppose that transceivers are operating polarization-division-multiplexed multilevel modulation formats with DSP-based coherent receivers, including equalization. For the optical links, we focus on state-of-the-art amplified and uncompensated fiber links, connecting network nodes including ROADMs, where add and drop operations on data traffic are performed. In such a transmission scenario, it is well accepted [VRS+16][BSR+12][CCB+05][ME06][SF11][JK04][DFMS04][SB11][SFP12][PBC+02][DFMS16][PCC+06][Sav05][BBS13][JA01] to assume that transmission performances are limited by the amplified spontaneous emission (ASE) noise generated by optical amplifiers and and by nonlinear propagation effects: accumulation of a Gaussian disturbance defined as nonlinear interference (NLI) and generation of phase noise. State-of-the-art DSP in commercial transceivers are typically able to compensate for most of the phase noise through carrier-phase estimator (CPE) algorithms, for modulation formats with cardinality up to 16, per polarization state [PJ01][SLEF+15][FME+16]. So, for backbone networks covering medium-to-wide geographical areas, we can suppose that propagation is limited by the accumulation of two Gaussian disturbances: the ASE noise and the NLI. Additional impairments such as filtering effects introduced by ROADMs can be considered as additional equivalent power penalties depending on the ratio between the channel bandwidth and the ROADMs filters and the number of traversed ROADMs (hops) of the route under analysis. Modeling the two major sources of impairments as Gaussian disturbances, and being the receivers *coherent*, the unique QoT parameter determining the bit error rate (BER) for the considered transmission scenario is the generalized signal-to-noise ratio (SNR) defined as

$$\text{SNR} = L_F \frac{P_{\text{ch}}}{P_{\text{ASE}} + P_{\text{NLI}}} = L_F \left(\frac{1}{\text{SNR}_{\text{LIN}}} + \frac{1}{\text{SNR}_{\text{NL}}} \right)^{-1}$$

where P_{ch} is the channel power, P_{ASE} and P_{NLI} are the power levels of the disturbances in the channel bandwidth for ASE noise and NLI, respectively. L_F is a parameter assuming values smaller or equal than one that summarizes the equivalent power penalty loss such as filtering effects. Note that for state-of-the art equipment, filtering effects can be typically neglected over routes with few hops [RNR+01][FCBS06].

To properly estimate P_{ch} and P_{ASE} the transmitted power at the beginning of the considered route must be known, and losses and amplifiers gain and noise figure, including their variation with frequency, must be characterized. So, the evaluation of $\mathrm{SNR}_{\mathrm{LIN}}$ *just* requires an accurate knowledge of equipment, which is not a trivial aspect, but it is not related to physical-model issues. For the evaluation of the NLI, several models have been proposed and validated in the technical literature [VRS+16][BSR+12][CCB+05][ME06][SF11][JK04][DFMS04][SB11][SFP12][PBC+02][DFMS16][PCC+06][Sav05][BBS13][JA01]. The decision about which model to test within the PSE activities was driven by requirements of the entire PSE framework:

i. the model must be *local*, i.e., related individually to each network element (i.e. fiber span) generating NLI, independently of preceding and subsequent elements; and ii. the related computational time must be compatible with interactive operations.

So, the choice fell on the Gaussian Noise (GN) model with incoherent accumulation of NLI over fiber spans [PBC+02]. We implemented both the exact GN-model evaluation of NLI based on a double integral (Eq. (11) of [PBC+02]) and its analytical approximation (Eq. (120-121) of [PCC+06]). We performed several validation analyses comparing results of the two implementations with split-step simulations over wide bandwidths [PCCC07], and results clearly showed that for fiber types with chromatic dispersion roughly larger than 4 ps/nm/km, the analytical approximation ensures an excellent accuracy with a computational time compatible with real-time operations.

1.1.2 The Gaussian Noise Model to evaluate the NLI

As previously stated, fiber propagation of multilevel modulation formats relying on the polarization-division-multiplexing generates impairments that can be summarized as a disturbance called nonlinear interference (NLI), when exploiting a DSP-based coherent receiver, as in all state-of-the-art equipment. From a practical point of view, the NLI can be modeled as an additive Gaussian random process added by each fiber span, and whose strength depends on the cube of the input power spectral density and on the fiber-span parameters.

Since the introduction in the market in 2007 of the first transponder based on such a transmission technique, the scientific community has intensively worked to define the propagation behavior of such a trasnmission technique. First, the role of in-line chromatic dispersion compensation has been investigated, deducing that besides being not essential, it is indeed detrimental for performances [CPCF09]. Then, it has been observed that the fiber propagation impairments are practically summarized by the sole NLI, being all the other phenomena compensated for by the blind equalizer implemented in the receiver DSP [CBC+09]. Once these assessments have been accepted by the community, several prestigious research groups have started to work on deriving analytical models able to estimating the NLI accumulation, and consequentially the generalized SNR that sets the BER, according to the transponder BER vs. SNR performance. Many models delivering different levels of accuracy have been developed and validated. As previously clarified, for the purposes of the PSE framework, the GN-model with incoherent accumulation of NLI over fiber spans has been selected as adequate. The reason for such a choice is first such a model being a "local" model, so related to each fiber spans, independently of the preceding and succeeding network elements. The other model characteristic driving the choice is the availability of a closed form for the model, so permitting a real-time evaluation, as required by the PSE framework. For a detailed derivation of the model, please refer to [PCC+06], while a qualitative description can be summarized as in the following. The GN-model assumes that the channel comb propagating in the fiber is well approximated by unpolarized spectrally shaped Gaussian noise. In such a scenario, supposing to rely - as in state-of-the-art equipment - on a receiver entirely compensating for linear propagation effects, propagation in the fiber only excites the four-wave mixing (FWM) process among the continuity of the tones occupying the bandwidth. Such a FWM generates an unpolarized complex Gaussian disturbance in each spectral slot that can be easily evaluated extending the FWM theory from a set of discrete tones - the standard FWM theory introduced back in the 90s by Inoue [Ino92]- to a continuity of tones, possibly spectrally shaped. Signals propagating in the fiber are not equivalent to Gaussian noise, but thanks to the absence of in-line compensation for choromatic dispersion, the become so, over short distances. So, the Gaussian noise model with incoherent accumulation of NLI has estensively proved to be a quick yet accurate and conservative tool to estimate propagation impairments of fiber propagation. Note that the GN-model has not been derived with the aim of an *exact* performance estimation, but to pursue a conservative performance prediction. So, considering these characteristics, and the fact that the NLI is always a secondary effect with respect to the ASE noise accumulation, and - most importantly - that typically linear propagation parameters (losses, gains and noise figures) are known within a variation range, a QoT estimator based on the GN model is adequate to deliver performance predictions in terms of a reasonable SNR range, rather than an exact value. As final remark, it must be clarified that the GN-model is adequate to be used when relying on a relatively narrow bandwidth up to few THz. When exceeding such a bandwidth occupation, the GN-model must be generalized introducing the interaction with the Stimulated Raman Scattering in order to give a proper estimation for all channels [CAC18]. This will be the main upgrade required within the PSE framework.

CHAPTER 2

Indices and tables

- genindex
- modindex
- search

CHAPTER 3

Contributors in alphabetical order

Name	Surname	Affiliation	Contact
Alessio	Ferrari	Politecnico di Torino	alessio.ferrari@polito.it
Anders	Lindgren	Telia Company	Anders.X.Lindgren@teliacompany.com
Andrea	d'Amico	Politecnico di Torino	andrea.damico@polito.it
Brian	Taylor	Facebook	briantaylor@fb.com
David	Boertjes	Ciena	dboertje@ciena.com
Esther	Le Rouzic	Orange	esther.lerouzic@orange.com
Gabriele	Galimberti	Cisco	ggalimbe@cisco.com
Gert	Grammel	Juniper Networks	ggrammel@juniper.net
Gilad	Goldfarb	Facebook	giladg@fb.com
James	Powell	Telecom Infra Project	james.powell@telecominfraproject.com
Jeanluc	Auge	Orange	jeanluc.auge@orange.com
Jonas	Martensson	RISE Research Sweden	jonas.martensson@ri.se
Mattia	Cantono	Politecnico di Torino	mattia.cantono@polito.it
Miguel	Garrich	University Catalunya	miquel.garrich@upct.es
Stefan	Melin	Telia Company	Stefan.Melin@teliacompany.com
Raj	Nagarajan	Lumentum	raj.nagarajan@lumentum.com
Vittorio	Curri	Politecnico di Torino	vittorio.curri@polito.it

- Goal is to build an end-to-end simulation environment which defines the network models of the optical device transfer functions and their parameters. This environment will provide validation of the optical performance requirements for the TIP OLS building blocks.
- The model may be approximate or complete depending on the network complexity. Each model shall be validated against the proposed network scenario.
- The environment must be able to process network models from multiple vendors, and also allow users to pick any implementation in an open source framework.
- The PSE will influence and benefit from the innovation of the DTC, API, and OLS working groups.
- The PSE represents a step along the journey towards multi-layer optimization.

Bibliography

[BSR+12] A. Bononi, P. Serena, N. Rossi, E. Grellier, and F. Vacondio. Modeling nonlinearity in coherent transmissions with dominant intrachannel-four-wave-mixing. *Optics Express*, 20(7):7777, 2012. URL: https://www.osapublishing.org/oe/abstract.cfm?uri=oe-20-7-7777, doi:10.1364/OE.20.007777.

[BBS13] Alberto Bononi, Ottmar Beucher, and Paolo Serena. Single- and cross-channel nonlinear interference in the Gaussian Noise model with rectangular spectra. *Optics Express*, 21(26):32254, 2013. URL: https://www.osapublishing.org/oe/abstract.cfm?uri=oe-21-26-32254, doi:10.1364/OE.21.032254.

[CAC18] Mattia Cantono, Jean Luc Auge, and Vittorio Curri. Modelling the impact of SRS on NLI generation in commercial equipment: an experimental investigation. In *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2018*. 2018. doi:10.1364/OFC.2018.M1D.2.

[CBC+09] A. Carena, G. Bosco, V. Curri, P. Poggiolini, M. Tapia Taiba, and F. Forghieri. Statistical characterization of PM-QPSK signals after propagation in uncompensated fiber links. In *European Conference on Optical Communications, 2010*, 1–3. IEEE, 2010-09. URL: http://ieeexplore.ieee.org/document/5621509/, doi:10.1109/ECOC.2010.5621509.

[CCB+05] A. Carena, V. Curri, G. Bosco, P. Poggiolini, and F. Forghieri. Modeling of the Impact of Nonlinear Propagation Effects in Uncompensated Optical Coherent Transmission Links. *Journal of Lightwave Technology*, 30(10):1524–1539, 2012-05. URL: http://ieeexplore.ieee.org/document/6158564/, doi:10.1109/JLT.2012.2189198.

[CPCF09] V. Curri, P. Poggiolini, A. Carena, and F. Forghieri. Dispersion Compensation and Mitigation of Nonlinear Effects in 111-Gb/s WDM Coherent PM-QPSK Systems. *IEEE Photonics Technology Letters*, 20(17):1473–1475, 2008-09. URL: http://ieeexplore.ieee.org/document/4589011/, doi:10.1109/LPT.2008.927906.

[DFMS04] Ronen Dar, Meir Feder, Antonio Mecozzi, and Mark Shtaif. Properties of nonlinear noise in long, dispersion-uncompensated fiber links. *Optics Express*, 21(22):25685, 2013-11-04. URL: https://www.osapublishing.org/oe/abstract.cfm?uri=oe-21-22-25685, doi:10.1364/OE.21.025685.

[DFMS16] Ronen Dar, Meir Feder, Antonio Mecozzi, and Mark Shtaif. Accumulation of nonlinear interference noise in fiber-optic systems. *Optics Express*, 22(12):14199, 2014-06-16. URL: https://www.osapublishing.org/oe/abstract.cfm?uri=oe-22-12-14199, doi:10.1364/OE.22.014199.

[FME+16] T. Fehenberger, M. Mazur, T. A. Eriksson, M. Karlsson, and N. Hanik. Experimental analysis of correlations in the nonlinear phase noise in optical fiber systems. In *ECOC 2016; 42nd European Conference on Optical Communication*, volume, 1–3. Sept 2016. doi:.

[FCBS06] Tommaso Foggi, Giulio Colavolpe, Alberto Bononi, and Paolo Serena. Overcoming filtering penalties in flexi-grid long-haul optical systems. In *International Conference on Communications*, 5168–5173. IEEE, 2015-06. URL: http://ieeexplore.ieee.org/document/7249144/, doi:10.1109/ICC.2015.7249144.

[Ino92] K. Inoue. Four-wave mixing in an optical fiber in the zero-dispersion wavelength region. *Journal of Lightwave Technology*, 10(11):1553–1561, Nov 1992. doi:10.1109/50.184893.

[JA01] Pontus Johannisson and Erik Agrell. Modeling of Nonlinear Signal Distortion in Fiber-Optic Networks. *Journal of Lightwave Technology*, 32(23):4544–4552, 2014-12-01. URL: http://ieeexplore.ieee.org/document/6915838/, doi:10.1109/JLT.2014.2361357.

[JK04] Pontus Johannisson and Magnus Karlsson. Perturbation Analysis of Nonlinear Propagation in a Strongly Dispersive Optical Communication System. *Journal of Lightwave Technology*, 31(8):1273–1282, 2013-04. URL: http://ieeexplore.ieee.org/document/6459512/, doi:10.1109/JLT.2013.2246543.

[ME06] Antonio Mecozzi and René-Jean Essiambre. Nonlinear Shannon Limit in Pseudolinear Coherent Systems. *Journal of Lightwave Technology*, 30(12):2011–2024, 2012-06. URL: http://ieeexplore.ieee.org/document/6175093/, doi:10.1109/JLT.2012.2190582.

[PCCC07] Dario Pilori, Mattia Cantono, Andrea Carena, and Vittorio Curri. FFSS: The fast fiber simulator software. In *International Conference on Transparent Optical Networks*, 1–4. IEEE, 2017-07. URL: http://ieeexplore.ieee.org/document/8025002/, doi:10.1109/ICTON.2017.8025002.

[PCC+06] P Poggiolini, A Carena, V Curri, G Bosco, and F Forghieri. Analytical Modeling of Nonlinear Propagation in Uncompensated Optical Transmission Links. *IEEE Photonics Technology Letters*, 23(11):742–744, 2011-06. URL: http://ieeexplore.ieee.org/document/5735190/, doi:10.1109/LPT.2011.2131125.

[PBC+02] P. Poggiolini, G. Bosco, A. Carena, V. Curri, Y. Jiang, and F. Forghieri. The GN-Model of Fiber Non-Linear Propagation and its Applications. *Journal of Lightwave Technology*, 32(4):694–721, 2014-02. URL: http://ieeexplore.ieee.org/document/6685826/, doi:10.1109/JLT.2013.2295208.

[PJ01] P. Poggiolini and Y. Jiang. Recent Advances in the Modeling of the Impact of Nonlinear Fiber Propagation Effects on Uncompensated Coherent Transmission Systems. *Journal of Lightwave Technology*, 35(3):458–480, 2017-02-01. URL: http://ieeexplore.ieee.org/document/7577767/, doi:10.1109/JLT.2016.2613893.

[RNR+01] Talha Rahman, Antonio Napoli, Danish Rafique, Bernhard Spinnler, Maxim Kuschnerov, Iveth Lobato, Benoit Clouet, Marc Bohn, Chigo Okonkwo, and Huug de Waardt. On the Mitigation of Optical Filtering Penalties Originating From ROADM Cascade. *IEEE Photonics Technology Letters*, 26(2):154–157, 2014-01. URL: http://ieeexplore.ieee.org/document/6662421/, doi:10.1109/LPT.2013.2290745.

[Sav05] Seb J. Savory. Approximations for the Nonlinear Self-Channel Interference of Channels With Rectangular Spectra. *IEEE Photonics Technology Letters*, 25(10):961–964, 2013-05. URL: http://ieeexplore.ieee.org/document/6491442/, doi:10.1109/LPT.2013.2255869.

[SLEF+15] C. Schmidt-Langhorst, R. Elschner, F. Frey, R. Emmerich, and C. Schubert. Experimental analysis of nonlinear interference noise in heterogeneous flex-grid wdm transmission. In *2015 European Conference on Optical Communication (ECOC)*, volume, 1–3. Sept 2015. doi:10.1109/ECOC.2015.7341918.

[SF11] M. Secondini and E. Forestieri. Analytical Fiber-Optic Channel Model in the Presence of Cross-Phase Modulation. *IEEE Photonics Technology Letters*, 24(22):2016–2019, 2012-11. URL: http://ieeexplore.ieee.org/document/6297443/, doi:10.1109/LPT.2012.2217952.

[SFP12] Marco Secondini, Enrico Forestieri, and Giancarlo Prati. Achievable Information Rate in Nonlinear WDM Fiber-Optic Systems With Arbitrary Modulation Formats and Dispersion Maps. *Journal of Lightwave Technology*, 31(23):3839–3852, 2013-12. URL: http://ieeexplore.ieee.org/document/6655896/, doi:10.1109/JLT.2013.2288677.

[SB11] Paolo Serena and Alberto Bononi. An Alternative Approach to the Gaussian Noise Model and its System Implications. *Journal of Lightwave Technology*, 31(22):3489–3499, 2013-11. URL: http://ieeexplore.ieee.org/document/6621015/, doi:10.1109/JLT.2013.2284499.

[VRS+16] Francesco Vacondio, Olivier Rival, Christian Simonneau, Edouard Grellier, Alberto Bononi, Laurence Lorcy, Jean-Christophe Antona, and Sébastien Bigo. On nonlinear distortions of highly dispersive optical coherent systems. *Optics Express*, 20(2):1022, 2012-01-16. URL: https://www.osapublishing.org/oe/abstract.cfm?uri=oe-20-2-1022, doi:10.1364/OE.20.001022.