Experimental Verification of Fast EGN Model for Multi-Span Metro-Access DSCM Systems

Tiago Silvério
Nokia & UPC
Munich, Germany
tiago.silverio@nokia.com

Giuseppe Parisi
Nokia
Munich, Germany
giuseppe.parisi@nokia.com

Pablo Torres-Ferrera
Nokia & UNAM
Munich, Germany
pablo.torresferrera@nokia.com

Esteban Paz
Nokia & UPC
Munich, Germany
esteban.paz@nokia.com

Sasipim Srivallapanondh
Nokia
Munich, Germany
sasipim.srivallapanondh@nokia.com

Miquel Masanas
Nokia
Munich, Germany
miquel.1.masanas@nokia.com

Luis Velasco
UPC
Barcelona, Spain
luis.velasco@upc.edu

Antonio Napoli
Nokia
Munich, Germany
antonio.napoli@nokia.com

***Abstract*—We experimentally verify a fast EGN model to estimate fiber Nonlinear Interference (NLI) and its impact in the performance of multi-span coherent transmission using Digital Subcarrier Multiplexing (DSCM) technology in metro-access networks. This theoretical model matches measurements with an error of required Optical Signal-to-Noise-Ratio (OSNR) below 0.20 dB, and an error of required received power of 0.12 dB, allowing reliable, fast and lower-complexity network planning.**

***Index Terms*—NLI, EGN, metro-access, DSCM, QoT.**

I. Introduction

One of the most promising coherent solutions for the metro-access segment is DSCM [1]. DSCM significantly improves the flexibility of the system by enabling asymmetric traffic flows, efficient hub-and-spoke traffic patterns, and flexible Point-to-Multipoint (P2MP) communication, creating a natural synergy with existing Passive Optical Network (PON) deployments and filterless network designs [2]. Although these links are often assumed to induce negligible nonlinear fiber penalties [3], key application scenarios in access and metro-aggregation networks present a more complex challenge. Path design in these environments requires carefully balancing the OSNR demands of the metro segments with the broad dynamic range of fiber losses in the access segment. This often requires operating at higher launch powers within the constraints of the link power budget to ensure sufficient signal strength reaches all network endpoints, pushing these links into a regime where fiber nonlinearities are no longer negligible [4]. This creates a critical research gap, that requires control and accurate evaluation of NLI for metro-access applications.

In this contribution, we address this open topic by testing the Monte Carlo-based Enhanced Gaussian Noise (EGN) model [3], [5] – in a multi-span, metro-access scenario using a DSCM signal composed of 16 low symbol-rate Digital Subcarriers (DSCs) (∼4 GBaud per subcarrier). We first perform a verification against numerical simulations based on the Split-Step Fourier Method (SSFM). Our findings confirm that the EGN model is highly effective, as it accurately accounts for two critical effects: Four-Wave Mixing (FWM), which is highly relevant at low symbol rates [4], and the increased intra-span coherence resulting from the reduced dispersion inherent in metro-access transmission. This work presents a comprehensive experimental validation of the EGN model for both access and metro-aggregation network scenarios, analyzing links up to 150 km. We demonstrate a strong agreement between the model's predictions and our measurements, which accounts for a Required OSNR (ROSNR) error below 0.20 dB and required received power error of 0.12 dB, for all configurations hereby presented. These findings further establish the EGN model as a reliable, accurate and low-complexity design tool for next-generation DSCM systems operating in nonlinear metro-access regimes. Thus, this paradigm will become more relevant with upcoming limitations within these segments, favoring reduced hardware requirements and relaxed power budget constraints.

The authors acknowledge the support of the EU Horizon Europe research and innovation programs, EU-funded ALLEGRO project (GA No.101092766), MSCA-DN NESTOR (GA No.101119983), and BMBF INTENSE (GA 16KIS2221K).

II. Experimental and Modeling Considerations

The experimental setup comprises essentially five blocks: Transmitter, Span Link, Noise Loading, Monitoring and Receiver. In Fig. 1, these blocks are represented and extended with their respective optical components, inspired in previous research [6]. The setup presents a transmitter (TX) based on DSCM coherent optics with 16 DSCs, operating at 200Gbps or 400Gbps with Quadrature Phase Shift Keying (QPSK) or 16 Quadrature Amplitude Modulation (16QAM), respectively. The remainder of the TX block is comprised by a standard Erbium Doped Fiber Amplifier (EDFA) and a Variable Optical Attenuator (VOA) which boost and control the total Launch Power, P_{T}, to the fiber link. The fiber link block consists of a 50 km fiber span, that can be repeated up to $M = 3$ spans

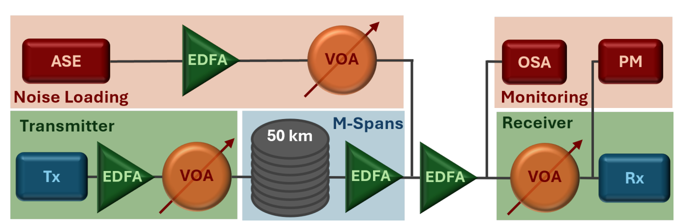

Fig. 1: Representation of an optical testbed tailored to analyze NLI noise with coherent DSCM pluggables.

978-3-903176-78-2

of Standard Single Mode Fiber (SSMF), with a respective EDFA in the case of multi-span. The Noise Loading stages add noise generated by the Amplified Spontaneous Emission (ASE) source, amplified and controlled by the combination of EDFA + VOA, and added to the fiber link, before another EDFA + VOA ensures that the received optical power is within the sensitivity of the receiver (RX) block. Additionally, about 15% of the total optical power is routed to a monitoring block comprising a Power Meter (PM) and an Optical Spectrum Analyzer (OSA), to allow for the calculation of OSNR and to monitor the received power. We use various metrics to evaluate the accuracy of the considered models. The first is the estimated NLI coefficient [5], η, used in the numerical investigation. The second is the Generalized Signal-to-Noise-Ratio (GSNR), a convenient system performance metric that can be directly associated with the Bit Error Ratio (BER) using analytical expressions, as shown by Eq. 1.

$$\mathrm{GSNR} = \left(\mathrm{SNR}_{\mathrm{ASE}}^{-1} + \mathrm{SNR}_{\mathrm{NLI}}^{-1} + \mathrm{SNR}_{\mathrm{TRX}}^{-1}\right)^{-1} \quad (1)$$

The term $\mathrm{SNR}_{\mathrm{NLI}}$ accounts for the nonlinearities in the fiber link according to: $\mathrm{SNR}_{\mathrm{NLI}} = (\eta P_{\mathrm{SC}}^2)^{-1}$, where P_{SC} is the per-subcarrier transmitted power. The $\mathrm{SNR}_{\mathrm{ASE}}$ includes the total loaded ASE noise from the EDFA at the Noise Loading stage. The $\mathrm{SNR}_{\mathrm{TRX}}$ term takes into account the intrinsic noise of the transceiver (TRX), which can be identified as a penalty for hardware implementation.

III. Results and Discussion

In Fig. 2, we evaluate η for all possible scenarios considered in this study and we discretize it over the number of DSCs. This analysis consolidates the knowledge that central DSCs are the most affected by NLI noise, since they are the ones most affected by Cross-Phase Modulation (XPM) and FWM. Given this scenario where the central DSC (i.e., ID=8, see Fig. 2) is the one most affected by NLI noise in DSCM systems, we will be considering it to evaluate all further results. In

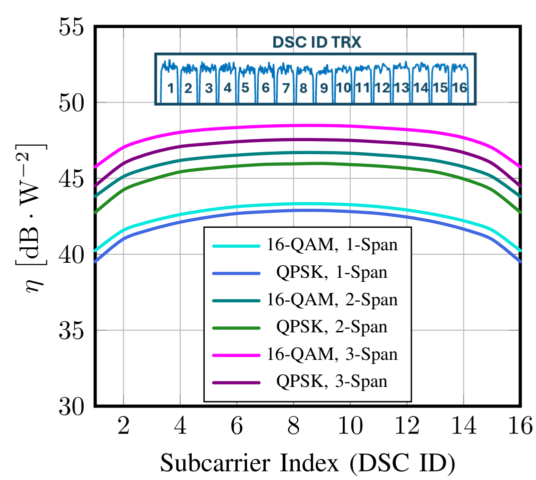

Fig. 2: EGN simulation for NLI noise over all DSCs, for all configurations.

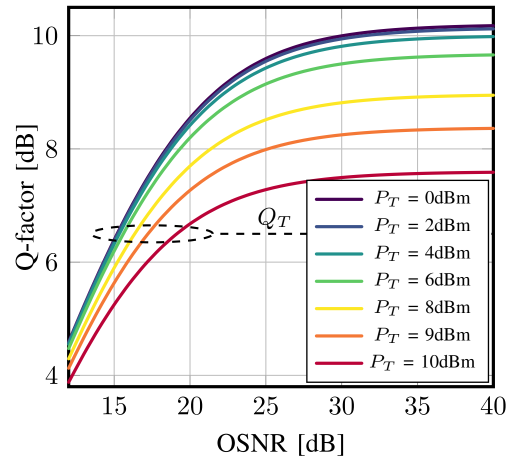

Fig. 3: Simulation of QoT metrics over OSNR in a 100 km scenario with 16QAM

Fig. 3, we demonstrate, through a Quality of Transmission (QoT) simulation based on EGN, how to calculate the ROSNR for a given Q-factor target (Q_{T}), assuming the fiber link of 100 km. It can be observed that the higher launch power provides lower Q-factor, considering the same OSNR value, due to higher nonlinearity in the fiber. Therefore, the higher OSNR is required to obtain the same Q-factor compared to the lower launch power. The ROSNR is evaluated at a specific Q_{T}, to be determined in the analysis depending on the modulation format. 16QAM and QPSK will be evaluated at Q_{T}= 6.5 and 10, respectively, corresponding to typical operating points that ensure low post-FEC error rates in our system, [7]. Given this value, we evaluate the attained ROSNR that assumes for $P_{\mathrm{T}} = 0$ dBm a value of ROSNR of 0 dB as a starting point in the linear regime.

We compare simulated and experimental ROSNR penalties, shown in Fig. 4 for 16QAM and in Fig. 5 for QPSK. The curves show each scenario with different distances up to 150 km (50 km per span, and up to 3 spans), while sweeping several total fiber launch powers, up to 12 dBm. In both figures, the coherent summation of NLI terms over the three spans is effectively captured by the model predicting an increasing penalty as function of the number of spans, accounting for a maximum of 5 dB and 3 dB, for 16QAM and QPSK formats, respectively. Moreover, similarly to previous research [5], we plot the result from the Gaussian Noise (GN) model, for a comparison with this commonly used method to evaluate NLI. Although the GN model's predictions align well with the experimental data for the first span, they diverge considerably over the subsequent two spans, consistent with the behavior predicted and detailed in [5], [8]. Additionally, we determined the TRX received power penalty under realistic, power-limited conditions typical of metro-access links in Fig. 6. These results illustrate the penalties for 16QAM, obtained from both experimental measurements and predictions derived from the EGN model, for all configurations. The close agreement between the EGN predictions and the experimental data indicates that

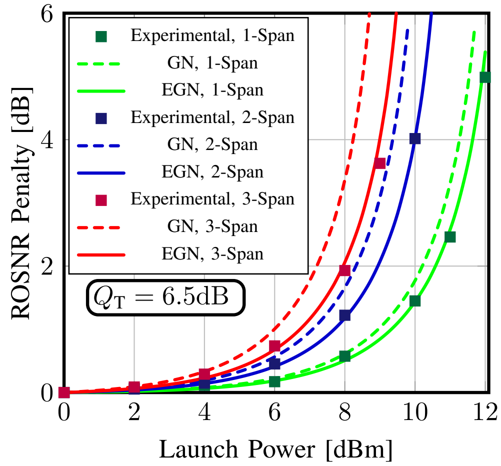

Fig. 4: ROSNR penalty as a function of total fiber launch Power for 16QAM.

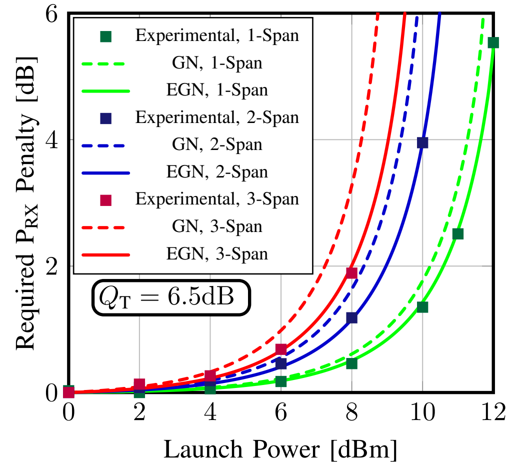

Fig. 6: P_RX Penalty at OSNR = 25 dB as a function of total fiber launch Power, P_T.

the model can effectively enhance the understanding of the line system by providing corresponding penalties at higher fiber launch power levels. This capability enables network planners to determine the required received power necessary for operation within the nonlinear regime, thereby supporting more accurate and efficient power budget estimations. These experimental results demonstrate the power and accuracy of the EGN model in predicting real NLI penalties. Excellent agreement is observed between experimental data and EGN predictions, with calculated ROSNR and received power penalty errors remaining below 0.20 dB and 0.12 db, even under highly nonlinear conditions, respectively. The EGN model significantly outperforms the standard GN model, which fails to adequately capture the low-dispersion effects characteristic of low-baud-rate multi-carrier propagation. This highlights the potential of EGN as a fast, reliable, and accurate tool for NLI penalty prediction, suitable for both access and metro-aggregation networks standards.

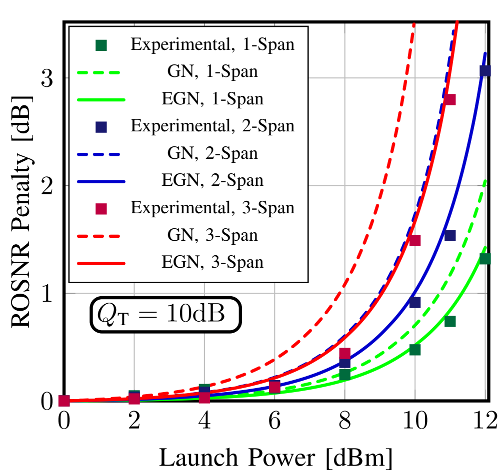

Fig. 5: ROSNR penalty as a function of total fiber launch Power for QPSK.

IV. Conclusion

This study experimentally validated a fast EGN for multi-span coherent transmission employing DSCM in metro-access networks. Addressing the critical research gap in the evaluation of NLI for short-reach applications, the proposed algorithm predicted a ROSNR penalty below 0.20 dB deviation compared to experimental measurements, even in regimes with considerable nonlinear power. The EGN model effectively accounts for significant nonlinear effects such as FWM and the increased intra-span coherence inherent in short-reach transmissions, ranging from 50 km to 150km scenarios and with two different modulation formats. This comprehensive validation solidifies the EGN model as a reliable and efficient design tool for next-generation coherent systems operating in the nonlinear short-reach regime. The work provides valuable insights for network planning and the deployment of high-bandwidth edge services.

References

[1] D. Welch, A. Napoli et al., "Digital subcarrier multiplexing: Enabling software-configurable optical networks," Journal of Lightwave Technology, vol. 41, no. 4, pp. 1175–1191, 2023.
[2] Z. Jia et al., "Coherent passive optical network: applications, technologies, and specification development [invited tutorial]," Journal of Optical Communications and Networking, vol. 17, no. 1, pp. A71–A86, 2025.
[3] P. Serena, C. Lasagni, S. Musetti, and A. Bononi, "On numerical simulations of ultra-wideband long-haul optical communication systems," Journal of Lightwave Technology, vol. 38, no. 5, pp. 1019–1031, 2020.
[4] X. Li, S. Faruk, and S. J. Savory, "Advanced nonlinear digital signal processing for short-reach applications," in Optical Fiber Communication Conference. Optica Publishing Group, 2021, pp. F2D–3.
[5] A. Carena et al., "EGN model of non-linear fiber propagation," Optics Express, vol. 22, pp. 16 335–16 362, 06 2014.
[6] T. Silvério et al., "Egn method for nli estimation in digital subcarrier allocation for horseshoe networks," in 2025 IEEE Photonics Society Summer Topicals Meeting Series (SUM), 2025, pp. 1–2.
[7] T. Yoshida, M. Mazur, J. Schröder, M. Karlsson, and E. Agrell, "Performance monitoring for live systems with soft fec," in 45th European Conference on Optical Communication (ECOC 2019), 2019, pp. 1–4.
[8] G. Parisi, T. Silvério et al., "Fiber nonlinearities in short-reach systems: Modeling and experimental verification with 400g digital subcarrier multiplexing," Journal of Lightwave Technology, pp. 1–10, 2026.