Experimental Study of Closed-Form GN Model Using Real-Time *m*-QAM Transceivers with Symbol Rate up to 69 GBd

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Abstract: Real-time transceivers were used to evaluate the accuracy of the closed-form GN model for SSMF and NZDSF C-band terrestrial applications with symbol rates from 34 to 69 GBd and modulation formats from QPSK to 64QAM. © 2020 The Author(s)

1. Introduction

Since the Gaussian-noise (GN) model was introduced [1], it has become a standard [2] for nonlinear impairment computation for polarization-division multiplexed coherent dispersion uncompensated systems. For practical applications of various models for link budgeting, the critical metrics are modeling accuracy and numerical speed. The closed-form version of GN-model provides very fast computation, compared to the full integral version of GN model. The accuracy of the GN closed-form version has been explored either through numerical split-step simulations, full integral GN model, or via lab/field transmission measurements. To date, experimental validation efforts with real-time transceivers have used modulation formats up to 16QAM and symbol rates not exceeding 45 GBd [3].

Introduction of new commercial coherent cards that support symbol rates >60 GBd and high-order modulation formats up to 64QAM requires additional validation of the GN approach for these new applications. Recently, numerical validation of the closed-form GN model was extended to high symbol rates and high-order modulation formats [4]. In this work the accuracy of the closed-form incoherent GN-model [5] is investigated experimentally using a multi-span C-band test-bed and real-time transceivers supporting variable symbol rates from 30 to 70 GBd, and variable modulation formats from QPSK to 64QAM, including fractional-QAM hybrid modulation [6]. Validation was completed for SSMF, LEAF, and TWRS transmission fibers for terrestrial applications. To our knowledge this is the first experimental validation of the GN model with a commercial real-time transceiver operating at 69 GBd. Even though some theoretical and simulation results show that the closed-form EGN model is more accurate for NZDSF applications [7], our results demonstrate that the closed-form GN-incoherent model provides the best choice for link budgeting, in terms of balance between accuracy and implementation speed, including both SSMF and NZDSF transmission.

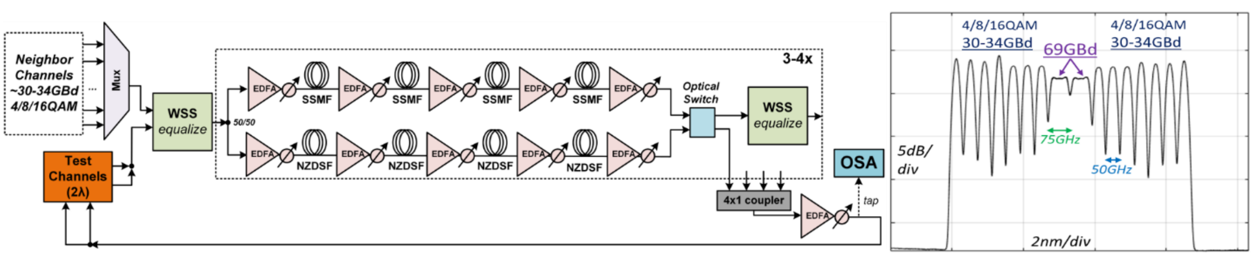

Fig. 1. Test-bed for SSMF and NZDSF transmission. Inset: OSA spectrum at transmit side (0.1 nm RBW) of the sixteen channel grid.

2. Experimental Setup and Modeling Description

The experimental straight line C-band transmission set-up is shown in Fig. 1. The channel plan used real-time coherent transceivers occupying 850 GHz bandwidth and comprised of two central test channels at 69.44 GBd (each occupying a 75 GHz slot) with 4/8/16/32QAM modulation as well as time-domain hybrid QAM, and fourteen neighbor channels on the 50 GHz grid from a mix of previous-generation coherent transceivers (~30-34 GBd 4/8/16QAM), emulating a possible upgrade field deployment. Channel powers were normalized to the slot width to achieve equal power spectral density, so 75 GHz-spaced channels had 1.76 dB higher signal power than 50 GHz channels. In addition to 69 GBd, the central test channels were also measured at 34.72 GBd 4/8/16/32/64QAM on 50 GHz grid. OSNR and pre-FEC BER data were measured for the central test channels. Due to the wavelength sensitivity of LEAF transmission results, we looked at three different cases for central test-channel wavelength: 1533, 1545, and 1558 nm. Characteristics of the system and fiber data used in the GN model are provided in Table 1. Commercial EDFAs compensated loss and spectral tilt per span and a WSS every four spans equalized accumulated gain ripple. An optical switch sent DWDM signals to the next 4-span segment, or to the receiver for OSNR/pre-FEC BER measurements, which were done without and with ASE loading at the receiver.

To model link performance, including nonlinear impairment, we use an approach similar to reference 3. This involves model for system parameter Q, based on coherent transceiver back-to-back characterization for each *m*-QAM modulation format, plus link nonlinear noise power computation according to the GN-incoherent model (see [5] and implementation in gnpy-tool [2]) with link/fiber parameters, summarized in Table 1. The Q parameter, related to pre-FEC BER as BER = 0.5 erfc(Q/√2), accounts for various performance impairments: signal GOSNR, transceiver noise, and receiver sensitivity. Measured channel OSNR values were used in signal GOSNR calculation. GN-incoherent model [5] supports channel type diversity (channel grid implementation with different types of coherent transceivers), which is essential for our set-up. Multiple metrics are available for GN model validation, which can be divided into two types: a) channel pre-FEC Q, GOSNR, and error-free max reach, all without Rx ASE noise loading; or b) OSNR penalty at a fixed pre-FEC BER using Rx ASE noise loading. In our work we used both types of validation metrics: pre-FEC Q and OSNR penalty. We take the OSNR penalty metric at pre-FEC BER = 3.0×10^{-2} (Q^2 = 5.5 dB).

Table 1. Characteristics of experimental link and transmission fiber

Fiber Type	**α [dB/km]**	**CD @ 1550 nm [ps/nm/km]**	**CD slope [ps/nm²/km]**	**γ [1/W/km]**	**Center λ [nm]**	**Avg Span Length [km]**	**Number of Spans**
SSMF	0.22	16.9	0.055	1.17	1553	79	16
LEAF	0.22	4.2	0.087	1.31	1533, 1545, 1558	73	12

3. Transmission Results and Analysis

Fig. 2 summarizes the SSMF validation results for 69 GBd QPSK, 8QAM, 16QAM, and 32QAM (200G-500G net data rates), at different distances: four, eight, and sixteen spans (twelve spans was also measured). In the validation scope we included cases with strong nonlinear penalty (>3dB) with signal power per channel to span input 2 dB above the optimum launch power. Such high signal power, above the GOSNR optimal level of the average channel, is generated through accumulated gain ripple, and can limit the reach. The difference between modeling and lab results for OSNR penalty was on average = 0.1 dB.

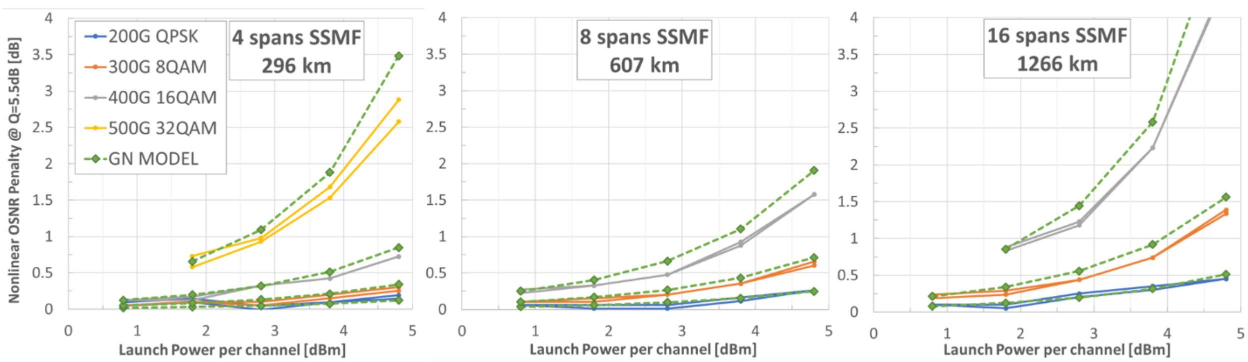

Fig. 2. Nonlinear OSNR penalty for 4, 8, and 16 spans SSMF. Both central test channels run at 69GBd and the same modulation format from the set: QPSK/8QAM/16QAM/32QAM; center λ = 1553 nm. Green dashed lines: GN MODEL (closed-form incoherent) results.

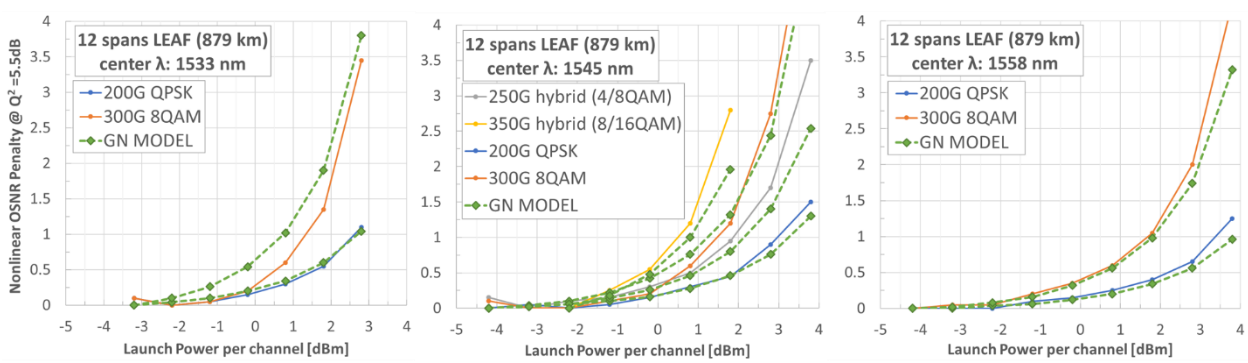

Fig. 3. Nonlinear OSNR penalty for 12 x 73km LEAF. Both central channels were run at 69 GBd and provisioned with different modulation formats. All cases used QPSK and 8QAM, and for 1545 nm case, hybrid modulation formats QPSK/8QAM and 8QAM/16QAM were also tested.

Fig. 3 summarizes results for 12 spans LEAF transmission. The two central channels were operated at 69 GBd with QPSK (200G) and 300G (8QAM) in three wavelength regions across the C-band. In addition, for the 1545 nm case only, we also tested hybrid modulation formats 250G (hybrid QPSK/8QAM) and 350G (hybrid 8QAM/16QAM) with 2.5 and 3.5 bits/symbol, respectively. The difference between modeling and lab results for OSNR penalty was on average, = -0.05 dB over the whole data set. Even though for longer wavelength region of 1558 nm there was some penalty underestimation (-0.9 dB) for 8QAM at the highest signal power of +3.8 dBm/ch (3 dB above optimum launch power), for the short wavelength sub-band (1533 nm), representing the worst part of C-band for nonlinear penalty generation due to lower fiber chromatic dispersion, the GN-incoherent model overestimated the measured penalty for 8QAM. The usage of coherent addition with the GN model would further overestimate the nonlinear penalty, while usage of EGN model would increase the number of configurations with underestimated nonlinear penalty. Similar tests were also performed on TrueWave-RS fiber (4/8/12 spans) and the closed-form incoherent GN model showed similar accuracy as on LEAF.

Fig. 4 shows the difference between experiment and GN model in terms of OSNR Penalty and pre-FEC Q, for all the conditions presented in Figs. 2 and 3 as well as additional data for LEAF (4 and 8 spans transmission with 69 GBd 8QAM and 16QAM) and 34GBd 64QAM over 4 spans SSMF, including 228 unique test conditions. For OSNR penalties up to 3 dB, representing the typical network use case including spectral power ripple, the GN-model prediction is always within 1 dB of the measured penalty. In the very high penalty regime (2-3 dB above the optimum launch power, well beyond normal operating conditions) there are two errors in the 1-2 dB range of penalty overestimation by the model. Overall, the average delta in predicted vs measured penalty is near zero (0.1 dB). The Q-factor is always predicted within +/-0.7 dB (0.1 dB average delta) for all test conditions.

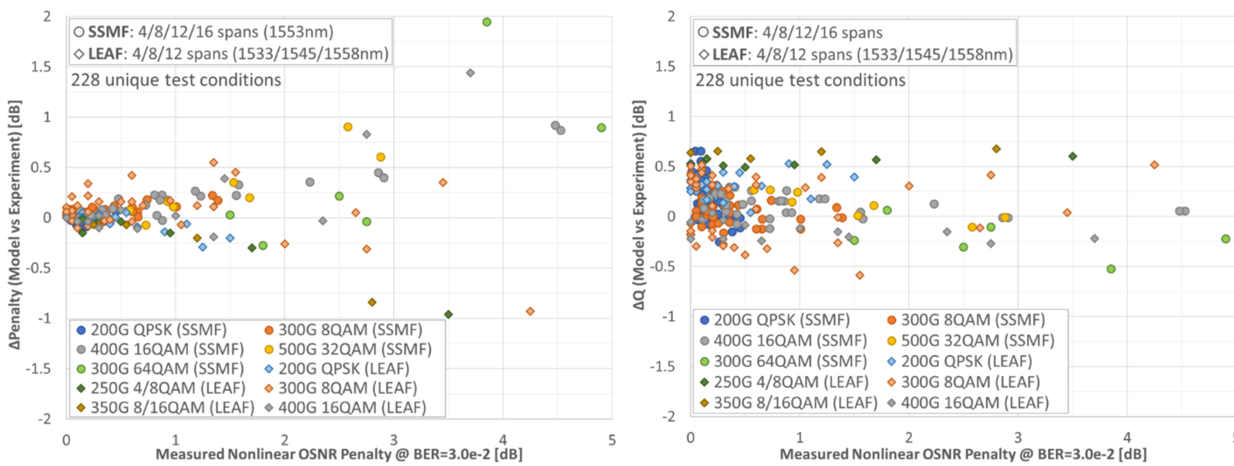

Fig. 4. Difference in (a) OSNR Penalty and (b) pre-FEC Q per channel between closed-form incoherent GN-model and experimental results, for all test data combined: SSMF and LEAF transmission, 69 GBd signals from QPSK up to 32QAM modulation and 34 GBd 64QAM signal.

4. Conclusion

Experimental results with real-time transceivers at different symbol rates up to 69 GBd and multiple modulation formats up to 64QAM were used to test the accuracy of the closed-form incoherent GN model. Based on 228 different test configurations, we demonstrate that the closed-form GN model provides the best practical choice for link budgeting for both SSMF and NZDSF applications.

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