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Accuracy of Nonlinear Interference Estimation on Launch Power Optimization in Short-Reach Systems with Field Trial / Mano, Toru; D'Amico, Andrea; Virgillito, Emanuele; Borraccini, Giacomo; Huang, Yue-Kai; Kitamura, Kei; Anazawa, Kazuya; Masuda, Akira; Nishizawa, Hideki; Wang, Ting; Asahi, Koji; Curri, Vittorio. - ELETTRONICO. - (2022), pp. 1-4. (Intervento presentato al convegno 2022 European Conference on Optical Communication (ECOC) tenutosi a Basel, Switzerland nel 18-22 Sept. 2022).

Availability:
This version is available at: 11583/2974612 since: 2023-01-19T10:09:45Z

Publisher:
IEEE

Published
DOI:

Accuracy of Nonlinear Interference Estimation on Launch Power Optimization in Short-Reach Systems with Field Trial

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Abstract *We show that even the approximate formula of the Gaussian noise model is accurate enough for launch power optimization in short-reach systems. We compare simulation and field trial results using two fiber types, showing the estimation error of signal Q-factor is less than 0.02 dB.*

Introduction

High-speed and short-reach optical communication systems are essential components of modern data centers (DCs). The regional DC architecture splits a couple of huge DCs with several middle-sized DCs to alleviate space and power limitations and reduce the impact of natural disasters[1],[2]. This architecture requires many high-speed and short-reach (up to around 120km) links to interconnect the distributed DCs[3]. Several open standards for digital coherent systems capable of 400G transmission aiming for DC interconnections have been finalized[4],[5], and compatible modules are commercially available[6]. To effectively utilize network resources and reduce costs, DC operators must optimize transmission configurations and maximize the quality of transmission (QoT) so as to use a higher data rate with fewer wavelengths. One of the effective ways to do so is via launch power optimization[7]–[9].

Launch power is related to the two major impairments triggered by signal propagation: Erbium doped-fiber amplifier's (EDFA's) amplified spontaneous emission (ASE) noise and nonlinear interference (NLI) noise[10]. Launch power optimization maximizes the QoT by striking a balance between the ASE and NLI noises[11]. The ASE noise can be obtained from the amplifiers' noise figures. Several methods exist for estimating the NLI noise and they have a trade-off between accuracy and computational complexity[10],[12]. The Split-Step Fourier Method (SSFM) numerically solves the nonlinear Schrodinger equation, making it accurate but time-consuming. While the Gaussian noise model (GN model) is an approximate nonlinear propagation model, it is simple but has proven to be sufficiently reliable[12],[13]. Even the analytical closed-form approximation formula is effective for performance prediction and system design, especially in long-haul systems[14],[15].

However, the GN model is less accurate in short-reach systems because the accumulated chromatic dispersion (CD) is small, and we can not rely on the GN model assumption that the transmitted channel statistically behaves as stationary Gaussian noise[12]. Thus, accurate NLI estimation requires complex physical layer modeling that increases computational complexity[13]. There are no prior studies on the required accuracy for NLI estimation in short-reach systems.

This paper shows that even the analytical closed-form approximate formula of the GN model is accurate enough to provide optimized launch powers in short-reach systems. This was done by performing a field trial using white-box 400G coherent transponders[16] and measuring the relationship between signal launch power and QoT. We also optimize the launch power through numerical simulations using the GN model and SSFM and compare the corresponding measured Q-factors. The resulting Q-factor differences are less than 0.02 dB on two different fiber types, confirming that the GN model can optimize the launch power as much as SSFM. The key finding is that the dominant factor of QoT is the noise mainly caused by the transceivers, not the ASE noise or NLI noise. Thus, the estimation accuracy of the non-dominant NLI noise has only a minor impact on QoT optimization. Our results also indicate that accurate QoT estimation for short-reach systems requires accurate quantification of transceivers' effect on QoT.

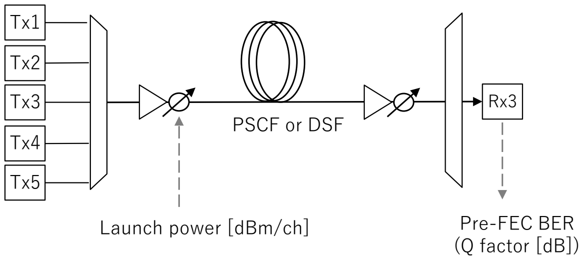

Fig. 1: Evaluation setup for launch power optimization

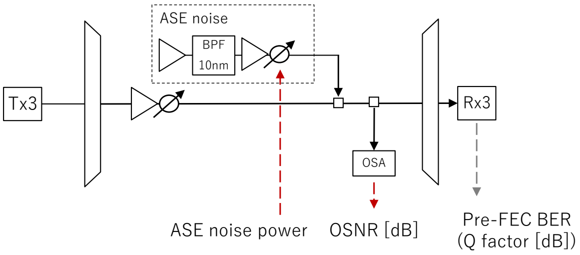

Fig. 2: Evaluation setup to obtain $\mathrm{SNR}_{\mathrm{res}}$

Field Evaluation

We use a five channel system (Fig. 1) with white-box 400G coherent transponders[16]. All five channels are 400 Gb/s (DP-16QAM, 63.1 Gbd, oFEC) with output power of 0.0 dBm/ch. The frequency spacing is 100 GHz. The channel under test (CUT) is the center channel, and its frequency is 193.4 THz. We use array waveguide gratings to mux and demux these five channels. The signal is transmitted over single span of field-deployed commercial fibers in Tokyo. We use two types of fiber: pure-silica-core fiber (PSCF) and dispersion-shifted fiber (DSF). PSCF fiber parameters are as follows: span length, total span loss including splice and connector loss, loss coefficient, and CD are 74 km, 14.2 dB, 0.172 dB/km, and 19.94 ps/nm/km, respectively. Those of DSF are 66 km, 18.3 dB, 0.228 dB/km, and -0.12 ps/nm/km, respectively. We keep the input power to the receiver at -7.0 dBm.

We change the attenuation value at the first variable optical attenuator (VOA) to change the launch power and record the pre-forward error correction (pre-FEC) bit error rate (BER) and optical signal to noise ratio (OSNR). We derive the EDFA's noise figures from these measured OSNR values.

Numerical Evaluation

We employ the additive white Gaussian noise channel model, and QoT is characterized by the generalized signal-to-noise ratio (GSNR)[12]. For DP-16QAM, pre-FEC BER is given as[17]

$$\mathrm{BER} = \frac{3}{8}\,\mathrm{erfc}\left(\sqrt{\frac{\mathrm{GSNR}}{10}}\right). \tag{1}$$

This paper uses the following GSNR to include impairments other than ASE and NLI:

$$\mathrm{GSNR}^{-1} = \mathrm{SNR}_{\mathrm{ASE}}^{-1} + \mathrm{SNR}_{\mathrm{NLI}}^{-1} + \mathrm{SNR}_{\mathrm{res}}^{-1} \tag{2}$$

where $\mathrm{SNR}_{\mathrm{ASE}}$ is the signal-to-noise ratio (SNR) of ASE noise, $\mathrm{SNR}_{\mathrm{NLI}}$ is the SNR of NLI noise, $\mathrm{SNR}_{\mathrm{res}}$ is the SNR of the residual noise other than ASE and NLI noises, such as noise generated at transceivers and filtering devices. This paper assumes that $\mathrm{SNR}_{\mathrm{res}}$ is independent of the launch power.

In the simulations, we compute $\mathrm{SNR}_{\mathrm{ASE}}$ from EDFA's noise figure and signal input power to EDFA. To compute $\mathrm{SNR}_{\mathrm{NLI}}$, we use SSFM and the analytical closed-form approximation formula of the GN model that is implemented in the open tool GNPy[15],[18]. In the computation, we set the fiber nonlinearity coefficient of PSCF and DSF to the values 0.98 1/W/km and 2.18 1/W/km, respectively. These nonlinearity coefficients are obtained by fitting the measured GSNR in the nonlinear regime launch powers[7]. To obtain $\mathrm{SNR}_{\mathrm{res}}$, we measure the BER-OSNR relationship in back-to-back configuration as in Fig. 2. Since the signal is not transmitted over fibers, we assume $\mathrm{GSNR}^{-1} \approx \mathrm{SNR}_{\mathrm{ASE}}^{-1} + \mathrm{SNR}_{\mathrm{res}}^{-1}$ and find the $\mathrm{SNR}_{\mathrm{res}}$ that best explains the measured BER values.

Before discussing the impact of NLI estimation accuracy on launch power optimization, we briefly review the accuracy of $\mathrm{SNR}_{\mathrm{ASE}}$ and $\mathrm{SNR}_{\mathrm{res}}$. We set all EDFA noise figures to 4.0 dB, and the root-mean-square error (RMSE) of $\mathrm{SNR}_{\mathrm{ASE}}$ is 0.19 dB. Calculated OSNR well matches the measured one for both PSCF and DSF cases. As for $\mathrm{SNR}_{\mathrm{res}}$, the RMSE of the Q-factor is 0.055 dB. We intentionally omit the actual value of $\mathrm{SNR}_{\mathrm{res}}$ to hide the bare performance of the transceivers to ensure confidentiality for transceiver vendors. Both results confirm that obtained $\mathrm{SNR}_{\mathrm{ASE}}$ and $\mathrm{SNR}_{\mathrm{res}}$ are accurate.

Results and Discussions

Fig. 3 compares the measured relationships between launch power and pre-FEC BER and numerically calculated one by GNPy and SSFM for PSCF (top) and DSF (bottom). The pre-FEC BER is converted to relative Q-factor to hide the bare performance of the transceiver. In Fig. 3, measurements and calculations via SSFM are consistent, and these results validate our simulation model. As for PSCF, the optimal power calculated by GNPy and SSFM are 1.58 dBm/ch and 2.61

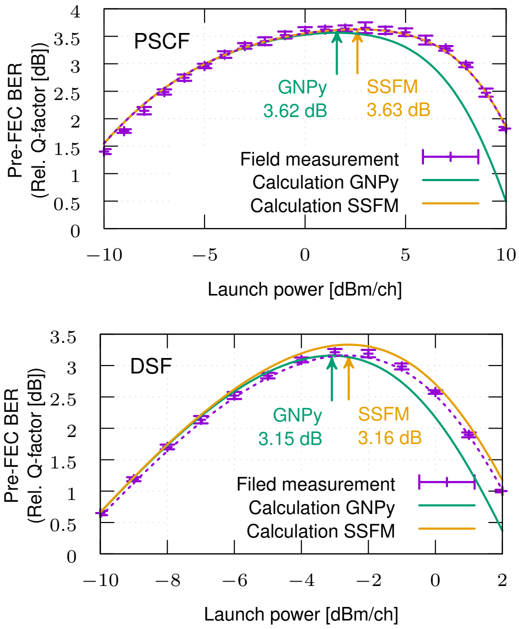

Fig. 3: Measured and calculated pre-FEC BER for each launch power in PSCF (top) and DSF (bottom). The dotted line is a fitting curve to measured points. The two arrows show the launch powers calculated by GNPy and SSFM.

dBm/ch, respectively. The GNPy's NLI estimation error is 3.07 dB, but the Q-factor difference is less than 0.02 dB. As for DSF, the optimal power calculated of GNPy and SSFM are −3.09 dBm/ch and −2.59 dBm/ch, respectively. The GNPy's NLI estimation error is 1.51 dB, but the Q-factor difference is also less than 0.02 dB. Even though GNPy completes NLI calculations orders of magnitude faster than SSFM, it achieves comparable Q-factors with SSFM.

Here, we quantitatively evaluate the impact of NLI estimation error on the obtained Q-factor based on the simulation model: Eq. (1) and (2). Let $\mathrm{SNR}_{\mathrm{NLI,est}}$ be the estimated SNR of NLI,

$$\delta = \frac{\mathrm{SNR}_{\mathrm{NLI,est}}}{\mathrm{SNR}_{\mathrm{NLI}}}$$

be the NLI estimation error, Q_{opt} be the Q-factor of the optimal launch power, and Q_{est} be the Q-factor obtained from the estimated SNR of NLI. Following the similar argument of the previous work[12], the change in Q-factor is given as follows:

$$\frac{Q_{\mathrm{est}}}{Q_{\mathrm{opt}}} \approx \frac{\left(2^{\frac{1}{3}} + 2^{-\frac{2}{3}}\right) + R}{\left((2\delta)^{\frac{1}{3}} + (2\delta)^{-\frac{2}{3}}\right) + R} \tag{3}$$

where

$$R = \left(\frac{\mathrm{SNR}_{\mathrm{ASE}}}{\mathrm{SNR}_{\mathrm{res}}}\right)^{\frac{2}{3}} \left(\frac{\mathrm{SNR}_{\mathrm{NLI}}}{\mathrm{SNR}_{\mathrm{res}}}\right)^{\frac{1}{3}}.$$

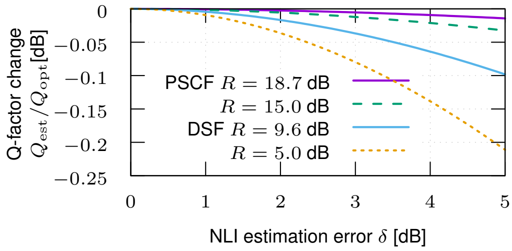

Fig. 4: The impact of NLI estimation error δ on Q-factor change $Q_{\mathrm{est}}/Q_{\mathrm{opt}}$ for each value of the SNR ratio R.

Note that, assuming $\mathrm{SNR}_{\mathrm{ASE}}$ is proportional to the launch power and $\mathrm{SNR}_{\mathrm{NLI}}$ is inversely proportional to the square of the launch power, the parameter R is independent of the launch power. This parameter R represents the ratio of $\mathrm{SNR}_{\mathrm{res}}$ to $\mathrm{SNR}_{\mathrm{ASE}}$ and $\mathrm{SNR}_{\mathrm{NLI}}$. Eq. (3) indicates that the Q-factor change is solely determined by the estimation error δ and the SNR ratio R.

Fig. 4 shows how the NLI estimation error δ changes the Q-factor for several values of R. We show the plots for positive δ because the GN model overestimates the amount of NLI noise. We select the values of R corresponding to PSCF (18.7 dB) and DSF (9.6 dB). We also plot the curves for 5.0 dB and 15.0 dB for references. Fig. 4 confirms that the NLI estimation accuracy has a minor impact on the Q-factor. For example, when the parameter R is larger than 10 dB and the NLI estimation error δ is less than 5.0 dB, then the change in Q-factor is less than 0.1 dB.

The values of R for PSCF and DSF also indicate that, for short-reach systems, the dominant factor of GSNR is the residual noise or $\mathrm{SNR}_{\mathrm{res}}$, and accurate QoT estimation requires accurate estimation of $\mathrm{SNR}_{\mathrm{res}}$. The residual noise mainly comes from the transceivers because it corresponds to the back-to-back characterization (Fig. 2). A more precise analysis of the $\mathrm{SNR}_{\mathrm{res}}$ estimation will be the focus of future investigations.

Conclusions

We optimize launch power in short-reach systems using GNPy and SSFM and compare the results with measured results from single-span field-deployed commercial fibers. Even though GNPy overestimates the NLI than SSFM by a larger amount in short-reach systems, it achieves a comparable estimation performance with the Q-factor difference of less than 0.02 dB. Our results also show that, for short-reach systems, neither ASE noise nor NLI noise is the dominant factor in QoT estimation. The dominant factor is the residual noise, and it mostly comes from the transceivers.

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