Modeling Transceiver BER-OSNR Characteristic for QoT Estimation in Short-Reach Systems

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***Abstract*—A transceiver BER-OSNR model is validated and applied the Q-factor estimation for short-reach systems. Experiments using pluggable transceivers with commercial DSPs show that the modeling and estimation errors are less than 0.05 dB and 0.15 dB, respectively.**

***Index Terms*—Transceiver model, QoT estimation, short-reach system**

I. Introduction

The regional data center (DC) architecture replaces a few full-size DCs with several middle-size DCs to avoid space and power limitations and reduce the impact of natural disasters [1]. These distributed DCs are interconnected by high-speed and short-reach optical links where the transmission distance is less than a couple of hundred kilometers. The digital coherent system is a good candidate for these interconnections. Several open standards capable of 400G have been finalized [2], [3], and compatible modules are commercially available. To deploy an optical link, DC operators must estimate the quality of transmission (QoT), i.e., the signal bit error ratio (BER), and confirm that it is sufficient to run their services.

The existing QoT estimation method [4] first assesses the generalized signal-to-noise ratio (GSNR), which includes amplified spontaneous emission (ASE) noise and nonlinear interference (NLI) impairment caused by the fiber propagation. Then, it converts the obtained GSNR into the signal BER by consulting the transceiver characteristics that are described by the relationship between BER and optical signal-to-noise ratio (OSNR) in the back-to-back (B2B) setup. In the last decade, we have seen many studies on modeling the fiber propagation effects [5], including nonlinear effects, along with deploying the digital coherent system. However, the proper modeling of the transceiver characteristics remains basically untouched since phenomena occurring outside the transceiver are the dominant factors determining QoT in the traditional long-haul system. However, in short-reach systems like DC interconnections, the transceiver is one of the dominant impairments [6], [7], and thus, modeling the transceiver is essential for QoT estimation. Existing studies [6], [7] treat the transceiver impairment as additive Gaussian noise, but the BER-OSNR relation is still unclear. A decade-old study [8] briefly implied that the BER-OSNR relation can be modeled using additive Gaussian noise with a few other parameters. However, that study mainly focused on nonlinear effects, and it is still unclear as to whether the implied model can be applied to current commercial systems. It is also unclear whether the implied model can be combined with other linear and nonlinear noise estimation methods to estimate the QoT accurately.

This paper revisits the transceiver model [8] and shows that this model can be applied to modern digital coherent systems equipped with commercial digital signal processors (DSPs). We evaluate the modeling error by using multiple transceivers with different modulation formats and baud rates, and the resulting root-mean-square error (RMSE) in Q-factor is less than 0.05 dB. We also demonstrate that the transceiver model combined with an open NLI noise estimation tool [4] can accurately estimate the QoT of short-reach systems. We set up multi-channel, multi-span short-reach systems comprising open and disaggregated transponders [9] and pluggable transceivers equipped with commercial DSPs. We compare the estimated and measured QoT for different span input powers and find that the estimation errors are less than 0.15 dB around the optimal power region.

II. Modeling of the Transceiver BER-OSNR Characteristic

We use the following BER-OSNR model based on the previous one [8]:

$$\mathrm{BER} = \Psi(\mathrm{GSNR}), \tag{1}$$

$$\mathrm{GSNR}^{-1} = \mathrm{SNR_{ASE}}^{-1} + \mathrm{SNR_{NLI}}^{-1} + \mathrm{SNR_{TRX}}^{-1}, \tag{2}$$

$$\mathrm{SNR_{ASE}} = \mathrm{OSNR}\frac{\Delta f}{R_s \eta}, \tag{3}$$

where $\mathrm{SNR_{ASE}}$ is the signal-to-noise ratio (SNR) of ASE noise, $\mathrm{SNR_{NLI}}$ is the SNR of NLI noise, $\mathrm{SNR_{TRX}}$ is the SNR of the transceiver noise corresponding to the transceiver impairments, Δf is the OSNR measuring bandwidth, which is usually 12.5 GHz, R_s is the signal baud rate, η represents the deviations of the receiver filter from the ideal matched filter. If the receiver uses the ideal matched filter, η equals to 1. Otherwise, η is greater than 1. Function Ψ is mathematically determined from the modulation format and symbol mapping [10]; e.g., $\Psi(x) = \frac{1}{2}\,\mathrm{erfc}\left(\sqrt{x/2}\right)$ for DP-QPSK, $\Psi(x) = \frac{2}{3}\,\mathrm{erfc}\left(\sqrt{\frac{3}{14}x}\right)$ for DP-8QAM, $\Psi(x) =$

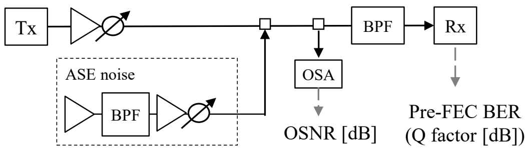


Fig. 1: B2B measurement.

$\frac{3}{8}\,\mathrm{erfc}\left(\sqrt{x/10}\right)$ for DP-16QAM. Considering geometric and probabilistic constellation shaping is one of our future works.

We assume that the input power to the receiver is kept constant, and parameters $\mathrm{SNR_{TRX}}$ and η are independent of other noises, OSNR and $\mathrm{SNR_{NLI}}$. However, these parameters depend on the transceiver operational mode, a combination of baud rate, modulation format, symbol mapping, and forward error correction scheme. When the operational mode is fixed, the BER-OSNR characteristic is modeled by using only two parameters, $\mathrm{SNR_{TRX}}$ and η. These two parameters can be calculated via least-squares fitting using measured B2B BER-OSNR values (Fig. 1).

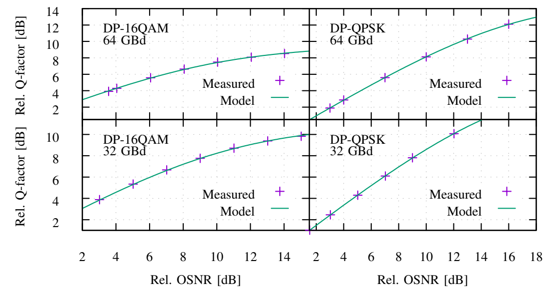
III. Evaluating Modeling Error through Back-to-Back BER-OSNR Measurements

We evaluate the modeling error using multiple transceivers with different modulation formats and baud rates. We measure B2B BER-OSNR characteristic (Fig. 1), calculate model parameters, $\mathrm{SNR_{TRX}}$ and η, and compute the modeling error as the RMSE in Q-factor.

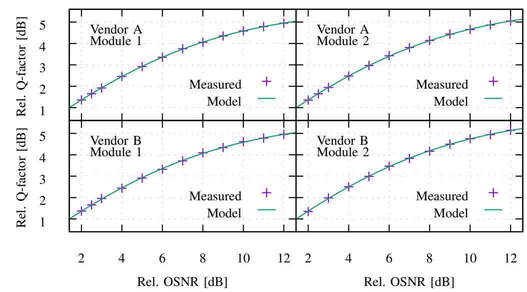
First, we evaluate the model using a DSP evaluation board with four operational modes; DP-16QAM 64 GBd, DP-QPSK 64 GBd, DP-16QAM 32 GBd, and DP-QPSK 32 GBd. Fig. 2a compares measured points with the curves provided by the model. All four model curves well fit measured values. RMSE is less than 0.05 dB for all four modes. The filter constant η is in the range of 1.10 ± 0.05 for all modes. Note that we intentionally omitted $\mathrm{SNR_{TRX}}$ and the absolute value of Q-factor and OSNR to obscure transceiver performance and ensure vendor confidentiality.

Then, we tested four CFP2-DCO modules equipped with commercial DSP. Two modules come from vendor A, and the other two come from vendor B (we mask the vendor names for confidentiality). These four transceivers use the same DSP, but each vendor employs different types of optical modulator. Vendor A uses indium phosphide (InP) modulators, while vendor B uses silicon photonic (SiP) modulators. All four modules were operated with DP-16QAM and 64 GBd. Fig. 2b compares the model curves with measured values. Although transceivers used different types of optical components, all four model curves fit measured values well. RMSE is less than 0.02 dB in all cases. The filter constant η is 1.10 ± 0.02. The results in Fig. 2 imply that the decade-ago transceiver model represented by Eqs. (1) to (3) is still applicable to modern transceivers equipped with a commercial DSP capable of higher baud rates and higher modulation formats.

We present a simpler method for calculating $\mathrm{SNR_{TRX}}$ without the least-squares fitting, but instead directly calculates it from the BER floor value, $\mathrm{BER_{floor}}$, that is, the BER at B2B with no ASE noise loaded. We can use this method



(a) DSP evaluation board.



(b) CFP2-DCO modules.

Fig. 2: Comparisons of measured Q-factor and model fitting curve in B2B setup.

when the filter constant η is known or a typical value, such as 1.1, is used. In this case, ASE and NLI noises can be ignored, so $\mathrm{SNR_{TRX}}$ can be approximately calculated as $\mathrm{SNR_{TRX}} \simeq \Psi^{-1}(\mathrm{BER_{floor}})$. However, it is difficult to apply this to modulation formats with higher noise tolerance, such as DP-QPSK, because $\mathrm{BER_{floor}}$ will be tiny, e.g., less than 10^{-12}, and it is challenging to measure $\mathrm{BER_{floor}}$ correctly. In addition, the modeling error would become large due to the small number of measurement points. When we apply this method to the four CFP2-DCO modules, the average modeling error is 0.10 dB, while the average error using least-squares fitting with all BER-OSNR measurements is 0.01 dB. However, if the high accuracy estimation is not required, this method is helpful because it requires only one measurement in the simple B2B setup.

IV. Application to QoT Estimation in Short-Reach Systems

We demonstrate that the combination of the transceiver model and an NLI estimation method can accurately estimate the QoT in short-reach systems. We build a multi-channel, multi-span system in a laboratory using an open and disaggregated transponder [9] and CFP2-DCO modules equipped with commercial DSPs that support a 400G operational mode compliant with an open standard [11]. Then, we compare the estimated and measured Q-factors. Fig. 3 depicts the system. The number of channels is five. All five channels are 400 Gb/s (DP-16QAM, 64 GBd) with output power of 0.0 dBm/ch. The frequency spacing is 100 GHz. The channel under test is the center channel, and its frequency is 193.4 THz. The number of spans is one, two, or three. Each span consists of 80 km standard single mode fiber (SSMF) whose loss coefficient is 0.189 dB/km, and chromatic dispersion is 16.75 ps/nm/km.

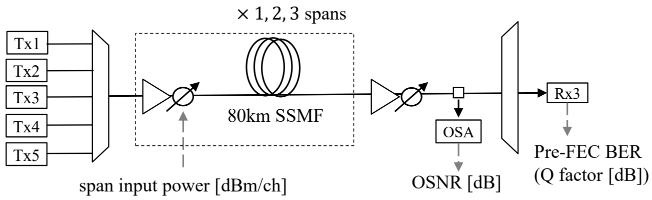


Fig. 3: Short-reach QoT estimation.

TABLE I: Q-factor changes caused by SNR 1.0 dB error

Total no. of spans	$\mathrm{SNR_{TRX}}$	$\mathrm{SNR_{ASE}}$	$\mathrm{SNR_{NLI}}$
1	0.92	0.03	0.03
2	0.88	0.05	0.05
3	0.84	0.08	0.08

We keep the input power to the receiver at -7.0 dBm. We change the span input powers and measure the BER and OSNR. We estimate Q-factor using Eqs. (1) to (3) that requires OSNR, $\mathrm{SNR_{NLI}}$, $\mathrm{SNR_{TRX}}$, and η. As for $\mathrm{SNR_{TRX}}$ and η, we calculate them from preliminary B2B measurements (Fig. 1). As for OSNR, we extract amplifier noise figures from the input power and OSNR relation measured in the short-reach systems (Fig. 3). Then, we compute OSNR as $(\sum_i N_i h f_0 \Delta f / P_{\mathrm{in},i})^{-1}$ where $P_{\mathrm{in},i}$ is the input power to the i-th amplifier, N_i is the i-th amplifier's noise figure, h is Planck's constant, and f_0 is the signal frequency. As for $\mathrm{SNR_{NLI}}$, we use two NLI estimation methods: GNPy [4] and the Split-Step Fourier Method (SSFM). In the NLI calculation, we set the fiber nonlinearity coefficient to the typical value of 1.3 1/W/km.

Fig. 4 shows estimated and measured Q-factors in 1-span, 2-span, and 3-span setups. The optimal input power that maximizes the measured Q-factor is around 2.0 dBm/ch in all three cases. We can see the gap between estimation and measurement in the high power region, say more than 5.0 dBm/ch. We suppose that this deviations comes from using typical values of the fiber nonlinearity coefficient instead of an actual measured value. If we can use the coefficient that matches the measurements, the model calculation result agrees well with the measurements (the dashed lines in Fig. 4). Thus, the estimation error in the high-power region is due to the NLI estimation error and not the transceiver model. The estimation errors in the range of the optimal power ± 3.0 dBm/ch, i.e., from -1.0 dBm/ch to 5.0 dBm/ch, are as follows. RMSE with GNPy of 1-span, 2-span, 3-span setup are 0.07 dB, 0.06 dB, 0.09 dB, respectively. Those with SSFM are 0.06 dB, 0.13 dB, 0.12 dB, respectively. Hence, regardless of the NLI estimator, the transceiver model well estimates the QoT of short-reach systems around the optimal power region.

Our quantitative Q-factor evaluations show that the accurate transceiver characteristic, i.e., the accurate value of $\mathrm{SNR_{TRX}}$, is vital for QoT estimation. To assess the impact of estimation accuracy on the Q-factor, we compute the Q-factor change caused by a 1.0 dB error in $\mathrm{SNR_{TRX}}$, $\mathrm{SNR_{ASE}}$, or $\mathrm{SNR_{NLI}}$, assuming other SNRs are accurate, at input power of 2.0 dBm/ch using Eqs. (1) to (3). Tab. I shows the results. The error in $\mathrm{SNR_{TRX}}$ has more impact than $\mathrm{SNR_{ASE}}$ and $\mathrm{SNR_{NLI}}$. If the number of spans is small, the impact of error in $\mathrm{SNR_{ASE}}$ and $\mathrm{SNR_{NLI}}$ is minor and could be negligible. Thus, in short-reach systems, accurately obtaining $\mathrm{SNR_{TRX}}$ is more critical than $\mathrm{SNR_{ASE}}$ and $\mathrm{SNR_{NLI}}$.

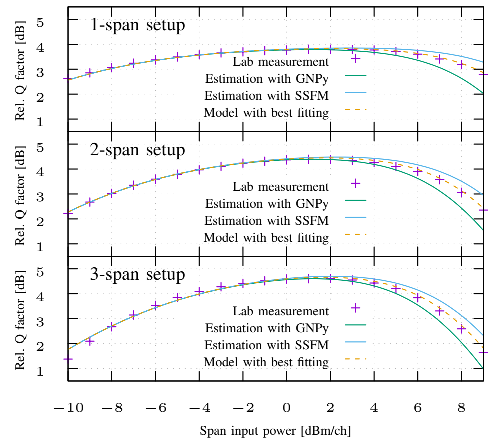


Fig. 4: Comparisons of Q-factor measurement and estimation.

V. Conclusion

We revisited a transceiver BER-OSNR characteristic model and validated it anew, showing that the modeling errors in Q-factor were less than 0.05 dB with modern commercial DSPs, and multiple modulation formats, and baud rates. Experiments showed that the transceiver model combined with GNPy could reasonably estimate the QoT of real short-reach systems, including open and disaggregated transponders and pluggable transceivers equipped with commercial DSPs. The estimation errors were less than 0.15 dB around the optimal power region. Together with these results, our analysis of Q-factor changes caused by SNR changes highlights the importance of accurately modeling and acquiring the transceiver characteristic in short-reach systems.

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