Nonlinear SNR Estimation based on Power Profile Estimation in Hybrid Raman-EDFA Link

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Abstract: We demonstrate the nonlinear SNR estimation based on longitudinal power profile obtained with coherent receiver. The estimation error is less than 0.6 dB in WDM transmission over hybrid Raman-EDFA link.

1. Introduction

Optical link monitoring is important for network management and optimizations. One of the interesting technologies is longitudinal power profile estimation (PPE) based on coherent receiver that does not require any additional hardware or probe signal like OTDR (optical time domain reflector) [1-5]. Furthermore, PPE works for end-to-end lightpath across multiple spans. Many interesting applications of PPE have been reported such as anomaly loss detection, spectral gain profile estimation, passband narrowing estimation, and optical fiber type identification [1-5]. However, there has not been any reports on application of PPE for transmission performance monitoring or estimation.

GSNR (generalized SNR) is a good metric for performance optimization to guarantee QoT in optical transmission system [6]. Nonlinear SNR is one of the key factors in GSNR calculation. In this paper, we utilize PPE for estimation of nonlinear SNR (SNR_{NL}) of transmitted signal in hybrid Raman-EDFA links with distributed forward Raman amplifier (DFRA). Raman link can be designed with known parameters, but actual optical fiber in the field may have different attenuation factor or anomaly loss that may affect the performance. For example, Corning®SMF-28™ optical fiber may have maximum deviation of 0.05 dB/km [7]. We demonstrate that PPE can be used to estimate SNR_{NL} for the first time as well as identify errors that may degrade performance of transmitted signal which is optimized based on design specifications. Especially, the error of estimated SNR_{NL} based on PPE using split-step Fourier method (SSFM) is less than 0.6 dB in WDM transmission.

2. Coherent receiver-based PPE and estimation of nonlinear SNR

Coherent receiver-based PPE is enabled by non-commutative properties of linear and nonlinear process of optical signal propagation in optical fiber [1]. Coherent receiver samples complex waveform of optical signal, which is reference waveform. Waveform at the transmitter side can be rebuilt based on received data or symbols and then transmitted in emulation (emulated waveform). In PPE, the longitudinal power profile in transmission link can be estimated by minimizing mean square error (MSE) between two waveforms, the reference waveform and the emulated waveform [2-4]. The optimal coefficients, γ', of minimum MSE (MMSE) is a product of step size (Δz), fiber nonlinear coefficient (γ_{nl}), and optical signal power (P_z) in each segment in transmission emulation. Thus, absolute power can be found if both γ_{nl} and Δz are known. In this study, MMSE based PPE proposed in [4] is used.

Once power profile of optical signal is found, then there are multiple techniques to estimate SNR_{NL}. Most straight forward way is to simulate transmission of optical signal following the estimated power profile with known optical fiber dispersion and nonlinear coefficients. Please note that fiber attenuation coefficient is not required because absolute power profile is used. In simulation, enough number of random symbols are transmitted for reliable estimation of SNR_{NL}. Profile of nonlinear noise can be found by subtracting constellation of back-to-back configuration from the recovered constellation at receiver side including compensating chromatic dispersion and aligning constellation by carrier phase recovery. SSFM is one of the most well-known transmission simulation techniques. To find nonlinear noise including XPM and SPM, PPE is conducted for each channel of co-propagating WDM signals. Alternative way of finding nonlinear SNR is using CF-GN (closed-form Gaussian noise) model by applying curve fitting to the power profile obtained from PPE [8]. Although, the current CF-GN model is fast compared with SSFM simulation, further study is required to find appropriate curve fitting method when there is anomaly loss in a link with DFRA. Since SSFM can be easily applied on any power profile (including anomaly loss), we used this technique for SNR_{NL} estimation in this study.

3. Transmission system for evaluation

The schematic diagram of transmission system is shown in Fig. 1. Hybrid Raman-EDFA link has span length of 100 km SMF with DFRA. EDFA with noise figure of 6 dB is added at the end of the link to compensate transmission

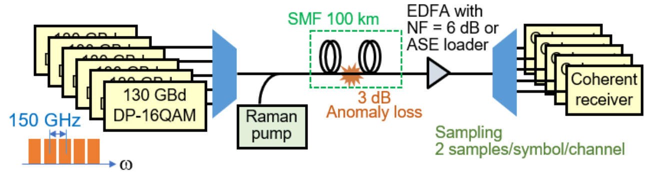


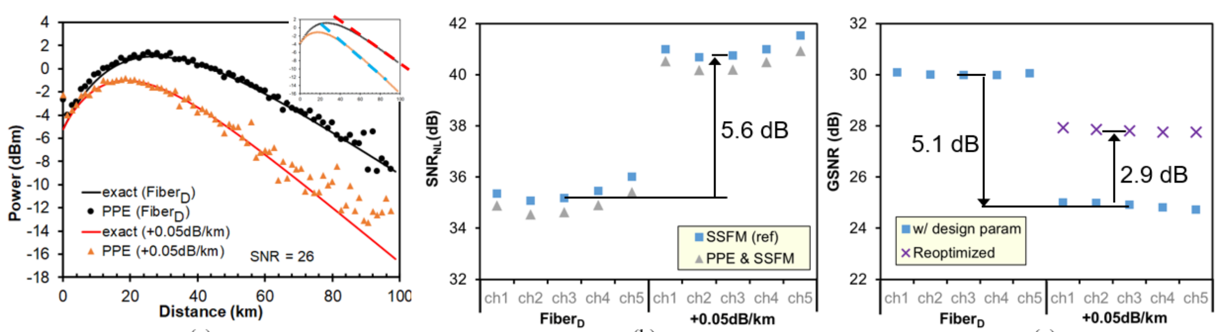
Fig. 1. Schematic diagram of transmission system.

loss or ASE loader is added at the end of link to set received SNR for evaluation of PPE. There are 5 channels of 130 Gbaud DP-16QAM with 150 GHz channel spacing where the wavelength of center channel is 1552.52 nm. Roll-off factor is 0.01 with square-root-raised cosine filter. Raman pump wavelength is 1452.9 nm. Fiber dispersion is about 16 ps/nm/km, nonlinear coefficient is 1.3 /W/km and attenuation of SMF without water peak is assumed. Peak Raman gain is 0.392 /W/km [8]. Optimization of hybrid Raman-EDFA link is achieved with above design parameters by maximizing GSNR of the center channel. For this, coupled differential equation is solved to find actual power profile in optical link and ASE noise from spontaneous Raman scattering [9]. ASE noise from EDFA is calculated based on noise figure and output power from fiber. The optimal launch power per channel and pump power are -5.25 dBm and 0.46 W respectively. Then, we introduced two scenarios of deviation from design specification in transmission link. The first case has higher loss of fiber by +0.05 dB/km than design specification in all wavelengths, and the other case has lumped anomaly loss of 3 dB located at 30 km or 60 km. Data for PPE evaluation is generated by nonlinear transmission simulation based on SSFM. For high fidelity, step size and sampling rate are set as 0.1 km/step and 32 samples per symbols respectively. 2^{18} symbols are transmitted. AWGN noise is added to reference waveform used in PPE assuming received SNR of 26 dB. Then, 2 samples/symbols are saved for each channel. In simulation with high fidelity, nonlinear SNR is calculated and used as a reference ($SNR_{NL,ref}$). We also reoptimized the transmission link to overcome the degradation from design specification by adjusting launch power and pump power to maximize GSNR of the center channel. For the case of optical fiber link with anomaly loss, SNR_{NL} is also calculated with SSFM on the estimated power profile for reoptimization.

PPE is carried out for each channel with 75 steps for 100 km span. Then, transmission simulation with SSFM is carried out to estimate nonlinear SNR, where number of symbols and sampling rates are reduced to save time. 2^{15} symbols and sampling rate of 16 samples/symbol are chosen. In the transmission simulation, linear interpolation of noisy PPE is used without any curve fitting or smoothing.

4. Results

Figure 2 compares results of WDM transmission in designed fiber ($Fiber_D$) and higher loss fiber (+0.05dB/km). Figure 2 (a) shows exact and estimated power profiles of the center channel when received SNR is set as 26 dB. Other copropagating channels show similar results. The PPE error tends to increase as signal power attenuates in optical fiber as expected due to smaller nonlinear interference noise. The estimated power profile with higher loss fiber (orange triangular markers) deviates from that of designed fiber (black circular markers). Inset figure of Fig. 2 (a) shows fitting curves of estimated power profiles based on the physical model for a loss profile in a link with DFRA [8]. The higher loss fiber (+0.05 dB/km) shows larger slope of power loss due to larger attenuation than fiber with design specifications (sky-blue vs. red dashed lines) as well as it shows smaller power (orange vs. black markers). Thus, analyzing estimated power profile can identify degradations in transmission link. Figure 2 (b) shows estimated SNR_{NL} compared with $SNR_{NL,ref}$. SNR_{NL} estimation by SSFM based on PPE shows close match to $SNR_{NL,ref}$ with less than 0.6 dB error even though measured PPE has noisy profiles because PPE shows accurate results near peak signal power. In addition, SNR_{NL} variation across channels also shows good agreement (blue square vs. gray triangular markers). Nonlinear noise decreases or SNR_{NL} is improved in higher loss fiber compared with design specifications because of reduced signal power along the optical fiber. Figure 2 (b) shows SNR_{NL} improvement of 5.6 dB (center channel) in higher loss fiber compared with designed fiber. But GSNR degrades by 5.1 dB as shown in Fig. 2 (c) compared with that of designed fiber due to increased ASE noise caused by reduced



(a) (b) (c)

Fig. 2. (a) Exact power profiles and estimated power profiles, (b) nonlinear SNR, and (c) GSNR of designed fiber and higher loss fiber.

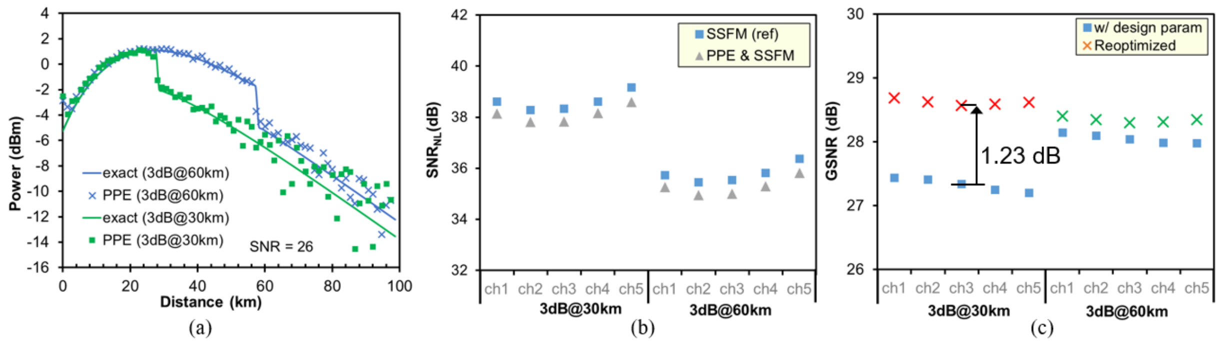


Fig. 3. (a) Exact power profiles and estimated power profiles, (b) nonlinear SNR, and (c) GSNR of in fiber links with anomaly loss.

output power from fiber as shown in Fig. 2 (a) (orange line). In this case, signal launch power and pump power can be reoptimized and GSNR can be improved significantly by 2.9 dB as shown with purple 'x' marker in Fig. 2 (c). In optimal signal transmission performance, nonlinear noise power is expected to be half of ASE noise power [10]. And we find that SNR_{NL} of center channel is slightly decreased to 34.3 dB (or increased nonlinear noise) with reoptimization compared with that of designed fiber (35.2 dB) because of increased nonlinear noise at new optimal operation point with increased ASE noise in higher loss fiber.

Figure 3 shows results of transmission over fiber link with anomaly loss of 3 dB located at 30 km or 60 km. Figure 3 (a) shows exact and estimated power profiles of the center channel when received SNR is set as 26 dB. Estimated power profile shows abrupt power drop at the location of anomaly loss as expected. Figure 3 (b) shows estimated SNR_{NL} compared with $SNR_{NL,ref}$. Again, SNR_{NL} estimation by SSFM based on PPE shows very close results to $SNR_{NL,ref}$ with less than 0.6 dB error even though measured PPE has noisy profiles. In Fig. 3 (b) with label '3dB@30km', SNR_{NL} is increased by about 3 dB compared with that of designed fiber (Fig. 2 (b) with label '$Fiber_D$') when anomaly loss is located at 30 km near the peak power in fiber link. In this case, GSNR can be improved more than 1.2 dB (red 'x' marker in Fig. 3 (c)) by reoptimizing. In other example in Fig. 3 (b) with label '3dB@60km', SNR_{NL} shows minor increase compared with that of designed fiber (Fig. 2 (b) with label '$Fiber_D$') when anomaly loss is located at 60 km where signal power is already significantly reduced compared with peak power in fiber as shown in Fig. 3 (a) (blue line). In this case, GSNR decreases compared with that of designed fiber (Fig. 2(c) '$Fiber_D$') due to increased ASE noise as shown in Fig. 3 (c) '3dB@60km'. However, GSNR cannot be improved much by reoptimizing signal launch power and pump power of forward Raman as shown with green 'x' marker in Fig. 3 (c). If the link included a distributed backward Raman amplifier, GSNR can be further improved by reoptimizing backward Raman pump power [11].

We believe PPE and nonlinear SNR estimation can help to find the imperfection of transmission link compared with design specifications. Furthermore, estimating the actual power profile and nonlinear SNR will help to reoptimize and control GSNR to adapt to degradation in the link.

4. Conclusion

We demonstrated the nonlinear SNR estimation based on PPE in WDM channel transmission over hybrid Raman-EDFA link with DFRA for the first time. The SNR estimation error based on PPE can be less than 0.6 dB in WDM transmission. We showed the benefit of using actual PPE for SNR_{NL} estimation under potential link degradation and then reoptimized the GSNR to alleviate the impact of degradation, thereby improving the transmission performance.

5. Acknowledgements

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6. References

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