Simultaneous monitoring technique for ASE and MPI noises in distributed Raman amplified systems

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Abstract: We develop a new technique for simultaneously monitoring the amplified spontaneous emission (ASE) and multi-path interference (MPI) noises in distributed Raman amplified (DRA) systems. This technique utilizes the facts that the degree-of polarization (DOP) of the MPI noise is 1/9, while the ASE noise is unpolarized. The results show that the proposed technique can accurately monitor both of these noises regardless of the bit rates, modulation formats, and optical signal-to-noise ratio (OSNR) levels of the signals.

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1. Introduction

In distributed Raman amplified (DRA) systems, the system’s performance could be limited by the multi-path interference (MPI) noise as well as the amplified spontaneous emission (ASE) noise [1]-[4]. Thus, for the proper operation of DRA systems, it would be desirable to have the capability of monitoring both of these noises. Previously, we have demonstrated that the in-band ASE noise can be monitored accurately by using the polarization-nulling technique [5]-[6]. This technique utilizes the different polarization properties of the signal and ASE noise. However, the MPI noise, which is a replica of the optical signal, has been considered as a difficult parameter to monitor. Accordingly, there have been only a few reports on the measurement technique of MPI noise [3]-[4]. The time-domain extinction method measures the MPI noise in the sampling window (where there is no signal) obtained by using a high-extinction (>90 dB) acousto-optic switch after launching a short test pulse [3]. However, this technique is not suitable for monitoring the MPI noise in a real DRA system as there can be multiple signals modulated in various formats at all times. The receiver noise analysis method estimates the MPI noise by subtracting the ASE noise density measured by using an optical spectrum analyzer (OSA) from the total noise density measured by using a homodyne receiver and an RF spectrum analyzer [4]. However, this technique can be inaccurate in a dynamic networking environment since the in-band ASE noise cannot be measured accurately by using an OSA. In this paper, we show that the polarization-nulling technique can also be used to monitor the MPI noise [7]. This is because the degree-of-polarization (DOP) of the MPI noise is 1/9 and its state-of-polarization (SOP) is identical with that of the signal in DRA systems (assuming that the MPI noise is generated mostly by double Rayleigh backscattered signals) [8]. Thus, if we nullify the signal by using the polarization-nulling technique and measure the in-band noise power, the measured value should have contributions from both the ASE and MPI noises. However, we can easily separate these contributions by using the deterministic DOP of the MPI noise (since the ASE noise is, in principle, unpolarized). For demonstration, we measure the MPI noises included in the 10-Gb/s and 40-Gb/s signals (modulated in NRZ and RZ formats) at various OSNR values in the ranges of 15 dB ~ 30 dB. In addition, we generate the MPI noise in a real DRA system and measure it as a function of the on-off gain of the Raman amplifier. The results show that we can accurately measure both the ASE and MPI noises in DRA systems regardless of the data rates and modulation formats.

2. Principle of operation

![Figure 1. Configuration of the proposed monitoring technique.](image)

Figure 1 shows the configuration of the proposed monitoring technique for both ASE and MPI noises. This configuration is identical with the setup used for the polarization-nulling method [6]. It has been previously reported that, by using this configuration, the in-band ASE noise

could be accurately measured even in the dynamic networking environment [6]. In this paper, we show that the MPI noise could also be measured by using the same configuration.

Figure 2(a) shows the spectrum of the optical signal together with ASE and MPI noises incident on the monitoring module. The spectrum of the MPI noise has an identical shape with that of the signal (since the MPI noise represents the crosstalk component generated by double Rayleigh backscattering of the signal in DRA systems [2]-[3]), whereas the spectrum of the ASE noise is flat over the entire signal’s bandwidth. We first adjust the tunable bandpass filter in Fig. 1, which has a bandwidth much narrower than the signal’s spectrum, to the center and slope of the signal’s spectrum, and measure the signal powers at two different wavelengths \((P_1, P_3)\) using a photodiode PD 1, as shown in Fig. 2(b). We then measure the noise powers \((P_2, P_4)\) after nullifying the signal by adjusting the polarization controller orthogonal to the signal’s polarization using PD 2, as shown in Fig. 2(c). However, if there is non-negligible MPI noise, the measured noise powers \((P_2, P_4)\) should have the contributions from both the ASE and MPI noises. Thus, \(P_2\) and \(P_4\) can be expressed as,

\[
P_2 = \frac{1}{2} P_{A\text{SE}} + \frac{1 - d}{2} \frac{r}{1 + r} (P_1 - P_{A\text{SE}})
\]

\[
P_4 = \frac{1}{2} P_{A\text{SE}} + \frac{1 - d}{2} \frac{r}{1 + r} (P_3 - P_{A\text{SE}})
\]

where \(P_{A\text{SE}}\) is the power of the ASE noise located within the bandwidth of the tunable optical filter, \(d\) is the DOP of the MPI noise, and \(r\) is the MPI noise level defined as the power ratio of the MPI noise to the optical signal (i.e., reciprocal of the signal-to-MPI noise ratio). In these equations, the first and second terms represent the contributions from the ASE and MPI noises, respectively. We assume that the MPI noise in DRA systems is mostly generated by double Rayleigh backscattering. In this case, the DOP of the MPI noise is determined to be 1/9 (since 5/9 of the MPI noise is co-polarized with the signal, while the rest is cross-polarized) [8]. Thus, \(P_{A\text{SE}}\) and \(r\) can be expressed as

\[
P_{A\text{SE}} = \frac{2(P_1P_4 - P_2P_3)}{P_1 - P_3 - 2P_1 + 2P_4}
\]

\[
r = \frac{1}{\frac{4}{9} \cdot \frac{P_1 - P_3}{P_2 - P_4} - 1}
\]

\[
(2)
\]
Using these equations, we can estimate the ASE noise power $P_{ASE}$ and the MPI noise level $r$ simultaneously by measuring $P_1$, $P_2$, $P_3$, and $P_4$. However, these results are based on the assumption that the MPI noise is mostly generated by double Rayleigh backscattering (i.e., the DOP of the MPI noise is 1/9). Thus, if the MPI noise is also generated by the reflection of the Rayleigh backscattered signal at the discrete optical component in the transmission link, the MPI noise level $r$ estimated by using (2) could be invalid since the DOP of the MPI noise is no longer equal to 1/9. In fact, it has been reported that the DOP of the MPI noise can be increased up to 1/3, when the reflectivity of the discrete component is larger than -25 dB (and the on-off Raman gain is 20 dB) [9]. Although it is difficult to imagine that any DRA systems could endure such large reflection, we use this extreme value of DOP for the worst case analysis. Thus, in the worst case, the factor 4/9 in the denominator of $r$ in (2) can be changed to 1/3. This represents that the maximum error in the estimated value of $r$ (caused by neglecting the effect of discrete reflection) is 1.26 dB, as long as the actual value of $r$ (caused by both double Rayleigh backscattering and discrete reflection) does not exceed -20 dB. However, this maximum error will be reduced to 0.3 dB if the reflectivity is decreased to -40 dB. Thus, considering that the typical reflectivity of the angled-physical-contact (APC) fiber connector is less than -65 dB, we believe that the accuracy of the proposed technique will not be affected by the discrete reflection in the transmission link of the DRA system.

3. Experiments and results

Figure 3 shows the experimental setup used to evaluate the performance of the proposed technique. This setup was used to adjust the ASE and MPI noise powers independently. For the evaluation, we used 10-Gb/s and 40-Gb/s signals modulated in NRZ and RZ formats (pattern length: 2^31-1). To generate the MPI noise, we tapped 90% of the modulated signal, transmitted through 1.5-km long single-mode fiber (SMF) (which was longer than the coherence length), and then sent to the MPI generator consisted of eight different noise paths (0 km ~ 7 km). Although it may be desirable to use a large number of noise paths for the accurate simulation, we implemented the MPI generator by using only eight paths as in other literatures [10]-[11]. We adjusted the polarization controllers to set the DOP of the MPI noise to be 1/9. The generated MPI noise was added to the modulated signal together with the ASE noise. The ratio between the MPI and ASE noise powers was determined by using the variable optical attenuators (VOA1 and VOA2). The 3-dB bandwidth of the tunable bandpass filter within the proposed monitoring module was 3 GHz. We measured the ASE noise power ($P_{ASE}$) and MPI noise level ($r$) by measuring the powers ($P_1$, $P_2$, $P_3$, and $P_4$) in Eq. (2), while varying $r$ from -30 dB to -15 dB and OSNR (which was defined as the power ratio between the signal and ASE noise only) from 15 dB to 30 dB. Figure 4 shows the measured OSNR errors at various MPI noise levels. The OSNR error increased slightly with OSNR due to the difficulty of accurately measuring the small noise power (when the OSNR was very high). However, regardless of the data rates, modulation formats, and MPI noise levels, the proposed
technique could measure the OSNR with accuracy better than 1 dB. On the other hand, the results in Fig. 5 show that the proposed technique could also measure the MPI noise level \( r \) accurately regardless of the data rates, modulation formats, and OSNRs. In particular, it is interesting to note that the proposed technique could accurately monitor the MPI noise level \( r \) even when the MPI noise was much smaller than the ASE noise.

![Fig. 4. Measured OSNR errors at various MPI noise levels](image)

Fig. 4. Measured OSNR errors at various MPI noise levels (a) 10-Gb/s NRZ signal, (b) 10-Gb/s RZ signal, (c) 40-Gb/s NRZ signal, (d) 40-Gb/s RZ signal. (○ \( r = -15 \) dB, ▽ \( r = -20 \) dB, △ \( r = -25 \) dB, □ \( r = -30 \) dB)
To further evaluate the performance of the proposed technique, we implemented a DRA system shown in the inset of Fig. 6. To generate large amount of MPI noise, we intentionally used the dispersion-compensating fiber (DCF) as Raman medium since it had large Raman gain efficiency and Rayleigh backscatter capture coefficient due to the small core diameter and high refractive-index difference ($\Delta n$). We transmitted 10-Gb/s NRZ signal through the Raman-pumped 16.3-km long DCF. The wavelengths of the signal and Raman pump were 1547 nm and 1445 nm, respectively. The total PMD of this DCF link was 1.4 ps. Figure 6 shows the measured MPI noise levels in comparison with the theoretically calculated curve as a function of the on-off Raman gain. In this calculation, we set the pump and signal attenuation to be 0.88 dB/km and 0.55 dB/km, respectively, and used the Rayleigh backscatter capture coefficient ($S = 0.0165$) obtained from $\Delta n$ of DCF [4]. The measured MPI noise levels agreed well with the calculated curve when the on-off gain was in the range of 12 dB ~ 22 dB. The small errors observed when the on-off gain was smaller than 12 dB were caused by the limited dynamic range of our monitoring module (i.e., it was difficult to accurately measure the extremely small noise power). When the on-off gain was higher than 22 dB, we could not measure the MPI noise level due to stimulated Brillouin scattering. Nevertheless, these results confirmed that the proposed technique could monitor both the ASE and MPI noises in real DRA systems. In principle, the monitoring accuracy of this technique could be affected by the PMD and nonlinear birefringence [6], [12]. However, it should be noted that the proposed technique could be relatively insensitive to the effect of PMD due to the extremely narrow bandwidth of the tunable filter (3-dB bandwidth: 3 GHz) used in our monitoring module [13]. Since the effect of nonlinear birefringence is negligible in typical DRA systems [14]-[15], it is not expected to seriously deteriorate the monitoring accuracy of the proposed technique.
Fig. 6. MPI noise levels measured in a real DRA system. The solid curve and symbols represent the calculated values and the measured data, respectively.

4. Summary

We have demonstrated that the polarization-nulling technique could be used to monitor the MPI noise as well as the ASE noise in DRA systems. This technique utilizes the facts that the DOP of the MPI noise (generated by double Rayleigh backscattering in DRA system) is 1/9, while the ASE noise is unpolarized. To evaluate the performance of the proposed technique, we measured the MPI noises included in the 10-Gb/s and 40-Gb/s signals (modulated in NRZ and RZ formats) at various OSNR values in the range of 15 dB ~ 30 dB. The results showed that the proposed technique could measure the MPI noise level with accuracy better than ±1 dB regardless of the data rates, modulation formats, and OSNR levels. We also confirmed that the proposed technique could accurately monitor the MPI noise in a real DRA system. In principle, the accuracy of the proposed technique could be deteriorated if the DOP of the MPI noise deviated from 1/9 due to the discrete reflection occurred in the transmission link of DRA systems. However, the maximum error in the measured MPI noise level would be less than 0.3 dB, as long as the reflectivity of the discrete optical component does not exceed -40 dB. From these results, we concluded that both the MPI and ASE noises in DRA systems could be monitored accurately by using the polarization-nulling technique.