Equivalent relationship between lumped model and distributed model of PDL based on SNR penalty*

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***Abstract*—We found the relationship for PDL value between the lumped model and the distributed model when the required OSNR penalty is equal, which greatly helps to simplify the analysis of the PDL effect.**

Keywords—polarization dependent loss, SNR penalty, lumped model, distributed model.

I. INTRODUCTION

Polarization division multiplexing (PDM) optical coherent systems with digital signal processing (DSP) are considered as a promising technology for improving data traffic in optical networks. Most of the transmission impairments, such as chromatic dispersion (CD) and polarization mode dispersion (PMD) can be easily compensated by the digital signal processing algorithm in the receiver [1,2]. Unfortunately, polarization dependent loss (PDL), which refer to polarization-dependent optical power fluctuations, cannot be well compensated in the coherent receiver. PDL causes fluctuations in signal power and polarizes amplified spontaneous emission (ASE) noise, most importantly, it causes the imbalance of signal-to-noise ratio (SNR) between the two polarizations of a PDM signal. This may lead to significant performance deterioration of the communication system.

PDL are mainly derived from EDFAs and WSSs. There are a large number of erbium-doped fiber amplifiers (EDFA) for amplifying signals and wavelength selective switches (WSS) for routing signals to specified destinations in the optical fiber transmission systems [3]. PDL from EDFAs and WSSs can cause serious impacts on the transmission performance of a communication system. It is important to understand PDL impairments and assign appropriate margins to PDL for proper system operation.

For analyzing the SNR penalty induced by PDL, there are two models available [4], lumped and distributed PDL models. The distributed model is closer to the real fiber links. However, the analysis process is complex and the time required is unacceptable. In addition, it is difficult to build distributed PDL models in the laboratory. Compared with distributed model, the lumped model has only one PDL component, the experiments of the lumped model are easier to operate when performing practical operations .However, the model itself is different from the PDL distribution of the real optical fiber link and cannot truly reflect the impact of PDL on communication systems. In this paper, we study the equivalence relations between the PDL value of the lumped model and the average PDL value of the distributed model when the required OSNR penalty is equal. This greatly helps to reduce the difficulty of verifying the SNR penalty of the fiber link. We also found that when the average PDL of the fiber link changes, we can use this equivalence relationship to quickly find the SNR penalty caused by the PDL of the changed link.

II. PRINCIPLE

A. Modeling and Formality

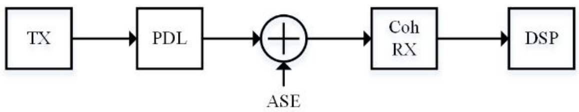

Fig.1. lumped PDL model.

As shown in Fig.1, the lumped model has only one PDL component and one amplified spontaneous emission noise source. The simplicity of the structure makes it very easy to build a lumped experimental system and understand its mechanism of effects.

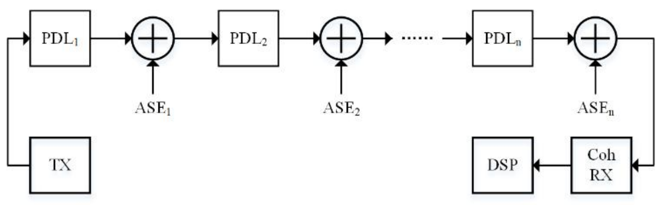

Fig.2. distributed PDL model.

The other commonly used model is the distributed model. The distributed PDL with distributed noise of the model is shown in Fig.2. The fiber link is considered as several spans, each of them contains a PDL component and an ASE noise source.

We can express the matrix of PDL components in the following form：

$$\mathbf{H}_{PDL} = \mathbf{R}_{eig}\mathbf{\Lambda}\mathbf{R}_{eig}^{-1} \tag{1}$$

The matrix $\mathbf{R}_{eig}$ is the solid SOP rotation, it should be expressed as [5]:

$$\mathbf{R}_{eig} = \begin{bmatrix} \cos\kappa e^{j\xi} & -\sin\kappa e^{j\eta} \\ \sin\kappa e^{-j\eta} & \cos\kappa e^{-j\xi} \end{bmatrix} \quad (2)$$

Where κ is the azimuth angle, ξ and η are the phase angles. The matrix of the PDL part of the component is in diagonal form as shown in (3).

$$\mathbf{\Lambda} = \begin{bmatrix} \sqrt{\frac{2\Gamma}{\Gamma+1}} & 0 \\ 0 & \sqrt{\frac{2}{\Gamma+1}} \end{bmatrix} \quad (3)$$

The parameter Γ represents the PDL value of the component, which is defined as the ratio of maximum transmitted power and minimum transmitted power through the PDL component for various possible input polarization states: $\Gamma = T_{\max} / T_{\min}$, expressed in dB as: $\Gamma_{dB} = 10\log_{10}\Gamma$.

Therefore, the channel cascade matrix experienced by the signal in the distributed model can be written as：

$$\mathbf{W}=\mathbf{H}_{PDLn} \cdots \mathbf{H}_{PDL2}\mathbf{H}_{PDL1} \quad (4)$$

The decomposition of this channel matrix with SVD can obtain the following form：

$$SVD(\mathbf{W}) = \mathbf{U}\begin{pmatrix} \sqrt{\frac{2\Gamma_{SVD}}{\Gamma_{SVD}+1}} & 0 \\ 0 & \sqrt{\frac{2}{\Gamma_{SVD}+1}} \end{pmatrix}\mathbf{V} \quad (5)$$

where $\mathbf{U}$ is the output principal modes of polarization, and $\mathbf{V}$ is the Hermite conjugation of input principal modes of polarization [6].

Hence, if the polarization ports of the transmitter and receiver are assumed to be aligned with the two principal modes of the channel, perfect polarization multiplexing can be achieved to obtain the SNR penalty on the high loss polarization tributary (the worst tributary). It should be noted that when the SNR penalty of the worst tributary is fully considered, then this penalty for both polarization tributaries is definitely sufficient. Therefore, it is more efficient and comprehensive to consider the problem from the worst tributary.

B. Theoretical SNR penalty using the lumped model

For the lumped model, after the treatment by SVD, The SNR of the worst tributary SNR_{worst} at the receiver can be found:

$$SNR_{worst} = \left(\sqrt{\frac{2}{\Gamma+1}}\right)^2 SNR_{BTB} \quad (6)$$

where SNR_{BTB} represents the initial SNR value of the system when no damage is added. Then the SNR penalty of the worst tributary can be easily obtained.

$$SNR_{penalty\_dB} = 10\log_{10}\left(SNR_{BTB}\right) - 10\log_{10}\left(SNR_{worst}\right) \quad (7)$$

$$SNR_{penalty\_dB} = 10\log_{10}\left(\frac{\Gamma+1}{2}\right) \quad (8)$$

Or Γ can be written in dB:

$$SNR_{penalty\_dB} = 10\log_{10}\left(\frac{10^{\frac{\Gamma_{dB}}{10}}+1}{2}\right) \quad (9)$$

From (9) we can see that in the theory of the lumped model, the SNR penalty induced by PDL is independent of the SNR of the back-to-back case, and is only related to the PDL value of the component.

In addition, in the distributed model, the amplified spontaneous emission noise will be affected by PDL and further degrade the system performance, it is not realistic to make a theoretical calculation. So we can only obtain the SNR penalty of the distributed model by the method of Monte Carlo simulation

III. SIMULATION AND ANALYSIS

Simulations are performed to investigate SNR penalties in PDM-QPSK coherent systems. When no damage is added, the initial SNR of the system is set to 8dB and the symbol rate is 140GBaud. For each polarization rotation in the simulation, multiple realizations of the channel are obtained by making the azimuth angle κ and the phase-dependent ξ and η values satisfy a uniform random distribution between(0,2π).

Impairments such as polarization mode dispersion and chromatic dispersion are ignored in the simulation, and the phase noise of the transmitter and the local oscillator are not considered either

In the previous derivation, although the SNR penalty of the worst tributary induced by the PDL using the lumped model is computable, a Monte Carlo simulation is performed with 10,000 channels to verify the accuracy of the results. The theoretically calculated SNR penalty versus the PDL value is plotted (solid line in Fig.3) for comparison with the simulated points. The good agreement between the theoretical results and the simulation points shown in Fig.3 is a good proof of the accuracy of the theoretical calculations.

It is worth noting that this theoretical result can be considered as an important property of the lumped model. With this property, the corresponding SNR penalty can be obtained directly for any lumped system with a given PDL value, so that any SNR penalty of the worst tributary using the lumped model is obtainable.

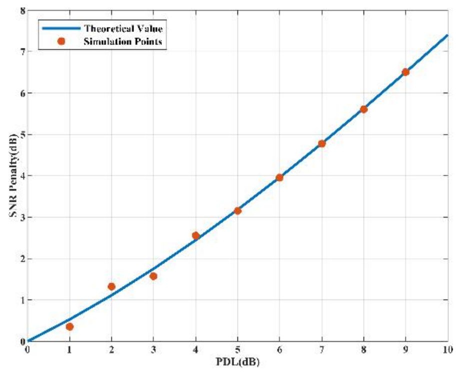

Fig.3. Comparison between the theoretically calculated SNR penalty and simulation points using the lumped model.

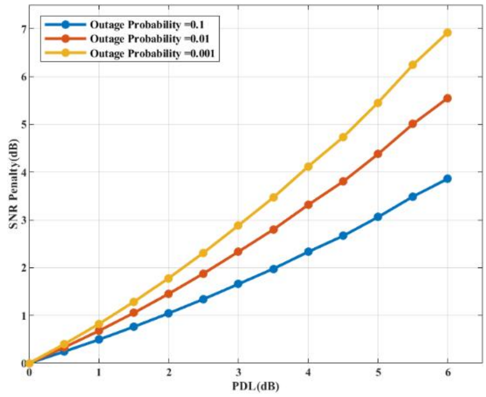

Fig.4. SNR penalty with average PDL value for the worst tributary using the distributed model.

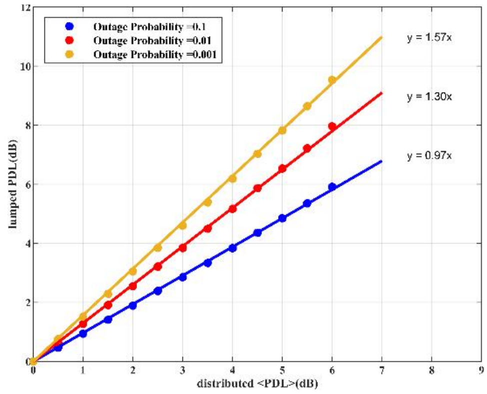

Fig.5. The equivalence relation between the PDL value of the lumped model and the average PDL value of the distributed model.

The net PDL of the link using the distributed model depends on the polarization rotation parameter chosen for each span, which is different from the lumped model, the SNR will also vary. Therefore, for statistical purposes, we perform Monte Carlo simulations using 100000 random channels at each average PDL value. When the outage probability of the system is exactly 10%, 1% and 0.1%, we record the corresponding SNR penalties and analyze them. We analyze and process a case with 20 spans. The PDL value and the ASE noise power of each span are equal so that the inaccuracy of the results caused by the interference of these factors can be avoided.

The relationship between the SNR penalty and the average PDL value using the distributed model is shown in Fig.4. The SNR penalty corresponding to different levels of outage probability is marked with a series of average PDL values (0-6 dB, with 0.5 dB interval between adjacent values) in the fiber link. In Fig.4, the SNR penalty of the worst tributary increases significantly with the increase of the average PDL value. Also the rise in the requirement for the outage probability corresponds to a rise in the SNR penalty.

The relationship between SNR penalty and PDL value using the lumped model has been obtained, and the relationship between SNR penalty and average PDL value using the distributed model as well. If the equal SNR penalty obtained using two models is used as a medium, the correspondence between the two models in terms of PDL values with the same SNR penalty can be obtained. This relationship is plotted in Fig.5. Fitting the simulation points of the same outage probability. It can be found that there is a clear linear relationship between the PDL value of the lumped model and the average PDL value of the distributed model for a constant outage probability and the smaller the outage probability, the greater the slope of the corresponding linear, which is considered as a good result.

After getting this relation, when conducting an experiment, it is only necessary to specify the average PDL value of the distributed system which needs to be equated and the required outage probability so that the PDL value of the corresponding equivalent lumped system can be given directly. Then we just need to experiment with a simple lumped system to indirectly accomplish the purpose of exploring the SNR penalty of a real optical fiber link. Besides, when the distribution of fiber links does not vary much and the average PDL value varies, we can find the corresponding PDL value of the lumped model by the relationship and then calculate the corresponding SNR penalty directly, which can be considered as a convenient way to find the SNR penalty.

IV. Summary

In this paper, based on singular value decomposition (SVD), we theoretically derived the relationship between the PDL value and SNR penalty of the worst tributary in the lumped model and verified the calculated results by Monte Carlo simulation. Then for the distributed model, the SNR penalty of the worst tributary induced by PDL for different outage probabilities is explored. Finally, the equal SNR penalties of the two models are used as a medium, and we found that PDL value of the lumped model show a linear relationship with the average PDL value of the distributed model, thus we can use a simple lumped experimental system instead of a complex distributed experimental system to explore the SNR penalties in the real fiber links. Also, using this relationship, we can accomplish a faster calculation of the SNR penalty for fiber links with different average PDL values.

Acknowledgment

This work is supported by the National Natural Science Foundation of China (62101062, 62071065).

References

[1] J. N. Damask. Polarization Optics in Telecommunications [M]. Springer, 2005.

[2] E. Matarazzo and M. Mayrock, "Capacity loss due to polarization effects in coherent optical systems," 36th European Conference and Exhibition on Optical Communication, Turin, Italy, 2010, pp. 1-3, doi: 10.1109/ECOC.2010.5621409.

[3] X K. Benyahya et al., "Analysis of Impact of Polarization Dependent Loss in Point to Multi-Point Subsea Communication Systems," 2022 Optical Fiber Communications Conference and Exhibition, San Diego, CA, USA, 2022, pp. 1-3.

[4] C. Xie, "Polarization-dependent loss induced penalties in PDM-QPSK coherent optical communication systems," 2010 Conference on Optical Fiber Communication, collocated National Fiber Optic Engineers Conference, San Diego, CA, USA, 2010, pp. 1-3.

[5] Nan Cui, Xiaoguang Zhang, Zibo Zheng, Hengying Xu, Wenbo Zhang, Xianfeng Tang, "Two-parameter-SOP and three-parameter-RSOP fiber channels: problem and solution for polarization demultiplexing using Stokes space," Optics Express, vol. 26, no. 16, 2018, pp. 21170-21183.

[6] Dumenil, A. , E. Awwad , and C. Measson . "PDL in Optical Links: a Model Analysis and a Demonstration of a PDL-Resilient Modulation." Journal of Lightwave Technology PP.99(2020):1-1.