Experimental Demonstration of PDL Penalty Reduction by Wavelength-Interleaving Transmission

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Abstract The validity of wavelength-interleaving (WI) transmission is demonstrated experimentally for reduction of PDL-induced penalty by the method of extreme value statistics. We confirm that WI technique between 2 channels can effectively reduce Q-penalty or outage probability induced by PDL.

Introduction

The use of polarization-division-multiplexing (PDM) transmission is one effective way of meeting the growing demand for optical link systems with increased spectral efficiency. The PDM optical signals, however, are more sensitive to the degradation due to polarization mode dispersion (PMD) and polarization dependent loss (PDL), than the single-polarized signals1. Digital equalization after coherent detection can enhance the tolerance of the impairment caused by PMD2. On the other hand, PDL causes temporal power fluctuation in each optical PDM-channel, which cannot be equalized in the receiver. As a result, PDL degrades system performance significantly3.

The n-wavelength-interleaving (n-WI) technique was originally proposed in [4] as a way to reduce the net burst error length in the optical links with PMD. Assuming the worst case, optical signals split into the two principal state of polarization, they evaluated the effect of the WI technique theoretically. They found that WI technique can enhance the performance of the forward error correction (FEC) by interspersing the bit errors in different wavelength channels. While their main conclusion is that the system performance with FEC can be improved on average by this technique, we emphasize here the ability of WI transmission to reduce the penalty or outage probability caused by PDL even under the condition without FEC.

In this paper, we experimentally demonstrate WI technique to improve the robustness to PDL-induced impairments by the statistical approach for the first time.

n-Wavelength-Interleaving Transmission

Fig. 1 illustrates n-WI transmission system (n=2 in this case) to explain the principle of n-WI technique: in the transmitter, given blocks (e.g. bits, bytes or frames) are interleaved between n channels. Hereafter, we distinguish the parameter related with i-th “original” channel by subscript i and that with interleaved channel by subscript int. Note that we mean that “original” channel is the one which is not applied WI technique yet in this context. Owing to existence of differential group delay (DGD), PDL values between n channels are statistically uncorrelated, if central frequencies of the channels are sufficiently separated5. Accordingly, signal degradations due to PDL are statistically independent between these original channels. Interleaved blocks are de-interleaved after demodulation at the receiver. Consequently, the data of one channel is transmitted over n wavelength. Thus, bit error ratio (BER) of the interleaved channel is equivalently given by

\[ \text{BERnt} = \frac{\sum \text{BERi}}{n} \]

Such averaging is expected to make the variance of the probability density functions (PDF) of BER (or Q-factor) smaller, which reduces outage probability. This “thinning effect” is confirmed later (Fig. 3(c)).

Experimental Setup and Results

To test the validity of WI transmission, we perform an experiment using DGD- and PDL-emulators as shown Fig. 2.

Continuous wave light of λ1 (1550.12nm) and λ2 (1547.72nm) are modulated by 2^11-1 PRBS pattern with a 32 GHz clock to create 128G bps PDM-QPSK optical signals. Note that two
channels are separated by 300 GHz and modulated by the same optical modulator. Optical signals enter the DGD-PDL-emulated link consisting of 9 sections, each of which has a 1km single mode fiber (SMF), a PDL-emulator, and a polarization-maintaining fiber (which works as DGD-emulator). Each DGD- and PDL-emulator has DGD of ~10ps and PDL of ~1dB, respectively. To increase the speed of exploration of DGD and PDL, 1km SMFs are set in an isothermal chamber whose temperature randomly fluctuates between 10 to 50 °C. Before entering optical front-end, optical signals are added with ASE noise to become OSNR=17dB (0.1nm resolution). Optical signals are detected by balanced Photodiode at the same time for both channels. After analog-to-digital conversion, the signals are demodulated by an offline program to calculate BER and Q-factor of ch1 and ch2.

We record the Q-factor sequence of both channels every minute for 5.7 hours (accordingly, the total number of datasets is 340). Fig. 3 shows the temporal change of Q-factor for both channels. After analog-to-digital conversion, the signals are demodulated by an offline program to calculate BER and Q-factor of ch1 and ch2. Fluctuations of Q-factor can be explained by the change of PDL itself and the relative angle between the state of polarization of optical signals and PDL-axes. Scatter plot between Q1 and Q2 are plotted in Fig. 3(b), which indicates that Q1 and Q2 are statistically uncorrelated: the calculated correlated coefficient is 0.102. Fig. 3(c) presents the PDF of Q1, Q2, and Qint. It is noteworthy that the variance of Qint becomes smaller than that of Q1 and Q2. Q1, Q2, and Qint have calculated variances of 0.092, 0.090 and 0.052 respectively.

Analysis by Extreme Value Statistics

In order to assess outage probability asymptotically using the datasets obtained in the above experiment, we apply extreme value statistics (EVS). EVS is usually used to model the extremely rare events, such as an earthquake or heavy rain. It is reported both experimentally and theoretically in [6] that the probability of the logarithm of BER in the optical link with PMD follows a Gumbel distribution based on EVS. Thus, in our analysis too, the application of EVS may reveal the validity of WI transmission more quantitatively.

We here use the peaks over threshold approach found in EVS literature. Note that EVS is designed for estimating maxima given a large number of data points; our analysis should deal with -Q (i.e. -1 is multiplied to Q-factor) as stochastic variables in order to estimate minimum Q-factor.

Let the obtained Q-factor sequence be an identically and independently random variables. If we set $X=-Q-u$ for given threshold $u$, EVS gives the conditional probability $H(x)=Pr\{x>X \mid X>0\}$. $H(x)$ is the probability that $X$ does not exceed $x$ given that $X>0$.

![Fig. 3: (a) Temporal change of observed Q-factor of ch1 and ch2. (b) Scatter plot of Q-factor between 2 channels. (c) Probability density of ch1, ch2, and interleaved channel as a function of Q-factor.](image)

![Fig. 4: Cumulative probabilities from experimental data (symbols) and fitted $H(x)$ drawn by Eq.(1) with estimated parameters (solid curves) for ch1 (a), ch2 (b), and interleaved channel (c).](image)
exceed $x$ under the condition of $X > 0$, i.e., $-Q > u$, which is referred as the generalized Pareto distribution. Cumulative probability $H(x)$ has the explicit form of

$$H(x) = 1 - \left(1 + \frac{\xi x}{\sigma}\right)^{-1/\xi}$$

(1)

where $\sigma$ and $\xi$ are the scale parameter and the shape parameter, respectively.

We use maxima likelihood method to estimate $\sigma$ and $\xi$. Since there may still be uncertainty in setting appropriate threshold level $u$, we determine it by using the mean excess function which is a familiar EVS technique (see [7] for more information). Fitted $H(x)$ and the cumulative probabilities calculated from the experiment data are plotted in Fig. 4; they show excellent agreement. The estimated parameters are summarized in Tab. 1.

We can now estimate minimum Q-factor within $m$-observations given the above experimental system, which is expressed as $Q_m$ below. From Eq. (1), $Q_m$ is approximated with estimated parameters after simple algebraic transformation as

$$Q_m = -u - \frac{\sigma}{\xi} \left(\frac{m^k}{N} - 1\right)$$

(2)

where $N$ and $k$ are the number of total experimental data and the number of data exceeding threshold $u$, respectively. Based on Eq. (2) and estimated parameters, we can know

expected minimum Q-factor $Q_m$ for given $m$: for example, if we observe Q-factor $m=10^6$ times for ch1 in this system, it is expected that we will, on average, witness the minimum Q-factor $Q_m$ of $\sim 8.0$ once. It can be also interpreted that this example corresponds to the link system in which designed Q-limit is $8.0$ and outage probability is $10^{-8}$, because outage probability is given by $1/m$.

From this viewpoint of system design, we can draw Q-limit curve as a function of outage probability in Fig. 5, which reveals the reduction effect of WI transmission for PDL-induced Q-penalty or outage probability, like following two scenarios: (1) For a fixed outage probability of $10^{-6}$, Q-limit can be mitigated from $\sim 8.1$ to $\sim 8.6$ dB, which can also be explained as Q-penalty can be improved by 0.5dB. (2) For a fixed Q-limit of $8.5$dB, outage probability can be decreased from $10^{-5}$ to $10^{-6}$. It should be noted that Q-limit generally depends on which FEC code is applied and what corrected BER is required for the system and that outage probability generally depends on the required reliability of the system.

Even though the above analysis considered only the case of 2 channels, it is reasonable to expect that WI transmission across $n$ channels ($n>2$) will decrease PDL-induced impairments more effectively.

**Conclusions**

Subjecting measured results to EVS analysis successfully demonstrated that WI transmission can decrease the Q-penalty or outage probability caused by PDL. We believe that n-WI transmission has the ability to shrink PDL-induced impairments drastically.

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**Tab. 1: Estimated parameters for ch1, ch2, and interleaved channel.**

|        | ch1    | ch2    | ch int |
|--------|--------|--------|--------|
| $u$ (threshold) | -9.5   | -9.5   | -9.5   |
| $\sigma$ (scale)  | 0.31   | 0.30   | 0.24   |
| $\xi$ (shape)     | -0.20  | -0.19  | -0.24  |

**Fig. 5: Estimated Q-limit from Eq. (2) as a function of outage probability for ch1, ch2 and interleaved channel.**