Evaluation of Outage Probability of Optical Communication System Impaired by Polarization Effects*

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Abstract: Using multiple importance sampling technique, the power penalty and outage probability of 10Gbit/s lightwave transmission system impaired by polarization-mode dispersion (PMD) and polarization-dependent loss (PDL) were investigated. The simulation results show that optical filter has significant influence on the power penalty, and the system with Fabry-Perot filter always performs better than that with four-order Gaussian filter. It is also found that the power penalty generally increases with the increasing of chirp factor, but the system performs best when chirp factor is about 0.5. It also demonstrated that DPSK is still more robust to PMD and PDL than OOK even though PMD and PDL coexist.

Key words: Optical fiber communication; Polarization-mode dispersion; Polarization-dependent loss; Multiple importance sampling
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0 Introduction

It is known that polarization-mode dispersion (PMD) and polarization-dependent loss (PDL) have become two critical limiting factors in modern long distance optical communication system at bit rates of 10Gbit/s and beyond[1]. The power penalty induced by PMD and PDL has become critical issues in optical fiber system design and certification. Past studies mainly focus on the dependence of lightwave communication system′s performance degradation on the values of PMD and PDL. However, it is difficult to exactly evaluate the performance degradation caused by PMD and PDL because they are stochastic in real fiber link[2]. In addition, a few works demonstrate that other factors have a significant impact on the system performance, such as optical filter, pulse initial chirp, modulation format, and so on[3-6]. It has been reported that narrow bandwidth optical filter can reduce pulse distortions that result from higher order PMD[3], and that π/2-DPSK outperforms conventional DPSK in the presence of strong optical filtering and PMD[4]. It has been found that power penalties due to the combined effect of PMD and PDL are significantly increased when frequency-chirped optical sources are used[5]. Recent studies show that strongly filtered π/2-DPSK is better immune against PMD compared with conventional DPSK, and DPSK has certain advantages over the traditional on-off keying (OOK)[6-7]. All these results show that the other factors should be taken into account when the power penalty induced by PMD and PDL is evaluated. In this paper, the power penalty and outage probability of 10Git/s optical communication system with PMD and PDL are exactly simulated by using multiple importance sampling technique (MIS), which can visit effectively the rare events of larger PMD and/or larger PDL through configuration biasing.

1 System model and simulation principle

Generally, a waveplate model is used to simulate the effects of PMD and PDL. The optical fiber link can be treated as a concatenation of N linear birefringence fiber sections, followed by one PDL element after each of them. A random model coupling occurs between every two adjacent sections. Although the PMD and PDL are random and obey Maxwellian distribution in real fiber link [2], the waveplate model can exactly simulate them if enough sections are applied. The Jones matrix of the fiber can be written as [8]

$$J_N(\omega)=\prod_{n=1}^{N} J_{nL} P_n(\omega) S_n \tag{1}$$

$$J_{nL}=\exp\,(\vec{\alpha}_n\cdot\vec{\sigma}/2) \tag{2}$$

$$P_n(\omega)=\exp\,(-\mathrm{i}\omega\vec{\tau}_n\cdot\vec{\sigma}/2)=\begin{pmatrix}\exp\,(-\mathrm{i}\omega\tau_n/2) & 0\\ 0 & \exp\,(\mathrm{i}\omega\tau_n/2)\end{pmatrix} \tag{3}$$

where J_{nL} and $P_n(\omega)$ model respectively the PDL and PMD effects of the n-th section, S_n models the random model coupling between the n-th section

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and the $(n+1)$-th section. ω represents the frequency difference between the general frequency and the optical carrier frequency, $\vec{\alpha}_n$ denotes the n-th PDL vector, $\vec{\tau}_n$ denotes the PDM vector, $\vec{\sigma}$ is the Pauli matrices vector.

To evaluate the performance of 10Gbit/s OOK and DPSK systems degraded by the PMD and PDL, as shown as Fig. 1, the impacts from pulse chirp, optical filter and modulation format are also taken into account . The DPSK or OOK signals

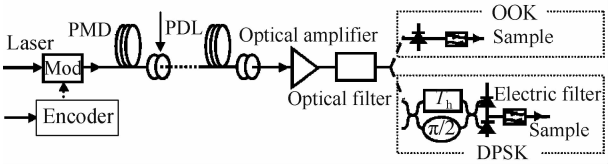


Fig. 1 Schematics of OOK or DPSK systems impaired by the PMD and PDL. Mod: modulator

generated by the modulator are launched into the optical link, through which the signals will be impaired by the PMD and/or PDL. The transmitted optical signals will be amplified by the optical amplifier and filtered by different optical filters. To recover the information bits, two different receivers are separately applied for DPSK and OOK modulations. In order to assess the influence of pulse chip, a chirped cosine pulse with 50% duty cycle are used.

$$p(t)=\sqrt{2E_b/T_b}\cos\left(\pi/2\cos\left(\pi t/T_b\right)\right)e^{jk\pi\cos(2\pi t/T_b)} \quad (4)$$

Here, T_b is the bit period, E_b denotes the optical energy per bit, k is the chirp factor. The light field at the optical fiber input can be written as

$$|E_i(t)\rangle=\sum_n I_n p(t-nT_b)\,|P_i\rangle \quad (5)$$

where $|P_i\rangle$ is the input polarization state, I_n represents the transmitted symbol sequences (For OOK, $I_n=1, 0$; for DPSK, $I_n=e^{j\Phi_n}$, and Φ_n-$\Phi_{n-1}=\pi$, 0 for bit 1, 0.), which is chosen as a $2^{10}-1$ pseudorandom bit sequence in following simulations.

The input field of optical filter is written as

$$|E_{out}(\omega)\rangle=J_N(\omega)\,|E_i(\omega)\rangle+|n_{ASE}(\omega)\rangle \quad (6)$$

where $|E_i(\omega)\rangle$ is the Fourier transform of the $|E_i(t)\rangle$, $|n_{ASE}(\omega)\rangle$ is frequency spectrum of the ASE noise. In order to investigate the influence of optical filter on the system performance, the Gaussian (Fourth-order) and Fabry-Perot filters are used [9].

$$H_{F-G}(f)=\exp\left(-[f/(0.65B_0)]^4\right) \quad (7)$$

$$H_{F-P}(f)=\frac{1}{1+j2f/B_0} \quad (8)$$

where B_0 is the 3 dB bandwidth, f is the frequency.

At the receiver, a direct detection is implemented for OOK and a balanced direct detection receiver with delay-line interferometer is used for DPSK[10]. The detected electric signal is filtered by a low-pass filter, which is assumed to be a fifth-order Bessel type. To accurately calculate the bit error rate (BER), the following formula is employed.

$$\mathrm{BER}=\sum_{j,k=0}^{1}p_{j1k}\,\mathrm{erfc}\left(\frac{|\langle I_{j1k}\rangle-I_D|}{\sigma_{j1k}}\right)+\sum_{j,k=0}^{1}p_{j0k}\,\mathrm{erfc}\left(\frac{|\langle I_{j0k}\rangle-I_D|}{\sigma_{j0k}}\right) \quad (9)$$

where, $\langle I_{j1k}\rangle$, σ_{j1k} (or $\langle I_{j0k}\rangle$, σ_{j0k}) are the mean value and standard deviation of the electric level at the sampling time for $j1k$ ($j0k$) data pattern, p_{j1k} (p_{j0k}) is the relative probability of each pattern, I_D is the decision level, erfc is the complementary error function.

2 Simulation results and discusses

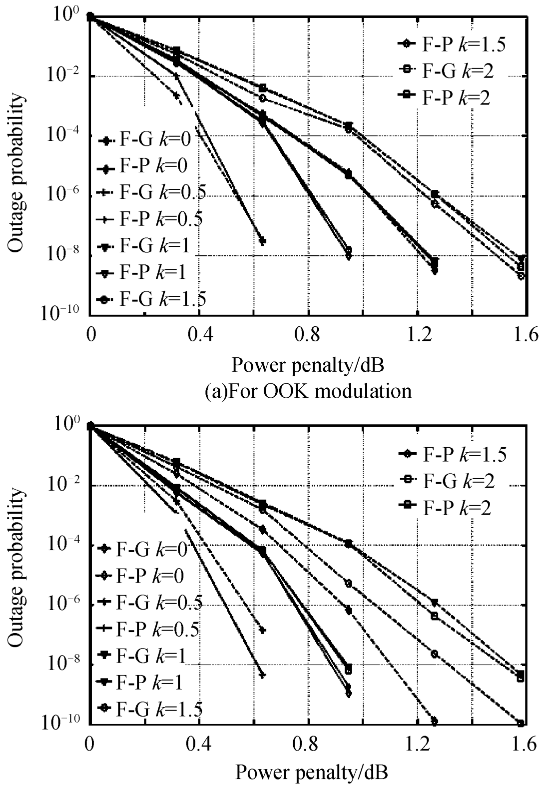
To quantify the performance degradation of 10Gbit/s system induced by the PMD and the PDL, some system parameters are optimized in the absence of the PMD, the PDL and pulse chirp. The optimized bandwidths of the filters are shown as Table 1, in which all the bandwidths have been chosen to minimize the BER to be 10^{-12}. These parameters also are used to evaluate the BER in presence of the PMD and PDL since the optical devices are fixed in the real fiber link.

Table 1 Optimized bandwidths of optical filters and electrical filters (normalized to the bit rate *R*)

F-G	OOK	2.3	0.95
F-G	DPSK	2.2	0.95
F-P	OOK	2.3	0.75
F-P	DPSK	2.2	0.65

From the views of statistics, the occurrence possibility of large power penalty increases with that of large PMD and PDL, it is necessary to get more frequent visit the rare large PMD and PDL. These rare events can be captured effectively by MIS technique if a set of rotation angles are chosen deliberately[11]. In order to effectively capture the events with occurrence probability lower than 10^{-8}, several biasing configuration of (α, β) are chosen to generate the distribution with 10^4 samples each as follows: $(1,0)$, $(1,\pi/3)$, $(1,\pi/2)$, $(1,\pi)$, $(2,0)$, $(2,\pi/3)$, $(2,\pi/2)$, $(2,\pi)$, $(3,0)$, $(3,\pi/3)$, $(3,\pi/2)$, $(3,\pi)$.

Fig. 2 shows the outage probability as a function of the power penalty margin when the PMD= 10ps and no existence of the PDL. The outage probability at a power penalty margin is the



(a)For OOK modulation

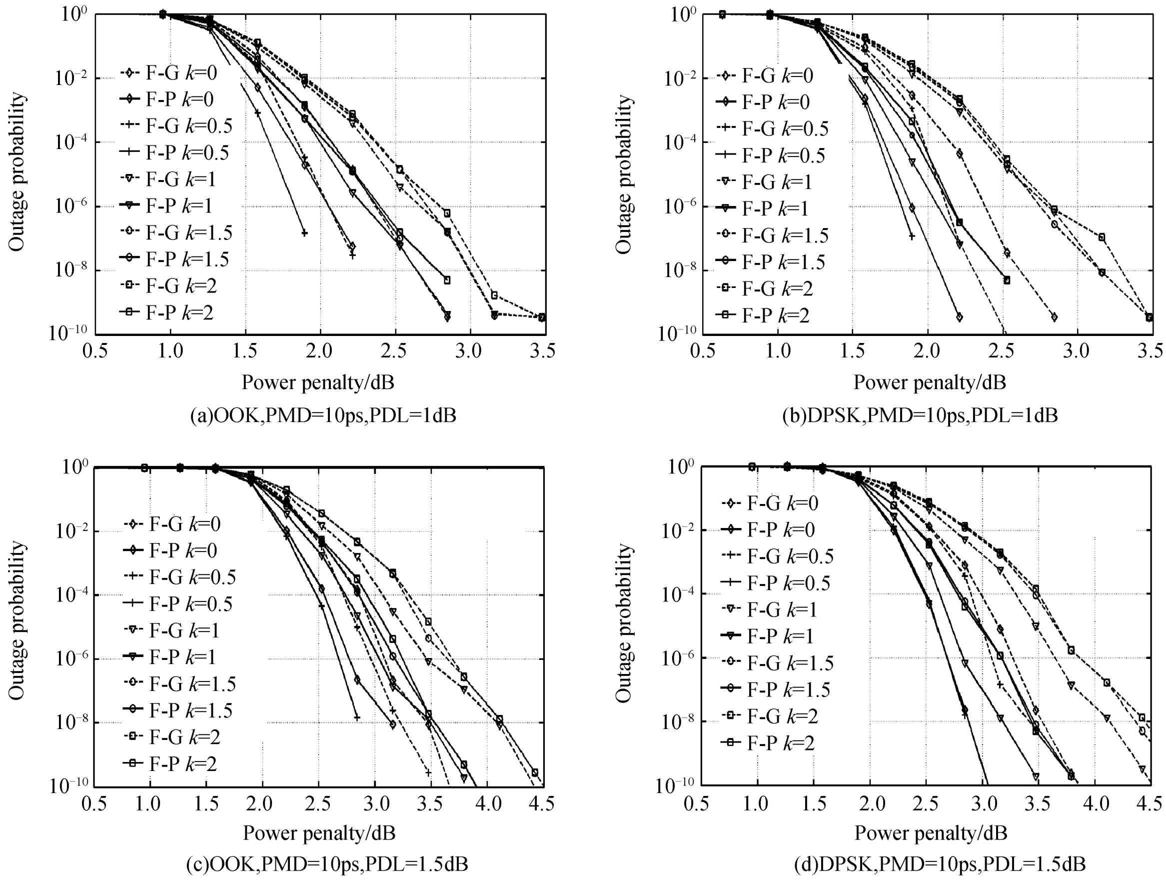
(b)For DPSK modulation

(F-P: Fabry-Perot filter, F-G: four-order Gaussian filter)

Fig. 2　The system outage probability against the power penalty margin in presence of pure PMD=10 ps

cumulative probability of the events with power penalty more than the margin. It is shown that the optical filter remarkably affects the system performance, and the system with Fabry-Perot optical filter outperforms that with four-order Gaussian optical filter regardless of the pulse chirp. To guarantee the outage probability less than 10^{-6}, the required power penalty margins of OOK and DPSK systems are less than 1 dB if Fabry-Perot filter is used, and the required power penalty margins are all small (< 1.3 dB) regardless of the optical filter type and chirp factor. Although the two systems perform best at chirp factor $k=0.5$, higher chirp will not always causes higher power penalty. Compared the Fig. 2 (a) with Fig. 2(b), it can be found that the system performance with DPSK modulation is always better than with OOK modulation. For example, to guarantee the outage probability less than 10^{-6}, if Fabry-Perot filter is chosen, the required power penalty margins of the DPSK are about 0.05, 0.1, 0.25, 0.04, 0.22 dB less than the OOK when the chirp changes from 0 to 2.

Fig. 3 shows that OOK and DPSK systems also exhibit the best performance when chirp factor



(a)OOK,PMD=10ps,PDL=1dB

(b)DPSK,PMD=10ps,PDL=1dB

(c)OOK,PMD=10ps,PDL=1.5dB

(d)DPSK,PMD=10ps,PDL=1.5dB

F-P: Fabry-Perot filter, F-G: Four-order Gaussian filter

Fig. 3　The system outage probability against the power penalty margin

$k=0.5$, same as the case that only pure PMD exists, regardless of the filter type and the PDL. It is obvious that the optical filter has a significant influence on the system performance, and the system with Fabry-Perot filter always performs better than that with four-order Gaussian filter. However, with the increasing of pulse chirp, the advantage of Fabry-Perot filter will disappear. When the other conditions are same, DPSK system has better performance than OOK system if the chirp factor is small ($k<1$), and they will have equivalent performance with the increasing of pulse chip. Fig. 2 and Fig. 3 indicate that the PDL gives a strong effect on the system performance and enhances the performance degradation caused by the chirp. Fig. 3 shows that, to guarantee the outage probability less than 10^{-6}, if no chirp exists, the required power penalty margins are about 2.1 dB and 1.65 dB respectively for OOK and DPSK systems with Fabry-Perot filter when PMD=10 ps and PDL=1 dB, and are both about 2.4 dB for that with Gaussian filter; OOK and DPSK systems with Fabry-Perot filter both require power penalty margins of 2.6 dB when PMD=10 ps and PDL=1.5 dB, and the required power margin will exceed 3 dB if Gaussian filter is used.

3 Conclusion

Using the MIS technique, we investigate the outage probabilities of 10Gbit/s OOK and DPSK system when PMD = 10ps. It is found that DPSK modulation always performs better than OOK although this advantage will fade away with the increasing of pulse chirp. The optical filter can remarkably affect the system performance, and generally the systems with Fabry-Perot filter have better performance than that with Gaussian filter. In addition, the simulation results indicate the PDL can enhance the system degradation caused by pulse chirp.

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偏振效应损伤的光通信系统失效概率估算

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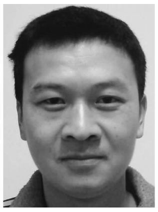
摘　要：采用多重重要抽样方法，研究了受偏振模式色散和偏振相关损耗损伤的 10 Gbit/s 光通信系统的功率代价和失效概率. 仿真结果表明，光滤波器对功率代价有重要影响. 采用法布里-珀罗滤波器的系统比采用四阶高斯型滤波器的系统有更好的性能表现；发现功率代价通常随着啁啾因子的增大而增大，但当啁啾因子为 0.5 左右时，系统性能达到最好. 仿真结果也表明，即使偏振模式色散和偏振相关损耗同时存在，DPSK 系统比 OOK 系统有更强的 PMD 和 PDL 耐受性.

关键词：光纤通信；偏振模式色散；偏振相关损耗；多重重要抽样法



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