Dispersion Compensation and Dispersion Tolerance of Optical 40 Gbit/s DBPSK, DQPSK, and 8-DPSK Transmission Systems with RZ and NRZ Impulse Shaping

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Abstract

In this paper we investigate and compare dispersion tolerance and dispersion compensation schemes for differential binary phase-shift keying, differential quadrature phase-shift keying, and differential 8-level phase-shift keying. 40 Gbit/s transmission systems with one and three spans of either standard single-mode fiber or nonzero dispersion-shifted fiber are considered. Both nonreturn-to-zero and return-to-zero impulse shaping are taken into account.

1 Introduction

Dispersion together with nonlinear fiber effects are a major source of signal distortion in optical fiber transmission systems [1]. Hence, dispersion tolerance and dispersion compensation schemes for optical transmission systems using intensity modulation (IM) have been studied extensively in the past [2]. Recently, transmission systems using differential binary phase-shift keying (DBPSK) [3], differential quadrature phase-shift keying (DQPSK) [4] and differential eight-level phase-shift keying (8-DPSK) [5] are being considered for reasons such as improved receiver sensitivity, increased tolerance to nonlinear fiber effects, and higher spectral efficiency. For these phase modulation schemes we investigate dispersion tolerance and dispersion compensation schemes, using computer simulations evaluating eye-opening penalties (EOP). We study nonreturn-to-zero (NRZ) as well as return-to-zero (RZ) impulse shaping at bit rate $R_b = 40\,\mathrm{Gbit/s}$. We consider both standard single-mode fiber (SSMF) and nonzero-dispersion-shifted fiber (NZDSF).

System models will be presented in section 2. Section 3 gives simulation results for the different systems using SSMF and NZDSF.

2 System models

2.1 8-DPSK receiver with multilevel electrical signals

In contrast to the 8-DPSK receiver from [5] with three optical delay & add filters, electrical analog signal processing and *binary* electrical signals, we present and investigate the new 8-DPSK receiver shown in **Figure 1**. It consists of only two branches with one delay & add filter (DAF) and one balanced detector each, thus reducing hardware effort by $1/3$ compared to the receicer from [5]. However, electrical signals at the receiver are *multilevel*.

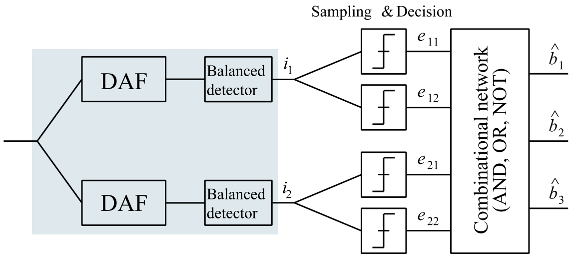

Figure 1: 8-DPSK receiver with multilevel electrical signals

The gray shaded part of the 8-DPSK receiver is the same as a DQPSK receiver. Its electrical output signals i_1 and i_2 are multilevel in the 8-DPSK case. A typical 8-DPSK eye-diagram is shown in **Figure 2**.

As can be seen from Figure 2, the electrical signal has five levels. The upper two and lower two levels represent the same logical level. Thus, there is one upper and one lower eye-opening as marked in the figure. The thresholds of the four binary decision devices lie in the middles of these eye-openings. The transmitted bit sequences are determined from the binary decision device outputs e_{11} through e_{22} with a combinational network. The functions of the combinational network are:

$$\begin{aligned} \hat{b}_1 &= \bar{e}_{12}\bar{e}_{21} + e_{11}e_{22}, \\ \hat{b}_2 &= e_{12}e_{21} + \bar{e}_{11}\bar{e}_{22}, \\ \hat{b}_3 &= e_{21} + \bar{e}_{11}e_{22}. \end{aligned} \tag{1}$$

Table 1 compares the properties of the binary receiver from [5] and the multilevel receiver. The binary receiver is not considered further in this paper, because in addition to

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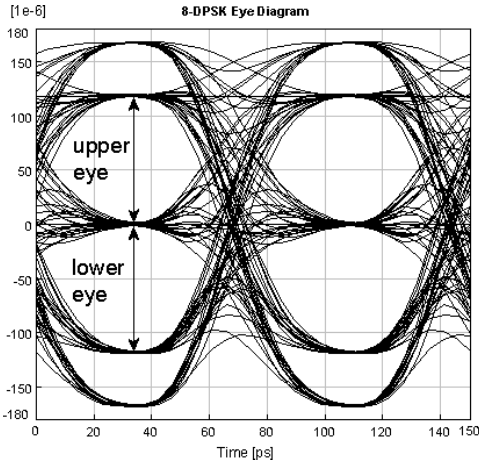


Figure 2: 8-DPSK multilevel eye-diagram

the greater hardware effort, the nonlinear signal processing for obtaining binary signals leads to a much greater susceptibility to distortion caused by dispersion and fiber nonlinearities [6].

2.2 Transmission systems

The three systems to be investigated are shown in **Figure 3**. The first one in Figure 3(a) consists of two dispersion-compensating fibers (DCF) for pre- and postcompensation and one transmission fiber (TF). The second system in Figure 3(b) again employs two DCF for compact dispersion compensation after the transmitter (Tx) and before the receiver (Rx) and three uncompensated TF spans. The third system in Figure 3(c) with three TF spans uses distributed dispersion compensation. Each of the first two TF spans is fully compensated by the associated DCF. The DCF after Tx and before Rx Figure 3(c) compensate for the dispersion of the third TF span. Rx and Tx operate with DBPSK and DQPSK, respectively. TF is either SSMF or NZDSF. Fiber parameters are given in **Table 2**. The length of each TF is 80 km. The values of the DCF dispersion slope are chosen in order to achieve full slope compensation for both TF types. DCF lengths are selected in order to achieve a fixed amount of residual dispersion r_d and precompensation p (setups Figure 3(a) and Figure 3(b) as well as first and last DCF in setup Figure 3(c)) or to fully compensate the TF dispersion (second and third DCF in setup Figure 3(c)). Precompensation p is the ratio of the length of the DCF after Tx to the sum of the lengths of the DCF after Tx and before Rx. DCF input power is $P_{DCF} = -2\mathrm{dBm}$, TF input power is equal for each span within a system and given below.

RZ impulse shaping is done by modulation of the respective optical NRZ signal in a subsequent Mach-Zehnder modulator (MZM) with a sequence of electrical Gaussian impulses. The full width at half maximum (FWHM) of the Gaussian impulses is $0.5 \cdot T$, where $T = 1/R_s$ is the symbol duration and R_s the symbol rate.

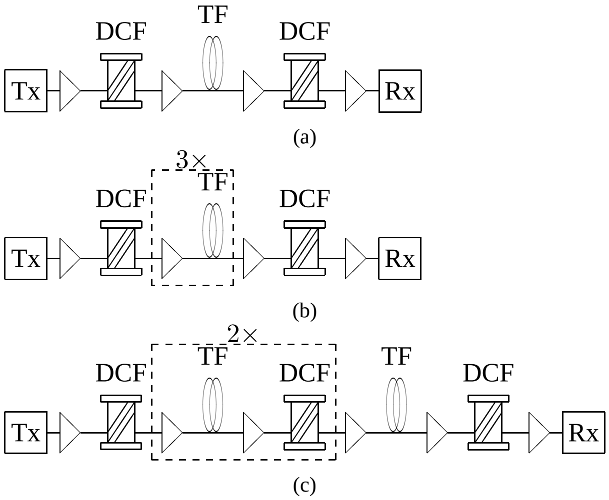


Figure 3: System setups: (a) Single-span, (b) 3 spans with compact dispersion compensation, and (c) 3 spans with distributed dispersion compensation

3 Simulation results

3.1 Single span transmission

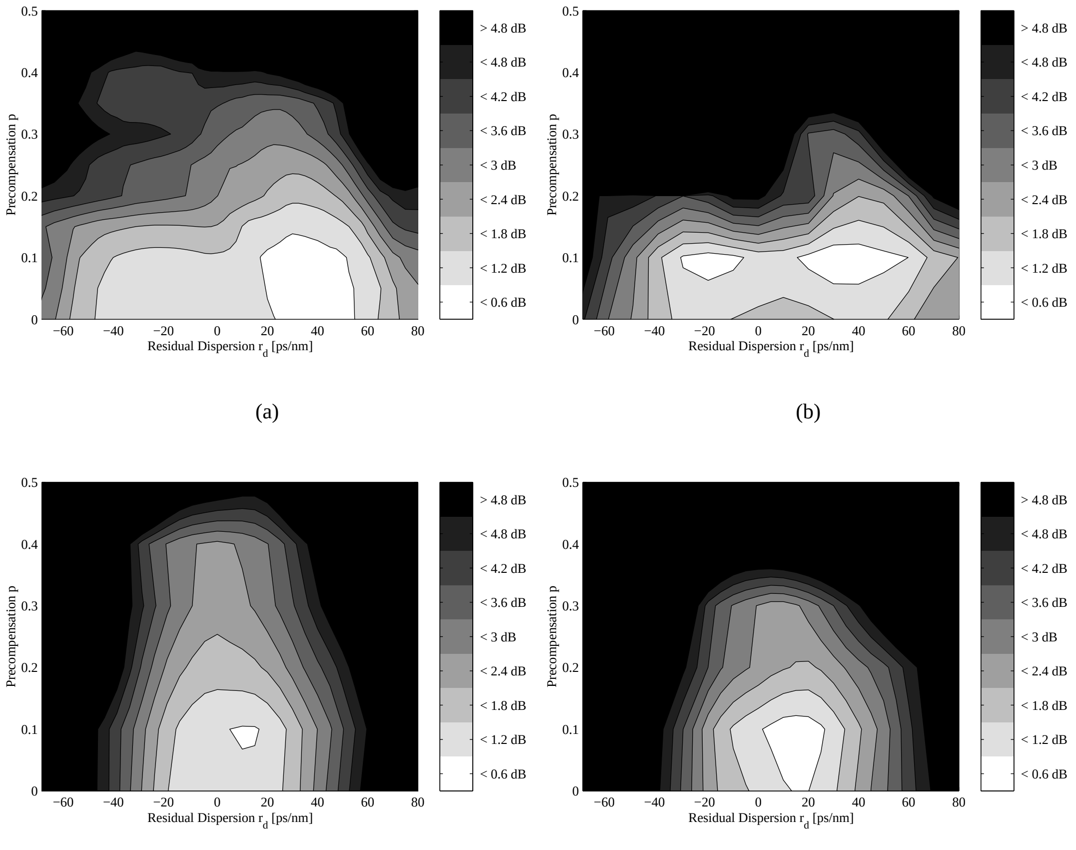
We first investigate single span transmission over SSMF and NZDSF accordding to Figure 3(a). **Figures 4-6** show EOP vs. residual dispersion r_d and precompensation p in contour diagrams for DBPSK, DQPSK, and 8-DPSK, respectively, with NRZ (upper to subfigures) and RZ impulse shaping (lower two subfigures) and SSMF (left two subfigures) and NZDSF (right two subfigures) for 15 dBm TF input power. Combinations of residual dispersion and precompensation leading to minimum EOP are listed in **Table 3**. Comparing tolerance zones with EOP below 0.6 dB one observes for DBPSK, that the centers of the zones lie at positive residual dispersion and around 0.1 precompensation. (For NRZ-DBPSK and NZDSF there is a small zone with EOP below 0.6 dB at negative residual dispersion, however, the local EOP minimum in this zone is greater than for the zone at positive residual dispersion.) The tolerance zones for RZ impulse shaping are smaller than for NRZ impulse shaping. For DQPSK the centers of the 0.6 dB tolerance zones are around $r_d = 100\,\mathrm{ps/nm}$ for NRZ and around $r_d = 50\,\mathrm{ps/nm}$ for RZ impuls shaping and precompensation between 0.1 and 0.2. RZ-DQPSK has larger tolerance zones than NRZ-DQPSK. DQPSK generally has larger tolerance zones than DBPSK. For 8-DPSK with NRZ impulse shaping, EOP below 0.6 dB cannot be achieved. However, for RZ impulse shaping the tolerance zones with EOP below 0.6 dB are much larger than for RZ-DQPSK and span a wide range of residual dispersion and precompensation values. Obviously, 8-DPSK is much more susceptible to fiber nonlinearties than DBPSK and DQPSK, which can be overcome by RZ instead of NRZ impulse shaping.

Table 1: Properties of binary and multilevel 8-DPSK receivers

	Binary receiver	Multilevel receiver
Delay & add filters	3	2
Photodiodes	6	4
Electrical signals	3 × binary	2 × five levels (three logial levels)
Decision devices	3	4
Additional hardware	Analog electrical signal processing	Combinational network

Table 2: Fiber parameters

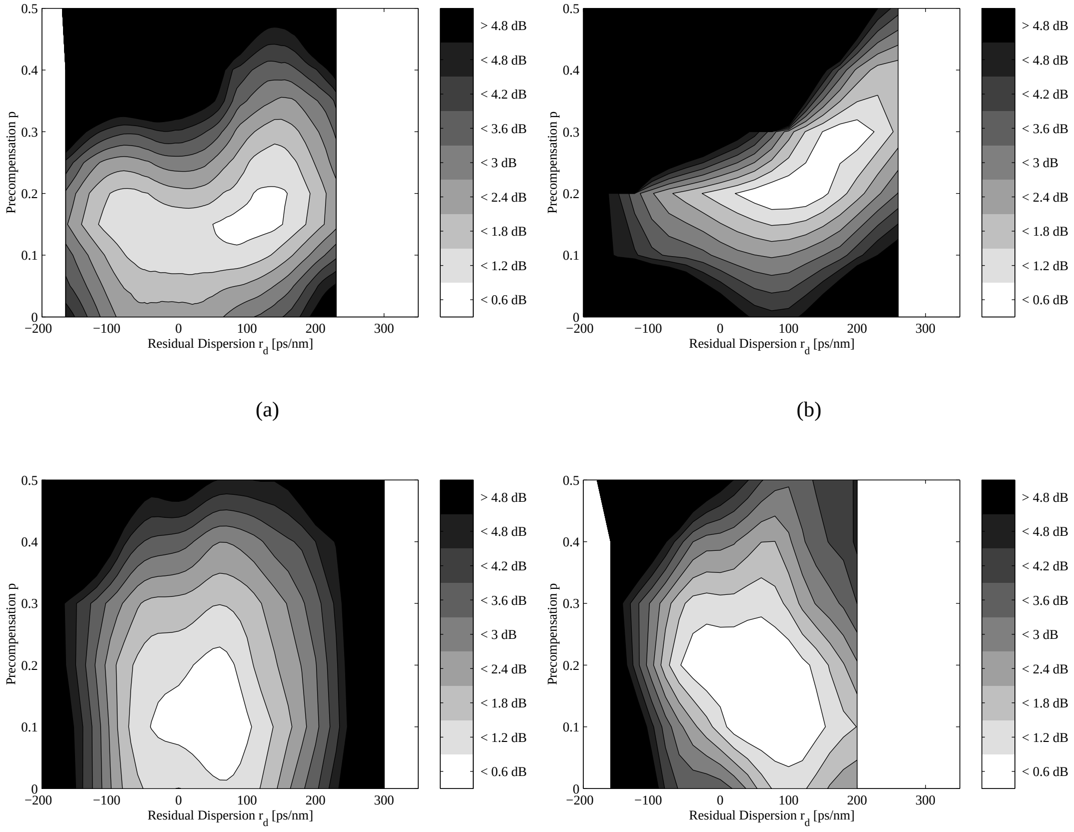
	SSMF	NZDSF	DCF
Attenuation α	$0.2\mathrm{dB/km}$	$0.2\mathrm{dB/km}$	$0.49\mathrm{dB/km}$
Dispersion coefficient D	$17\mathrm{ps/(nm \cdot km)}$	$8\mathrm{ps/(nm \cdot km)}$	$-95\mathrm{ps/(nm \cdot km)}$
Dispersion slope S	$0.057\mathrm{ps/(nm^2 \cdot km)}$	$0.058\mathrm{ps/(nm^2 \cdot km)}$	variable
Nonlinear index n_2	$2.2 \cdot 10^{-20}\mathrm{m^2/W}$	$2.7 \cdot 10^{-20}\mathrm{m^2/W}$	$2.66 \cdot 10^{-20}\mathrm{m^2/W}$
Effective area A	$80\mu\mathrm{m}^2$	$65\mu\mathrm{m}^2$	$19\mu\mathrm{m}^2$



(a) (b)

(c) (d)

Figure 4: EOP vs. precompensation and residual dispersion for single span DBPSK system with 15 dBm TF input power for (a) NRZ impulse shaping and SSMF (b) NRZ impulse shaping and NZDSF, (c) RZ impulse shaping and SSMF, and (d) RZ impulse shaping and NZDSF



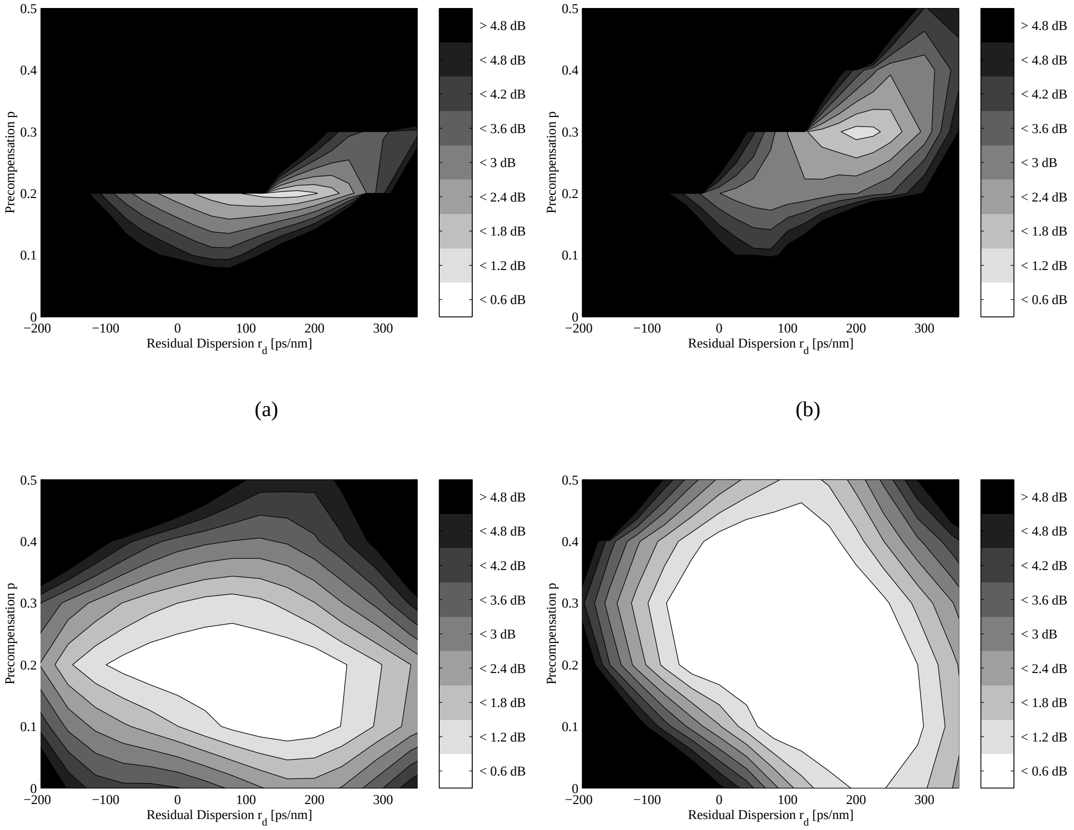
(a) (b)

(c) (d)

Figure 5: EOP vs. precompensation and residual dispersion for single span DQPSK system with 15 dBm TF input power for (a) NRZ impulse shaping and SSMF (b) NRZ impulse shaping and NZDSF, (c) RZ impulse shaping and SSMF, and (d) RZ impulse shaping and NZDSF

Table 3: Fiber parameters

	TF type	Impulse shaping	p	r_d [ps/nm]	EOP [dB]
DBPSK	SSMF	RZ	0.1	10	0.55
	SSMF	NRZ	0.1	32.5	0.39
	NZDSF	RZ	0.1	15	0.27
	NZDSF	NRZ	0.1	30	0.15
DQPSK	SSMF	RZ	0.1	50	-0.04
	SSMF	NRZ	0.15	85	0.32
	NZDSF	RZ	0.2	60	-0.54
	NZDSF	NRZ	0.3	100	-0.12
8-DPSK	SSMF	RZ	0.2	80	-0.36
	SSMF	NRZ	0.2	150	0.87
	NZDSF	RZ	0.2	120	-1.39
	NZDSF	NRZ	0.3	200	0.94



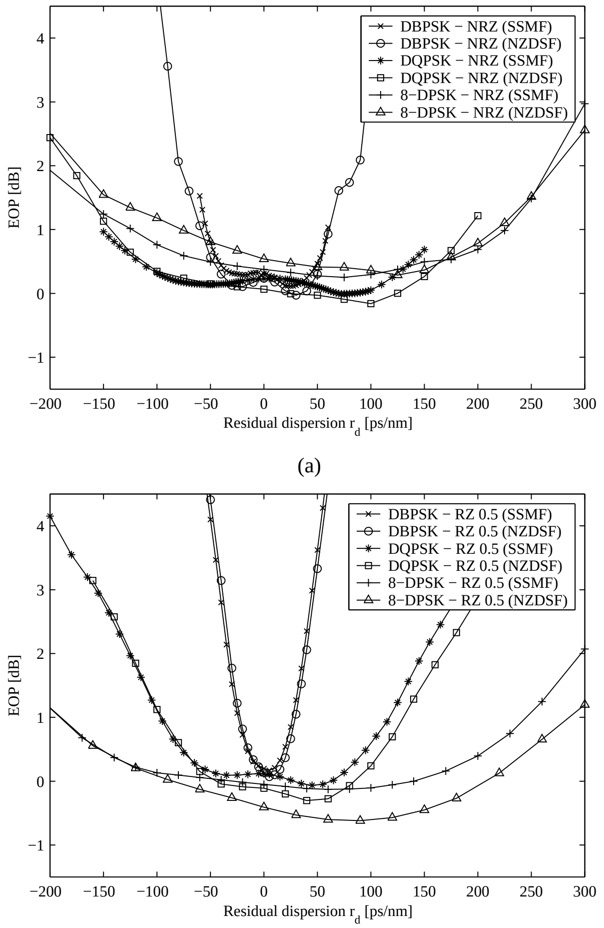
(a)

(b)

(c)

(d)

Figure 6: EOP vs. precompensation and residual dispersion for single span 8-DPSK system with 15 dBm TF input power for (a) NRZ impulse shaping and SSMF (b) NRZ impulse shaping and NZDSF, (c) RZ impulse shaping and SSMF, and (d) RZ impulse shaping and NZDSF



(a)

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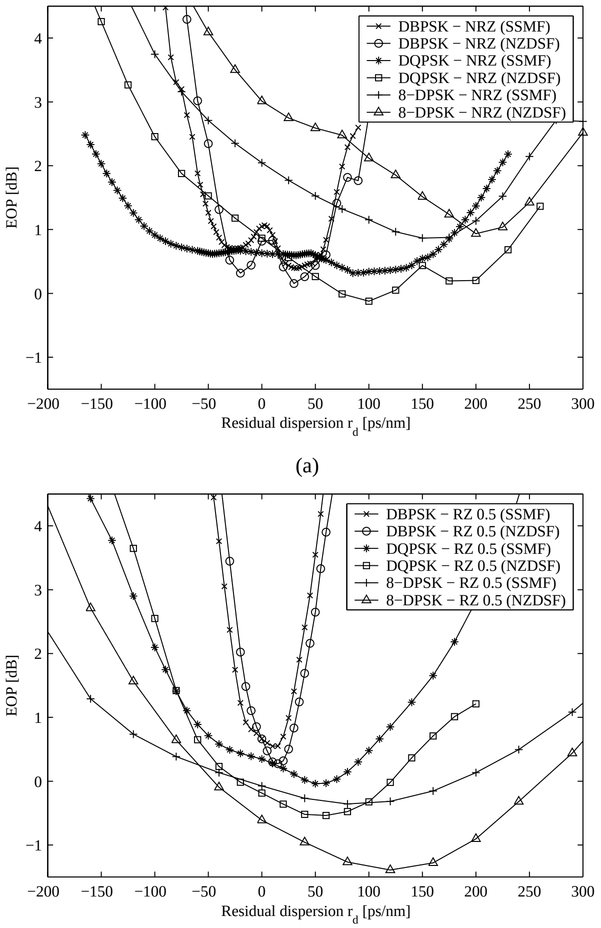
Figure 7: EOP vs. residual dispersion for one TF span with pre- and post-dispersion compensation, 10 dBm TF input power and (a) NRZ and (b) RZ impulse shaping.



(a)

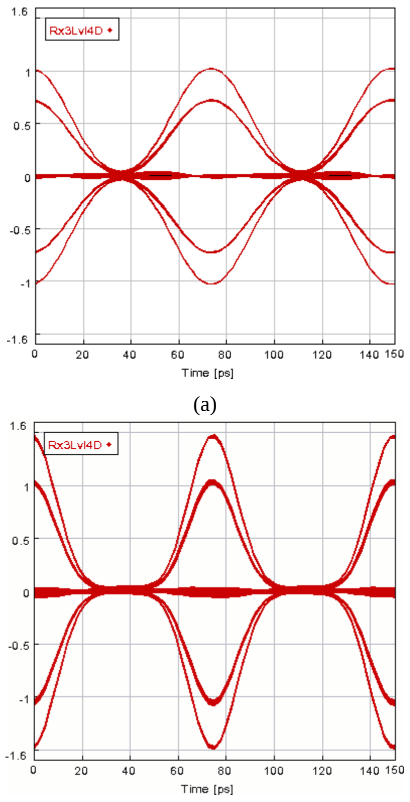
(b)

Figure 8: EOP vs. residual dispersion for one TF span with pre- and post-dispersion compensation, 15 dBm TF input power and (a) NRZ and (b) RZ impulse shaping.

Figure 7 shows EOP vs. residual dispersion r_d for the case, that for each value of r_d precompensation p is chosen in order to achieve minimum EOP. SSMF or NZDSF input power, respectively, is 10 dBm. NRZ impulse shaping is depicted in Figure 7(a) and RZ impulse shaping in Figure 7(b). In the NRZ case, clearly DQPSK exhibits a greater dispersion tolerance then DBPSK: The EOP curves are much broader for DQPSK. For DBPSK and DQPSK NZDSF leads to approx. 0.2 dB lower EOP than SSMF. 8-DPSK behaves surprisingly: Although it has the lowest symbol R_s EOP is the greatest of all three modulation schemes. In contrast to DBPSK and DQPSK, SSMF leads to a little lower EOP than NZDSF. This changes for RZ impulse shaping. Here, RZ-8-DPSK has the lowest EOP and RZ-DBPSK has the highest one for both SSMF and NZDSF transmission. For all three schemes, NZDSF leads to lower EOP. For RZ-8-DPSK the EOP difference between the two fiber types is 0.5 dB, 0.2 dB for RZ-DQPSK and 0.1 dB for RZ-DBPSK.

Figure 8 shows EOP vs. residual dispersion r_d for the case, that for each value of r_d precompensation p is chosen in order to achieve minimum EOP. SSMF or NZDSF input power, respectively, is increased to 15 dBm as for the contour plots. NRZ impulse shaping is depicted in Figure 8(a) and RZ impulse shaping in Figure 8(b). Qualitatively, the behaviours of the three modulation schemes stay the same. With NRZ impulse shaping EOP increases with increased TF input power. With RZ impulse shaping, however, EOP for DQPSK and 8-DPSK decreases with increased TF input power. For NZDSF the EOP decrease for RZ-DQPSK is 0.4 dB and for RZ-8-DPSK it is 0.8 dB.

Negative EOP for RZ-DQPSK or RZ-8-DPSK result from impulse compression on the transmission fiber as shown in **Figure 9** for 15 dBm RZ-8-DPSK single span NZDSF transmission. The RZ impulses of the received signal in Figure 9(b) have significantly reduced temporal width compared to the RZ impulses of the reference signal in Figure 9(a) although their powers are equal. The same effect can be observed for RZ-DQPSK, although it is not that significant.



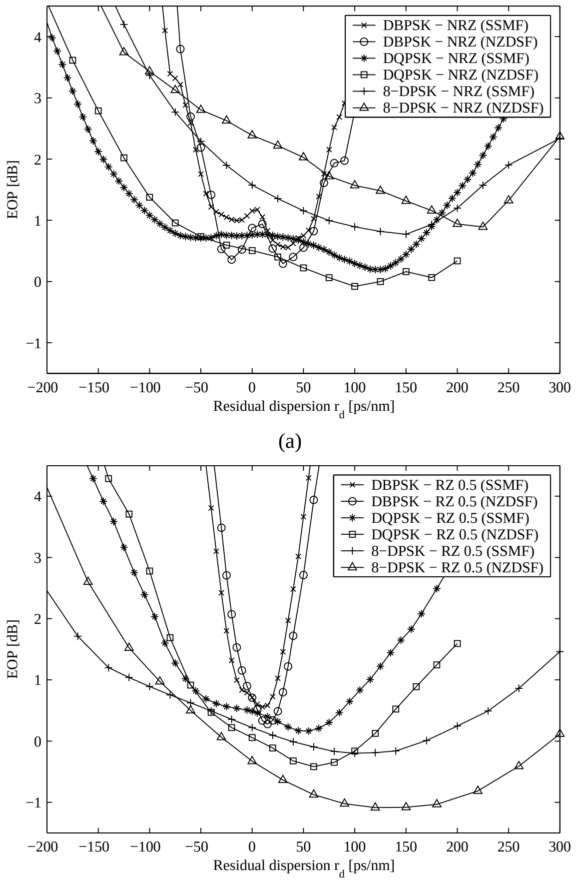
(a)

(b)

Figure 9: RZ-8-DPSK eye diagrams: (a) reference and (b) after single span transmission with 15 dBm NZDSF input power

3.2 Distributed dispersion compensation for three spans of SSMF and NZDSF

For distributed dispersion compensation according to Figure 3(c) we studied EOP for SSMF and NZDSF transmission. In **Figure 10** EOP vs. resdiual dispersion r_d is plotted for 10 dBm TF input power for the case, that for each value of r_d precompensation p is chosen in order to achieve minimum EOP. With NRZ impulse shaping in Figure 10(a) for both DBPSK and DQPSK, NZDSF transmission yields an approx. 0.5 dB lower EOP than SSMF transmission. For 8-DPSK however, SSMF transmissoin yields an approx. 0.2 dB lower EOP than NZDSF transmission. It must be noted, though, that EOP of 8-DPSK with NRZ impulse shaping is already above EOP of DBPSK and DQPSK regardless of the TF fiber type. This situation changes for RZ impulse shaping in Figure 10(b). Here, RZ-8-DPSK has the lowest EOP and RZ-DBSPK has the highest EOP. NZDSF leads to lower EOP than SSMF, the differences increasing from 0.6 dB for RZ-DBPSK over 1.1 dB for RZ-DQPSK up to 1.8 dB for RZ-8-DPSK. Again, it can be observed zhat 8-DPSK is much more susceptible to nonlinearties than DBPSK and DQPSK, which can be overcome by RZ instead of NRZ impulse shaping.



(a)

(b)

Figure 10: EOP vs. residual dispersion for three TF spans with distributed dispersion compensation, 10 dBm TF input power and (a) NRZ and (b) RZ impulse shaping.

For 15 dBm TF input power, the eyes are totally closed for NRZ, so **Figure 11** shows RZ only. Again, for all three modulation schemes, EOP is lower for NZDSF transmission than for SSMF transmission. For RZ-DBSPK, EOP with NZDSF is 0.3 dB lower than with SSMF, for RZ-DQPSK, EOP with NZDSF is 1.2 dB lower and for RZ-8-DPSK EOP is even 2.9 dB lower. With RZ-8-DPSK, 0 dB EOP can be achieved with NZDSF transmission and proper dispersion compensation.

3.3 Compact vs. distributed dispersion compensation for three spans of SSMF

Compact dispersion compensation (Figure 3(b)) is considered for DBPSK and DQPSK transmission over SSMF. **Figure 12** shows EOP vs. residual dispersion r_d for optimized precompensation p for 5 dBm and 10 dBm SSMF input power. For 5 dBm, the compact compensation scheme performs only slightly worse than the distributed scheme. For 10 dBm however, performance of the compact scheme is siginificantly worse. For compact dispersion compensation positive nonzero residual dispersion leads to minimum EOP.

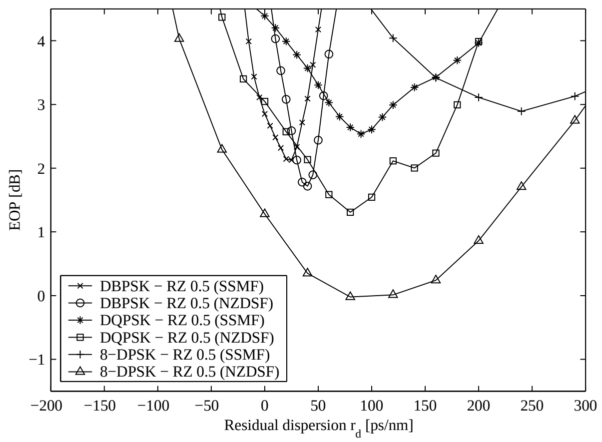


Figure 11: EOP vs. residual dispersion for three TF spans with distributed dispersion compensation and 15 dBm TF input power.

4 Conclusions

We compared dispersion tolerance and compensation for DBPSK, DQPSK and 8-DPSK transmission with NRZ and RZ impulse shaping. For all modulation schemes, positive residual dispersion and moderate precompensation leads to minimum EOP. For NRZ-DBPSK and NRZ-DQPSK NZDSF leads to lower EOP in the single span transmission system as well as in the three span transmission system with distributed dispersion compensation, whereas for NRZ-8-DPSK there is small advantage for SSMF. However, with RZ impulse shaping NZDSF leads to lower EOP for all three modulation schemes. Further the comparison of distributed and compact dispersion compensation for NRZ-DBSPK and NRZ-DQPSK shows, that distributed dispersion compensation yields much lower EOP than compact dispersion compensation.

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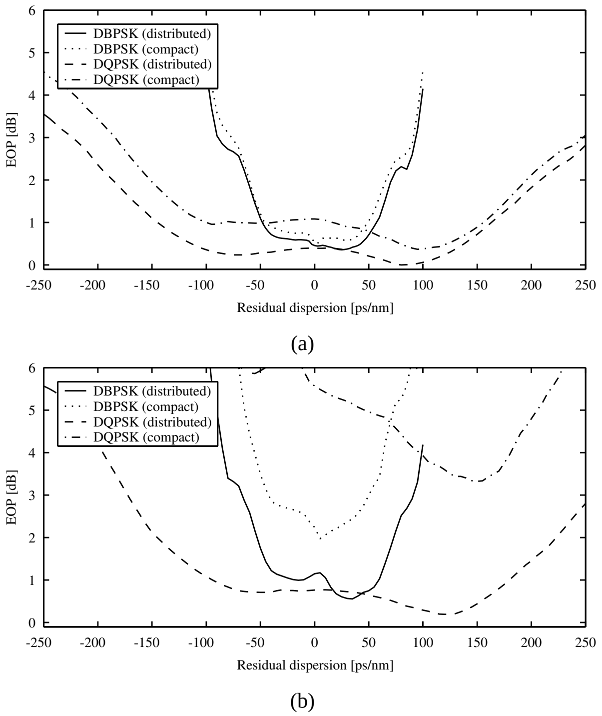

(a)

(b)

Figure 12: EOP vs. residual dispersion for three SSMF spans with distributed and compact dispersion compensation with (a) 5 dBm SSMF input power and (b) 10 dBm SSMF input power.

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