Optimal amplitude ratios and chromatic dispersion tolerances of optical quaternary ASK-DPSK and 8-ary ASK-DQPSK

Michael Ohm and Joachim Speidel

Institute of Telecommunications, University of Stuttgart,
Pfaffenwaldring 47, 70569 Stuttgart, Germany

ABSTRACT

In this paper we investigate quaternary combined amplitude- and differential binary phase-shift keying (ASK-DPSK) and 8-ary combined amplitude- and differential quadrature phase-shift keying (ASK-DQPSK) at a bit rate of 40 Gbit/s. For both formats, optimal values for amplitude ratios of the signal points and electrical and optical receiver bandwidths are given. Required optical signal-to-noise ratios (OSNR) at the receivers for bit error probabilities of 10^{-9} and chromatic dispersion tolerances are compared to amplitude-shift keying (ASK), binary differential phase-shift keying (DPSK) and quadrature phase-shift keying (DQPSK). For our numerical investigations we use a semi-analytical method for bit error probability computations.

Keywords: Optical communications, optical modulation formats, quaternary amplitude-/differential phase-shift keying (ASK-DPSK), 8-ary amplitude/-differential quadrature phase-shift keying (ASK-DQPSK)

1. INTRODUCTION

Multilevel optical modulation formats such as differential quadrature phase-shift keying (DQPSK)[1,2], quaternary combined amplitude- and differential phase-shift keying (ASK-DPSK)[3,4] and 8-ary combined amplitude- and differential quadrature phase-shift keying (ASK-DQPSK)[5] are attracting attention, because of greater spectral efficiencies and chromatic dispersion tolerances than binary modulation formats such as amplitude-shift keying (ASK) or differential phase-shift keying (DPSK). Quaternary ASK-DPSK is an interesting alternative to DQPSK as its receiver requires less components and is thus simpler to implement than the DQPSK receiver. 8-ary ASK-DQPSK further increases spectral efficiency compared to the quaternary formats.

In this paper we investigate the important impact of the amplitude ratio of the signal points in the constellation diagrams on bit error probabilities (BEP) and show optimal solutions for both ASK-DPSK and ASK-DQPSK. Further, required optical signal-to-noise ratios (OSNR) for BEP $= 10^{-9}$ and chromatic dispersion tolerances of ASK-DPSK and ASK-DQPSK are compared to ASK, DPSK, and DQPSK for bit rate $R_b = 40\,\text{Gbit/s}$. Both non-return-to-zero (NRZ) and return-to-zero (RZ) impulse shaping are considered.

2. ASK-DPSK AND ASK-DQPSK TRANSMITTERS

The ASK-DPSK transmitter in Fig. 1(a) consists of a Mach-Zehnder modulator (MZM) and a phase modulator (PM) in series. The electrical drive signal $a(t)$ generated from the bit sequence a_k modulates the amplitude of the optical signal from the continuous-wave laser, resulting in two different amplitudes a and b. The electrical drive signal $b(t)$ generated from the differentially encoded bit sequence b_k modulates the phase of the optical signal, such that two phase angles 0 and π exist. The ASK-DPSK constellation diagram and the transitions between the signal points are shown in Fig. 1(b) for NRZ impulse shaping and in Fig. 1(c) for RZ impulse shaping. The amplitude ratio (AR) b/a of the signal points is related to the extinction ratio (ER) of the optical signal by $10 \cdot \log\left(b^2/a^2\right)$. The same basic setup can be applied as the DQPSK transmitter used as a reference. However, in this case, the MZM is used to modulate the phase of the optical signal and both bit sequences a_k and b_k are differentially encoded.[2]

The ASK-DQPSK transmitter in Fig. 2(a) consists of two MZM and one PM in series. Here, the electrical drive signal $a(t)$ generated from the bit sequence a_k modulates the amplitude of the optical signal from the continuous-wave laser such that there are two amplitudes d and c. The second MZM and the PM build up a DQPSK transmitter.[2] The electrical drive

Further author information: E-mail: ohm@inue.uni-stuttgart.de, Telephone: +49 711 685-7938, Fax: +49 711 685-7929

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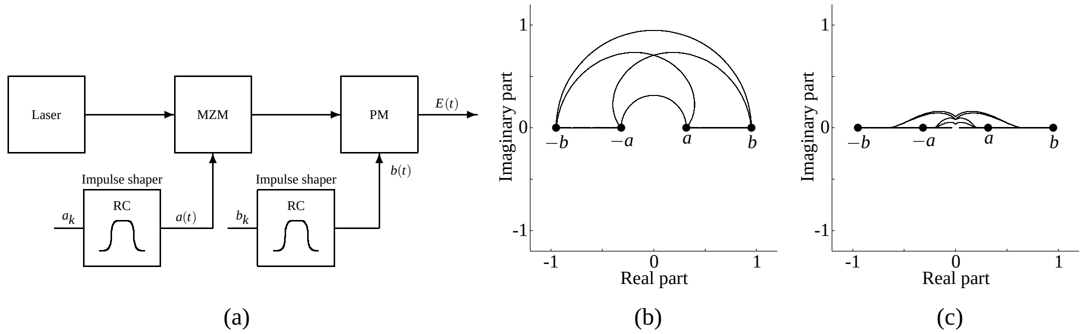


Figure 1. (a) ASK-DPSK transmitter and constellation diagrams with phase transitions for (b) NRZ-ASK-DPSK and (c) RZ-ASK-DPSK

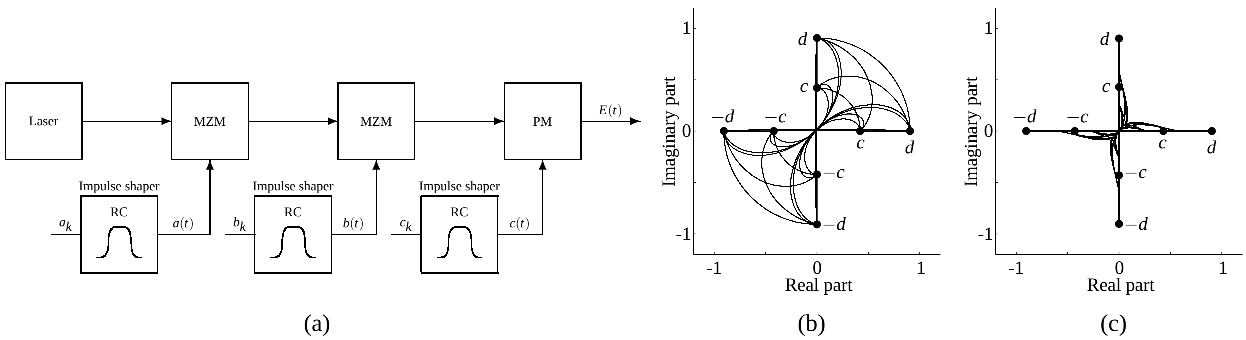


Figure 2. (a) ASK-DQPSK transmitter and constellation diagrams with phase transitions for (b) NRZ-ASK-DQPSK and (c) RZ-ASK-DQPSK

signals generated from the differentially encoded bit sequences b_k and c_k modulate the phase of the optical signal such that there are four phase angles $0, \pi/2, \pi, 3\pi/2$. The ASK-DQPSK constellation diagram and the transitions between the eight signal points are shown in Fig. 2(b) for NRZ and in Fig. 2(c) for RZ impulse shaping. Analog to ASK-DPSK, d/c is related to the ER by $10 \cdot \log\left(d^2/c^2\right)$.

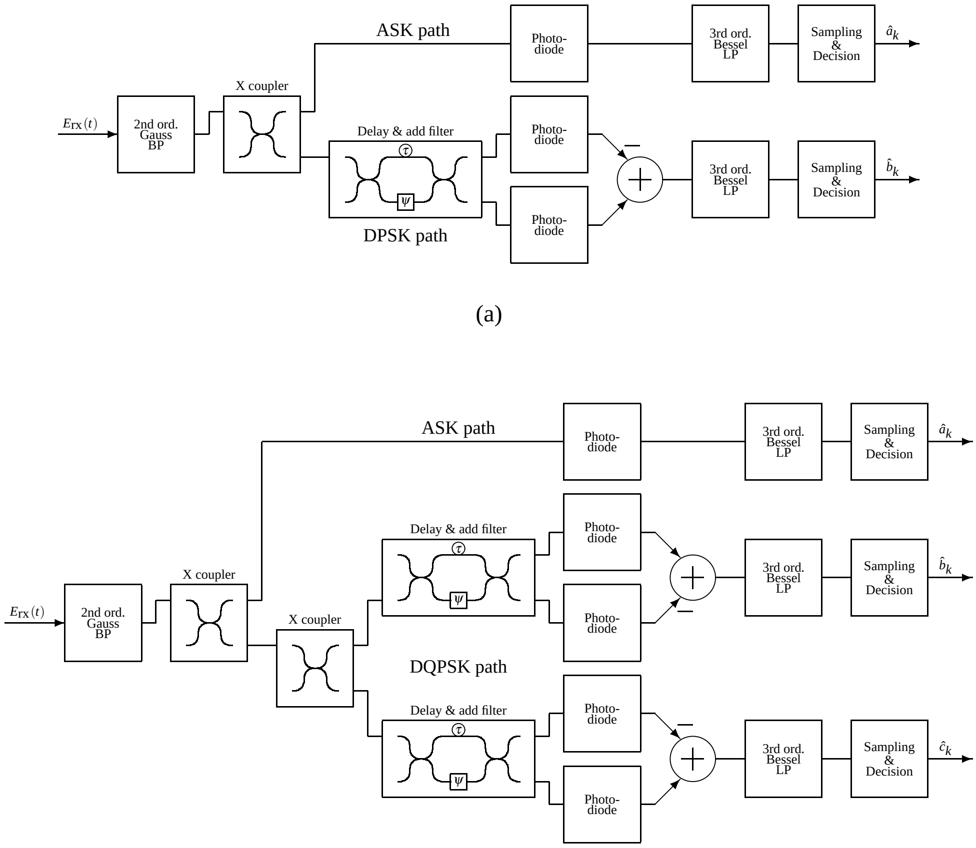
The time-domain raised cosine (RC) impulse shapers both in the ASK-DPSK and ASK-DQPSK transmitter and for all references have impulse responses

$$h(t) = \begin{cases} 1 & , |t| \leq \frac{T}{2}(1-\alpha) \\ \cos^2\left[\frac{\pi}{4}\frac{2|t|-T(1-\alpha)}{\alpha T}\right] & , \frac{T}{2}(1-\alpha) < |t| < \frac{T}{2}(1+\alpha) \\ 0 & , |t| \geq \frac{T}{2}(1+\alpha) \end{cases} . \tag{1}$$

$T = 1/R_s$ is the symbol duration, α is the roll-off factor. $R_s = R_b/\log_2(M)$ is the symbol rate with M representing the number of signal points of the modulation format. Return-to-zero (RZ) impulse shaping is done by modulating the amplitudes of the respective non-return-to-zero (NRZ) signals in a subsequent MZM with a periodic sequence of electrical Gaussian impulses. Their full widths at half maximum are $0.5 \cdot T$.

3. ASK-DPSK AND ASK-DQPSK RECEIVERS

The ASK-DPSK receiver in Fig. 3(a) has an ASK path with a photodiode for direct detection and a DPSK path with a delay & add filter (DAF) and a balanced detector with two photodiodes. Binary sampling & decision devices estimate the bit sequences in both paths. Similarly, the ASK-DQPSK receiver in Fig. 3(b) has an ASK path and a DQPSK path. The ASK path again uses a single photodiode and a binary sampling & decision device, whereas the DQPSK path needs two



(a)

(b)

Figure 3. (a) ASK-DPSK receiver and (b) ASK-DQPSK receiver

DAF, two balanced detectors and two binary sampling & decision devices. The optical receiver filters are 2$^{\text{nd}}$ order Gauss band-pass filters and the electrical receiver filters are 3$^{\text{rd}}$ order Bessel low-pass filters. The greater the amplitude ratios b/a or d/c, respectively, the greater the electrical eye opening in the ASK path, but the smaller the electrical eye opening in the DPSK path or DQPSK path, respectively, and vice versa. This is investigated for ASK-DPSK[3] and is similar for ASK-DQPSK. Thus, b/a and d/c need to be optimized in order to achieve minimum BEP in the presence of optical noise.

Table 1 shows the number of major components in the receivers for ASK-DPSK and ASK-DQPSK in comparison to ASK, DPSK and DQPSK. The advantage of ASK-DPSK over DQPSK is, that is uses only one DAF instead of two and three photodiodes instead of four. ASK-DQPSK needs the greatest number of components, but the advantage is that they all work at the lowest symbol rate $R_s = R_b/3$.

In the following, BEP are calculated using a Karhunen-Loeve based semi-analytical method[6] as the use of standard Gaussian estimation methods leads to inaccurate results for differential phase-shift-keying systems.[7] Roll-off factors in the impulse shapers for ASK-DPSK, ASK-DQPSK and for all references are set to $\alpha = 0.5$ as an example for nonrectangular NRZ impulse shaping. Optical additive white Gaussian noise is the dominant noise at the receiver.

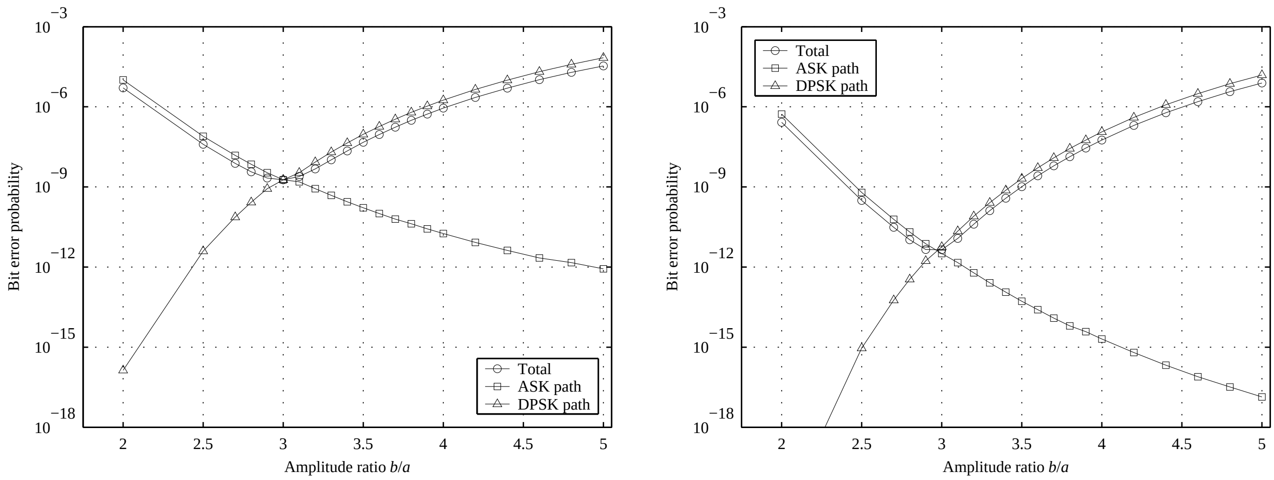
4. OPTIMAL AMPLITUDE RATIOS

4.1. ASK-DPSK

Fig. 4 shows BEP vs. b/a at OSNR $= 23\,$dB for both NRZ and RZ impulse shaping. For each AR, electrical and optical receiver filter bandwidths are optimized with respect to BEP. These filter bandwidths are given in Table 2 for some selected

Table 1. Comparison of receiver hardware amount for ASK, DPSK, DQPSK, ASK-DPSK, and ASK-DQPSK

	Delay & add filters	Photodiodes	Sampling & decision devices	Symbol rate R_s for bit rate $R_b = 40\,\text{Gbit/s}$
ASK	—	1	1	40 Gsymbols/s
DPSK	1	2	1	40 Gsymbols/s
DQPSK	2	4	2	20 Gsymbols/s
ASK-DPSK	1	3	2	20 Gsymbols/s
ASK-DQPSK	2	5	3	13.3 Gsymbols/s



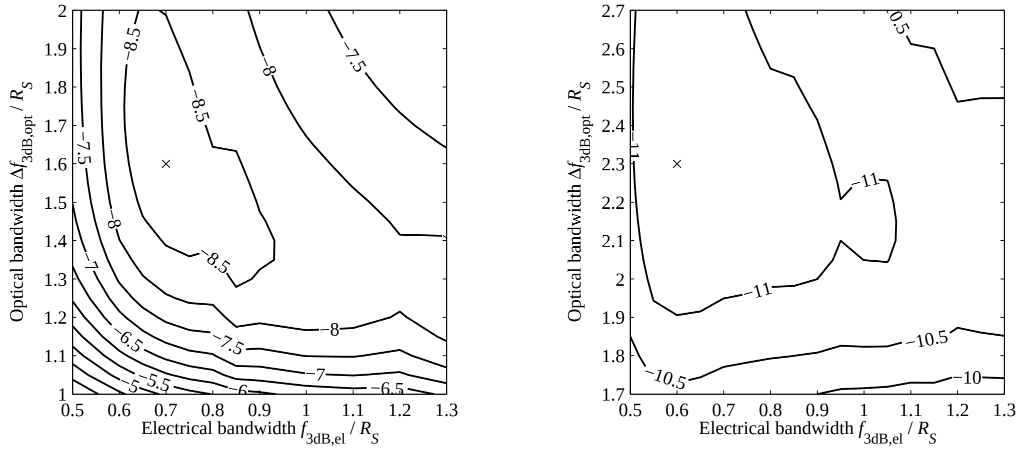
(a) (b)

Figure 4. Bit error probabilities vs. amplitude ratio b/a of ASK-DPSK at OSNR $= 23\,\text{dB}$: (a) NRZ and (b) RZ

AR and are used for all following investigations. BEP has its minimum for $b/a = 3$ for both NRZ and RZ impulse shaping. For lower AR, BEP is dominated by errors in the ASK path, for greater AR it is dominated by errors in the DPSK path. Further, BEP for ASK-DPSK with RZ is by factor 10^3 lower than for NRZ. Fig. 5 shows BEP vs. electrical and optical receiver bandwidths for the optimal AR of NRZ- and RZ-ASK-DPSK. The filter bandwidths which lead to the lowest BEP are marked with '$\times$' . OSNR at BEP $= 10^{-9}$ vs. b/a for a link with zero residual dispersion is presented in Fig. 6. For NRZ and RZ a variation of $\Delta(b/a) \approx 1$ around the optimum is acceptable for an OSNR penalty of 1 dB.

Table 2. Optimized optical and electrical receiver filter bandwidths for ASK-DPSK

b/a	2		3		4	
	NRZ	RZ	NRZ	RZ	NRZ	RZ
$\Delta f_{3\,\text{dB,opt}}/R_s$	1.6	2.6	1.6	2.3	1.4	2.15
$f_{3\,\text{dB,el}}/R_s$	0.65	0.55	0.7	0.6	0.85	0.6



(a) (b)

Figure 5. Base 10-logarithm of bit error probability vs. rx filter bandwidths with amplitude ratio $b/a = 3$ at OSNR $= 23$ dB for (a) NRZ-ASK-DPSK and (b) RZ-ASK-DPSK

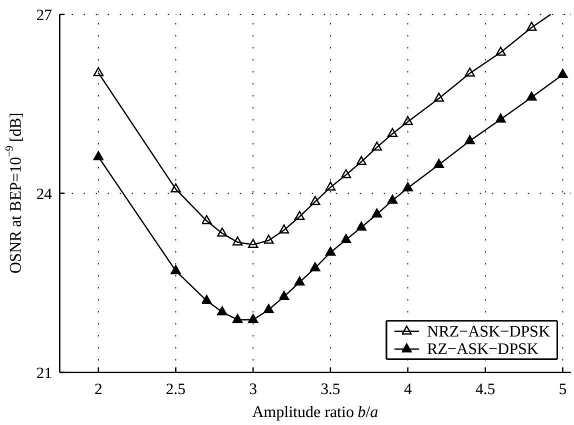


Figure 6. OSNR at BEP $= 10^{-9}$ vs. amplitude ratio of ASK-DPSK (zero residual dispersion)

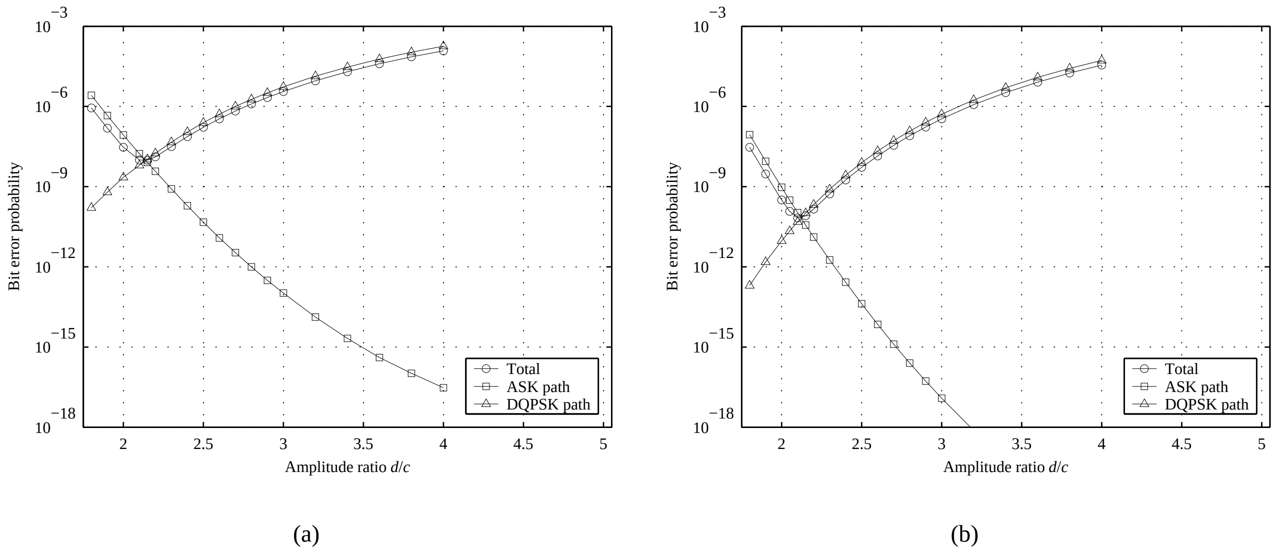


Figure 7. Bit error probabilities vs. amplitude ratio d/c of ASK-DQPSK at OSNR $= 23\,\mathrm{dB}$: (a) NRZ and (b) RZ

Table 3. Optimized optical and electrical receiver filter bandwidths for ASK-DQPSK

d/c	1.8		2.15	2.1	2.4	
	NRZ	RZ	NRZ	RZ	NRZ	RZ
$\Delta f_{3\,\mathrm{dB,opt}}/R_s$	1.85	2.55	2.2	2.5	2.25	2.3
$f_{3\,\mathrm{dB,el}}/R_s$	0.7	0.55	0.65	0.55	0.65	0.6

4.2. ASK-DQPSK

For ASK-DQPSK, Fig. 7 presents BEP vs. d/c at OSNR $= 23\,\mathrm{dB}$ for both NRZ and RZ impulse shaping. For NRZ impulse shaping, BEP has its minimum for $d/c = 2.15$, whereas for RZ impulse shaping $d/c = 2.1$ leads to the lowest BEP. Similar to ASK-DPSK, for lower AR, BEP is dominated by errors in the ASK path, for greater AR it is dominated by errors in the DQPSK path. Further, BEP for ASK-DQPSK with RZ is by approx. factor 10^3 lower than for NRZ. Fig. 8 shows BEP vs. electrical and optical receiver bandwidths for the optimal AR of NRZ- and RZ-ASK-DQPSK. The filter bandwidths which lead to the lowest BEP are marked with '$\times$' . Optimal filter bandwidths for other selected values are presented in Table 3 and will be used for all further investigations. OSNR at BEP $= 10^{-9}$ vs. d/c for a link with zero residual dispersion is presented in Fig. 9. For NRZ and RZ a variation of $\Delta(d/c) \approx 0.6$ around the optimum is acceptable for an OSNR penalty of 1 dB. For ASK-DQPSK, the AR must thus be adjusted more carefully than for ASK-DPSK.

5. CHROMATIC DISPERSION TOLERANCE

First, in subsection 5.1 ASK-DPSK and then, in subsection 5.2 ASK-DQPSK are investigated separately. Finally, chromatic dispersion tolerances of both formats are compared to ASK, DPSK, and DQPSK in subsection 5.3.

5.1. ASK-DPSK

Fig. 10 shows OSNR at BEP $= 10^{-9}$ vs. residual dispersion R_d for ASK-DPSK. ASK, DPSK and DQPSK are included as references, but a detailed comparison will be given later in subsection 5.3. Three different AR are considered: Optimal AR $b/a = 3$ from section 4, an AR below the optimum ($b/a = 2$) and an AR above the optimum ($b/a = 4$). For NRZ-ASK-DPSK in Fig. 10(a) the slopes of the ONSR curves decrease for $b/a > 3$, thus dispersion tolerance increases. This is because the ASK part benefits from the increased extinction ratio and the DPSK part is generally more tolerant to

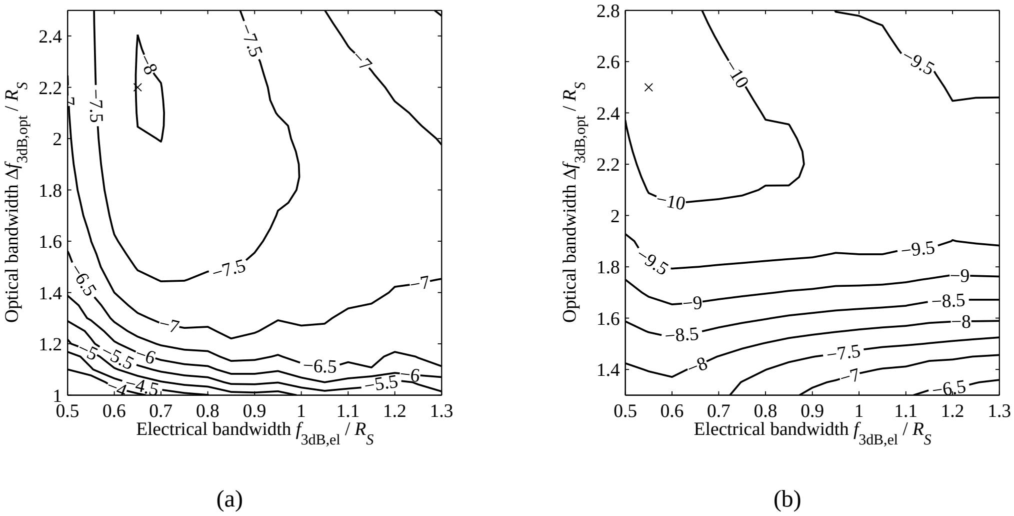


Figure 8. Base 10-logarithm of bit error probability vs. rx filter bandwidths at OSNR = 23 dB for (a) NRZ-ASK-DQPSK with $d/c = 2.15$ and (b) RZ-ASK-DQPSK with $d/c = 2.1$

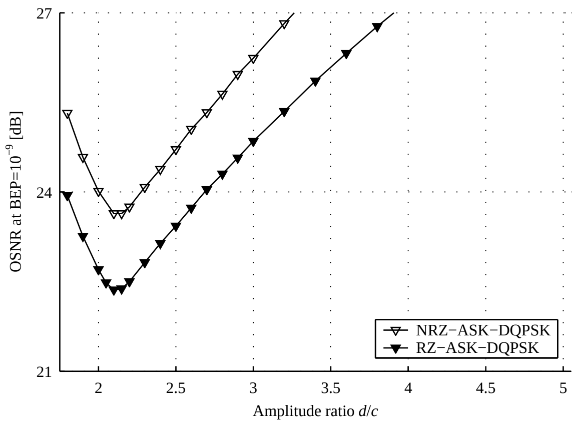
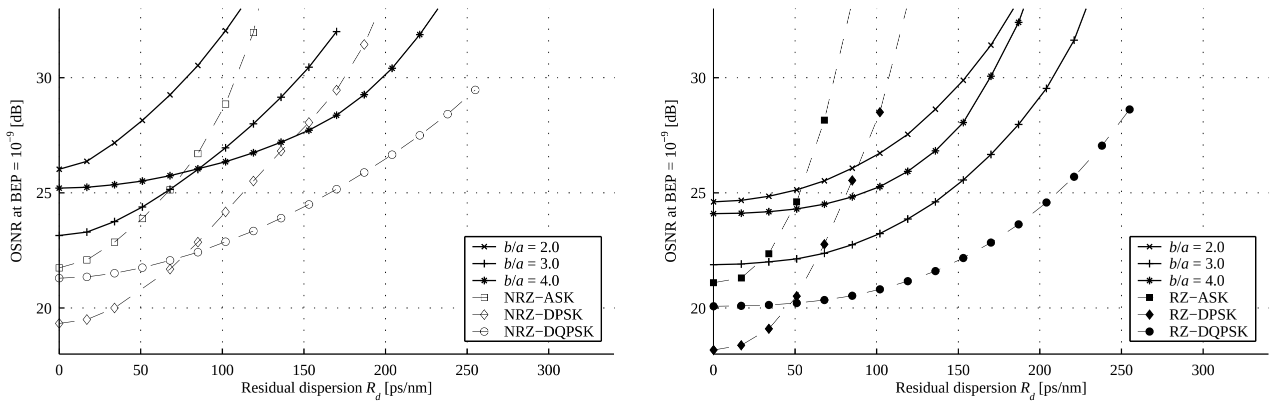


Figure 9. OSNR at BEP $= 10^{-9}$ vs. amplitude ratio of ASK-DQPSK (zero residual dispersion)



(a) (b)

Figure 10. OSNR at BEP $= 10^{-9}$ vs. residual dispersion R_d: (a) NRZ-ASK-DPSK and (b) RZ-ASK-DPSK

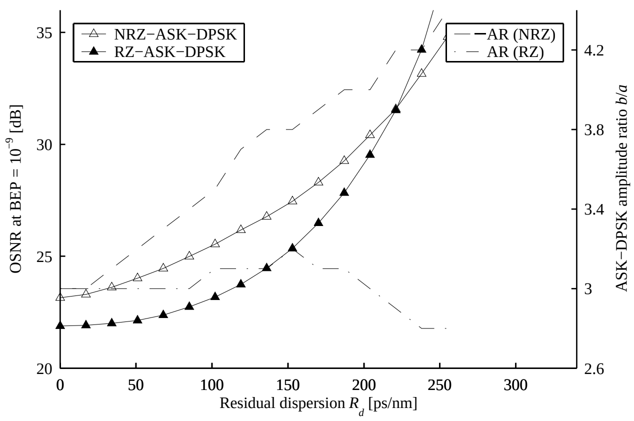
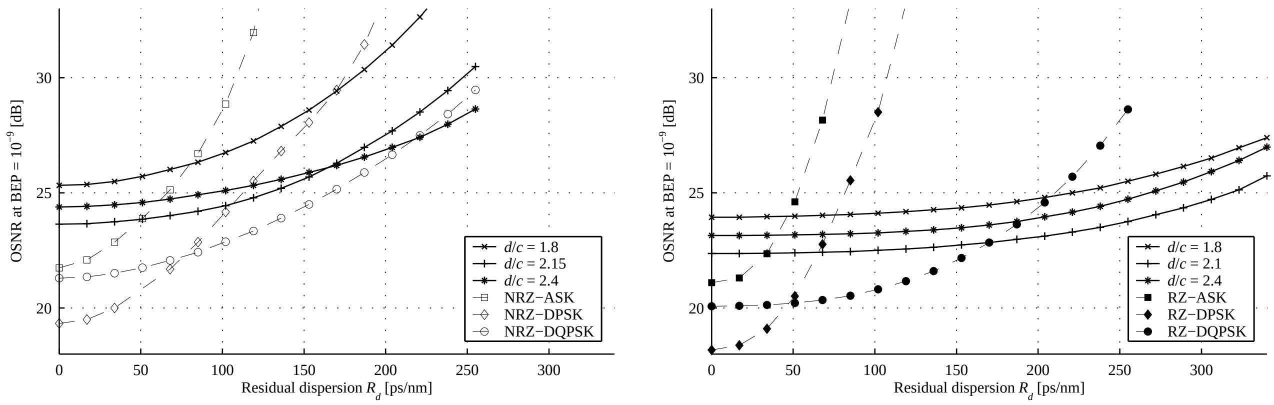


Figure 11. OSNR at BEP $= 10^{-9}$ and optimal amplitude ratios vs. residual dispersion R_d for ASK-DPSK

dispersion. However, required OSNR for zero residual dispersion becomes larger. For $b/a < 3$, required OSNR for zero residual dispersion is larger and also the curve increases more steeply than for $b/a = 3$. Now consider Fig. 10(b) where the RZ formats are depicted. Obviously, the curves for ASK-DPSK with $b/a = 2$, 3 and 4 are shifted to lower OSNR values and do not intersect compared to Fig. 10(a). Fig. 11 finally shows the required OSNR for BEP $= 10^{-9}$ vs. residual dispersion with the left ordinate for the case that the AR of ASK-DPSK are chosen such that they lead to the lowest required OSNR. The respective AR are given in Fig. 11 with the right ordinate. For NRZ-ASK-DPSK they increase with R_d, whereas they remain almost constant around 3 for RZ-ASK-DPSK.

5.2. ASK-DQPSK

Now, OSNR at BEP $= 10^{-9}$ vs. residual dispersion R_d for ASK-DQPSK is given in Fig. 12. Again, ASK, DPSK, and DQPSK are included as references, but a detailed comparsion will be given later in subsection 5.3. For ASK-DQPSK three different AR are considered: Optimal AR $d/c = 2.15$ or $d/c = 2.1$, respectively, and $d/c = 1.8$ and $d/c = 2.4$. Similar to NRZ-ASK-DPSK we observe from Fig. 12(a) for NRZ-ASK-DQPSK that for $d/c > 2.15$ the slopes of the OSNR curves decrease and thus dispersion tolerance increases. However, required OSNR for zero residual dispersion increases. For $d/c < 2.15$, required OSNR for zero residual dispersion is larger and also the curve increases more steeply than for $d/c = 2.15$. Results for RZ-ASK-DQPSK are displayed in Fig. 12(b). Similar to RZ-ASK-DPSK, the curves are shifted to lower OSNR values and do not intersect anymore. Fig. 13 shows required OSNR for BEP $= 10^{-9}$ vs. residual dispersion



(a) (b)

Figure 12. OSNR at BEP $= 10^{-9}$ vs. residual dispersion R_d: (a) NRZ-ASK-DQPSK and (b) RZ-ASK-DQPSK

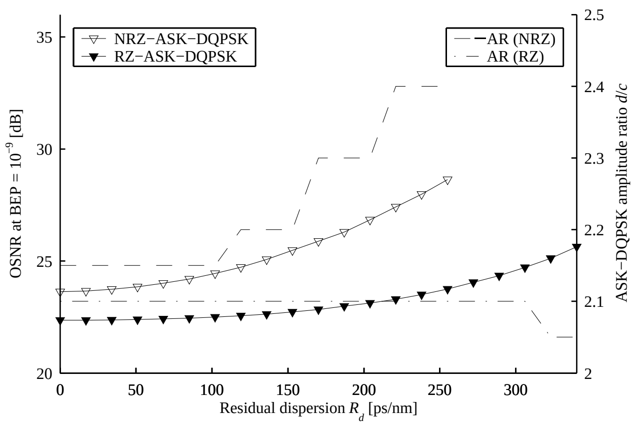


Figure 13. OSNR at BEP $= 10^{-9}$ and optimal amplitude ratios vs. residual dispersion R_d for ASK-DQPSK

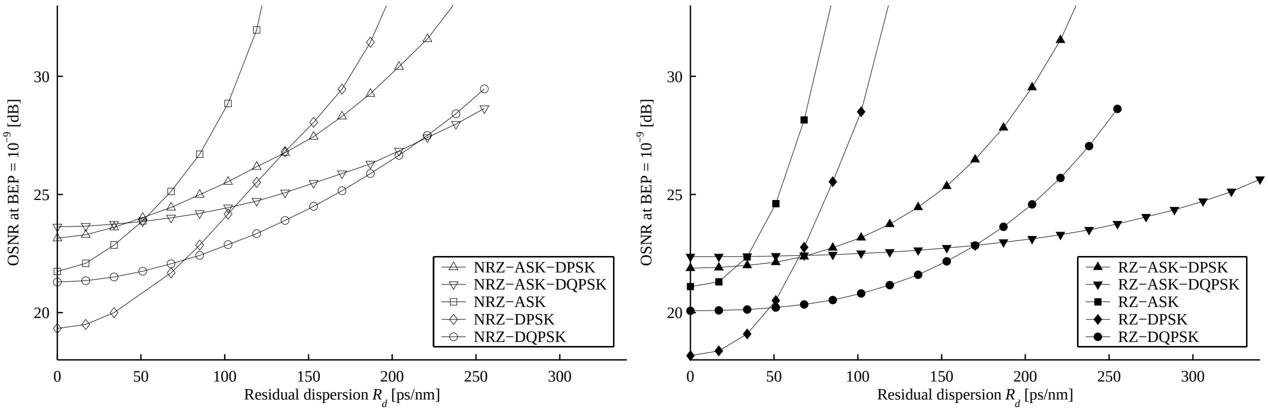
with the left ordinate for the case that the AR of ASK-DQPSK are chosen such that they lead to the lowest required OSNR. The respective AR are given in Fig. 13 with the right ordinate. For NRZ, the AR increase with increasing R_d, whereas they remain almost constant around $d/c = 2.1$ for RZ.

5.3. Comparison with ASK, DPSK and DQPSK

In this subsection we compare ASK-DPSK and ASK-DQPSK with ASK, DPSK and DQPSK. For ASK-DPSK and ASK-DQPSK, optimal AR are chosen. First, for zero residual dispersion, required OSNR for BEP $= 10^{-9}$ are listed in Table 4. For NRZ, compared to the binary formats, ASK-DPSK requires a 1.4 dB higher OSNR than ASK and a 3.8 dB higher OSNR than DPSK. The difference to DQPSK amounts to 1.8 dB. ASK-DQPSK needs only a 0.5 dB higher OSNR than ASK-DPSK. For RZ, quantitativly similar results are obtained. The OSNR for ASK-DPSK needs to be 0.8 dB higher than for ASK and 3.7 dB higher than for DPSK. The difference to DQPSK is again 1.8 dB and ASK-DQPSK also needs only a 0.5 dB higher OSNR than ASK-DPSK. For comparing chromatic dispersion tolerances, required OSNR vs. BEP $= 10^{-9}$ for all formats are shown together in Figs. 14(a) and (b) for both NRZ and RZ, respectively. From these figures, maximum allowed residual dispersion $R_{d,\max}$ for OSNR penalties of 1 dB and 3 dB are determined and listed in Table 5. ASK-DPSK exhibits much higher $R_{d,\max}$ than the binary formats ASK and DPSK. However, it performs slightly worse than DQPSK. ASK-DQPSK possesses the highest $R_{d,\max}$ of all formats. For RZ impulse shaping, it is by factor 7.6 higher than for ASK

Table 4. Required OSNR for BEP $= 10^{-9}$ at zero residual dispersion

OSNR [dB] for BEP $= 10^{-9}$	ASK	DPSK	DQPSK	ASK-DPSK	ASK-DQPSK
NRZ	21.7	19.3	21.3	23.1	23.6
RZ	21.1	18.2	20.1	21.9	22.4



(a) (b)

Figure 14. OSNR at BEP $= 10^{-9}$ vs. residual dispersion R_d: Comparison of all (a) NRZ and (b) RZ formats with amplitude ratios optimized to residual dispersion.

Table 5. Chromatic dispersion tolerance: Maximum allowed residual dispersion $R_{d,\max}$ for OSNR penalties of 1 dB and 3 dB

$R_{d,\max}$ [ps/nm] for OSNR penalty of	ASK		DPSK		DQPSK		ASK-DPSK		ASK-DQPSK	
	NRZ	RZ	NRZ	RZ	NRZ	RZ	NRZ	RZ	NRZ	RZ
1 dB	31	30	41	35	79	115	56	91	114	227
3 dB	63	47	77	56	147	175	118	144	198	331

and by factor 6.5 higher than for DPSK at an OSNR penalty of 1 dB. In comparison to the two quaternary formats, it is by factor 2 higher than for DQPSK and by factor 2.5 higher than for ASK-DPSK.

6. CONCLUSION

We found that for zero residual dispersion the optimal amplitude ratio of the ASK-DPSK signal points is $b/a = 3$ in the presence of optical noise for both NRZ and RZ impulse shaping. The optimal amplitude ratios of ASK-DQPSK are $d/c = 2.15$ for NRZ and $d/c = 2.1$ for RZ impulse shaping, respectively. For both formats, the amplitude ratios should be greater than the optimal values for fiber transmission without full dispersion compensation using NRZ. Quaternary ASK-DPSK shows higher chromatic dispersion tolerance than ASK and DPSK. Although compared to DQPSK, it requires a 1.8 dB higher OSNR for BEP $= 10^{-9}$ and dispersion tolerance is slighty worse, ASK-DPSK is a good alternative, as the receiver has only about half the hardware amount. 8-ary ASK-DQPSK needs only 0.5 dB more OSNR for BEP $= 10^{-9}$ than ASK-DPSK and exhibits the greatest dispersion tolerance of all considered formats. Although the receiver requires the highest hardware amount, all components operate at only $1/3$ of the bit rate.

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