Receiver sensitivity, chromatic dispersion tolerance and optimal receiver bandwidths for 40 Gbit/s 8-level optical ASK-DQPSK and optical 8-DPSK

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***Abstract*— In this paper we investigate optimal receiver sensitivity, chromatic dispersion tolerance and receiver bandwidths of optical 8-level combined amplitude-/differential quadrature phase-shift keying (ASK-DQPSK) and optical 8-level differential phase-shift keying (8-DPSK) at bit rate 40 Gbit/s. We compare both 8-level formats to binary ASK and DPSK as well as quaternary DQPSK. For our numerical investigations we use a semi-analytical method for bit error probability calculations.**

1. Introduction

Among multilevel optical modulations formats, both 8-level combined amplitude-/differential quadrature phase-shift keying (ASK-DQPSK) [1], [2] and 8-level differential phase-shift keying (8-DPSK) [3]–[9] have recently received quite some attention, as they have higher spectral efficiency than quaternary formats such as differential quadrature phase-shift keying (DQPSK) [10], [11] or combined amplitude-/differential phase-shift keying (ASK-DPSK) [12], [13].

First, we present transmitters and receivers for ASK-DQPSK and 8-DPSK. Then, we investigate optimal receiver bandwidths, receiver sensitivity and chromatic dispersion tolerance of both formats at bit rate 40 Gbit/s and compare the results to binary ASK and DPSK and quaternary DQPSK.

2. System Setup

2.1 8-DPSK transmitter

The 8-DPSK transmitter in Fig. 1(a) consists of two Mach-Zehnder modulators (MZM) and a phase modulator (PM). Three bit sequences $b_{1,k}$, $b_{2,k}$ and $b_{3,k}$ are differentially encoded. The electrical drive signals $a(t)$, $b(t)$ and $c(t)$ are generated by impulse shapers with raised-cosine impulse responses

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

$T=1/R_s$ is the symbol duration, α is the roll-off factor which is set to 0.5 throughout this paper. R_s is the symbol rate. The inner part with two parallel MZM corresponds to a DQPSK transmitter [10]. The optical signal $E_c(t)$ can thus take on four possible phase angles. In the following PM the binary drive signal $c(t)$ induces an additional phase shift of $\pi/4$ for bit 1 or leaves the optical signal unaltered for bit 0. At the sampling instants $t=nT$ the optical output signal $E(t)$ can take on 8 different phase angles $\varphi(nT)=\varphi_n\in\{n\pi/4; n=0\dots7\}$. Return-to-zero (RZ) impulse shaping with 50% duty cylce is achieved by modulating the amplitude of the non-return-to-zero (NRZ) signal in a subsequent MZM with a periodic sequence of electrical Gaussian impulses. Their full widths at half maximum are $T/2$.

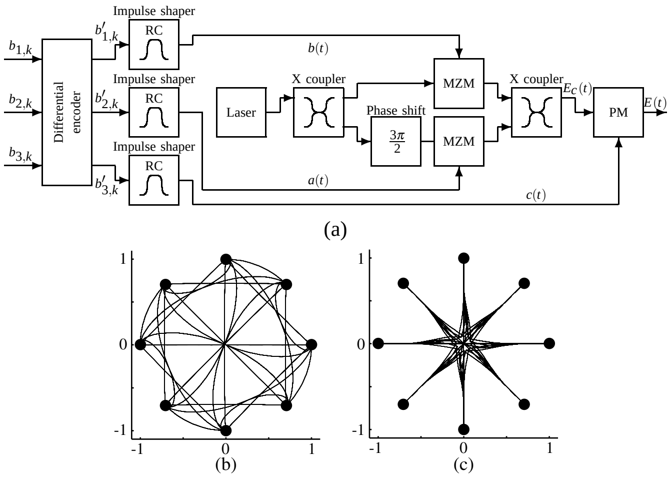

Fig. 1. (a) 8-DPSK transmitter and constellation diagrams with transitions for (a) NRZ and (b) RZ impulse shaping

Figs. 1(b) and (c) show the constellations diagrams with 8 signal points, which all have the same magnitude, and the phase transitions between them for NRZ and RZ impulse shaping, respectively. Note, that for RZ impulse shaping all signal point transitions go through the origin, as can be seen in Fig. 1(c). Obviously, this is not always the case for NRZ impulse shaping, as shown in Fig. 1(b).

2.2 ASK-DQPSK transmitter

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 $b_{1,k}$, 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 in serial structure

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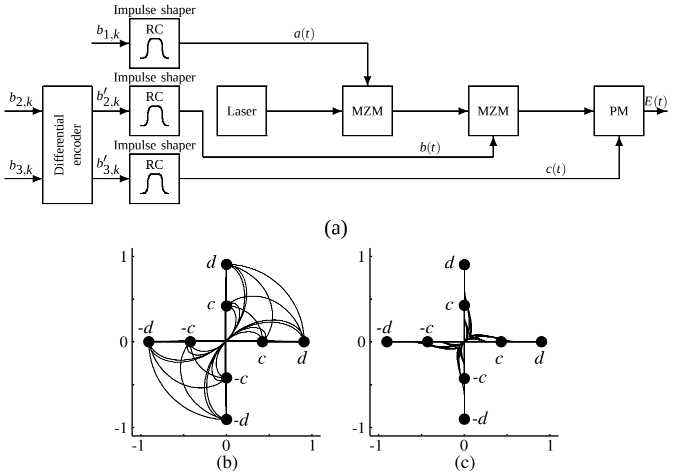

Fig. 2. (a) ASK-DQPSK transmitter and constellation diagrams with transitions for (a) NRZ and (b) RZ impulse shaping

[11]. The electrical drive signals $b(t)$ and $c(t)$, generated from the differentially encoded bit sequences $b'_{2,k}$ and $b'_{3,k}$, modulate the phase of the optical signal such that there are four different phase angles. So finally, at the sampling instants $t = nT$ the optical output signal $E(t)$ can have 2 different amplitudes $A(nT) = A_n \in \{d, c\}$ and 4 different phase angles $\varphi(nT) = \varphi_n \in \{n\pi/2; n = 0\ldots3\}$. The ASK-DQPSK transmitter uses the same raised-cosine impulse shapers as 8-DPSK with roll-off factor $\alpha = 0.5$ according to (1). RZ impulse shaping is identical to 8-DPSK.

The ASK-DQPSK constellation diagrams and the transitions between the 8 signal points are shown in Fig. 2(b) for NRZ and in Fig. 2(c) for RZ impulse shaping.

2.3 Bit error probability calculation

Throughout this paper we assume that *optical* additive white Gaussian noise is the dominant noise at the receivers. Bit error probabilities (BEP) are calculated using a semi-analytical method [14] as Gaussian Q-Factor based estimation of BEP can lead to inaccurate results for differentially phase modulated signals [15]. As we assume noise along the signal polarization only, we define the optical signal-to-noise ratio $\mathrm{OSNR} = 10 \cdot \log_{10}\left[P_{\mathrm{signal}}/(1 \cdot N_0 \cdot B)\right]$ with signal power P_{signal}, noise power density N_0 and reference bandwidth $B = 12.5\,\mathrm{GHz}$.

2.4 8-DPSK receivers

The basic receiver element in Fig. 3(a) is composed of a delay & add interferometer filter (DAF) with delay $\tau = T$ in one arm and phase shift ψ_j in the other arm together with a balanced detector using two photodiodes as shown. The electrical output signal is $I_j \sim \cos(\Delta\varphi + \psi_j)$. $\Delta\varphi$ stands for the phase difference of two consecutive symbols in the optical input signal $E(t)$. In principal, a receiver with two of these basic elements, in which the phase shifts of the two DAF satisfy $|\psi_2 - \psi_1| = \pi/2$, can be used to detect DPSK formats with an arbitrary number of levels, as all combinations

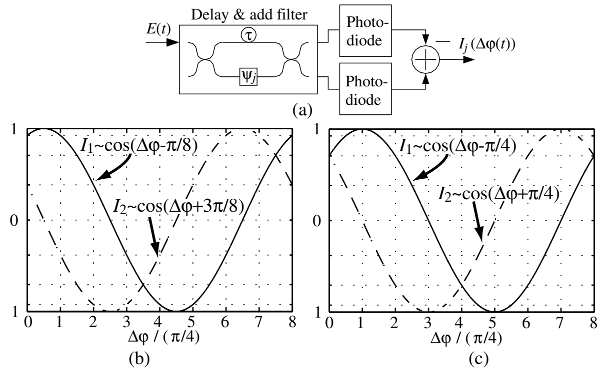

Fig. 3. (a) Basic receiver element with delay & add filter and balanced detector and electrical output signals vs. optical phase difference for (b) $\psi_1 = -\pi/8$ and $\psi_2 = 3\pi/8$ and (c) $\psi_1 = -\pi/4$ and $\psi_2 = \pi/4$

of $I_1(\Delta\varphi)$ and $I_2(\Delta\varphi)$ are unique for any $\Delta\varphi$. For 8-DPSK, two sets $\{\psi_1, \psi_2\}$ are useful: $\{-\pi/8, 3\pi/8\}$ (Fig. 3(b)) and $\{-\pi/4, \pi/4\}$ (Fig. 3(c)). As for 8-DPSK the phase differences $\Delta\varphi$ are integer multiples of $\pi/4$, the first set produces 4-level electrical signals and the second set provides 5-level electrical signals.

We have investigated the two 8-DPSK receivers shown in Figs. 4(a) and (b). The corresponding eye diagrams of their electrical signals at the inputs of the decision devices are depicted in Fig. 5(a) and (b) together with the decision thresholds E_{ik} and E_i for RZ impulse shaping. The phase shifts of the two DAF of the first receiver in Fig. 4(a) are set to $\psi_1 = -\pi/8$ and $\psi_2 = 3\pi/8$ [5], [9]. As can be seen from Fig. 5(a) the electrical signals have 4 logical levels, the receiver is thus labeled 8-DPSK-4L. In the upper branch there are 3 binary decision devices, in the lower branch only one. With proper differential encoding one single OR gate as shown in Fig. 4(a) can be used for recovering the bit sequence $\hat{b}_2$ from e_{11} and e_{13}. The other two bit sequences $\hat{b}_1$ and $\hat{b}_3$ correspond directly to the outputs of the decision devices e_{12} and e_{21}, respectively.

For the second receiver in Fig. 4(b) with the same hardware complexity the phase shifts of the DAF are now $\psi_1 = -\pi/4$ and $\psi_2 = \pi/4$ as in a DQPSK receiver. This produces 5-level electrical signals as can be seen from Fig. 5(b). However, they have only 3 logical levels [8]. This receiver is thus labeled 8-DPSK-3L. Both in the upper and lower branch there are two binary decision devices and a logic recovers the transmitted bit sequences from $e_{11}, e_{12}, e_{21}, e_{22}$.

Both receivers use 2^{nd} order optical Gaussian band-pass filters and 3^{rd} order electrical Bessel low-pass filters.

2.5 ASK-DQPSK receiver

The ASK-DQPSK receiver in Fig. 4(c) has an ASK branch with a single photodiode and binary decision device and a DQPSK branch with two DAF, two balanced detectors and two binary decision devices. The 2-level eye diagram in the ASK branch is shown in Fig. 5(c). The eye diagram in the DQPSK branch (Fig. 5(d)) has 6 electrical levels but only 2 logical levels, so that a binary decision device is sufficient. Note, that

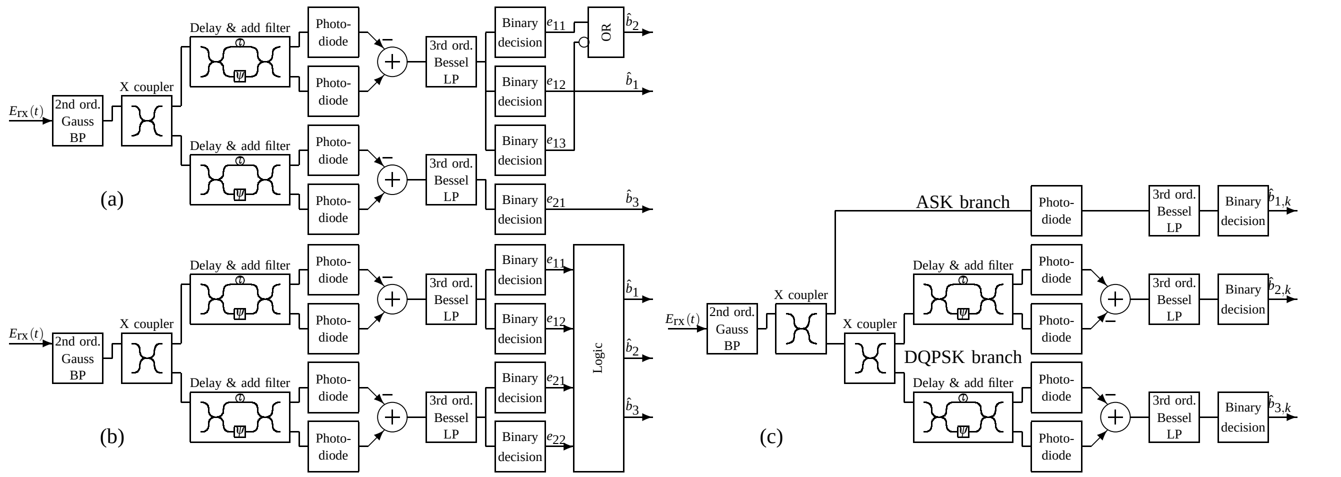

Fig. 4. 8-DPSK receiver with (a) 4-level electrical signals (8-DPSK-4L) and with (b) 3-level electrical signals (8-DPSK-3L), and (c) ASK-DQPSK receiver.

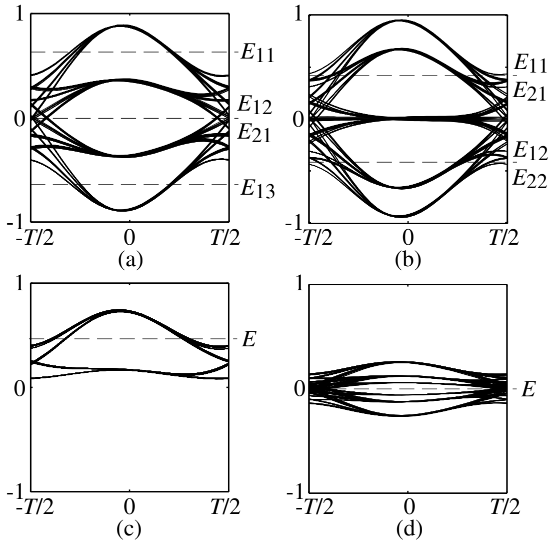

Fig. 5. Normalized eye diagrams at decision devices: (a) 8-DPSK-4L with 4 logical levels, (b) 8-DPSK-3L with 3 logical levels, (c) ASK branch of ASK-DQPSK and (d) DQPSK branch of ASK-DQPSK.

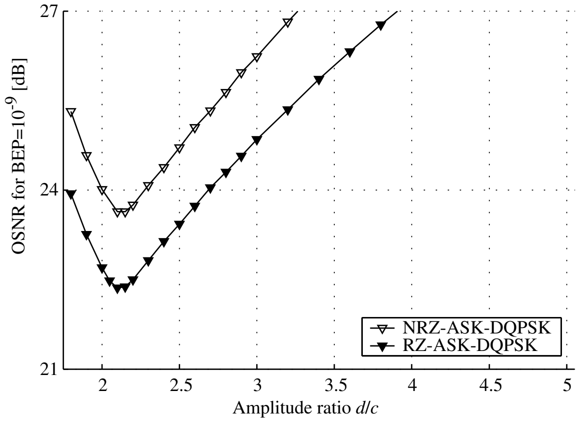

Fig. 6. Required OSNR for BEP $= 10^{-9}$ vs. ASK-DQPSK amplitude ratio d/c

all eye diagrams in Fig. 5 are for the same optical power in front of the optical band-pass filter, so that for ASK-DQPSK they appear by factor 2 smaller than for 8-DPSK because of the additional cross-coupler in Fig. 4(c), which attenuates both signal and noise.

The greater the ASK-DQPSK amplitude ratio d/c, the greater the eye opening in the ASK branch, but the smaller the eye opening in the DQPSK branch and vice versa. Thus, d/c needs to be optimized for minimal BEP. This has been investigated in [2]. The result is shown in Fig. 6 as required OSNR for BEP $= 10^{-9}$ vs. amplitude ratio d/c. For NRZ-ASK-DQPSK $d/c = 2.15$ and for RZ-ASK-DQPSK $d/c = 2.1$ are optimal as these ratios require the lowest OSNR. In Fig. 6, optimized optical and electrical receiver filter bandwidths for each amplitude ratio are considered.

The ASK-DQPSK receiver also uses 2nd order optical Gaussian band-pass filters and 3rd order electrical Bessel low-pass filters.

3. Performance Comparison

3.1 Receiver bandwidths

Fig. 7, Fig. 8 and Fig. 9 show contour plots of required OSNR for BEP $= 10^{-9}$ vs. electrical and optical receiver 3 dB bandwidths normalized to the symbol rate R_s. Subfigures (a) show the results for NRZ impulse shaping and subfigures (b) for RZ impulse shaping. In each plot the bandwidth pair which leads to the lowest required OSNR is marked with '$\times$'. These optimal bandwidths are summarized in Table I. Note that all plots are equally scaled but the value ranges may differ. For ASK-DQPSK the optimal amplitude ratios from subsection 2.5 have been used.

For NRZ-8-DPSK the optimal electrical bandwidth is $f_{3\,\mathrm{dB,el}} = 0.65 \cdot R_s$ and for RZ-8-DPSK it is $f_{3\,\mathrm{dB,el}} = 0.6 \cdot R_s$. For NRZ-8-DPSK-4L as well as for NRZ-8-DPSK-3L the 0.5 dB tolerance region around the optimum with respect to the electrical bandwidth is rather narrow from approx.

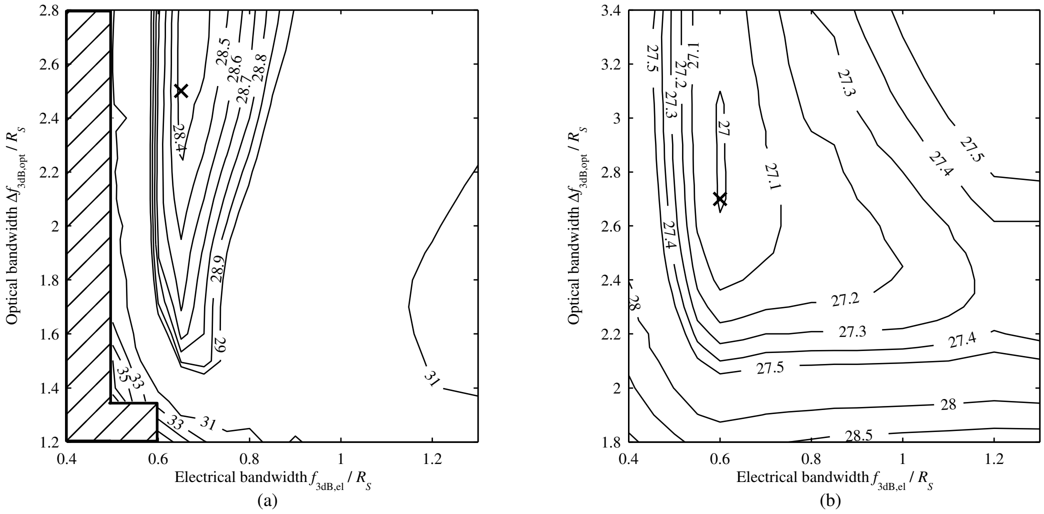

Fig. 7. Required OSNR for $\mathrm{BEP} = 10^{-9}$ vs. optical and electrical 8-DPSK-4L receiver bandwidths: (a) NRZ and (b) RZ

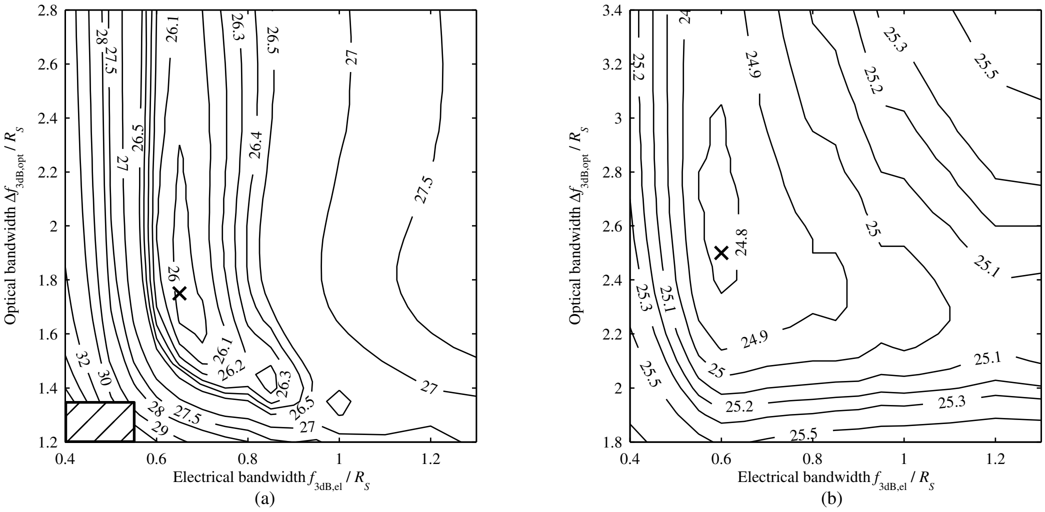

Fig. 8. Required OSNR for $\mathrm{BEP} = 10^{-9}$ vs. optical and electrical 8-DPSK-3L receiver bandwidths: (a) NRZ and (b) RZ

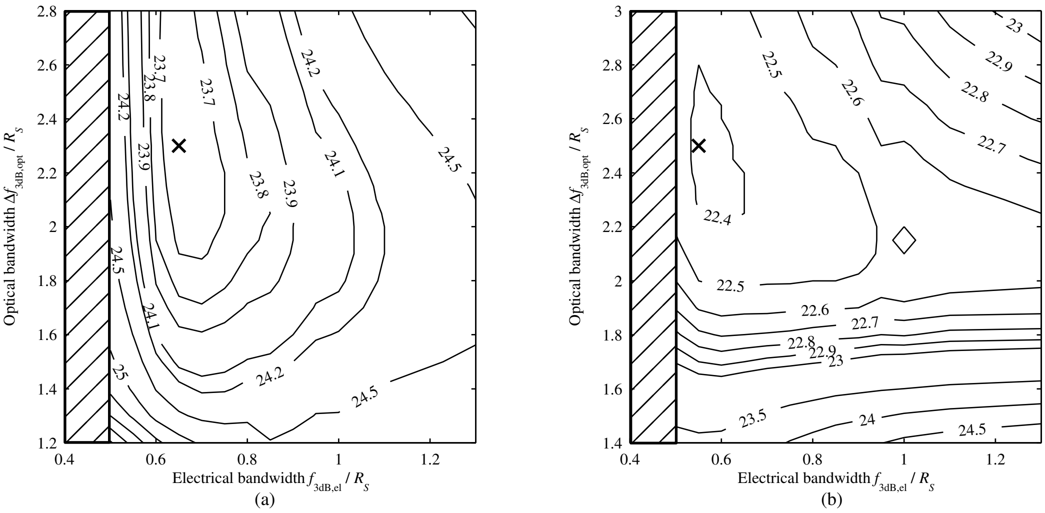

Fig. 9. Required OSNR for $\mathrm{BEP} = 10^{-9}$ vs. optical and electrical ASK-DQPSK receiver bandwidths: (a) NRZ and (b) RZ

TABLE I

OPTIMIZED OPTICAL AND ELECTRICAL RECEIVER FILTER BANDWIDTHS

Format	8-DPSK (4L)		8-DPSK (3L)		ASK-DQPSK	
	NRZ	RZ	NRZ	RZ	NRZ	RZ
$\Delta f_{3\,\mathrm{dB,opt}}/R_s$	2.5	2.7	1.75	2.5	2.3	2.5
$f_{3\,\mathrm{dB,el}}/R_s$	0.65	0.6	0.65	0.6	0.65	0.55

$0.6\ldots0.9\cdot R_s$. For RZ, however, the 0.5 dB tolerance region spans almost the whole considered electrical bandwidth range from $0.4\ldots1.3\cdot R_s$. The optimal optical bandwidth $\Delta f_{3\,\mathrm{dB,opt}}$ for NRZ-8-DPSK-3L is just $1.75\cdot R_s$ compared to $2.5\cdot R_s$ for NRZ-8-DPSK-4L. The 0.5 dB tolerance region reaches down to $\Delta f_{3\,\mathrm{dB,opt}} = 1.3\cdot R_s$ for NRZ-8-DPSK-3L, making it well suited for close channel spacing in dense wavelength-division multiplexing (DWDM). For RZ, 8-DPSK-3L again requires lower optical bandwidth than 8-DPSK-4L and also the 0.5 dB tolerance region goes to lower optical bandwidths.

For NRZ-ASK-DQPSK the 0.5 dB tolerance region with respect to the electrical bandwidth is with $0.55\ldots1.1\cdot R_s$ larger than for 8-DPSK. For RZ-ASK-DQPSK all considered electrical receiver bandwidths lead to required OSNR values less than 0.3 dB greater than the optimum, if the optical bandwidth is chosen properly. With respect to the optical bandwidth, the 0.5 dB tolerance region for NRZ-ASK-DQPSK goes down to $1.4\cdot R_s$ and for RZ-ASK-DQPSK down to $1.7\cdot R_s$.

The target is to use optimal receiver bandwidths for all ASK-DQPSK amplitude ratios. However, but computation of required OSNR vs. bandwidths turns out to be very time consuming. So we compute BEP vs. bandwidths for a fixed OSNR and then choose the bandwidth pairs with lowest BEP as adequate solution. For the previously considered amplitude ratios $d/c = 2.15$ (NRZ) and $d/c = 2.1$ (RZ), this method leads to the same optimal bandwidths in the RZ case and to the same optimal electrical but $0.1\cdot R_s$ higher optical bandwidth in the NRZ case. However, for this $0.1\cdot R_s$ higher bandwidth the required OSNR for $\mathrm{BEP} = 10^{-9}$ is just 0.01 dB higher than the OSNR at the bandwidth pair given in Table I.

3.2 Receiver sensitivities

As a direct result from the bandwidth optimization in subsection 3.1 receiver sensitivities in terms of required OSNR for $\mathrm{BEP} = 10^{-9}$ are listed in Table II. ASK, DPSK and DQPSK, all with raised-cosine impulse shaping according to (1) and with optimized receiver bandwidths, are also included in Table II.

Among the 8-level formats, ASK-DQPSK achieves the best sensitivity for both NRZ and RZ. Required OSNR for NRZ-ASK-DQPSK is 4.6 dB lower than for NRZ-8-DPSK-4L and 2.3 dB lower than for NRZ-8-DPSK-3L. RZ-ASK-DQPSK requires again 4.6 dB less OSNR than RZ-8-DPSK-4L and 2.4 dB less than RZ-8-DPSK-3L.

NRZ-ASK-DQPSK needs 1.8 dB, 5.2 dB and 2.3 dB more OSNR than NRZ-ASK, NRZ-DPSK and NRZ-DQPSK, respectively, and NRZ-ASK-DQPSK needs 1.3 dB, 4.2 dB and

TABLE II

RECEIVER SENSITIVITIES: REQUIRED OSNR FOR $\mathrm{BEP} = 10^{-9}$ AT ZERO RESIDUAL DISPERSION

OSNR [dB] for $\mathrm{BEP} = 10^{-9}$	ASK	DPSK	DQPSK	ASK-DQPSK	8-DPSK-4L	8-DPSK-3L
NRZ	21.8	18.4	21.3	23.6	28.2	25.9
RZ	21.1	18.1	20.1	22.4	27.0	24.8

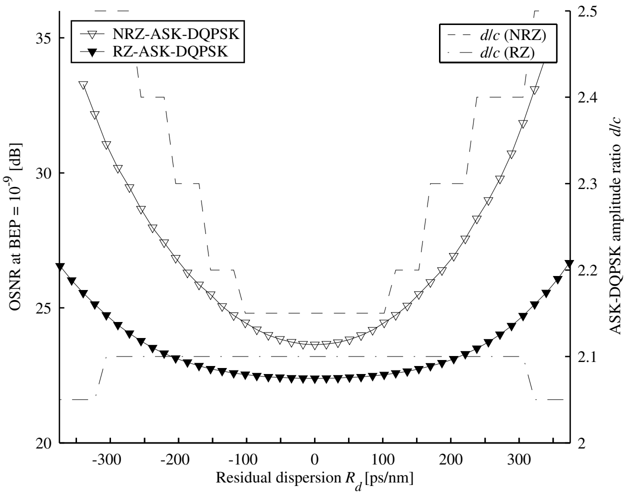

Fig. 10. Required OSNR for $\mathrm{BEP} = 10^{-9}$ vs. residual dispersion (left ordinate) and corresponding amplitude ratio d/c (right ordinate) for ASK-DQPSK

2.3 dB more OSNR than RZ-ASK, RZ-DPSK and RZ-DQPSK, respectively.

3.3 Chromatic dispersion tolerance

In [2] it has been shown, that the ASK-DQPSK amplitude ratio d/c needs to be adjusted for each amount of residual dispersion R_d in order to achieve the lowest required OSNR for $\mathrm{BEP} = 10^{-9}$. This result is depicted in Fig. 10. The right hand ordinate gives the optimal amplitude ratio d/c vs. residual dispersion, whereas the left ordinate shows the required OSNR. For NRZ, d/c needs to be increased for increasing magnitude of residual dispersion. For RZ, d/c remains almost constant. In the following investigations, the optimal amplitude ratios d/c according to Fig. 10 are chosen for each value of residual dispersion.

Fig. 11 now shows required OSNR for $\mathrm{BEP} = 10^{-9}$ vs. residual dispersion R_d for 8-DPSK, ASK-DQPSK, ASK, DPSK and DQPSK with (a) NRZ and (b) RZ impulse shaping. Tolerable residual dispersion ΔR_d for 1 dB and 2 dB OSNR penalties with respect to the minimal values are given in Table III.

Among the 8-level formats, 8-DPSK-3L and ASK-DQPSK have similar dispersion tolerance. Tolerable residual dispersion varies by less then 2% for RZ and less than 5% for NRZ. Further, at 1 dB(2 dB) OSNR penalty 8-DPSK-3L tolerates 6%(6%) more residual dispersion than 8-DPSK-4L for RZ and 16%(18%) more for NRZ. All 8-level formats tolerate more

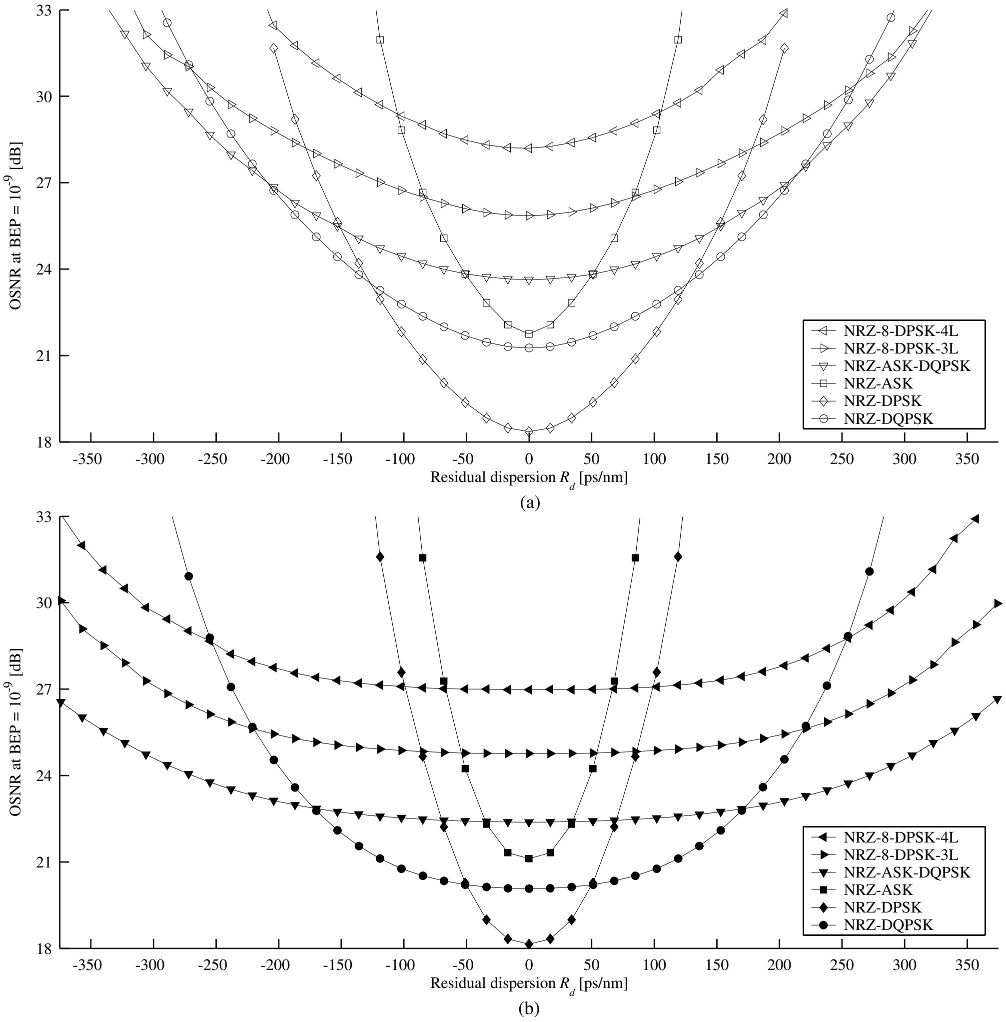

Fig. 11. Required OSNR for BEP $= 10^{-9}$ vs. residual dispersion for various modulation formats

TABLE III

TOLERABLE RESIDUAL DISPERSION ΔR_d

ΔR_d [ps/nm]	ASK		DPSK		DQPSK		ASK-DQPSK		8-DPSK-4L		8-DPSK-3L	
for OSNR penalty of	NRZ	RZ	NRZ	RZ	NRZ	RZ	NRZ	RZ	NRZ	RZ	NRZ	RZ
1 dB	64	61	101	72	161	234	226	455	188	437	216	461
2 dB	99	82	149	99	238	304	317	581	274	533	324	570

residual dispersion than ASK, DPSK and DQPSK. At 1 dB OSNR penalty, RZ-8-DPSK-3L allows 2 times more residual dispersion than RZ-DQPSK, about 6 times more than RZ-DPSK and about 7 times more than RZ-ASK.

4. CONCLUSION

We investigate the two 8-level optical modulation formats ASK-DQPSK and 8-DPSK. The transmitters of both formats have similar hardware complexity. With ASK-DQPSK the amplitude ratio of the signal points needs to be adjusted at the transmitter.

For 8-DPSK two receivers are considered: 8-DPSK-4L with 4-level electrical signals and 8-DPSK-3L with 3-level electrical signals. The ASK-DQPSK and the two 8-DPSK receivers need 2 delay & add filters. Further, the two 8-DPSK receivers require 4 photodiodes, compared to 5 for ASK-DQPSK. However, the 8-DPSK receivers need one binary decision device more plus a logic for recovering the transmitted bit sequences. The logic of the 8-DPSK-4L receiver can be reduced to one single OR gate.

For RZ impulse shaping, all three receivers can operate within a large range of optical and electrical receiver bandwidths while keeping the penalty below 0.5 dB with respect to the minimum required OSNR. For NRZ-8-DPSK the range of electrical receiver bandwidths is rather narrow around the optimum. For NRZ-ASK-DPQSK this range is slightly broader than for 8-DPSK. The 8-DPSK-3L optical receiver bandwidth can be reduced to as low as $1.3 \cdot R_s$ within a 0.5 dB penalty.

The receiver sensitivity of ASK-DPSK is 4.6 dB better than for 8-DPSK-4L and 2.3 dB(NRZ) or 2.4 dB(RZ) better than for 8-DPSK-3L. All 8-level formats have lower sensitivities than ASK, DPSK and DQPSK.

8-DPSK-3L and ASK-DQPSK have similar dispersion tolerance, which is the best of all considered formats. At 1 dB OSNR penalty, RZ-8-DPSK-3L tolerates 2 times more residual dispersion than RZ-DQPSK, about 6 times more than RZ-DPSK and about 7 times more than RZ-ASK.

Both ASK-DQPSK and 8-DPSK-3L are potential candidates for optical transmission systems using an 8-level modulation format. ASK-DQPSK is favorable when receiver sensitivity is the major issue, whereas 8-DPSK is better suited when the lower number of opto-electronic components at the receiver is more important.

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