Optimal Receiver Bandwidths, Bit Error Probabilities and Chromatic Dispersion Tolerance of 40 Gbit/s Optical 8-DPSK with NRZ and RZ Impulse Shaping

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Abstract: For the first time, optimal optical and electrical receiver bandwidths, bit error probabilities and chromatic dispersion tolerance of optical differential 8-level phase-shift keying are studied using a Karhunen-Loeve based semi-analytical method.

OCIS codes: (060.2330) Fiber optics communications; (060.5060) Phase modulation

1. Introduction

Multilevel optical modulation formats such as differential quadrature phase-shift keying (DQPSK)[1,2] and quaternary combined amplitude- and differential phase-shift keying (ASK-DPSK)[3] have drawn attention because of greater spectral efficiencies and dispersion tolerances than binary modulation formats such as amplitude-shift keying (ASK) or differential phase-shift keying (DPSK). Recently, differential 8-level phase-shift keying (8-DPSK) for even higher spectral efficiency has been proposed [4-6]. As the receivers in [5,6] are rather complicated and only thermal receiver noise [5] or Q-factor analysis [6], which is inaccurate for DPSK systems [7], are considered, we base our investigations on a slightly modified version of the much simpler original receiver from [4] and use a Karhunen-Loeve based semi-analytical method for bit error probability (BEP) calculation, which accounts for optical additive white Gaussian noise in front of the receiver [8]. For this case, we optimize optical and electrical receiver bandwidths and investigate BEP vs. optical signal-to-noise ratio (OSNR) and chromatic dispersion tolerance for 8-DPSK. The results are compared to DQPSK and DPSK for non-return-to-zero (NRZ) and return-to-zero (RZ) impulse shaping at bit rate $R_b = 40\,\text{Gbit/s}$.

2. 8-DPSK transmitter and receiver

The 8-DPSK transmitter is shown in Fig. 1. 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

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

$T = 1/R_s$ is the symbol duration, α is the roll-off factor, which is set to 0.5 throughout this paper. $R_s = R_b/3$ is the symbol rate. The inner part of the transmitter with the two parallel Mach-Zehnder modulators (MZM) corresponds to a DQPSK transmitter [1]. The optical signal $E_c(t)$ can thus take on four possible phase angles. In the following phase modulator (PM) the binary electrical signal $c(t)$ induces an additional phase shift of $\pi/4$ for bit 1 or leaves the optical signal unaltered for bit 0, producing the optical 8-level phase-shift keying signal $E(t)$. RZ impulse shaping with 50% duty cycle is achieved by modulating the amplitude of the NRZ signal in a subsequent MZM, which is not shown in Fig. 1(a), with a periodic sequence of electrical Gaussian impulses. Their full widths at half maximum are $0.5 \cdot T$. Constellation diagrams with phase transitions for NRZ and RZ are shown in Fig. 1(b,c).

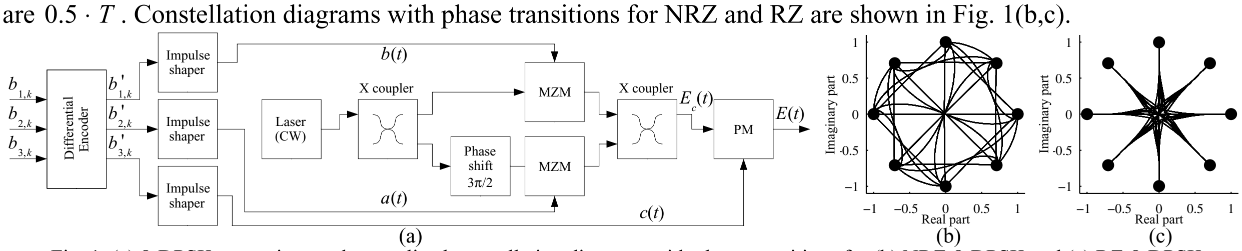

Fig. 1. (a) 8-DPSK transmitter and normalized constellation diagrams with phase transitions for (b) NRZ-8-DPSK and (c) RZ-8-DPSK

The 8-DPSK receiver is depicted in Fig. 2(a). The gray shaded part corresponds to a DQPSK receiver using two delay & add filters (DAF) with balanced detectors. However, other than for DQPSK the phase shifts in the DAF are set to $\psi = -\pi/8$ in the upper DAF and $\psi = 3\pi/8$ in the lower DAF. Then, the output signals of the electrical low-pass filters have four levels as shown in Fig. 2(b). The two multilevel electrical signals are processed by four binary decision

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devices with thresholds E_{ij}, $i = \{1, 2, 3\}$, $j = \{1, 2\}$, also indicated in Fig. 2(b), and a simple logic for obtaining estimates of the transmitted bit sequences $\hat{b}_1 = e_{12}$, $\hat{b}_2 = e_{11} + \overline{e_{12}} \cdot e_{13}$ and $\hat{b}_3 = e_{21}$. The considered receiver is a modified version of the receiver in [4] with the same number of DAF and photodiodes but with 4-level instead of 5-level electrical signals and a much simpler logic.

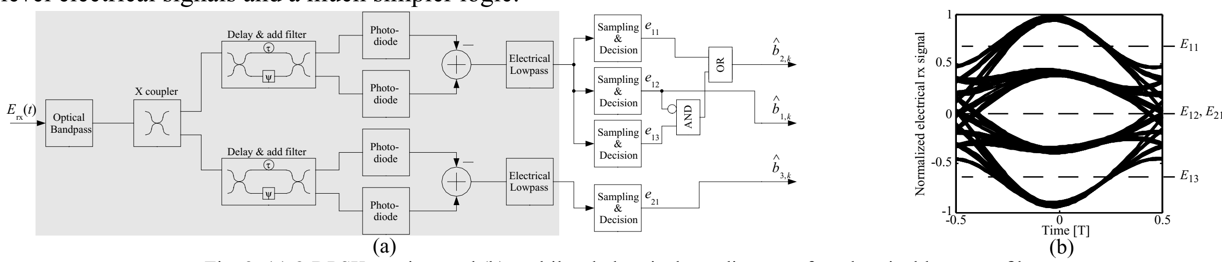

Fig. 2. (a) 8-DPSK receiver and (b) multilevel electrical eye diagram after electrical low-pass filter

For calculating BEP with the semi-analytical method we use a pseudo random sequence of 512 8-DPSK symbols, containing all possible combinations of three consecutive phase differences. The decision thresholds are optimized for minimal BEP throughout our investigations. The optical receiver filter is a 2nd order Gaussian band-pass filter and the electrical receiver filters are 3rd order Bessel low-pass filters. DPSK and DQPSK are references and use the same impulse shaper and receiver filter types as 8-DPSK.

3. Optimal optical and electrical receiver bandwidths

In Fig. 3 $\log_{10}(\text{BEP})$ at $\text{OSNR} = 28\,\text{dB}$ is plotted vs. electrical and optical receiver filter bandwidths normalized to the symbol rate R_s for NRZ and RZ impulse shaping. The points with lowest BEP are marked by '×'. Note, that both diagrams show different ranges on the vertical axes but have the same scaling.

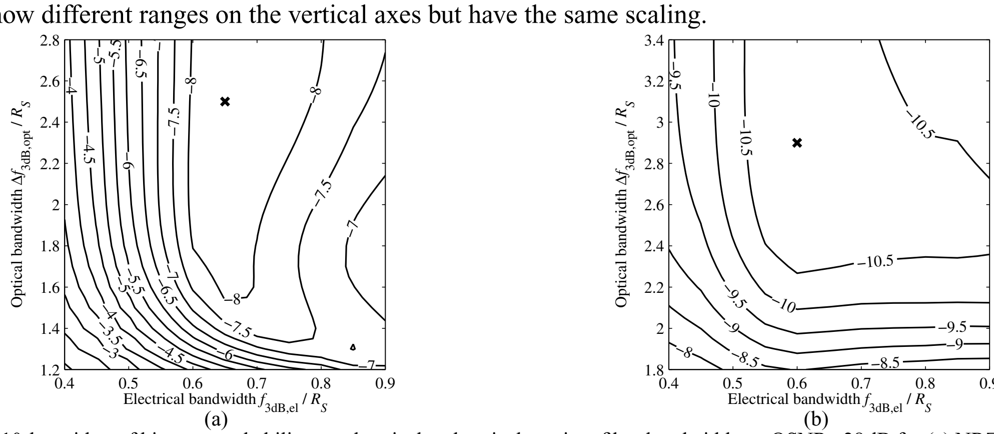

Fig. 3. Base-10-logarithm of bit error probability vs. electrical and optical receiver filter bandwidths at OSNR=28dB for (a) NRZ and (b) RZ

For NRZ in Fig. 3(a) the optimal electrical bandwidth is $0.65 \cdot R_s$ and the optimal optical bandwidth is $2.5 \cdot R_s$ with $\text{BEP} = 3.3 \cdot 10^{-9}$. The area in which $10^{-8.5} < \text{BEP} < 10^{-8}$ reaches down to an optical bandwidth of $1.6 \cdot R_s = 21.3\,\text{GHz}|_{R_b = 40\,\text{Gbit/s}}$, allowing for a close channel spacing in dense wavelength-division multiplexing (DWDM). For RZ in Fig. 3(b) the optimal electrical bandwidth is $0.6 \cdot R_s$ and the optimal optical bandwidth is $2.9 \cdot R_s$ with $\text{BEP} = 1.1 \cdot 10^{-11}$. The area in which $10^{-11} < \text{BEP} < 10^{-10.5}$ reaches down to an optical bandwidth of $2.3 \cdot R_s = 30.7\,\text{GHz}|_{R_b = 40\,\text{Gbit/s}}$.

4. Bit error probabilities

BEP vs. OSNR is plotted in Fig. 4 for NRZ and RZ with optimal receiver bandwidths. Obviously, 8-DPSK has a much higher BEP than DQPSK and DPSK, because the 8-DPSK signal points in the constellation diagram are much closer together than for DQPSK and DPSK. For achieving $\text{BEP} = 10^{-9}$, in the NRZ case 8-DPSK needs a 7.1 dB (9.0 dB) higher OSNR than DQPSK (DPSK). In the RZ case 8-DPSK needs a 6.9 dB (8.8 dB) higher OSNR than DQPSK (DPSK). In Fig. 4 the results of 8-DPSK Monte-Carlo simulations are included showing excellent agreement with the calculations, thus verifying the validity of the semi-analytical model for 8-DPSK.

5. Chromatic dispersion tolerance

Required OSNR for $\text{BEP} = 10^{-9}$ vs. residual dispersion R_d for linear fiber transmission is shown in Fig. 5. From this figure we can find the tolerance ranges of residual dispersion ΔR_d for which OSNR penalties of 1 dB or 3 dB are not exceeded. They are listed in Table 1.

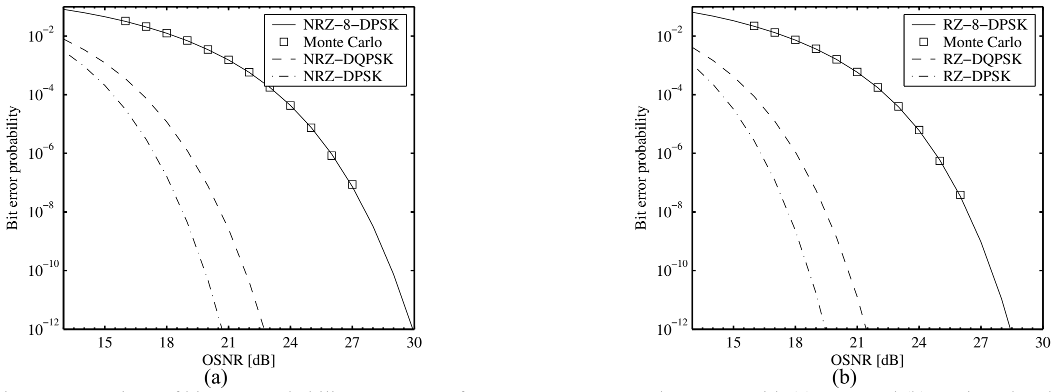

Fig. 4. Comparison of bit error probabilites vs. OSNR for DPSK, DQPSK, and 8-DPSK with (a) NRZ and (b) RZ impulse shaping

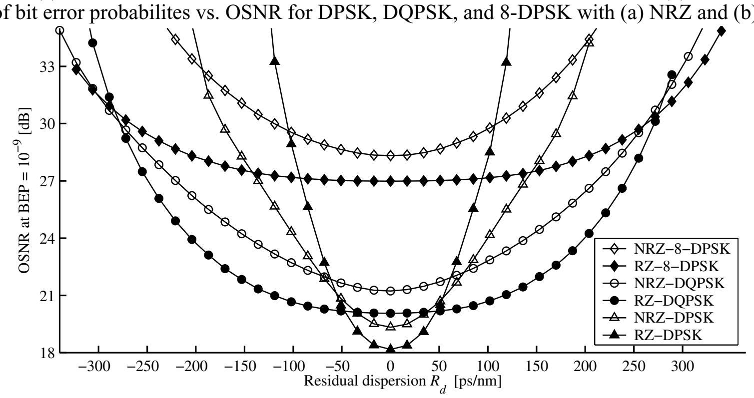

Fig. 5. Required OSNR for BEP=10^{-9} vs. residual dispersion for linear fiber transmission of DPSK, DQPSK, 8-DPSK

Table 1. Chromatic dispersion tolerance ranges ΔR_d

	NRZ-DPSK	RZ-DPSK	NRZ-DQPSK	RZ-DQPSK	NRZ-8DPSK	RZ-8DPSK
1 dB OSNR penalty	82 ps/nm	70 ps/nm	157 ps/nm	243 ps/nm	177 ps/nm	368 ps/nm
3 dB OSNR penalty	152 ps/nm	112 ps/nm	300 ps/nm	367 ps/nm	305 ps/nm	528 ps/nm

For both OSNR penalties 8-DPSK outperforms DPSK as well as DQPSK for NRZ and RZ. The greatest advantage is obtained for RZ impulse shaping. In this case, ΔR_d for RZ-8-DPSK is by about factor 1.5 larger than for RZ-DQPSK. Moreover, for $R_d < -300\,\mathrm{ps/nm}$ and $R_d > 280\,\mathrm{ps/nm}$ RZ-8-DPSK requires the lowest OSNR of all considered formats. However, within these boarders, OSNR is mostly higher.

6. Conclusion

For the first time we investigated optimal receiver bandwidths, bit error probabilities and chromatic dispersion tolerance of optical 8-DPSK using a semi-analytical method and Monte-Carlo simulations and compared the results to DPSK and DQPSK. As a modular solution, 8-DPSK transmitter and receiver are based on DQPSK building blocks. The additional hardware amount is small. We found that 8-DPSK offers a much higher dispersion tolerance than DPSK and DQPSK. As 8-DPSK requires a higher OSNR, however, it is especially suited for transmission without dispersion compensation but sufficient optical power at the receiver, e.g. metro systems. Furthermore, the low optical receiver bandwidths enable close channel spacing in DWDM.

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