16-level differential phase shift keying (D16PSK) in direct detection optical communication systems

Rakesh Sambaraju, Torger Tokle,
Jesper Bevensee Jensen and Palle Jeppesen
COM•DTU, Department of Communications, Optics and Materials,
Technical University of Denmark, Ørsteds Plads, 345V, DK-2800, Kgs. Lyngby, Denmark.
tt@com.dtu.dk

Abstract: Optical 16-level differential phase shift keying (D16PSK) carrying four bits for every symbol is proposed for direct detection optical communication systems. Transmitter and receiver schematics are presented, and the receiver sensitivity is discussed. We numerically investigate the impact of chromatic dispersion and nonlinear transmission degradations.

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

References and links

1. A. H. Gnauck and P. J. Winzer, "Optical phase-shift-keyed transmission," J. Lightwave Technol. **23**, 115–130, (2005).
2. T. Tokle, C. R. Davidson, M. Nissov, J.-X. Cai, D. G. Foursa, and A. Pilipetskii, "6500 km transmission of RZ-DQPSK WDM signals," Electron. Lett. **40**, 444–445, (2004).
3. A. H. Gnauck, P. J. Winzer, S. Chandrasekhar, and C. Dorrer, "Spectrally efficient (0.8 b/s/Hz) 1 Tb/s (25×42.7 Gb/s) RZ-DQPSK transmission over 28 100 km SSMF spans with 7 optical add/drops," in *Proceedings European Conference on Optical Communication, ECOC'04*, Stockholm, Sweden, paper Th4.4.1, (2004).
4. M. Ohm and J. Speidel, "Quaternary optical ASK-DPSK and receivers with direct detection," IEEE Photon. Technol. Lett. **15**, 159–161, (2003).
5. T. Tokle, P. A. Andersen, Y. Geng, B. Zsigri, C. Peucheret, and P. Jeppesen, "Generation, transmission and wavelength conversion of an 80 Gbit/s RZ-DBPSK-ASK signal," in *Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science and Photonic Applications Systems Technologies*, Technical Digest (CD), (Optical Soceity of America, 2005) paper CMQ4. http://www.opticsinfobase.org/abstract.cfm?URI=CLEO-2005-CMQ4
6. C. Kim and G. Li, "Direct-detection optical differential 8-level phase-shift keying (OD8PSK) for spectrally efficient transmission," Opt. Express **12**, 3415–3421, (2004). http://www.opticsexpress.org/abstract.cfm?URI=OPEX-12-15-3415
7. C. Kim, G. Goldfarb, Y. Han, Z. Li, X. Li, and G. Li, "WDM transmission over 320 km EDFA-amplified SSMF using 30 Gb/s return-to-zero optical differential 8-level phase-shift keying (OD8PSK)," Opt. Express **13**, 4044 – 4049, (2005). http://www.opticsexpress.org/abstract.cfm?URI=OPEX-13-11-4044
8. Y. Han, C. Kim, and G. Li, "Simplified receiver implementation for optical differential 8-level phase-shift keying," *Electron. Lett.*, **40**, 1372–1373, (2004).
9. S. Hayase, N. Kikuchi, K. Sekine, and S. Sasaki, "Chromatic dispersion and SPM tolerance of 8 state/symbol (binary ASK and QPSK) modulated signal," in *Optical Fiber Communication Conference*, Technical Digest (CD), (Optical Society of America, 2004), paper MF81. http://www.opticsinfobase.org/abstract.cfm?URI=OFC-2004-MF81
10. T. Tokle, M. Serbay, Y. Geng, J. B. Jensen, W. Rosenkranz, and P. Jeppesen, "Penalty-free transmission of multilevel 240 Gbit/s RZ-DQPSK-ASK using only 40 Gbit/s equipment," in *Proceedings European Conference on Optical Communication, ECOC'05*, Glasgow, Scotland, **6**, 11–12, post-deadline paper Th4.1.6, (2005)
11. K. Sekine, N. Kikuchi, S. Sasaki, S. Hayase, C. Hasegawa, and T. Sugawara, "Proposal and demonstration of 10 Gsymbol/sec 16-ary (40 Gbit/s) optical modulation / demodulation scheme," in *Proceedings European Conference on Optical Communication, ECOC'04*, Stockholm, Sweden, **3**, 424–425, paper We3.4.5, (2004).

#72466 - $15.00 USD
Received 28 June 2006; revised 6 October 2006; accepted 9 October 2006

1. Introduction

Differential binary phase shift keying (DBPSK) has attracted a lot of interest lately for long haul wavelength division multiplexing systems for its high tolerance towards fibre nonlinearities and the 3 dB receiver sensitivity improvement compared to on-off keying systems [1]. However, binary modulation formats offer relatively poor spectral efficiency. Recently, several methods of transmitting more than one bit per symbol have been investigated for optical communication systems. The main focus has been on differential quadrature phase shift keying (DQPSK), as demonstrated in several ultra-long-haul transmission experiments [2,3]. 4-level modulation has also been proposed using a combination of binary amplitude shift keying and binary differential phase modulation (ASK-DBPSK) [4,5]. Recently, there has also been some interest in optical modulation formats with 8 symbol levels, both differential 8-level phase shift keying (D8PSK) [6–8], and the combination of binary amplitude shift keying and differential quadrature phase modulation (ASK-DQPSK) [9,10]. Furthermore, the combination of quadrature amplitude shift keying and differential quadrature phase modulation (QASK-DQPSK) has been used to obtain 16 symbol levels, or 4 bits per symbol [11].

Here, we propose a 16-level differential phase shift keying (D16PSK) modulation format for upgrading existing 10 Gbit/s optical communication systems to 40 Gbit/s. D16PSK carries four bits for every symbol and thus the symbol rate for a 40 Gbit/s signal is 10 Gbaud, and consequently the spectral width is identical to that of 10 Gbit/s DBPSK. Thus, a 40 Gbit/s D16PSK channel could easily be substituted to an existing channel in a 10 Gbit/s wavelength division multiplexing (WDM) system.

We numerically study the transmission properties of 42.8 Gbit/s D16PSK over ten 80 km fibre spans, and the tolerance to chromatic dispersion. The performance of 42.8 Gbit/s D16PSK is compared to that of 10.7 Gbit/s DBPSK. Our results indicate good transmission performance and excellent dispersion tolerance of the D16PSK modulation format.

2. D16PSK transmitter and precoder

In D16PSK modulation format four data signals $[D_a(k), D_b(k), D_c(k), D_d(k)]$ each at a bit rate $\frac{B}{4}$ are input to a pre-coder, which output the pre-coded signals $[P_a(t), P_b(t), P_c(t), P_d(t)]$ also at a bit rate $\frac{B}{4}$. These pre-coded signals drive the modulators to generate a 16-level differential phase modulated optical signal at a symbol rate of $\frac{B}{4}$. As each symbol carries four bits, the signal bit rate is then B. In this work we focus on a symbol rate of 10.7 Gbaud, and thus a bit rate rate of 42.8 Gbit/s.

As shown in Fig. 1, light from a continuous wave laser is split into the two arms of the Mach-Zehnder parallel structure, where the Mach-Zehnder modulators are biased at the zero transmission point, and driven by a peak to peak voltage of $2V_\pi$, where V_π is the voltage required

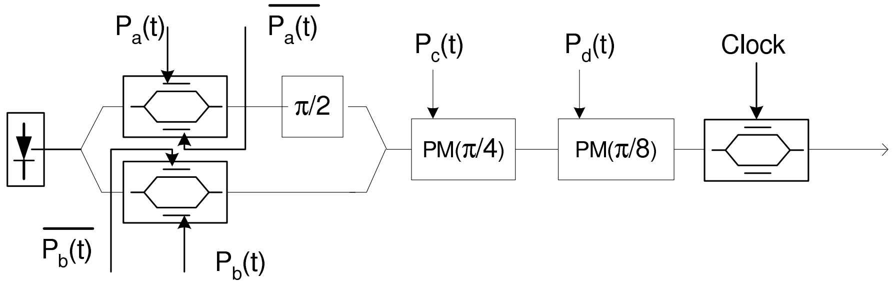


Fig. 1. Schematic of a D16PSK transmitter.

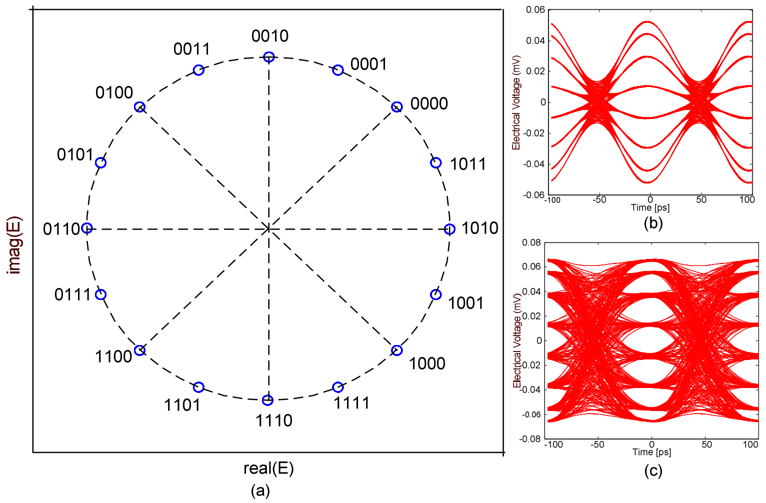


Fig. 2. Symbol allocation diagram of D16PSK as a function of pre-coded signal $[P_aP_bP_cP_d]$ (a). Eye diagram of demodulated D16PSK $R_a(t)$ with (b) and without (c) pulse carving in the back-to-back configuration.

to induce a π phase shift. By combining the upper and lower arms with a $\frac{\pi}{2}$ phase shift in the upper arm, a DQPSK signal is generated. Then, two concatenated phase modulators driven with the pre-coded electrical signals $P_c(t)$ and $P_d(t)$ add $\pi/4$ and $\pi/8$ phase modulation, respectively. Thus, a 16-level phase shift keyed signal is generated, having phase changes between successive symbols of $n\frac{\pi}{8}$, with $n = [0, 1, 2 \ldots 15]$. The output field can be written as

$$E(t) = E_0 \cos\left[\frac{\pi(P_a(t) - P_b(t)) + \frac{\pi}{2}}{2}\right] e^{j\left(\frac{\pi(P_a(t)+P_b(t))+\frac{\pi}{2}}{2} + P_c(t)\frac{\pi}{4} + P_d(t)\frac{\pi}{8}\right)}, \qquad (1)$$

where E_0 is the field at the input of the transmitter. In order to study return-to-zero (RZ) pulse shape, one last Mach-Zehnder modulator driven with a clock signal at the frequency equal to the symbol rate is used to carve pulses with a full width half maximum (FWHM) pulse width of 50 ps.

Since the receiver is based on differential demodulation, pre-coding of the input data signals is required to ensure reception of the correct data. The pre-coder was implemented as a look-up table, by calculating the pre-coded data as a function of all combinations of input data and the previous pre-coded data (2^8 combinations). This can easily be implemented once the output phase in the transmitter as a function of pre-coded data, and the output data in the receiver as a function of the differential phase change are known.

The D16PSK symbol allocation is illustrated in a constellation diagram as shown in Fig. 2, which shows the phase level as a function of the pre-coded signal $[P_aP_bP_cP_d]$. Also shown in Fig. 2 are the eye diagrams of NRZ-D16PSK and RZ-D16PSK after delay demodulation in the receiver.

3. Receiver

In the receiver, the phase modulated signal is demodulated to amplitude modulated signals using six Mach-Zehnder delay interferometer (MZDI) demodulators with delay equal to the symbol duration $\frac{4}{B}$, and detected using balanced photodiodes. The receiver design is based on the simplified D8PSK receiver as presented in [8]. The received data sequences

#72466 - $15.00 USD
Received 28 June 2006; revised 6 October 2006; accepted 9 October 2006

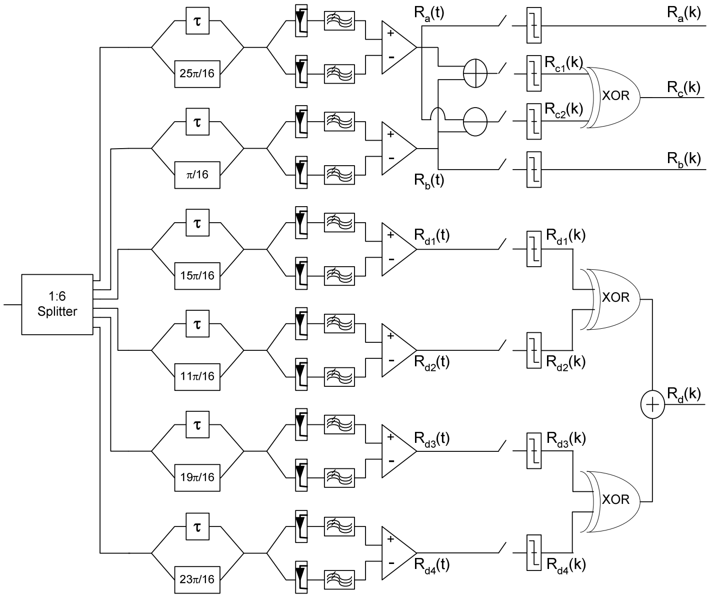


Fig. 3. Simplified D16PSK direct detection receiver. τ is equal to the symbol period.

$[(R_a(k)R_b(k)R_c(k)R_d(k))]$ are found using simple binary decision. The receiver has been designed in such a way that the received data is Gray coded with changes to the differential phase $\Delta\phi$.

As shown in the receiver schematic shown in Fig. 3, $R_a(t)$ and $R_b(t)$ are detected directly with one delay demodulator each, and the phase offsets in the MZDIs are $25\pi/16$ and $\pi/16$ respectively. R_c is found by processing $R_a(t)$ and $R_b(t)$ as

$$\begin{aligned} R_{c1}(k) &= R_a(k)+R_b(k) \\ R_{c2}(k) &= R_a(k)-R_b(k) \\ R_c(k) &= R_{c1}(k)\oplus R_{c2}(k), \end{aligned}$$

where $\oplus$ represents the logical XOR operation.

R_d is found by post-processing the outputs of the four MZDIs with phase offsets of $15\pi/16$, $11\pi/16, 19\pi/16, 23\pi/16$, respectively

$$R_d(k) = (R_{d1}(k)\oplus R_{d2}(k)) + (R_{d3}(k)\oplus R_{d4}(k)) \tag{2}$$

Where R_{d1}, R_{d2}, R_{d3} and R_{d4} are the balanced signals from the four demodulators.

4. Dispersion tolerance

In a noise-free system, we calculate the eye opening penalty (EOP) of of 42.8 Gbit/s D16PSK and compared it with 10.7 Gbit/s DBPSK for various values of accumulated dispersion. We quantify the system penalty as the average EOP for all six electrical signals $R_a(t)$, $R_b(t)$, $R_{d1}(t)$, $R_{d2}(t)$, $R_{d3}(t)$ and $R_{d4}(t)$. The resulting EOP versus accumulated dispersion is presented in Fig. 4.

The 1 dB EOP for 42.8 Gbit/s RZ-D16PSK is after ±380 ps/nm of accumulated dispersion, and ±200 ps/nm for 42.8 Gbit/s NRZ-D16PSK. For 10.7 Gbit/s DBPSK we observe a dispersion tolerance of ±500 ps/nm for RZ and ±1250 ps/nm for NRZ.

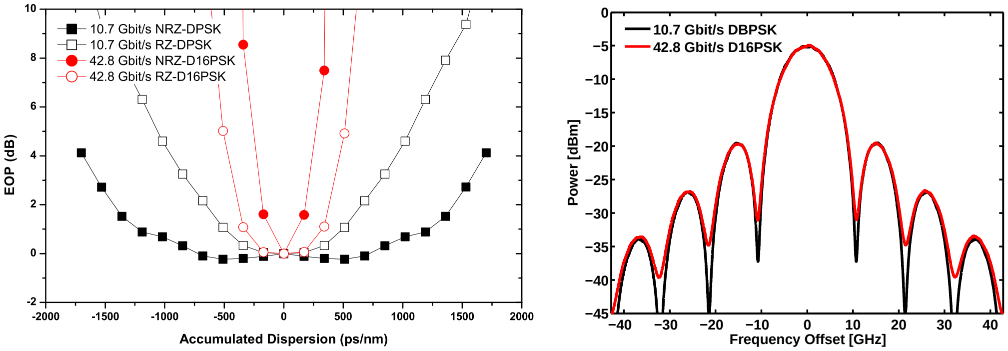


Fig. 4. Dispersion tolerance (left) and optical power spectra (right) of 42.8 Gbit/s D16PSK and 10.7 Gbit/s DBPSK. (Optical power spectra are shown for RZ pulse carving.)

An interesting point to notice is that 42.8 Gbit/s RZ-D16PSK only has 36% lower dispersion tolerance compared to 10.7 Gbit/s RZ-DBPSK. On the other hand, 42.8 Gbit/s NRZ-D16PSK suffers from very poor dispersion tolerance, six times lower than 10.7 Gbit/s NRZ-DBPSK.

5. Transmission properties

The transmission performance of D16PSK was numerically evaluated at a bit rate of 42.8 Gbit/s, both for RZ and NRZ coding. The schematic of the system under investigation is presented in Fig. 5. The fibre span consists of 80 km standard single-mode fibre (SSMF) and 13.6 km of dispersion compensating fibre (DCF), and the input power to the span was varied from −9 dBm to +9 dBm. The input power to the DCF was fixed at −6 dBm. A second order Gaussian optical band pass filter with a 3 dB bandwidth of 100 GHz is followed by a pre-amplified balanced receiver. The detected electrical signals are low-pass filtered with a fourth order low-pass Bessel filter with a 3 dB bandwidth of 7.5 GHz, before the receiver sensitivity calculation. The bit error rate (BER) of the system as a whole was calculated using Monte-Carlo simulations and found as $BER_{D16PSK} = \frac{1}{4}(BER_a + BER_b + BER_c + BER_d)$.

We study the transmission performance after 5 spans (400 km) and 10 spans (800 km) for various span input powers. The system quality is quantified by the power penalty at a BER threshold of 10^{-3}, the BER level at which the system will be error free after forward error correction (FEC) decoding.

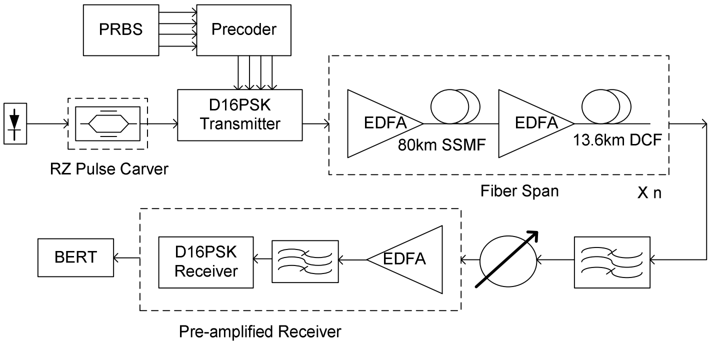
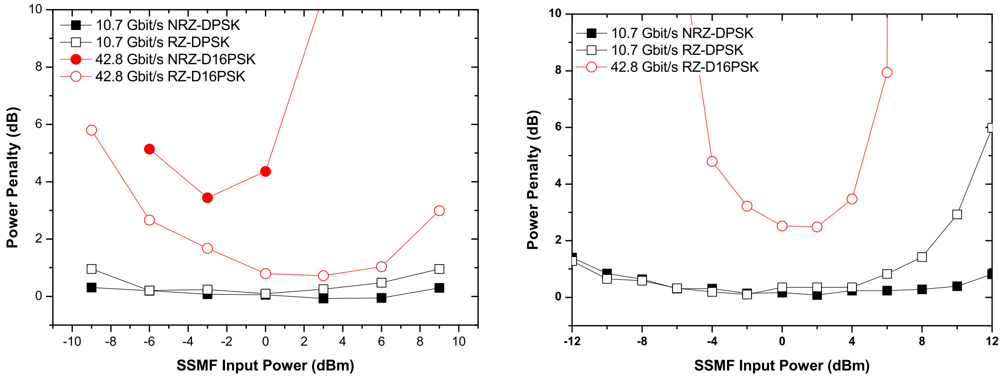


Fig. 5. Simulation setup of a D16PSK transmission system.

#72466 - $15.00 USD
Received 28 June 2006; revised 6 October 2006; accepted 9 October 2006



(a) 400 km (b) 800 km

Fig. 6. Input power tolerance of a 42.8 Gbit/s D16PSK transmission system, compared to 10.7 Gbit/s DBPSK, after 5 spans (a) and 10 spans (b).

The resulting power penalty versus SMF input power is plotted in Fig. 6. For comparison, the results of 10.7 Gbit/s DBPSK is also shown. We notice that the 10.7 Gbit/s DBPSK signals suffer almost no power penalty at these distances and power levels. For 42.8 Gbit/s RZ-D16PSK, we see a power penalty less than 1 dB for span input powers from -1 dBm to $+6$ dBm after 400 km (5 fibre spans), and less than 3 dB power penalty for span input powers between -2 dBm and $+3$ dBm after 800 km (10 spans). NRZ-D16PSK severely suffers from low tolerance to self-phase modulation, and has a power penalty above 3 dB after 400 km. ’

6. Conclusion

16 level differential phase shift keying (D16PSK) modulation format for use in direct detection optical communication systems has been proposed. We have presented transmitter and receiver structures, and have implemented pre-coding using a look-up table.

42.8 Gbit/s RZ-D16PSK offers a factor four bit rate increase at the cost of a 36% dispersion tolerance reduction compared to 10.7 Gbit/s RZ-DBPSK. Numerical simulations on a full optical communication system shows that 42.8 Gbit/s RZ-D16PSK only has 0.7 dB (400 km) and 2.5 dB (800 km) higher power penalty compared to 10.7 Gbit/s RZ-DBPSK at optimum span input power. NRZ-D16PSK is shown to suffer dramatically from self-phase modulation, and induces a power penalty over 3 dB already after 400 km.

RZ-D16PSK can thus be an attractive modulation format for upgrading the per channel bit rate from 10 Gbit/s to 40 Gbit/s for optical communication systems with a maximum transmission distance of a few hundred kilometres.

Acknowledgements

This work was partially funded by the *MultiSpeed* project under The Danish Council for Strategic Research.

Received 28 June 2006; revised 6 October 2006; accepted 9 October 2006