

Bit-error rate performance of 20 Gbit/s WDM RZ-DPSK non-slope matched submarine transmission systems

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ABSTRACT

Applying direct error counting, we assess the performance of 20 Gbit/s wavelength-division multiplexing return-to-zero differential phase-shift keying (RZ-DPSK) transmission at 0.4 bit/(s Hz) spectral efficiency for application on installed non-zero dispersion-shifted fibre based transoceanic submarine systems. The impact of the pulse duty cycle on the system performance is investigated and the reliability of the existing theoretical approaches to the BER estimation for the RZ-DPSK format is discussed.

Keywords: optical fibre, bit-error rate, submarine fibre, transoceanic submarine systems

1. INTRODUCTION

New submarine fibre transmission solutions are required to meet transoceanic traffic needs over the next few years. Existing optical fibre undersea networks are designed for $N \times 2.5$ Gbit/s or $N \times 10$ Gbit/s bit rate and amplitude-shift keying (ASK) modulation. These systems, which have been installed in large numbers over the last decade, usually use a mix of negative dispersion, non-zero dispersion-shifted (NZ-DSF) fibre and standard single mode fibre (SMF). Their upgrades by means of higher bit rates and advanced modulation formats have recently attracted considerable attention¹⁻⁷. It should be noted that higher bit rates generally afford higher spectral efficiencies insofar as the optical bandwidth occupied by a wavelength channel of double the bit rate (for instance) will usually occupy less than double the spectral bandwidth of the system. The reasons for this are that the theoretical optimum bandwidth of a low bit rate system may be too narrow to be manufacturable, and that the channels can be packed more closely owing to the lower susceptibility of high bit rate pulses to nonlinear interactions with adjacent channels. On the other hand, the recent advances in forward-error correction (FEC) technology can help to offset the optical signal-to-noise ratio penalty that results from the reduced power per pulse for a given channel power associated with the increased bit rate. The application of differential phase-shift keying (DPSK)⁸⁻¹⁰ - a format shown to have about 3-dB improved receiver sensitivity and enhanced tolerance to nonlinear impairments over ASK - to legacy undersea systems using the conventional non-slope matched DSFs has already been demonstrated at both 10 Gbit/s¹ and 40 Gbit/s^{2,3}. However, recently a side-by-side comparison of 10 Gb/s and 40 Gb/s return-to-zero (RZ) DPSK using the same nominal spectral efficiency over transoceanic distances showed a lower net bit-error rate (BER) margin for 40 Gbit/s⁴. Most recently, 20 Gbit/s RZ-DPSK was indicated as a strong candidate for upgrading non-slope matched undersea transmission links⁵⁻⁷, by offering the potential for similar performance as 10 Gbit/s RZ-ASK at twice the spectral efficiency, and higher performance than 40 Gbit/s RZ-DPSK at the same spectral efficiency. Since currently it does not seem possible, even with new generation modulation formats and FEC, to achieve transatlantic transmission at 40 Gbit/s with any comfortable margin, it may be that 20 Gbit/s is the bit rate of choice for long-haul transmissions.

The major goal of this paper is to theoretically assess the BER performance of a typical non-slope matched transoceanic WDM submarine transmission link using 50-GHz spaced RZ-DPSK at a bit rate of 20 Gbit/s (0.4 bit/(s Hz) spectral efficiency) with different duty cycles of the signal pulses. Note that a variety of new transmission regimes similar to that in high-bit-rate systems can be applied even in existing systems operating at lower bit rate. For instance, as it was.

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pointed out in reference¹¹, a pseudo-linear, bit-overlapping transmission regime that is typically attributed to 40 Gbit/s systems can be advantageously applied at 10 Gbit/s rates using short carrier pulses and RZ-DPSK format. We would like to stress that by varying the pulse duty cycle at 20 Gbit/s channel rate it is possible to realise quite different transmission regimes, ranging from a pseudo-linear regime to a dispersion-managed soliton-like one. Therefore, an optimal choice of the duty cycle in 20 Gbit/s ultra-long-haul systems is an interesting research problem⁶. We also discuss the reliability of different available Q-factor approaches to the BER estimation for the RZ-DPSK format^{12,13}, and investigate their accuracy with respect to the different duty cycles by comparing their predictions to the results of direct error counting

2. SYSTEM DESCRIPTION AND NUMERICAL MODELLING

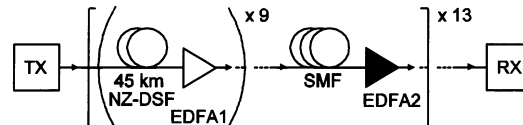


Fig. 1. Setup of the transmission link.

The transmission link used in our analysis is depicted in Figure 1. It emulates a non-slope matched submarine type link^{5,6}. The unit cell of the system comprises nine sections of NZ-DSF of length 45 km each, followed by a section of standard SMF. The NZ-DSF has a dispersion of $D = -3\text{ps}/(\text{nm km})$, a dispersion slope of $S = 0.09 \text{ ps}/(\text{nm}^2 \text{ km})$, an attenuation of $\alpha = 0.2 \text{ dB}/\text{km}$, and an effective area of $A_{\text{eff}} = 54 \mu\text{m}^2$. The parameters of the SMF are: $D = 16\text{ps}/(\text{nm km})$, $S = 0.057 \text{ ps}/(\text{nm}^2 \text{ km})$, $\alpha = 0.2 \text{ dB}/\text{km}$, and $A_{\text{eff}} = 80 \mu\text{m}^2$. The values of D , α and A_{eff} are given at 1550 nm. The nonlinear Kerr coefficient is $2.35 \times 10^{-20} \text{ m}^2/\text{W}$. The residual path-averaged dispersion of the line at 1550 nm is zero. Erbium-doped fibre amplifiers (EDFAs) with a noise figure of 4.5dB are used at the end of each fibre section to compensate for the energy losses in the fibres. The unit cell of the system is repeated thirteen times to yield a total transmission length of approximately 6300 km. Seven wavelength 20 Gbit/s RZ-DPSK data channels symmetrically distributed around 1550 nm and with a spacing of 50 GHz are transmitted over the line. Each channel is modelled by a random bit sequence formed with Gaussian pulses. The input pulses have the duty cycles of 20%, 33% and 50%, which enables us to realize quite different propagation regimes. Signal multiplexing is accomplished by use of a Gaussian optical bandpass filter (OBPF). At the receiver, the signal is filtered using an OBPF/demultiplexer (DEMUX) identical to the multiplexer (MUX), detected using a balanced Mach-Zehnder delay interferometer, and then filtered electrically by a fourth-order Butterworth filter with a cut-off frequency equal to the bit rate.

In our modelling, we compute the signal BER by direct counting of errors. For comparison, we also use BER estimates in terms of the signal Q-factor, which is closely related to the error probability and is a widely used tool to estimate the performance of optical transmission systems because it is relatively easy to evaluate, thus preventing the need for time-consuming direct counting. We use here the standard Q-factor of the received electrical signal (Q_{el})¹², and the Q-factors defined for the optical (differential) phase ($Q_{\Delta\phi}$) and the field amplitude before demodulation (Q_A) of the signal, which were introduced in reference¹³ to estimate the BER in a DPSK channel in the nonlinear and linear regimes, respectively.

The BER is estimated from Q_{el} , $Q_{\Delta\phi}$ and Q_A using the expressions: $\text{BER}(Q_{\text{el}}) = (1/2) \text{erfc}(Q_{\text{el}}/\sqrt{2})$, $\text{BER}(Q_{\Delta\phi}) = \text{erfc}(Q_{\Delta\phi}/\sqrt{2})$ and $\text{BER}(Q_A) = (1/2) \exp(-Q_A^2/2)$ ^{12,13}, which are calculated using the Gaussian approximation of the intensity noise, the field amplitude noise and the noise at the centre of each rail of the differential phase eye diagram, respectively.

3. NUMERICAL RESULTS AND DISCUSSION

First, we optimize the pre- and post-compensation dispersions of the system and the launch signal power for the different input pulse duty cycles used in this work. We use the electrical Q-factor as an indicator of the system performance. The Q-factor is calculated at the end of the unit cell of the link, and averaged over a number of 1024-bit pattern runs. The 3-dB bandwidth of the MUX/DEMUX is optimized for each duty cycle through back-to-back simulations. Figure 2 shows

contour-plots of the Q^2 -factor of the weakest channel at the output of the transmission link in the plane pre-compensation dispersion (D_{pre} , given at 1550 nm) – launch average power per channel. Here, the post-compensation dispersion, D_{post} , is selected such that $D_{post} = -D_{pre} + \delta D$ (at zero line average dispersion), i.e. fine tuning of the 50/50 pre/post-compensation ratio is performed by addition of a dispersion amount δD . The results are shown at the optimum δD , which turns out to fall around 50 ps/nm for the 20% and 33% duty cycles, and around 300 ps/nm for the widest duty cycle (see Fig. 3). It can be seen that the optimum pre-compensation and average power vary from approximately (400 ps/nm, -2.4 dBm) for the 20% duty cycle, to approximately (700 ps, -4.5 dBm) for the 33% duty cycle, and to (700 ps/nm, -6.2 dBm) for the 50% duty cycle, while there are sufficiently large power margins within the dispersion range 300 ps/nm to 1000 ps/nm for all duty cycles. It is also seen that narrower pulses than the conventional 50% duty-cycle pulses offer superior performance in terms of higher Q -values, as it is observed in the case of a single-channel transmission⁶. The tolerance of the system performance to deviations of the fine-tuning post-compensation dispersion δD from its optimal value is illustrated in Fig. 3, which shows the Q^2 -factor penalty as a function of δD for the three duty cycles studied. Here, the Q^2 -penalty is defined as $10 \log_{10} (Q_{opt}/Q)$, where Q is the Q -factor at a given δD and Q_{opt} is the Q -factor at the optimal δD . It can be seen that the largest duty cycle is the most tolerant to variations in δD , as it might be expected. Overall, the results of Figs. 2 and 3 indicate that the use of shorter pulse duty cycles than the conventional 50% can improve the performance margin of the system. This gain in performance, however, can be achieved at the expenses of a reduced tolerance against variations/fluctuations of the net link dispersion and, hence, more tough conditions imposed on the post-compensation of chromatic dispersion. Selection of the duty cycle should therefore be performed in accordance with availability of tuneable dispersion post-compensating devices.

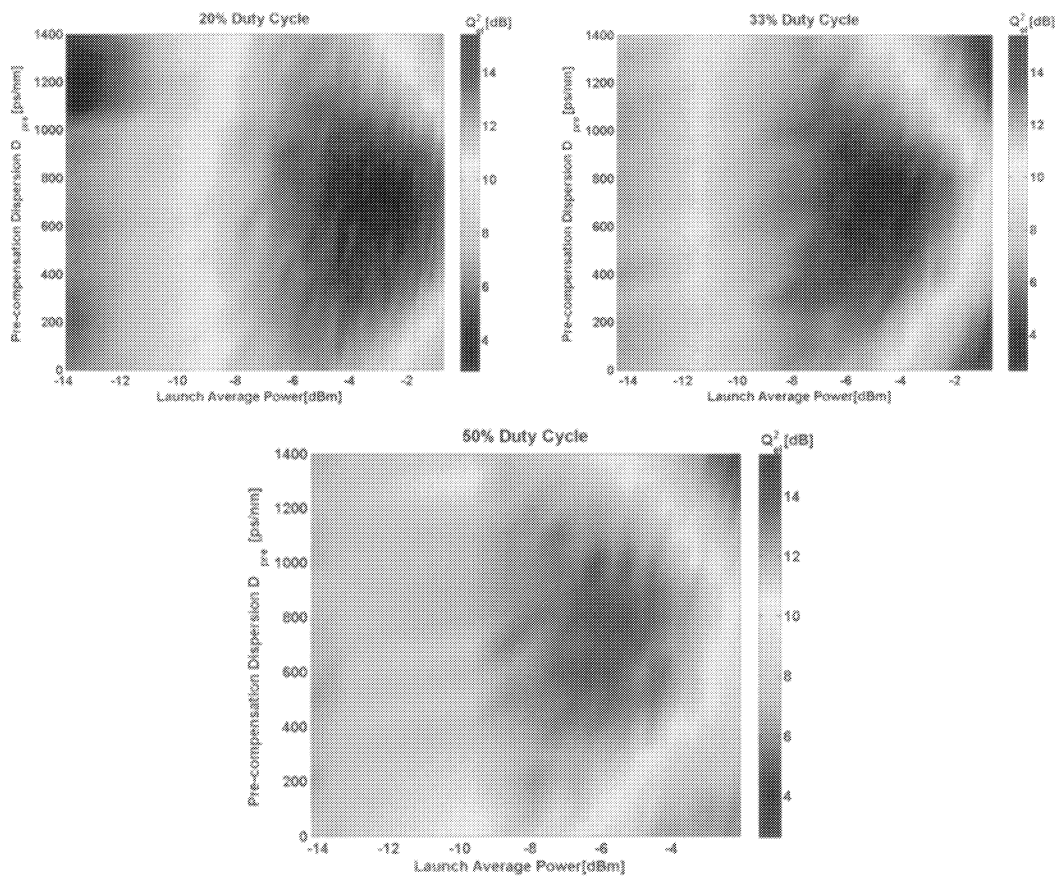


Fig. 2. Electrical Q^2 -factor versus launch average power per channel and pre-compensation dispersion for 50 GHz-spaced 20 Gbit/s WDM RZ-DPSK transmission.

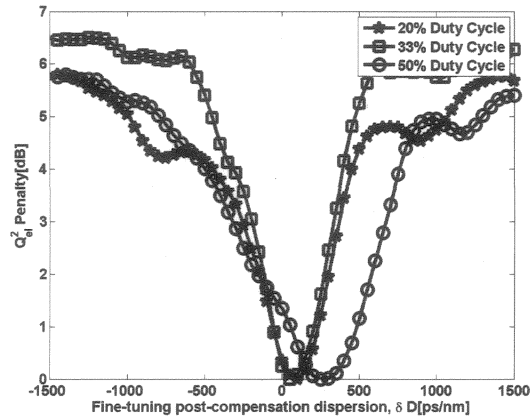


Fig. 3. Q^2 -factor penalty of deviation from optimal fine-tuning post-compensation dispersion.

Based on the optimal pre-/post-compensation dispersion settings suggested by the results in Fig. 2, we assess the BER performance of the system through direct error counting. Direct computation is limited to BERs of 10^{-5} or higher so that good error statistics can be obtained within a reasonable amount of computation time. Note that this corresponds to an acceptable error level before FEC. Sequences of 16384 bits were transmitted over larger distances than the total length of the transmission link, and the results were averaged over a number of runs. Figure 4 shows the evolution of the BER of the weakest WDM channel over the transmission distance at different launch per-channel average powers for the three duty cycles studied. A range of powers is used which covers the optimal operating regions depicted in the results of Fig. 2. An exemplary variation of the BER with the launch average power is shown in Fig. 5, where the BER is recorded at 11500 km transmission distance. It appears from Figs. 4 and 5 that the 33% duty cycle outperforms both the 20% and 50% duty cycles by offering the highest BER margin as well as substantial tolerance to variations in the signal power. It can also be noted that the optimal launch power and pre-compensation combination suggested by the Q-factor estimates of Fig. 2 is not necessarily adhered to when the actual BER is computed.

Next, we compare the accuracy of the electrical, differential phase, and amplitude Q-factor models versus the directly computed BER. Figure 6 shows the evolution of the theoretical BERs and the actual BER over the transmission distance at the optimal launch average power given by the results in Fig. 5. It can be seen that for all duty cycles Q_A and Q_{el} compete to one another at yielding the most reliable estimate of the actual BER, and the predictions based on these Q-factor models are more accurate at large distances. On the other hand, $Q_{\Delta\phi}$ significantly overestimates the actual BER.

This is an indication that the transmission regime is quasi-linear¹³. The fact that the conventional electrical Q-factor is a fairly performance indicator would suggest that electrical current statistics in such channels are largely Gaussian – these assumptions have been subject to recent investigation¹⁴. It is also seen clearly from Fig. 6 that the 33% duty cycle pulses achieve the highest BER margin, which confirms the conclusion drawn from Fig. 4. Indeed, supposing an extension of the directly computed BER curves to the region of short distances with either $BER(Q_A)$ or $BER(Q_{el})$ as a reference curve, a BER of 10^{-9} would relate to a transmission distance of approximately 5500 km for the 20% duty cycle, 6500 km for the 33% duty cycle, and 5000km for the widest duty cycle. In any case, the results for the three duty cycles studied show that error-free 20 Gbit/s RZ-DPSK transmission at 50 GHz channel separation is feasible beyond the design length of typical installed submarine links with no need for in-band slope compensation of chromatic dispersion, which confirms the experimental observations and theoretical predictions of previous works⁵⁻⁷.

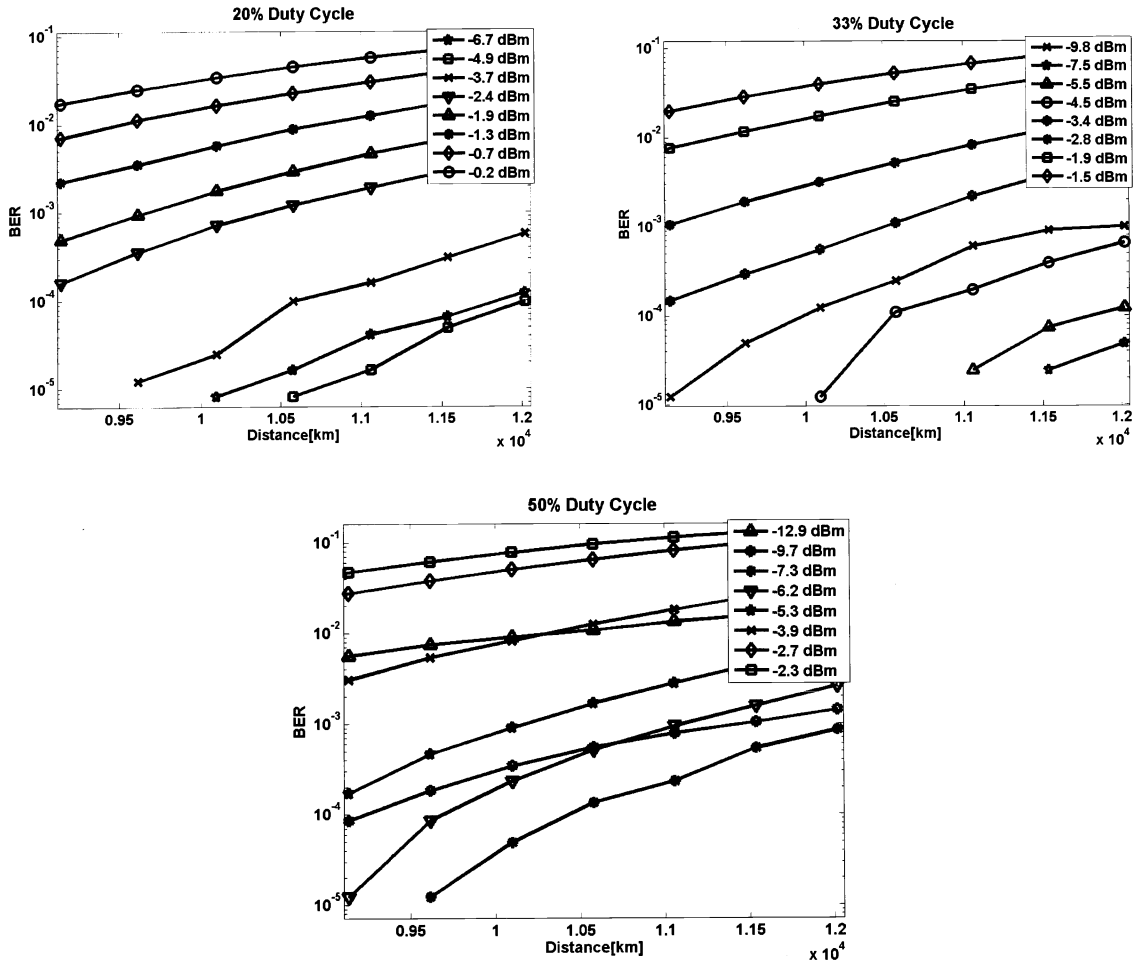


Fig. 4. BER evolution over the transmission distance at different launch average powers per channel for 50 GHz-spaced 20 Gbit/s WDM RZ-DPSK transmission.

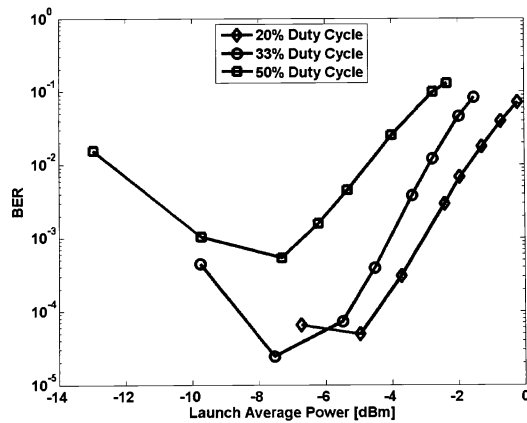


Fig. 5. BER variation with launch average power per channel at 11500 km transmission distance.

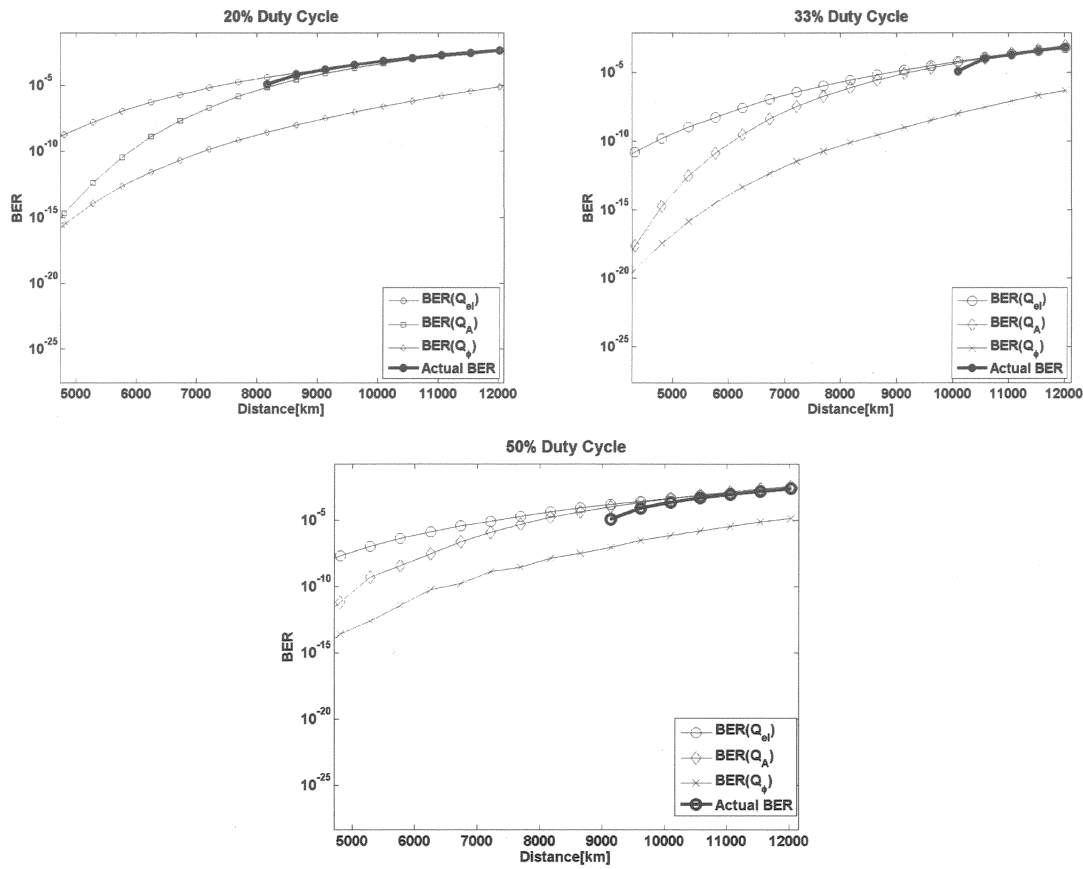


Fig. 6. Theoretical BERs and directly computed BER versus distance for 50 GHz-spaced 20 Gbit/s WDM RZ-DPSK transmission.

4. CONCLUSIONS

Through direct counting of errors, BER performance was assessed of a typical non-slope matched transoceanic WDM submarine transmission link using 50-GHz spaced RZ-DPSK at a bit rate of 20 Gbit/s. The important issue of the impact of the duty cycle of the carrier pulses on the system performance has been addressed. Overall, we have observed that shorter duty cycles (33%) than the conventional 50% improve the performance margins of the system, at the expenses of a reduced tolerance against dispersion variations. These results indicate that the pulse width can and should be chosen carefully to tune the system performance for RZ-DPSK transmission, in accordance with available channel bandwidth and availability of tuneable dispersion post-compensating devices. The validity of different existing numerical Q-factor approaches to the BER estimation for RZ-DPSK was analysed, with the results indicating that the conventional Q-factor of the received electrical signal and the Q-factor defined for the field amplitude before demodulation compete to one another at offering the most reliable indication of the system performance in the considered range of parameters. The results obtained in this paper confirm and extend further the results of previous works⁵⁻⁷, where 20 Gbit/s RZ-DPSK transmission has been indicated as a feasible technique for the upgrade of existing submarine links.

ACKNOWLEDGEMENTS

We thank Prof. Sergei K. Turitsyn, Prof. Keith J. Blow and Dr. Vladimir K. Mezentsev for useful discussions.

REFERENCES

1. J. -X. Cai, D. G. Foursa, L. Liu, C. R. Davidson, Y. Cai, W. W. Patterson, A. J. Lucero, B. Bakhshi, G. Mohs, P. C. Corbett, V. Gupta, W. Anderson, M. Vaa, G. Domagala, M. Mazurczyk, H. Li, S. Jiang, M. Nissov, A. N. Pilipetskii, and N. S. Bergano, "RZ-DPSK field trial over 13100 km of installed non-slope-matched submarine fibers," *J. Lightwave Technol.*, 23, 95-103 (2005).
2. J. -X. Cai, C. R. Davidson, M. Nissov, H. Li, W. Anderson, Y. Cai, L. Liu, A. N. Pilipetskii, D. G. Foursa, W. W. Patterson, P. C. Corbett, A. J. Lucero, and N. S. Bergano, "Transmission of 40 Gb/s WDM signals over 6,250 km of conventional NZ-DSF with > 4 dB FEC margin," *Tech. Dig. of Optical Fiber Communication Conference (OFC 2005)*, Anaheim, CA, PDP 26 (2005).
3. J. -X. Cai, M. Nissov, H. Li, C. R. Davidson, W. Anderson, L. Liu, D. G. Foursa, A. N. Pilipetskii, and N. S. Bergano, "Experimental comparison of 40 Gb/s RZ-, CSRZ-, and NRZ-DPSK modulation formats over non slope-matched fibres," *Proc. of 31st European Conference on Optical Communication (ECOC 2005)*, Glasgow, United Kingdom, Th1.2.2 (2005).
4. J. -X. Cai, M. Nissov, W. Anderson, M. Vaa, C. R. Davidson, D. G. Foursa, L. Liu, Y. Cai, A. J. Lucero, W. W. Patterson, P. C. Corbett, A. N. Pilipetskii, and N. S. Bergano, "Long-haul 40 Gb/s RZ-DPSK transmission with long repeater spacing," *Tech. Dig. of Optical Fiber Communication Conference (OFC 2006)*, Anaheim, CA, OFD3 (2006).
5. R. Freund, L. Molle, C. Caspar, J. Schwartz, S. Webb, and S. Barnes, "Mixed bitrate and modulation format upgrades of non-slope matched submarine links," *Proc. of 32nd European Conference on Optical Communication (ECOC 2006)*, Cannes, France, Th1.6.5 (2006).
6. B. Slater, S. Boscolo, T. Broderick, S. K. Turitsyn, R. Freund, L. Molle, C. Caspar, J. Schwartz, and S. Barnes, "Performance analysis of 20 Gb/s RZ-DPSK non-slope matched transoceanic submarine links," *Opt. Express*, 15, 10999-11007 (2007).
7. L. Molle, C. Caspar, R. Freund, S. Desbruskais, R. Oberland, and J. Schwartz, "Upgrades of non-slope matched submarine transmission systems using differential phase shift keying," *Tech. Dig. of Optical Fiber Communication Conference (OFC 2007)*, Anaheim, CA, OWM2 (2007).
8. L. Becouarn, G. Vareille, P. Pecci, and J. F. Marcero, "3 Tbit/s transmission (301 DPSK channels at 10.709 Gb/s) over 10270 km with a record efficiency of 0.65 bit/s/Hz," *Proc. of 29th European Conference on Optical Communication (ECOC 2003)*, Rimini, Italy, Th4.3.2 (2003).
9. A. H. Gnauck, G. Raybon, S. Chandrasekhar, J. Leuthold, C. Doerr, L. Stulz, A. Agarwal, S. Banerjee, D. Grosz, S. Hunsche, A. Kung, A. Marhelyuk, D. Maywar, M. Movassaghi, X. Liu, C. Xu, X. Wei, and D. M. Gill, "2.5 Tb/s (64 x 42.7 Gb/s) transmission over 40 x 100 km NZDSF using RZ-DPSK format and all-Raman-amplified spans," *Tech. Dig. of Optical Fiber Communication Conference (OFC 2002)*, Anaheim, CA, FC2 (2002).
10. A. H. Gnauck and P. J. Winzer, "Optical phase-shift-keyed transmission," *J. Lightwave Technol.*, 23, 115-130 (2005).
11. A. N. Pilipetskii, "Propagation effects at high bit rates," *Tech. Dig. of Optical Fiber Communication Conference (OFC 2006)*, Anaheim, CA, OWJ7 (2006).
12. N. S. Bergano, F. W. Kerfoot, and C. R. Davidson, "Margin measurements in optical amplifier system," *IEEE Photon. Technol. Lett.*, 5, 304-306 (1993).
13. C. Xu, X. Liu, and X. Wei, "Differential phase-shift keying for high spectral efficiency optical transmissions," *IEEE J. Sel. Top. Quantum Electron.*, 10, 281-293 (2004).
14. T. Broderick, B. Slater, S. Boscolo, and S. K. Turitsyn, "Statistical analysis of RZ-DPSK fiber communication channels," *Proc. of XVI International Workshop on Optical Waveguide Theory and Numerical Modelling (OWTNM 2007)*, Copenhagen, Denmark, PO-01.04 (2007).