Nonlinear Threshold of RZ-DBPSK and RZ-DQPSK

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Abstract
The nonlinear thresholds of differential binary and quaternary phase-shift keying are compared for a wide range of fibre types and symbol rates. Optimum fibre types for symbol rates of practical interest are derived.

Introduction
Return-to-zero differential quaternary phase-shift keying (RZ-DQPSK) has been proposed as a robust and spectrally efficient modulation format for high-speed wavelength-division multiplexed (WDM) transmission [1]. It has been experimentally demonstrated to be suitable for transmission over transoceanic distance [2] and is considered as a promising option for next-generation 100 Gb/s Ethernet [3]. However, there has been no systematic assessment of the impact of fibre nonlinearity for all nonlinear transmission regimes. In this contribution we compare the performance of RZ-DQPSK to that of its binary counterpart RZ-DBPSK for five channel WDM transmission with a wide range of practical symbol rates and fibre types.

System Setup
A schematic of the system setup employed for the numerical simulations is shown in Fig. 1. Five transmitters (Tx) generate chirp-free RZ-DBPSK and RZ-DQPSK with a duty cycle of 33% at symbol rate Rs. The channel spacing is adjusted to give a spectral efficiency of 0.4 b/s/Hz and 0.8 b/s/Hz for RZ-DBPSK and RZ-DQPSK, respectively. In case of RZ-DBPSK, the transmitted data is a 2^10 de Bruijn binary sequence, while a 4^5 pseudo-random quaternary sequence has been used for RZ-DQPSK to accurately model pattern-dependent effects [4]. Multiplexer and demultiplexer filters are modelled as second-order Gaussian band-pass filters with a 3-dB bandwidth of twice the symbol rate. After dispersion precompensation, the optical signal is transmitted over a single span of single-mode fibre (SMF) with varying group-velocity dispersion β2 and attenuation and nonlinear coefficients of α = 0.2 dB/km and γ ≈ 1.31 W⁻¹km⁻¹, respectively. The dispersion compensating fibre (DCF) is adjusted such that the net residual dispersion at the receiver is always zero. After demultiplexing and differential demodulation the signal is received with a balanced receiver. The resulting electrical signal is filtered by a fifth-order Bessel low-pass filter with a cut-off frequency of 0.7Rs. The bit-error ratio (BER) of the centre channel at wavelength λ = 1.55 μm is estimated based on a Karhunen-Loève expansion and saddle-point approximation. Therefore amplifier noise is considered as additive white Gaussian noise at the receiver and nonlinear interactions between noise and signal (such as Gordon-Mollenauer phase noise) are not considered. The nonlinear threshold is defined as the average launch power resulting in a 1-dB penalty in required optical signal-to-noise ratio (OSNR) with respect to the back-to-back required OSNR for a BER of 10⁻⁹.

Results and Discussion
Fig. 2(a) shows a contour plot of nonlinear threshold against precompensation (normalised by the symbol rate Rs) and normalised dispersion -R_s^2β2/α, which has been shown to be a practical criterion to characterize nonlinear impairments [5]. Some points of interest are: 40 Gb/s RZ-DBPSK over standard single-mode fibre at -R_s^2β2/α ≈ 0.2 and 100 Gb/s RZ-DQPSK over non-zero dispersion-shifted fibre (NZDSF with D = 6 ps/nm/km) at -R_s^2β2/α ≈ 0.4. Fig. 2(b) compares the nonlinear thresholds of RZ-DBPSK and RZ-DQPSK at optimised precompensation. The results can be scaled to arbitrary fibre types and multi-span systems with N spans by keeping the average nonlinear phase shift φNL = N/P1α constant (P: average launch power) [6], provided that Gordon-Mollenauer phase noise is negligible or considered separately. This is also indicated by experimental results for RZ-DBPSK [7]. In Fig. 2(b) there are two main transmission regimes: interchannel nonlinear effects dominate for -R_s^2β2/α < 0.2, while intrachannel nonlinear effects limit system performance for -R_s^2β2/α > 0.2. Since the two formats are compared at equal symbol rates and channel spacings, their power spectra and time-domain intensity waveforms (in the absence of cumulated dispersion) are identical. Thus they show the same characteristic behaviour in both regimes. With increasing -R_s^2β2/α phase matching between interacting fields and thus efficiency of four-wave mixing is reduced. Furthermore increasing walk-off between wavelength channels leads to averaging of...
cross-phase modulation-induced phase shifts. Therefore the nonlinear threshold increases. For \(-R_s^2\beta_2/\alpha > 0.2\) dispersion leads to overlapping of an increasing number of pulses and intrachannel nonlinear effects become the dominating nonlinear impairments. A major obstacle for obtaining accurate results in the presence of intrachannel nonlinear effects (especially for \(-R_s^2\beta_2/\alpha > 1\)) is the large system memory and therewith needed long bit sequences [8]. In our simulations 1024 symbols are considered. This is sufficient to capture all possible combinations of ten interacting symbols for binary formats, while it is only sufficient for up to five interacting symbols for quaternary formats. Therefore the nonlinear threshold is likely to be overestimated in the shaded region in Fig. 2, especially in case of RZ-DQPSK. For this reason the following discussion is limited to \(-R_s^2\beta_2/\alpha \leq 1\). Both formats reach their maximum nonlinear threshold (RZ-DBPSK: 16.4 dBm, RZ-DQPSK: 14.4 dBm) at \(-R_s^2\beta_2/\alpha = 0.4\). While there are no comparable experimental results for RZ-DQPSK, this is in good agreement with existing experimental results for RZ-DBPSK [7]. Fig. 3 shows sample constellation diagrams (without amplifier noise) after transmission over 80 km fibre at \(-R_s^2\beta_2/\alpha = 0.4\) and optimised precompensation. Due to shorter symbol distance similar distortions lead to larger penalties. A possible strategy for maximising system reach and OSNR margin at the receiver is to use a fibre with \(\beta_2\) as large as possible (today that is super-large effective area fibre (SLA) with \(D = 20\) ps/nm/km) and choose the symbol rate such that \(-R_s^2\beta_2/\alpha = 0.4\) (about 26 Gbd for SLA fibre). This way, the required OSNR at the receiver is minimised, while the launch power resulting in 1 dB OSNR penalty is maximised. Fig. 2(b) can also be used to find the optimum fibre type for a desired per-channel bit-rate. E.g. for RZ-DQPSK at a symbol rate of 50 GBd, which is of interest for 100 Gb/s Ethernet [3], the transmission fibre allowing for maximum nonlinear threshold is a non-zero dispersion-shifted fibre with a dispersion parameter of about 6 ps/nm/km.

Conclusions

The maximum nonlinear thresholds of RZ-DBPSK and RZ-DQPSK for single-span transmission are 16.4 dBm and 14.4 dBm, respectively. Systems can be optimised for maximum reach and OSNR margin at the receiver by choosing symbol rate \(R_s\) and fibre type (with group-velocity dispersion \(\beta_2\) and attenuation \(\alpha\)) such that \(-R_s^2\beta_2/\alpha = 0.4\). The results can be scaled to multi-span systems and arbitrary fibre type by keeping the average nonlinear phase shift constant. At equal symbol rate and channel spacing RZ-DQPSK has at least 2 dB smaller nonlinear threshold than RZ-DBPSK.

References

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