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Published in:
I E E E Photonics Technology Letters

Link to article, DOI:
[10.1109/LPT.2005.848403](https://doi.org/10.1109/LPT.2005.848403)

Publication date:
2005

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Xu, Z., Rottwitt, K., & Jeppesen, P. (2005). Analyses of spectral efficiency and nonlinear tolerance of DPSK formats in 160-Gb/s Raman amplified systems. I E E E Photonics Technology Letters, 17(7), 1552 - 1554. DOI: 10.1109/LPT.2005.848403

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Analyses of Spectral Efficiency and Nonlinear Tolerance of DPSK Formats in 160-Gb/s Raman Amplified Systems

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Abstract—Five-channel 160-Gb/s wavelength-division-multiplexing (WDM) systems using ABA dispersion map and Raman amplification are investigated numerically. Transmission distance and system margin are evaluated for return-to-zero differential phase-shift keying (RZ-DPSK) and carrier-suppressed return-to-zero (CSRZ)-DPSK formats. The results show that RZ-DPSK can offer 2300-km system reach at large WDM channel spacing, while CSRZ-DPSK is more robust against nonlinear effects in the fibers and offers a reach of 1900 km at a spectral efficiency of 0.53 b/s/Hz. CSRZ-DPSK can also provide twice the dispersion tolerance of RZ-DPSK and larger spectral efficiency.

Index Terms—Differential phase-shift keying (DPSK), modulation format, optical transmission, Raman scattering.

I. INTRODUCTION

ADVANCED modulation formats have been extensively employed in 40-Gb/s wavelength-division-multiplexing (WDM) systems to achieve high spectral efficiency and to greatly upgrade the system capacity. For instance, ultrahigh spectral efficiency of 1.6 b/s/Hz over 320-km nonzero dispersion-shifted fiber using carrier-suppressed return-to-zero differential quadrature phase-shift keying (CSRZ-DQPSK) has been reported [1]. And a distance-capacity product of 20 Pb · km/s has been achieved by CSRZ-DPSK across the *C*- and *L*-band [2], [3]. RZ ON-OFF keying and return-to-zero differential phase-shift keying (RZ-DPSK) have been compared numerically for single-channel 40-Gb/s systems with Raman amplification [4], [5]. Furthermore, RZ-DPSK and CSRZ-DPSK have been compared numerically in dense WDM 40-Gb/s systems without Raman amplification [2]. However, the increased complexity and cost of WDM systems with many channels and high spectral efficiency drive the channel bit rate from 40 toward 160 Gb/s. As a consequence, the signal spectrum of a single channel is broadened which leads to significant nonlinear distortions such as intra- and inter-Raman crosstalk, intra-cross-phase modulation (IXPM), intra-four-wave mixing (IFWM), in addition to XPM and FWM. The advantages of DPSK with its higher sensitivity in balanced detection attract interest although the transceiver setups become more complicated. In 160-Gb/s per-channel experiments, many new components and techniques are employed to investigate RZ-DPSK [6]. A record reach of 2000 km was demonstrated in a six-channel WDM system using RZ-DPSK and forward-error

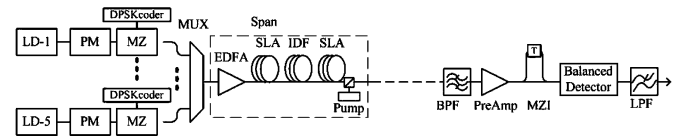


Fig. 1. System configuration. PreAMP: Preamplifier. BPF: Bandpass filter. LPF: Low-pass filter. *T*: One bit delay.

correction technique [7]. However, to the best of our knowledge, for 160-Gb/s per-channel systems, few numerical investigations of DPSK modulation formats have been reported [8], [9].

In this letter, we numerically investigate DPSK modulation formats in 160-Gb/s per-channel systems. Raman amplification is employed to greatly increase the system reach. We predict longest Raman-amplified transmission reach, nonlinear effects, as well as dispersion and power margins for RZ-DPSK and CSRZ-DPSK. Furthermore, we evaluate the potential of these two modulation formats for high spectral efficiency.

II. SYSTEM CONFIGURATION

The transmitter consists of five laser sources and the channel wavelengths are allocated with equal channel spacing with the center channel at 1552 nm. Each channel is carrying an uncorrelated pseudorandom binary sequence and is modulated onto an RZ-DPSK or CSRZ-DPSK lightwave by a phase and a Mach-Zehnder modulator [2]. Each laser source has a random initial optical phase to take into account realistic XPM and FWM interactions between channels. The polarization state for all channels is identical and PMD effects are ignored. The system configuration is shown in Fig. 1. A symmetrical dispersion map, a so-called “ABA” map, is used with a 105-km span length. The span dispersion and dispersion slope are fully compensated by using two 35-km superlarge effective area (SLA) fibers and a 35-km inverse dispersion fiber (IDF) [5]. The dispersion, dispersion slope, nonlinear coefficient, and attenuation of the SLA equal 20 ps/nm/km, 0.06 ps/nm²/km, 2.23×10^{-20} m²/W, and 0.25 dB/km, respectively, while the values for IDF are -40 ps/nm/km, -0.12 ps/nm²/km, 2.37×10^{-20} m²/W, and 0.25 dB/km, respectively. Before each span there is an erbium-doped fiber amplifier (EDFA), which is used to optimize the signal input power into the span. The noise figure of the EDFA is 5 dB. A Raman amplifier is backward pumped at a wavelength of 1450 nm, and we assume the Raman gain is the same for all channels since the total bandwidth of all channels is much smaller than the Raman gain bandwidth. The simulated gain profile is fitted to the realistic characteristics of the SLA and IDF. The maximum Raman gain

Manuscript received October, 2004; revised March 12, 2005.

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Digital Object Identifier 10.1109/LPT.2005.848403

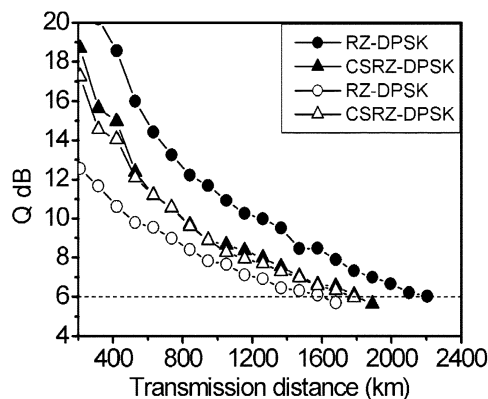


Fig. 2. Longest five-channel WDM system reach. At 0.4 b/s/Hz (filled symbols), optimized Raman pump power for RZ-DPSK and CSRZ-DPSK is 1.05 and 1.05 W; at 0.53 b/s/Hz (open symbols), the value is 0.9 and 0.8 W, respectively. The optimized span per-channel input power for each $Q = 6$ case is shown in Fig. 3.

coefficient equals 0.3 and $0.9 \text{ W}^{-1} \cdot \text{km}^{-1}$ for the SLA and IDF, respectively. The receiver contains an optical preamplifier with a noise figure of 4 dB. In the receiver, a sixth-order optical Gaussian filter and a fifth-order electrical Bessel filter are used. We employ a one bit delay Mach-Zehnder interferometer (MZI) and balanced detection for demodulation of the RZ-DPSK and CSRZ-DPSK formats. The nonlinear Schrödinger equation is solved by the split step method with the simulation tool VPItransmissionMakerV5.5 to take into account linear and nonlinear items including not only dispersion, XPM, FWM, and self-phase modulation (SPM) effects but also IXPM, IFWM, and intra/inter-Raman effects. A pseudorandom bit sequence of length $2^{10} - 1$ is used in the simulations for accuracy. We use χ^2 statistics model for the noise density distributions in the DPSK receiver [10].

III. WDM SYSTEMS

We investigate the system performance at 160-Gb/s per-channel with five channels placed on a 400- and 300-GHz spacing frequency grid, equivalent to a spectral efficiency of 0.4 and 0.53 b/s/Hz, respectively. We evaluate the performance of the center channel at 1552 nm, which experiences the strongest nonlinear effects from adjacent channels. The transmission performance is optimized for longest system reach by adjusting the per-channel input span signal power and Raman pump power. Then the Q -values are extracted after each span. The results are shown in Fig. 2 in terms of Q -value as a function of transmission distance for the two spectral efficiencies. For the rather large channel spacing of 400 GHz, corresponding to the spectral efficiency of 0.4 b/s/Hz, the RZ-DPSK format gives best performance of 2300 km for $Q = 6$ ($\text{BER} = 10^{-9}$). The reason is that SPM is the limiting mechanism in this system, so the narrower pulsewidth of RZ-DPSK, compared to CSRZ-DPSK, induces quicker pulse broadening and, hence, less SPM. However, when the channel spacing is reduced to 300 GHz, corresponding to an increased spectral efficiency of 0.53 b/s/Hz, the system reach of RZ-DPSK is reduced from 2300 to 1600 km. In contrast, the performance of the CSRZ-DPSK format is almost unchanged with 1900-km system reach, which shows its larger tolerance to nonlinear and linear noise.

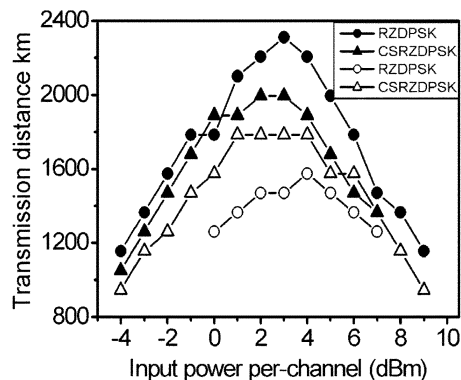


Fig. 3. Longest transmission distance versus span input power per channel at spectral efficiencies of 0.4 (filled symbols) and 0.53 b/s/Hz (open symbols).

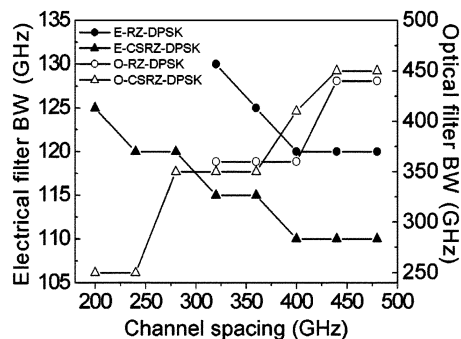


Fig. 4. Optimization of optical and electrical filter bandwidths versus channel spacing. E indicates electrical, O optical bandwidth.

Fig. 3 shows transmission distance as a function of span input power per-channel for $Q = 6$. The Raman pump power is optimized for longest transmission distance for each span input power. The curves in Fig. 3 show that for small input power, the systems perform better when the input power is increased due to better optical signal-to-noise ratio (OSNR); however, when the power exceeds the optimum value, the nonlinear impairments become noticeable and degrade the system performance. At the spectral efficiency of 0.4 b/s/Hz, RZ-DPSK offers longer transmission distance than CSRZ-DPSK due to quicker pulse broadening and less SPM. However, this is reversed when the spectral efficiency is increased to 0.53 b/s/Hz. It can be explained as the wider spectrum of RZ-DPSK, compared to CSRZ-DPSK, causes larger interplay between signal spectrum and linear noise, thus inducing lower OSNR which dramatically reduces the transmission distance. Therefore, a higher input power is needed for RZ-DPSK; for instance, at 0.53 b/s/Hz, RZ-DPSK has 2-dB lower power margin than CSRZ-DPSK, at a transmission distance of 1260 km.

In dense WDM systems, the mutual interactions between signals and also between signals and accumulated amplified spontaneous emission (ASE) noise cause inevitable linear and nonlinear crosstalk impairments. Therefore, to give an accurate comparison between various modulation formats, optimization of optical and electrical filters in the receiver for each channel spacing is important [10]. We evaluate the filter performance on the basis of highest receiver sensitivity after four spans. In Fig. 4, we plot the optimum optical and electrical filter bandwidth in the case when the channel spacing is still larger than the signal bandwidth. The optimum results show that for

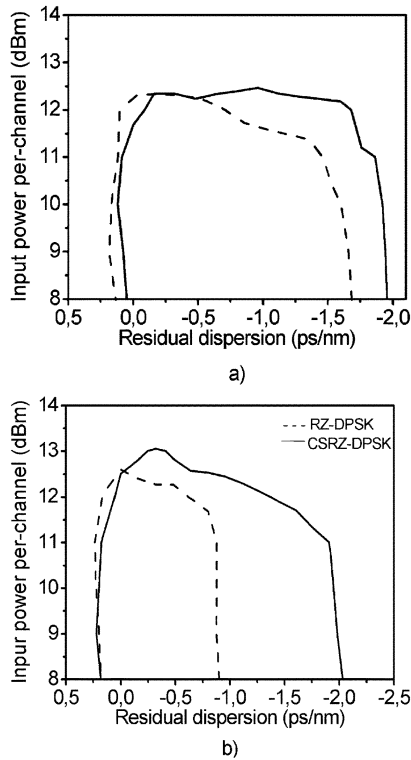


Fig. 5. Margin of dispersion and input power for EOP = 1 dB at (a) 0.4 and (b) 0.53 b/s/Hz.

smaller channel spacing, larger electrical bandwidth is needed. This demonstrates that in narrow channel spacing WDM systems, the impairment from pulse amplitude degradation is more important than intersymbol interference and ASE noise. This impairment can be reduced by using wider electrical bandwidth.

The results in Fig. 5 are obtained after two spans of transmission without Raman amplification. We use eye-opening penalty (EOP) as performance criterion. The penalty was found by comparing eye-opening at the output of the receiver with and without transmission. In Fig. 5(a) and (b), we present contour plots for EOP as a function of residual dispersion and input power; the curves apply for EOP = 1 dB and spectral efficiencies of 0.4 and 0.53 b/s/Hz, respectively. When the spectral efficiency is increased, the dispersion margin for CSRZ-DPSK remains at 2 ps/nm, while the margin of RZ-DPSK drops from 1.7 to 1 ps/nm. The induced per-channel input power nonlinear effects interplay with dispersion which results in an offset from the zero dispersion point in agreement with [11]. The input power tolerance of CSRZ-DPSK slightly exceeds that of RZ-DPSK, while the power tilt comes from the numerical power step size.

Fig. 6 shows the maximum allowable spectral efficiency as a function of per-channel input power after two spans for $Q = 6$. In the low power linear regime where ASE is dominant, the allowable spectral efficiencies increase with increasing input power until an optimum is reached. However, for high input power, the allowable spectral efficiencies drop due to nonlinear effects. Because of its narrower spectrum the CSRZ-DPSK format allows a larger spectral efficiency than RZ-DPSK for same input power—like for 40-Gb/s systems, for instance.

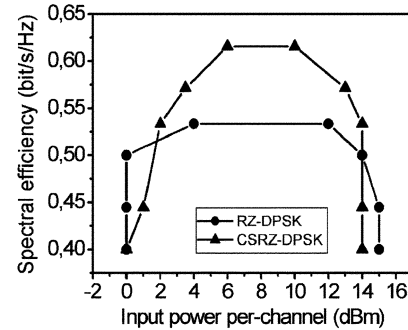


Fig. 6. Spectral efficiencies versus per-channel input power for $Q = 6$.

IV. CONCLUSION

We have presented numerical simulations for DPSK modulation formats in 160-Gb/s five-channel WDM systems using an ABA dispersion map and Raman amplification. Compared to RZ-DPSK, CSRZ-DPSK is more robust against XPM and FWM due to its narrower spectrum; at narrow channel spacing, it provides double dispersion tolerance and nearly stable 1900-km transmission distance with slightly larger power margin. Furthermore, CSRZ-DPSK allows higher spectral efficiency. The receiver was optimized with respect to optical and electrical filter bandwidth, which is essential for evaluation of ultrahigh-speed WDM system performance.

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