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Evaluation of Modulation Formats for 160 Gb/s Transmission Systems Using Raman Amplification

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Abstract We evaluate 160 Gb/s systems with different modulation formats. RZ-DPSK gives best performance for a single channel system with 40% reach improvement compared to RZ, CSRZ-DPSK is more robust in a WDM system.

Introduction

Recently, 8 channels at 40 Gb/s have been transmitted with a spectral efficiency of 1.6 bit/s/Hz using CSRZ-DQPSK(differential-quadrature-phase-shift-keying) modulation format [1]. Furthermore,160 channels at 40 Gb/s have been transmitted using CSRZ-DPSK [2]. However, the increased complexity and cost of WDM systems with many channels might make it attractive to increase the channel bit rate from 40 to 160 Gb/s. A 7-channel 160 Gbit/s WDM experiment has been demonstrated using RZ-DPSK [3]. However, to the best of our knowledge, the DPSK modulation format has not been numerically investigated with respect to the transmission performance in 160 Gb/s systems [4]. In this paper we numerically evaluate RZ, RZ-DPSK and CSRZ-DPSK both for 160 Gb/s single channel and WDM systems. In addition, we use Raman amplification to counter balance the intrinsic fiber loss and thereby extend the transmission reach significantly [5].

Format generation and system configuration

An RZ signal of duty cycle 50 % is generated by modulating a CW lightwave on the quadrature point of a Mach Zehnder (MZ) modulator using a voltage swing of $V_\pi/2$. The CSRZ signal with a duty cycle of 66 % is generated by modulating the CW lightwave at the minimum point of the MZ with a clock that runs at half the bit rate and full swing of $2V_\pi$. The DPSK data generated by the DPSK pre-coder is then applied to a phase modulator (PM), which transfers the data to the CW light. The generated optical DPSK signal is launched into a MZ modulator to carve RZ and CSRZ pulse shapes. As a result RZ-DPSK or CSRZ-DPSK signals are generated. The system configuration is shown in Fig. 1. Each channel is carrying an uncorrelated pseudo random bit sequence. Each CW lightwave has a random initial optical phase to give realistic XPM and FWM interactions between different channels and PMD is ignored. The receiver contains a preamplifier with a noise figure of 4 dB, an optical and an electrical filter. A one bit delay Mach Zehnder interferometer (MZI) for balanced detection [3] is included in the receiver for demodulation of the RZ-DPSK and CSRZ-DPSK formats.

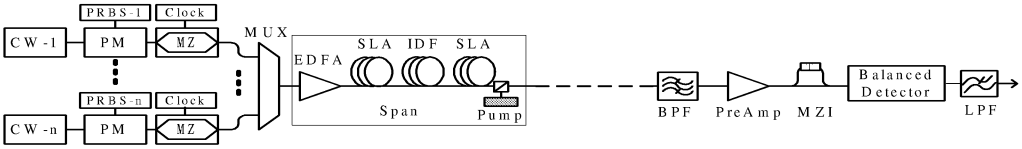

Figure 1. System configuration.

A symmetrical dispersion map configuration is used with a 105 km span length. The span dispersion and dispersion slope are fully compensated by using a 70 km SLA (super large effective area) fiber and a 35 km IDF (inverse dispersion fiber) [5]. The dispersion, dispersion slope and attenuation of the SLA equals 20 ps/nm/km, 0.06 ps/nm^2/km and 0.25 dB/km, respectively, while for the IDF these values equal -40 ps/nm/km, -0.12 ps/nm^2/km and 0.25 dB/km, respectively. Before each span there is an EDFA with noise figure of 5 dB. A Raman amplifier is backward pumped at a wavelength of 1450 nm; we assume the Raman gain is the same for all channels since the total channel bandwidth is much less than the Raman gain bandwidth. The Raman gain coefficient equals 0.3 $W^{-1}\cdot km^{-1}$ and 0.9 $W^{-1}\cdot km^{-1}$ for the SLA and IDF, respectively. A pseudorandom bit sequence of length $2^{10}-1$ is used.

Numerical results

First, we investigate the system performance with respect to the modulation format in a single channel system at 160 Gb/s. In each case the transmission performance is optimized by adjusting the span input power and the Raman pump power for best system performance. In the receiver, a 3rd-order optical Gaussian filter and a 3rd-order electrical Bessel filter is used [5]. The transmission distance as a function of Q value is shown in Fig. 2. It is seen that at Q=6 (BER=10^{-9}) the RZ format has worst performance equivalent to 1600 km. The RZ-DPSK format shows the best performance and allows for an improvement of around 40%, i.e. 2200 km, compared to RZ. And it also allows for

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20% longer system reach for the CSRZ-DPSK format. Hence, the combined use of DPSK modulation and balanced detection results in significant Q improvement for fixed transmission distance.

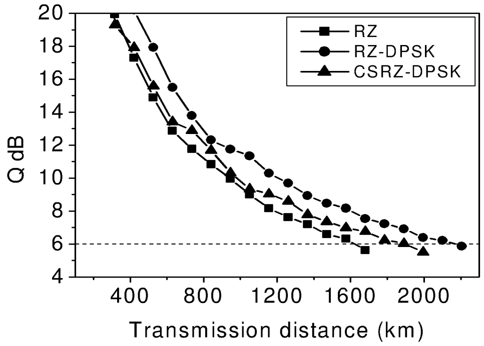
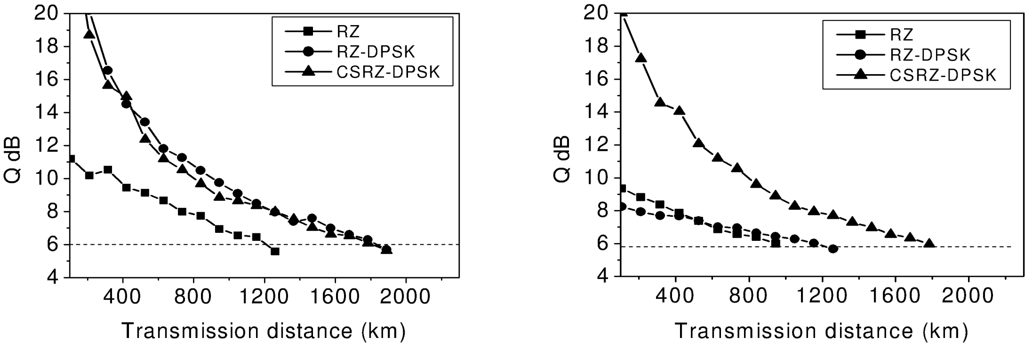


Figure 2. Q vs. transmission distance for single channel systems based on RZ, RZ-DPSK and CSRZ-DPSK.



a) b)

Figure 3. 5-channel WDM systems. a) Spectral efficiency 0.4 bit/s/Hz. b) Spectral efficiency 0.53 bit/s/Hz.

Secondly, we now consider a WDM system, with 5 channels placed on a 400 and 300 GHz frequency grid, equivalent to a spectral efficiency of 0.4 and 0.53 bit/s/Hz. We evaluate the performance of the center channel at 1552 nm, which experiences the most nonlinear effects from adjacent channels. In the receiver, a 6th-order optical Gaussian filter and a 5th-order electrical Bessel filter are used [4]. The transmission distance at Q=6 in Fig. 3 are found by using the optimum per-channel signal power and the optimum pump power. Compared to Fig. 2, at spectral efficiency of 0.4 bit/s/Hz, the RZ system reach is reduced from 1600 km to 1200 km, and the system reach of RZ-DPSK is also reduced from 2200 km to 1800 km. While at spectral efficiency of 0.53 bit/s/Hz, RZ and RZ-DPSK drop to 900 km and 1200 km, respectively. This is mainly because of XPM and FWM induced degradation between channels in the WDM system. However, the CSRZ-DPSK is almost unchanged with 1800 km system reach on both spectral efficiencies. Hence, CSRZ-DPSK is more robust to XPM and FWM than the other modulation formats.

Conclusions

Our results show that by comparing a single channel system against a 5 channel WDM system, the RZ-DPSK and CSRZ-DPSK formats show much better performance in WDM systems than RZ. The RZ-DPSK format has superior performance in a single channel system with a system reach of 2200 km, which is a 40% improvement in system reach compared to RZ. When the spectral efficiency is increased, CSRZ-DPSK is found to be more robust towards XPM and FWM in WDM systems compared to other formats.

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