Cyclic-Spectrum Pulse Shaping for Increased Nonlinear Tolerance

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***Abstract*—We exploit excess spectrum of DWDM systems, where the Nyquist bandwidth of the optical signals is narrower than the channel spacing. Digitally generated cyclic-spectrum RZ shaping is shown to enhance nonlinear tolerance. Simulations show a 26% reach increase in a 7-channel DWDM PolMux 16QAM long-haul transmission.**

Keywords—Long-haul optical transmission; DWDM systems; pulse shaping; nonlinear tolerance.

I. Introduction

Kerr nonlinearities constitute the major capacity limitation in long-haul coherent optical systems. Several digital-domain nonlinear compensation algorithms have been proposed in the literature: the split-step Fourier backpropagation [1]; Volterra series expansion [2]; and general perturbation method [3]. These methods have several limitations: high computational complexity; stochastic nature of nonlinear noise and polarization mode dispersion (PMD); limited field information of the co-propagating channels [4]. An alternative strategy is to reduce the impact of nonlinearities by optimizing signal characteristics. Thus, in [5], the authors showed that distributing the information among low-rate subcarriers enhances system performance. In [6], the authors presented a family of Nyquist pulses with increased nonlinear tolerance. An M-shaped Nyquist pulse was proposed in [7], showing a 33% reach increase over root-raised cosine shaping. Ref. [8] introduced polynomial pulses, yielding a 300-km reach increase. In [9], it was shown that digital emphasis improves nonlinear performance, especially for high order modulation formats. Similar results were obtained in [10] for optical emphasis.

In this work we propose the use of digitally generated cyclic-spectrum return-to-zero (RZ) pulses [11] when optical channels have a great excess bandwidth over the signal Nyquist bandwidth. This situation typically occurs in current deployed 100G systems, where the Nyquist bandwidth is only 56-64% of the grid spacing. Simulations show a 26% reach increase in a PolMux-16QAM DWDM scenario.

II. Cyclic-Spectrum Shaping

A cyclic spectrum is obtained by copying the information contained within the signal Nyquist bandwidth to outer bands (Fig. 1(a)). Here, the lower and upper spectral portions (*red* and *blue*) of a $1/T_s$-GBd Nyquist signal, centered around a carrier frequency, f_c, are replicated outside the Nyquist bandwidth. In practice, a cyclic spectrum can be digitally generated by zero-interleaving the modulated symbols. The resulting pulses are return-to-zero, and will be referred to as the digital-RZ (D-RZ), to differentiate them from the optical RZ with entirely different spectral characteristics [12]. A key feature of cyclic spectrum is the constructive interference of the corresponding spectral copies due to their coherent addition. Remarkably, as was shown in [11], the task of coherent addition can be seamlessly performed by the dynamic equalizer, updated by the least mean squares (LMS), or constant modulus (CMA) algorithms.

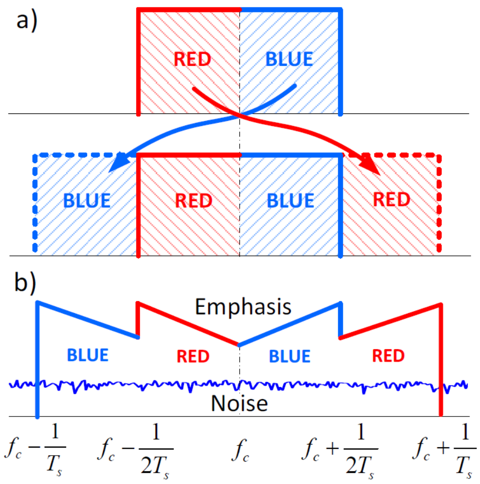

Fig. 1. a) Cyclic spectrum generation; (b) cyclic-spectrum with applied emphasis.

We also investigate the impact of applying pre-emphasis to the D-NRZ signals, as illustrated in Fig. 1(b). Note that, for any emphasis strength, the D-RZ pulses satisfy the Nyquist criterion for zero intersymbol interference (ISI) [6].

III. Simulation Results

The simulations were performed in VPI TransmissionMaker™, with MATLAB™ pre- and post-processing, as follows: 56 random bit sequences are mapped in groups of 4 onto 16QAM for PolMux DWDM transmission (32,768 symbols per polarization). After pulse shaping at 2 samples-per-symbol, the sequences are upsampled to 16 samples-per-symbol for analogue signal emulation. The resulting 14 streams drive an array of PolMux in-phase and

This work was supported by the Australian Research Council (FL130100041, CE110001018).

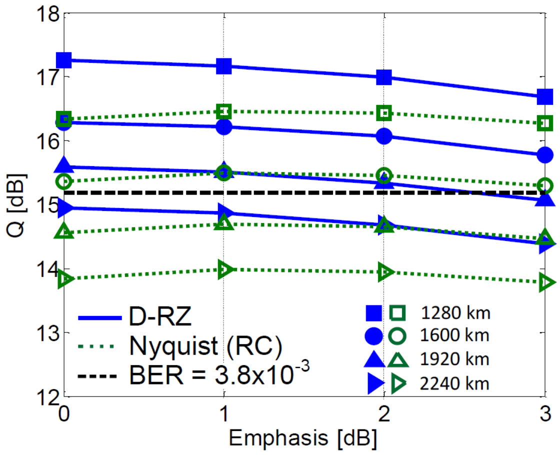

Fig. 3. Q factor vs emphasis for Nyquist and D-RZ signals.

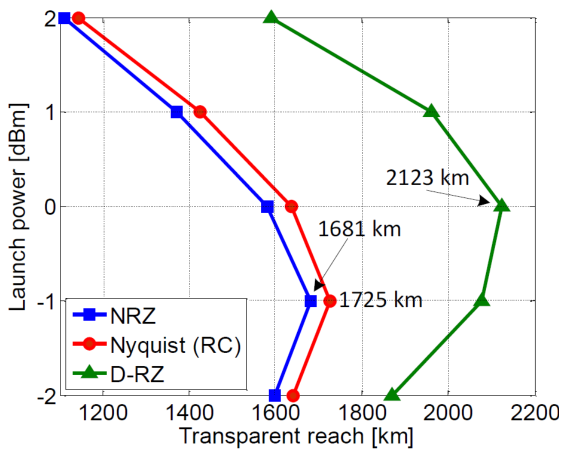

Fig. 2. Q factor vs emphasis for Nyquist and D-RZ signals.

quadrature modulators (PM-IQMs) that modulate 7×50-GHz-spaced 100-kHz linewidth external cavity lasers at 28 GBd. The optical signals are multiplexed, amplified, and transmitted through an optical loop, comprising 4×80-km spans of standard single-mode optical fiber (loss 0.2 dB/km; CD parameter 16 ps/nm.km; PMD parameter 0.1 ps/√km; nonlinear index 2.6×10^{-20}m^2/W), interleaved with erbium-doped fiber amplifiers (noise figure 6 dB). The fiber model solves the Manakov approximation of the nonlinear Schrödinger equation [13] using split-step Fourier method. At the receive-side, central channel is extracted by an optical demultiplexer, and detected by a coherent receiver (Rx). After opto-electrical conversion by balanced photodiodes (PD) and downsampling to 2 samples-per-symbol, the signals are processed in MATLAB by DSP algorithms, including orthonormalization, static and dynamic equalization, and carrier recovery [14]. For dynamic equalization we used the blind radius-directed equalizer, initialized by the CMA. Optical and electrical components' frequency responses were modelled as follows. PM-IQM: 32-GHz, 4th-order Bessel filter; MUX/DEMUX: 50-GHz, 4th-order Gaussian filter; Rx: 33-GHz, 2nd-order Bessel filter; PD: 25-GHz, 2nd-order Bessel filter.

Fig. 2 shows the impact of the applied emphasis for Nyquist (raised-cosine, roll-off 0.01) and D-RZ signals, for selected transmission distances. Here, the launch powers are -1 and 0 dBm, respectively, which yield the optimal results (see Fig. 3). The figure also shows 7% pre-FEC BER threshold 3.8×10^{-3} (Q = 15.19 dB). The Nyquist signal shows a moderate gain of about 0.1 dB, when a 1-2-dB emphasis is applied. At the FEC limit, this gain results in ~50-km transparent reach increase (from 1674 to 1725 km). Conversely, the D-RZ signal presents penalties when emphasis is applied, suggesting that the benefit of pre-emphasis reduces when the signal is spread over broader bandwidth and has lower power spectral density. Note also that on average the D-RZ signal outperforms the Nyquist counterpart by 0.8-1 dB in terms of signal quality factor (Q).

Fig. 3 shows the transparent reach as a function of the launch power for the pre-FEC BER = 3.8×10^{-3}. A 1-dB emphasis is applied to the Nyquist signal for optimal results (see Fig. 2). The cyclic-spectrum D-RZ outperformed the NRZ and Nyquist signals by 442 and 398 km, corresponding to 26 and 23% reach increase. Also, observe that the optimal launch power for D-RZ is 1-dB higher than for NRZ and Nyquist signals, further indicating superior nonlinear tolerance.

IV. Conclusion

We have proposed the use of cyclic-spectrum D-RZ pulse shaping for situations where the optical channels have high excess bandwidth. D-RZ pulses are easily generated in the digital-domain by zero-interleaving the modulated symbols. Computer simulations of a DWDM PolMux-16QAM system indicate that D-RZ signals have superior nonlinear performance, yielding a 442-km (26%) transparent reach increase over NRZ.

References

[1] E. Ip and J. M. Kahn, "Compensation of dispersion and nonlinear impairments using digital backpropagation," J. Lightwave Technol., vol. 26, no. 20, pp. 3416–3425, Oct 2008.

[2] F. P. Guiomar et al., "Digital postcompensation using Volterra series transfer function," IEEE Photon. Technol. Lett., vol. 23, no. 19, pp. 1412-1414, Oct 2011.

[3] A. Vannucci, P. Serena, and A. Bononi, "The RP method: A new tool for the iterative solution of the nonlinear Schr¨odinger equation," J. Lightwave Technol., vol. 20, no. 7, p. 1102, 2002.

[4] R. Dar and P. J. Winzer, "On the limits of digital back-propagation in fully loaded WDM systems," IEEE Photon. Technol. Lett., vol. 28, no. 11, pp. 1253–1256, June 2016.

[5] L. B. Du and A. J. Lowery, "Optimizing the subcarrier granularity of coherent optical communications systems," Opt. Express, vol. 19, no. 9, pp. 8079–8084, Apr 2011.

[6] [6] B. Châtelain et al., "A family of Nyquist pulses for coherent optical communications," Opt. Express, vol. 20, no. 8, pp. 8397-8416, Apr 2012.

[7] X. Xu et al., "A nonlinearity-tolerant frequency domain root M-shaped pulse for coherent optical communication systems," Opt. Express, vol. 21, no. 26, pp. 31 966–31 982, Dec 2013.

[8] A. Karar et al., "Polynomial pulses for mitigating fiber nonlinearity in coherent optical fiber communications," IEEE Photon. Technol. Lett., vol. 27, no. 15, pp. 1653–1655, Aug 2015.

[9] D. Rafique et al., "Digital pre-emphasis in optical communication systems: On the nonlinear performance," J. Lightwave Technol., vol. 33, no. 1, pp. 140–150, Jan 2015.

[10] L. Carvalho et al., "Multidimensional optimization of optical spectral shaping for fiber nonlinearities mitigation in high baud-rate systems," in ECOC, Sept 2014, p. P.5.5.

[11] B. Corcoran et al., "Cyclic spectra for wavelength-routed optical networks," Opt. Lett., vol. 42, no. 6, pp. 1101–1104, Mar 2017.

[12] E. Ip and J. M. Kahn, "Power spectra of return-to-zero optical signals," J. Lightwave Technol., vol. 24, no. 3, p. 1610, Mar 2006.

[13] D. Marcuse, C. R. Manyuk, and P. K. A. Wai, "Application of the Manakov-PMD equation to studies of signal propagation in optical fibers with randomly varying birefringence," J. Lightwave Technol., vol. 15, no. 9, pp. 1735–1746, Sep 1997.

[14] S. J. Savory, "Digital coherent optical receivers: algorithms and subsystems," IEEE J. Sel. Top. Quantum Electron., vol. 16, no. 5, pp. 2120-2126, 2010.