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# Linear and Nonlinear Impairment Mitigation in a Nyquist Spaced DP-16QAM WDM Transmission System with Full-Field DBP

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**Abstract** A RRC filter with a 0.1% roll-off factor reduces the impact of linear crosstalk-induced penalty in a Nyquist spaced 10GBd DP-16QAM transmission system with a net ISD of 7.47(b/s)/Hz and the maximum reach is extended to 1940km using full-field DBP.

## Introduction

The information spectral density (ISD) of an optical communications network can be increased by using complex modulation formats with higher cardinality or by reducing the frequency spacing between WDM channels; however both techniques are accompanied by significant limitations. Increasing the cardinality of the modulation format comes at the expense of requiring a higher received optical-signal-to-noise-ratio (OSNR) and stronger forward error correction (FEC) codes, while reducing the WDM channel spacing can cause significant performance penalties due to linear crosstalk.

Optical, electrical or digital filtering can be employed to constrain the bandwidth (BW) of WDM channels, thus avoiding inter-channel interference and it has been shown that digital filtering currently provides the optimum performance<sup>1</sup>. A root-raised cosine (RRC) filter is typically employed at the transmitter for pulse-shaping, with a corresponding matched RRC filter at the receiver. By reducing the roll-off ( $\alpha$ ) factor of the RRC filters, the WDM channel spacing can be constrained closer to the Nyquist rate, without incurring significant penalties due to linear crosstalk.

Nyquist spaced WDM transmission has previously been achieved using the DP-QPSK modulation format with an ISD of 3.6(b/s)/Hz<sup>2</sup>, while net ISDs of 6.66(b/s)/Hz and 8.67(b/s)/Hz have been achieved for DP-16QAM<sup>3</sup> and DP-64QAM<sup>4</sup>, respectively. For 16QAM transmission systems, the channel spacing has been reduced to the symbol rate<sup>3</sup>, with various RRC filter roll-off factors reported, ranging from 30% down to 0.1%<sup>3,5</sup>.

In this paper, we experimentally investigate the optimum roll-off factor of the pulse-shaping RRC filter as a function of the WDM channel spacing, in order to mitigate linear crosstalk induced penalties in a 7-channel 10GBd DP-16QAM transmission system with a net ISD of 7.47(b/s)/Hz. The maximum reach of the 7-

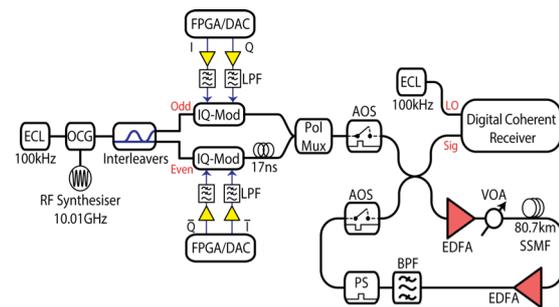


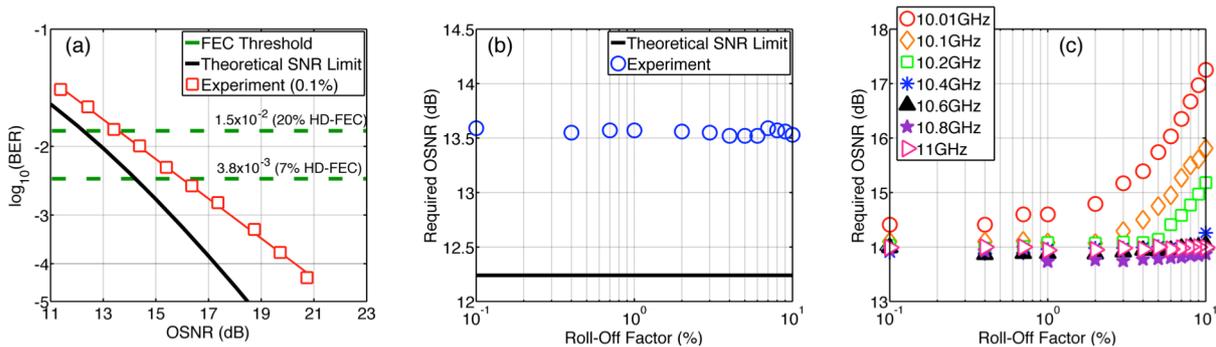
Fig. 1: DP-16QAM WDM transmission system

channel system is further increased through the application of full-field (all 7-channels) digital back-propagation (DBP) at the receiver, to mitigate for the effect of fibre nonlinearities.

## DP-16QAM WDM Transmission System

The experimental setup used in this work is illustrated in Fig. 1. An external cavity laser (ECL) with a linewidth of 100kHz was passed through an optical comb generator (OCG), which generated 7 evenly spaced, frequency-locked comb lines. The comb was separated into odd and even carriers using cascaded Kyliia interleavers and modulated using two independent IQ modulators.

Four de-correlated pseudo-random bit sequences, each of length  $2^{15}-1$ , were digitally generated offline and combined to provide two 4-level driving signals, which were subsequently digitally filtered using a truncated RRC filter with a specified roll-off factor ranging from 0.1% to 10%. The resulting pulse-shaped in-phase (I) and quadrature (Q) signals were pre-emphasised to overcome the electrical bandwidth limitations of the transmitter before being loaded onto a pair of field programmable gate arrays and outputted using two digital to analogue converters operating at 20GS/s. An 8<sup>th</sup>-order analogue electrical low pass filter (LPF), with a cut-off frequency of 5.5GHz, was used after each linear electrical amplifier for image rejection. The odd and even channels were de-correlated by 170 symbols before being



**Fig. 2:** B2B performance of digitally pulse-shaped DP-16QAM transmitter. (a) Single channel performance for a RRC filter roll-off factor of 0.1%, (b) required OSNR to achieve a BER of  $1.5 \times 10^{-2}$  for a single channel as a function of the RRC roll-off factor and (c) corresponding WDM performance as a function of both the filter roll-off factor and the WDM channel spacing

combined and polarisation-multiplexed to form a 7-channel 10GbD DP-16QAM signal.

For back-to-back (B2B) analysis, the output of the polarisation multiplexing stage was passed directly into the signal port of the coherent receiver, while a re-circulating loop consisting of a single 80.7km span of standard SMF was used for transmission experiments. A polarization-diverse integrated coherent receiver with a 3dB electrical bandwidth of 24GHz utilized a second 100kHz ECL as a local oscillator and the received signals were captured using an 80GS/s real-time sampling oscilloscope with 33GHz analogue electrical bandwidth. For full-field DBP measurements, 65GHz U2T photodetectors were employed in conjunction with a 160GS/s Agilent sampling oscilloscope with 66GHz analogue electrical bandwidth. The digital signal processing (DSP) was performed offline using Matlab.

**Back-to-Back Transmission Performance**

The B2B performance of the digital transmitter was initially verified using a single channel with a RRC roll-off factor of 0.1% and is illustrated in Fig. 2(a). The implementation penalty relative to the theoretical signal-to-noise-ratio (SNR) limit was 1.3dB at a FEC threshold of  $1.5 \times 10^{-2}$  (20% overhead for HD-FEC) and increased to 1.7dB at a BER of  $3.8 \times 10^{-3}$  (7% overhead for HD-FEC). Fig. 2(b) illustrates the required OSNR to achieve a BER of  $1.5 \times 10^{-2}$  as the roll-off factor of the RRC filter was varied from 0.1% to 10%. The average OSNR was ~13.6dB and varied by  $\pm 0.05$ dB, which was within the measurement accuracy of our system. This demonstrates that there was no intrinsic pulse-shaping penalty and provides a base-line level of performance for the 10GbD DP-16QAM digital transmitter.

Fig. 2(c) shows the B2B performance for the full 7-channel 16QAM transmitter as a function of both the WDM channel spacing and RRC filter roll-off factor. An additional implementation penalty of 0.4dB was measured at a channel spacing of 11GHz, relative to the single channel

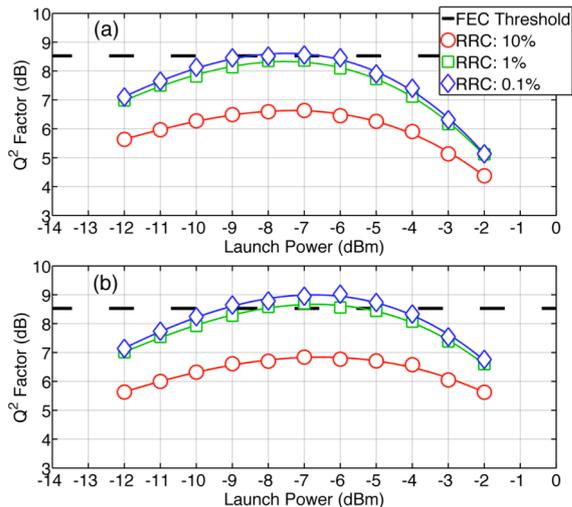
case, which was due to the finite stop-band (~20dB) attenuation of the RRC digital filter in the transmitter. At this WDM channel spacing, the required OSNR to achieve a BER below  $1.5 \times 10^{-2}$  was constant (13.9dB) as a function of the RRC filter roll-off factor. This was expected, as the largest roll-off factor used in this work was 10%, therefore the optical bandwidth did not exceed 11GHz. As a result no linear crosstalk induced OSNR penalty was experienced at this spacing.

However, as the channel spacing was reduced, there was a corresponding increase in the required OSNR to achieve a BER below  $1.5 \times 10^{-2}$  for a filter roll-off factor of 10%. This penalty was due to linear crosstalk between neighbouring WDM channels and caused the required OSNR to gradually increase to 14.3dB as the channel spacing approached 10.4GHz. Below this spacing there was a sharp degradation in performance, thus requiring a reduction in the channel bandwidth or decrease in the RRC filter roll-off factor. The OSNR penalty reduced linearly as the filter roll-off factor decreased and the minimum penalty for the Nyquist spaced system was realized by using a roll-off factor of 0.1%. This RRC filter essentially minimized the linear crosstalk between WDM channels.

**Transmission Performance**

From the B2B system characterization, a channel spacing of 10.01GHz and a 7% HD-FEC overhead was chosen for WDM transmission as this provided the highest net ISD of 7.47(b/s)/Hz with an acceptable implementation penalty. The channel spacing was increased by 10MHz to avoid an artificial performance enhancement associated with the use of odd and even channels spaced at the symbol rate<sup>6</sup>.

Fig. 3(a) shows the transmission performance (central channel) of the 7-channel 10GbD WDM system at a fixed distance of 1200km and with linear compensation only. The Nyquist spaced



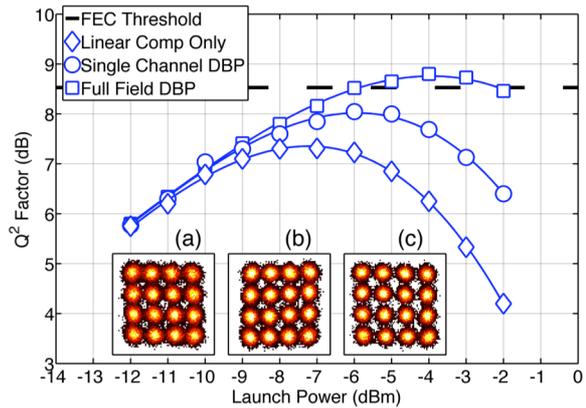
**Fig. 3:** Transmission performance of the digitally pulse-shaped DP-16QAM transmitter at a fixed distance of 1200km, (a) with linear compensation only and (b) with single channel DBP

WDM transmitter, with a RRC roll-off factor of 0.1%, achieved a  $Q^2$ -factor of 8.6dB at a launch power of -7dBm per channel, which was slightly greater than the FEC threshold of 8.5dB. However, as the roll-off factor of the RRC filter was increased to 1%, the  $Q^2$ -factor at the optimum launch power reduced to 8.5dB. A sharp deterioration in performance was experienced at a roll-off factor of 10% and the received  $Q^2$ -factor reduced to 6.7dB, which was due to significant linear crosstalk occurring between adjacent WDM channels.

Nonlinearity compensation, through the use of DBP<sup>7</sup>, was employed on the central channel in order to improve the transmission performance of the 10GBd DP-16QAM WDM system and is illustrated in Fig. 3(b). The performance significantly improved using DBP and the  $Q^2$ -factor increased by 0.5dB when using a RRC filter with a 0.1% roll-off factor. Nonlinear compensation also provided a 4.7dB launch power margin at the FEC threshold and the optimum launch power increased to -6dBm per channel. The improvement in transmission performance is due to the compensation of intra-channel nonlinearities through the use of DBP.

**Full-Field DBP**

Fig. 4 illustrates the experimentally measured  $Q^2$ -factor for the 7-channel system after traversing 1940km of SSMF and for a RRC roll-off factor of 0.1%. The performance was analysed for three scenarios; with only linear compensation employed in the receiver, with single channel DBP (central channel only) and with full-field DBP (all 7-channels), respectively. At this transmission distance, single channel



**Fig. 4:** Transmission performance at a fixed distance of 1940km and with a RRC filter roll-off factor of 0.1%. Inset (a), (b) and (c) illustrate the received 16QAM constellations at the optimum launch power for linear compensation only, single channel DBP and full-field DBP respectively

DBP provides a  $Q^2$ -factor gain of 0.7dB over the standard linear compensation case. However, an additional gain of 0.8dB was achieved when all 7-channels were digitally back propagated. The central channel exhibited a  $Q^2$ -factor of 8.8dB at an optimum launch power of -4dBm per channel, which provided a 3.5dB launch power margin at the FEC threshold. This increase in  $Q^2$ -factor, relative to single channel DBP, is due to the combined compensation of both inter-channel and intra-channel nonlinearities, which is achieved by back propagating the entire 7-channel optical signal.

**Conclusion**

It has been demonstrated that the combination of digital pulse-shaping and full-field DBP enables the transmission of a 7-channel 10GBd DP-16QAM signal over 1940km with a net ISD of 7.47(b/s)/Hz. This results in a spectral efficiency distance product (SEDP) of 14,500(b.km)/s/(Hz).

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