Digital Pulse Shaping to Mitigate Linear Crosstalk in Nyquist-Spaced 16QAM WDM Transmission Systems

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Paper Summary
We demonstrate that a 128-tap RRC filter with 1% roll-off factor is sufficient to limit linear crosstalk induced OSNR penalty to <1dB in a Nyquist-spaced DP-16QAM WDM transmission system with a net ISD of 6.66b/s/Hz.

Introduction

The information spectral density (ISD) of a wavelength division multiplexed (WDM) system can be increased by either reducing the spacing between WDM channels or by employing a modulation format with higher cardinality. Although higher-order modulation formats increase the gross ISD, the capacity increase is obtained at the expense of requiring higher signal to noise ratio (SNR) and stronger forward error correction (FEC) codes, which ultimately may reduce the net ISD [1]. Reducing the spacing between WDM channels can lead to penalties caused by linear crosstalk, while employing tight filtering to avoid such crosstalk results in strong intersymbol interference (ISI) within each WDM channel.

If an appropriate filter shape is employed, for example a sinc shaped pulse with corresponding rectangular spectrum, then the Nyquist criterion can be met. This ensures that the impulse maxima coincide with the zeros of the adjacent pulses, thereby negating ISI. A raised cosine (RC) pulse shape satisfies the Nyquist criterion and is a common filter employed to constrain the bandwidth of WDM channels. A root raised cosine (RRC) filter is typically employed at the transmitter, with a corresponding matched RRC filter at the receiver, thus providing an overall RC spectral shape. By adjusting the roll-off (α) parameter of the RRC filters, the WDM channel spacing can be reduced to the symbol rate without incurring significant penalties due to linear crosstalk or ISI [2]. In addition, the maximum received SNR is achieved with ideal matched filtering.

It has been demonstrated that implementing the RRC filters in the digital domain currently outperforms analog or optical filtering techniques [3], while simulations have also shown that there is a trade-off between complexity and performance when choosing the optimum characteristics of the digital Nyquist filter [4]. In this paper, we experimentally demonstrate the performance of a 7-channel 10GBd dual polarization (DP) 16QAM transmitter, in a Nyquist-spaced 1288km WDM transmission system. The optimum RRC filter roll-off factor and number of taps required to mitigate linear crosstalk in the transmitter is investigated and the experimental results are verified using numerical simulations of the nonlinear Schrodinger equation (NLSE) for this system.

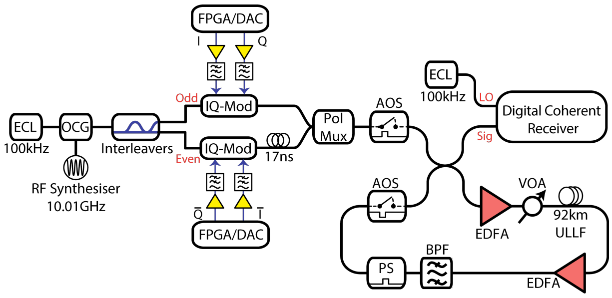

Fig. 1. Nyquist pulse shaped DP-16QAM WDM transmission test-bed.

WDM DP-16QAM 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 consisted of a Mach-Zehnder modulator (MZM) followed by a phase modulator, both overdriven with a 10.01GHz sinusoid. This generated 7 evenly spaced, frequency-locked comb lines that were subsequently separated into odd and even carriers using cascaded Kylia micro interferometer (MINT) interleavers. Each set of comb lines were separately modulated using independent Oclaro IQ modulators

Four decorrelated pseudo-random bit sequences (PRBS) of length 2^{15}-1 were digitally generated offline and combined to provide two 4-level driving signals, which were subsequently filtered using a truncated RRC filter with a specified number of taps (from 11 to 301) and roll-off factor (0.1%, 1%, 5% and 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 (FPGAs) and outputted using two digital to analog convertors (DACs) operating at 20GS/s (2 samples per symbol). An 8^{th}-order analog electrical low pass filter (LPF) with a cut-off frequency of 5.5GHz was used for image rejection. The odd and even channels were de-correlated by 170 symbols before being combined and polarisation multiplexed to form a 7-channel 10GBd DP-16QAM signal with a net information spectral density of 6.66b/s/Hz (8b/s/Hz with 20% overhead for FEC).

For back-to-back analysis, the output of the polarisation multiplexing stage was passed straight into

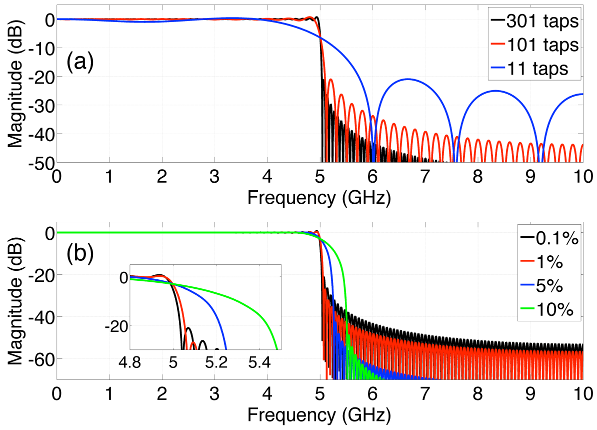

Fig. 2. (a) Digital RRC filter with a fixed roll-off factor (0.1%) and varying number of taps, (b) fixed number of taps (301) and varying roll-off factor. Inset: zoomed in portion of spectrum around 5GHz.

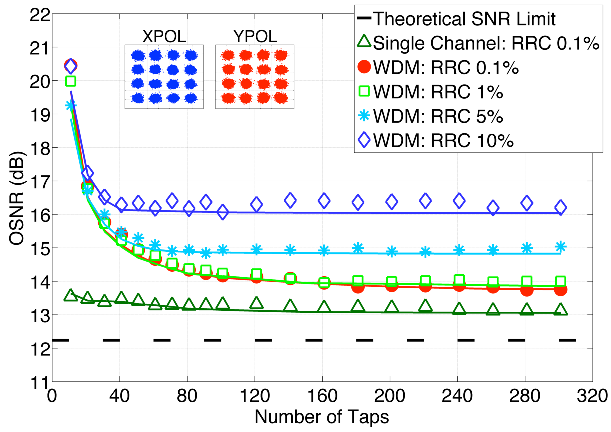

Fig. 3. Required OSNR at FEC threshold as a function of RRC filter roll-off and number of taps. Solid lines are simulation results, whereas symbols are experimental points. Inset: scatter plots for X and Y-polarisations at an OSNR of 40dB.

the signal port of the coherent receiver. A recirculating loop consisting of a single 92km span of ultra-low loss Corning SMF-28 fibre (ULLF), an ASE rejection filter, polarisation scrambler and two EDFAs were used for transmission experiments. A polarisation-diverse integrated coherent receiver utilised a second 100kHz ECL as a local oscillator and the received signals were captured using an 80GS/s real time sampling oscilloscope.

The offline digital signal processing (DSP) initially resampled the received signals to two samples per symbol prior to matched Nyquist filtering. An ideal RRC filter was employed in the receiver in order to isolate the performance degradation caused by the transmitter side digital RRC filter. The signal was equalised using a 21-tap (T/2-spaced) radius directed equaliser (RDE) [5], with the constant modulus algorithm (CMA) equaliser used for pre-convergence. The intermediate frequency (IF) offset was estimated and removed from the signal using the 4th order nonlinearity algorithm [6]. The carrier phase was estimated per polarisation using a decision directed (DD) phase estimation algorithm and the complex field was averaged over a 64 T-spaced sliding window to improve the estimate [7]. Bit error rate (BER) counting was performed on the central WDM channel and the Q^2 factor was calculated from the recorded BER.

Simulations were carried out by generating a RRC-filtered 16QAM WDM signal and by introducing additive white Gaussian noise (AWGN) at the transmitter. The transmitter also included parameters based on the experiment, such as the effective number of bits (ENOB) of the DAC (measured ENOB of 3.2 at 10GHz).

Back-to-Back Performance

The spectrum of the simulated digital RRC filter applied to the 4-level data signals offline with a fixed roll-off factor of 0.1% and varying number of taps is illustrated in Fig. 2(a). The 11-tap finite impulse response (FIR) filter departs from the ideal brick wall frequency response and has a significant proportion of power in the stop band (>5GHz). However, the filter bandwidth begins to approach the Nyquist rate as the tap number is increased, while the power contained within the stop band is dramatically reduced. In addition, if the number of filter taps remains constant and the RRC roll-off factor is increased, the bandwidth of the FIR filter also increases, as seen in Fig. 2(b). It is evident that the detrimental impact of linear crosstalk is a function of both the roll-off factor and the number of taps used to represent the filter. Therefore careful consideration of these characteristics is required in order to mitigate inter channel interference in a Nyquist-spaced WDM system.

The back-to-back performance of the digital transmitter was initially verified using a single WDM channel with a RRC roll-off factor of 0.1% and is illustrated in Fig. 3. The required optical signal to noise ratio (OSNR) to achieve a BER below a FEC threshold of $1.5\text{x}10^{-2}$ (corresponding to a HD-FEC with 20% overhead [8]) was recorded as the number of taps in the RRC filter was varied. The implementation penalty relative to the theoretical SNR limit (dashed line) at the FEC threshold was 0.9dB when 301 taps were used in the transmitter RRC filter. This penalty was constant for any number of taps greater than 301, therefore this was the upper limit of the performance measurement. The required OSNR to achieve a BER below the FEC threshold increased from 13.1dB to 13.5dB for 301 and 11 FIR filter taps respectively. This demonstrates an additional intrinsic penalty of 0.4dB caused by departure from the ideal Nyquist filter as the number of taps is reduced. The experimental results (symbols) show excellent agreement with simulations (solid lines) and provide the base-line performance for the digital transmitter.

The 7-channel 10GBd WDM transmitter exhibits an additional implementation penalty of 0.6dB for a roll-off factor of 0.1% and with 301 taps (central channel). Similar performance was achieved using a 1% roll-off factor, however as the WDM channels are spaced at 10.01GHz, the implementation penalty increases significantly as the RRC roll-off factor approaches 10%.

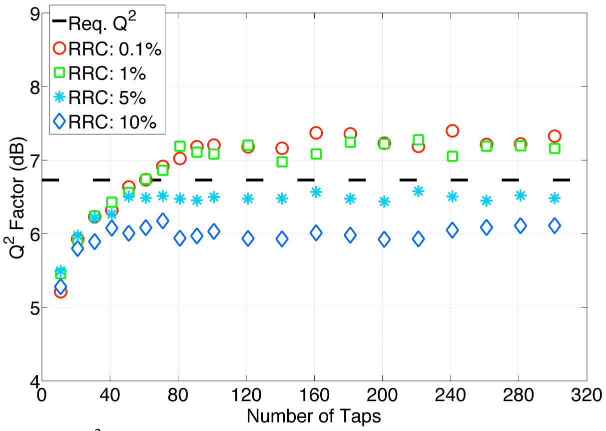

Fig. 4. Q^2 factor of the central channel from the Nyquist-spaced 10GBd 16QAM WDM signal at a fixed transmission distance of 1288km. Also shown, required Q^2 at FEC threshold (dashed line).

This is due to linear crosstalk in the transmitter and culminates in an additional penalty of 3.1dB relative to the single channel performance.

A channel spacing of 10.01GHz was chosen as an artificial performance enhancement was experienced when the channel spacing was identical to the symbol rate. This is a common problem when employing odd and even modulated channels to represent a Nyquist-spaced WDM system [9, 10]. A small shift in channel spacing (10MHz) was sufficient to negate this unrealistic performance improvement, which was confirmed using simulations that incorporated fully de-correlated data.

As the number of taps used in the RRC filter is decreased, both the bandwidth of the digital filter and the power in the stop band increases (Fig. 2a), resulting in greater crosstalk. The OSNR performance begins to degrade for roll-off factors of 0.1% and 1% as the number of filter taps is reduced below 160. A penalty of ~1dB is exhibited relative to the single channel case when the number of taps is decreased to 128. Below this point the OSNR degrades rapidly and the performance of each filter eventually converges for 21 filter taps.

Transmission Performance

The transmission performance of the Nyquist pulse shaped 7-channel 16QAM signal was also investigated. Fig. 4 illustrates the received Q^2 factor as a function of the RRC filter characteristics at a fixed transmission distance of 1288km (14 spans). There was a 6dB power margin at this transmission distance for a roll-off factor of 0.1% and for 301 taps; therefore it was not the maximum reach of the WDM system.

As with the back-to-back case, the transmitter demonstrated consistent performance when the RRC roll-off parameter was set to either 0.1% or 1%, with the Q^2 factor remaining relatively constant as a function of the number of taps at approximately 7.2dB. The transmission penalty increased slightly when the tap number was reduced below 160, but degraded sharply below ~80 taps. The required Q^2 factor (6.73dB) at the BER threshold was reached when the number of filter taps was reduced to 60, representing a 0.5dB Q^2 penalty relative to the highest filter tap number. When the roll-off parameter was set at 5% or 10%, a Q^2 factor above the FEC threshold was not possible for any number of filter taps at this distance. This is again due to the linear crosstalk caused by the increased bandwidth of the RRC filter. It is evident that a RRC filter with a roll-off of 1% and 128 taps is sufficient to ensure an acceptable OSNR penalty for a dense WDM network where the frequency locked channels are spaced at the symbol rate.

In this experiment a channel spacing of 100.1% of the symbol rate was employed to negate an artificial performance enhancement due to using odd and even modulated channels. However, no performance degradation was experienced in either the back-to-back case or after transmission over 1288km of ULLF when the roll-off factor of the digital RRC filter was varied between 1% and 0.1%. Therefore, no additional penalty would be expected for a practical system that used fully independent WDM channels if the channel spacing was identical to the symbol rate and if a roll-off factor of 0.1% was used.

Conclusions

In this paper we have demonstrated a 7-channel Nyquist-spaced DP-16QAM WDM transmission system with a net ISD of 6.66b/s/Hz. The performance of the digital transmitter was analysed by varying the characteristics of the RRC FIR filter. It was demonstrated that a roll-off parameter of 1% and 128 filter taps was sufficient to incur a linear crosstalk induced OSNR penalty of less than 1dB. The transmission performance of the 7-channel WDM signal over 1288km of ULLF was also experimentally assessed. Good agreement between the experimental and simulation results were obtained.

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References

1. A.D. Ellis et al, J. Lightwav. Technol. 28 (2010) p.423
2. J.-X. Cai et al, ECOC (2010) PD2.1
3. R. Schmogrow et al, J. Lightwav. Technol. 31 (2013) p.2570
4. J. Wang et al, Photon. Technol. Lett. 25 (2013) p.772
5. M.J. Ready et al, ICASSP (1990) D11.16
6. S.J. Savory et al, Opt. Express 15 (2007) p.2120
7. T. Pfau et al, J. Lightwav. Technol. 27 (2009) p.289
8. F. Chang et al, Commun. Mag. 48 (2010) p.48
9. S.K. Ibrahim et al, Photonics J. 2 (2010) p.833
10. L.B. Du et al, Opt. Express 20 (2012) p.445