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

Robert Maher*, Masaki Sato, Tianhua Xu, Lidia Galdino, Sean Kilmurry, Seb Savory, Benn Thomsen, Robert Killey and Polina Bayvel

Optical Networks Group, University College London, London, United Kingdom

*r.maher@ucl.ac.uk

Paper Summary

We demonstrate that a 128-tap RRC filter with 1% roll-off 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 guard band 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 guard band 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 previously been demonstrated that implementing the RRC filters in the digital domain 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 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 test-bed. The optimum RRC filter roll-off factor and number of taps required to mitigate linear crosstalk in the transmitter is investigated and the

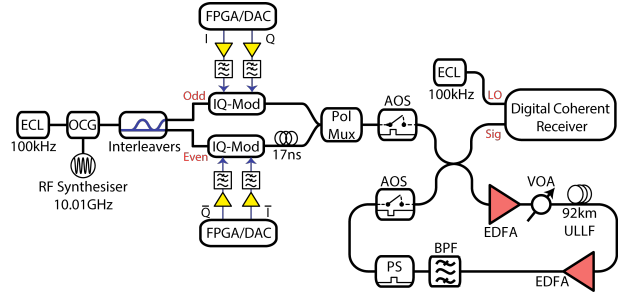


Fig. 1. Nyquist pulse shaped DP-16QAM WDM transmission test-bed.

experimental results are verified using simulations based on parameters similar to the experiment.

WDM DP-16QAM Transmission Test-Bed

The experiential 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 interleavers. Each set of comb lines were separately modulated using independent 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 (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 field programmable gate array (FPGA) and outputted using a digital to analog convertor (DAC) operating at 20GS/s (2 samples per symbol). An 8th 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 the signal port of the coherent receiver. A recirculating loop consisting of a single 92km span of ultra-low loss

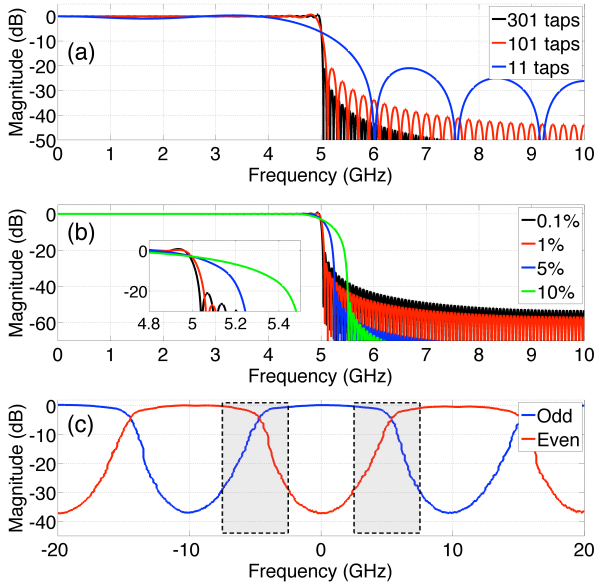


Fig. 2. (a) Digital RRC filter with a fixed roll-off (0.1%) and varying number of taps, (b) fixed number of taps (301) and varying roll-off and (c) optical spectra of odd and even channels, with shaded regions illustrating linear crosstalk.

Corning SMF-28 fibre (ULLF), an ASE rejection filter, polarisation scrambler and two EDFA's were employed 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 a 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 (ENOB of 3.2 at 10GHz). The receiver side DSP was similar to that used in the experiment.

Results and Discussion

The digital RRC filter applied to the 4-level data signals offline with a fixed roll-off factor of 0.1% and varying

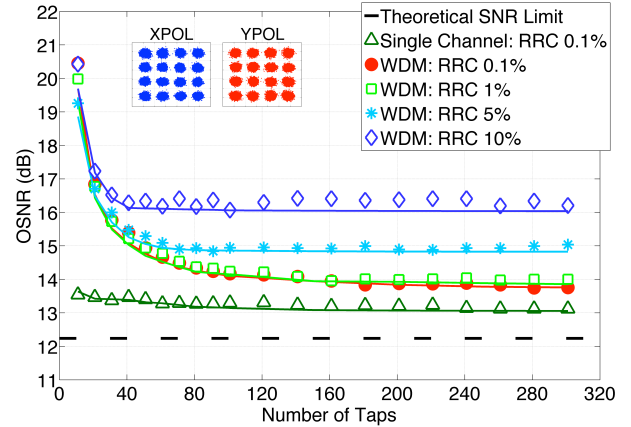


Fig. 3. Required OSNR at FEC threshold as a function of RRC filter roll-off and number of taps. Solid lines are simulation results, whereas symbols are experimental points.

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 (>5 GHz). 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 parameter is increased, the bandwidth of the FIR filter also increases, as seen in Fig. 2(b). The extent of linear cross talk occurring on a WDM channel is highlighted in Fig. 2(c), which shows the optical spectra of the odd and even WDM channels. It is evident that the detrimental impact of linear cross talk is a function of both the filter roll-off and the number of taps used to represent the filter. Therefore careful consideration must be placed on the filter characteristics in order to mitigate inter channel interference in a Nyquist spaced WDM system.

The performance of the digital transmitter was initially verified using a single WDM channel with a RRC roll-off factor of 0.1%. The required optical signal to noise ratio (OSNR) to achieve a BER below a FEC threshold of 1.5×10^{-2} (corresponding to a HD-FEC with 20% overhead [8]) was recorded as the number of taps in the RRC filter was varied. The back-to-back performance of the single channel 10GBd Nyquist shaped 16QAM signal with a roll-off of 0.1% is illustrated in Fig. 3. 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. The required OSNR to achieve a BER below the FEC threshold (1.5×10^{-2}) 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 greater departure from the ideal Nyquist filter as the number of taps is reduced. The experiential results (symbols) show excellent agreement with simulation (solid lines) and provide the base-line performance for the digital transmitter.

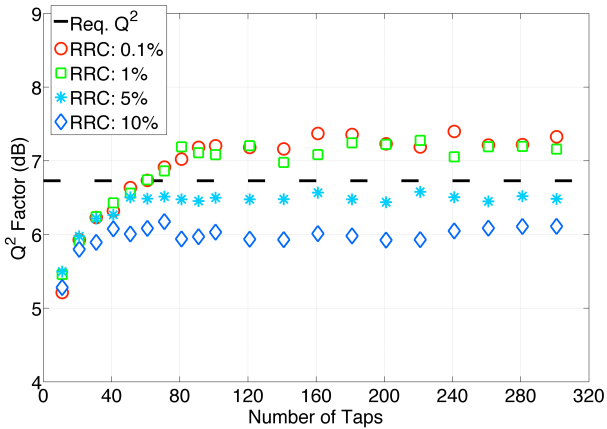


Fig. 4. Q^2 factor of the central channel from the Nyquist spaced 10GBd 16QAM WDM signal at a fixed transmission distance of 1288km. Also shown, required Q^2 at FEC threshold (dashed line).

The 7-channel 10GBd WDM transmitter incurs 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%. 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 reduces, 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 and incurs a penalty of ~1dB relative to the single channel case at 128 taps. Below this point the OSNR degradation increases rapidly and the performance of each filter eventually converges. It is important to note that an ideal RRC matched filter was used in the receiver DSP. If the receiver DSP also utilised a filter with an equal number of taps as that used in the transmitter, an additional penalty would be incurred. This penalty was negligible for a large number of taps, but a maximum Q^2 factor penalty of 0.4dB was experienced for lower tap numbers. However, if 128 taps are used at both the transmitter and receiver, the Q^2 penalty is below 0.1dB.

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). The Q^2 factor (6.73dB) required to achieve a BER of 1.5×10^{-2} is also displayed. As with the back-to-back case, the transmitter demonstrates consistent performance when the RRC roll-off parameter is 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 increases slightly when the tap number is reduced below 160, but begins to degrade sharply below ~80 taps. The required Q^2 factor at the BER threshold is reached when the number of filter taps is reduced 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. The transmission performance of the 7-channel 10GBd DP-16QAM system confirms the back-to-back performance of the digital transmitter. It is evident that a RRC filter with a roll-off of 1% and 128 taps is sufficient to incur an acceptable OSNR penalty for a dense WDM network where the frequency locked channels are spaced at the symbol rate.

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 demonstrated. The results were verified both experimentally and with simulations based on practical experimental parameters.

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