Nyquist-WDM-based system performance evaluation

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ABSTRACT

We describe an experimental evaluation of a Nyquist-WDM-based transmission system. Nine 10.7 GHz-spaced WDM channels were generated, carrying polarisation-division-multiplexed QPSK with digital Nyquist pulse shaping at 10 Gbaud. Back-to-back characterisation and long-haul transmission tests using a recirculating fibre loop are described, and a comparison of experimental performance with that predicted by theory, based on the Gaussian-noise model of nonlinear propagation, is carried out.
Keywords: Nyquist WDM, fibre nonlinearity

1. INTRODUCTION

The continued increase in demand for bandwidth across the world's optical fibre communication networks has led to strong interest in signalling techniques which increase the efficiency with which the available optical bandwidth is utilised. Alongside the use of higher order formats (for example, polarization-division-multiplexed 16-QAM), spectral efficiency gains can be achieved by reducing the channel spacing to values at, or approaching, the Nyquist limit, at which point the channel spacing is equal to the baud-rate. A key research question concerns the optimum signaling format to minimise inter-channel crosstalk at such low channel spacing, and to provide high tolerance to distorting effects such as dispersion and fibre nonlinearity [1]. A number of approaches are possible, including the use of orthogonal frequency division multiplexing (OFDM) [2], DFT-spread OFDM [3], all-optical OFDM [4] and single-carrier formats with Nyquist (sinc-like) pulse shaping [5]. In this paper, we focus on the digital Nyquist pulse shaping technique and describe recent work implementing a field programmable gate array (FPGA) and digital-to-analogue (DAC)-based transmitter for the characterization of Nyquist WDM systems. We describe back-to-back testing of the transmitter, and a long-haul transmission experiment using a recirculating fibre loop, and compare theoretical and experimental performance of the system.

2. NYQUIST-WDM TRANSCEIVER DESIGN

The experimental set-up of the 10 Gbaud Nyquist-WDM PDM-QPSK transmitter is shown in Figure 1. An external cavity laser (ECL) with a linewidth of approximately 10 kHz was used as the seed for an optical comb generator (OCG). The OCG comprised a pair of $LiNbO_3$ amplitude modulators in series, driven with a 10.7 GHz sinusoid, followed by a phase modulator, driven with frequency components at 10.7 GHz and 21.4 GHz, to generate 9 wavelength channels with a spacing of 10.7 GHz. By adjusting drive amplitudes, delays and modulator biases, and using a variable optical filter (Finisar WaveShaper) at the output, this configuration allows a power variation of less than ±1 dB across the nine channels. Odd and even channels were separated to allow decorrelated bit sequences to be encoded on neighbouring channels. Two pairs of Xilinx Virtex 5 FPGAs and Micram VEGA DACII digital-to-analog converters were used to generate the modulator drive waveforms. Linear driver amplifiers were used to boost the power of the drive signals. Anti-imaging filters were placed after the driver amplifiers to remove the images in the spectra resulting from the sample-and-hold operation of the DACs (to avoid the crosstalk between WDM channels caused by the images above the Nyquist frequency). The anti-imaging filters were 5^{th} order Bessel filters with a 3-dB bandwidth of 7 GHz. The digital modulator drive waveforms were generated offline with Matlab, quantized to 6 bits and uploaded to memory in the FPGAs. Nyquist pulse shaping (root-raised-cosine (RRC) filters with a roll-off factor of 0.01) and pre-emphasis to compensate for the frequency response of the DACs, anti-imaging filters and modulators were applied to four de-correlated 2^{15} de Bruijin sequences. After odd and even channels were separately modulated by IQ-MZMs, the two sets of channels were combined with a 3 dB optical coupler to form the 9 channel 10 GBaud Nyquist-QPSK signal with 10.7 GHz channel spacing. Next, polarization division multiplexing (PDM) was emulated by passing the signal through a polarization multiplexing stage. The optical spectrum of the resulting 9-channel signal is shown in Figure 2. It should be noted that, although the modulator drive waveforms were calculated offline and uploaded to the FPGAs' memory in these experiments, the FPGA-based transmitter offers the possibility to implement and assess real-time DSP for Nyquist WDM signal generation, as we described in [6].

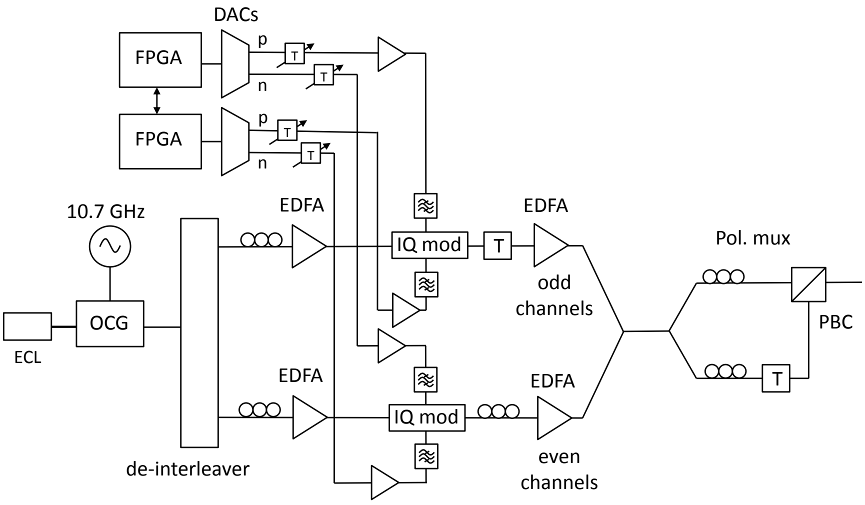

Figure 1. Experimental Nyquist-WDM PDM-QPSK transmitter (OCG – optical comb generator, PBC – polarization beam combiner, T – delay line)

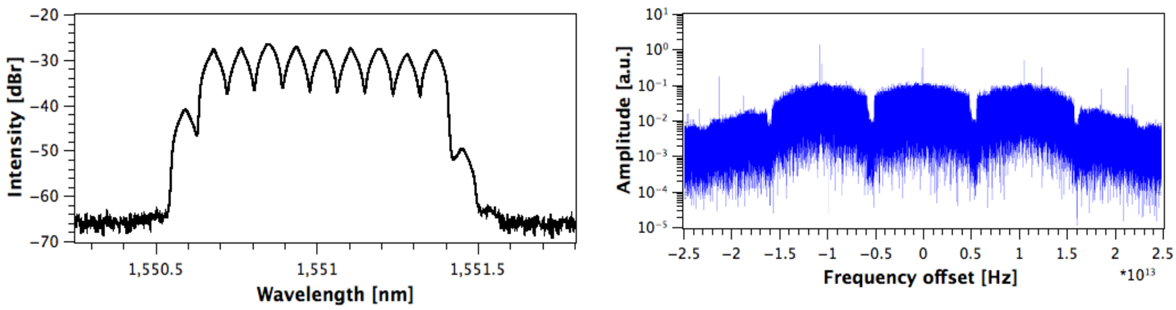

Figure 2. Left: Optical spectrum of 9 x 10 GBaud Nyquist-WDM PDM-QPSK. Right: Digital spectrum of the received Nyquist-WDM PDM-QPSK signal.

A polarization- and phase-diverse coherent receiver was used to receive the central of the nine channels. The incoming optical signal was combined with a free running local oscillator (LO), an ECL with 100kHz linewidth, to generate signals proportional to in-phase and quadrature components of the two orthogonal polarizations. Four pairs of balanced PIN photodiodes with 32.5GHz electrical bandwidth were used to receive the four quadratures. A 50GSamples/s Tektronix DPO 72004 digital sampling oscilloscope with an analogue bandwidth of 16.5GHz was used to digitise the signals, and subsequent digital signal processing (DSP) was carried out offline. A root-raised-cosine filter was applied to the signal, to achieve matched filtering, and the signal was downsampled to two samples per symbol. An adaptive equaliser was then used to carry out dispersion equalisation and maximise the received SNR. This adaptive equaliser comprised a MIMO structure of 4 FIR filters with adaptive updating of the filter taps. Frequency offset recovery was carried out by applying a higher order nonlinearity and deducing the frequency offset from the resulting spectrum. Phase recovery was carried out by the Viterbi and Viterbi algorithm, following which, complex decisions were made and errors were counted.

Figure 2 shows the spectrum of the received digital signal prior to RRC filtering and downsampling, obtained using an FFT. Due to the relatively wide bandwidth of the photodetectors and ADCs, three Nyquist-WDM channels were detected simultaneously by a single receiver. The channel-of-interest (COI) at the LO wavelength is in the centre of the spectrum, with neighbouring channels to either side. The downsampling and RRC filtering removes the outer two channels, and only the centre channel (the COI) is processed.

3. BACK-TO-BACK TRANSCEIVER CHARACTERISATION

The transmitter performance was characterised in noise-loaded back-to-back tests. The output of an EDFA, generating wideband ASE noise, was passed through a variable optical attenuator before being combined with the signal, allowing the BER to be investigated at different OSNR values. BER versus OSNR was measured for PDM-QPSK with Nyquist pulse shaping, initially for a single channel, next 5-channel 21.4 GHz-spaced using only the odd channels from the transmitter, and finally 9-channel 10.7 GHz-spaced (3.48 b/s/Hz net SE) with both odd and even sets of channels combined. Figure 3 shows the resulting BER versus OSNR curves (measured with a 0.1 nm bandwidth), compared with the theoretical curve for PDM-QPSK. The required OSNR with nine channels with 10.7 GHz spacing was 9.8 dB at the FEC limit BER = 3.8×10^{-3}.

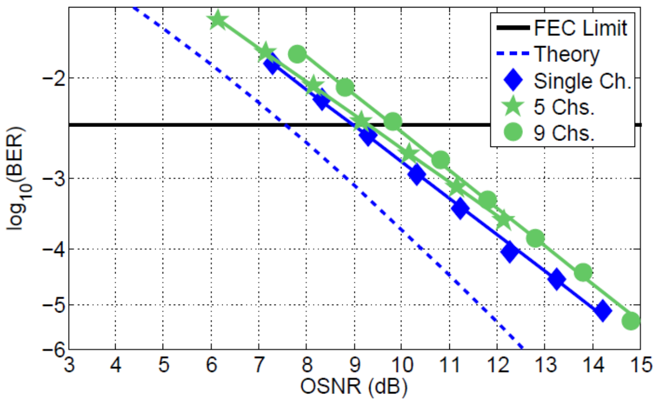

Figure 3. Theoretical and measured back-to-back BER versus OSNR for WDM Nyquist pulse-shaped DP-QPSK.

4. TRANSMISSION EXPERIMENTS

A recirculating fibre loop, with the configuration shown in Figure 4, was used to assess the transmission performance of the 9-channel Nyquist-WDM signals over long-haul links. The power of the signal from the transmitter was boosted using an EDFA, and controlled using a variable optical attenuator (VOA). A tunable optical bandpass filter (serving the dual purpose of gain flattening and ASE filtering) was followed by an EDFA and VOA, which controlled the signal launch power into the fibre span. The span comprised 82 km of standard SMF (G.652), and no inline dispersion compensation was used. At the end of the span, a second EDFA and VOA were used to control the power. The EDFAs operated in saturation with a total output power of 18 dBm and noise figure of 4.5 dB. At each distance, the signal launch power was varied, and the lower launch power, P_{min} (determined by ASE noise from the EDFAs) and upper power P_{max} (limited by fibre nonlinearity) of the channel were found for BER $\leq 3.8 \times 10^{-3}$ (the FEC limit). From these values, the range of signal launch powers resulting in BER values below the FEC limit ($\Delta P = P_{max} - P_{min}$) versus distance was obtained (Figure 4). At 20 spans (1240 km), the allowable range of signal launch powers was 8 dB. This reduced to 0 dB at 62 spans (5084 km), which consequently was the maximum distance over which the 9-channels could be transmitted with the BER below the FEC limit.

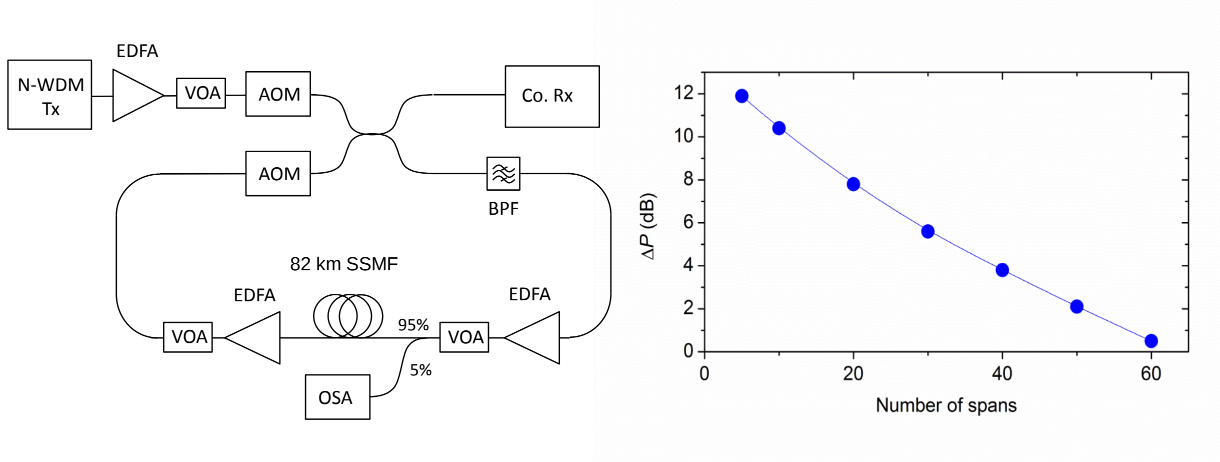

Figure 4. Left: Recirculating loop testbed design (VOA – variable optical attenuator, AOM – acousto-optic modulator, OSA – optical spectrum analyser, Co. Rx – coherent optical receiver). Right: Signal launch power range, ΔP, for BER ≤ 3.8×10^{-3} versus number of spans, for the central channel in nine-channel 10.7 GHz-spaced 10 Gbaud Nyquist WDM PDM-QPSK transmission.

5. COMPARISON WITH THEORY

To determine if this maximum transmission distance is in-line with that predicted by theory, we calculated the OSNR including terms for the linear amplified spontaneous emission (ASE) noise power and the nonlinear interference (NLI) noise power, for Nyquist-spaced WDM transmission with the same signal optical bandwidth as used in the experiments, and with the link configuration that was used in the recirculating loop. The following equation was used to calculate OSNR [8]:

$$\mathrm{OSNR} = \frac{P_{Tx,ch}}{P_{ASE} + P_{NLI}} \tag{1}$$

where $P_{TX,ch}$ is the launch power per WDM channel, and P_{ASE} and P_{NLI} are, respectively, the amplified spontaneous emission noise power, and the nonlinear interference noise power in a 0.1 nm ($\Delta\upsilon$ = 12.5 GHz) bandwidth. Expressions for the power spectral density (PSD) of the FWM-induced noise in Nyquist-limited WDM transmission are derived in [8]-[10]. The expression below gives the NLI noise PSD [8]:

$$I_{NLI} = \left(\frac{2}{3}\right)^3 N_S \gamma^2 L_{eff} \frac{\ln\left(\pi^2 |\beta_2| L_{eff} B^2\right)}{\pi |\beta_2|} I_{Tx}^3 \tag{2}$$

where $I_{Tx} = P_{Tx,ch}/\Delta f$ is the signal PSD (Δf is the WDM channel spacing), γ = 1.2 W^{-1} km^{-1} is the fibre nonlinear coefficient, the nonlinear effective length L_{eff} = 21 km, β_2 = -21.7 ps^2 km^{-1} is the fibre group velocity dispersion, and the optical bandwidth of the signal B = 96.3 GHz. The resulting FWM-induced noise power, $P_{NLI} = I_{NLI}\,\Delta\upsilon$ is added to the ASE noise power, calculated assuming an EDFA noise figure of 4.5 dB noise figure and total output power of 18 dBm (8.5 dBm per channel). With a launch power into the fibre span of -4.5 dBm per channel (controlled by the VOA loss set to 13 dB), and assuming a fibre span loss of 18 dB (including connector and splice losses), the values of P_{ASE} and P_{NLI} each reach -12.8 dB relative to the signal power at a transmission distance of 65 spans (5330 km). From (1), the resulting OSNR is 9.8 dB, the value at which the BER = 3.8 × 10^{-3} with the experimental transceiver (Figure 3). Hence, good agreement between theoretically predicted and experimental maximum transmission distances is found.

6. CONCLUSIONS

We described an experimental evaluation of a Nyquist-WDM-based transmission system. A transmitter was implemented based on field programmable gate arrays (FPGAs) and digital-to-analogue converters (DACs), and an optical comb generator. We used the system to generate and characterise nine 10.7 GHz-spaced WDM channels, with single-carrier 10 Gbaud polarization-division-multiplexed QPSK signal format with digital Nyquist pulse-shaping. We firstly assessed back-to-back performance, measuring a required OSNR of 9.8 dB at BER = 3.8 × 10^{-3}, and, secondly performed long-haul transmission experiments using a recirculating fibre loop. The experimental results were compared with values predicted by the theoretical models of linear and nonlinear noise. The maximum transmission distance of 5084 km was quite accurately predicted using the Gaussian-noise model of nonlinear propagation.

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