Nonlinear Transmission Performance of Very High Spectral Efficiency WDM Comparing Nyquist Pulse Shaping and OFDM

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Abstract: The long distance transmission performance of Nyquist-WDM and OFDM, using PDM-QPSK at baud rate channel spacing, is investigated over uncompensated single mode fibre. Results show similar performance for both signal formats and good agreement with closed-form expressions for the nonlinear transmission performance of densely spaced coherent optical systems.

1. Introduction

Coherent optical detection with digital signal processing (DSP) is the most promising approach to realize high speed, high capacity systems due to its sensitivity and capability to overcome transmission impairments that have hitherto had a critical impact on the performance of optical transmission systems [1]. To meet an expected tenfold increase in global IP traffic over the next decade it is envisaged that both Terabit/s channel capacity and Tb/s network interfaces will be required by the end of the decade in order to limit the core network complexity [2]. In meeting these requirements it is crucial to improve the spectral efficiency of transmission systems through higher order modulation formats, such as QAM-16, and/or by the use of densely spaced WDM channels.

One approach to meet the demand for a Tb/s channel is to combine a number of lower baud rate channels into one 'super-channel' through the use of Nyquist filtering or orthogonal frequency division multiplexing (CO-OFDM) [3]. The concept of a super-channel, has been developed in an attempt to address limitations in the transmitter and receiver electronics [4] which currently make the deployment of a single Tb/s channel impractical.

The first approach makes use of channels which operate at high baud-rates (e.g. >25 Gbaud) with raised cosine (RC) pulse filtering to minimize the spectral width of the channel, avoiding channel overlap and hence inter-channel interference (ICI). In the limit, when the roll-off factor of the RC filters is 0, the channel spectrum is rectangular, and it is possible to set the channel spacing equal to the symbol rate, $f_c = R_s$. The signaling is termed Nyquist-WDM [5] and the resulting pulse shape is almost sinc-like in time. Experimental demonstrations of the concept are shown using optical filtering in [6] and electrical filtering using DSP prior to a DAC in [7], where a spectral efficiency of 4 bit/s/Hz is achieved with negligible power penalty.

An OFDM super-channel can be created by electrically generating the sub-carriers using an IFFT/FFT pair [8] or by optically multiplexing conventionally modulated single carrier (SC) PDM-QPSK carriers, with overlapping spectra spaced at the symbol rate $\Delta f_c = R_s$ [9]. It has been found through simulation in [5] that for optically generated OFDM to match the transmission reach of Nyquist-WDM, it requires prohibitively large receiver bandwidth and an oversampling rate, in the receiver digital to analog converter (DAC), of greater than 4 samples-per-symbol (SpS). Similar results have also been shown experimentally in [10]. Thus we conclude that optically generated OFDM is not suitable for high speed, high spectrally efficient optical transmission.

It is well known that electrically generated OFDM (which from here on we will just refer to as OFDM) has a very well defined narrow optical spectrum resulting from the efficient generation of a large number of sub-carriers using an IFFT [11]. The spectral efficiency of OFDM is reduced by the inclusion of a cyclic prefix to accommodate chromatic dispersion (CD) induced inter-symbol interference (ISI). When a one tap equalizer is used to correct this ISI, the length of the cyclic prefix, which needs to be longer that the channel memory, can be large for high speed long-haul optical fiber transmission. Depending on the size of the OFDM symbol and the length of the fibre channel, the overhead due to the CP can be greater the 15%. By using a frequency-domain equalization scheme in the receiver [12] to compensate for ISI, the length of the CP can be reduced to accommodate the ISI with short memory, such as that induced by transmitter bandwidth limitations or fiber polarization mode dispersion (PMD) [13]. This enables OFDM to achieve a similar spectral efficiency to Nyquist-WDM.

In deciding whether to use Nyquist-WDM or OFDM for high spectrally efficient optical transmission a number of factors need to be considered, including nonlinear transmission performance, DSP complexity and practical implementation penalties. In this paper, we describe a simulation study of long-haul transmission over uncompensated standard SMF of PDM-QPSK using single carrier (SC) and OFDM signal formats. The study focuses on the relative tolerance to fibre nonlinearity of the two schemes and we compare the results, through simulation, to two recently published closed-form expressions for nonlinear transmission performance of densely spaced coherent optical systems [14, 15].

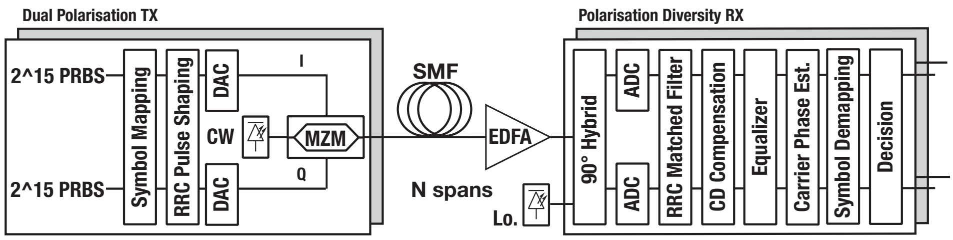

Figure 1: Simulation system diagram for SC-PDM-QPSK.

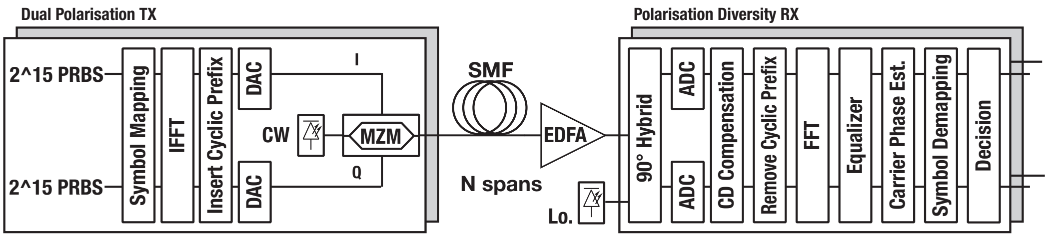

Figure 2: Simulation system diagram for OFDM-PDM-QPSK.

2. Simulation setup

The transmitter and receiver simulation system diagrams for SC-PDM-QPSK and OFDM-PDM-QPSK are shown in figures (1) and (2). Each system is transmitting 112Gb/s PDM-QPSK which includes forward error correction and Ethernet overhead for a net data rate of 100Gb/s.

At the transmitter a 2^{15} deBruijn sequence is generated, duplicated, de-correlated and then mapped to encode a 2D differential QPSK signal [16]. The In-phase and Quadrature components of the SC-PDM-QPSK signal are electrically shaped using a Root Raised Cosine (RRC) finite impulse response filter (FIR) with a roll-off factor of 0.1 and order 32 operating, at 2 SpS prior to DAC. The OFDM signal consisted of 128 sub-carriers all of which carried data to maximize the spectral efficiency. A cyclic prefix equivalent to 4 sub-carriers was added giving an overhead of $\sim 3\%$ which also necessitated a corresponding increase in the transmission rate in order to maintain parity with the SC-QPSK system. The signal is then clipped for peak to average power reduction with clipping ratio 7.5dB. A 6 bit DAC/ADC resolution was assumed for both systems and quantization effects were included in the simulations. This was the minimum resolution required for the OFDM receiver to achieve the same sensitivity as the SC receiver in a noise loaded back-to-back sensitivity test. The electrical bandwidth was modeled using a 5th order Bessel filter with an optimized bandwidth of $0.6R_s$ and both DAC and ADCs were assumed to operate at 2 SpS. The electrical signals for both systems drive an IQ-Mach Zehnder modulator (MZM) operating in the linear region which is modulating a continuous wave (CW) laser at 1550nm with a linewidth of 100kHz.

Transmission of the optical signal through single mode fibre spans (SMF) of length 80km was simulated using the Split-Step Fourier Method using a step size of 100m with the following fibre parameters: attenuation $\alpha = 0.2dB/km$, dispersion $D = 17ps/nm/km$, dispersion slope $S = 0.06ps/nm^2/km$, nonlinear parameter $\gamma = 1.2/W/km$ and polarization mode dispersion $D_p = 0.1ps/\sqrt{km}$. Erbium-doped fiber amplifiers (EDFAs) with a noise figure of 4.5dB were used to compensate for the in-span losses. All dispersion compensation was performed in the receiver and 32 SpS resolution was used for fiber transmission simulations.

At the receiver the incoming signal is mixed with a optical local oscillator with a linewidth of 100kHz, gain of 18dB and we assumed a zero frequency offset between the Tx and Rx lasers. Each polarization is then detected separately by a phase diversity homodyne receiver using a 90° optical hybrid and balanced photodiodes. The optical front ends for both receivers were assumed to be ideal. The I and Q components of each detected polarization were resampled at 2 SpS and then quantized with a 6 bit resolution ADC. In the SC receiver a matched RRC-FIR filter is applied prior to CD compensation. A frequency domain equalizer using the overlap and add method was used to compensate the fibre dispersion for both transmission systems. For OFDM the cyclic prefix is removed prior to the demodulation of the sub-carriers using an FFT. Dynamic-channel equalization, in the SC receiver, for PMD and any residual dispersion was performed using four FIR filters (7 taps long) in a butterfly configuration. After the equalizer had converged the tap weights were adaptively updated using the LMS-CMA [1]. In the OFDM system 24 training symbols were used to estimate the channel and a Zero Forcing Equalizer used to compensate for PMD and any narrowband filtering distortions to the OFDM subcarriers. We assume that after the initial training period, channel estimation, for OFDM, can then be updated on a symbol by symbol basis or by the insertion of periodic training sequences. Carrier phase estimation was performed for SC and OFDM using the Viterbi and Viterbi phase estimation algorithm. While a number of other schemes are available for OFDM CPE, for example through the insertion of pilot tones in each OFDM symbol, we chose the V&V algorithm to maximize the spectral efficiency. After CPE the symbols were decoded and the bit error rate (BER) was measured by counting the number of errors.

3. Simulation results

The back-to-back sensitivity for both systems was measured and the required received OSNR (0.1nm Ref. BW) for a BER of 10^{-3} was found to be 14.2dB. To investigate the long distance transmission performance of both systems, a 9 channel WDM was simulated and the maximum transmission reach, for a BER of 4×10^{-3} (FEC limit), was measured for different channel launch powers at a set of different channel spacings. The launch power per channel was swept, from -8dBm to 4dBm, in increments of 1dB. The channel spacing between each optical channel was 31.5GHz, 29.75GHz, 28.875GHz and 28GHz. The channel spacings were chosen to be integer multiples of the OFDM subcarrier spacings (218.75MHz) to maintain the orthogonality between the OFDM channels.

The optimum launch power to achieve the maximum transmission distance was found to -2dBm in both cases. Figure (3) shows the maximum reach for a launch power of -2dBm at the the four different channel spacings. We can see that the maximum transmission decreases linearly as the channel spacing is varied from 31.5GHz to 28.875GHz. When we include the OFDM cyclic prefix overhead, the minimum channel spacing that can be achieved is equal to the combined bandwidth required for the symbol rate and the cyclic prefix. In these results that corresponds to 28.875GHz and gives a maximum spectral efficiency of ~ 3.9 b/s/Hz. Beyond this point the cross talk between the neighboring channels has a very severe impact and an error floor was reached which can be clearly seen in figure (3) at 28GHz. The SC-PDM-QPSK spectrum is not perfectly rectangular and includes a tail from the filter rolloff. This minimum bandwidth required for ISI free transmission when using a RRC pulse shaping filter is $(1+\alpha)R_s$, where α is the filter rolloff factor. As we have violated this condition, ISI and the cross-talk between the SC channels explains the sudden drop in maximum reach at the baud rate spacing, 28GHz.

The maximum transmission distance versus channel launch power is plotted in figure (4). From this we can see that both the SC and OFDM systems have an almost identical transmission performance. The SC system has a slightly lower maximum reach than the OFDM system which we attribute to the slightly higher cross-talk and ISI due to the pulse shaping filter. The closed-form expressions for the nonlinear transmission performance of densely spaced coherent optical systems are also plotted in figure (4), green for SC derived by Poggiolini *et al* [15] and black for OFDM derived by Chen *et al* [14]. Very good agreement between the simulation results and the analytical curves can be clearly seen.

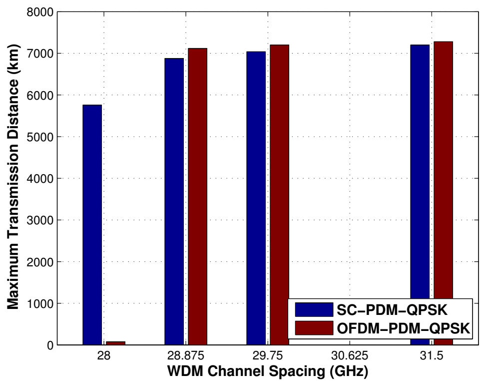

Figure 3: Maximum transmission distance -2dBm per channel, for different channel spacing, BER of 4×10^{-3} (FEC limit)

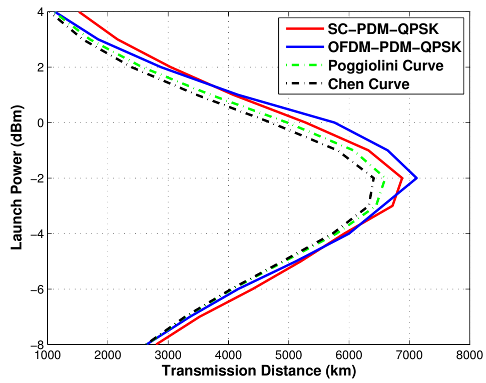

Figure 4: Launch power vs. transmission distance for 9 WDM 28GBaud channels at a channel spacing of 28.875GHz, BER of 4×10^{-3} (FEC limit)

4. Conclusion

We have investigated two alternative approaches to achieving very high spectral efficiency WDM, firstly SC-PDM-QPSK with Nyquist pulse shaping and secondly OFDM-PDM-QPSK. We compared the nonlinear performance at the baud rate channel spacing and found them to offer very similar performance. The minimum channel spacing for error free transmission is limited to bandwidth required for the symbol rate and the cyclic prefix for OFDM-

PDM-QPSK and results in spectral efficiency lower the theoretically achievable maximum. SC-PDM-QPSK can reach the theoretical maximum even in the absence of perfect Nyquist filters though, with a corresponding drop in the transmission reach, due to it greater tolerance to ISI and ICI.

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