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Impairment mitigation in high speed optical communications using digital signal processing

R. I. Killey, P. M. Watts, S. J. Savory, R. Waegemans, Y. Benlachtar, V. Mikhailov, M. Glick*, and P.Bayvel
Optical Networks Group, University College London, Torrington Place, London, WC1E 7JE, UK, r.killey@ee.ucl.ac.uk
* Intel Research Pittsburgh, 4720 Forbes Avenue, Suite 410, Pittsburgh, USA

Abstract We present results of recent studies on transmission impairment mitigation techniques using digital signal processing. The methods investigated include electronic predistortion, and coherent polarisation-multiplexed QPSK transmission with receiver-based equalization.

Introduction

The use of digital signal processing (DSP) in the next generation of optical transmission systems, to compensate for chromatic dispersion, fibre nonlinearity and optical filtering, offers the advantages of low cost and size, and adaptive operation. Ongoing increases in the speed and reductions in the power consumption of CMOS make this technology suitable for signal processing at optical line-rates of 10 Gb/s and above. Recent demonstrations of A/D and D/A converters operating at 20 GSa/s confirm the feasibility of these components for applications in high bit-rate optical communications.

A key question concerns the fundamental limits to the performance that can be achieved with DSP. Many studies to date have focused on direct (square law) detection schemes in which electronic dispersion compensation (EDC) is implemented at the receiver. However, in comparison to conventional optical compensation methods, the performance of such schemes is limited due to the loss of the optical phase information following detection. In contrast, signal processing techniques which operate directly on the optical field, either using electronic predistortion (EPD) [1,2] or coherent detection [3], offer the possibility to overcome these limitations.

With EPD, the optical amplitude and phase are predistorted at the transmitter to achieve the desired signal waveform at the receiver, allowing direct-detection to be used, and avoiding the requirement for local oscillators. We have carried out studies, assessing the transmission performance that can be achieved by electronic compensation of dispersion and intra-channel nonlinearities. In addition, we are developing EPD transceiver designs, based on field programmable gate array (FPGA) devices, to operate at up to 10 Gb/s.

In our research on coherent systems, the approach we adopt is based on a phase- and polarization-diverse coherent receiver combined with DSP to compensate for transmission impairments and to recover the data. By using polarization multiplexed QPSK as the modulation format, since each symbol carries 4 bits of information, a capacity of 40 Gbit/s can be achieved at 10 GBaud, allowing the use of 20 GSa/s DSP. Using this technique, we have recently reported transmission over 6480 km of standard fiber without optical dispersion compensation [4].

In this paper we describe work carried out at UCL assessing DSP-based EDC. Firstly, results of numerical studies of electronic predistortion are presented. Following this, the use of FPGAs in the implementation of digital EDC schemes is discussed. Finally, recirculating loop transmission studies on 42.8 Gb/s polarization-multiplexed QPSK are described.

Electronic predistortion

The EPD transmitter generates predistorted signals such that the chromatic dispersion (CD) and/or nonlinearity of the fibre reverse the distortion during transmission, resulting in the desired signal waveform at the receiver. Fig. 1 shows the design of an EPD transmitter, based on a Cartesian Mach-Zehnder modulator (MZM).

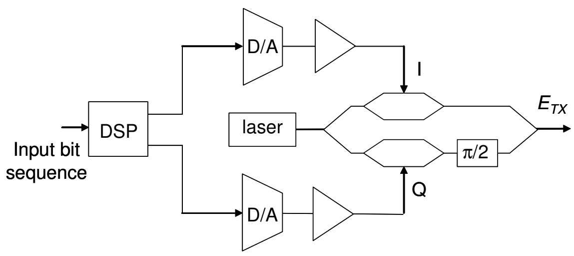

Fig. 1 Precompensating transmitter based on a dual-drive Cartesian Mach-Zehnder modulator..

Transmission simulations were carried out with predistorted 10 Gb/s NRZ-OOK signals over 1200 km of standard SMF, with no optical compensation. Details of the simulations are presented in [5]. Fig. 2 shows the required OSNR plotted for the case of chromatic dispersion compensation alone, and for simultaneous dispersion and SPM compensation. In the latter case, the penalty at 0 dBm launch power was reduced from 3.7 dB to 0.2 dB. The upper limit on launch power is governed by the sampling rate of the modulator drive signals, in this case 20 GSa/s (2 samples per bit). Experimental confirmation of the effectiveness of combined CD and SPM compensation is presented in [6]. An experimental demonstration of 72 channel WDM EPD signal transmission over 1600 km of standard SMF is described in [7], while [8] presents a detailed numerical assessment of multi-channel nonlinear effects.

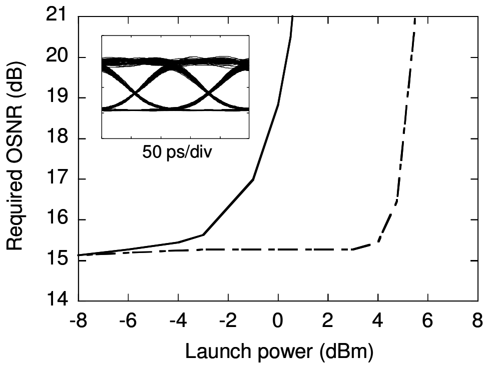

Fig. 2 Calculated required OSNR (0.1nm RBW, BER=10^{-5}) following EPD transmission over 1200 km (15 x 80 km) of standard SMF: compensation of chromatic dispersion only (solid line) and for simultaneous dispersion and nonlinearity compensation (dashed line). Inset: Received eye with CD and nonlinearity compensation at +3 dB [5].

FPGA-based EPD transmitter design

For the implementation of digital EDC schemes, while custom integrated circuit designs offer optimum performance, the field programmable gate array (FPGA) is a useful alternative tool for experimental work, as it is low cost and reprogrammable. In the latest FPGAs, high speed serial interfaces are increasingly being used. Chips with up to 10 Gb/s input/output capabilities are in production or under development, allowing the latest FPGAs to be used for real-time DSP operating on signals at standard optical line rates. We are currently assessing the use of FPGAs to implement experimental EPD transceivers.

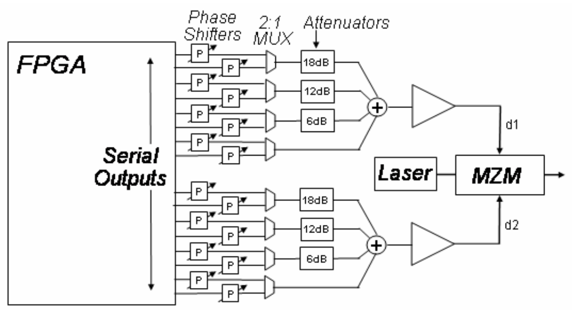

Fig. 3 FPGA-based EPD transmitter design

Fig. 3 shows the proposed EPD transmitter design based on the Xilinx Virtex-4 chip. For each modulator drive signal, eight of the FPGA serial outputs (each 10 Gb/s) are time-division multiplexed to four 20 Gb/s signals. D/A converters consisting of attenuators and 4:1 power combiners generate the analog drive voltages. Details of the VHDL design, and results of simulations assessing its performance are presented in [9].

Coherent polarization multiplexed QPSK

In our work on coherent systems, we carried out polarization multiplexed QPSK recirculating loop transmission experiments at 10.7 GBaud, giving a channel capacity of 42.8 Gb/s. At the receiver a local oscillator with linewidth of 100 kHz was combined with the signal via two asymmetric 3 fiber couplers, with coupling ratios 1:2:2, to detect the in-phase and quadrature components of the two polarizations. On conversion into the electrical domain, the signal was digitized at 20GSa/s using a Tektronix TDS6154C digital storage oscilloscope with the waveforms then processed off-line. Further details of the experiment are given in [4].

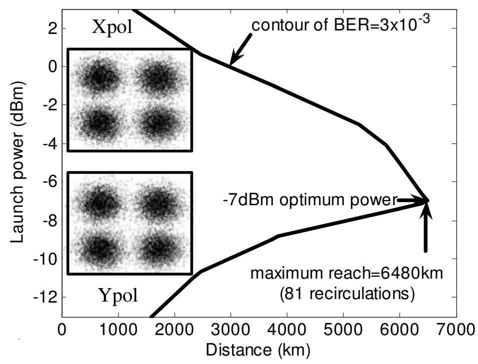

Fig. 4 Contour plot of launch power vs distance for BER=$3x10^{-3}$ with 512 tap FIR filters (inset are the constellation diagrams for the X & Y polarizations recovered after 6400km with -7dBm launch power)

Transmission over distances up to 6480km over standard fiber with no optical dispersion compensation was demonstrated (Fig. 4). A total dispersion of 107,232ps/nm was compensated using digital signal processing, with an OSNR penalty of 1.2dB.

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