Digital Equalisation of 40Gbit/s per Wavelength Transmission over 2480km of Standard Fibre without Optical Dispersion Compensation

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Abstract *We demonstrate transmission and demodulation of 40Gbit/s per wavelength data, using 10Gbaud polarisation multiplexed QPSK. The digital coherent receiver includes carrier recovery and equalisation of all linear impairments, including chromatic dispersion and polarisation mode dispersion.*

Introduction

Digital signal processing and coherent detection is a powerful combination[1-4]. Not only does it have the potential to compensate for all linear transmission impairments but digital intradyne carrier recovery can be used to avoid the complications associated with homodyne receivers[1,2]. Furthermore spectrally efficient modulation formats such as polarisation multiplexed QPSK (PMQPSK) can be used, allowing a capacity of 40Gbit/s per wavelength, while permitting processing using 20GSa/s DSP[3,4]. In this paper we focus on the demodulation of 40Gbit/s PMQPSK after transmission over 2480km of standard fibre without optical dispersion compensation.

Signal processing algorithms

The output of a phase and polarisation diverse receiver is the optical field within the sampling bandwidth mapped into the electrical domain. After digitising, we have two complex signals corresponding to the two polarisations. These pass through three stages, firstly the signals are filtered by an FIR filter, after which the carrier is recovered, before finally deciding on which symbol was transmitted. Within the FIR filter, we separate the functionality into a fixed FIR filter (of length 128 taps), and four adaptive FIR filters having significantly fewer taps, (up to 13 taps within this paper).

The output of the adaptive FIR filter is given by

$$\begin{aligned} x' &= \mathbf{h}_{xx} \cdot \mathbf{x} + \mathbf{h}_{xy} \cdot \mathbf{y} \\ y' &= \mathbf{h}_{yx} \cdot \mathbf{x} + \mathbf{h}_{yy} \cdot \mathbf{y} \end{aligned} \qquad (1)$$

These taps are then updated using stochastic gradient constant modulus algorithm[5], such that

$$\begin{aligned} \mathbf{h}_{xx} &= \mathbf{h}_{xx} + \mu\varepsilon_x x' \cdot \overline{\mathbf{x}} \\ \mathbf{h}_{xy} &= \mathbf{h}_{xy} + \mu\varepsilon_x x' \cdot \overline{\mathbf{y}} \\ \mathbf{h}_{yx} &= \mathbf{h}_{yx} + \mu\varepsilon_x y' \cdot \overline{\mathbf{x}} \\ \mathbf{h}_{yy} &= \mathbf{h}_{yy} + \mu\varepsilon_x y' \cdot \overline{\mathbf{y}} \end{aligned} \qquad (2)$$

where the error terms, for unit radius, are given by $\varepsilon_x = \left(1 - |x'|^2\right)$ $\varepsilon_y = \left(1 - |y'|^2\right)$ and μ is the convergence parameter. The phase is estimated, by using a 4th order nonlinearity such that[6]

$$\phi = \frac{1}{4} \arg \sum_{i=-N}^{N} x_i^4 \qquad (4)$$

Once the tap weights have converged and the bulk frequency offset has been estimated, the receiver moves from blind mode, to a decision directed mode.

Simulation results

In order to determine the feasibility of transmission over 2500km, we simulated linear propagation at 10.7GBaud with a chromatic dispersion of 16 ps.nm^{-1}km^{-1} and PMD of up to 10 ps.km$^{-1/2}$. No optical dispersion compensation was used, with the equalisation of chromatic dispersion and PMD carried out purely by electronic equalization at the receiver. As can be seen in figure 1, a 1.5 dB penalty in OSNR for a BER of 10^{-3} is observed, which is unaffected by a mean PMD of 500ps. Additional optimisation may reduce this 1.5 dB penalty.

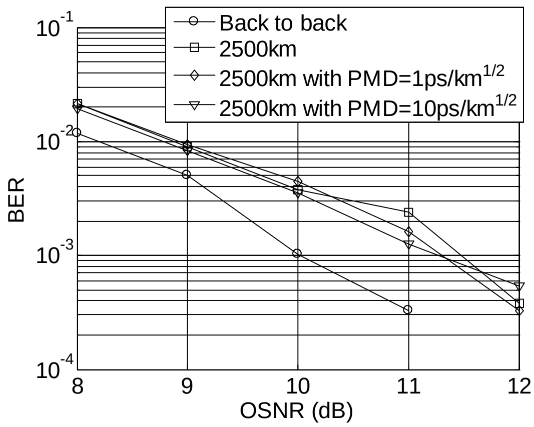

Figure 1: OSNR versus BER for 0 and 2500km

Experimental coherent receiver

Rather than the conventional passive quadrature network, we used an asymmetric 3 fibre coupler, with coupling ratios 1:2:2. It can be shown that this gives inphase and quadrature components of the optical signal, without the need for active control, required for the passive quadrature network.

In our receiver we used two asymmetric couplers in order to achieve a phase and polarisation diverse receiver (figure 2). On conversion into the electrical domain, the signal was digitised at 20GSa/s using a

Tekronix TDS6154C digital storage oscilloscope with the waveforms then processed off-line using Matlab.

Initial experimental results

To test the principle of the DSP, we carried out a preliminary loop experiment, over a distance of 2480km, with a total dispersion of 41,600 $ps.nm^{-1}$

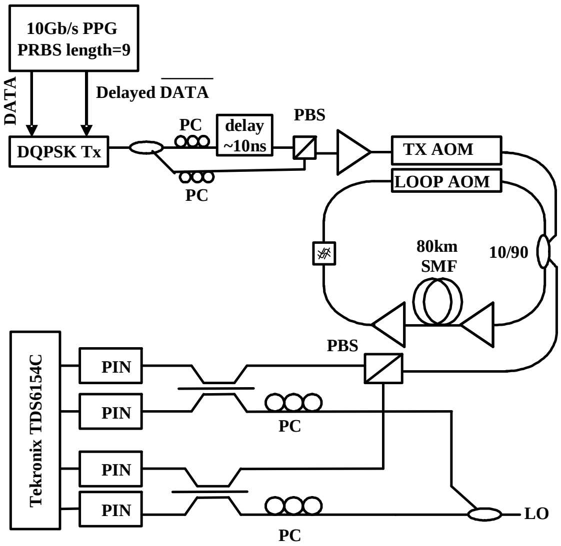

Figure 2: Schematic of experimental setup

In order to avoid the additional distortions associated with nonlinear transmission the input power was maintained deliberately low at -5dBm. As can be seen in the constellation diagrams 3 & 4 the data is successfully recovered. Table 1 gives the BER for all channels, each being within the FEC limit of $3x10^{-3}$. This promising result demonstrates the principle of the DSP; further experimental work is in progress, the results of which will be presented at the conference.

Channel	Bits in error	BER
Inphase X	12 out of 7665	1.6×10^{-3}
Quadrature X	4 out of 7665	5.2×10^{-4}
Inphase Y	5 out of 7665	6.5×10^{-4}
Quadrature Y	8 out of 7665	1.0×10^{-3}
Overall	29 out of 30660	9.5×10^{-4}

Table 1: Performance of loop experiment

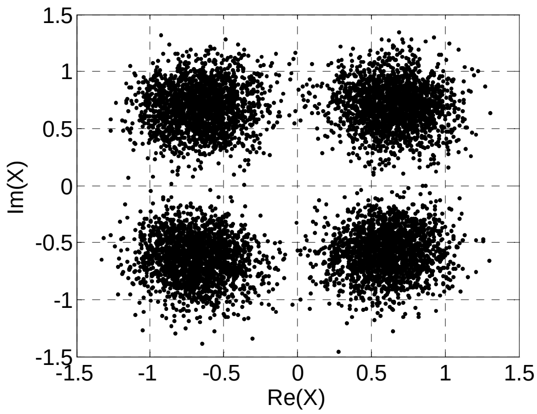

Figure 3: Constellation diagram for X polarisation

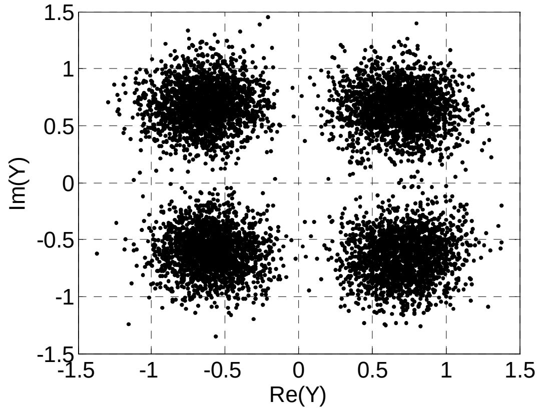

Figure 4: Constellation diagram for Y polarisation

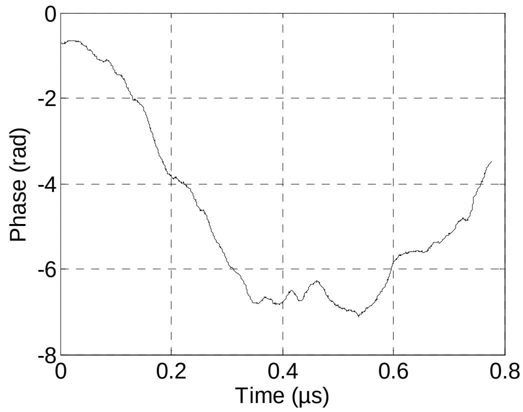

Figure 5: Evolution of phase, after correction of the bulk frequency offset of 860MHz

Conclusions

In this paper we have demonstrated adaptive equalisation at 40Gbit/s per wavelength over a distance of 2480km without optical dispersion compensation. The use of the constant modulus algorithm allows the receiver to acquire the data without the need for a training sequence. Preliminary loop experiments demonstrate the feasibility of the proposed approach, with simulation indicating the robustness of the system to PMD and chromatic dispersion.

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