Joint Equalization and Timing Recovery for Coherent Fiber Optic Receivers

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Abstract *A new low-complexity, dispersion-robust digital timing recovery for coherent systems is presented as a joint implementation with the FIR-equalizer, demonstrated for 112Gb/s RZ-CP-QPSK.*

Introduction

In coherent receivers with digital processing the dispersion tolerance of blindly adapted finite impulse response (FIR) equalizers depends heavily on the preceding timing phase recovery. As conventional timing recoveries only tolerate a certain amount of dispersion [1], this limits the system design flexibility, requiring either very precise optical dispersion maps or an accurate electric domain dispersion compensator, limiting the flexibility of system design.

The timing recovery presented in [1] can be merged with the FIR equalizer, as it has the identical requirements regarding dispersion tolerance, thus combining low-complexity with any specified dispersion limit, and outperforming conventional algorithms.

Coherent Digital Receiver Design

A typical setup for digital coherent receivers is shown in Fig. 1. After analog-to-digital conversion (ADC), dispersion compensation can be performed, as in the receiver presented in [2]. For proper and fast convergence of the filter taps, the timing recovery has to precede the FIR butterfly equalizer, which compensates for residual dispersion and PMD. Widely used timing recovery algorithms include Gardner [3] and the square timing recovery [4] that is often used for laboratory measurements.

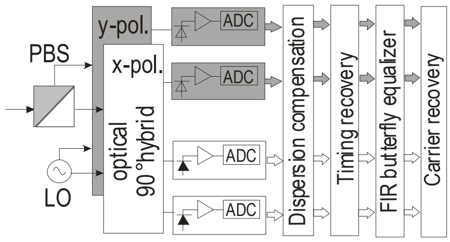

Fig. 1: Polarization diversity receiver design

Timing Recovery Design and Performance

In [1], a histogram-based timing phase algorithm was presented that offers virtually unlimited dispersion tolerance operating on two samples per symbol (Fig. 2). The number of taps in the structure depends on signal spread due to chromatic dispersion. Although the performance of T/2-spaced FIR filters does not depend on the absolute sampling phase for Nyquist rate sampling, the sampling frequency offset of the ADC has to be compensated to prevent symbol cycle slips.

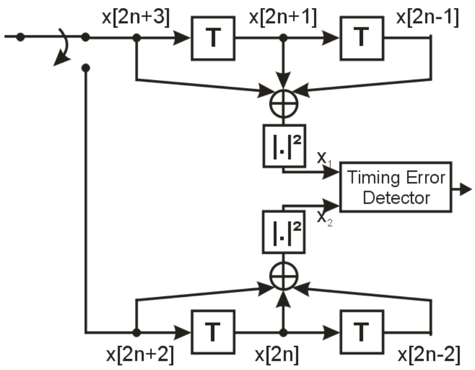

Fig. 2: Histogram-based timing recovery, N=3 taps [1]

After a sliding average over N odd and even samples, a two-dimensional discrete probability density function (pdf) $H(x_1,x_2)$ is evaluated over L_0 symbols (Fig. 3).

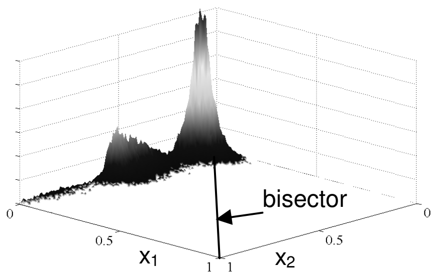

Fig. 3: Discrete pdf for sampling at [0; T/2] for QPSK-modulation and back-to-back (b2b) transmission

The timing error for q bits of quantization is given by

$$\phi = \sum_{x_1=1}^{2^q} \sum_{x_2=1}^{x_1} \left(H(x_1,x_2) - H(x_2,x_1)\right) \cdot r$$

with r defined as the distance of the point (x1, x2) to the bisector between the x_1 and x_2 axis of the histogram given by

$$r = \sin\left(\frac{\pi}{4} - \arctan\frac{x_2}{x_1}\right)\sqrt{x_1^2 + x_2^2}$$

For a given spectrum of the receive signal $G(f)$ and an estimation length L_0, the performance of the timing recovery can be evaluated versus the modified Cramer-Rao bound (MCRB) [5]. The normalized timing error is then given by

$$\frac{\sigma^2}{T^2} = \frac{1}{8\pi^2 L_0 \xi \frac{E_s}{N_0}}$$

with

$$\xi = \frac{T^2 \int_{-\infty}^{\infty} f^2 |G(f)|^2 df}{\int_{-\infty}^{\infty} |G(f)|^2 df}$$

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Fig. 4 compares the proposed timing recovery (histogram) for N=1, with the Gardner and the square timing recovery (STR) algorithm for MZM-RZ50% modulation and appropriate filtering for b2b transmission.

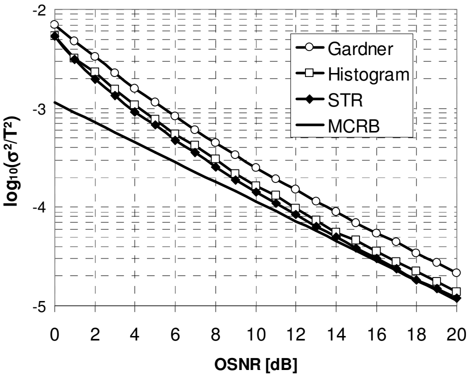

Fig. 4: Performance vs. MCRB for b2b transmission

Joint Equalization and Timing Recovery

In the proposed timing recovery, the number N of taps for the averaging has to be determined according to the dispersive spread of the signal, which is identical to the tap requirements of the FIR equalizer. Therefore, a joint equalizer and timing recovery structure for two-fold over-sampling and T/2-spaced equalization can be proposed (Fig. 5), with $M = 2N+1$ taps.

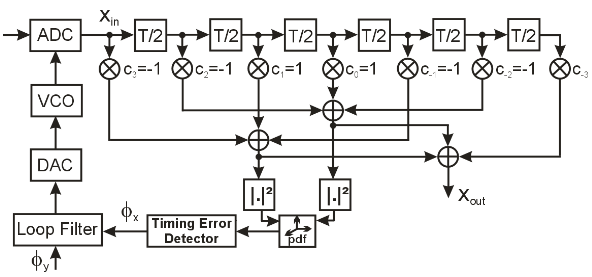

Fig. 5: Joint equalizer and timing recovery during symbol timing acquisition, M = 7

During acquisition, the equalizer is in timing recovery mode with odd and even taps each set to 1 with alternating sign, thus resulting in a band-pass pre-filtering centered at the Nyquist frequency. After the timing phase and frequency offsets have been acquired using a 2nd order PLL, the system can switch to equalization mode and the taps can be adapted according to the inverse impulse response of the channel. Since the timing phase fluctuations around the frequency offset are minimal on the timing scale required for equalization, the filter adaptation is not critical. Once the taps have converged, the timing phase error can be derived from the equalizer taps using known methods [6].

In Fig. 6 the performance of the timing recovery is evaluated for the case of up to 1000ps/nm of dispersion in a 112Gb/s coherently demodulated, polarization-multiplexed *RZ-CP-QPSK* system with M=15 and OSNR=15dB. While an increasing number of taps degrades the b2b performance, the phase error variance in presence of dispersion decreases with a higher tap number. Although higher estimation lengths are required in order to reach b2b performance if dispersion increases, this is not really an issue, since the timing recovery is used for acquisition only.

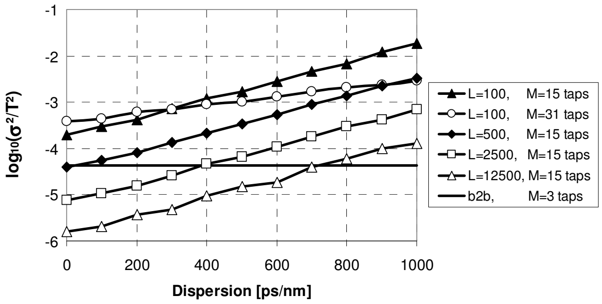

Fig. 6: Normalized timing phase variance for tracking versus dispersion for varying L_0 and M, OSNR=15dB

Besides chromatic dispersion, the proposed algorithm is also tolerant against any kind of further distortions, like non-linear effects, narrowband filtering, and PMD.

The dispersion-tolerance is identical to FIR equalization and can be measured by the mean maximum of the s-curve **$<\phi_{max}>$** (Fig.7). If the tolerance limit is reached, the mean of the s-curve is 0 independently of the timing phase error.

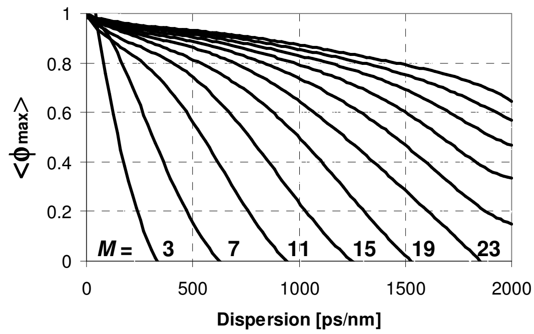

Fig. 7: Interpolated mean maximum timing phase error detector output $<\phi_{max}>$ in the proposed scheme for an increasing number of T/2 equalizer taps

Conclusion

A joint equalization and timing recovery approach has been proposed that allows for great flexibility in system design, with virtually unlimited dispersion tolerance for the timing recovery that can be implemented as a by-product of equalization.

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