Outils avancés de traitement de signal pour les réseaux optiques à haut débit

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1 Introduction

Fiber-optic communication systems have revolutionized the telecommunications industry and have played a major role in the advent of the information age since their introduction in the 1970's. Because of its advantages over electrical transmission, optical fibers have been largely deployed in core networks. During the last years, IPTV, HDTV, VoD, mobile broadband services and internet applications have boomed, causing saturation issues in the networks and leading to an increase in bandwidth demand. This pushed carriers to increase the capacity of WDM channels by introducing 40G and 100G.

With the new possibilities offered for the high speed digital circuits, coherent systems have attracted a lot of attention during the last years. A part from the receiver sensitivity the interest lies now in the increase of spectral efficiency as well as tolerance against dispersion effects and fiber nonlinearities. Those are today's the most limiting factors in ultra long haul communication systems.
Additionally in contrast to Intensity Modulation Direct Detection (IM-DD) systems or differential Phase Shift Keying (PSK) systems, the received electrical signal in coherent receiver is proportional to the electrical field vector of the optical signal. Therefore the system becomes linear, which means that all linear distortions like Chromatic Dispersion (CD) and Polarization Mode Dispersion (PMD) can theoretically be compensated without any losses and also non linear effects can be compensated very efficiently. Moreover, the access to both the phase and the amplitude of the signal makes the use of advanced modulation formats such as multilevel formats such as Qaudrature PSK (QPSK) and Quadrature Amplitude Modulation (QAM), which can raise the spectral efficiency up to several bit/s/Hz, compared to only 1 bit/s/Hz for IM-DD systems. However, these advantages have their price. A coherent receiver is much more complex than a simple direct detection receiver. High speed analog to digital converters (ADC) are needed to convert the received signal into the digital domain. And these ADCs must be interfaced with a digital signal processing unit, which performs polarization control, equalization and finally the carrier and data recovery. To develop these components for the next generation of optical communication systems, which can run at 40G or even 100G is still a challenging issue.

The aim of this thesis is to develop robust Digital Signal Processing (DSP) tools specific to the optical channel. Those algorithms at least deal with the operations of carrier phase recovery, frequency offset estimation, equalization and the tracking of the variation of PMD. Knowing that those algorithms are to be implemented in circuits running with a speed of some tens of MHz, the optimization of those tools is essential.
Moreover, the already proposed tools are well adapted for QPSK formats, and as higher order modulation formats are more sensitive to signal distortions, accurate estimators and robust equalizers are still required. Our proposed algorithms are to be tested using a simulation setup of an optical transmission system using coherent detection and to be validated with offline processing of real measurements in the framework of the European Network of Excellence (EURO-FOS).

2 Architecture of an optical transmission system using coherent detection

In a coherent system using Polarization Multiplexing (PolMux), the trasmit laser output is split into 2 orthogonal polarization components, which are modulated seperately (QAM in general) and combined in a Polarization Beam Combiner (PBC) as depicted in Fig.1.
A digital coherent receiver uses a phase and polarization diversity architecture to map the optical filed into four electrical signals, corresponding to the in-phase and quadrature field components of the two polarization. Once digitized, DSP is applied to compensate for CD, and track the polarization, and estimate both the frequency offset and the phase. The different functions and DSP algorithms required for coherent receivers is depicted in Fig.3

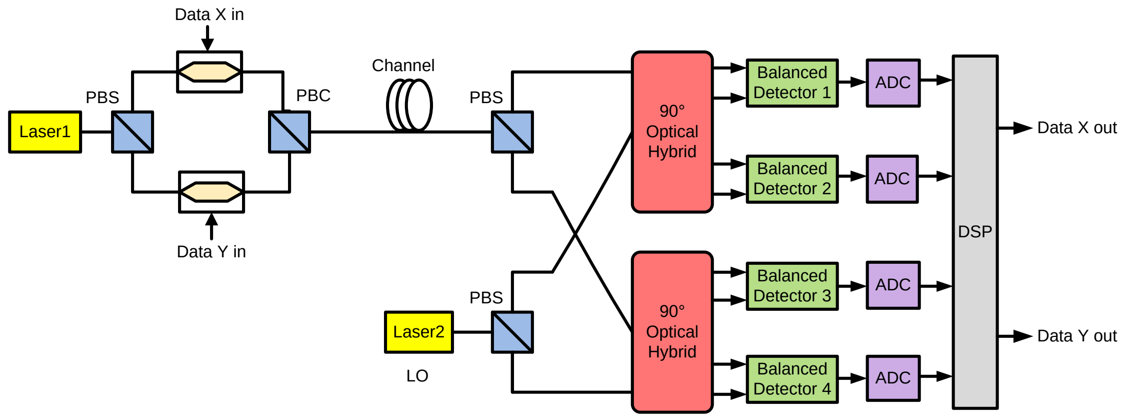


FIG. 1 – **Architecture of an optical transmission system using coherent detection** - LO : Local Oscillator, PBS : Polarization Beam Splitter, PBC : Polarization Beam Combiner, DSP : Digital Signal Processor

3 Simulation setup of a QAM coherent system

In order to study the performances of the DSP algorithms described above, we simulated a Gray encoded QAM optical transmission system using coherent detection and PolMux. Noise is generated at the transmitter, phase noise and frequency offset estimation are simulated as well. The propagation channel is modelled with the effects of birefringence, DGD, and polarization rotation. we also used a square root raised cosine filters with a roll-off factor equal to 1 both at the transmitter and the receiver side to reduce the wide spectrum of the QAM signal. The received electrical signal is digitized using a rate of 2 samples per symbol.

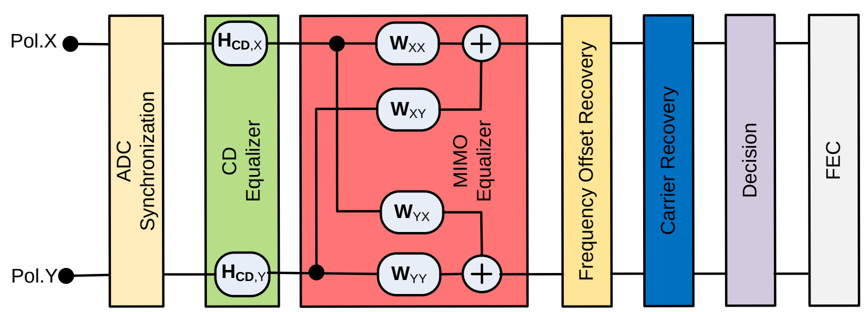


FIG. 2 – **Architecture of an digital signal processor for coherent receiver**

Finally, a 5^{th} order Bessel electrical filter with a 3dB bandwidth 80% of the Baud rate was included as the anti-aliasing filter
The back-to-back performances (theoretical and by simulation) of the simulated system is given by Fig. 3 for different modulation formats.

3.1 Frequency offset Estimation

Several Frequency Offset (FO) estimators have been already presented for QPSK based optical transmissions. These algorithms rely either on the phase difference between two adjacent receive samples (1; 2) or the maximization of the discrete-frequency spectrum of the fourth-power received samples (Viterbi&Viterbi algorithm). Let N be the number of available independent received samples. The Mean Square Error (MSE) on the FO decreases as $1/N$ for the first kind of algorithms, and as $1/N^2$ for the second kind of algorithms. As M-QAM is more sensitive to FO, designing more accurate estimators is still required. Therefore, we proposed a new non-data-aided FO estimator whose MSE decreases as as $1/N^3$. This algorithm operates in

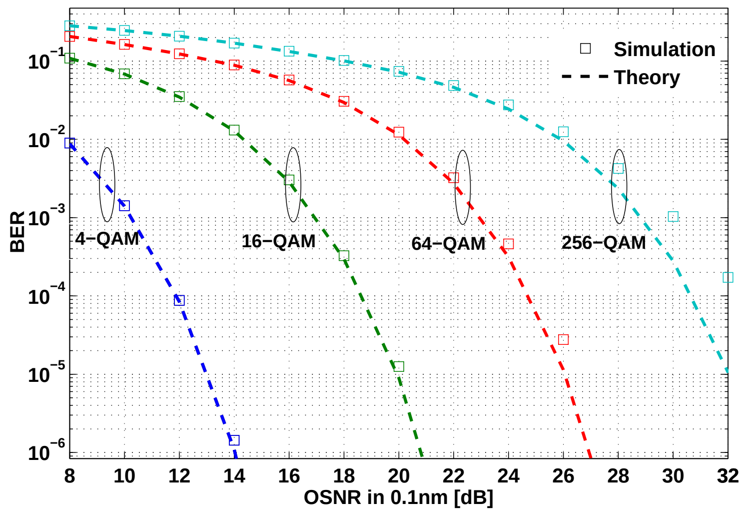
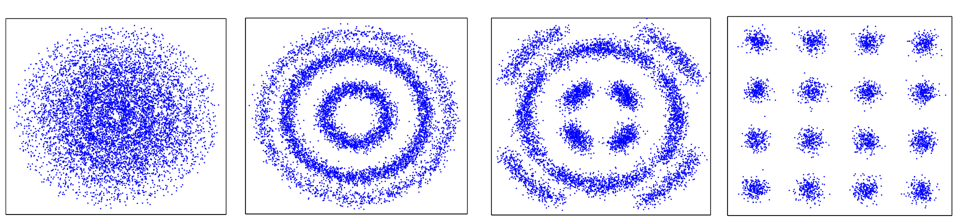


FIG. 3 – **Back-to-Back performance of the simulation setup for different modulation formats and Symbol rate=14Gbaud**

single or PolMux context and adapted for any QAM or PSK formats as well.Unlike what is usually done in optical communications, we propose to compute the maximization of the periodogram into two steps as follows :

1. A coarse step which detects the maximum magnitude peak which should be located at around the frequency . This is carried out via a Fast Fourier Transform (FFT) of size N (N-FFT). The MSE associated with this step is of order of magnitude $1/N^2$.
2. A fine step which inspects the cost function around the peak detected by the coarse step. This step may be implemented by a gradient-descent algorithm.

The proposed estimator is accurate, blind, adapted to QAM modulated signal. For coherent 100Gbit/s QAM PolMux transmission, FO can be recovered with an accuracy of few KHz. To illustrate the performance of the proposed equalizer, we show in Fig. 4, the constellations of a PolMux 16QAM 112Gbit/s, after the source seperation and the compensation of FO using both the coarse and the fine steps.



(a) (b) (c) (d)

FIG. 4 – **16QAM constellations for OSNR=22dB, N=512 FO=2.75GHz. (a) At the input of the CMA equalizer. (b) At the output of the CMA. (c) FO compensation using the Coarse step,(d) FO compensation using the Coarse and the fine steps**

	CMA	**DD**
$f(n)$	$2\|z(n)\|^2$	1

TAB. 1 – $f(n)$ for CMA and DD algorithms

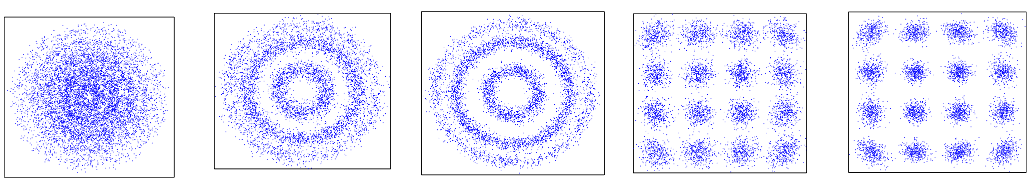
3.2 Adaptive equalization

Mutiple Input Multiple Output (MIMO) equalization is an essential part of a digital signal processor for QAM systems using PolMux. This equatlization deals at least with the compensation of the Inter-Symbol Interference (ISI) and source separation. Those signal impairments are mainly genererated by residual CD and PMD.

In the state of the art, all the proposed adaptive equalizers are based on the minimization of a cost function $\mathbf{W} \mapsto J(\mathbf{W}) = \mathbb{E}[J_n(\mathbf{W})]$ ($\mathbf{W}$ are the coefficients of the filter ans J_n the error function at time n) using either the constant modulus or the decision directed criterion. This minimization can be implemented using the gradient descent algorithm as follows.

$$\mathbf{W}_{n+1} = \mathbf{W}_n - \mu \nabla J_n(\mathbf{W})|_{\mathbf{W}_n} \tag{1}$$

where μ is the constant step-size parameter, ∇J_n is the gradient at time n, and $\mathbf{W}_n$ is the equalizer at time n. The choice of the step-size is a crucial task for gradient algorithm and arises from a trade-off between convergence speed and steady-state performance. To overcome this problem, we proposed to implement variable step-size approach by replacing μ with μ_n in Eq. (1).



(a) (b) (c) (d) (e)

FIG. 5 – **PolMux 16-QAM constellations (Polarization rotation= $\frac{\pi}{4}$, CD=1250ps/nm, DGD=50ps, laser linewidth= $1.4MHz$). (a) Input of the equalizers. (b) (c) equalized and recovered (CMA),(d)(e) equalized and recovered (PN-CMA)**

To derive μ_n, we considered the Pseudo-Newton algorithm (3) that exploits the Hessian matrix as follows

$$\mu_n = \mu H_n^{-1}(\mathbf{W}), \quad \text{with} \quad H_n(\mathbf{W}) = \frac{\partial^2 J_n(\mathbf{W})}{\partial \mathbf{W}^{\mathrm{H}} \partial \mathbf{W}} \tag{2}$$

where the $(.)^{\mathrm{H}}$ denotes the complex-transpose operator. In order to reduce the computational load, the inverse Hessian matrix can be updated in a recursive way. Let $\mathbf{y}(n)$, and $z(n)$ be the data sequences resp. at the input and the output of the equalizer.

$$H_n^{-1}(\mathbf{W}) = \lambda^{-1} H_{n-1}^{-1}(\mathbf{W}) - \frac{\lambda^{-2} H_{n-1}^{-1}(\mathbf{W}) \mathbf{y}(n) \mathbf{y}^{\mathrm{H}}(n) H_{n-1}^{-1}(\mathbf{W})}{[(1-\lambda) f(n)]^{-1} + \lambda^{-1} \mathbf{y}^{\mathrm{H}}(n) H_{n-1}^{-1}(\mathbf{W}) \mathbf{y}(n)} \tag{3}$$

where λ is a forgetting factor ($0 \leq \lambda \leq 1$ and assuming $\lambda + \mu = 1$ (3)) and $H_0^{-1}(\mathbf{W}) = \delta \mathbf{Id}$ with the identity matrix $\mathbf{Id}$ and a fixed positive number δ. In Table 1, we summarize the value $f(n)$ for CMA and DD algorithms. The computational load of the gradient (resp. Pseudo-Newton) approach is $\mathcal{O}(L)$ (resp. $\mathcal{O}(L^2)$). In 16QAM, 112Gbit/s optical coherent transmission context,the considered algorithms offer better steady state performance and convergence speed than standard adaptive equalizers.

3.3 Block based equalizers

The main advantage of an adaptive approach is its ability to track propagation channel variation. However in optical communications, the propagation channel may vary quite slowly compared to the symbol period (4; 5), i.e., the channel can be assumed to be constant over a large observation window. Therefore it is worth treating the data block-by-block and not sample-by-sample.
The proposed algorithm is a block one (i.e., operating block-by-block) instead of being adaptive (i.e., operating sample-by-sample). The main advantage of this new approach is to improve the statistics estimation and so the algorithm behavior. As depicted in Fig.7 blockwise algorithm is able to estimate the channel with a

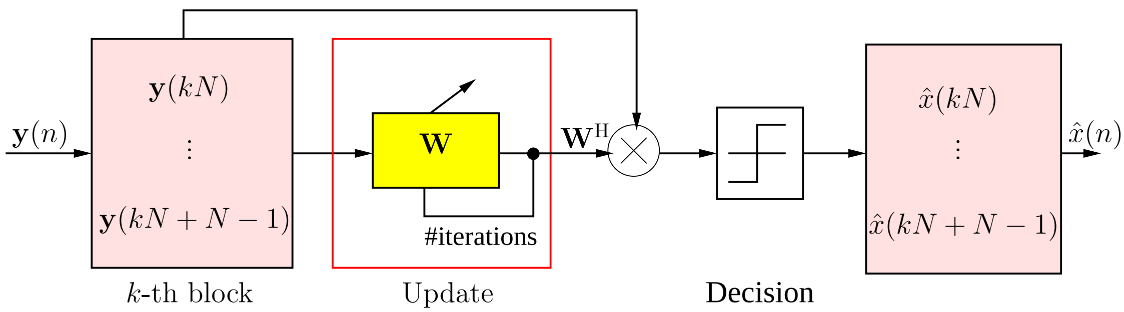


FIG. 6 – **Structure of the propopsed blockwise equalizer**

few thousands of samples. As a consequence, if the channel is dramatically modified inside one block, the blockwise algorithm will be able to find fastly the new channel value with the next block while the adaptive equalizer will find this new channel value after at least a few tens of thousands iterations and thus samples. Surprisingly the blockwise approach is more adapted to channel variation than the adaptive one.
The computational complexity of the proposed blockwise equalizer was also investigated in comparison to

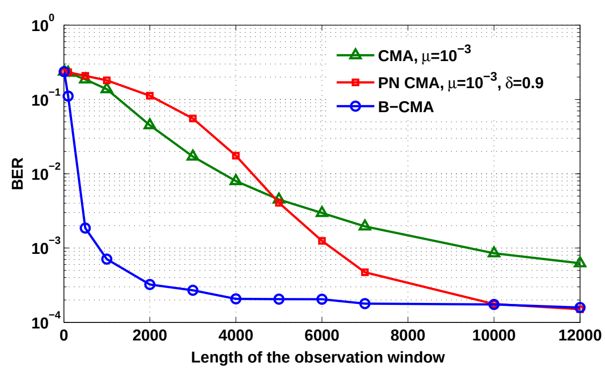


FIG. 7 – **BER vs. the length of the observation window. (#iterations= 50 for the Block CMA, OSNR=20dB, DGD=50ps, polarization rotation=** $\frac{\pi}{4}$**)**

the adaptive equalizers operating on a sample-by-sample approach. The block equalizer was found to have a speed of convergence ~ 10 faster than the classical CMA at the expense of an increasing complexity by a factor of ~ 4.

4 Experimental results

In the framework of the European Network of Excellence EURO-FOS, a project aiming at comparing offline DSP algorithms for different partners (HHI, PoliTo, ...), we had access to measurments data from experiments conducted by the HHI optical communications group. Those data concern, QPSK and 8-PSK modulation formats and using different scenarios (Back-to-Back, propagation with inline CD compensation, propagation with offline CD compensation)   Those data allowed us to test the developed algorithms that

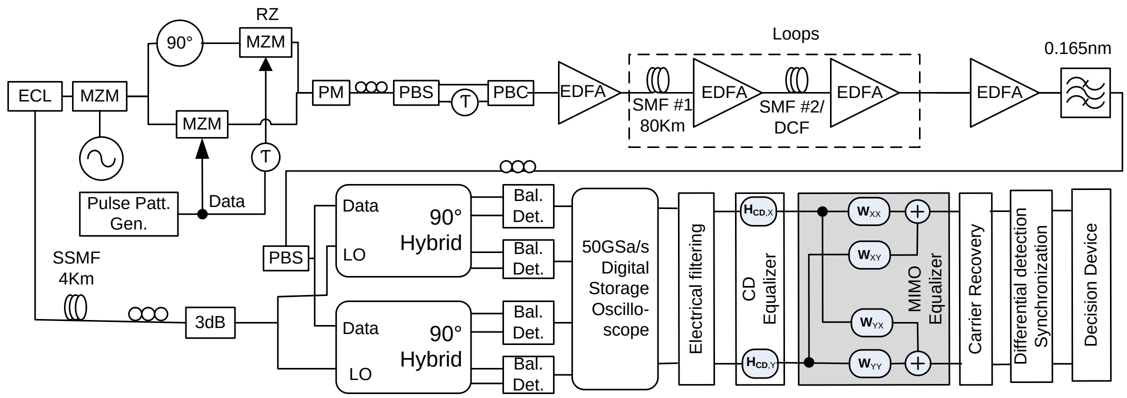


FIG. 8 – **Measurement setup of the 10Gbaud transmission system using polarization multiplexing with the offline DSP blocks**

concern the compensation of chromatic dispersion using FIR filters, the Viterbi&Viterbi carrier phase estimator, the functions of downsampling, synchronization, decision and error counting. Two activity reports were released and results were compared to those obtained by the HHI team.
Moreover, I had the opportunity to spend 2 weeks at HHI (October 2010). We made joint activities concerning the generation of 16-QAM signals with a 28Gbaud real time transmitter, and the results of this collaboration led to a joint submitted publication in the *IEEE Journal of Lightwave Technology.*

5 Conclusion and future work

Singularity is an issue for optical communications using PolMux, this means the two outputs of the MIMO equalizer could converge to the same source. A good initialization of the equalizer, resetting the equalizer once the determinant of the Jones matrix approaches zero, adding a penalty term in the CMA cost function and using two-stage CMA were proposed for solving this problem. We are investigating the possibility to upgrade the proposed block CMA to avoid the singularity problem by adding a penality to the cost function (cross correlation between the two output data), and using the deflation method.

List of Publications

[A] Selmi, M. and Jaouen, Y. and Ciblat, P., *Optical Communication, 2009. ECOC '09. 35th European Conference on* "**Accurate digital frequency offset estimator for coherent PolMux QAM transmission systems**", 2009, 20-24, 1-2.

[B] Selmi, Mehrez and Ciblat, Philippe and Jaouen, Yves and Gosset, Christophe, *Optical Fiber Communication (OFC), collocated National Fiber Optic Engineers Conference, 2010 Conference on (OFC/NFOEC)*, "**Pseudo-Newton based equalization algorithms for QAM coherent optical systems**", 2010, 21-25, 1-3.

[C] Selmi, M. and Ciblat, P. and Jaouen, Y. and Gosset, C., *Optical Communication, 2010. ECOC '10. 36th European Conference on* "**Block versus Adaptive MIMO Equalization for Coherent PolMux QAM Transmission Systems**", 2010.

[D] Selmi, M. and Gosset, C and Noelle, M. and Ciblat, P. and Jaouen, Y., "**Blockwise Digital Signal Processing for PolMux QAM/PSK Optical Coherent Systems** ", submitted to : *IEEE Journal of Lightwave Technology*.

[E] Selmi, M. and Ciblat, P. and Jaouen, Y. and Gosset, C., " **Complexity Analysis of Block Equalization Approach for PolMux QAM Coherent Systems** ", submitted to : *SppCom, Toronto June 2011*.

Workshops

[F] Selmi, M. and Jaouen, Y. and Ciblat, P. and Gosset, C., " **Traitement numerique du signal pour un systeme coherent 60Gbit/s PolMux 8-PSK** ", *Workshop 50 ans Laser December 2010*.

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