Joint Frame Synchronization and Frequency Offset Estimation in Coherent Optical Transmission Systems

Fabio Pittalà(1,2), Juan Qi(1), Majdi Msallem(1,2), Josef A. Nossek(2)

(1) European Research Center, Huawei Technologies Duesseldorf GmbH, Riesstrasse 25, D-80992 Munich, Germany, fabio.pittala@huawei.com,
(2) Institute for Circuit Theory and Signal Processing, Technische Universität München, Arcisstr. 21, D-80290 Munich, Germany.

Abstract A novel method for frame synchronization and frequency offset estimation employing CAZAC sequences is demonstrated in a 256 Gb/s PDM-16QAM transmission system. The proposed algorithm is tolerant to residual CD, PMD, PDL and fast time-varying SOP rotation.

Introduction

Frequency domain equalization (FDE) in combination with training-aided (TA) channel estimation (CE) is a promising low-complexity 2×2 multi-input multi-output (MIMO) equalization solution for next generation flexible coherent optical communication system[1-3].

However, TA-CE is high sensitive to frequency-offset (FO) due to the mismatch between the laser frequencies used by the transmitter and the receiver. Therefore, accurate FO estimation (FOE) and compensation is required before performing TA-CE[2,3]. In principle the frame synchronization (FS) and the FOE should be fast, robust to optical channel impairments and should not require any special preamble which reduces the transmission spectral efficiency.

In this paper, we present a joint FS and FOE method which uses the same training sequences (TS) employed for CE in a 256 Gb/s polarization-division multiplexed (PDM) 16-level quadrature amplitude modulation (QAM) transmission system. The proposed method is robust to residual chromatic dispersion (CD), polarization-mode dispersion (PMD), polarization-dependent loss (PDL) and fast time-varying state-of-polarization (SOP) rotation.

Working Principle

As shown in Fig. 1, FS and FOE are jointly performed after compensating the bulk of CD and before the 2×2 MIMO FDE with TA-CE. The digital signal processing (DSP) at the receiver is based on constant amplitude zero auto-correlation (CAZAC) TS coded by using the Alamouti scheme[4]. The TS are placed between the payload forming frames of P symbols, Fig 2.

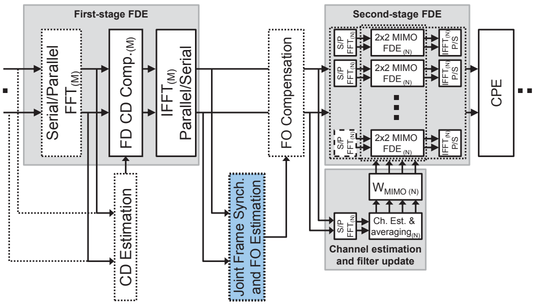

Fig. 1: DSP for receivers with 2×2 MIMO TA-FDE.

The proposed FS and FOE algorithm consists of three stages: Rough-FS, Fine-FS with Rough-FOE and finally Fine-FOE.

In the Rough-FS each data-block of length P symbols taken from a set of consecutive data-blocks C, is divided into R sub-blocks B of length Q symbols, where $R = 1/\kappa \cdot P/Q$ and κ is the overlap factor between 2 consecutive sub-blocks, Fig. 2. The value κ has to be chosen in such a way to guarantee that the overlap between consecutive sub-blocks is larger than the length of the TS, for simplicity here we consider $\kappa = 0.5$. The correlation between sub-blocks distant P symbols is then calculated as:

$$corr_r[n] = \sum_{c=1}^{C} B_{(r,c)}[n] B^*_{(r,c-1)}[n] \quad \text{for } r \in \{0,1,\dots,R-1\} \tag{1}$$

The strongest correlation calculated by (2) gives which sub-block, indexed by r, contains the TS:

$$\Sigma corr_r = \sum_{n=1}^{Q} |corr_r[n]| \tag{2}$$

This stage needs data of only one polarization.

In contrast, the Fine-FS and Rough-FOE requires the data of both polarizations. However, it operates only on the sub-blocks containing the TS $B^x_{(r,c)}$ and $B^y_{(r,c)}$ which are multiplied in frequency domain by ideal sub-blocks A^x and A^y containing the TS and zero data information:

$$\zeta^{xx}_{\Delta_{FO}}[n] = \left| \mathcal{F}^{-1}\left\{ \mathcal{F}\{B^x_{(r,c)}[k]\} \mathcal{F}\{A^x[k+\Delta_{FO}]\} \right\} \right| \tag{3}$$

$$\zeta^{xy}_{\Delta_{FO}}[n] = \left| \mathcal{F}^{-1}\left\{ \mathcal{F}\{B^x_{(r,c)}[k]\} \mathcal{F}\{A^y[k+\Delta_{FO}]\} \right\} \right| \tag{4}$$

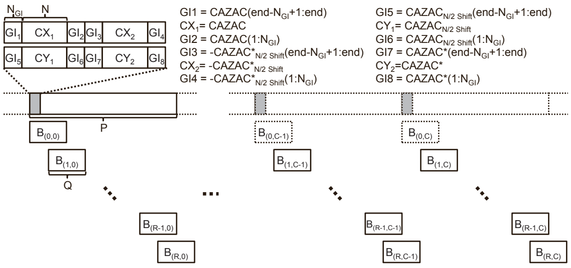

Fig. 2: Frame Structure and Rough-FS stage.

$$\zeta^{yx}_{\Delta_{FO}}[n] = \left|\mathcal{F}^{-1}\left\{\mathcal{F}\left\{B^{y}_{(r,c)}[k]\right\}\mathcal{F}\{A^{x}[k+\Delta_{FO}]\}\right\}\right| \quad (5)$$

$$\zeta^{yy}_{\Delta_{FO}}[n] = \left|\mathcal{F}^{-1}\left\{\mathcal{F}\left\{B^{y}_{(r,c)}[k]\right\}\mathcal{F}\{A^{x}[k+\Delta_{FO}]\}\right\}\right| \quad (6)$$

The sum of (3), (4), (5) and (6) is the cost function described by (7) where the maximum corresponds to the fine starting point of the TS including a rough estimation of the FO, Fig. 3.

$$Z_{\Delta_{FO}}[n] = \zeta^{xx}_{\Delta_{FO}}[n] + \zeta^{xy}_{\Delta_{FO}}[n] + \zeta^{yx}_{\Delta_{FO}}[n] + \zeta^{yy}_{\Delta_{FO}}[n] \quad (7)$$

The value Δ_{FO} is chosen in accordance to a predefined set of expected FO values. The resolution of the FO scanning range is given by: $Res_{\Delta_{FO}} = \mathcal{B} \cdot o/Q$, where $\mathcal{B}$ is the signal baudrate and o is the oversampling ratio at the receiver. Here, we consider $\mathcal{B}$=32 GBaud, o=2 samples per symbols and Q =512 samples, therefore $Res_{\Delta_{FO}}$=125 MHz. Fig. 3 plots the cost function $Z_{\Delta_{FO}}[n]$ for transmission impaired by different channel effects. It can be observed that $Z_{\Delta_{FO}}[n]$ exhibits a peak at the starting position of the TS, however, the peak is repeated along the FO scanning range axis at interval $\nu_{amb} = \mathcal{B}/\mathrm{N}$, where N is the length of the CAZAC block in symbols. Here, we consider N =16 symbols leading to ν_{amb}=2 GHz. As illustrated in Fig. 3, the strength and the position of the ν_{amb} spaced peaks are influenced by the impairments present in the transmission system.

The Fine-FOE is the final stage of the estimator. It eliminates the ambiguous peaks visible in the function $Z_{\Delta_{FO}}[n]$. The cost function of the Fine-FOE is given by:

$$\gamma_{\Delta'_{FO}} = \sum_{n=1}^{N}\left|h^{xx}_{\Delta'_{FO}}[n]\right| + \sum_{n=1}^{N}\left|h^{xy}_{\Delta'_{FO}}[n]\right| + \sum_{n=1}^{N}\left|h^{yx}_{\Delta'_{FO}}[n]\right| + \sum_{n=1}^{N}\left|h^{yy}_{\Delta'_{FO}}[n]\right| \quad (8)$$

where $h^{xx}_{\Delta'_{FO}}[n]$, $h^{xy}_{\Delta'_{FO}}[n]$, $h^{yx}_{\Delta'_{FO}}[n]$, $h^{yy}_{\Delta'_{FO}}[n]$ are the time domain components of the 2×2 MIMO channel[3] calculated by setting the transmitted TS $S_i = S_i \cdot e^{-j2\pi\Delta'_{FO}t}$ where $i \in \{x, y\}$. The value Δ'_{FO} is chosen between a range of expected FO values selected around the Rough-FOE value. Fig. 4 presents the cost function $-\gamma_{\Delta'_{FO}}$ for polarization rotation angles between 0° and

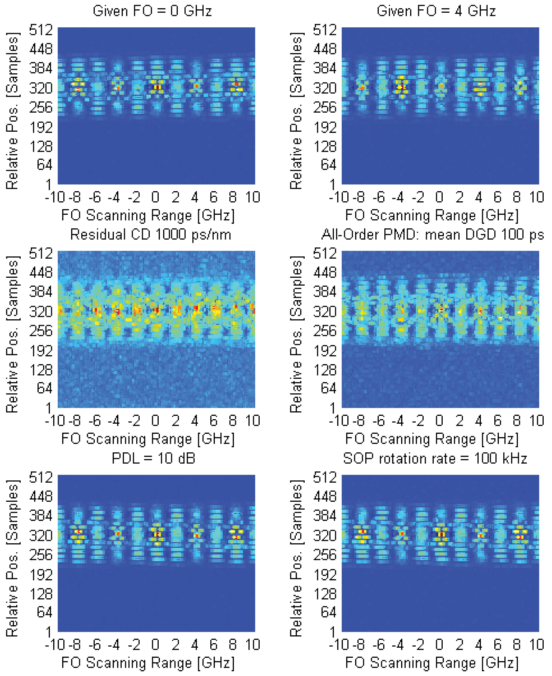

Fig. 3: Fine-Frame Synchronization and Rough-FOE cost function for given FO = 0 GHz (top-left), given FO = 4 GHz (top-right), Residual CD = 1000 ps/nm (middle-left), All-Order PMD (mean DGD = 100 ps) (middle-right), PDL = 10 dB (bottom-left), SOP rotation rate = 100 kHz (bottom-right). OSNR = 20 dB.

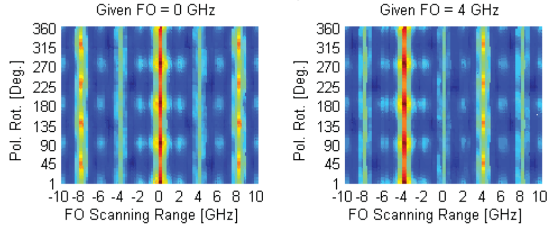

Fig. 4: Fine-FOE cost function for a given frequency offset equal to 0 GHz (left) and 4 GHz (right).

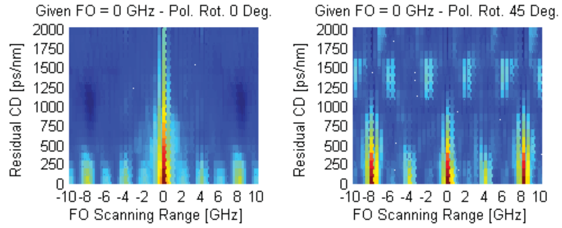

Fig. 5: Fine-FOE cost function as function of CD for polarization rotation equal to 0° (left) and 45° (right).

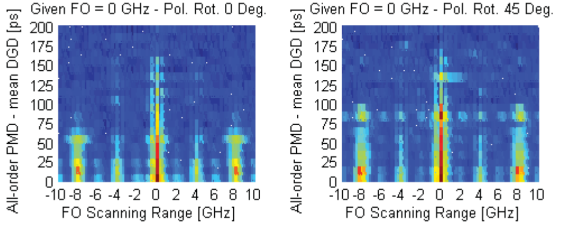

Fig. 6: Fine-FOE cost function as function of PMD for polarization rotation equal to 0° (left) and 45° (right).

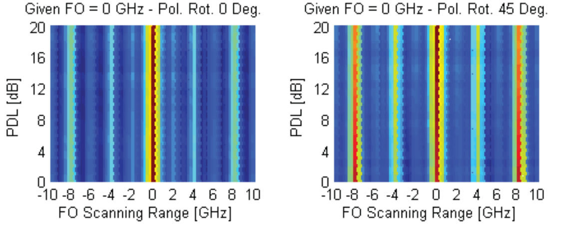

Fig. 7: Fine-FOE cost function as function of PDL for polarization rotation equal to 0° (left) and 45° (right).

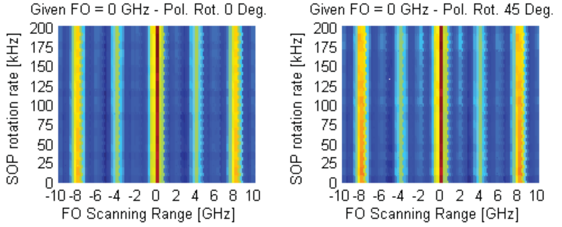

Fig. 8: Fine-FOE cost function as function of SOP rotation rate for polarization rotation equal to 0° (left) and 45° (right).

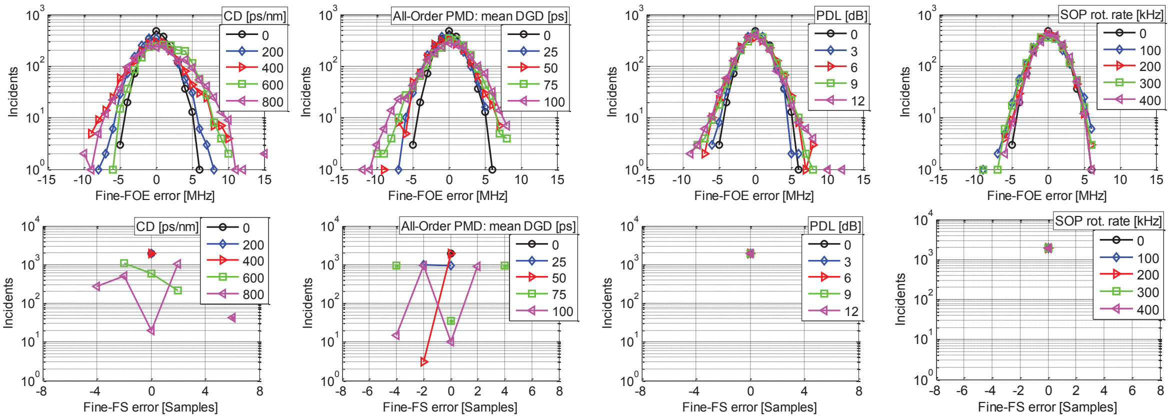

Fig. 9: Performance Evaluation

360°. It can be observed that with 90° periodicity the cost function $-\gamma_{\Delta'_{FO}}$ exhibits a peak repeated along the FO scanning range axis at interval $\nu'_{amb} = \mathcal{B}/4$ which reduces the scanning range of the Fine-FOE estimation between $\pm\mathcal{B}/8$. Fig. 5, 6, 7, 8 shows the behavior of $-\gamma_{\Delta'_{FO}}$ when the FOE is based on distorted received TS.

Performance Evaluation

The evaluation of the proposed algorithm is based on a 32 GBaud PDM system with 16-QAM leading to a transmission rate of 256 Gb/s. The lasers used in the system have a linewidth of 100 kHz. Simulations of the linear channel include residual CD, all-order PMD, polarization rotation angle α and polarization phase ϕ defining the initial SOP state and SOP rotation rate. At the receiver, white Gaussian noise is loaded onto the signal, followed by an optical Gaussian band-pass filter (4th-order, double-sided 40 GHz), the polarization-diverse 90°-hybrid and an electrical Bessel filter (5th-order, 16 GHz). A 64 Gsamples/s analog-to-digital-converter (ADC) stage digitalizes the received signal at 2 samples per symbol.

The transmitted data is framed in blocks P=2048 symbols including a CAZAC-Alamouti TS of total length of 64 symbols (N=16 symbols and N_{GI} =8 symbols). The CAZAC-Alamouti sequence with QPSK constellation is mapped in the external ring of the 16-QAM plot[5]. The Rough-FS is based on C=20 consecutive frames and each frame is divided in sub-blocks B of Q=512 samples. The Fine-FS and Rough-FOE scans FO values between ±3.75 GHz with resolution of 125 MHz. The Fine-FOE scans between ±100 MHz at intervals of 2 GHz the FO value estimated by the Rough-FOE stage so that the 2 GHz spaced ambiguity is eliminated and the estimation error is minimized.

For any combination of FO and CD, PMD, PDL or SOP rotation rate, with parameters range and distrubutions specified in Table 1, 100 channel trials have been performed with constant OSNR=20 dB and random α and ϕ. In Fig. 9, the distribution of the FS and FOE errors are represented by histograms that demonstrate the precision and robustness of the proposed algorithm.

Tab. 1: Parameter Range and Distribution for Channel Simulations

Impairment	Distribution	Value Range
All-order PMD	Maxwellian	Mean [0:25:100] ps
Residual CD	Uniform	[0:200:800] ps/nm
PDL	Uniform	[0:3:12] dB
α	Uniform	[0:360] Deg.
ϕ	Uniform	[0:360] Deg.
SOP rot. rate	Uniform	[0:100:400] kHz
FO	Uniform	[-3.6:0.1:3.6] GHz

The joint FS and FOE algorithm can tolerate residual CD values up to 800 ps/nm with a maximum frame misallinement of 3 symbols and maximum FOE error of 15 MHz. Considering All-order PMD, mean DGD smaller than 100 ps can be tolerated with maximum FS error of 2 symbols and FOE error of 12 MHz. PDL values below 12 dB can be tolerated with no error in the FS and maximum 12 MHz FOE error. The estimator seems to be insensitive to time-varying SOP rotation. For any SOP rotation rate tested the estimator exhibits perfect FS and maximum FOE error equal to 9 MHz.

Conclusions

A novel method for joint frame synchronization and frequency offset estimation based on CAZAC sequences has been demonstrated in a PDM-16QAM transmission system. The proposed estimator covers frequency offsets between ±3.6 GHz and shows high tolerance with respect to residual CD (≤~800 ps/nm), PMD (≤~mean DGD 100 ps), PDL (≤~12 dB) and SOP rotation rate (≤~400 MHz).

Reference

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