Training-based Channel Estimation for Signal Equalization and OPM in 16-QAM Optical Transmission Systems

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Abstract Efficient channel estimation for signal equalization and OPM based on short CAZAC sequences with QPSK and 8PSK constellation formats is demonstrated in a 224-Gb/s PDM 16-QAM optical linear transmission system.

Introduction

Multilevel modulation formats in combination with polarization division multiplexing (PDM) allow high spectral efficient optical transmission systems at rate beyond 100-Gb/s. In particular, PDM 16-level quadrature amplitude modulation (QAM) which allows for a spectral efficiency of 4-bits/s/Hz seems to be the most promising candidate for 400-Gb/s and 1-Tb/s systems.

Traditional PDM systems use blind algorithms for the 2x2 multi-input multi-output (MIMO) equalizer to separate the two polarizations and to compensate for channel impairments. The most adopted solution combines the constant modulus algorithm (CMA) for pre-convergence and the decision-directed least-mean-square (DD-LMS) to reduce the steady state error of the tap coefficients and to track channel variations. Attempt to reduce this high-complexity dual stage procedure by a single algorithm for QAM systems have been recently reported[1] and algorithm such as DD-least radius distance (LRD) have been proposed[2]. However, such algorithms are still influenced by the properties of the modulation format and suffer from a relatively slow convergence with potential sub-optimum acquisition and even failures. All these problems can be solved at the cost of slight bandwidth efficiency degradation by using frequency domain equalization (FDE) combined with training-based channel estimation[3].

In this paper we demonstrated efficient channel estimation for signal equalization and optical parameter monitoring (OPM) in a 224-Gb/s PDM 16-QAM optical linear transmission system.

Channel Estimation based on CAZAC Training Sequences

Efficient channel estimation can be supported by perfect-squares minimum-phase (PS-MP) constant amplitude zero autocorrelation (CAZAC) sequences[4]. For sequences of length $N=2^{2m}$ symbols with $m \in \{1,2,3,...\}$, the constellation plot refers to a $\log_2(N)$-phase-shift keying (PSK) modulated signal. The length of the training sequences has to be chosen in relation with the maximum channel impulse response (CIR) to be estimated. In order to keep low the required overhead for channel estimation, we have chosen training sequences of length N=16 symbols (QPSK) and N=64 symbols (8PSK). The training sequences plus a guard interval of length $N_{GI}=N/4$ symbols at the beginning and end of each sequence are periodically transmitted between the payloads of data. In principle, the modulation formats of the training sequences and that of the payloads of

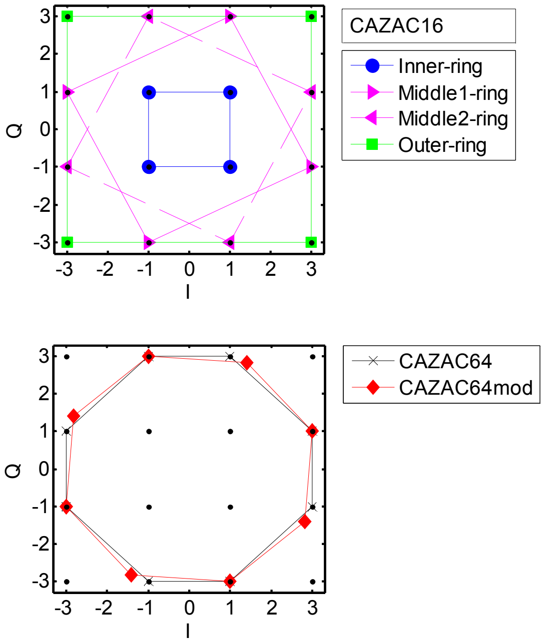

Fig. 1: Mapping short-length CAZAC sequences with low-order modulation format on a 16QAM constellation diagram: 16-symbol QPSK-CAZAC sequences (top) and 64-symbol 8PSK-CAZAC sequences (bottom).

Tab. 1: Parameter Range and Distribution for Channel Simulations

Impairment	Distribution	Value Range
All-order PMD	Maxwellian	Mean 25 ps
Residual CD	Uniform	[-400:400] ps/nm
α	Uniform	[0:2π]
φ	Uniform	[0:2π]

data are independent assuming that the modulator allows generating all constellation points of the transmission stream. As shown in Fig. 1, 16-symbol QPSK-CAZAC sequences can be perfectly mapped on a 16-QAM constellation diagram or in the outer-ring, or in the inner-ring or in one of the middle-rings. In contrast for 64-symbols 8PSK-CAZAC sequences not all points are matching with the corresponding points of the 16-QAM constellation. However, the 3°-mismatch can be eliminated by aligning the four offset 8PSK points to the nearest 16-QAM points with consequent alteration of the CAZAC properties. Respect to the 16-QAM inner points the signal-to-noise-ratio (SNR) is 2.24 times and 3 times larger in the middle and outer points, respectively.

System Setup

Performance of the signal equalization and OPM is based on a 28-GBaud PDM system with 16-QAM leading to a transmission rate of 224-Gb/s. Simulations of the linear channel include residual chromatic dispersion (CD), all-order polarization mode dispersion (PMD), polarization rotation angle α and polarization phase ϕ. At the receiver, white Gaussian noise is loaded onto the signal, followed by an optical Gaussian band-pass filter (2nd-order, double-sided 35-GHz), the polarization-diverse 90°-hybrid and an electrical Bessel filter (5th-order, 19-GHz). An analog-to-digital-converter (ADC) stage digitalizes the received signal at 2 samples per symbol. The channel is estimated with the aid of the received and transmitted training sequences spectra[4]. Averaging over channel estimations following the scheme illustrated in Fig.2 is applied prior to filter update. The received signal is equalized by a 2×N-tap FDE employing a minimum-mean square-error (MMSE) filter whereas OPM is based on a zero-forcing (ZF) filter both updated after 20 channel estimation averages.

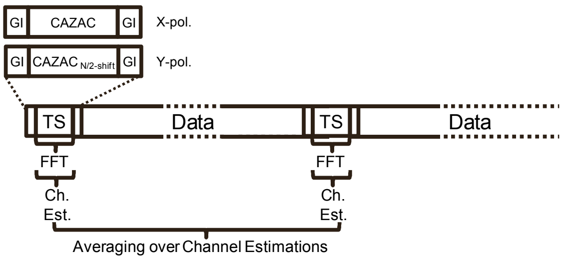

Fig. 2: Training-based transmission stream.

Signal Equalization Performance

For each OSNR value (ranging between 15 and 30 dB), 100 random channels have been generated with parameters randomly chosen from the distributions specified in Tab. 1.

As shown in Fig. 3-left, estimating the channel by using 16-symbol QPSK-CAZAC sequences, the required OSNR at BER=10^{-3} is 21.37 dB if the sequences are mapped in the outer-ring of the 16-QAM constellation diagram, 22.78 dB if mapped in one of the middle-rings and 24.75 dB if mapped in the inner-ring. For channel estimations based on 64-symbol 8PSK-CAZAC sequences the required OSNR at BER=10^{-3} is 22.71 dB and by alternating the CAZAC properties to make the sequence fitting with the 8 points of the middle-ring of the 16-QAM plot we get an OSNR penalty of 0.1 dB. The better estimation quality of CAZAC sequences mapped in the outer-ring is due to higher SNR that these points have. In addition, as illustrated in Fig. 3-right, the channel estimation averaging converges faster for training sequences mapped on the outer-ring than for sequences mapped in the internal rings (inner/middle-ring). The curves of Fig. 3-right do not converge to a single point because of a

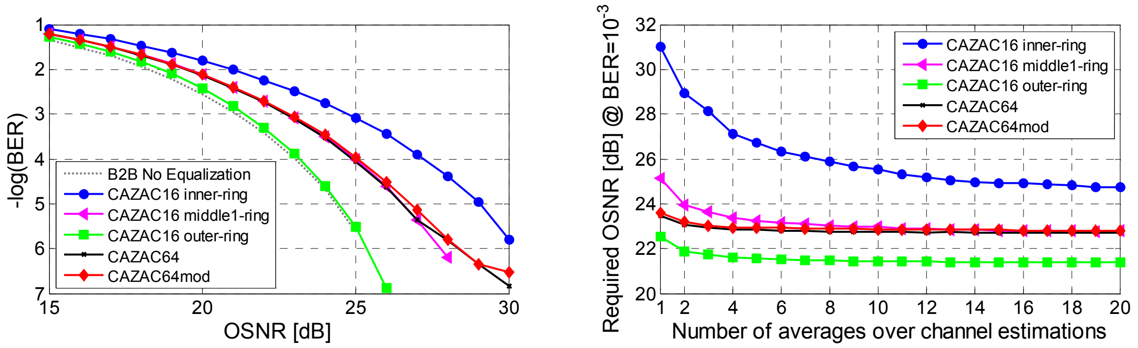

Fig. 3: Signal Equalization Performance: BER versus OSNR for different CAZAC mappings on the 16-QAM constellation (left) and required OSNR at BER=10^{-3} for different channel estimation averages (right).

channel estimation error that cannot be reduced by simply averaging the channel estimations. The BER performance of a single 64-symbol CAZAC sequences equals that obtained by averaging four 16-symbol sequences mapped on the middle-ring. This is true as far as the time windowing[4] used to extract the CIR in the channel estimation is 8 symbols long. In this case both sequences have same tolerance to channel impairments. On the other hand, if the time windowing is set to N/2 symbols CAZAC sequences of 64 symbols would have four times larger tolerance to channel impairments than 16-symbol sequences, but for the same number of channel estimation averages the two sequences would have same BER performance.

Optical Parameter Monitoring

For each CAZAC-mapping scheme, 1000 random channels have been generated with a constant OSNR of 21 dB (0.1 nm bandwidth) and parameters randomly chosen from the distributions specified in Tab. 1.

The residual CD is estimated from the quadratic fit of the resulting parabolic phase function[5], the DGD estimation is achieved by averaging over the central taps of the DGD spectrum[5], and the PDL is estimated by averaging the condition number of the central taps of the ZF filter[6]. The estimation performance is analysed with respect to the estimation errors with distributions represented by histograms that demonstrate the precision and robustness of the training-based OPM.

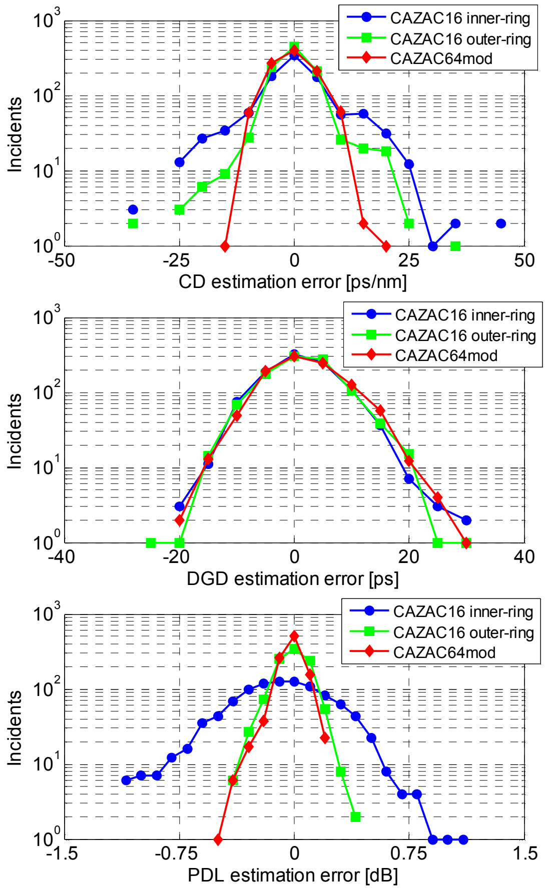

Fig. 4: OPM: histogram of CD (top), DGD (center) and PDL (bottom) estimation errors.

CD estimation based on the modified version of 64-symbol 8PSK-CAZAC sequences has a max error equal to ±20 ps/nm while for 16-symbol QPSK-CAZAC sequences it equals to ±35 ps/nm. The DGD estimation exhibits same performance independently from the schemes used and the max estimation error equals ±20 ps. In the PDL estimation the precision of the channel estimation has an important role; in fact, estimation based on 16-symbol CAZAC mapped in the inner-ring brings to noisy channel estimations significantly degrading the PDL estimation (max estimation error equal to ±1.1dB). By using 16-symbol QPSK-CAZAC mapped in the outer-ring or 64-symbol 8PSK-CAZAC the accuracy of the estimation improves to ±0.5 dB. All parameter estimations exhibit zero mean error.

Conclusions

Successful signal equalization and OPM has been demonstrated in a 16-QAM optical linear transmission system by using short CAZAC sequences with QPSK and 8PSK constellation diagram. In transmission with combined CD, all-order PMD and SOP rotation, using 16-symbol QPSK-CAZAC sequences mapped on the outer-ring of the 16-QAM constellation, the required OSNR at BER=10^{-3} is 21.37 dB. The OPM has zero mean error and accuracy within ±35 ps/nm, ±20 ps and ±0.5 dB, for CD, DGD and PDL estimation, respectively.

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