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Published in:
39th European Conference and Exhibition on Optical Communication (ECOC 2013)

Link to article, DOI:
10.1049/cp.2013.1606

Publication date:
2013

Joint Iterative Carrier Synchronization and Signal Detection for Dual Carrier 448 Gb/s PDM 16-QAM

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Abstract *Soft decision driven joint carrier synchronization and signal detection, employing expectation maximization, is experimentally demonstrated. Employing soft decision offers an improvement of 0.5 dB compared to hard decision based digital PLL carrier synchronization and demodulation*

Introduction

In order to achieve line rates of 400 Gb/s and beyond, approaches relaying on spectrally efficient modulation formats such as quadrature amplitude modulation (QAM) have been reported[1-2]. As we are moving towards higher order QAM signaling, accurate estimation of carrier frequency and phase is becoming challenging. Additionally, the signal is becoming more vulnerable to linear and also nonlinear impairments, i.e. I/Q imbalance, I/Q nonlinearities, nonlinear phase noise etc. It has been shown that carrier phase and frequency recovery can be performed by various techniques: digital phase-locked loop (PLL), Viterbi-Viterbi, blind-phase-search, decision aided Maximum Likelihood (ML) estimation etc, and references therein[3-6]. Furthermore, it has been demonstrated that by employing ML signal detection, different linear and nonlinear signal impairments can be mitigated[7-8].

An optimum ML receiver therefore *jointly* estimates carrier frequency and phase, and the transmitted data[9]. This is a very challenging task and direct computation is intractable, especially for system operating at low SNR or experiencing large degradations. It has been shown recently that joint ML carrier frequency and phase estimation, can be performed iteratively, and without taking any approximations, by employing expectation maximization[10]. The problem with the approach, proposed in[10] is that algorithm needs to be properly initiated in order to provide accurate estimation. Additionally, the range of the carrier phase estimation is limited.

In this paper, we solve the problem observed in[10], for joint carrier synchronization and symbol estimation, by employing expectation maximization together with a clustering algorithm *k*-means. The joint estimation provides soft decisions such that, maximum a posteriori (MAP) symbol detection can be performed. We show that the joint carrier synchronization and symbol detection algorithm is robust towards linear and nonlinear impairments affecting the signal constellation in dual carrier 448 Gb/s 16 QAM transmission system. Finally, we show experimentally that joint, soft decision based, estimation offers an improvement of 0.5 dB, compared to a case when hard decision based digital PLL carrier synchronization and demodulation is employed.

Experimental set-up and the algorithm

The experimental set-up for generation, transmission and demodulation of dual-carrier 448 Gb/s polarization division multiplexed

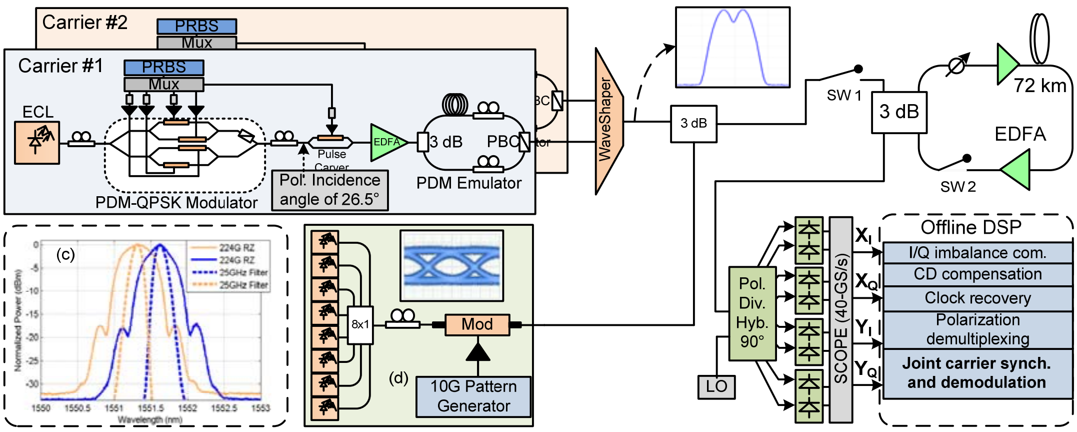


Fig. 1 Experimental setup for generation of 448-Gb/s signal employing dual carrier RZ-PDM-16-QAM PDM: polarization division multiplexing, RZ: return to zero, LO: local oscillator

(PDM) 16-QAM signal in a mixed line rate WDM environment (8 neighboring 10 Gb/s channels in 50 GHz gird) is shown in Fig.1. For each 16-QAM optical carrier, an external-cavity laser (ECL) with 100 kHz linewidth is used as an optical source. For data signal generation, four lines of uncorrelated pseudo-random-bit sequence (PRBS) with 2^{15}-1 length at 28 Gb/s are used to modulate each carrier into a 112 Gb/s PDM QPSK signal. We employ pulse carving, and at the same time, the pulse carver acts used as a polarizer in order to convert a 112 Gb/s PDM QPSK signal into 112 Gb/s 16 QAM signal. A PDM emulator is used to generate a 224 Gb/s return-to-zero (RZ) PDM 16 QAM signal in each optical carrier. The two optical subcarriers at 224 Gb/s are then optically filtered and a dual-carrier 448 Gb/s signal is obtained. The signals are then launched into an optical re-circulating loop, see Fig.1. At the receiver, the incoming signal is coherently mixed with a tunable local oscillator (LO) in order to recover a desired carrier of the 448 Gb/s signal. A four-channel scope with 40 GS/s and 18-GHz bandwidth is used to sample the electrical signals for subsequent signal processing. The DSP module consists of an I/Q imbalance compensation, clock recovery, polarization demultiplexing, a coarse frequency estimator and finally an algorithm for joint carrier synchronization and symbol estimation is performed.

The proposed algorithm performs iteratively, by using expectation maximization, a joint maximum likelihood estimation of carrier frequency, phase and noise variance (used for computing soft decisions). The algorithm consists of two steps: i) expectation step, were soft decisions are computed; ii) maximization step where the likelihood function is maximized in terms of estimated parameters. At each iteration, the likelihood function is increasing until the convergence is reached. The algorithm is blind to modulation format and operates on the blocks of data. Only frequency offsets that satisfy $|\Delta f T_{sym}| < 10^{-4}$, can be compensated ($T_{sym}$: symbol rate and Δf: frequency offset. Therefore, coarse frequency estimation is necessary.

Experimental results

As the iterative parameter estimation is employed, an important parameter to consider is the required number of iterations in order to reach the convergence. In Fig. 2, -log(BER) is plotted as a function of the number of iterations for block lengths varying from 1200 to 1500 symbols. The transmission link under consideration is 216 km long and the input optical signal power to the link is -3 dBm. Fig. 2 shows that the convergence speed improves as the block length is decreased. For the block length of 1200 symbols, the convergence already occurs after 3 iterations. For the block length of 1700 symbols, more than 10 iterations are needed. For the block lengths below 1200, we observed that k-means had problems converging due to insufficient number of points.

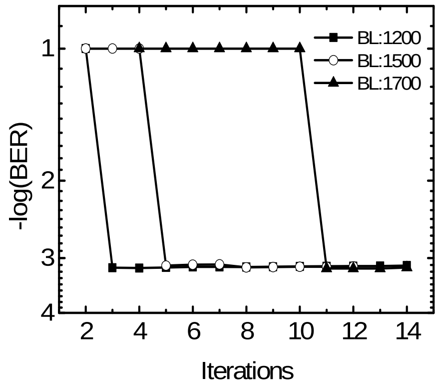
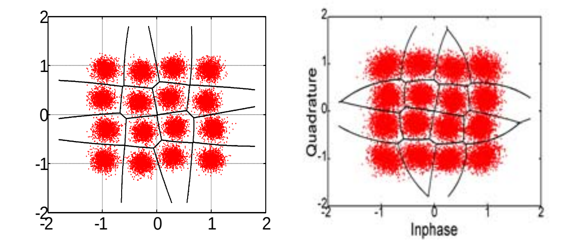


Fig. 2: BER as a function of the number of iterations for different block lengths

Soft decisions obtained from joint carrier synchronization and symbol estimation can be used to determine optimum decision boundaries in ML sense. This can be used to compensate impairments that have an imprint on the signal constellation such as rotation and distortion of constellation points.

The recovered constellation, distorted by impairments originating from the transmitter, is shown in Fig. 3(a) together with optimum ML decision boundaries. Employing joint carrier synchronization and signal detection -log(BER) of 3.12 is obtained. In contrast, when employing digital PLL based carrier synchronization and demodulation, which is hard decision based, the resulting -log(BER) is 2.90.



(a) (b)

Fig. 3: *Recovered signal constellation, together with optimum decision boundaries. (a)Signal impaired by transmitter imperfections, (b) Signal impaired by fibre nonlinearities*

Next, we consider the case when the input signal power to the span is 5 dBm. The corresponding recovered constellation is shown in Fig. 4(b). Joint carrier synchronization and symbol estimation results in -log(BER) of 3.12 compared to -log(BER) of 2.12 when PLL is employed. Next, we would like to investigate more systematically, the tolerance of the joint carrier synchronization and signal detection towards nonlinear phase shift affecting the signal constellation.

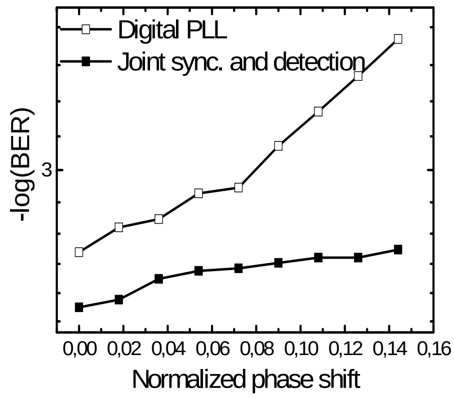


Fig. 4: BER as a function of normalized mean nonlinear phase

In Fig. 4, -log(BER) is plotted as a function of the mean normalized nonlinear phase shift. We compare joint carrier synchronization and signal detection with the PLL based synchronization and demodulation. Fig. 4, shows that -log(BER) is affected by the nonlinear phase shift, when digital PLL is employed. This is especially valid when the mean normalized phase shift exceeds 0.08. For the joint synchronization and signal detection -log(BER) is very little impacted by the nonlinear phase shift.

Next, we investigate the system performance, in terms of -log(BER), as a function of input signal power to the transmission span for the transmission distance of 278 km. The results are shown in Fig 5. It is observed that an improvement of approximately 0.5 dB is obtained when employing joint carrier synchronization and symbol estimation, compared to when digital PLL based approach is used. It should also be noted that for input signal powers above 4 dBm, an improvement of approximately 1 dB is observed. This is because under strong signal degradations, as in the case of high input signal power, the PLL does not give accurate estimates of carrier frequency and phase[9].

One of the advantages of the proposed scheme, which remains to be shown in future work, is that it is very well suited to be integrated with Soft Decision Forward Error Correction (SD-FEC). This is because the algorithm estimates noise covariances which are necessary to compute Log Likelihood Ratio (LLR) for SD-FEC.

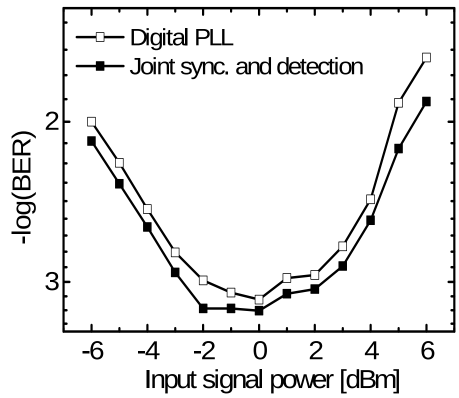


Fig. 5: BER as a function of input signal power when joint carrier synchronization and demodulation and digital PLL is used, respectively.

Conclusion

We have presented an iterative joint carrier frequency and phase, and symbol estimation by employing expectation maximization. The presented approach offers accurate frequency and phase estimation combined with robustness towards linear and nonlinear impairments that affects the signal constellation. Joint estimation offers an improvement of 0.5 dB compared to when digital PLL, followed by hard-decisions, is used.

Acknowledgments

Research leading to these results has received funding from the Danish Council for Independent Research, project CORESON and Villum Foundation Young Investigator program.

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