Carrier Frequency Offset Estimation Using Godard Timing Recovery in Coherent Optical Systems

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Abstract: Based on conventional timing recovery (TR) algorithm, we propose a novel method for carrier frequency offset (CFO) estimation by exploiting the available spectrum information from TR. We experimentally validate our proposal in 4-subcarrier 100-GBaud coherent systems.

1. Introduction

Optical coherent technology plays an important role for the current 800G and beyond transceiver generations. It has been shown that applying the probabilistic constellation shaping (PCS) can approach the channel capacity [1]. Besides single carrier modulation, digital subcarrier multiplexing (DSCM) technique is a promising alternative, owing to its enhanced fiber nonlinearity and equalization-enhanced-phase-noise (EEPN) tolerance, flexible designs of bandwidth and modulation format [1].

Carrier frequency offset (CFO) between the transmitter (Tx) and receiver (Rx) lasers causes a spectrum shifting of the digital signal at the Rx side. In single-carrier systems, CFO can be estimated and compensated after MIMO. However, in DSCM systems estimating the CFO after MIMO can result in performance penalty due to the demultiplexing (demux) operation (Fig. 1 in [2]). To solve this problem, a CFO compensation method, which uses the DSCM spectrum dips, has been proposed [2]. This solution comes however at the expense of adding an extra CFO estimation block before subcarrier demux.

On the other hand, timing recovery (TR) is a compulsory part in digital signal processing (DSP). Several non-data-aided TR algorithms have been proposed so far, thanks to their modulation format transparency and robustness against noise ([3, 4] and references therein). Compared to time domain TR counterpart, frequency domain (FD) TR is more suitable when working with a fractional oversampling rate, where the traditional Godard TR can be customized to adapt to any oversampling rate greater than one [4].

The impacts of channel impairments on TR such as residual CD [5], polarization mode dispersion and rotation [6] have been well investigated. However, to the best of our knowledge, the impact of CFO on TR has not yet been studied in depth. In this paper, we investigate the CFO impact on the traditional FD Godard TR, showing the TR sensitivity degradation at large CFO. We propose a modified TR cost function in order to estimate the CFO, exploiting the spectrum information already available for TR block. Since the TR block is after demux, we propose to perform match filtering after TR-based CFO compensation (Fig. 1(b)), while in the demux stage we maintain the full bandwidth (the subcarrier baudrate multiplied by the samples per symbol). Therefore, there is no penalty from the combination of tight filtering in the demux and frequency offset. Owing to this scheme, TR is robust against CFO, as the compensation (by simple spectrum reshifting) could be implemented before the TR operation and only the residual CFO would be calculated. Compared to [2], the performance will be similar without the need of an extra CFO compensation stage since we use the information from TR. We experimentally validate the effectiveness of our proposal in a 4-subcarrier 100 GBaud systems.

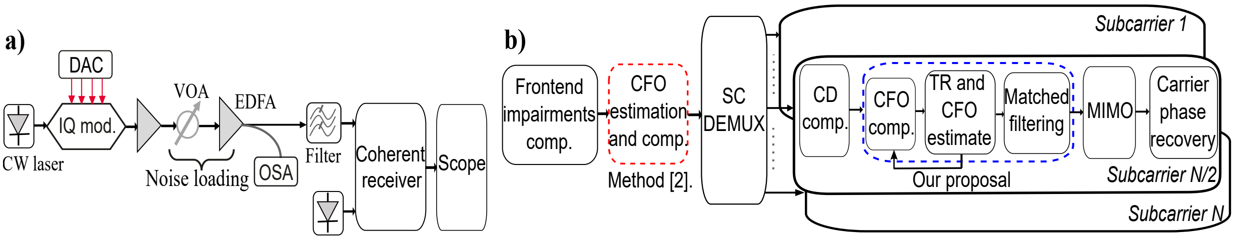

Fig. 1: (a) Experimental setup; (b) DSP blocks with joint TR-based CFO estimation.

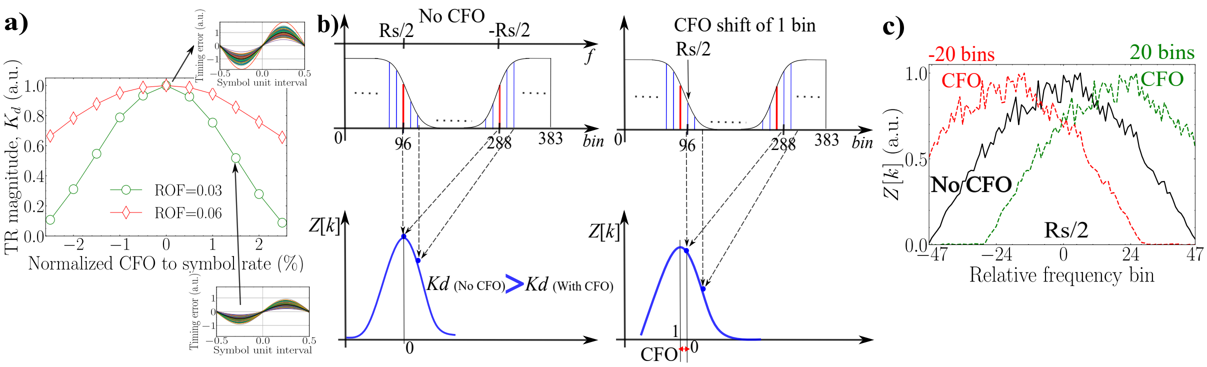

Fig. 2: (a) TR sensitivity K_d at different CFO when ROFs = 0.03 and 0.06. Illustration of (b) CFO impact on K_d and (c) $Z[k]$ without CFO and with ±20 bins CFO shift.

2. Investigation of CFO Impact on TR and Proposed Solution

2.1. Setup

We use the setup in Fig. 1(a) for both simulations and experiments. An external cavity laser (ECL) at 1548.4 nm wavelength is used at the transmitter side. The 4-carrier dual-polarization 100 Gbaud PCS-64QAM signals of entropy 5.33 (corresponding to ∼800G net capacity, assuming 25% FEC overhead and 3.25% pilot/protocol overheads) are generated by a 120 GSa/s digital-to-analog converter (DAC) and modulated onto the optical carrier by a PDM IQ modulator. Note that the QPSK pilots are inserted every 32 symbols to help the DSPs. We put an Erbium-doped fibre amplifier (EDFA) at the output of the IQ modulator in order to compensate for the modulator loss. A noise loading is carried out by cascading a variable optical attenuator (VOA) followed by an EDFA. An optical bandpass filter is applied to remove the out-of-band amplified spontaneous emission (ASE) noise. At the receiver side, the signal is mixed with another ECL local oscillator in the coherent receiver. The mixed components are converted into the electrical domain using four balanced photodetectors. The electrical signals are sampled with an oscilloscope operating at 256 Gsample/s. The digital signals are then processed offline, including the front-end compensation, coarse CFO estimation/compensation, subcarrier demux and per subcarrier processing (CD compensation, TR, MIMO equalization and CPR) (Fig. 1(b)). Note that, the coarse CFO estimation block can be removed if the CFO is estimated jointly inside TR block as detailed later.

2.2. Impact of CFO on TR

It is well-known that the TR performance is characterized based on S-curve, where the jitter (S-curve variance at zero-crossing point) and the sensitivity K_d (S-curve magnitude) are the main metrics. The Godard TR cost function is defined as $\tau_{err} = \sum_{k=(1-\alpha)N/4}^{(1+\alpha)N/4-1} Im\{Z[k]\}$, while the TR sensitivity is based on $K_d = \sum_{k=(1-\alpha)N/4}^{(1+\alpha)N/4-1} Re\{Z[k]\}$, where $Z[k] = X_k \cdot X^*_{k+N/2}$, X is the FD of subcarrier signal of N-FFT size after CD compensation and α is pulse shaping roll-off factor (ROF) [4]. For a fair comparison at different CFO, K_d is normalized to the one without CFO. The CFO value is normalized to the signal baudrate. In this study, we take 4-subcarrier signals to investigate the CFO impact, but it is straightforward to extend to other number of subcarriers.

Firstly, we numerically evaluate the impact of CFO on TR sensitivity. The FFT size w.r.t. the baudrate is set to 1536, which is large enough in order to ensure fine granularity of the algorithm. Fig. 2(a) shows the TR magnitude at different CFO values when ROFs are set to 0.03 and 0.06. It is observed that the TR sensitivity is degraded when CFO is large. For instance, a CFO smaller than 3% baud rate (3 GHz at 100 GBaud) is required to have TR sensitivity > 0.1 at 0.03 ROF. Higher ROF shows larger tolerance against CFO. It can be intuitively explained in Fig. 2(b) that the CFO causes the mismatch in the spectrum grid, leading to the power degradation of the product among spectrum lines around the half of signal rate ($\pm R_S/2$), where the TR algorithm considers. We show in Fig. 2(c) the $Z[k]$ shape without CFO, which is shifted to the right/left side when CFO are set to ±20 frequency bins.

2.3. Proposed CFO Estimation

Based on the observation in Figs. 2(b) and (c), it is found that the $Z[k]$ is symmetric when there is no CFO and its peak is shifted in the presence of CFO, hence we can estimate the CFO based on the form of $Z[k]$. By computing the peak shift, the CFO can be estimated accordingly. The shift can be estimated by either using a simple weighted method or finding the delay when correlating $Z[k]$ with different delayed reference sinusoidal forms.

We further numerically investigate the proposed CFO estimation and compare its performance to the dips-based method [2]. Fig. 3(a) shows the estimated CFO versus the pre-defined CFO when ROF and SNR are set to 0.06 and 13 dB (close to FEC limit at 4e-2 BER), respectively. To characterize the *asymptotic* estimate tendencies, these estimated values are averaged over several hundreds of FFT blocks. It is seen that our proposal exhibits a nonlinear behavior, which the estimated CFO is biased more at the larger CFO values, due to fewer useful spectrum lines

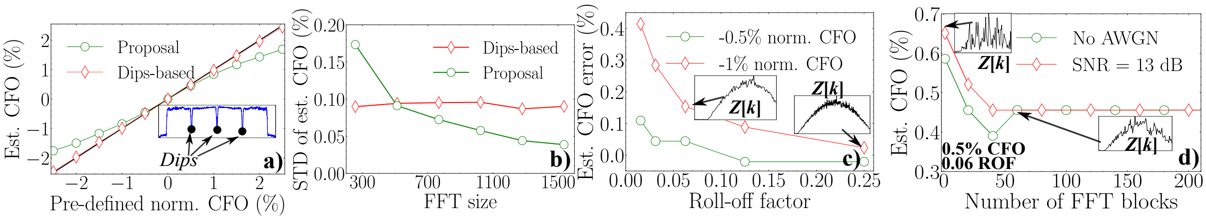

Fig. 3: (a) Estimated CFO versus pre-defined CFO and (b) Standard deviation of estimated CFO versus FFT size at ROF = 0.06, SNR = 13 dB. (c) Estimated CFO errors for different ROFs. (d) Estimated CFO over different averaging FFT block numbers.

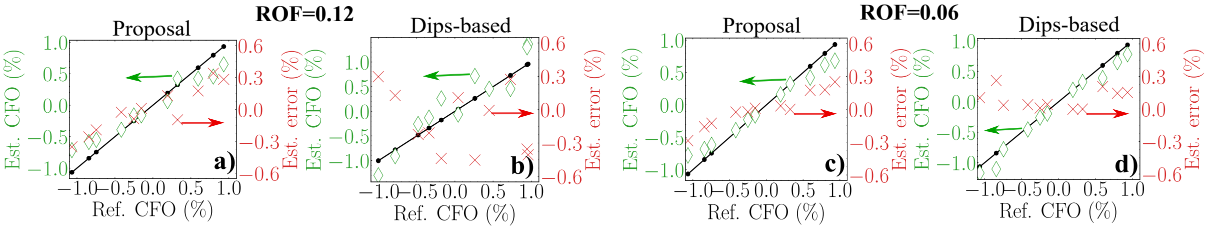

Fig. 4: Experimental validation with proposed CFO estimation ((a) and (c)) compared to dips-based method ((b) and (d)) at ROFs = 0.12 and 0.06.

being used in the estimation. The dips-based method shows a good CFO estimation, at a slightly higher complexity than our proposal (due to the extra operators of spectrum smoothing and averaging over 3 dips of 4-subcarrier). The inset illustrates the detected dips after searching over signal spectrum. The two methods are compared in terms of the standard deviation of the estimated CFO at different FFT sizes (Fig. 3(b)), when normalized CFO is set to 0.5%. The proposed method provides a better standard deviation than the dips-based method when FFT size is bigger than 600. Note that, due to high additive noise level, the standard deviations of dips-based method are not much improved with the increase of FFT size. We characterize our proposed method at different ROFs (Fig. 3(c)) and number of averaging FFT blocks (Fig. 3(d)). The estimated CFO errors reduce at bigger ROF values, because more significant spectrum lines are taken into account in the estimation. The proposed method is robust against additive noise when the number of averaging FFT blocks is greater than 50.

2.4. Experimental Validation

We carry out the experimental studies to validate our proposal. For a fair comparison, the spectrum lines used in both methods are set equally to the FFT size of 1536. Note that, the CFO is generated by gradually moving the ECL frequencies. The benchmark reference CFO is estimated with very high resolution CFO estimation ($\sim$ 0.2 MHz) by unrealistic spectrum correlation between the received signal and the reference one. Figs. 4(a) and (b) present the estimated CFO along with estimated error versus reference CFO at ROF = 0.12 for the proposed and dips-based methods, respectively, at the highest OSNR. Similar study is performed for ROF = 0.06 and results are presented in Figs. 4(c) and (d). It can be observed that our proposed method exhibits a larger nonlinear behavior (about 0.4% CFO estimation errors at 1% CFO), as predicted by simulations. The dips-based method has a big error deviation. It can be reduced by averaging over several FFT blocks, at a cost of higher complexity. Note that, our proposed method can work in an iterative way to overcome the nonlinear behavior when CFO is large, at the cost of slight increased complexity. At low OSNRs (not shown due to the space constraint), more averaging blocks are needed to maintain the accuracy of CFO estimation.

Regarding the TR performance, at 1% normalized CFO and 0.06 ROF, we have observed $>$6 dB jitter enhancement (not shown due to limited space) when the CFO is compensated before TR, confirming the benefit of CFO compensation for TR algorithm.

3. Conclusion

We have numerically and experimentally investigated the CFO impact on TR in 100 Gbaud 4-subcarrier PCS-64QAM systems, showing the degradation of TR sensitivity at large CFO. We propose a novel method to estimate CFO exploiting the already available spectrum information from TR block, showing good estimation standard deviation compared to the dips-based method. The proposed method also minimizes additional DSP block.

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