Simple feed-forward wide-range frequency offset estimator for optical coherent receivers

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Abstract: We propose and experimentally demonstrate a hardware-efficient, feed-forward, wide-range frequency offset estimator for DSP-based optical coherent receivers. Using a simple relationship of signal spectrum, this estimator is capable to estimate offsets in a range compliant with OIF requirements. Obtained results show that this estimator has a high tolerance to spectrum asymmetry caused by electrical and optical signal filtering, even when using return-to-zero pulse shaping.

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1. Introduction

One of the most important blocks for DSP-based coherent optical receivers is carrier synchronization [1,2]. Common algorithms for carrier phase estimation (PE) have low tolerance to frequency offset (FO) between carrier and local oscillator (LO). Instead of controlling LO laser frequency, it is often preferable to estimate the FO digitally in an intradyne approach. Leven et al. [3] proposed a frequency offset estimator (FOE) based in $m^{th}$-power multiplication of the received symbol with its conjugate complex predecessor. Later, improvements in Leven's algorithm [4] and a frequency-domain implementation [5] were presented. The estimation ranges of these algorithms were limited to $R_s/2m$, where $R_s$ is the symbol rate and $m$ is the number of constellation states. For PM-QPSK systems at 112Gb/s, this estimation range is ± 3.5 GHz. Commercial distributed feedback (DFB) lasers have an end-of-life accuracy of ± 2.5 GHz [6]. Because of that, at the worst case scenario, there can be FO as large as ± 5 GHz. To outline it, some wide-range algorithms were proposed. The algorithms were pre-decision-based [7], BER-aided [8], maximum-phase-error-based [9] and based at spectrum symmetry [10], being the later with better results. However, one main limitation of the spectrum-based methods is the effect of linear filtering, both electrical low-pass filtering, at receiver, and optical band-pass filtering, such as 50-GHz grid commercial Reconfigurable Optical Add-Drop Multiplexers (ROADM) [11]. The filtering process causes an asymmetry in received signal spectrum penalizing the frequency offset estimation. Return-to-zero (RZ) pulse shaping has a wider spectrum [12] and it can cause more asymmetry and penalize more the previous spectrum based FOEs.

We propose a new FOE, robust to electrical and optical filtering. This FOE uses a simple relationship between the powers from two sides of received signal spectrum. Simulation and experimental results are also demonstrated.

2. Operation principle

As a spectrum-based method for estimating frequency offsets, the proposed algorithm relies on the principle that a FO implies a proportional shift in received signal base-band spectrum. Spectral asymmetry can be measured from the ratio between the power of two sides of signal’s spectrum. It was empirically determined the following relationship between power ratio and frequency offset:

$$\Delta f = \alpha \cdot \log_{10} \left( \frac{P_+}{P_-} \right) = \alpha \cdot \left( \log_{10} (P_+) - \log_{10} (P_-) \right)$$

Here, $P_+$ and $P_-$ are the powers of each side of spectrum (Fig. 1) and $\alpha$ is a previously determined constant that depends on type and cutoff frequency of the receiver low-pass filters (LPF). That simple relation leads to a feed-forward algorithm scheme, able to estimate a wide range of frequency offsets with estimation error far below 3.5 GHz, which can be refined by the $m^{th}$-power algorithm [3–5]. Figure 2 shows a block diagram of the proposed method. Spectrum is obtained through a Fast Fourier Transform (FFT) from received signal.

Fig. 1. Received power spectrum with $\Delta f > 0$, showing two sides of spectrum.
In order to improve the FOE accuracy, both polarizations are considered while calculating spectrum power. A moving average is applied, over successive acquired spectra, to reduce the impact of the noise. The sum of the components of each spectrum side leads to $P_+$ and $P_-$. Frequency offset can be obtained applying Eq. (1). As the method gives a value of frequency offset for a simple power relation, the convergence time required to find estimated frequency offset depends only on the number of averages done.

The estimated FO can be used as a coarse estimation to eliminate the frequency ambiguity from the $m^{th}$-power FOE as described by [10], or to control a numeric controlled oscillator (NCO) that will impose a contrary FO to the signal, letting fine FO compensation for $m^{th}$ compensator [9]. Figure 3(a) shows the NCO-based implementation and Fig. 3(b) shows the feed-forward way to act with the coarse FO estimation.

As shown in [10], one major drawback of spectrum-based FOE is the penalty imposed by low cutoff frequency of the electrical low-pass filters (LPF) after signal detection. Table 1 summarizes the effect of different filter bandwidths over the signal spectrum. Discrete Fourier transform of signals was shifted by $N/2$, where $N$ is the FFT block size, for better understanding.

| Cutoff Frequency | Low-pass Filter | Received Power Spectrum |
|------------------|-----------------|-------------------------|
|                  |                 | $\Delta f = -5$ GHz     | $\Delta f = 0$ GHz      | $\Delta f = +5$ GHz |
| 28 GHz           |                 |                         |                         |                    |
| 25 GHz           |                 |                         |                         |                    |
| 20 GHz           |                 |                         |                         |                    |
| 16 GHz           |                 |                         |                         |                    |

As the electrical filtering induces asymmetry in the signal spectrum, it could impact on frequency offset estimation. Optical filtering has a similar impact, but it can be more striking as the number and bandwidth of the optical filters can change with network reconfiguration. The simulation and experimental results show that the proposed method is robust to both electrical and optical filtering.
3. Algorithm evaluation

To evaluate the proposed method simulations were performed in presence of electrical and optical filtering at 112 Gb/s PM-QPSK system. We considered a PM-QPSK transmitter, an optical amplifier (to control OSNR), an optical loop with a 50 GHz optical filter and a polarization diversity coherent receiver.

In all simulations, frequency offset was set from −5GHz to +5GHz, tuning simultaneously the local oscillator and the transmission laser in a ± 2.5 GHz range, around 193.4 THz. The signal was corrupted by amplifier's noise and laser's phase noise due to 500 kHz linewidth of each laser. The OSNR used was 15dB (at 0.1 nm resolution). For each simulation, we transmitted 32768 symbols at 2 samples per symbol. First, electrical filtering was performed by fourth order Gaussian filters with cut-off frequencies of 16, 20, 25 and 28 GHz and NRZ pulse shape. Then, optical filtering was performed by second order Gaussian filters with 44 GHz bandwidth, modeling typical ROADM optical filters in operation at 50 GHz grid [11], for NRZ and RZ (50% duty cycle) pulse shapes. FFT block size was N = 128 and α parameter used by the algorithm was 14.3 GHz for NRZ and 21 GHz for RZ50%. Figures 4 and 5 show the simulation results of proposed method for electrical and optical filtering, respectively.

![Figure 4. FOE performance for 112 Gb/s PM-QPSK with different receiver LPFs.](image1)

![Figure 5. FOE performance for 112 Gb/s PM-QPSK passing through different number of cascaded 50GHz optical filters. (a) Using NRZ pulse shape and (b) using RZ50% pulse shape.](image2)

Electrical filtering has a mild effect over the frequency estimation, even when a 16 GHz LPF is employed. The estimation error reaches 1GHz at the worst case scenario. The proposed method also exhibits high tolerance to optical filtering. When the signal passed through 15 optical filters, the maximum estimation error reach approximately 2.5 GHz, even using a pulse shape with wider spectrum as RZ. The estimation error were always less than the...
\(m^{th}\)-power FOE estimation range of ± 3.5 GHz, enabling this method to be used as a coarse FOE robust to filtering.

4. Experimental validation

Two experiments were carried out to evaluate the proposed method performance. The modulation format was 112 Gb/s PM-QPSK, generated by a tunable laser together with a polarization diversity quadrature modulator and four 28 Gbd lines of pseudorandom bit sequence (PRBS) generator. To evaluate FOE performance with electrical filtering, it was performed a back-to-back experiment and to evaluate the performance with optical filtering we used a recirculation loop with EDFAs, 295 km of single mode fiber and a 50GHz grid ROADM. After transmission, the optical signal was converted to baseband signals by a tunable local oscillator (LO) and a 90° hybrid, and then sampled by two synchronized 80 GS/s real time scopes with LPF bandwidth ranging from 16 to 30 GHz. The digitized data were processed offline in a PC. The frequency offset was set manually by varying the tunable LO. Experimental setup is depicted in Fig. 6.

In the first experiment, we set OSNR to 20 dB (at 0.1 nm resolution) by controlling pump power of EDFA, before intradyne coherent receiver. We varied FO in a range of ± 5.25GHz and set cutoff frequency of scope to 16 and 30GHz. The \(\alpha\) value was set to 14.5GHz and the FFT block size was \(N = 128\). We acquired 40k samples for each FO value. We also used in our experiment the spectrum symmetry-based FOE proposed by [10] for comparison purposes. Figure 7 shows experimental results for electrical filtering in back-to-back configuration.

We can observe that our method suffers fewer penalties in FO estimation compared to previous works [10] when limiting LPF cutoff frequencies, being robust to electrical filtering.

In the second experiment, it was transmitted the optical signal through 1475km of single mode fiber (5 turns in the loop). We varied FO in a range of ± 6GHz and set the cutoff
frequency of scope to 30GHz. The FFT block size was $N = 128$ and the $\alpha$ parameter was 14.5GHz. We acquired 40k samples for each FO value.

To measure BER penalties imposed by large frequency offsets we processed the experimental data using the DSP sequence shown in Fig. 3. The proposed algorithm was used as a coarse FOE, using FFT information from received signal, available at static equalization algorithm (used for chromatic dispersion compensation). The other algorithms are explained by [1,2]. Figure 8 shows the experimental results for optical filtering.

![Fig. 8. Experimental performance of proposed FOE for 112Gb/s PM-QPSK passing through loops with 50GHz grid ROADMs. (a) Coarse FOE. (b) Estimated BER.](Image)

As we can observe in Fig. 8(a), the proposed FOE also exhibits high tolerance to optical filtering. The estimation error were always below ±3.5GHz limit, letting fine estimation to $m^{th}$-power FOE. After fiber transmission at recirculation loop the received data was corrupted by amplifier noise, with OSNR near 15dB (at 0.1nm optical spectrum analyzer resolution), while in back-to-back experiment, the OSNR was about 35dB. In Fig. 8(b), we see that when increasing the FO absolute value in back-to-back configuration there is considerably BER penalty due to receiver bandwidth limitations. However, after fiber transmission, when OSNR was low enough that the system operates at BER close to FEC limit ($BER = 2 \times 10^{-3}$), the penalty introduced by amplifier noise overcame the penalty caused by receiver bandwidth limitations. Then, penalties in system performance are mainly affected by amplifier noise.

5. Conclusions

We proposed a simple feed-forward, spectrum-based method for wide-range frequency offset estimation, with lower complexity than previous spectrum based techniques. The proposed algorithm also exhibits a higher tolerance to both electrical and optical filtering, even if we use RZ signals, which have a wider spectrum than the NRZ signals. The FOE performance was demonstrated through simulation and experimental results. If the receiver uses both, the proposed estimator as a coarse FOE, and the $m^{th}$-power algorithm as a fine FOE, then the receiver will be capable to compensate a wide-range of frequency offsets without worrying about signal filtering. As a spectrum-based FOE, it can be used with any single-carrier modulation format.

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