Non-Data-Aided Wide-Range Frequency Offset Estimator for QAM Optical Coherent Receivers

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Abstract: We propose and experimentally demonstrate a novel blind frequency offset estimator for coherent quadrature amplitude modulation (QAM) receivers. Its frequency offset estimation range is more than three times the conventional estimation range.

OCIS codes: (060.4510) Optical communication; (060.1660) Coherent communication; (0605060) Phase modulation

1. Introduction

Quadrature amplitude modulation (QAM) is very attractive for beyond 100-Gbit/s optical transmission systems [1]. There are two types of carrier recovery for receivers for QAM modulation formats, i.e., feedback type [2,3], and feed-forward type [4]. Both types can compensate for frequency offset to a certain extent, but their frequency limit decreases as the modulation order increases due to the decrease in the angles between adjacent signals on the constellation. For example, when the modulation format is16-QAM and the symbol rate is 14 Gbaud, the upper limit of frequency offset compensation of the feedback type is about 100 MHz [2]. The feed-forward type of carrier recovery is superior to the feedback type regarding laser phase noise tolerance [4], but its limit of frequency offset compensation is narrower than that of the feedback type. Carrier frequency offset between a transmitter and a local laser can reach up to ±5 GHz [5]. In QAM receivers, therefore, carrier frequency offset must be estimated and compensated for using frequency offset estimators (FOEs) prior to phase recovery.

The Mth power algorithm is widely used for frequency offset estimators in blind M-PSK receivers [6,7]. However, this method cannot be applied to QAM receivers because Mth power operation cannot remove data modulation of QAM signals. Frequency offset estimators for blind QAM receivers have been investigated [8-13]. The algorithms in [8-10] use power detection and signal extraction of particular positions in the constellation (e.g. corner symbols or middle ring symbols), but their performance would be degraded for high-order QAM due to signal extraction error. The algorithms using the periodogram [11-13] do not need power detection, but their frequency offset estimation range is restricted due to phase periodicity and 4th power operation. Widening the estimated frequency range for QPSK modulation has been studied [5,14,15], but has yet to be reported for the algorithms using the periodogram.

In this paper, we present a novel blind frequency offset estimator with wide frequency range for QAM receivers. The estimator is based on the algorithms using the periodogram but improves their frequency limit. Experimental results obtained for it are also demonstrated.

2. Operation Principle

The algorithm using the periodogram of the 4th power of the received QAM signal is given by the following equation [11-13]:

$$\hat{f} = \frac{1}{4}\arg\max_{f}\sum_{p=1}^{2}\left|\frac{1}{N}\sum_{t=0}^{N-1} y^4(t)e^{-j2\pi ft}\right|^2, \quad \left(-\frac{R_S}{2}\le f\le\frac{R_S}{2}\right). \tag{1}$$

where y(t) is the received signal, R_S is the symbol rate, N is the number of available samples, p is the polarization, and $\hat{f}$ is an estimated frequency offset. The physical meaning of (1) is to search for a frequency that maximizes the time average of the 4th power of the received signal multiplied by various frequencies within the range of $-R_S/2$ to $R_S/2$. When the frequency, f, is equal to four times the frequency offset of y(t), the rotation of $y^4(t)$ on the constellation is removed and the time average of $y^4(t)\exp(-j2\pi f)$ has non-zero value. At other frequencies, the time average of $y^4(t)\exp(-j2\pi f)$ is almost zero. The form of (1) is actually the definition of the discrete Fourier transform of $y^4(t)$, thus searching for a frequency that maximizes the time averaging is equivalent to searching for a peak line in the frequency spectrum of $y^4(t)$.

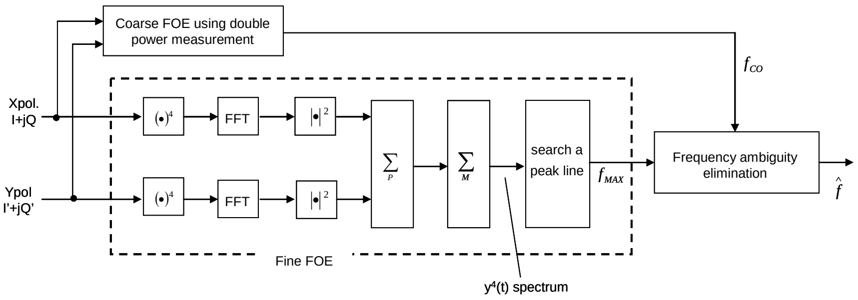

Fig. 1. Proposed frequency offset estimator.

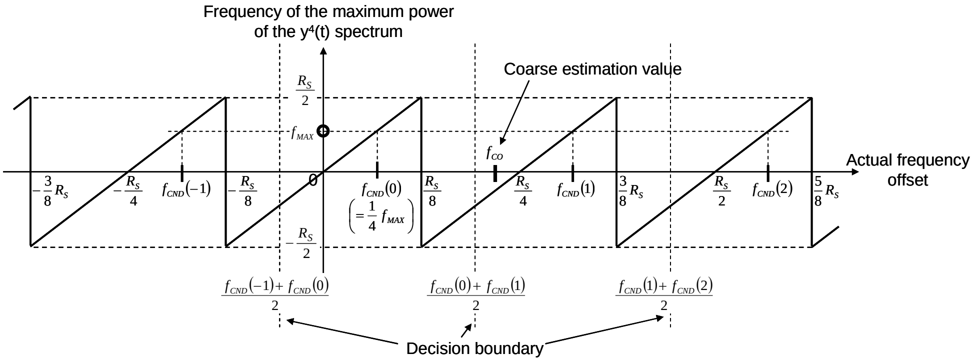

Fig. 2. Operation of frequency ambiguity elimination.

The spectrum of $y^4(t)$ has the periodicity of Rs in the frequency domain because QAM constellations have a rotational symmetry of angle $\pi/2$. Thus the frequency range of spectrum observation is limited to $[-R_S/2, R_S/2]$ in (1). This means that the range of frequency offset estimation is restricted to $[-R_S/8, R_S/8]$.

To overcome this restriction, we propose the frequency offset estimator shown in Fig. 1. It includes both a fine and a coarse frequency offset estimator. The former is based on (1); the operation $\sum_M$ is a superposition of the spectrum, which emphasizes the peak line to allow it to be distinguished from other spurious signals. The latter is based on double power measurement of the signal spectrum [15]. It has a wide estimation frequency range but its estimated values are not accurate because of the asymmetric spectrum caused by filters in the transmission channels and frequency offset. However, we use this only as a coarse estimator to mitigate the estimation accuracy requirement as described below.

The frequency ambiguity estimation block uses the coarse estimation value to eliminate the frequency ambiguity of the fine frequency offset estimator. This operation is shown in Fig. 2. When the frequency of the maximum power of the $y^4(t)$ spectrum is f_{MAX} (shown as an open circle), the candidate frequency of actual frequency offset $f_{CND}(k)$ is given by

$$f_{CND}(k) = \frac{1}{4} f_{MAX} + k\frac{R_S}{4}, \quad (k=0, \pm1, \pm2, \cdots). \tag{2}$$

Decision boundaries are set at the center of the adjacent $f_{CND}(k)$s. The surrounding area of the adjacent decision boundaries including the coarse estimation value f_{CO} gives the determinate frequency offset $\hat{f}$. In the case shown in Fig. 2, $\hat{f} = f_{CND}(1)$ and the frequency ambiguity is eliminated. As long as the coarse estimation value is within the surrounding area, this frequency ambiguity elimination is carried out normally. Hence the allowable error of the coarse estimator is $\pm R_S/8$. For example, when R_S is 28 GHz, the allowable error is ±3.5 GHz, while as a carrier recovery it is as high as several tens of MHz. This mitigation makes the proposed frequency offset estimator practical.

3. Experimental results

Experiments were carried out to evaluate the frequency offset estimator performance. The modulation format in them was single-polarization 64-QAM with the symbol rate of 10.03 GBaud. Eight-level electrical signals were

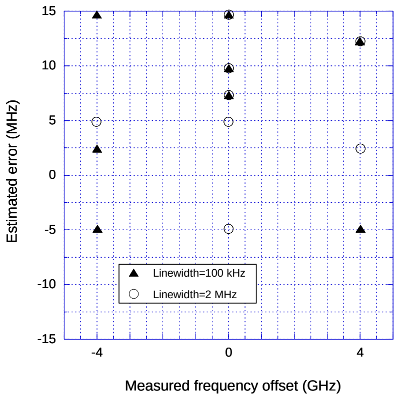

Fig. 3. Estimated error of the 64-QAM signal obtained after 80-km transmission.

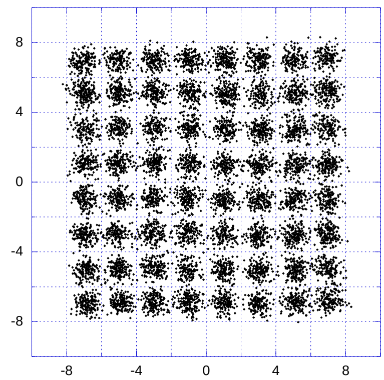

Fig. 4. 64-QAM constellation diagram obtained using the proposed FOE and feed-forward phase recovery for 4-GHz frequency offset.

generated by an arbitrary waveform generator (AWG). After 80-km transmission of a single mode fiber and converting the optical signals to baseband signals by means of a local laser, photodetectors, and a PLC-based dual polarization optical 90° hybrid [16], the baseband signals were sampled by a digital storage scope. The digitized data were processed in a PC. The frequency offset was set manually and observed with a spectrum analyzer. Two kinds of lasers were used for the receiver. One was an external-cavity laser (ECL) with a linewidth of about 100 kHz and the other was a distributed feed-back (DFB) laser with a linewidth of 2 MHz. The laser for the transmitter was an ECL.

In the offline processing, chromatic dispersion was compensated for with a fixed frequency domain equalizer (FDE) and polarization mode dispersion and residual dispersion were compensated for with a blind adaptive equalizer with the constant modulus algorithm (CMA). After that, frequency offset was estimated. The size of each FFT block in Fig. 1 was 1024 and the number of superpositions of the spectrum, M, was 70. Fig. 3 shows the estimated error of the proposed frequency offset estimator. As the figure shows, the error is less than 15 MHz in the frequency offset range of -4 GHz to 4 GHz regardless of laser linewidth. This estimation frequency range is more than three times the ordinary estimation range of $\pm R_S/8$ (= ±1.25 GHz).

After frequency offset was compensated for using the estimated value of the proposed frequency offset estimator, phase was recovered with the feed-forward phase recovery described in [4]. The number of test phase angles between 0 to $\pi/2$ was 128. Phase averaging was performed on 31 consecutive symbols. The results are shown in Fig.4, where the given frequency offset was 4 GHz and the receiver laser was an ECL. Good demodulation performance was obtained. To the authors' knowledge, this is the first experimental demonstration of feed-forward carrier recovery of optical coherent QAM modulation under a frequency offset value greater than that of $R_S/8$.

4. Conclusions

We proposed a novel blind frequency offset estimator with wide frequency range for coherent QAM receivers. The results of experiments for 64-QAM modulation were also presented. The proposed frequency offset estimator can be applied to both feedback and feed-forward types of carrier recovery for QAM receivers.

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