Novel Ultra Wide-Range Frequency Offset Estimation for Digital Coherent Optical Receiver

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Abstract: We propose and experimentally demonstrate a novel, dual-stage frequency offset estimator and achieve the widest range of ±0.5 times the system symbol rate for the first time in a 42.8-Gbit/s coherent PolMux QPSK receiver.

OCIS codes: (060.4510) Optical communications; (060.1660) Coherent communication; (060.5060) Phase modulation

1. Introduction

With the recent advance of high-speed analog-to-digital converters (ADC), coherent detection has attracted strong interest because such scheme in conjunction with advanced modulation formats can offer a higher spectrum-efficiency and better receiver sensitivity over direct detection. In coherent receivers, the electric field information can be retained to allow digital signal processing (DSP) techniques to cope with the transmission impairments of a system. One of the key DSP functions is to recover the carrier phase using DSP-based phase estimation (PE) rather than optical phase-locked loops, thus allowing for a free-running LO laser. Some popular phase estimations, such as *M*th-power [1], require that the frequency offset between transmitter and local oscillator (LO) laser should be quite small compared to symbol rate [2]. The frequency offset between transmitter and LO lasers, however, can be as large as ±5 GHz [6]. As a result, an additional DSP-based frequency offset estimator (FOE) is imperative to ensure that subsequent PE algorithms accurately recover the phase of received signals [3].

A feed-forward FOE is preferred to avoid performance degradation when being implemented in parallelism. *M*th-power is generally performed to remove data modulation in feed-forward FOEs. Consequently, the maximal estimation range is limited to $[-R_s/2M, R_s/2M]$, where R_s refers to the system symbol rate and M is the number of constellation states [4]. For instance, the estimation range is only $\pm 0.125R_s$ for quadrature phase-shift keying (QPSK). In this paper, we propose a novel dual-stage, cascaded FOE consisting of a coarse FOE and a fine FOE. In a 42.8Gbit/s polarization-multiplexing (PolMux) return-to-zero (RZ-) QPSK system, the estimation range of the proposed dual-stage FOE is experimentally shown to be 4 times what can be achieved with the *M*th-power algorithm. The estimation range of our dual-stage FOE can be up to almost $\pm 0.9R_s$ in simulation and $\pm 0.5R_s$ in experiment, to our best knowledge, the largest range of FOEs reported so far in the literatures.

2. Principle of the dual-stage cascaded FOE

Timing recovery, such as Gardner algorithm [5], is usually required to correct for the timing phase error between the transmitter and receiver clocks in coherent receivers [6]. The simple Gardner algorithm can be used to generate a phase error output when only two samples per symbol are available. In a coherent PolMux phase-shift keying (PSK) system with Nyquist sampling rate (2 samples per symbol), the Gardner algorithm can be mathematically represented by [5]

$$U_t(2k) = I_x(2k-1)\left[I_x(2k) - I_x(2k-2)\right] + Q_x(2k-1)\left[Q_x(2k) - Q_x(2k-2)\right] \qquad (1)$$

where I_x and Q_x are the samples of in-phase and quadrature, respectively, for X-polarization state. Here, $U_t(2k)$ is the phase error output of the Gardner algorithm corresponding to the current sampling with timing offset t. The calculated *S*-curves through (1) represent the open-loop relationship between sampling timing offset and the estimated phase error in the system [6]. However, the performance of the Gardner algorithm suffers from performance degradation in the presence of frequency offset [6].

To investigate the impact of frequency offset on the phase error outputs of Gardner algorithm, we firstly perform simulations to emulate a real 42.8Gbit/s coherent PolMux RZ-QPSK system. The order of pseudo random binary sequence (PRBS) is 10 in the PolMux RZ-QPSK transmitter. The linewidth of both transmitter and LO lasers is set to be 100 KHz. The outputs of balanced detectors are passed through a 5^{th}-order Bessel electrical low-pass filter with bandwidths at 75% of the symbol rate. The effective number of bit for ADCs is 8 in simulation.

A series of *S*-curves, representing the phase error output of Gardner algorithm from (1), is obtained as shown in Fig. 1(a) when sweeping the sampling timing offset *t* and tuning the frequency offset in the system. It can be observed that the *S*-curve becomes more flat as frequency offset increases, i.e., the maximal phase error (MPE) outputs of Gardner algorithm decreases. Thus, non-zero frequency offset makes the Gardner timing recovery algorithm less insensitive to the sampling offset in coherent receivers, conforming to the results in [6]. On the other hand, we may utilize the underlying relationship between frequency offset and MPE of Gardner algorithm as a measure to estimate the frequency offset in a system. The normalized MPE outputs are plotted against different frequency offsets in Fig. 1(b). Note that the absolute value of MPE varies at different optical signal-to-noise ratio (OSNR). Therefore, we normalize MPE to the one at zero FO. As illustrated in Fig. 1(b), the normalized MPEs under different OSNR exhibit almost the same trend within ±9 GHz. A 4th-order polynomial is applied to well emulate the relationship between the normalized MPE and FO. It is worth mentioning that the polynomial fit can only offer a coarse estimation of FO ($\Delta\hat{f}_c$). In our simulations, we find that the estimation error of $\Delta\hat{f}_c$ is limited to ±1 GHz, which is within the estimation range of FOEs based *M*th-power in current simulated system. As a result, we propose a coarse FOE based on examining MPE to cascade with an FOE involving *M*th-power, thus enlarging the estimation range of FOEs, as depicted in Fig. 2(a). In the paper, we choose fast-Fourier transform (FFT)-based FOE [7] to deal with the residual frequency offset after data modulation is removed by *M*th-power. Throughout our paper, the FOEs based on MPE and FFT are called as coarse FOE and fine FOE, respectively, according to their estimation ranges of frequency offset. As for the implementation structure in Fig. 2(a), the polynomial fit of the relationship between frequency offset and normalized MPE (see Fig. 1(b)) can be realized using a look-up table. By sweeping the sampling offset *t*, the MPE obtained in Gardner algorithm (1) is normalized to estimate a coarse frequency offset ($\Delta\hat{f}_c$) while the residual frequency offset can be estimated through the FFT-based FOE ($\Delta\hat{f}_f$). Another problem is that the normalized MPE would find two different frequency offsets with opposite sign because of the even characteristic of the polynomial, as indicated in Fig. 1(b). This is can be settled by pre-defining the sign according to the specified wavelength of the transmitter and LO lasers or using a feedback bit error.

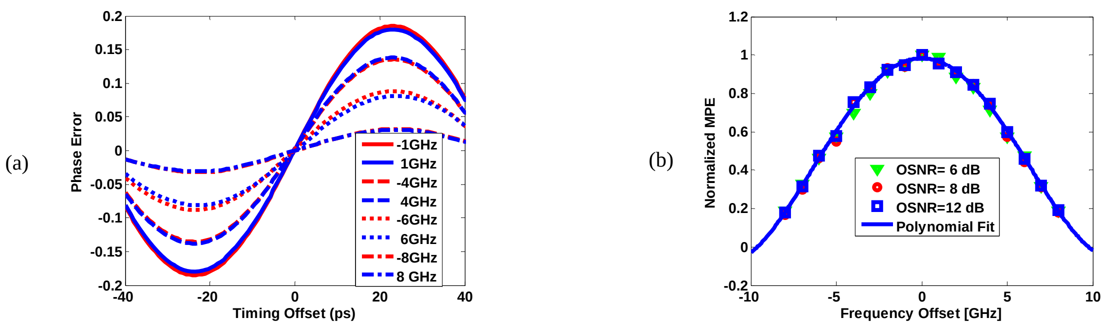

Fig. 1 Simulation results on (a) *S*-curves (phase error output of Gardner algorithm) versus timing offset at different frequency offsets in a coherent 42.8 Gbit/s PolMux-RZ-QPSK system (OSNR=10dB); (b) Normalized MPE versus frequency offsets under different OSNR levels.

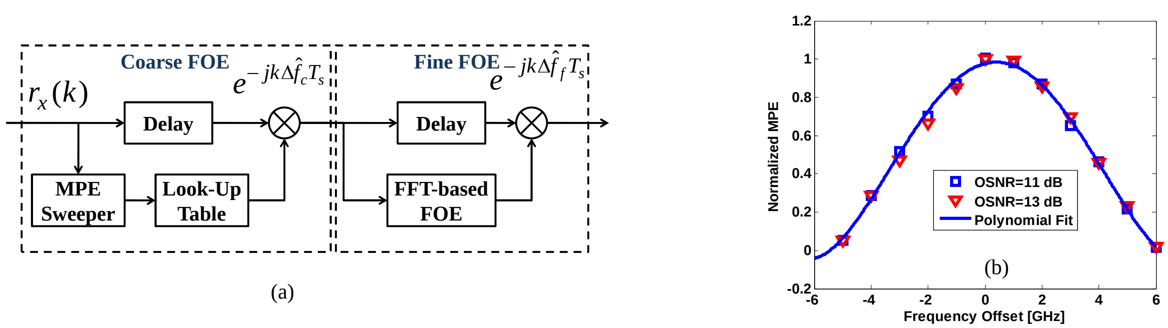

Fig. 2 (a) A proposed structure of the dual-stage cascaded FOE; (b) Measured normalized MPE versus frequency offset for experimental configuration of 42.8 Gbit/s PolMux RZ-QPSK system.

3. Experimental Configuration and Results

Experiments are carried out to demonstrate our proposed dual-stage cascaded FOE. The configuration of a 42.8-Gbit/s coherent PolMux RZ-QPSK system is shown in Fig. 3. The lightwave at wavelength 1547.983nm, generating from an external cavity laser (ECL) with linewidth about 100kHz, is modulated by an *IQ*-modulator, which is driven by two 10.7 Gbit/s 2^{15}-1 PRBS data. An additional Mach-Zehnder modulator (MZM) is added as a pulse carver to generate an RZ-pulse shape. The polarization-multiplexing is achieved by dividing and recombining the signal with a 235 symbol delay using a polarization beam combiner (PBC). After down-converting the optical signal by a tunable LO laser (about 150 kHz linewidth) in a polarization-diversity coherent receiver, the outputs from four single-ended photodetectors are sampled by using a 4-channel digital storage scope (Tektronix DSA72004) with 50 Gs/s sampling rate and 12 GHz electrical bandwidth. The captured data is then post-processed using a desktop PC.

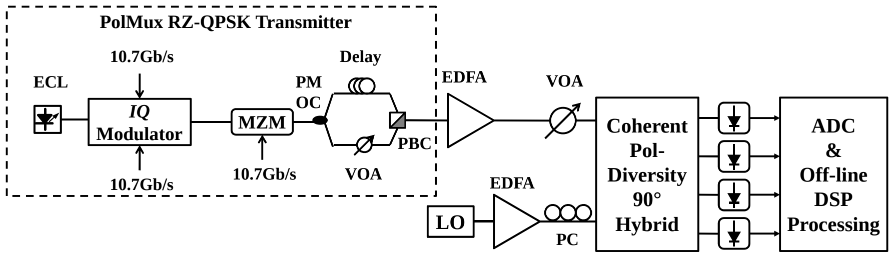

Fig. 3 Experimental configuration of 42.8 Gbit/s PolMux RZ-QPSK system. PM OC: polarization-maintaining optical coupler; VOA: variable optical attenuator; EDFA: erbium-doped fiber amplifier; PC: polarization controller.

(a) (b)

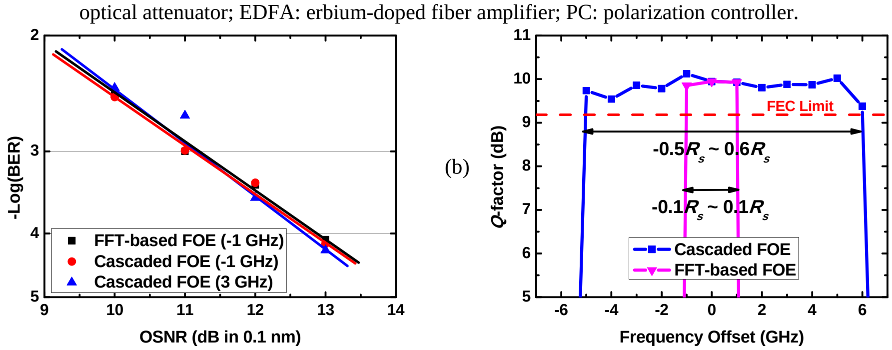

Fig. 4 (a) measured BER performance of cascaded and conventional FOE at frequency offset of -1 GHz and 3 GHz; (b) comparison of the measured *Q*-factor between proposed dual-stage cascaded FOE and single FFT-based FOE. The enhanced FEC limit is $2x10^{-3}$.

The normalized MPE is measured underdifferent frequency offsets (1GHz step) at different OSNRs in 0.1nm, as illustrated in Fig. 2(b). Similar to the simulations, a 4^{th}-order degree polynomial is also used to fit the trend found in our experimental setup. It can be observed the estimation range of cascaded FOE reduces to almost [-6GHz, 6GHz] for our experiment configuration. With the knowledge of the normalized MPE as a function of frequency offset, we can set up a look-up table for the dual-stage cascaded FOE for further data processing. As a performance comparison, we also plot the performance when using single FFT-based FOE. Fig. 4(a) shows the bit error rate (BER) performance of cascaded or single FFT-based FOE used in the DSP processing of the captured data at different frequency offsets (-1 GHz and 3 GHz). Note that the BER of single FFT-based FOE at 3GHz frequency offset is omitted since it cannot deal with a frequency offset exceeding its theoretical limit (±1.34 GHz for 10.7GBaud). It can be seen that the BER performance of our proposed dual-stage FOE can consistently and accurately recover the data even though the frequency offset is 3 GHz without having any performance degradation. Furthermore, the improvement of the proposed cascaded FOE can be well illustrated in Fig. 4(b), where the *Q*-factor is displayed against different frequency offsets. The *Q*-factor corresponding to the enhanced forward error correction (FEC) limit ($2x10^{-3}$) is also plotted. The experimental results confirm that our cascaded FOE is capable of estimating a frequency offset up to the range [$-0.5R_s$, $0.6R_s$], which is almost 4 times the theoretical limit of single FOE using *M*th-power. This excellent improvement is attributed to the fact that the coarse FOE based on MPE of Gardner algorithm can well track the frequency offset variations.

4. Conclusion

In this paper, a novel cascaded frequency offset estimator with an ultrawide range of [$-0.5R_s$, $0.6R_s$] is proposed and experimentally demonstrated in a 42.8-Gbit/s coherent PolMux QPSK receiver. The authors with National Univ. of Singapore would like to thank the funding support by A*STAR SERC PSF 092 101 0054.

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