# Novel Wide-range Frequency Offset Compensator Demonstrated with Real-time Digital Coherent Receiver

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**Abstract** A novel frequency offset estimator is proposed and implemented in a 1Gbit/s real-time coherent receiver to demonstrate all-digital frequency offset compensation up to ±0.4 symbol rate.

### Introduction

Optical coherent receiver technology with digital signal processing is attracting increasing interest for high bit-rate optical communication systems because of its well-known optical signal noise ratio (OSNR) benefits as well as high chromatic dispersion and high polarization mode dispersion tolerance enabled by digital equalization. One of the keys in realizing coherent receivers is the carrier synchronization. Feed-forward carrier phase estimation is used in most optical receivers reported so far because of its lower hurdle in hardware implementation [1-3]. Such feed-forward approach, however, needs the frequency offset between the source and local oscillator (LO) laser to be tightly controlled [4]. On the other hand, most commercially available tuneable lasers are specified to have a frequency accuracy of ±2.5GHz over lifetime [5]. Feedback control of the laser frequency is possible, but preferably the carrier synchronization algorithm tolerates the possible frequency offsets between the lasers as large as 5GHz.

We previously proposed a novel wide-range frequency offset estimator named “pre-decision-based angle differential frequency offset estimator” (PADE) [6], which can cover wide frequency offset range. In this paper, we implemented PADE to a 1Gbit/s real-time coherent RZ-QPSK receiver and investigated its frequency offset tolerance.

### Compensation of frequency offset

Frequency offset can be estimated and compensated through digital signal processing. Fig. 1 shows the block diagrams of two frequency offset estimators.

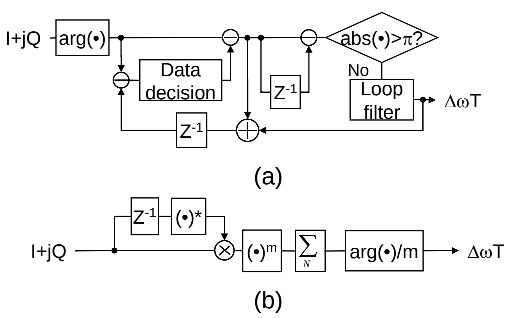


*Figure 1: (a) PADE frequency offset estimator, (b) Frequency offset estimator using $m^{th}$ power method.*

PADE (Fig. 1(a)) [6] uses the pre-decision-based method to detect phase error instead of the widely-used Viterbi-and-Viterbi method which uses $m^{th}$ power to retrieve the optical carrier phase (Fig. 1(b)) [1, 4]. In the $m^{th}$ power method, the phase detection range is limited to $\pm\pi/m$ where m is the number of the constellation states (m=4 for QPSK). On the other hand, the pre-decision-based method can cover a detection range of $\pm\pi$, which means that PADE can expand the range of frequency offset estimation from ±Br/2m to ±Br/2, where Br is the symbol rate.

### Experimental setup and BER measurement

The experimental setup is shown in Fig. 2. An external cavity laser (ECL) was used as the source laser whose linewidth is specified with 100kHz. The in-phase and quadrature-phase signals applied to the RZ-QPSK modulator were differentially pre-coded pseudorandom binary sequence (PRBS) with $2^{23}$-1 length at 500Mbit/s. After loading ASE noise, a 0.3nm optical band pass filter was inserted to eliminate out-of-band ASE noise.

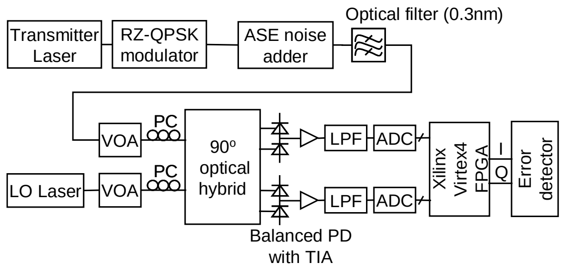


*Figure 2: Experimental setup for 1Gbit/s RZ-QPSK digital coherent receiver evaluation.*

The optical signal was converted to an electrical complex signal with a $90^o$ optical hybrid followed by two differential photo detectors. The LO laser was another ECL with 100kHz specified linewidth. The states of polarization of signal and LO was adjusted with polarization controllers (PC) in front of the $90^o$ optical hybrid. The converted electrical signals were followed by a pair of $5^{th}$-order Bessel filters with 350MHz cut-off frequency and ADCs (e2v AT84AD001B). The ADCs sampled the electrical signals with 1Gsamples/s (2samples/symbol). The ADC input was maintained constant by adjusting the LO power. The 8-bit ADC data streams are fed into

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a Xilinx Virtex4 FPGA. Two output channels at 500Mbit/s demodulated and digitally processed in the FPGA were connected to an error detector for real-time BER measurements. Inside the FPGA, the input signals were de-multiplexed to eight parallel lanes and then passed to the circuits for down-sampling, frequency offset estimation, frequency offset compensation, carrier recovery, decision, and differential de-coding. The PADE and $m^{th}$ power method were implemented for comparison as frequency offset estimator. The frequency offset estimation was performed by using only data on $1^{st}$ and $2^{nd}$ lanes. Fig. 3 shows measured BER versus OSNR of receivers with PADE and with $m^{th}$ power method for almost zero frequency offset. At a BER of $10^{-3}$ the required OSNR was -5dB. The realized OSNR sensitivity is only 1dB worse compared to what is predicted by communications theory.

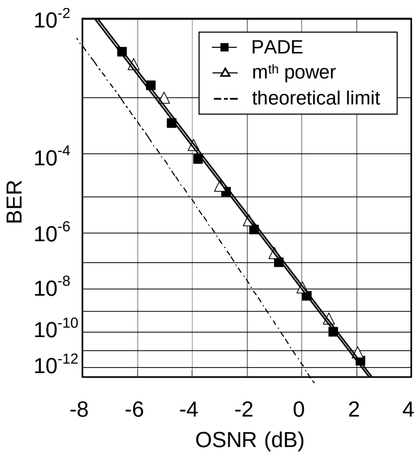



*Figure 3: BER against received OSNR in 0.1nm noise band width without frequency offset.*

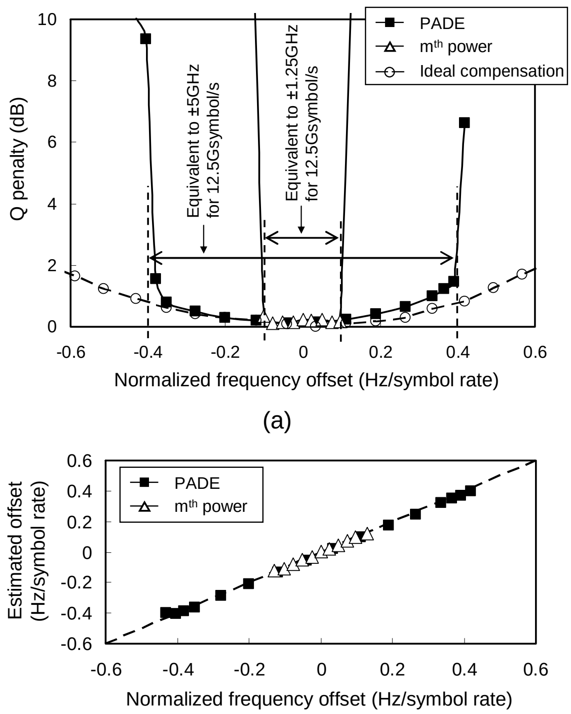
### Frequency offset tolerance

Fig. 4 shows the measured frequency offset tolerance and the estimated offset for the two estimators. Here, the horizontal axes are normalized to the symbol rate (500MBaud). The tolerances of PADE and $m^{th}$ power estimator were approximately ±200MHz (±0.4Br) and ±50MHz (±0.1Br), respectively. Both methods are accurate within their respective estimation ranges. A slight Q-penalty with increasing frequency offset was due to electrical low-pass filtering in the 350MHz Bessel filters, which was confirmed by measuring the penalty with ideal frequency offset compensation (open circles in Fig. 4). This result also shows that the excess Q-penalty due to compensation error of PADE was less than 0.5dB within its compensation range of ±200MHz compared with the ideal compensation case.

### Discussion

The measured frequency offset tolerances for PADE and $m^{th}$ power method were a little narrower than the theoretical expectations which are ±Br/2 and ±Br/2m. It can be ascribed to the slight frequency fluctuation of the lasers used, whose impact should become negligible as the signal symbol rate is higher.

Considering that the compensation range scales linearly with the symbol rate, coherent receivers for less than 50Gsymbol/s cannot accept ±5GHz frequency offset with $m^{th}$ power estimator. If the PADE is used, on the other hand, coherent receivers for more than 12.5Gsymbol/s should be able to compensate ±5GHz frequency offset.




(b)

*Figure 4: (a) Frequency offset tolerance with PADE and $m^{th}$ power method at OSNR of -2dB. (b) Estimated frequency offset with each method.*

### Conclusion

We have demonstrated that PADE can compensate the frequency offset of ±0.4 symbol rate (±200MHz) with less than 0.5dB penalty in 1Gbit/s real-time digital coherent receiver. Without the need for laser frequency control, and for symbol-rates higher than 12.5Gsymbol/s, a digital coherent receiver utilizing PADE can be realized with widely available standard tuneable lasers.

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