Novel Baud-Rate Estimation Technique for M-PSK and QAM Signals based on the Standard Deviation of the Spectrum

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Abstract *A robust baud-rate estimation technique that is integrated into a coherent receiver prior to digital equalization and intermediate frequency estimation based on the standard deviation of the signal spectrum is presented. It is shown to operate from 4 to 25 GBaud QPSK signals with a maximum estimation error of 2% at the FEC limit of $3.8 \cdot 10^{-3}$.*

Introduction

Baud-rate estimation at the receiver is an important problem occurring in the control of heterogeneous or cognitive optical networks[1] utilizing coherent modulation formats. Such networks adjust the transmitted signal baud-rate to optimize network performance in response to both traffic demands and physical layer impairments. Along with accuracy, a fast response time is a desirable quality for a baud-rate estimation technique employed in adaptable and re-configurable networks.

Previous baud-rate estimation techniques have explored the signal properties in the time-domain (detecting the symbol transitions)[2,3], frequency-domain (introducing spectral peaks at the baud-rate location and performing peak detection)[4], or time-frequency domain (applying wavelet transforms to detect symbol transitions)[5]. However, all these methods are sensitive to chromatic dispersion (CD) and thus unsuitable for the initialization or control of subsequent DSP, which relies on a correct baud-rate estimation.

The method we demonstrate in this paper uses the signal power spectral density (PSD) to estimate the baud-rate and is therefore CD and 1st order polarization mode dispersion (PMD) tolerant. It is also independent of the intermediate frequency, as long as the signal spectrum does not fall outside of the receiver bandwidth. Without requiring equalization and carrier recovery, this method is more robust and ensures a faster response time, compared to the previously mentioned methods. The estimator is applicable to both M-PSK and QAM signals since their PSDs are identical[6].

Description of the technique

The metric of the proposed baud-rate estimation technique uses the standard deviation of the received power spectrum. Regarding the spectrum as a probability density function, the spectral standard deviation can be defined as the second order non-central moment:

$$\sigma = \frac{\int (f-\mu)^2 S(f)df}{\int S(f)df} \qquad (1)$$

where f is the frequency component, μ is the spectral mean measuring the intermediate frequency, and $S(f)$ is the power spectral density measured at frequency f.

Assuming that the signal has been band-limited by pulse-shaping prior to transmission, with for example a Root-Raised Cosine (RRC) filter, the baud-rate is directly proportional to the standard deviation of the spectrum. A look-up table (LUT) is then used to convert the measured spectral standard deviation of a received signal into its baud-rate. Different LUTs can be defined for different transmitter pulse shaping. The LUT can be created in a pre-configuration step, requiring a minimum of two known baud-rates with their corresponding measured spectral standard deviation values.

Having the advantage of being independent on CD and Local Oscillator (LO) frequency, this method can be employed at the beginning of the DSP stage of the digital coherent receiver, as shown in Fig. 1. It can be used as a control input to the timing recovery stage, for example.

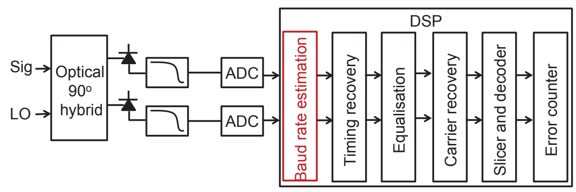

Fig. 1: Digital coherent receiver including a baud-rate estimation stage for QPSK signals.

Simulation model

The method was tested by simulation under different noise loading conditions, as shown in Fig. 2. QPSK signals were generated from 2^7-1 PRBSs, to simulate typical optical signals with

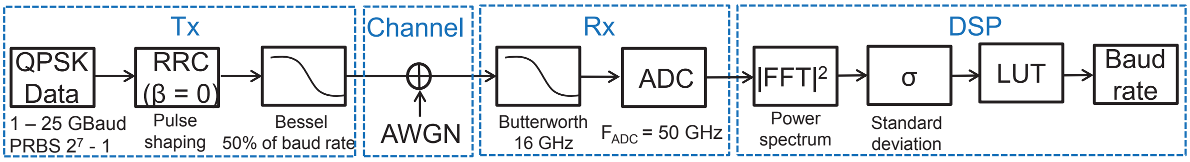

Fig. 2: Simulation setup for testing the baud-rate estimation technique for QPSK signals.

line-coding. The intermediate frequency was set to be 500 kHz and the LO linewidth 100 kHz. Without loss of generality, the transmitter signal shape was trapezoidal with rise- and fall-times of 10% of the baud-rate and a RRC filter with a roll-off factor of 0. The two additional low-pass filters were used to account for the transmitter bandwidth limitations (5th order Bessel filter with a cut-off frequency equal to 50% of the baud-rate) and the receiver bandwidth (16 GHz 9th order Butterworth filter). The receiver sampling rate was set to 50 GSa/s.

Experimental setup

The technique was also tested experimentally for baud-rates up to 14 GBaud. As in the simulations, the QPSK signals were generated with a PRBS length of 7 and had a trapezoidal shape with rise- and fall-times of 10% of the baud-rate and with 0 roll-off RRC. The in-phase and quadrature components of the signals were generated with an Arbitrary Waveform Generator (AWG), as seen in Fig. 3, depicting the experimental setup. After modulation in the optical domain, the QPSK signals were noise loaded and subsequently converted back into the electrical domain using a coherent optical receiver with a sampling rate of 50 GSa/s. The baud-rate estimation was subsequently carried out using offline processing.

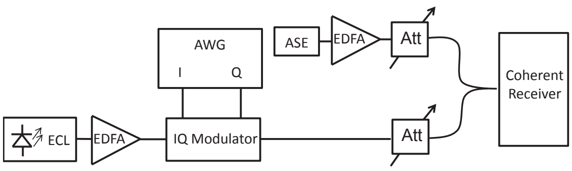

Fig. 3: Optical back-to-back experimental setup for testing QPSK signals.

Estimation accuracy

The estimation accuracy was measured by the signed percentage error. The mean and variance of the percentage signed errors were obtained from 100 different runs per baud-rate.

As shown in Fig. 4, the estimation accuracy increases with the number of captured samples. This is expected, since an increase in number of captured samples is equivalent to a higher frequency granularity, resulting in a more accurate spectral representation of the signal. Also, as more frequency components enter the computation of the spectral standard deviation, the lower the variance of the estimation accuracy becomes.

Experimentally, a minimum of 2^{15} samples (corresponding to a capture time of 655 ns) for all baud-rates are required to ensure an estimation accuracy of less than 2% at 5.9 dB OSNR, making this method suitable for fast acquisition and control. These results include noise reduction, described in the next section. The LUT was experimentally determined in order to include all spectral shaping that occurs in the system (RRC, Bessel and Butterworth filters as shown in Fig. 2).

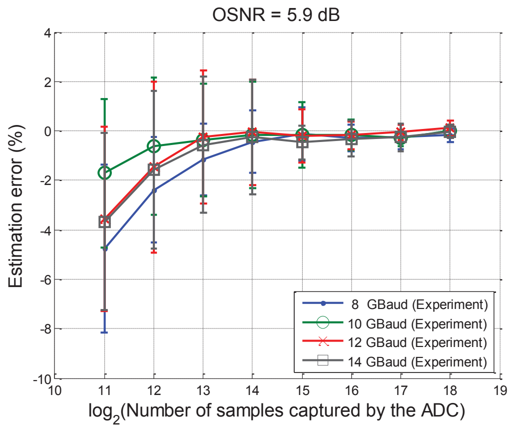

Fig. 4: Estimation accuracy dependence on the number of captured samples, verified experimentally.

Impact of noise

The impact of OSNR on the estimation technique is shown in Fig. 5(a). At lower OSNRs the contribution of noise components to the value of the spectral standard deviation is higher, resulting in overestimation and high errors. These noise contributions become less significant for higher baud-rates, as the signal bandwidth increases, whilst the noise bandwidth is fixed by the receiver sampling rate. The errors obtained by experimental verification are slightly different than those obtained by simulation due to the mismatch between the simulated spectra and the experimental spectra at the receiver.

The QPSK signal spectrum is obtained by averaging the spectra of the in-phase and quadrature signal components, which reduces the noise contribution through averaging. In order to reduce the impact of noise even further, the maximum noise floor power is estimated using a band of frequencies outside the signal bandwidth as shown in Fig. 6.

The signal spectrum is thresholded at the maximum noise power estimate in order to remove out-of-band noise. The noise threshold significantly improves the performance of the estimator, especially at low baud-rates where the signal bandwidth is much less than the acquisition bandwidth, as shown in Fig. 5(b). At low OSNRs, the estimation error increases due to the in-band noise not being completely removed by the threshold. For baud-rates between 8 GBaud and 14 GBaud, at a minimum of 5.9 dB OSNR and 2^{15} samples, the spectral method results in estimation errors less than 2%.

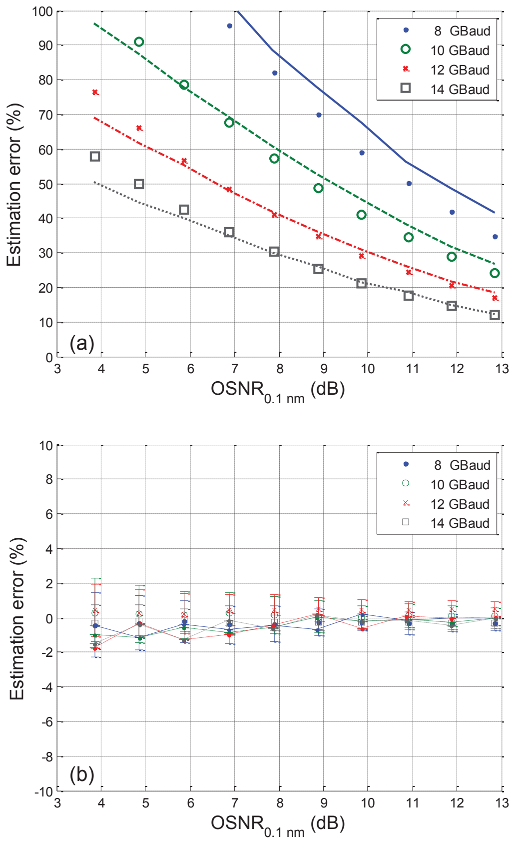

Fig. 5: Impact of noise on the estimation verified by simulation (lines) and experiment (symbols) of QPSK signals with 2^{15} captured samples (a) without noise thresholding and (b) with noise thresholding.

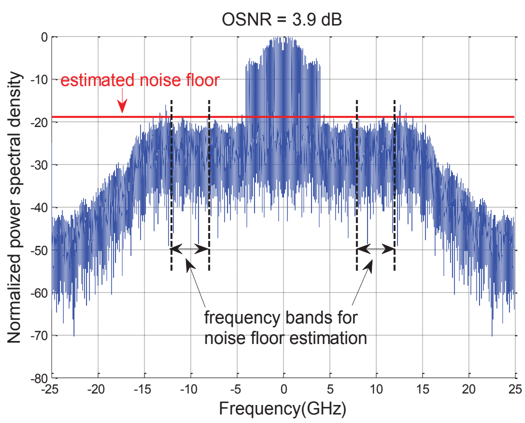

Fig. 6: Signal spectrum of a 8 GBaud pulse-shaped QPSK signal showing the frequency bands used for estimating the noise floor threshold.

The estimation of a wider range of baud-rates was tested via Monte-Carlo simulations, with results summarized in Fig. 7. Here the SNR level was set to give the same BER of $3.8{\cdot}10^{-3}$ at each baud-rate, to show the estimation performance at the worst case operating point for each baud-rate. At baud-rates higher than 32 GBaud the estimation technique is limited by the receiver bandwidth (16 GHz in this system), when the RRC roll-off is 0.

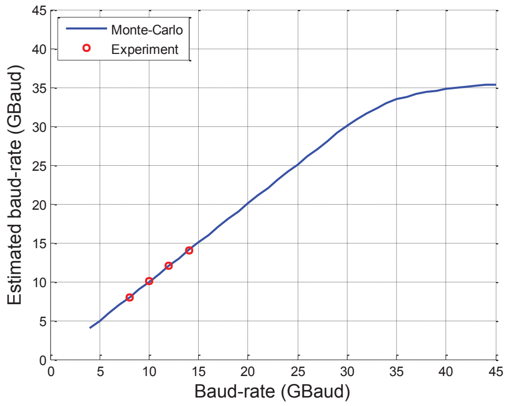

Fig. 7: Receiver bandwidth impact on the estimaton, for fixed SNR equivalent to BER=$3.8{\cdot}10^{-3}$, with applied noise threshold and 2^{15} captured samples.

Conclusions

The presented method has the advantages of being CD and 1st order PMD independent, as it relies on power spectrum of the signal. Additionally, by using 1st and 2nd order statistics of the spectrum, the intermediate frequency at the receiver is taken into account. The method was verified experimentally and by simulation for QPSK signals sampled at 50 GSa/s, resulting in errors up to 2% for baud-rates from 4 to 25GBaud and a minimum of 2^{15} processed samples, at a fixed SNR corresponding to a BER of $3.8{\cdot}10^{-3}$. The 2% error obtained is accurate enough to distinguish between a set of baud-rates and the FEC level, where typical FEC overheads range between 6.69–25%[7].

Acknowledgements

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