Baud-Rate Timing Phase Detector for Systems with Severe Bandwidth Limitations

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Abstract: A novel timing phase detector using one sample per symbol is developed. The phase detector is especially suitable for systems suffering from serious bandwidth limitations. Its superior performance is demonstrated in simulations and experiments.

1. Introduction

Most commercial optical systems are based on pulse or quadrature amplitude modulation (PAM, QAM). PAM-n modulation formats such as PAM-2 and PAM-4 are often used in cheap low-complexity non-coherent systems to cover distances up to 100 km while n-QAM modulation formats, utilized in more expensive coherent systems, e.g. 4-, 16-, and 32-QAM, cover much longer distances. The forecasted traffic demands in the near future require high-bandwidth low-noise optical and electrical components and high-order modulation formats, which are very sensitive to any transmission impairments. The use of advanced digital signal processing (DSP) in faster than Nyquist (FTN) systems seems to be a promising solution to minimize the requirements on component bandwidth [1]. However, in such severely bandwidth-limited systems, DSP normally relies upon advanced equalization algorithms to enable data recovery and timing recovery (TR) design becomes very critical. In particular, for such systems TR requires very sophisticated algorithms such as advanced timing phase detection, TR equalization, and accurate TR loop design.

Digital timing phase detectors (PDs) require one or more samples per symbol and use some logical and/or arithmetical operations to derive the clock tone. The most popular PD operating with one sample per symbol (1 sps), which is very often used in non-coherent systems, is the so-called Mueller and Müller PD (MMPD) [2] that is also suitable for FTN systems. In coherent systems, due to its superior performance and simple implementation in the frequency domain, the Gardner PD (GPD) is often used [3, 4]. When realized in the time domain, this PD requires samples at a half symbol period (2 sps) and fails in FTN systems. Its modification employing the signal power enables clock recovery also in FTN systems [5-7]. We call this variant of the GPD, which is described in [5, 6], squared GPD (SGPD). The GPD shows the best performance in non-FTN systems while MMPD, SGPD, and the PD described in [7] are more convenient for FTN systems. The main problem of PDs in FTN systems is the PD self-noise that limits the PD robustness against random and deterministic jitter and clock frequency variations.

In this paper, we introduce a novel baud-rate PD called the abs PD (ABSPD) as it uses the absolute values of the samples to derive the clock information. In simulations and experiments, we compare the ABSPD with other known PDs. Our results indicate that the novel PD achieves the best performance in FTN systems.

2. Novel Phase Detector

The ABSPD for the real signal x (e.g. in direct detection systems) with a symbol period $T_s=1/f_s$ can be described by

$$s(\tau,k)=|x(\tau+kT_s)+x(\tau+(k+1)T_s)|(|x(\tau+kT_s)|-|x(\tau+(k+1)T_s)|), \tag{1}$$

where $s(\tau,k)$ is the PD output at the sampling phase $\tau+kT_s$ and $0\leq\tau<T_s$. Only two symbol-spaced samples for clock extraction are required. The PD output for the complex signal $x=x_r+jx_i$ (e.g. in coherent systems) is defined by

$$s(\tau,k)=\sum_{m=r,i}|x_m(\tau+kT_s)+x_m(\tau+(k+1)T_s)|(|x_m(\tau+kT_s)|-|x_m(\tau+(k+1)T_s)|). \tag{2}$$

The ABSPD uses the absolute value of real samples to generate spectral components at high frequencies, which in a FTN system are suppressed by bandwidth limitations. As a comparison, the SGPD uses the squaring operation to achieve similar effects (replacing 2 by 1 in the exponents in (3) yields the GPD):

$$s(\tau,k)=x(\tau+kT_s)^2(x(\tau+kT_s+T_s/2)^2-x(\tau+kT_s-T_s/2)^2). \tag{3}$$

The sign MMPD exploits the sign nonlinear operation to emphasize frequencies around the Nyquist frequency:

$$s(\tau,k)=x(\tau+kT_s)\mathrm{sign}\big(x(\tau+(k+1)T_s)\big)-x(\tau+(k+1)T_s)\mathrm{sign}\big(x(\tau+kT_s)\big). \tag{4}$$

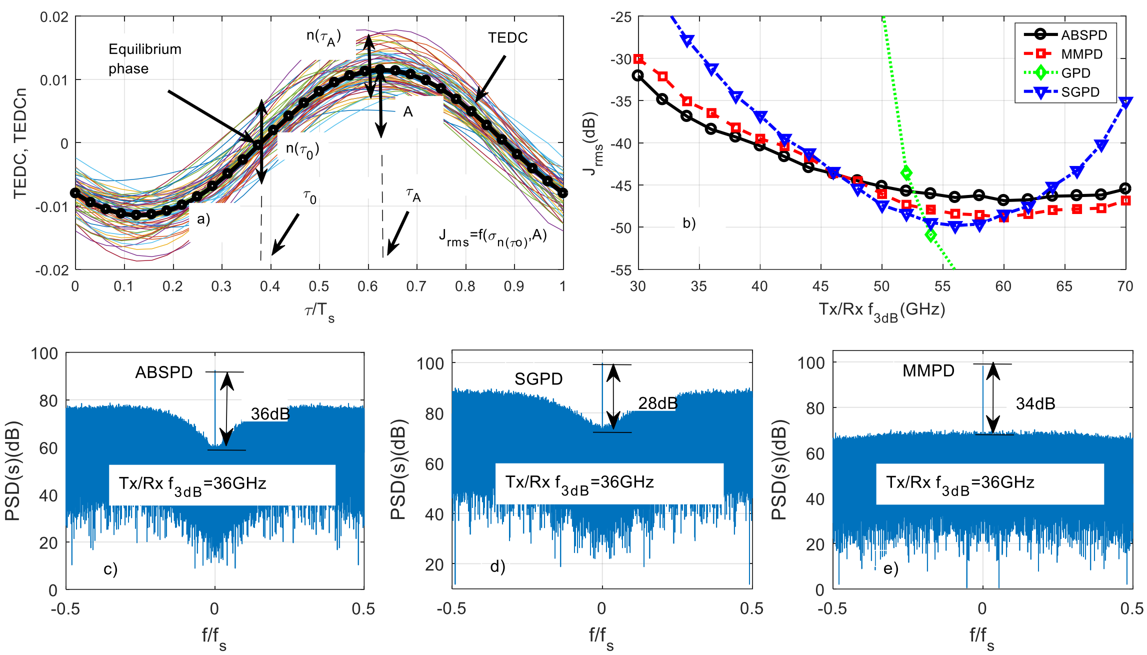

Fig. 1. a) ABSPD TEDC; b) J_{rms} vs. Tx and Rx f_{3dB}; c) ABSPD PSD; d) SGPD PSD; e) MMPD PSD.

Another MMPD variant uses decisions instead of signs, but it is more difficult to realize in real systems as it requires very complicated and careful design of the TR equalizer and TR loop.

The ABSPD timing error detector characteristic (TEDC) has a quasi-sinusoidal shape as shown in black in Fig. 1a. The other curves (TEDCn) in the figure represent experimental TEDC instances obtained by averaging over 4096 symbols and are indicative through their spread of the PD noise.

The root-mean-square jitter (J_{rms}) of a TR is a function of the TEDC maximum value A, the noise n at the equilibrium phase τ_0, and the transfer function of the phase-locked-loop (PLL). For many PDs (including ABSPD, MMPD, and SGPD) but not for the GPD, the noise level $n(\tau_0)$ is very similar to the noise level $n(\tau_A)$ at the sampling point τ_A at which the TEDC has its maximum value A. Therefore, a clock-to-noise ratio (CNR) can be estimated at the zero frequency. To compare PDs, we simulated a non-coherent 112 GBd optical transmission link with a receiver input power (Pin) of -6 dBm. The transmitter and receiver transfer functions are modeled by a 4th order Gaussian filter with 36 GHz 3-dB bandwidth. We found that a generalized Gaussian filter is suitable for modeling state-of-the-art high-bandwidth analog-to-digital and digital-to-analog converters. We show the power spectral density (PSD) of the PD output signal (s at τ_A) in Fig. 1c, 1d, and 1e. The clock signal is placed at the zero frequency. As shown in Fig. 1c, the CNR of the ABSPD is 36 dB, whereas the SGPD (Fig. 1d) and the MMPD (Fig. 1e) are worse by 8 dB and 2 dB, respectively. For this channel, the GPD fails and therefore its PSD is not presented here.

The same conclusions are obtained from the estimation of the root-mean-square jitter (J_{rms}) at the equilibrium phase in open loop simulations [8]. Here, instead of the open-loop estimation method, we report the J_{rms} in closed-loop simulations, because we think that the latter is more accurate. Fig. 1b shows J_{rms} measured in a 4 MHz second-order loop as a function of the 3-dB bandwidth of the Gaussian filter. The ABSPD performs best up to f_{3dB}=0.43f_s. The GPD wins for f_{3dB}>0.48f_s while the SGPD is the best choice in the small frequency region 0.43f_s <f_{3dB}<0.48f_s.

2. Phase Detector performance in experiments

The ABSPD is tested using 112 GBd PAM4 data samples acquired in C-band short-reach transmission experiments. The experimental setup is described in [1]. The data are transmitted with and without digital pre-distortion (DPD) and the corresponding received PSDs are shown in Fig. 2a for Pin=-6 dBm. The 3-dB bandwidth in the presence of DPD is around 42 GHz. While all PD candidates fail in the absence of DPD, the GPD does not work even with DPD. Data without DPD require carefully designed PD filters equalizing the signal before the PD and enabling the clock extraction. Therefore, we designed a 15-tap symbol-spaced PD filter, which yields the filtered spectrum shown by the dotted blue curve in Fig. 2a. This spectrum is very similar to the DPD spectrum for frequencies between 35 and 55 GHz. In the non-DPD case, we estimated J_{rms} for different PD filter lengths using 2 and 4 MHz PLLs. As expected, J_{rms} drops by 3 dB when the loop bandwidth is halved, however, at least a 5-tap PD filter is required to enable the correct TR functionality (see Fig. 2b). Some improvement is possible by increasing the number of taps up to 9 before the jitter level saturates. The ABSPD outperforms the competitors for any PD filter length greater than 3 although the SGPD shows similar performance when a 15-tap filter is used. In the non-DPD case with a 4 MHz loop, the MMPD with 5- and 7-tap PD filters lags behind the ABSPD by 3 dB and this difference drops to 2 dB as the number of taps is increased. As expected, a similar trend can be observed with the 2 MHz loop.

In the following we use the 5-tap PD filter to estimate J_{rms} at different input powers Pin. The results shown in Fig. 2c prove the superiority of the ABSPD for any input power. Higher Pin should correspond to lower J_{rms}, however, the photo-detector noise was not dominant in the experiments and imperfections such as clock source instability and power variations affected the results. As the SGPD is too complex for practical PAM systems (due to the high ADC oversampling and the four multiplications), we restrict the comparison to the ABSPD and MMPD with and without DPD in a 4 MHz loop at Pin=-6 dBm for different PD filters. The results shown in Fig. 2d indicate that the ABSPD achieve consistently a better performance. The PD filter does not help significantly in the DPD case and the ABSPD performance with and without DPD are very close for seven and more PD filter taps. The DPD reduces the distance in J_{rms} between ABSPD and MMPD to within 1 dB for more than 5 taps.

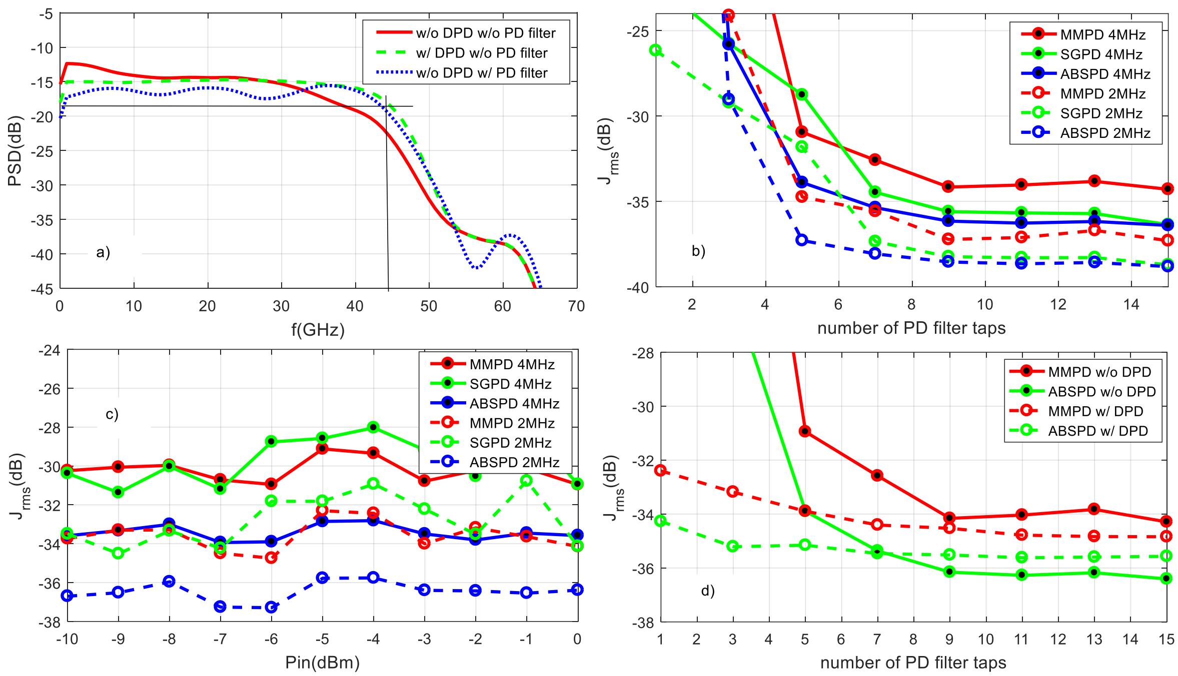

Fig. 2. Experiments a) Signal spectra at Pin=-6 dBm; b) J_{rms} without DPD vs. PD filter taps; c) J_{rms} without DPD vs. input power; d) J_{rms} with and without DPD vs. number of PD filter taps.

3. Conclusion

We presented a novel timing phase detector, called ABSPD, that is capable to extract the clock tone in coherent and non-coherent systems with severe bandwidth limitations. Thanks to its low complexity and superior performance the ABSPD appears to be the best choice for timing recovery in most practical systems.

4. References

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