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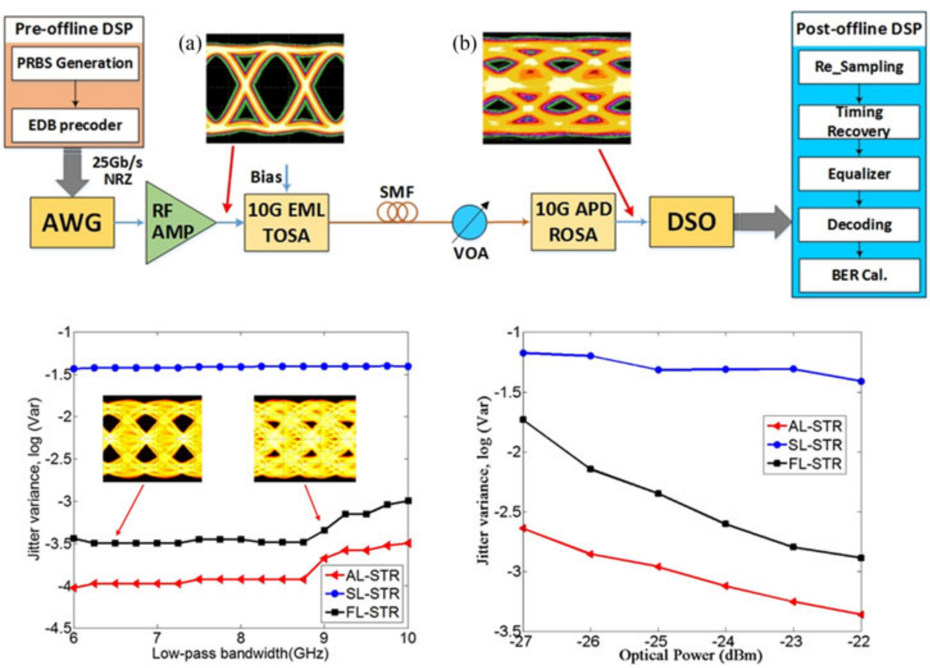
Junqi Xia
Yingchun Li
Tingting Xu
Jian Chen
Yingxiong Song



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Timing Recovery Algorithm Selection for Duo-Binary Signal Used in Next Generation 25G-EPON

Junqi Xia, Yingchun Li, Tingting Xu, Jian Chen, and Yingxiong Song

The authors are with the Key Laboratory of Specialty Optics and Optical Access Networks, Shanghai Institute for Advanced Communication and Data Science,Shanghai University, Shanghai 200072, China

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Abstract: Low complexity and effective symbol timing recovery (STR) algorithm is a serious challenge for high speed NG-EPON system with 25 Gb/s serial bit-rate per channel. In this paper, the frequently used nonlinear function based timing algorithms are compared in 25 Gb/s Duo-binary transmission system through simulation and experiment. Both simulation and experiment results show that absolute-law based STR (AL-STR) algorithm has minimum timing jitter and lowest computational complexity for Duo-binary receiver. The jitter of STR caused by the nonideal Duo-binary signal is also investigated by simulating different bandwidths of the commercial 10G optical devices. Results show that there are only little effect on STR performance when the –3 dB bandwidth changes from 6 to 8.75 GHz. Maximum likelihood sequence estimation (MLSE), linear and nonlinear equalizer are, respectively, performed after STR in 10G optics-based 25 Gb/s Duo-binary receiver. An optical power sensitivity of –25.6 dBm can be obtained with AL-STR and MLSE.

Index Terms: Symbol timing recovery, 25 Gb/s Duo-binary receiver, NG-EPON.

1. Introduction

Driven by the increasing demand for high speed data services such as cloud computing, 4 K TVs and 5G Infrastructure Public Private Partnership (5G PPP), the upgrade for high speed passive optical networks (PONs) is essential. Around 2011, NGPON2, a time and wavelength-division multiplexed (TWDM) PON, has been selected by the Full Service Access Network (FSAN) community as the cardinal technology [1]. Until 2015, the IEEE 802.3 Working Group began exploring the market potential and technology options for next generation ethernet passive optical network (NG-EPON) to achieve 100Gb/s through multiplexing four wavelengths [2]. Some advanced modulation techniques such as optical Duo-binary (ODB) [3], [4], electrical Duo-binary (EDB) [5], [6], quaternary level pulse amplitude modulation (PAM-4) [6], [7], and non-return to zero (NRZ) [8], [9] modulation schemes have been studied to achieve 25 Gb/s per channel. Until now, EDB detection has gained the most attention [10], [11] since its signal spectrum is reduced compared to NRZ and high volume mature 10G optical parts can still be used. As in traditional PON systems, symbol timing recovery (STR) is required to enable effective signal detection in NG-EPON. In the existing 25 Gb/s or

100Gb/s transmission experiments, digital square and filtering algorithm is used for the off-line timing recovery of PAM-4 and NRZ formats [9], [12]. And the technique for evaluating the performance of a popular type of STR circuit for baseband synchronous PAM data signal has been presented [13]. But the STR algorithms for partial response signal, including EDB, the most promising modulation scheme in NG-EPON, have not been studied yet.

Several popular non-data-aided (NDA) feed-forward algorithms for STR to get the spectral component at pulse frequency $1/T$ have been reported in [14]. And the main difference between these STR structures is the non-linear function utilized in each STR estimator, consisting of absolute-law (AL), square-law (SL) and fourth-law (FL) functions. In this paper, we amend the STR algorithm expression to apply to EDB signal and compares the performance of these algorithms. Both simulation and experiment results show that SL algorithm is not applicable to EDB-STR, and the AL algorithm has better performance than the other two algorithms, which are inconsistent with the results of ordinary PAM signals. EDB signal can be created approximately through a low-pass filter with -3 dB bandwidth of about one quarter of the serial bit-rate. So we design several butterworth low-pass filters with different bandwidths which are near the ideal bandwidth to create EDB signal through simulation, to investigate the impact of the non-ideal EDB signal created by practical 10G optical component on the performance of these STR algorithms. Furthermore, we demonstrate a 25 Gb/s experimental transmission system, using EDB detection with low-cost 10G TOSA (EML) and ROSA (APD), to evaluate the STR algorithm and bit error ratio (BER) performance. The experiment results show that an optical power sensitivity of -25.6 dBm can be obtained with AL based STR and MLSE.

The rest of this paper is organized as follows. In Section 2, we compare the jitter performance of AL-STR, SL-STR and FL-STR with EDB signal detection and discuss the effects of low-pass filter bandwidth on EDB-STR variance jitter through simulation. The experimental setup and results for 25 Gb/s EDB transmission system are presented in Section 3. Finally, we conclude in Section 4.

2. Simulation Analysis

We simulate a communication system with EDB signal transmission through additive white Gaussian noise (AWGN) channel and analysis the performance of different STR algorithms, which mainly rely on the non-linear function to distinguish. The estimation values of normalized timing error $\hat{\epsilon}$ based on these amended STR algorithms for EDB signal are:

$$\begin{cases} \hat{\epsilon} = -\dfrac{1}{2\pi}\left[arg\left(\displaystyle\sum_{k=mLN}^{(m+1)LN-1}\left|r\left(\frac{kT}{N}\right)\right|^{p} e^{-\frac{j2\pi k}{N}}\right)+\pi\right], p=1 \\ \hat{\epsilon} = -\dfrac{1}{2\pi}\left[arg\left(\displaystyle\sum_{k=mLN}^{(m+1)LN-1}\left|r\left(\frac{kT}{N}\right)\right|^{p} e^{-\frac{j2\pi k}{N}}\right)\right], p=2 \text{ or } p=4 \end{cases} \tag{1}$$

Where $p = 1, 2, 4$ corresponds to AL-STR, SL-STR and FL-STR respectively, the phase offset π is introduced to revise normal STR algorithm and make them apply to EDB signal. $r(\frac{kT}{N})$ are the received signal samples, and N is the number of signal samples per symbol. $\hat{\epsilon}$ is calculated every section of length LT with LN samples, and four samples per symbol ($N = 4$) are used in this paper. m is the order of every calculation section.

A pseudo-random bit sequence (PRBS) of length $2^{15} - 1$ is precoded and shaped by raised cosine pulse as the original three level EDB signal. The normalized timing error $\hat{\epsilon}$ is calculated based on AL-STR, SL-STR and FL-STR algorithm respectively. The variance of normalized timing error versus signal to noise ratio (SNR) is shown in Fig. 1 based on different STR algorithms and different symbol lengths L, i.e. AL-STR, SL-STR, FL-STR and $L = 100$, $L = 64$, $L = 16$. The value of practical normalized timing offset ϵ in simulation is successively set to 0, 0.25, 0.5, 0.75 on fixed STR algorithm, L and SNR, then we calculate the jitter variance respectively in these four cases. Every variance value in this figure is the average of these four variances. SNR is

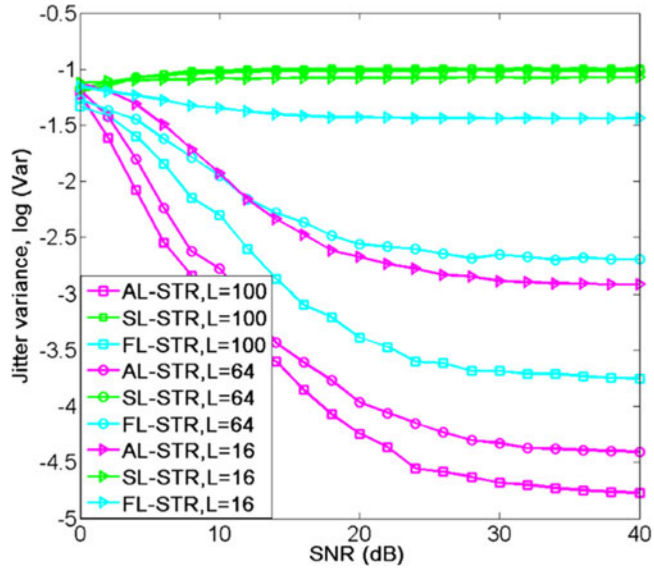

Fig. 1. Timing jitter variance versus SNR.

simulated from 0 to 40 dB. The results indicate that SL-STR algorithm is not applicable for EDB signal. Timing jitter performance of AL-STR is much better than FL-STR. The jitter performances are also compared with different symbol lengths L involved in the calculation in formula (1). When L decreases, the timing jitter variances are increased in both AL-STR and FL-STR algorithms and the jitter performance of FL-STR decreased faster than AL-STR with L reduction. In addition, considering the implementation of the non-linear function, four real multiplications are required per sample for FL-STR. But for AL-STR, only an absolute operation is required in each sample. These simulation results and analysis lead to the conclusion that AL-STR has the minimum jitter variance and lowest computational complexity in these EDB-STR algorithms. Considering the overhead of ADC, lower sampling rate is recommended. While $N = 3$, similar timing jitter performance can be obtained compared with $N = 4$ for AL-STR, SL-STR and FL-STR algorithms. But the performance of interpolation after timing is poorer than the $N = 4$ case. And while $N = 2$, timing information can't be extracted with the timing algorithm introduced in this paper.

Theoretically, the −3 dB bandwidth of low-pass filter used to generate 3-level EDB signal is one-fourth of the bit-rate of NRZ [15]. So a 6.25 GHz bandwidth is needed for 25 Gb/s EDB signal. The typical bandwidth measurement result of commercial 10G EML and 10G APD is shown in Fig. 2, and there are some differences compared with ideal EDB signal. Furthermore, the effective bandwidth of 10G optics produced by different manufactures may also have some differences. So we investigate the impact of bandwidth of low-pass filter on timing jitter by simulation.

As shown in Fig. 3, timing jitter variance with different bandwidths of low-pass filters are plotted with $L = 100$ and $N = 4$. Performance is almost same when the bandwidth changes from 6 GHz to 8.75 GHz and just become a little bit worse when the bandwidth is over 7.5 GHz for both AL-STR and FL-STR algorithms. The EDB signal eye diagrams are illustrated where the bandwidths of low-pass filter are 6.5 GHz and 9 GHz respectively. When the bandwidth exceeds 9 GHz, the eye diagram would be seriously skewed and the jitter performance of AL-STR and FL-STR declines rapidly.

3. Experimental Setup and Results

The performance of the timing recovery algorithm for 25 Gb/s EDB receiver is evaluated by using 10G optical devices as shown in Fig. 4. In that system, both the pre-DSP and post-DSP

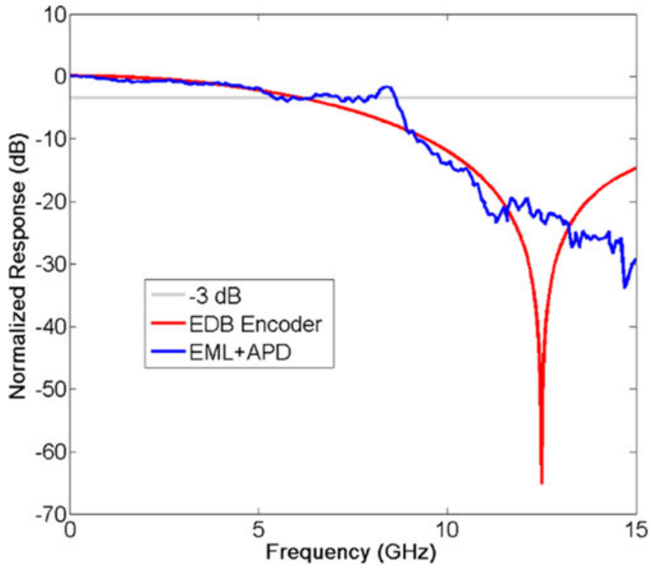

Fig. 2. Measured frequency response of used 10G EML+10G APD and theoretical response of EDB encoder.

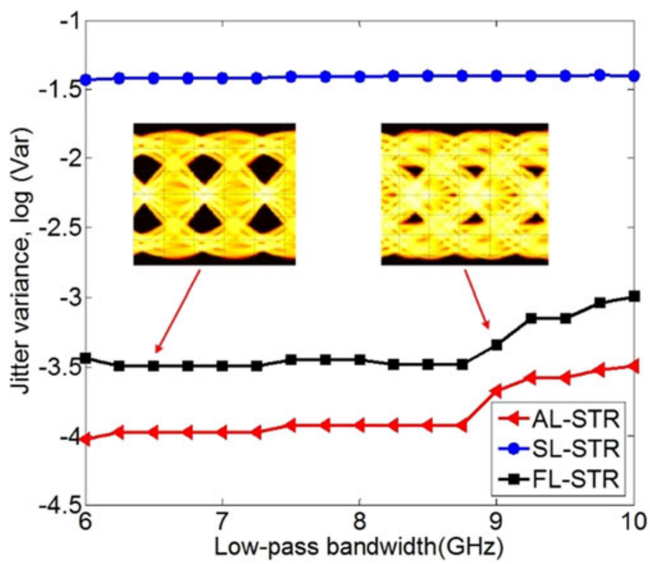

Fig. 3. Timing jitter variance versus bandwidth of low-pass filter.

are processed offline by MATLAB. In transmitter, PRBS is generated and precoded by an EDB precoder to prevent error propagation caused by the feedback structure in the decoder. After the precoded sequence loading to arbitrary waveform generator (AWG), electrical NRZ signal will output periodically for system transmission. The output of AWG is driven by a linear driver, and then modulated by a commercial available 10G electro-absorption modulated laser (EML) with wavelength of 1550 nm and +5 dBm transmitting power. At the receiver, after detected by 10G avalanche photodiode (APD), the 3-level EDB signal waveform is obtained. The received electrical signal is sampled by a real-time digital storage oscilloscope (DSO) with 80 GSa/s sampling rate. Offline DSP based on EDB decoder is then processed with the order shown in Fig. 4, including data resampling, timing recovery, equalizer, 3-level detection based EDB decoding and BER calculation modules.

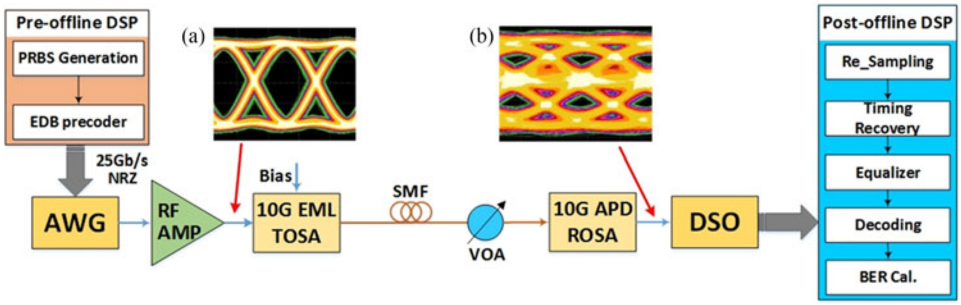

Fig. 4. Experimental setup for 25 Gb/s EDB B2B transmission system using 10 G-class optics. AWG: Arbitrary waveform generator; DSO: digital storage oscilloscope; Cal.: Calculation. Insets: (a) Electrical eye diagram before 10G EML; (b) Electrical eye diagram received by 10G APD with −20 dBm optical power.

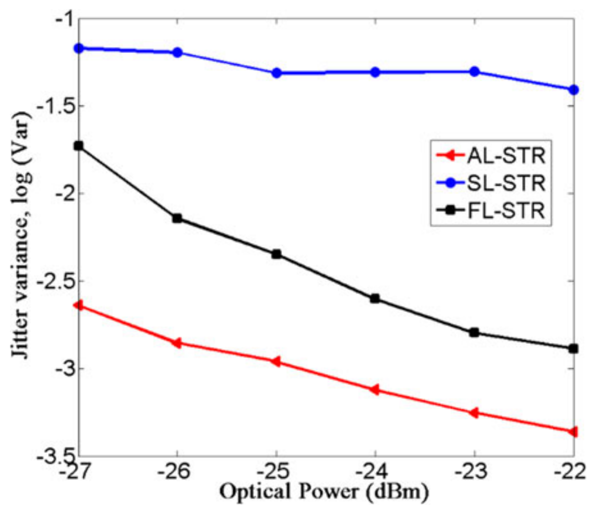

Fig. 5. Timing jitter performance of the 25 Gb/s EDB system versus received optical power.

The eye diagrams before 10G EML and after 10G APD with −20 dBm received optical power is illustrated in inset (a) and (b) in Fig. 4. Due to the bandwidth of 10G EML and APD is slightly greater than 6.25 GHz (as shown in Fig. 2), the received signal is similar to EDB signal but not ideal. So we use a viterbi algorithm based maximum likelihood sequence estimation (MLSE), a feed-forward equalization (FFE) and a decision-feedback equalization (DFE) respectively to equalize the received signal. The MLSE memory length is three, which corresponds to 8 states. In addition, a hard decision decoding based on 3-level detection without any equalization is also implemented for performance comparison.

Fig. 5 shows the timing jitter performance of the 25 Gb/s EDB transmission experiment versus received optical power for AL-STR, SL-STR and FL-STR algorithms. Consistent with the simulation above, the performance of SL-STR algorithm is the worst. The jitter variances of the normalized timing error $\hat{\epsilon}$ based on AL-STR and FL-STR share the same curve trend and the variances decrease continuously with the increase of optical power. When the received optical power is between −27 dBm and −22 dBm, the jitter variance of AL-STR is reduced by 0.5 to 1 order of magnitude compare to FL-STR, and the FL-STR algorithm deteriorates faster with the decrease of optical power. The SNR at −22 dBm, −24 dBm, −26 dBm optical power are 15.62 dB, 13.43 dB, 11.37 dB respectively. Compare the jitter variances correspond to these SNRs in Fig. 1 and these optical power in Fig. 5, it will be found that the experimental results are in good agreement with the

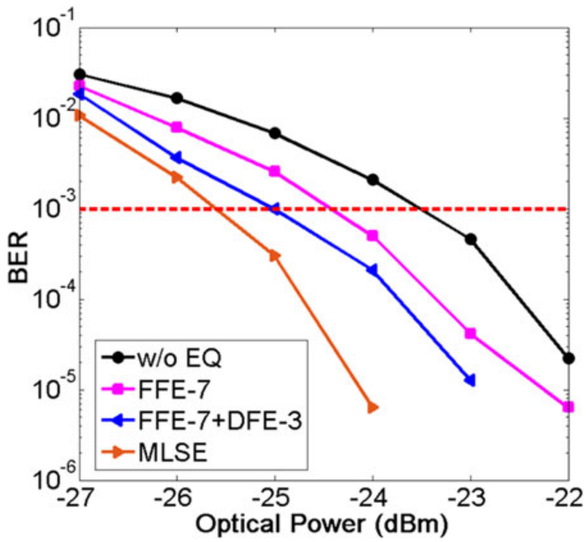

Fig. 6. BER performance of the 25 Gb/s EDB system versus received optical power.

simulation results. So we choose AL-STR for timing recovery in the post-offline DSP because of its lower algorithm complexity and better timing jitter performance.

The validity of the AL-STR algorithm is further proved by the BER results. The experimentally measured BER performances of the 25 Gb/s EDB system based on AL-STR are shown in Fig. 6. The receiver sensitivities for the transmission experiment with MLSE, 7-tap FFE (FFE-7), DFE with 7-tap feedforward filter and 3-tap feedback filter (DFE 7-3), and without any equalization cases are about −25.6 dBm, −24.3 dBm, −24.9 dBm and –23.4 dBm, respectively, at the forward error correction (FEC) threshold with a BER of 1×10^{-3}. Therefore, the MLSE algorithm provides the best sensitivity performance, which is ∼2.2 dB better than the hard detection case, ∼1.3 dB better than the 7-tap FFE, and ∼0.7 dB better than the DFE 7-3 case. With +5 dBm launch power and −25.6 dBm receiving sensitivity, link power budget of over 30 dB can be achieved.

4. Conclusion

The STR algorithms for EDB signal used in next generation 25G EPON system are simulated and experimentally demonstrated. Both results show that AL-STR is most suitable because of its minimum timing jitter variance and lowest computational complexity. It is also shown that the bandwidth of the low-pass filter for creating EDB signal has small effect on the STR performance when the −3 dB bandwidth is changed from 6 GHz to 8.75 GHz, which covers the bandwidth of 10G optics. In the off-the-shelf low cost 10G EML and 10G APD based 25 Gb/s EDB transmission systems, timing and decoding are completed based on AL-STR algorithm and MLSE, achieving a receiver sensitivity of −25.6 dBm, and only ∼1.3 dB and ∼0.7 dB declining for 7-tap FFE and DFE with 7-tap feedforward filter and 3-tap feedback filter scheme respectively.

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