Clock Recovery of a 180 Gbaud Faster-than-Nyquist Signal Enabled by a Novel Adaptive Equalizer-Aided Algorithm

Yo Nakamura, Guoxiu Huang, Hisao Nakashima, and Takeshi Hoshida
Fujitsu Limited, 4-1-1 Kamikodanaka, Nakahara-ku, Kawasaki 211-8588, Japan
nakamura-yo@fujitsu.com

Abstract: We proposed a novel adaptive equalizer-aided clock recovery algorithm for faster-than-Nyquist coherent optical systems and experimentally demonstrated good performance for Tomlinson-Harashima pre-coded 16QAM signal until 180Gbaud under the system with 10dB bandwidth of 65GHz.

1. Introduction

The demand for lower-cost and higher-capacity optical transport systems is driven by the continuous increase in network traffic [1]. To satisfy such demands and simultaneously reduce system power consumption, the capacity of transceivers must be increased. However, in conventional Nyquist systems, the symbol rate of the transceiver is limited by the analog bandwidth of optical and electrical devices and thus the transceiver's capacity. Faster-than-Nyquist (FTN) signaling techniques are attractive to overcome the constraints through digital signal processing (DSP) [2]. Among FTN technologies, we have focused on Tomlinson-Harashima pre-coding (THP) [3] that can be implemented in DSP at the symbol rate without oversampling, leading to considerably lower power consumption compared to the conventional transceiver. In [4], we applied THP to a coherent optical system and experimentally demonstrated 135-Gbaud 120 km transmission with a 35-GHz narrow bandwidth optical modulator. For practical applications of FTN coherent optical systems, including THP, clock recovery algorithms compatible with filtered signals are regarded as critical technology. However, to the best of our knowledge, there have been no reports about the successful clock recovery of FTN coherent optical signal.

In this paper, we propose a novel clock recovery algorithm that does not rely on the Nyquist frequency component and is thus compatible with FTN systems. We experimentally evaluated the performance of the proposed algorithm by comparing timing jitter after clock recovery and Q factor with the conventional Gardner algorithm [5] using THP signals with symbol rates up to 180 Gbaud under a system with 10 dB bandwidth of 65 GHz.

2. Conventional and Proposed Clock Recovery Algorithms

The timing error detector (TED) in the clock recovery function of a receiver estimates sampling phase error and thus can dominate the overall system performance since it affects the residual timing jitter after clock recovery. Fig. 1(a) shows the TED based on the Gardner algorithm. The Gardner TED relies on the symbol rate frequency, i.e., Nyquist frequency, component of the squared input waveform to generate phase error [6]. That is the reason why the Gardner TED loses its sensitivity in FTN transmission, where the channel bandwidth is less than the Nyquist frequency. On the other hand, the novel TED we propose in this paper, whose structure is schematically shown in Fig. 1(b), can overcome this issue with the aid of an adaptive equalizer. In the proposed TED, an error signal is calculated from the tap coefficients of the 2×2 finite impulse response (FIR) filters inside the adaptive equalizer. Since the tap coefficients of the FIR filters are adapted for the sampling phase delay/advance with each update, the amount of sampling phase error can be derived from them: the difference between half of the tap length and the group delay of the filter gives the timing error. The group delay can be computed as the frequency derivative of the phase of the Fourier transform of the tap coefficients. Note that the error signal obtained by the proposed TED is proportional to the phase error, while the output of Gardner TED exhibits a sublinear characteristic as it is represented by so-called S-curves.

In this study, to facilitate the comparison of TEDs in offline processing, the clock recovery function was implemented in a feed-forward format as shown in Fig. 1(c). The offline TED block is the feed-forward implementation of the Gardner TED or the proposed TED as shown in Fig. 1(d) and (e) respectively. The sampling phase adjustment block consists of FIR filters. In Fig. 1(d), since the error signal of the original Gardner TED does not directly represent the phase error, we up-sampled the signal to determine the sampling phase where the error signal becomes zero. On the other hand, in Fig. 1(e), we only need to interpolate the error signal between the adaptive equalizer updates to obtain the sampling phase for every sample. For both implementations, the time window of averaging was set to 3000 symbols to compare the jitter. In actual DSP implementations, feed-back structures to the analog-to-digital converters must be used jointly to compensate large clock deviation due to the buffer size limitation.

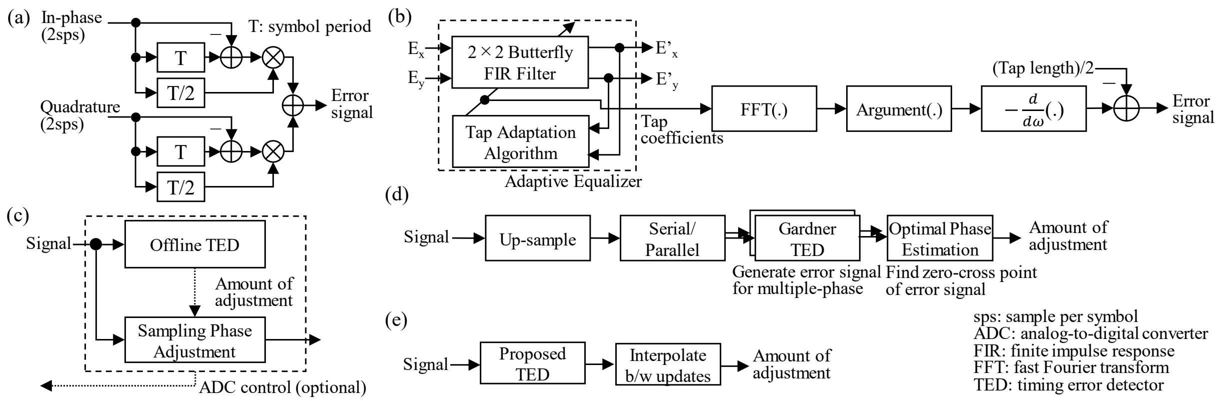

Fig. 1. DSP block diagrams. (a) Gardner TED, (b) Adaptive equalizer-aided TED, (c) Offline clock recovery implementation, Implementations for (d) Gardner algorithm and (e) adapive equalizer-aided algorithm.

3. Experimental Setup

The experimental setup is depicted in Fig. 2(a). In the transmitter DSP, a pseudo-random binary sequence (PRBS) 20 was generated and mapped into 16 quadrature amplitude modulation (QAM) symbols. To assist receiver DSP, a quadrature phase-shift keying (QPSK) pilot symbol was inserted every 64 data symbols. The amplitude of the pilot symbol was set to the boundary of the modulo (MOD) operation, described later, thereby realizing a 12 dB higher signal-to-noise ratio compared to the data symbols at the receiver. After the pilot insertion, the signal was processed by THP to enhance the tolerance for bandwidth limitation. In the THP block, as depicted in Fig. 2(b), the signal was feedback equalized using the tap weights derived from the frequency response of the transmitter to mitigate inter-symbol interference. THP is characterized by the MOD operation which keeps the feedback loop stable. After the THP block, the signal was up-sampled to 256 GSa/s and inputted to an arbitrary waveform generator (AWG). The output signal of AWG drove a dual-polarization (DP) in-phase and quadrature modulator (IQM) of 35-GHz bandwidth at 3 dB attenuation to generate an optical signal. We used a programmable optical filter to enhance the system bandwidth that resulted in the transmitted optical spectrum as shown in Fig. 2(c). The spectrum after the optical filter was used for the calculation of THP tap weights.

In the 120 km transmission link, a 1st-order polarization-mode dispersion (PMD) emulator was inserted to evaluate the PMD tolerance of the clock recovery algorithms. The signal power was set at 7 dBm to launch into the standard single-mode fiber (SSMF). Optical switches were inserted to bypass the transmission fiber for optical back-to-back (B2B) measurement.

The received optical signal was detected by a coherent-optical frontend and captured by a digital storage oscilloscope (DSO) at 256 GSa/s. When evaluating the clock recovery algorithms, the AWG and DSO were free-running without external clock synchronization. In the receiver DSP, the signal was down-sampled to 2 sps, and the effect of the chromatic dispersion (CD) was compensated. After the CD compensation, the sampling phase error was compensated by the clock recovery algorithms. The signal after the clock recovery was fed into an adaptive equalizer for the PMD compensation and polarization de-multiplexing. Then carrier phase recovery and linear filter were performed, and the bit error ratio and corresponding Q factor were calculated for 5.42×10^{6} data bits subsequently.

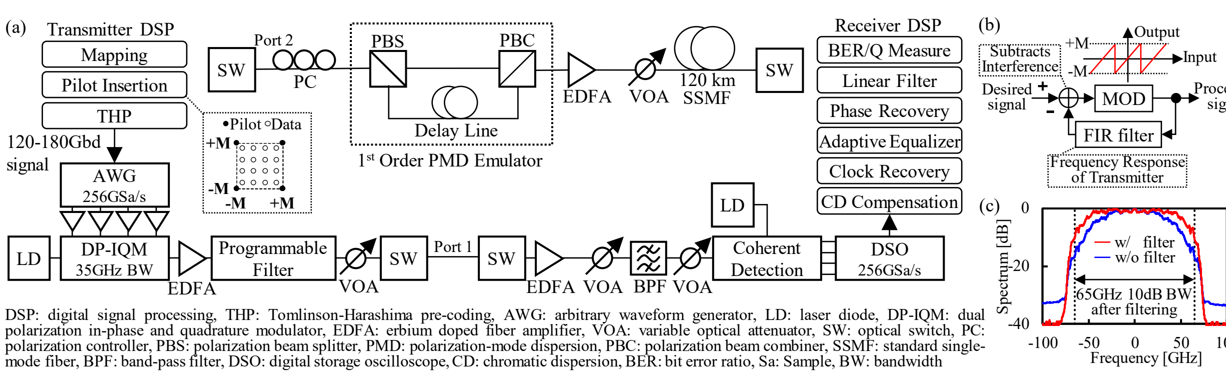

Fig. 2. Experimental setup. (a)THP coherent optical system, (b)THP DSP block, (c)Transmitted optical spectra with and without the programmable optical filter.

4. Experimental Results

Fig. 3 shows the experimental results. To compare the performance of clock recovery algorithms, we evaluated the jitter in decibel (dB) format to express the amount of timing jitter at the output of the TED,

$$jitter = 10\log_{10}(\sigma_t{}^2)$$

where σ_t is the standard deviation of the sampling phase error in unit interval. Fig. 3(a) shows the performance of the system with external clock synchronization thus the clock recovery disabled conditions. The Q factor of 180-Gbaud signal was 7.6 dB and 6.4 dB for B2B and after 120 km transmission, respectively. Thus, the net data rate of the system reaches 1.23 Tbps for 180-Gbaud signal based on OFEC [7]. Fig. 3(b) shows the symbol rate tolerance of the algorithms in B2B. When the Gardner algorithm was used, the jitter significantly increased beyond 130 Gbaud, which corresponds to 10 dB attenuation of the Nyquist frequency component, resulting in a critical degradation of the Q factor. In contrast, the proposed algorithm showed a significantly better performance until 180 Gbaud with smaller jitter under −37 dB and negligible Q-penalty compared to external clock synchronization conditions.

The tolerance to residual CD and 1st-order PMD for the proposed method and Gardner method are shown in Fig. 3(b) and (c), respectively. This evaluation was conducted at 130 Gbaud where the Gardner method could operate stably. While the Gardner method suffered from the residual CD and PMD, the proposed algorithm was almost insensitive to those parameters, and the Q-penalty and the jitter increase were almost ignorable. The proposed TED algorithm is thus expected to provide larger flexibility in the overall THP receiver design.

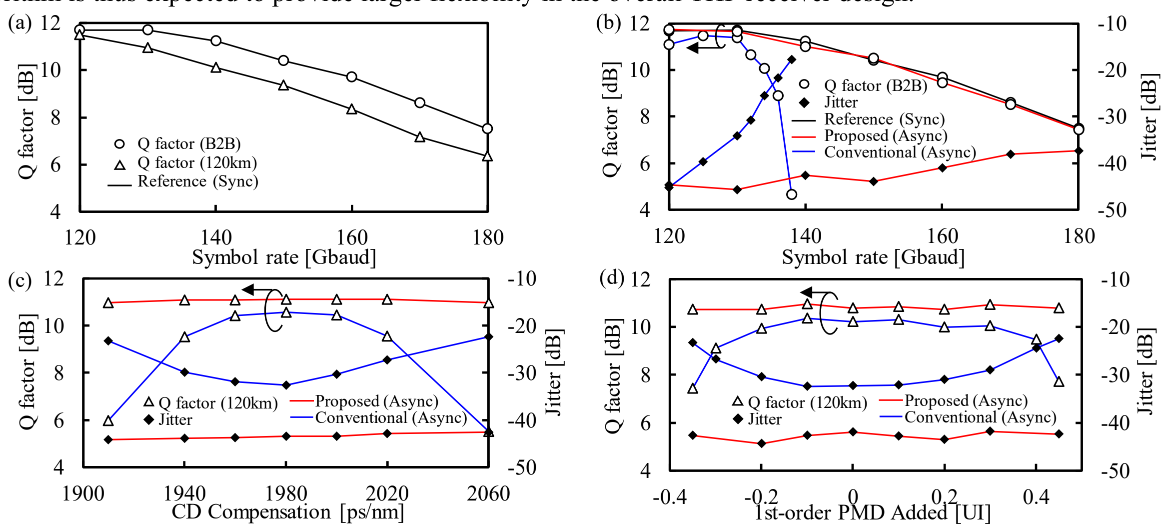

Fig. 3. Experimental results. (a)Performance under clock synchronization, Tolerance to (b)symbol rate, (c)residual CD, (d)1st-order PMD.

5. Conclusion

We proposed and experimentally demonstrated a novel adaptive equalizer-aided clock recovery algorithm for THP signals. The results show that the proposal achieves approximately 25 dB lower timing jitter compared to the conventional Gardner method at 130 Gbaud and can operate up to 180 Gbaud under the channel bandwidth limitation of 65 GHz at −10 dB. In addition, we have confirmed that the proposed algorithm is highly tolerant to PMD and residual CD in a 120 km transmission experiment.

6. Acknowledgements

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