Correction of timing mismatches between two channels for photonic analog-to-digital converters*

ZHANG He (张贺), WU Gui-ling (吴龟灵)**, WANG Cheng (王成), and CHEN Jian-ping (陈健平)
State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

(Received 30 March 2018; Revised 22 April 2018)
©Tianjin University of Technology and Springer-Verlag GmbH Germany, part of Springer Nature 2018

This paper presents a scheme to identify and compensate the timing mismatches between two channels for time interleaved photonic analog-to-digital converters (TIPADCs). The impact of electro-optic sampling is removed by preprocessing firstly. Then a calibration method combining chopping processing and a Hilbert transform is proposed to identify the timing mismatches, which can be further compensated by using various mature compensation algorithms. The principle of the proposed method is derived theoretically. The performance of the scheme is analyzed by simulation. The results show that the harmonic induced by timing mismatches can be suppressed by more than 30 dB using the proposed correction scheme.

DOI https://doi.org/10.1007/s11801-018-8049-2

Analog-to-digital converters (ADCs) are an essential part of signal processing systems and communication systems. Many fields now have an increasing requirement on high-sampling rate and high-resolution ADCs such as radar, ultra-wideband system, and so on. Time interleaved photonic analog-to-digital converters (TIPADCs) provide a promising solution to improve the performance of ADCs in terms of broader bandwidth and higher accuracy by combining photonics technology with time-interleaved sampling[1,2].

In a TIPADC, a high-speed optical sampling clock is used to sample the radio frequency (RF) signal by electro-optic modulation and is demultiplexed to several low speed channels suitable for electronic processing[3]. In order to realize a high-performance TIPADC with high speed and high resolution, it is one of the key issues to estimate and compensate the channel mismatches such as gain, offset, and timing mismatches. Among these three types of mismatches, timing mismatches are the most difficult to be identified and compensated[4,9]. The effects of the mismatches in TIPADC are analyzed and estimated for hardware adjustment[7,10,11]. The method based on hardware, however, is hard to realize and limited by the accuracy of the device. Many timing mismatch correction methods based on digital signal processing have been proposed for time-interleaved electric analog-to-digital converters (TIEADCs)[9,12,13]. Digital signal processing based correction methods are easy to be implemented, flexible and low cost. Although TIPADC can be equivalent to TIEADC under ideal conditions[14], some significant differences between them must be considered in practice, such as the nonlinearity of electro-optic modulation in TIPADC. It is inappropriate to directly apply the processing method for TIEADC to TIPADC. Effective digital signal correction methods for TIPADCs are still open issues.

In this paper, we propose a scheme to identify and compensate the timing mismatches between two channels for TIPADCs. A preprocessing scheme is presented to eliminate the impact of electro-optic sampling, such as its nonlinear response and direct-current (DC) offset. The timing mismatches between two channels are identified by using a calibration method based on chopping processing and a Hilbert transform, and then can be compensated by certain mature compensation algorithms, such as compensation filter algorithm[9,13] and adaptive signal processing algorithm[8,12]. The simulation results show that the spurious free dynamic range (SFDR) related to timing mismatches can be improved by more than 30 dB using the proposed processing scheme.

Fig.1 shows the basic architecture of the TIPADC system[14]. The periodic pulses produced by a mode-locked laser (MLL) are multiplied after wavelength division multiplexing (WDM), multi-channel time/amplitude adjustment, and wavelength multiplexing process. The generated high-speed optical sampling clocks sample an RF signal through a Mach-Zehnder modulator (MZM), and are then demultiplexed to multiple channels. The signal on each channel is detected by a photodetector (PD) and quantized by an EADC. The quantized data is then sent into data processing module to recover the sampled RF signal. Several factors, such as the limited delay

---

* This work has been supported partly by the National Natural Science Foundation of China (Nos.61535006 and 61627817).
** E-mail: wuguling@sjtu.edu.cn
adjustment precision and dispersion, will induce timing mismatches between channels.

Fig.1 Block diagram of the TIPADC system

The proposed timing mismatch correction method consists of three parts of preprocessing, identification and compensation, as shown in Fig.2(a). A calibration signal with a certain frequency \( \omega_c \) is applied for the first. The sampled data in each channel is input to the preprocessing part to obtain the parameters for the correction of nonlinearity and DC offset caused by MZM based electrooptical sampling. The processed data is obtained, and then input to the identification part to obtain the timing mismatch. According to the identified timing mismatch, a corresponding compensation filter is built in the compensation part. After that, when a sampled signal is applied, the sampled data is preprocessed using the correction parameters for nonlinearity and DC offset from above calibration, and then input to the compensation part to obtain the timing mismatch corrected result.

Fig.2 (a) Block diagram of timing mismatch correction including (b) preprocessing, (c) identification, and (d) compensation modules

The preprocessing procedure is shown in Fig.2(b). The output optical pulse power \( P_{out} \) from the MZM can be expressed as follows:

\[
P_{out} = [A + B \cos \left( \frac{\pi}{V_s} (v_{RF} + V_s) \right)]P_e,
\]

where \( P_e \) is the power of optical pulse in the input optical sampling clock, \( A \) and \( B \) are related to the splitting ratio of two couplers and attenuation coefficient of two arms of MZM, \( V_s \) is the half-wave voltage and \( V_e \) is the DC bias of the modulator. For the maximum modulation efficiency, MZM should be biased at \( V_s = \frac{V_e}{2} \) as possible.

\( v_{RF} = V \cos(\omega_{RF} t) \) denotes the input RF signal with frequency \( \omega_{RF} \) and amplitude \( V \).

In order to eliminate the impact of transformation features of MZM in Eq.(1), the DC component \( A \) in the data is eliminated by a Remove-DC processing, which subtracts the mean value of all data after EADC from all data. Then we go through an arccosine transform processing. In order to estimate the value of \( B \), we use a feature of the arccosine operations, that is for a single-tone sampled signal, there will exist its odd harmonics in the spectrum of arccosine result after Remove-DC if the value of \( B \) is not equal to 1. Based on this feature, we adopt a search approach to estimate the value of \( B \) when applying the calibration signal. In the approach, the data after the first Remove-DC module for the calibration signal is divided by an estimated value \( B' \) and arccosine operation is performed, so we have

\[
\cos^{-1} \left( \frac{B}{B'} \cos \left( \frac{\pi}{V_s} (v_{RF} + V_s) \right) \right).
\]

By scanning different \( B' \) within a certain range, and observing the difference between the calibration signal and its highest (the third) harmonic component in the result from Eq.(2), we can get the “true” \( B \) value corresponding to the maximum difference. The search range of \( B \) can be determined according to the parameters of MZM:

\[
B = \sqrt{\rho_1 \rho_2 (1-\rho_1)(1-\rho_2) \alpha_1 \alpha_2},
\]

where \( \rho_1, \rho_2 \) are splitting ratios of two couplers and \( \alpha_1, \alpha_2 \) are attenuation coefficients of two arms of the modulator. Since the parameters \( \rho_1, \rho_2, \alpha_1, \alpha_2 \) are all in \([0, 1]\), the range of \( B \) is \([0, 0.5]\).

The obtained value of \( B \) is provided to the arccosine operator. In the arccosine operator, the input data is divided by \( B \) and then goes through the arccosine operation, so the result can be expressed as \( \frac{\pi}{V_s} (v_{RF} + V_s) \). In the process of normalization, the constant before \( \omega_{RF} \) is removed by the operation \( \frac{\pi}{V_s} (v_{RF} + V_s) \), where Max is the maximum value.