Adaptive Correction of Amplitude Noise for Time-Interleaved Photonic Analog-to-digital Converter

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Abstract—**This paper presents an adaptive noise cancellation method for time-interleaved photonic analog-to-digital converters (TIPADC), where a part of the optical sampling clock signal is divided to back-end processing module to eliminate the amplitude noises in the optical sampling clock induced by laser sources and the pulse repetition rate multiplication like OTDM. The principle of the proposed method is derived theoretically. The effects of the splitting ratio of couplers in OTDM and the modulation depth on the correction efficiency of the method are analyzed by simulation. The results show that the signal-to-noise and distortion (SINAD) of system can be improved more than 30dB by using the proposed scheme.**

Keywords—Photonic Analog-to-Digital Conversion, Adaptive noise cancellation, Amplitude noise, Effective Number of Bit.

I. INTRODUCTION

Photonic ADCs (PADCs) have been proposed as a promising technique to overcome the limitation of electronic analog-to-digital converters (EADCs) in many applications, such as high-speed communications, advanced radar and electronic instrumentation, etc. [1-2]. The time-interleaved PADC (TIPADC) is one of the most practically feasible schemes among various proposed schemes [3-4], where a high-speed optical sampling clock is used to sample the RF signal by electro-optic modulation and is demultiplexed to several “low” speed channels suitable for electronic processing via wavelength division multiplexing (WDM) and/or optical time-division multiplexing (OTDM). The amplitude fluctuation and time jitter of the high-speed optical sampling clock have significant effects on the signal-to-noise and distortion (SINAD) or effective number of bit (ENOB) of TIPADCs [5]. Nowadays, the time jitter of commercial passive mode-locked lasers (MLL) has been able to be better than 10 fs. Their amplitude fluctuation, however, is still limited. Moreover, in order to reach high-speed sampling rate, a pulse repetition rate multiplication like OTDM is often needed since passive mode-locked lasers with broadband and high repetition rate are not commercially available yet [4]. The repetition rate multiplication will induce further amplitude fluctuation due to the limited precision of used components and their changes with the ambient environment. J. C. Twichell et al., proposed a phase-encoded TIPADC scheme to eliminate the effect of the amplitude fluctuation in optical sampling clocks by using the complementary of the two outputs of electro-optic modulators (EOM) [6]. R. C. Williamson et al., presented a precision calibration method to correct the amplitude noise in the optical sampling clock [7].

In this paper we propose a digital correction scheme based on the adaptive noise cancellation theory [8] to suppress the amplitude noises in the optical sampling clock induced by laser sources and repetition rate multiplication. The principle and efficiency of the proposed scheme is analyzed theoretically by simulation. The results show that the SINAD of the system can be improved more than 30 dB after using the proposed scheme.

II. PRINCIPLE

Fig.1 shows the architecture of the TIPADC with the proposed correction scheme. The repetition rate of optical pulse train from MLL is multiplied by an *M*-times OTDM. The optical pulse train from OTDM is separated into two parts. One is used as a reference for the adaptive noise cancellation while the other is sent to a *N*-channels WDM to generate a

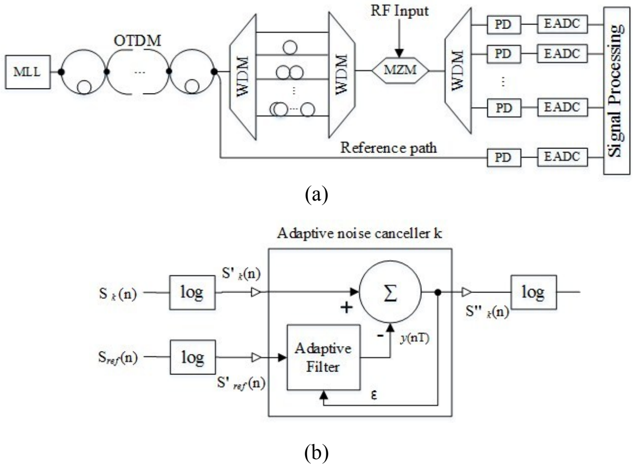

Fig. 1. The architecture of the TIPADC with the proposed correction scheme. (b) The adaptive cancellation process in each channel.

time-wavelength interleaved optical sampling clock. The optical sampling clock sample the RF signal through a Mach-Zehnder intensity modulator (MZM), and is then demultiplexed to several channels. The signal on each channel is detected by a photo-detector (PD) and quantized by an EADC while the reference optical pulse train is also digitized by an EADC after photon detection. In the signal processer, the detected signal is corrected and combined to output the sampled RF signal with the assistant of the received reference signal.

The intensity of the generated optical sampling pulse after the OTDM and WDM in Fig.1 (a), $I_{TDM}(t)$ and $I_{WDM}(t)$, can be written as, respectively,

$$
\begin{aligned}
I_{TDM}(t) &\propto \frac{I_0}{M}\sum_{i=0}^{M-1}\sum_{m=0}^{\infty}\delta_{i,m}\times\left[1+\sigma_{MLL}\left(t-\frac{iT_S}{M}\right)\right]\times\left[1+\sigma_{TDM}(t)\right] \\
I_{WDM}(t) &\propto \frac{I_0}{MN}\sum_{k=0}^{N-1}\sum_{i=0}^{M-1}\sum_{m=0}^{\infty}\delta_{i+\frac{k}{N},m}\times\left[1+\sigma_{MLL}\left(t-\frac{kT_S}{MN}-\frac{iT_S}{M}\right)\right] \\
&\quad\times\left[1+\sigma_{TDM}\left(t-\frac{kT_S}{MN}\right)\right]\times\left[1+\sigma_{WDM}(t)\right] \\
\delta_{i,m} &= \delta\left(t-\frac{iT_S}{M}-mT_S\right)
\end{aligned}
\tag{1}
$$

where, T_s and I_0 is the repetition period and the average intensity of the pulses from MLL, respectively; σ_{MLL}, σ_{TDM} and σ_{WDM} are the relative amplitude fluctuation induced by MLL, OTDM and WDM, respectively.

The signal after EADC in the k^{th} WDDM channel can be expressed as after a simple derivation,

$$
\begin{aligned}
s_k(n) &\propto \frac{I_0}{2MN}\left(1+\sigma_{MLL}\left(\lfloor n/M\rfloor T_S/M\right)\right)\left(1+\sigma_{TDM}\left(nT_S/M\right)\right) \\
&\quad\times\left(1+\sigma_{WDM}\left(\frac{nT_S}{M}+\frac{kT_S}{MN}\right)\right)\left(1+\sigma_{back}\left(\frac{nT_S}{M}+\frac{kT_S}{MN}\right)\right) \\
&\quad\times\left(1+\cos\left[\frac{\pi}{V_\pi}\left(V_b+V_{RF}\left(\frac{nT_S}{M}+\frac{kT_S}{MN}\right)\right)\right]\right) \\
&\quad n = 0,1,2\ldots
\end{aligned}
\tag{2}
$$

where,$V_{RF}(t)$ is the voltage of the RF signal applied on the MZM at time t; V_π is the half-wave voltage of the MZM; V_b is the bias voltage; σ_{back} represents the relative amplitude fluctuation induced by back-end optical and electrical modules (such as WDDM, PD etc.) in each WDDM channel, $\lfloor \bullet \rfloor$ represents the rounding operation.

In (2), σ_{back} mainly comes from the mismatching among channels, and can be corrected by some channel matching methods such as calibration [9]. On the other hand, the noise related to the MLL and OTDM is the internal-channel noise which cannot be cancelled by any channel matching methods.

Here we propose an adaptive correction method to suppress the internal-channel noise with the assistant of the received reference signal, see Fig.1 (b). In the scheme, the detected signal in each channel and the reference signal are passed by a "log" operation respectively to convert the multiplicative noise to additive noise since only additive noise uncorrelated to the RF signal can be cancelled by the adaptive correction method.

The signal in each channel and the reference signal after the "log" operation, $s'_k(n), s'_{ref}(n)$, are inputed to a corresponding adaptive noise canceller to eliminate the noise related to MLL and OTDM. The "e^x" operation following each adaptive noise canceller is used to cancel the "log" operation. After that, an inter-channel and nonlinear correction can be adopted to correct the channel mismatching and the nonlinear response of MZM, and the sampled RF signal can be reconstructed by combining the corrected signal in each channel.

III. SIMULATION RESULTS

Simulations for a 32 GS/s TIPADC system have been carried out to validate the proposed scheme. The system is composed with a 250 MHz MLL, 8-times OTDM and 16-channels WDM. In order to focus on the effect of the proposed scheme on inter-channel noises, all channels of WDM and WDDM are assumed to be matched.

The relationship between SINAD of TIPADC and the amplitude noise of the MLL with and without correction are shown in Fig.2. The modulation depth is 20%. The splitting ratio of each coupler in OTDM is 0.087 dB. One can see that the SINAD can be improved more than 30 dB by adopting adaptive correction. The SINAD almost does not change with the increase of the amplitude noise of MLL. This may be because the effect of the splitting ratio of coupler on SINAD is dominant.

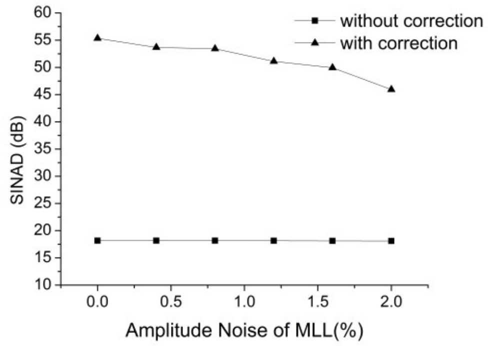

Fig. 2. The SINAD of the TIPADC as a function of the amplitude noise of the MLL with and without adaptive correction.

Fig.3 represents the SINAD of TIPADC as a function of the splitting ratio of each coupler in OTDM. The modulation depth is 20%, amplitude noise of MLL is 1%. Without correction, the SINAD decreases as the splitting ratio of couplers increases. The result is reasonable since a higher splitting ratio of couplers will cause a higher fluctuation related to OTDM, which will decrease the SINAD. After adaptive correction, the SINAD can be raised more than 30 dB. One can also see that the SINAD after adaptive correction is almost not related to the splitting ratio of coupler in the OTDM, which indicates the effect of the amplitude fluctuation for the OTDM has been eliminated effectively.

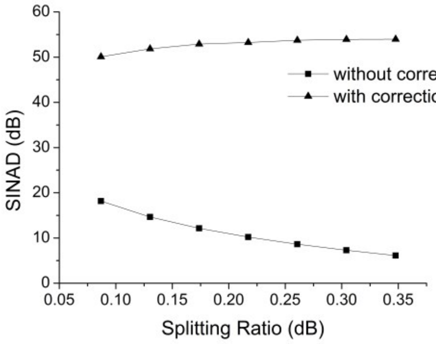

Fig. 3. The SINAD of the TIPADC as a function of the splitting ratio of couplers in the OTDM with and without correction.

The impact of the modulation depth on the SINAD of TIPADC is shown in Fig.4. The amplitude noise of MLL is 1% and the splitting ratio of couplers in the OTDM is 0.087 dB. We can see that as the increase of modulation depth, the SINAD without adaptive correction rises up to a maximum value (about 25 dB in the figure) and then goes down slowly while the SINAD with adaptive correction always decreases. The reason can be explained as follows. Both the component of signal and the modulation nonlinearity increase with the increase of the modulation depth. Since the increase of the modulation nonlinearity is larger than that of signal, the SINAD with adaptive correction, which is equal to the ratio of signal to distortion caused by modulation nonlinearity, always decreases with the increase of modulation depth. In the case of without adaptive correction, however, there exists the amplitude noise. The SINAD is equal to the ratio of signal to the sum of noise and distortion, which has a maximum value since the ratio of signal to distortion and the ratio of noise to distortion have inverse effects on SINAD.

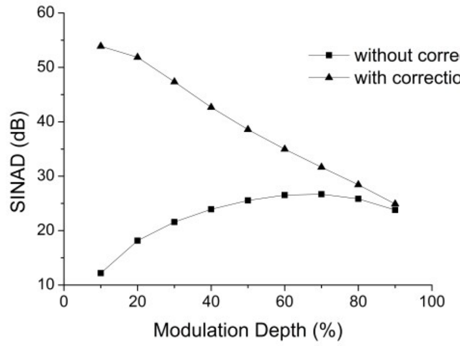

Fig. 4. The SINAD of the TIPADC as a function of the modulation depth with and without correction.

IV. CONCLUSION

In this paper, we present an adaptive cancellation method for TIPADCs to suppress the effect of the internal-channel amplitude fluctuations caused by the laser source and repetition rate multiplication. This scheme divides part of the internal-channel optical sampling pulse train as reference and takes an adaptive digital processing in the back-end processing module. The principle of the proposed method is analyzed theoretically, and validated by simulations for a 32 GS/s TIPADC composed with a 250 MHz MLL, 8-times OTDM and 16-channels WDM. The results show that the SINAD of the system can be improved more than 30 dB by using the proposed adaptive correction scheme.

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