Calibration of static nonlinearity mismatch errors in TIADC based on periodic time-varying adaptive method

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Abstract The nonlinear behaviors of time-interleaved analog-to-digital converter (TIADC) caused by non-ideal circuit implementations degrade performance of TIADC significantly. This paper proposes a calibration method based on model inversion strategy to compensate for static nonlinearities in TIADC, since static nonlinearities are the major compositions of the nonlinear behaviors in most situations. The proposed periodic time-varying adaptive calibration method can estimate coefficients of inverse polynomial model directly and capture variations of the nonlinear parameters when environment changes. The method proposed in this paper is also applicable to dynamic nonlinearities by changing polynomial with Volterra series. Simulation results show the effectiveness and robustness of the proposed method.

Keywords: time-interleaved analog-to-digital converter, static nonlinear mismatches, polynomial, calibration, adaptive, model inversion

Classification: Circuits and modules for electronic instrumentation

1. Introduction

Analog-to-digital converter plays a critical role in modern telecommunication systems [1, 2, 3]. Time-interleaved architecture is an effective solution for emerging demand requiring high speed and high resolution ADCs [4, 5], which can increase sampling rate beyond a certain technology limit. In the ideal case, an M channel time-interleaved ADC (TIADC) acts like a single ADC with M times higher sampling rate than individual sub-ADCs.

Unfortunately, the non-ideal effects in the analog building block implementations cause significant performance degradation for TIADC system [6, 7]. During the past few decades, the estimation and compensation methods for offset, gain, time, and frequency mismatches are investigated extensively [8, 9, 10, 11, 12, 13]. In recent years, there has been an increasing interest in nonlinear mismatch problems in TIADC system [14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25].

The nonlinear behaviors of TIADC system are caused by non-ideal circuit implementations (e.g., sample-and-hold, buffer amplifier) [20], which will degrade the performance of the whole system significantly. Therefore, it is of considerable importance to estimate and compensate the nonlinear mismatches in TIADC system.

In [14], the authors investigates the effects of differential nonlinearities (DNL) and integral nonlinearities (INL) in TIADC system. In [19], the nonlinear behaviors of TIADC system are modeled with nonlinear hybrid filter bank and it is pointed out nonlinear hybrid filter banks can be used to model offset, gain, time and nonlinear mismatch errors. An adaptive background estimation method for static nonlinearity mismatches is proposed in [17], where authors provide two implementation strategies to meet demand for different applications.

Most existing papers for nonlinear calibration are based on error reconstruction strategy [22, 23, 24]. In [23], a joint blind compensation method based on error reconstruction strategy is proposed to calibrate nonlinear mismatch errors in TIADC, where the normalized least-mean square algorithm is utilized for compensation. In [24], an efficient blind method is proposed to calibrate nonlinearity mismatches in M-channel TIADC by exploiting binary Hadamard transform, which is also based on error reconstruction strategy.

In this paper, we propose the usage of model inversion strategy [26] to compensate for static nonlinear mismatch errors in TIADC, since static nonlinearities are the major compositions of the nonlinear behaviors in most situations [17]. Firstly, we derive the time-varying expressions for nonlinear TIADC behavioral model based on polynomial model, which provides the theoretical foundation to use time-varying compensation structures to calibrate nonlinearities in TIADC. Then we propose the periodic time-varying adaptive calibration method to compensate for static nonlinearities in TIADC, which can estimate coefficients of inverse polynomial directly and is capable to capture variations of the nonlinear parameters when environment changes. We show the effectiveness and robustness of our proposed algorithm in simulation. In general, we can extend the method proposed in this paper to dynamic nonlinearities by changing polynomial with Volterra series, which has similar representations and structures with the polynomial model and shares the same principle as this paper essentially.

The rest of this paper is structured as follows. In section 2, the time-varying nonlinear behavioral model of TIADC based on polynomial is derived. In section 3, periodic time-varying adaptive calibration method is proposed. The simulation results are provide in section 4 to show the validity of proposed method. Finally, Section 5 concludes the paper.

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2. System model

In order to focus on nonlinearities in TIADC system, we assume that the linear mismatches have been calibrated. In this paper, we investigate the static nonlinearities in TIADC since static nonlinearities are the major compositions of the nonlinear behaviors in most cases.

Fig. 1 shows the nonlinear behavioral model of an M channel TIADC. The analog input signal \( x(t) \) is fed to the \( m \)th channel's nonlinear function \( F_m(x) \) \((m = 0, \ldots, M - 1)\) and then sampled at instant \( mT_s + kMT_s \) to obtain \( m \)th channel output \( y_m(n) \), where \( T_s \) is the sampling period of the overall TIADC system. The digital streams from \( M \) sub-ADCs are then multiplexed to form the TIADC output \( y[n] \) with sampling rate \( f_s \) \((f_s = 1/T_s)\).

Stone-Weierstrass theorem states that any continuous function defined on a closed interval \([a, b]\) can be uniformly approximated as closely as desired by a polynomial function defined on a closed interval with sampling rate \( f_s \). Thus, we use polynomial function to describe the nonlinear behaviors of TIADC system in this paper. The \( m \)th channel nonlinear function of TIADC system can then be represented as

\[
F_m(x) = \sum_{p=0}^P a_{m,p} x^p \quad (1)
\]

where \( a_{m,p} \) represents the \( p \)th order polynomial coefficients of \( m \)th channel.

Then the discrete-time (DT) model of TIADC system can be obtained as in Fig. 2. The input signal \( x(n) \) passes through the \( m \)th channel polynomial function \( F_m(x) \) to get the output \( y_m(n) \), which is given by

\[
y_m(n) = F_m[x(n)] \cdot s_m(n) \quad (3)
\]

where

\[
s_m(n) = \sum_{k=\infty}^\infty \delta(n - m - kM) \quad (4)
\]

\( \delta(n) \) is the Dirac-delta function.

The output \( y(n) \) can then be obtained as

\[
y(n) = \sum_{m=0}^{M-1} y_m(n) = \sum_{m=0}^{M-1} F_m[x(n)] \cdot s_m(n) \quad (5)
\]

According to Poisson's summation formula, (4) can be transformed as

\[
s_m(n) = \sum_{k=\infty}^\infty \delta(n - m - kM) = \frac{1}{M} \sum_{k=0}^{M-1} e^{j2\pi k(n-m)/M} \quad (6)
\]

The TIADC output \( y(n) \) can then be given by

\[
y(n) = \frac{1}{M} \sum_{m=0}^{M-1} y_m(n) = \frac{1}{M} \sum_{m=0}^{M-1} \sum_{k=0}^{M-1} e^{j2\pi k(n-m)/M} F_m[x(n)]
\]

Define

\[
A(k, p) = \frac{1}{M} \sum_{m=0}^{M-1} a_{m,p} e^{-j2\pi km/M} \quad (8)
\]

Assuming \( n = m + qM \) \((q = -\infty, \ldots, \infty)\), (8) becomes

\[
A(k, p) = \frac{1}{M} \sum_{n=\infty}^{\infty} \sum_{q=\infty}^{\infty} a_{n-qM,p} e^{-j2\pi k(n-qM)/M}
\]

Since \( n - qM = m \) with \( m = 0, \ldots, M - 1 \), we define \( a_{<n> M,p} \) as the \( M \)-periodic extended version of \( a_{m,p} \). Then (9) becomes

\[
A(k, p) = \frac{1}{M} \sum_{n=\infty}^{\infty} a_{<n> M,p} e^{-j2\pi kn/M} \quad (10)
\]

where it can be seen that \( A(k, p) \) is the discrete-time Fourier series (DTFS) of \( a_{<n> M,p} \) [28].

According to [28], the inverse DTFS of (10) is given as

\[
a_{<n> M,p} = \sum_{k=0}^{M-1} A(k,p) e^{j2\pi kn/M} \quad (11)
\]

Then the output of TIADC \( y(n) \) is obtained by combining (10) and (11) with (7), which is given by

\[
y(n) = F_{<n> M}[x(n)] = \sum_{p=0}^{P} a_{<n> M,p} x^p(n) \quad (12)
\]

From (12), it can be seen that the TIADC output \( y(n) \) can be generated by feeding the input signal \( x(n) \) through an...
$M$-periodic time-varying polynomial function $F_{<n \geq M} [\cdot]$, i.e. for each instant, different coefficient set is used. The model proposed in this section can model offset, gain, and higher order nonlinear mismatches in TIADC system. In principle, we can extend the above derivations to dynamic nonlinearities by changing polynomial model with Volterra series, which have similar representations and structures with the polynomial mode.

3. Time-varying adaptive calibration method

The calibration method is based on model inversion strategy [26], i.e. we compensate nonlinearities in TIADC system by cascading an inverse nonlinear system to recover the linearity of the TIADC. According to [29], the $p$th order polynomial inverse is defined as when cascaded with $P$th order polynomial, the output of 1st order coefficient is unity and 2nd to $p$th order coefficients equal to zero, which is given by

$$g(f(x)) = x + b_{p+1}x^{p+1} + \cdots + b_p x^p$$  \hspace{1cm} (13)

where $f(\cdot)$ is the static nonlinear function of the system, $g(\cdot)$ is the $p$th order inverse of $f(\cdot)$ and $b_p$ is the coefficient of function $g(f(x))$. The $p$th order inverse $g(\cdot)$ is also a polynomial, which is given by

$$g(x) = g_0 + g_1 x^1 + \cdots + g_p x^p$$  \hspace{1cm} (14)

where $g_p$ is the coefficient of function $g(x)$.

From section 2, it can be concluded that TIADC is a periodic time-varying system, which makes the inverse system also a periodic time-varying one. The compensation structure for TIADC system is depicted in Fig. 3. The TIADC output $y(n)$ passes through the $p$th order time-varying polynomial to get the calibrated output $\hat{y}(n)$, which is given by

$$\hat{y}(n) = G_{<n > M} [y(n)]$$

$$= 1 + g_{<n > M, 1} y(n) + \cdots + g_{<n > M, p} y^p(n)$$  \hspace{1cm} (15)

where $g_{<n > M, p}$ is the coefficient of the time-varying polynomial.

In order to obtain the coefficients of inverse polynomial, the coefficients of the system model should be estimated firstly. In this paper, we propose the usage of an adaptive $M$-periodic time-varying polynomial to calibrate the nonlinear mismatches in TIADC, which can estimate coefficients of inverse polynomial directly and is capable to capture variation of the nonlinear parameters.

The block diagram of the calibration architecture is shown in Fig. 4. There are two modes for the proposed calibration method, which are denote as training mode and operating mode, respectively. In the training mode, the TIADC output $y(n)$ is feeded into the adaptive block to provide adaptive adjustment of the coefficients for the inverse model using proposed $M$-periodic time-varying adaptive algorithm. The calibration is finished until the variance of the error $e(n)$ is low enough to meet the system’s demand. Then the coefficients are fixed and the TIADC output $y(n)$ is cascaded with $M$-periodic time-varying inverse model with the fixed coefficients to get into operating mode. In practice, the training mode and operating mode are supposed to switch to each other within certain time intervals to capture variations of the nonlinear parameters when environmental changes.

The aim of this paper is to discuss the calibration method for TIADC system, rather than the performance of the adaptive algorithms themselves. Thus, we use LMS (least mean square) algorithm to illustrate the calibration method due to its simplicity. It is easy to substitute LMS with other adaptive algorithms to obtain different performance of the calibration method.

Compared to standard LMS algorithm (with one coefficient set), the proposed $M$-periodic time-varying adaptive algorithm has $M$ coefficient sets. Fig. 5 shows the block diagram of the realization of the $M$-periodic time-varying adaptive algorithm. The input of the time-varying adaptive structure at time instant $n$ is given in vector form as

$$u(n) = [1, y(n), y^2(n), \cdots, y^p(n)]^T$$  \hspace{1cm} (16)

The multiplexer selects the output from adaptive block one
at a time, which means there is no need to update coefficients of the \( m \)th adaptive block under full sampling rate \( f_s \). The coefficients of \( m \)th \( (m = 0, \cdots, M-1) \) adaptive block update every \( MT_s \). The \( m \)th adaptive block updates at time instant \( n \) with \( m = \langle n \rangle_M \). The coefficients of the time-varying filters is defined in vector form as

\[
\tilde{g}_{\langle n \rangle_M} = [\tilde{g}_{\langle n \rangle_M 1}, \cdots, \tilde{g}_{\langle n \rangle_M M}]^T
\]

(17)

The update equations for \( M \)-periodic time-varying LMS algorithm are then given as

\[
ed(n) = d(n) - \tilde{g}_{\langle n \rangle_M} u(n)
\]

(18)

\[
\tilde{g}_{\langle n \rangle_M} = \tilde{g}_{\langle n-M \rangle_M} + \mu u(n)ed(n)
\]

(19)

where \( d(n) \) and \( e(n) \) represent the desired and error signal respectively, \( \mu \) denotes the update step size.

However, since input of the TIADC is an analogue signal in practice, it cannot be employed as the desired signal \( d(n) \) directly. Fig. 6 depicts a simplified block diagram of the generating procedure of desired signal. First, the digital signal \( d(n) \) is generated in PC with software, such as MATLAB, and stored in the memory of the hardware. Then the digital signal \( d(n) \) is converted into analog signal with DAC or signal generator. The generated analog signal can then be used as the analog input of the TIADC system, and \( d(n) \) is just the desired signal for proposed adaptive algorithm.

However, the DAC or signal generator has nonlinear behaviors itself, which would affect the estimation of the inverse model. In order to improve the performance of the proposed algorithm, a very accurate DAC with high linearity than TIADC is required, which is not easy to realize in practice.

Fortunately, since static nonlinearities are the dominant part of nonlinear behaviors in most situations, and static nonlinearities are independent of frequency, we can adopt a sinusoid as the desired signal. Then a narrow band filter is connected to the output from DAC or signal generator to suppress noise and nonlinear distortions generated by them. This clean analog input signal is then fed into the TIADC system. Although filter can introduce some amplitude difference with the original signal, this difference can be reduced by measuring filter with vector network analyzer and then multiply the desired signal \( d(n) \) with reciprocal of gain of filter at given frequency. In fact, a slight amplitude difference of the original signal will not affect our algorithm, which is shown in simulation results.

4. Simulation results

In this section, we investigate the effectiveness of the proposed calibration method with MATLAB. In the simulation, we use four channel TIADC model based on polynomial with sampling rate 1 GSPS. Since for a reasonably designed TIADC, the dominant nonlinearities are second and third order distortions [30], we use polynomial with nonlinear order up to third as our ADC model. The coefficients of the polynomial are set as \( a_{m,n} = [-0.013, 0.025, 0.010, -0.003], a_{m,1} = [0.311, 0.992, 0.983, 1.023], a_{m,2} = [0.004, -0.003, -0.001, 0.002], a_{m,3} = [0.001, 0.013, -0.002, 0.004]. \)

To make a comparison with the coefficients of the inverse system calculated from expression, we provide the analytical expression of the inverse system. The coefficients of the inverse model from zero to third order are given by [29]

\[
g_0 = -a_0, \quad g_1 = \frac{1}{a_1}, \quad g_2 = \frac{a_2}{(a_1)^3}, \quad g_3 = \frac{2(a_3)^2 - a_1a_3}{(a_1)^5}
\]

(20)

The coefficients of the inverse system for TIADC model are then given as \( g_{m,0} = [0.0130, -0.0250, -0.0100, 0.0030], g_{m,1} = [0.9899, 1.0081, 1.0173, 0.9775], g_{m,2} = [-0.0039, 0.0031, 0.0011, -0.0019], g_{m,3} = [-0.0009, -0.0134, 0.0021, -0.0036]. \)

We adopt a 113 MHz sinusoidal signal as the input of TIADC system, which is also the desired signal for adaptive algorithm. The order of the inverse model is set as 3, which can compensate for nonlinearities up to third order. The total samples are 20K and \( \mu \) is chosen as 0.01. The initial values for \( g_{m,1} \) is set as 1 while others are set as 0.

The convergence curves for the inverse system of four coefficient set are shown in Fig. 7. It can be seen that the estimated value of \( \tilde{g}_{m,p}(n) \) converges to the analytical calculated value \( g_{m,p}. \)

Further, Fig. 8(a) and (b) shows the frequency spectrum before and after calibration with third order 4-periodic time-varying adaptive calibration method. It is seen that there are plenty of spurious tones in the output spectrum before calibration, which are caused by nonlinear mismatch errors of TIADC system. There is a significant improvement after calibration by using the proposed calibration method. The spurious free dynamic range (SFDR) of the simulated TIADC before and after calibration are 39.77 dBc and 101.50 dBc, with an improvement of 61.73 dB.

Fig. 8(c) depicts the spectrum after calibration with desired signal differ slightly in amplitude due to analog filter. The desired signal used for adaptive algorithm in this situation is set as \( d(n) = 0.96d(n) \). From the results, we can see that the SFDR in this situation is 97.72 dBc, with an improvement of 57.95 dB. The performance with desired signal differ slightly in amplitude only has a minor effect of the calibrated signal, which shows the robustness of our proposed algorithm.

To further prove the validity of our proposed method, we add weak fourth and fifth order nonlinearities to the TIADC model with coefficients as \( a_{m,4} = [0.002, 0.001, -0.001, 0.004], a_{m,5} = [0.005, 0.003, -0.002, 0.002]. \) The order of the inverse model is still set as 3. Fig. 9 shows the spectrum before and after calibration with proposed method with third order inverse. From Fig. 9(a), it can be seen that apart from previous spurious, there are additional spurs in the output spectrum caused by fourth and fifth nonlinear mismatch errors. After calibration, the
Fig. 7 Convergence curves for the proposed method, the blue, orange, yellow, purple indicate estimation results for four coefficient sets respectively. (a) Zeroth order. (b) First order. (c) Second order. (d) Third order

Fig. 8 The spectrum of TIADC with nonlinearities up to third order. (a) Before calibration. (b) After calibration with third order 4-periodic time-varying adaptive calibration method. (c) After calibration with slight difference of desired signal SFDR improves from 36.21 dBc to 77.52 dBc as shown in Fig. 9(b). The nonlinear mismatch errors up to third order are suppressed to noise floor. According to [21], the frequency location of residue spurs are all caused by fourth and fifth nonlinear behaviors, which can be compensated with higher order inverse model. It can be concluded that even with higher order existing, the proposed calibration method is still validity to compensate for nonlinearities up to the specified order of the inverse nonlinear models.

5. Conclusion

In this paper, we propose an usage of periodic time-varying adaptive calibration method to compensate for static nonlinearities in TIADC, which is based on model inversion strategy. Simulation results show that the proposed method is effective and robust even if higher order nonlinearities exists. The method proposed in this paper is also suitable for dynamic nonlinearities calibration, which can be obtained by changing polynomial with Volterra series or other dynamic nonlinear models.

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