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Review Paper

Comparative Survey on Time Interleaved Analog to Digital Converter Mismatches Compensation Techniques

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Abstract

This survey investigates recent "time interleaved analog to digital converters (TI-ADCs)" mismatches correction techniques. It includes each technique performance evaluation on the basis of SNDR, SFDR, Frequency and Input signal. Many algorithms have been developed over the past two decades, mainly emphasizing on the digital calibration of TI-ADCs mismatches. The aim of this survey is to review a number of more promising techniques which are offering efficient mismatch corrections.

Keywords: Inherent, Compensate, Frequency Mismatch, SFDR, SINDR

Introduction

Today communication systems are going towards digital form to offer more correctness and flexibility. For this purpose communication systems need high speed and larger bandwidth which can be achieved with TI-ADCs[1-3]. TI-ADCs means "time-interleaved analog to digital converters" which utilize *M* parallel low rate ADCs to increase the sampling rate[4-5]. Figure 1 shows M channel TI-ADCs where a low rate channel of ADCs operates with an *fs/M* sampling frequency[6-7]. TI-ADCs generate output each time and each channel periodically has a sampling time *MTs* where as overall system (TI-ADCs) sampling time is *Ts.*[8]. X (t) is the input going to all ADCs and Y(nT) is the output after combining the low rate ADCS through mux[9].

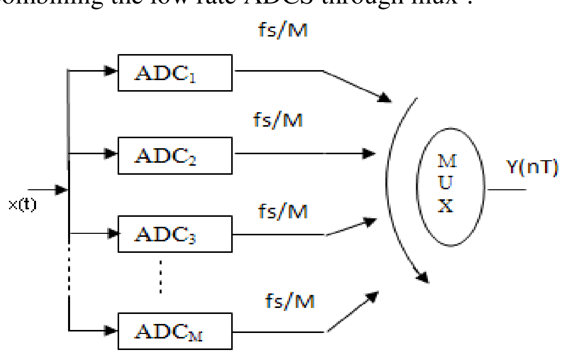

Figure-1
***M* channel time interleaved ADCs**

TI-ADCs comprise of parallel low rate channels which take analog singles at input and generate output with different parameters among the channels. These parameters are gain, offset, trimmings and bandwidth which generate mismatch errors. Mismatches occur among the channels components generating mismatch error in single channel. The mismatch error is different at different channels. Gain mismatch is difference among the slope of ideal transfer curve and transfer curve with gain errors. Similarly offset, bandwidth and timing mismatches are difference among the offset, bandwidth and timing errors respectively[10]. Also there are a number of techniques utilized for minimizing mismatch errors to achieve compensated output. The compensated output includes improved SINDR which means signal to noise-and-distortion ratio and improved SFDR which means spurious free dynamic range. In this paper different techniques are reviewed under SNDR, SFDR, frequency and input signal.

Mismatch Compensation Techniques

There are several techniques to tackle mismatch errors classified as according to figure 2. TI-ADCs primarily have two categories; static and dynamic[10]. Static mismatch includes offset and gain mismatch which means fixed mismatch. Similarly dynamic mismatch includes timing mismatch which means variable mismatch with time.

Timing mismatch techniques are poly-phase, transfer characteristic tuning, LMS, Multichannel filters, background, blind, adaptive blind, on blind etc. Gain mismatch correction techniques include adaptive blind, sigma delta and on blind. Similarly offset mismatches are sigma delta and nonwhite etc. Among the mismatches as timing, gain and offset, timing mismatches are crucial because it decreases the performance more as compared to other mismatches.

Timing Mismatch Compensation Techniques

The time-interleaved analog to digital converters performance primarily suffers through timing mismatches which are dominant at high frequencies[11]. Different techniques exist to compensate these timing mismatches. A comparative evaluation of each technique is given in Table 1 under said parameters as SNDR and SFDR. To deal with timing mismatch errors, the least mean square based mismatch compensation approach is presented in which, an input signal is oversampled and band is limited with 6×10^4 samples. In the technique the band of input signal [-0.7π, 0.7π] with least mean square LMS algorithm achieves SINDR of 59dB. The timing mismatch is identified by energy minimization in mismatch band and based on the identification, LMS compensate the output[12]. In mixed-signal scheme, the timing mismatch is identified with timing error detection subsystem. The detection subsystem is controlled by the voltage bootstrapped switch. The system takes 200MSps and after compensation the achieved SINDR is 77.4dB and SFDR is 84.4dB[13].

Another approach is demonstrated known as background calibration for timing mismatch error compensation. The approach utilizes digital interpolation to compensate samples at the output and as a result spurious free dynamic range SFDR is improved from 20dB to 60dB. For ideal system, background calibration technique gets SNR 85dB and SFDR 120dB[14]. Similarly in blind calibration technique for timing mismatch error correction, take three sinusoidal components at 0.1π, 0.45π and 0.75π. The method improves 12dB at the output and finally gets the SINDR 46.1dB[16].

Another approach for minimizing timing mismatches includes finite impulse response filter with one linear-phase cascaded with one multiplier for assisting magnitude response minimization. In the technique narrow and wide band signals have become computationally cheap operations and multiplier changes the signal sign through short tap size FIR filter. The technique is developed for wide band signal and gets the signal to noise-and-distortion ratio 63.23dB after magnitude compensation. Also the approach achieves SINDR of 56.71dB[17]. Blind calibration algorithm minimizes the timing mismatches adaptively in TI-ADCs converters whereas TI-ADCs poly-phase model requires slight oversampling to parameterize the timing mismatches[15,18]. Compensating timing and bandwidth mismatch errors, a multichannel filtering based approach is presented. In the approach each sub-channel is down sampled for analog to digital converter when filtered outputs are summed and each channel comprises of *N* coefficients for every one filter bank. Then the weighted least square method calculates the inverse for optimization and input signal is taken at different frequencies[19]. The technique known as Lagrange polynomial interpolation includes the compensation method comprised of three steps. Initially mismatch parameters are compensated, secondly finite impulse response filtering operation is performed for all ADCs and lastly multiplexer is used at the output. The presented solution is computationally efficient and non sensitive to fluctuation for timing mismatch. The approach at 70MHz input frequency produces 30dB improvement in spurious free dynamic range. Similarly multi rate filter banks compensation method enhances 19dB of SFDR. Also at 40 points for interpolation, the approach achieves 94dB at 320MHz[20]. Furthermore, another approach which utilizes digital signal processing has been used for sample time error detection and correction. The approach utilizes finite impulse response filters with 29-taps at input frequency *0.1fs* and achieves SINDR signal to noise-and-distortion ratio more than 60dB[21]. Similarly the approach known as back ground using random data includes 800 MS/s for the input at 350MHz frequency and enhances the spurious free dynamic range to 58.1 dB and SNDR 50.1 dB. Also at 5 MHz frequency, the achieved SNDR is 59.6 dB[22].

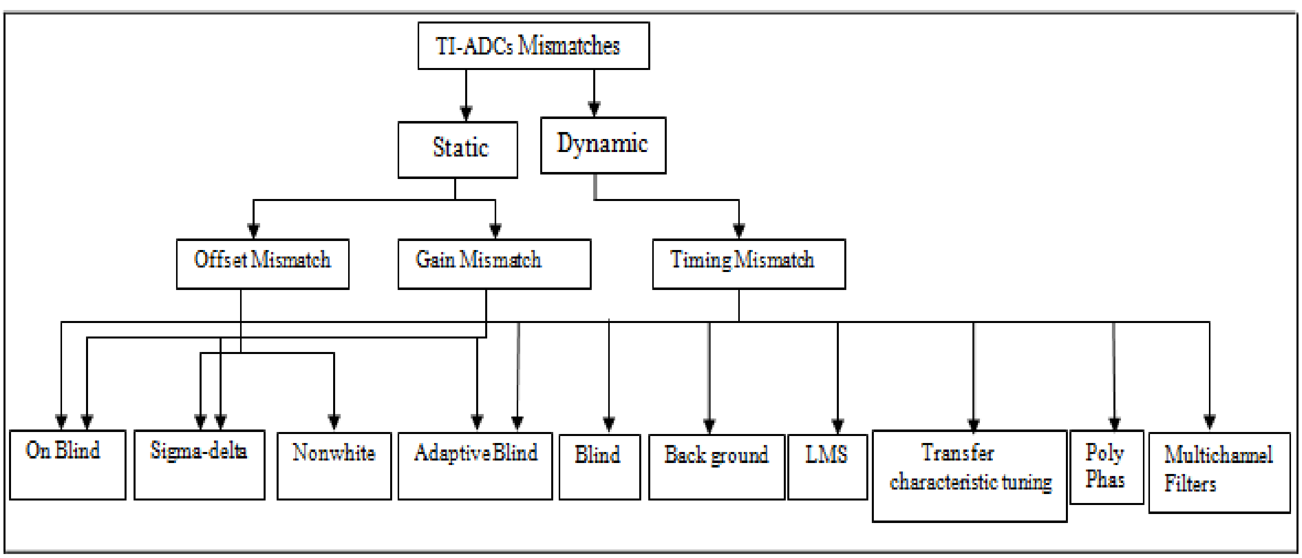

Figure-2
Classification of different methodologies to compensate TI-ADCs mismatches

Moreover to compensate timing mismatch errors reordering the number of channels based approach is presented. In the technique the sorting algorithm achieves 61dB SFDR at 8-channels, 31dB SFDR at 128-channels and 10dB SINDR in ENOB at 128-channels[23]. In low resolution and time varying filter approach, the adaptive structure minimizes the mismatches through time varying finite impulse response filters and an extra low-resolution analog to digital converter. Compensating linear frequency response mismatch errors, a structural based approach is presented. In the approach, the weights of least-mean square (LMS) algorithms are adopted by the time varying filter, input signal at $0.8\Omega_s/2$ with random amplitude and phase[22]. The approach achieves SNR of 57.2dB[3]. Similarly utilizing the frequency domain, a timing mismatch compensation method is used in the oversampled input signals to identify timing mismatch and it depends on the relation of frequency signals between the continuous input and after sampled output. The approach achieves white noise band limited input signal $\Omega_b = 7/10\Omega_s$ with 16384 samples and larger signal to noise-and-distortion ratio with 11 effective number of bits[24].

Offset Mismatch Compensation Techniques

In table 2 different offset mismatch compensation techniques are comparatively analyzed according to SINDR, SFDR, frequency and input signal. In data chopping, the inherent offset mismatches are compensated through nonwhite data chopping approach. The nonwhite sequences generally allow faster compensation of offset and better spectral shaping. Average offset compensation has been developed in many ADCs realizations but the best estimation is achieved when the transformed signal is assumed to be a Gaussian process. The technique achieves SNR of 29.82 db with white chopping and 33.85 with low pass chopping[25].

Random chopper sampling offset compensation method is based on PRBS which takes the input and converts it to noise. The batch size is controlled by the randomization process which is used for offset compensation. The approach achieves SFDR of 72dB and SINDR of 59dB[26]. Similarly in background calibration approach, to overcome gain and offset mismatches in time-interleaved ADCs, 2nd order structure is used. Simulation result shows that the approach achieves 12dB better as compared to conventional modulator at the same frequency[27]. In the technique the offset and gain mismatches are compensated through analog and monolithic background calibration by extra channel and mixed signal integrators. Also with the approach the calibrated signal has peak SINDR of 58dB [28].

Channel and Gain mismatches compensation techniques

To compensate channel and gain mismatches, there are a number of techniques and are comparatively elaborated in table 3. Compensating gain and timing mismatch errors collectively an approach is presented which utilizes digital blind identification structure to estimate gain and timing mismatches adaptively. In the approach “filtered error least mean square (FxLMS)” algorithm is applied which uses a single high-pass filter. The approach achieves elimination of spurious images from the output spectrum of TI-ADC and enhances the “signal to noise ratio (SNR)” to 69.3 dB with 2^{22} samples[29]. Similarly in another approach called input band limited “white Gaussian noise (WGN)” signal, identified gain and timing mismatches in a TI-ADC 4-channel shows significant improvement in the SNR. Assuming a “wide-sense stationary (WSS)” input, yielding a WSS output and online calibration can be used without disturbance or any committed signal. In the approach wide and sine input signals reduced the mismatches by 20 dB and 50 dB respectively at 100000 samples[30]. Moreover, expectation maximize algorithm compensates the gain and time offsets[31].

Table-1
Timing mismatches compensation techniques comparison

Methodology	SINDR[dB]	SFDR[dB]	Frequency	Input signal
LMS	59	00	[-0.7π, 0.7π]	6×10^4 Samples
Mixed signal	77.4	84.4	00	200MSps
Background	SNR=85dB	Improved 20 to 60	00	00
Blind	46.1	00	0.1π, 0.45π and 0.75π	00
Finite impulse response filter	63.23	00	00	00
Poly phase	00	improved 20	[-0.875π, 0.875π]	00
Lagrange Polynomial Interpolation	00	94	320	00
Random Data	more than 60	00	*0.1fs*	00
Back Ground using Random Data	50.1	58.1	350MHz	800 MS/s
Spectral Shaping	10 in ENOB	61	00	00
Low resolution and Time varying filter	SNR=57.2	00	$0.8\Omega_s/2$	2^{22} samples

Table-2
Offset mismatches compensation techniques comparison

Methodology	SINDR [dB]	SFDR [dB]	Frequency	Input signal
Data Chopping	SNR=29.82	00	00	1000 cycle
Random Chopper Sampling	59	72	00	00
Background calibration	58	00	00	00

Table-3
Channel mismatches compensation techniques comparison

Methodology	SINDR [dB]	SFDR [dB]	Frequency MHz	Input signal
Orthogonal digital calibration	SNR = 49.04	53.94	00	00
Comprehensive digital cal	80	<50	Up to 175	00
Randomization Strategy	00	59.8 to 72	00	00
Mixed-signal	71.7	85.8	00	500 sample
Adaptive Blind	SNR=66	00	00	131072 sample
Digital Filter Bank	71.8963	92.0058	75.3	100 MS/s

An approach known as orthogonal digital calibration compensates timing, offset and gain mismatches. It is based on code division multiple access (CDMA) technique. In the technique the calibration can occur at run time (online) and the FFT spectrum of calibrated output shows signal to noise ratio of 49.04dB and spurious free dynamic range of 53.94dB[32]. In comprehensive digital calibration**,** the approach utilizes transfer function of channel which includes all linear errors between analog input signal x(t), digital output signal y(n) and series of sinusoidal signals used for measuring each channel linear errors. A parallel finite-impulse response (FIR) filter also provides frequency-dependent mismatch correction weighted by least squares principle. The technique achieves spurious free dynamic range of 80dB at the input frequency of 175MHz[33]. An approach considered as randomization strategy and the compensation technique investigated the channel non-linearity (DNL) mismatches and calibrated the upper frequency band due to baseband frequency disturbance. The approach achieves SFDR 59.8dB to 72dB[34]. Similarly the mixed-signal clock-skew calibration method is developed to compensate the linearity of time interleaved analog to digital converters. The approach achieves compensated output signal with spurious free dynamic range of 73dB[35] at the 19.9MHz input frequency. Another approach achieves SFDR of 85.8dB and SINDR of 71.7dB over the 500 samples while using hybrid filter bank[36]. Similarly phase skew compensation analysis is used in the wideband input signals to compensate multiple mismatches[37]. A technique which utilizes least mean square algorithm overcomes the offset mismatch, gain mismatch, sample-time mismatch and bandwidth mismatches among TI-ADCs simultaneously. The presented compensation method is used for the baseband and at high speed receiver. All mismatches are compensated by the blocks of digital signal processing. The approach achieves with MSE, -37.2dB Gain, -36.8dB offset, -36.6dB sample time and -36.7dB bandwidth[38]. Similarly in adaptive blind technique, least mean square algorithm has been used blindly to compensate the timing and gain mismatches. The presented compensation technique is based on arbitrary number of channels and oversampled input signal[39]. The technique achieves signal to noise ratio of 66dB[40] for 131072 samples at the input. In digital filter bank approach, the weighted least square coefficients are used for the compensation of time and gain mismatches errors carried by the poly-phase structure. Each channel operates at 100 MS/s with filter bank order of 40. The approach achieves calibrated output at input frequency of 75.3MHz with 71.8963dB SINDR and 92.0058 SFDR[41].

Conclusion

In this paper a review of the techniques assisting different mismatches compensations in TI-ADCs is presented. The techniques are evaluated on the basis of how much signal to noise ratio SNDR and SFDR are achieved. Form the literature it can be seen that there are a lot of promising techniques for compensating timing, gain, offset and channel mismatches of TI-ADCs. Some techniques are compensating single mismatch while some are compensating multiple mismatches. In the paper the techniques are comparatively analyzed under said parameters as SNDR and SFDR. Although a number of promising TI-ADCs mismatches compensation techniques exist but still there is a need of better compensation techniques for TI-ADCs which could give maximum compensated output and to tackle any single mismatch or multiple mismatches of TI-ADCs.

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