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MATLAB-Based Modeling and Spectral Analysis of Inter-Channel Mismatch Errors in Time-Interleaved ADCs

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Abstract

Time-interleaved analog-to-digital converters (TIADCs) increase the overall sampling rate by operating multiple sub-ADCs with uniformly shifted sampling phases. However, channel-to-channel differences caused by device variations, analog front-end mismatch, and sampling-clock errors introduce deterministic interleaving spurs that degrade the output spectrum. This paper develops a MATLAB-based numerical model for the three dominant mismatch mechanisms: gain mismatch, offset mismatch, and timing-skew mismatch. A four-channel, 14-bit, 1-GS/s TIADC with 8192 samples is considered. The ideal interleaved sampling sequence is first formulated, after which the three mismatch terms are incorporated into a unified channel-dependent output model. FFT-based analysis is then used to identify the spectral characteristics of each mismatch type. Gain mismatch produces input-frequency-dependent image spurs, offset mismatch generates fixed components associated with the interleaving frequency, and timing skew produces input-dependent images whose amplitudes increase with the input-signal slope. The resulting model provides a controllable simulation platform for analyzing TIADC nonidealities and for supporting subsequent mismatch-estimation and digital-calibration studies.

Keywords

Time-interleaved analog-to-digital converter; inter-channel mismatch; MATLAB modeling; gain mismatch; offset mismatch; timing skew; spectral analysis.

1. Introduction

High-speed analog-to-digital conversion is a fundamental requirement in broadband communication, radar, electronic measurement, navigation, and high-speed data-acquisition systems. As signal bandwidth increases, the sampling rate of the analog-to-digital converter (ADC) must increase while adequate conversion resolution and dynamic performance are maintained. For a conventional single-channel ADC, however, a higher sampling rate reduces the time available for sampling, settling, and quantization, leading to a more severe tradeoff among speed, resolution, power consumption, and circuit complexity.

Time interleaving provides an effective means of overcoming the sampling-rate limitation of a single converter. The basic interleaved converter-array concept was demonstrated by Black and Hodges [1], and later analyses clarified the architectural and mismatch-related design constraints of high-speed interleaved ADCs [2]. In an M-channel TIADC, the same analog input is applied to multiple sub-ADCs. The channels operate with uniformly shifted sampling phases, and their digital outputs are recombined according to the sampling order. Therefore, the overall sampling rate can be increased approximately in proportion to the number of interleaved channels while each sub-ADC operates at a lower individual rate.

The benefit of time interleaving depends strongly on the matching accuracy among the sub-ADCs. Practical circuits exhibit channel-dependent gain, DC offset, and sampling-time deviations caused by fabrication spread, analog front-end differences, layout parasitics, and

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clock-distribution errors. Because the TIADC output is assembled periodically from different channels, these errors also enter the reconstructed sequence periodically and produce deterministic interleaving spurs. Background-calibration studies have shown that offset, gain, and timing mismatch are among the principal error mechanisms that must be characterized and compensated in high-performance TIADCs [3-6].

MATLAB provides a convenient environment for independently controlling these mismatch parameters while maintaining identical input and sampling conditions. In this work, a MATLAB-based four-channel TIADC model is established. The ideal and nonideal sampling sequences are generated under the same input conditions, the three mismatch mechanisms are described by a unified channel-dependent model, and their spectral effects are evaluated using the fast Fourier transform (FFT). The developed model is intended as a numerical basis for subsequent mismatch-estimation and digital-calibration research.

2. TIADC Architecture and Inter-Channel Mismatch Modeling

2.1. Ideal TIADC Sampling Model

Consider an M-channel TIADC with an overall sampling frequency fs. If the sampling frequency of each sub-ADC is denoted by fch, the relationship between the overall sampling rate and the channel sampling rate is

$$f_s = M f_{\mathrm{ch}} \tag{1}$$

The overall sampling period is

$$T_s = \frac{1}{f_s} \tag{2}$$

where each individual sub-ADC operates with a sampling period of MTs. The analog input x(t) is connected to all sub-ADCs, while the channel clocks have identical frequencies but uniformly shifted phases. For the i-th channel, the ideal sampled output is

$$y_i[n] = x[(nM + i)T_s] \tag{3}$$

After the channel outputs are digitally multiplexed according to their sampling instants, the reconstructed TIADC sequence satisfies

$$y[nM + i] = y_i[n] \tag{4}$$

Thus, adjacent samples in the reconstructed output are separated by Ts, even though a single channel generates one sample every MTs. The architecture and sampling sequence are illustrated in Fig. 1.

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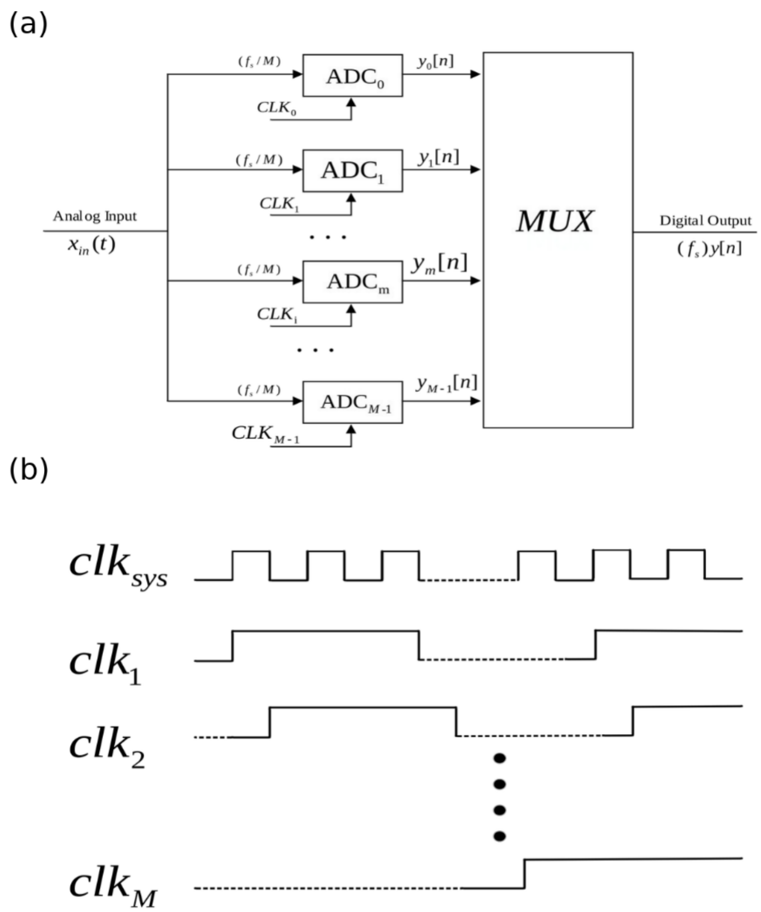

Figure 1. Architecture and interleaved sampling sequence of an M-channel TIADC.

For the four-channel model considered in this paper, M = 4. With an overall sampling rate of 1 GS/s, the sampling rate of each individual sub-ADC is 250 MS/s. Under ideal interleaving conditions, the four channel sequences therefore form a uniformly sampled 1-GS/s output stream.

2.2. Unified Inter-Channel Mismatch Model

In an ideal TIADC, all sub-ADCs have identical gains, offsets, frequency responses, and sampling instants. In practice, the channel responses are not perfectly matched. Let gi, oi, and Δti denote the gain mismatch, offset mismatch, and timing skew of channel i, respectively. The actual channel output can be modeled as

$$y_i[n] = (1 + g_i)x[(nM + i)T_s + \Delta t_i] + o_i \tag{5}$$

Equation (5) provides a unified representation of the three dominant mismatch mechanisms. The factor gi changes the amplitude scaling, oi shifts the output reference level, and Δti changes the actual sampling position. Since these quantities depend on the channel index, the corresponding errors repeat periodically after interleaving. Fig. 2 shows the physical relationship among the three channel-dependent nonidealities.

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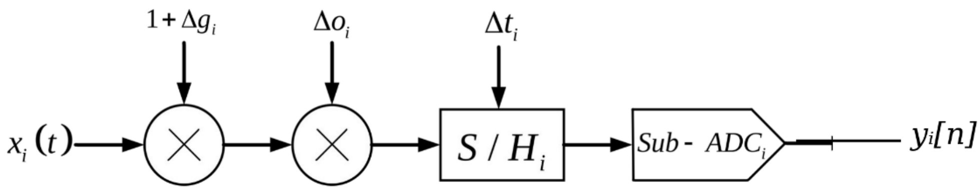

Figure 2. Unified inter-channel mismatch model of a sub-ADC channel.

Gain mismatch. When only gain mismatch is considered, the offset and timing terms are set to zero, giving

$$y_i^{(g)}[n] = (1 + g_i)x[(nM + i)T_s] \tag{6}$$

Gain mismatch is therefore a multiplicative channel error. Because the gain coefficients repeat every M output samples, the input is effectively multiplied by a periodic gain sequence. For a single-tone input with frequency fin, the principal gain-mismatch images can be expressed as

$$f_{g,k} = \left|\frac{kf_s}{M} \pm f_{\mathrm{in}}\right| \tag{7}$$

where k denotes the interleaving order and components outside the first Nyquist zone are folded into the observable band. Consequently, gain-mismatch spur locations move when the input frequency changes.

Offset mismatch. When only offset mismatch is considered, the output becomes

$$y_i^{(o)}[n] = x[(nM + i)T_s] + o_i \tag{8}$$

The offset sequence is additive and repeats with the interleaving period. Its principal spurious components occur at

$$f_{o,k} = \frac{kf_s}{M} \tag{9}$$

Unlike gain mismatch, these frequencies are determined by the system sampling rate and the number of interleaved channels rather than by the input frequency. For a four-channel TIADC operating at 1 GS/s, the fundamental interleaving frequency is 250 MHz.

Timing-skew mismatch. Timing skew changes the actual sampling position. With gain and offset mismatch disabled, the channel output is

$$y_i^{(t)}[n] = x[(nM + i)T_s + \Delta t_i] \tag{10}$$

For sufficiently small timing deviations, the input waveform can be approximated around the ideal sampling instant using the first-order expansion

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$$x(t+\Delta t_i) \approx x(t) + \Delta t_i \frac{\mathrm{d}x(t)}{\mathrm{d}t} \tag{11}$$

The corresponding first-order timing-induced error is

$$e_{t,i}(t) \approx \Delta t_i \frac{\mathrm{d}x(t)}{\mathrm{d}t} \tag{12}$$

Equation (12) shows that timing error depends not only on the channel timing deviation but also on the local slope of the input waveform. For a sinusoidal input

$$x(t) = A\sin(2\pi f_{\mathrm{in}} t + \varphi) \tag{13}$$

the derivative magnitude increases with input frequency. Therefore, a fixed timing deviation generally produces a larger amplitude error at higher input frequencies. The principal timing-skew image locations have the form

$$f_{t,k} = \left| \frac{k f_s}{M} \pm f_{\mathrm{in}} \right| \tag{14}$$

which are similar to the gain-mismatch image locations. The physical mechanisms are nevertheless different: gain mismatch changes channel amplitude response, whereas timing mismatch changes the sampling instant.

3. MATLAB-Based Modeling and Simulation Analysis

3.1. Simulation Configuration

A four-channel TIADC numerical model is constructed in MATLAB according to the preceding sampling and mismatch equations. The simulation parameters are selected to remain consistent with the thesis model used for subsequent algorithm verification. The main parameters are summarized in Table 1.

Table 1. Main parameters of the MATLAB-based TIADC model

Parameter	Value
Number of channels, M	4
ADC resolution	14 bit
Overall sampling frequency, fs	1 GS/s
Sampling frequency per channel	250 MS/s
Number of output samples, N	8192
Nyquist frequency	500 MHz
Input signal	Single-tone sinusoid
Representative input frequency	78.125 MHz

The representative 78.125-MHz input corresponds to coherent sampling for an 8192-point sequence at 1 GS/s. Therefore, the FFT can be evaluated without an additional window when

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the signal is generated exactly on the corresponding FFT bin. The global output-sample index is mapped to its source channel through

$$i = \mathrm{mod}(n, M) \tag{15}$$

The MATLAB model first generates the ideal sampling sequence. It then assigns each sample to one of the four channels, applies the channel-dependent gain, offset, and timing deviations, performs 14-bit quantization, recombines the four channel sequences, and finally evaluates the output spectrum. By setting selected mismatch vectors to zero, the same program can generate the ideal output, a gain-only case, an offset-only case, a timing-only case, or a combined-mismatch case.

3.2. Spectral Analysis of Individual Mismatches

To distinguish the spectral signature of each error source, the three mismatch mechanisms are first activated separately. The complete 8192-point output sequence is used for FFT analysis, and the single-sided spectrum is displayed from 0 to 500 MHz. The spectral magnitude is normalized to the fundamental component and expressed in dBc.

For gain mismatch, the periodic amplitude modulation produces images around combinations of the 250-MHz interleaving frequency and the input tone. With fin = 78.125 MHz, important image locations include 171.875 MHz and 328.125 MHz. The simulated spectrum in Fig. 3 clearly exhibits these input-dependent gain-mismatch spurs.

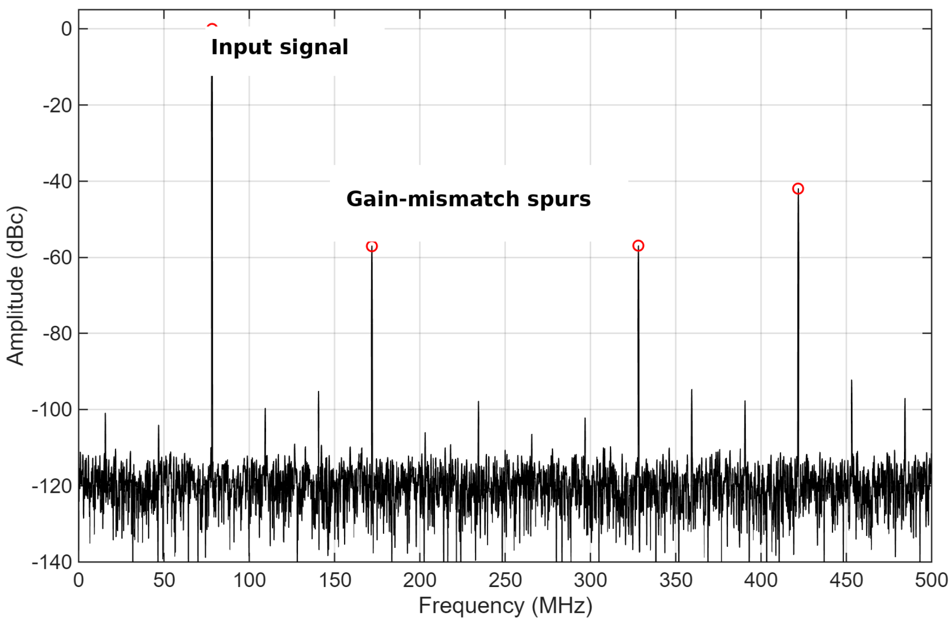

Figure 3. Output spectrum of the TIADC with gain mismatch.

For offset mismatch, the periodic additive offset sequence produces fixed interleaving-related spectral components. In the four-channel model, a dominant offset-related component appears at 250 MHz. Unlike gain-mismatch images, this frequency does not move when the input frequency is changed, as shown in Fig. 4.

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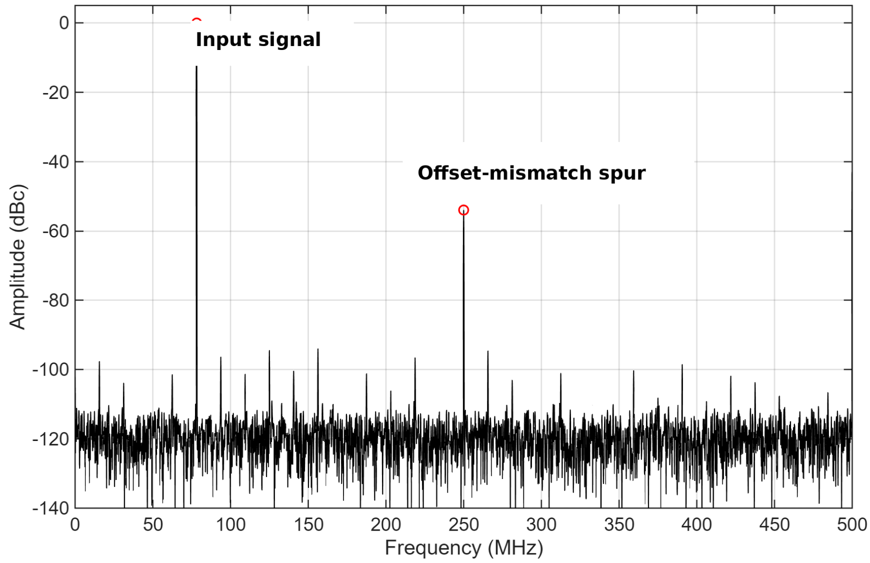

Figure 4. Output spectrum of the TIADC with offset mismatch.

Timing-skew mismatch also produces images related to the interleaving and input frequencies. However, its magnitude is strongly related to the local signal derivative, so the same timing deviation causes greater distortion for a higher-frequency input. Fig. 5 shows the timing-skew spectrum for the representative simulation case.

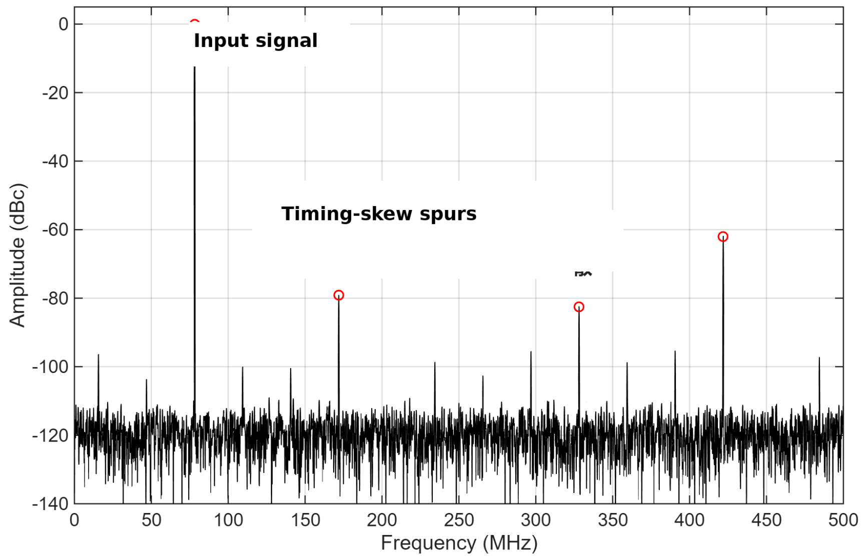

Figure 5. Output spectrum of the TIADC with timing-skew mismatch.

Table 2. Spectral characteristics of major TIADC inter-channel mismatches

Mismatch type	Error characteristic	Main spectral behavior	Input-frequency dependence
Gain mismatch	Multiplicative amplitude error	Image/interleaving spurs	Yes
Offset mismatch	Additive DC error	Fixed interleaving spurs	No
Timing skew	Sampling-position error	Image/interleaving spurs	Strong
Combined mismatch	Mixed error	Fixed and moving spurs coexist	Mixed

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3.3. Combined Mismatch Analysis

In practical TIADC systems, gain mismatch, offset mismatch, and timing skew generally coexist. The MATLAB model therefore allows the three channel-dependent parameter vectors to be enabled simultaneously. In this condition, offset-related fixed components and gain- or timing-related input-dependent image components are superimposed in the output spectrum.

For the representative 78.125-MHz input, components related to 171.875 MHz, 250 MHz, and 328.125 MHz can be interpreted directly from the interleaving relationships. Higher-order products may also fold into the first Nyquist zone. Importantly, gain and timing mismatch can generate components at the same theoretical locations. A single spur position is therefore not always sufficient to identify the underlying mismatch mechanism. Their different dependence on the input waveform and input frequency provides additional diagnostic information.

The controlled-variable structure of the MATLAB model is useful for this reason: one error source can be activated at a time to verify the theoretical mechanism, after which the complete mismatch model can be used to represent a more realistic TIADC. The same framework can also incorporate quantization and thermal noise when a more complete nonideal dataset is required.

4. Conclusion

A MATLAB-based model for analyzing inter-channel mismatch errors in a time-interleaved ADC has been developed. The model considers a four-channel, 14-bit TIADC operating at an overall sampling rate of 1 GS/s and generates an 8192-point output sequence for FFT-based evaluation. The ideal interleaving process is first formulated, and gain mismatch, offset mismatch, and timing skew are then incorporated into a unified channel-dependent sampling equation.

The theoretical and numerical analyses show that the three mismatch mechanisms exhibit distinct spectral characteristics. Gain mismatch behaves as a multiplicative amplitude error and generates input-frequency-dependent image components. Offset mismatch behaves as a periodically repeated additive error and produces fixed spurs associated with the interleaving frequency. Timing skew modifies the actual sampling positions and produces input-dependent images whose amplitudes become more pronounced as the signal variation rate increases.

The developed MATLAB model provides a controllable numerical platform for investigating TIADC nonidealities. By independently configuring the channel-dependent mismatch parameters, it can support subsequent mismatch identification, digital calibration, and algorithm-verification studies.

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