Digital Third-Order Nonlinearity Correction for Time-Interleaved A/D Converters with VCOs

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Outline

Background and Objectives

- Time-interleaved A/D Converters (TI-ADCs) with Voltage-Controlled Oscillators (VCOs)

Third-order Nonlinearity Correction

- HD_3 and IM_3 Products in Bandpass ADC
- Digital Correction Method and Architecture

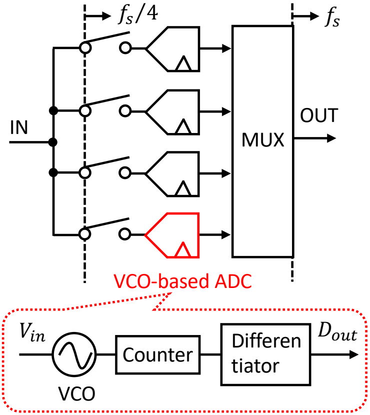
Simulation

- MATLAB/Simulink Model
- Output Spectra and Constellation
- Comparison

Summary

TI-ADC with VCOs:

- Consists of multiple (M) VCO-based ADCs
- Reduces quantization noise around f_s/M (bandpass)
- Achieves 4 GS/s and 10 bit with 20 mW (VLSI '08 [5])
- Realizes direct-RF sampling receivers
- Has nonlinearity of K_{VCO}, third-order nonlinearity, causing HD_3 and IM_3 products



f_s : Sampling frequency, MUX: Multiplexer

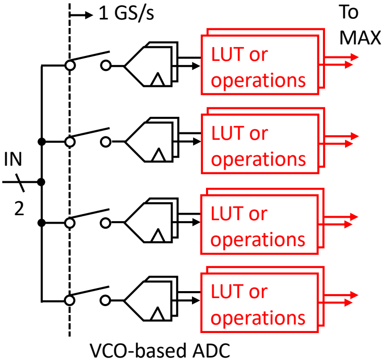
VCO: Voltage-controlled oscillator, K_{VCO}: VCO gain, HD_3: Third-order harmonic distortion, IM_3: Third-order intermodulation

Digital Correction Methods for VCO-based ADCs

Conventional methods increase complexity and power consumption of TI-ADCs.

Linearizing K_{VCO} with lookup tables (LUTs):

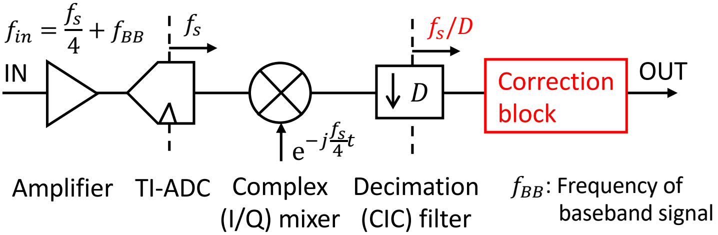
- Needs to know K_{VCO} with external ramp signal [6], replica ADCs/VCOs [7,8], or dither [9]
- Uses eight 1 GS/s LUTs for 4 GS/s four-channel TI-ADC (differential)



Canceling harmonics with auxiliary ADC [10]:

- Requires 1 GS/s logical operations (multipliers and adders) in eight paths for TI-ADC.

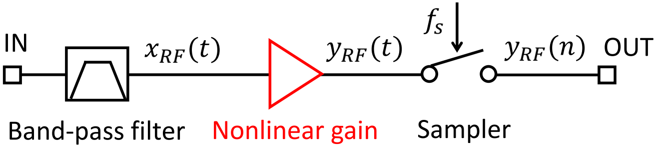
Objectives



Digital correction method for third-order nonlinearity of TI-ADCs in direct-RF sampling receivers:

- Deals with input signals at $f_s/4$, whose HD_3 appears around $f_s/4$
- Detects HD_3 tone for continuous wave (CW) signal to estimate third-order nonlinearity of TI-ADC
- Cancels HD_3 and IM_3 products for modulated signals
- Needs no LUTs, auxiliary ADCs/VCOs, and GS/s operations

Model of Nonlinear Bandpass ADC



Nonlinear gain:

- Represents nonlinearity of ADC
- Deals with $x_{RF}(t) = 2\,\mathrm{Re}[x(t)e^{j\omega_c t}] = x(t)e^{j\omega_c t} + x^*(t)e^{-j\omega_c t}$
  - $x(t)$: Equivalent baseband signal, ω_c: Carrier frequency
- Outputs $y_{RF}(t) = a_1 x_{RF}(t) + a_2 x_{RF}^2(t) + a_3 x_{RF}^3(t)$
  - a_i: ith-order nonlinearity coefficient
  - HD_3 components: $a_3\left\{x^3(t)e^{j3\omega_c t} + [x^*(t)]^3\, e^{-j3\omega_c t}\right\}$
  - IM_3 products: $a_3\left\{3x^2(t)x^*(t)e^{j\omega_c t} + 3x(t)\,[x^*(t)]^2\, e^{-j\omega_c t}\right\}$

If we estimate a_3 exactly, we can generate the same HD_3 and IM_3.

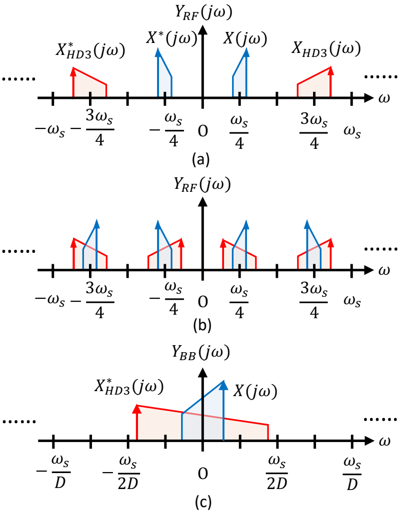
Spectra of Desired and HD$_3$ Components

Spectra of modulated signal at output of:

(a) Nonlinear gain block
- $X(j\omega)$: Fourier transform (FT) of $x(t)$
- $X_{HD3}(j\omega)$: FT of $x^3(t)$

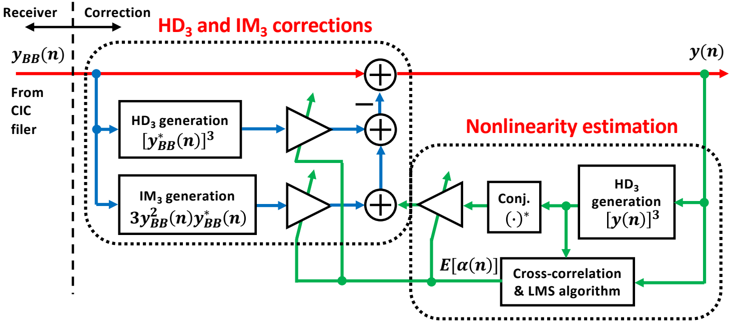
(b) Sampler
- (a) sampled at ω_s ($= 2\pi f_s$)

(c) Receiver
- (b) at $\omega_s/4$ downconverted and decimated
- $X(j\omega)$ and $X^*_{HD3}(j\omega)$ overlap, but not for CW signal



We detect HD$_3$ component for CW signal to estimate a_3.

Proposed Correction Architecture



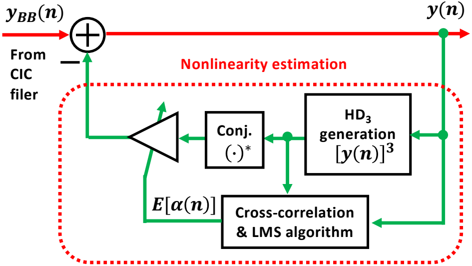
Proposed correction architecture:

- Consists of HD_3/IM_3 corrections and nonlinearity estimation
- Estimates a_3 by using CCF and LMS algorithm for CW signal around $f_s/4$, generated by transmitter (calibration mode)
- Generates HD_3 and IM_3 products for modulated signals and subtracts them from $y_{BB}(n)$ (operation mode).

CCF: Cross-correlation function, LMS: Least mean square

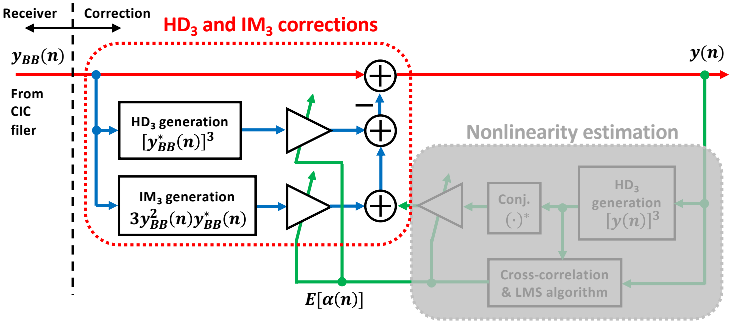
Nonlinearity estimation block:

- Removes HD$_3$, $[x^*(t)]^3$ $(=[x^3(t)]^*)$, from $y_{BB}(n)$ by calculating
  $y(n) = y_{BB}(n)$
  $-\alpha(n-1)\,[y^*(n-1)]^3$



- Detects HD$_3$ with CCF between $y(n)$ and $[y^*(n)]^3$,
  $r_{y(y^*)^3}(\tau) \stackrel{\text{def}}{=} E[y(n)\left([y^*(n-\tau)]^3\right)^*] = E[y(n)y^3(n-\tau)]$
  - If $y(n)$ has no HD$_3$ component, $r_{y(y^*)^3}(\tau) = 0$.
    $E[\cdot]$: Expected value, τ: Time lag
- Obtains $E\,[\alpha(n)]$ with LMS algorithm:
  $\alpha(n+1) = \alpha(n) + \mu \cdot y(n)y^3(n)$, μ: Adaptive step size

Removal of HD_3 and IM_3 Products (Operation Mode)



HD_3 and IM_3 correction blocks:

- Generate HD_3 ($[y^*_{BB}(t)]^3$) and IM_3 ($3y^2_{BB}(n)y^*_{BB}(n)$) products, multiplied by $E[\alpha]$ obtained in calibration mode
- Subtract them from $y_{BB}(n)$ to have
  $$y(n) = y_{BB}(n) - E[\alpha]\left\{\left[y^*_{BB}(n)\right]^3 + 3y^2_{BB}(n)y^*_{BB}(n)\right\}$$

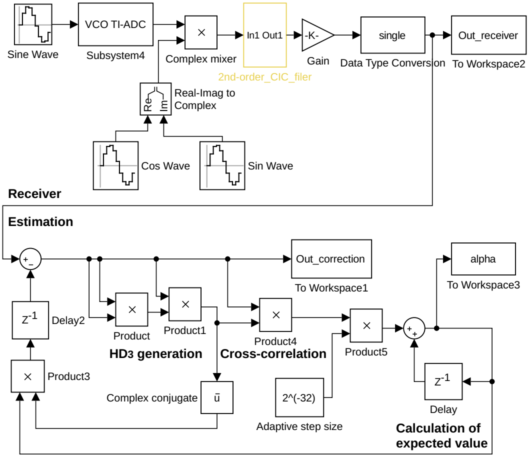
MATLAB/Simulink Model (Calibration Mode)

Receiver consists of:

- Four-channel TI-ADC with VCOs
- Complex mixer
- CIC filter

Estimation block consists of:

- HD_3 generation
- Cross-correlation
- Calculation of $E[\cdot]$



- HD_3 and IM_3 correction blocks designed (not shown)
- Calibration and operation modes simulated on MATLAB

Simulation Conditions

Block	Parameter	Variable	Value
	Number of data	N	2^{24}
	Sampling frequency	f_s	1
TI-ADC with VCOs	Number of channel	M	4
	Gain	a_1	2.57×10^{-2}
	2nd-order nonlinearity	a_2	6.60×10^{-3}
	3rd-order nonlinearity	a_3	7.04×10^{-4}
Decimation filter	Number of decimation	D	16
Correction	Adaptive step size	μ	2^{-32}
Input signal (CW)	Frequency	f_{in}	$1/4 + 1/2^{13}$
	Amplitude	A_{in}	0.69
Input signal (modulated)	Date rate	-	$1/2000$
	Modulation	-	16 QAM

- Nonlinearity coefficients, a_i $(i = 1, 2, 3)$, obtained by dividing K_{VCO} of ring VCO (APMC '17 [14]) with 4 GHz.

Simulated Output Spectra of Receiver (Cal. Mode)

- CW signal input

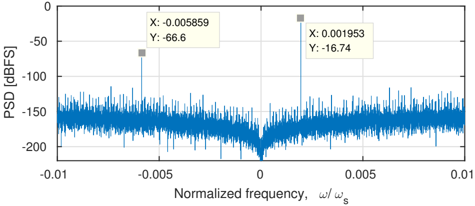
(a) FFT spectrum without estimation block

- Desired signal: -16.7 dBFS
- HD_3 tone: -66.6 dBFS

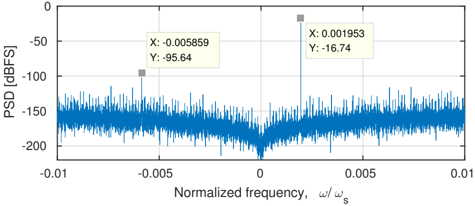
(b) FFT spectrum with estimation block

- HD_3 tone: -95.6 dBFS
- $\alpha = 1.17 \times 10^{-4} - 3.67 \times 10^{-5} j$

FFT: Fast Fourier transform



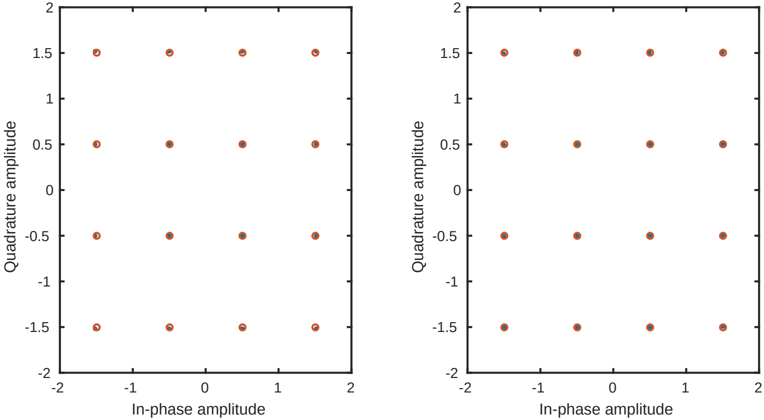
(a)



(b)

Estimation block operated successfully.

Simulated Constellation (Operation Mode)



- Left: w/o correction, Right: w/i correction for 16-QAM signal
- Outer blue symbols moved closer to ideal (red) symbols.

Correction improved EVM from 1.13% to 0.37%.

Comparison to Conv. Methods for VCO-based ADCs

	This work	TCAS-I '10	JSSC '13	JSSC '14	TCAS-I '15	JSSC '14
External signal	CW	Ramp	No	No	No	No
Nonlinearity estimation	Offline	Offline	Back-ground	B.G.	B.G.	B.G.
Operating freq.	f_s/D	f_s	f_s	f_s	f_s	f_s
LUT	No	Yes	Yes	Yes	Yes	No
Auxiliary ADC/VCO	No	No	Yes	Yes	No	Yes
Analog dither	No	No	No	No	Yes	No
TI-ADC	Yes	No	No	No	No	No

Proposed correction method:

- Uses CW signal, generated with transmitter in RF transceiver
- Executed in start-up calibration of RF transceiver
- Operates at lower clock rates (f_s/D)
- Requires no LUTs, auxiliary (replica) ADCs/VCOs, and dither

Summary

Digital correction method for third-order nonlinearity of TI-ADCs with VCOs in direct-RF sampling receivers:

- (Calibration mode for CW signal) Estimates nonlinearity with CCF and LMS algorithm of HD_3 tone.
- (Operation mode for modulated signals) Generates HD_3 and IM_3 products and subtracts them from receiver output
- Operates at lower clock rates (f_s/D)
- Requires no LUTs, auxiliary (replica) ADCs/VCOs, and dither
- Reduced HD_3 tone by 29 dB and improved EVM of 16-QAM signal by 0.7% on simulation

Proposed method can be applied to TI-ADCs with little additional area and power consumption.

Acknowledgments

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Appendix: Simulated Spectra of Two Tones (Op. Mode)

- Two-tone signal input

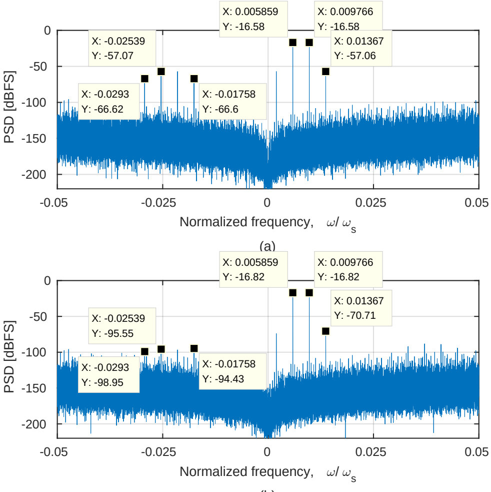
(a) FFT spectrum w/o HD_3/IM_3 correction blocks

- Desired signals: -16.6 dBFS
- IM_3 tone: -57.0 dBFS

(b) FFT spectrum w/i HD_3/IM_3 correction blocks

- IM_3 tone: -70.7 dBFS

FFT: Fast Fourier transform



(b)

HD_3 and IM_3 correction blocks operated successfully.