IEEE Asian Test Symposium, Yilan, Taiwan (Nov. 2013)

Digital Compensation for Timing Mismatches in Interleaved ADCs

R. Yi, Minghui Wu, K. Asami, H. Kobayashi
R. Khatami, A. Katayama, K. Katoh

Gunma University
Advantest Corporation
Tsuruoka National College of Tech.

Contents

- Research Background and Objective
- Time Interleaved ADC System
- Proposed Calibration System
- Simulation Results
- Extension to 4ch Interleaved ADCs
- Conclusion

Contents

Research Background & Objective

ATE System

Background

High-speed sampling time-interleaved ADC for ATE system

Timing skew ➡ Big issue

Error compensation of timing skew effects

Conventional

Analog method + Digital method

Objective

Proposal

Full digital method

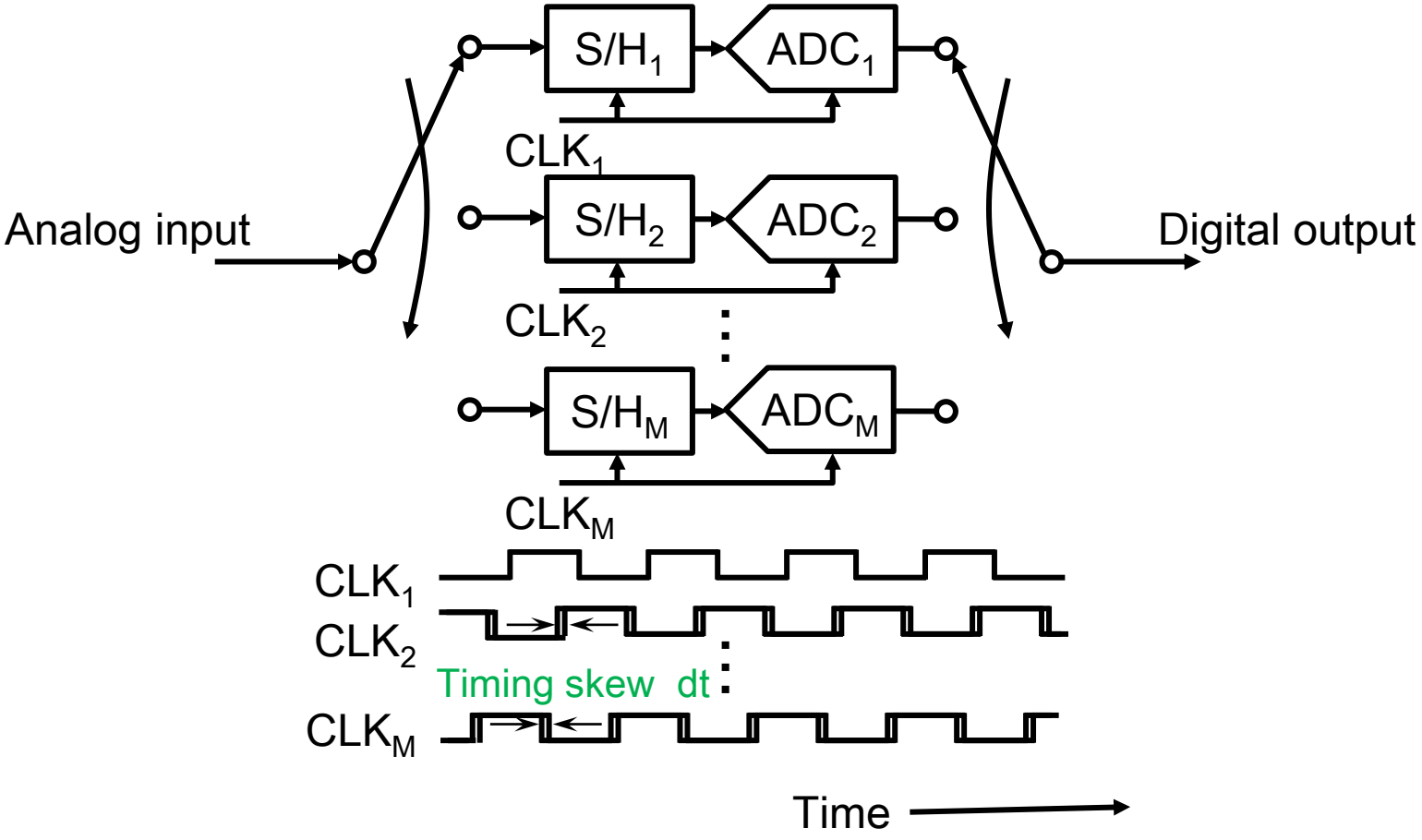
High accuracy, Stable, Reliable

Contents

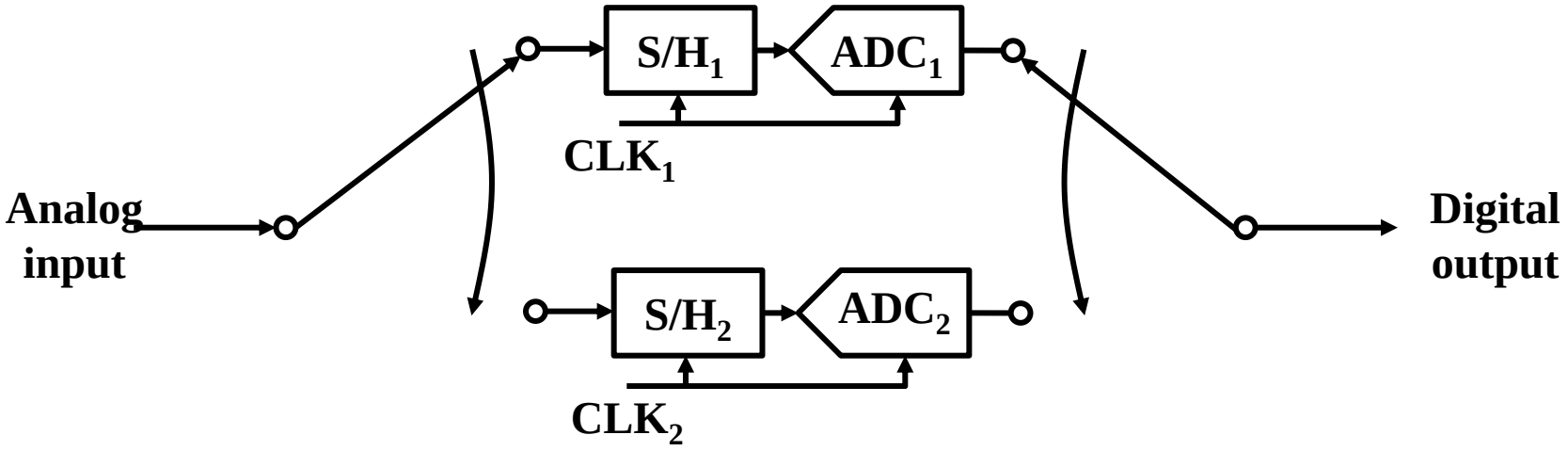
Principle of Time-Interleaved ADC

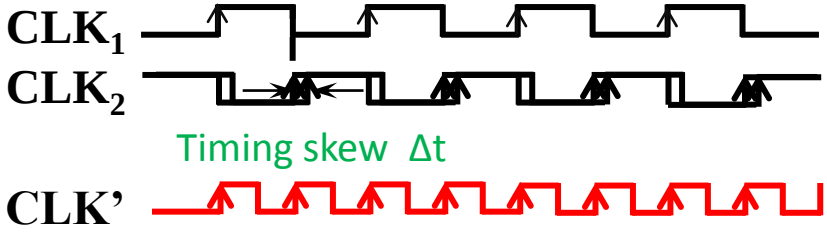
M times sampling rate with M-channel ADCs

➡ High-speed sampling



2-channel Interleaved ADC



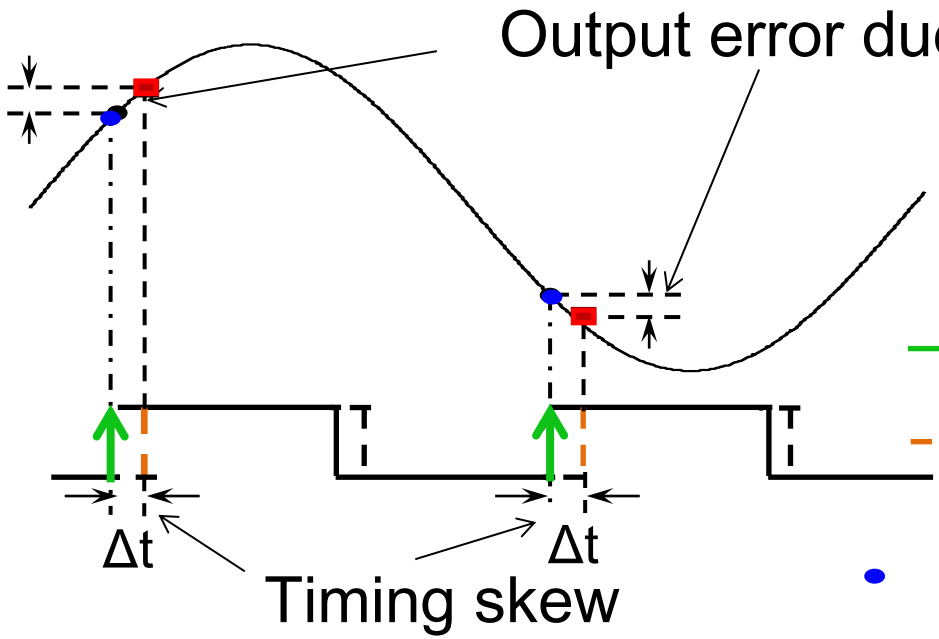


CLK1 reference

CLK2 delayed by half period

2 times sampling rate

Timing Error in Sampling



Ideal clock

Actual clock

Ideal sampling points

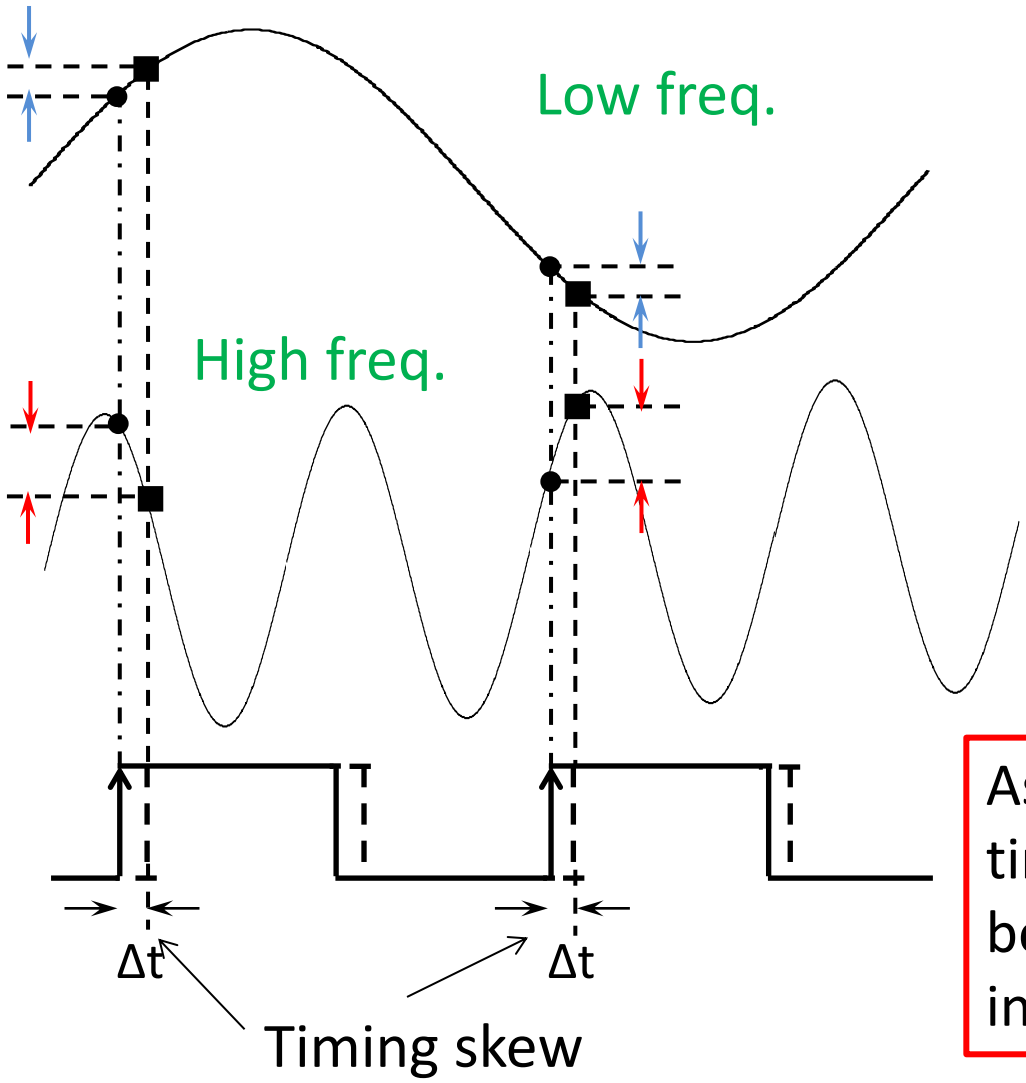
Actual sampling points

Timing error (horizontal error)

↓

Sampled voltage error (vertical error)

Input Frequency & Output



Input freq. ⬆

Output error ⬆

As input frequency increases, timing skew problem becomes serious in interleaved ADC.

Contents

- Research Background and Objective
- Time Interleaved ADC System
- Proposed Calibration System
- Simulation Results
- Extension to 4ch Interleaved ADCs
- Conclusion

Proposed Calibration System

- Full digital
- Timing Skew Detection
  - Cross-correlation of two channel ADC outputs
- Timing Skew Effect Compensation
  - Delay linear digital filter
- Calibration Control
  - Successive approximation algorithm
  - Foreground calibration

Cross-Correlation

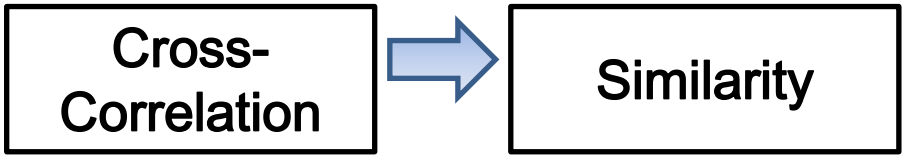
Continuous-time signal

$$(f * g)(t) = \int_{-\infty}^{\infty} f^*(\tau) g(t+\tau) d\tau$$

Discrete-time signal

$$(f * g)(m) = \sum_{m=-\infty}^{\infty} f^*[n] g[n+m]$$

The similarity of two time series signals f, g



Correlation of R(0)and R(1)

CH1 ADC output: $f[n]$

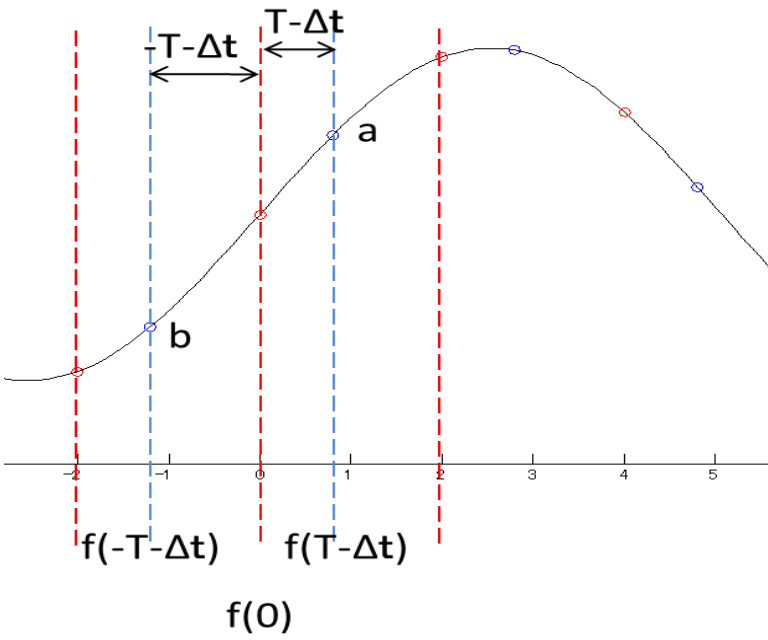
CH2 ADC output: $g[n] = f[n+T-\Delta t]$

lag 0,

$$R(0) = R_{ff}[0] = \lim_{n\to\infty} \frac{1}{n} \sum_{-n}^{n} f[n] f[n+T-\Delta t]$$

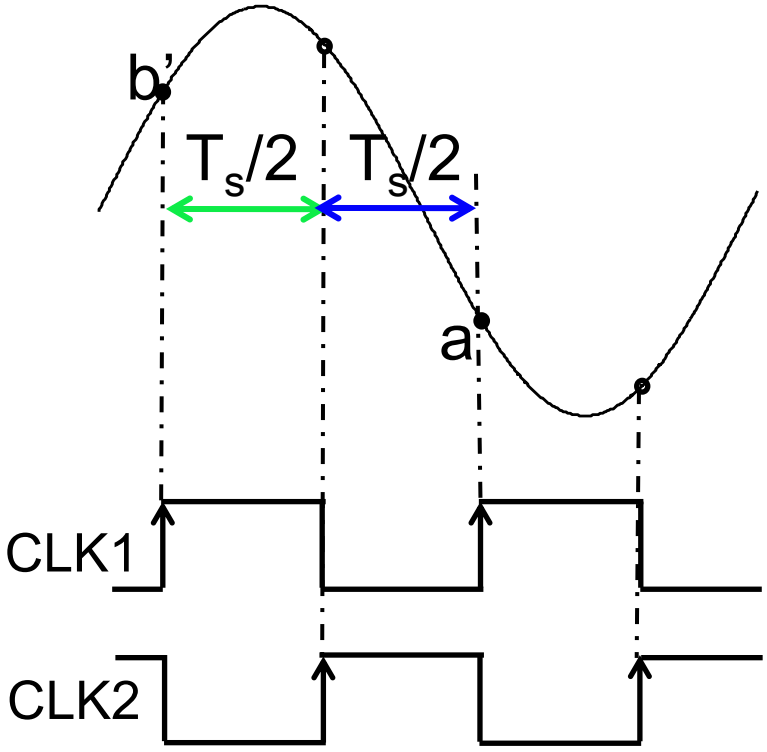
lag 1,

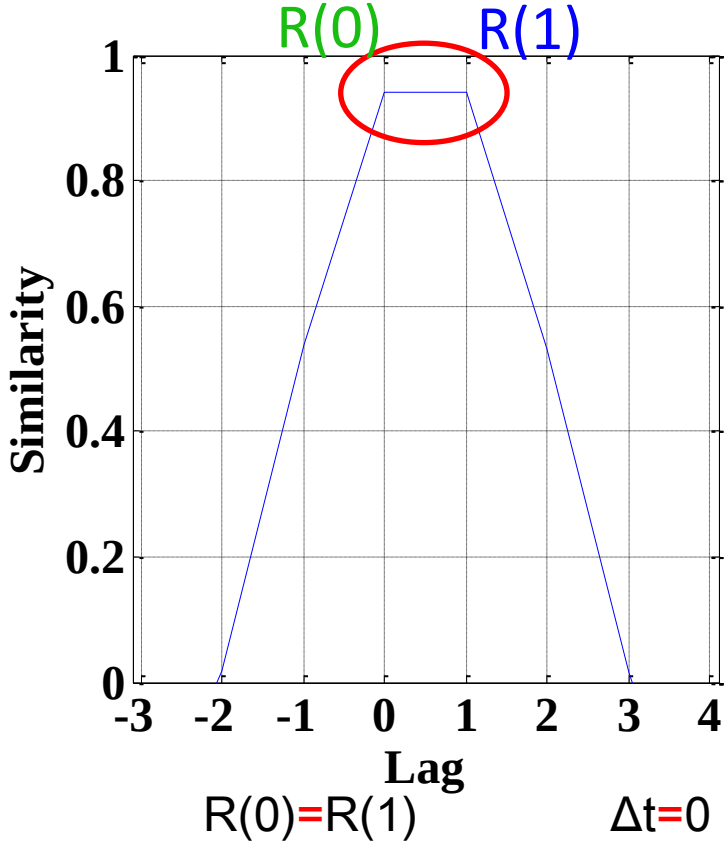
$$R(1) = R_{ff}[-2T] = \lim_{n\to\infty} \frac{1}{n} \sum_{-n}^{n} f[n] f[n-T-\Delta t]$$



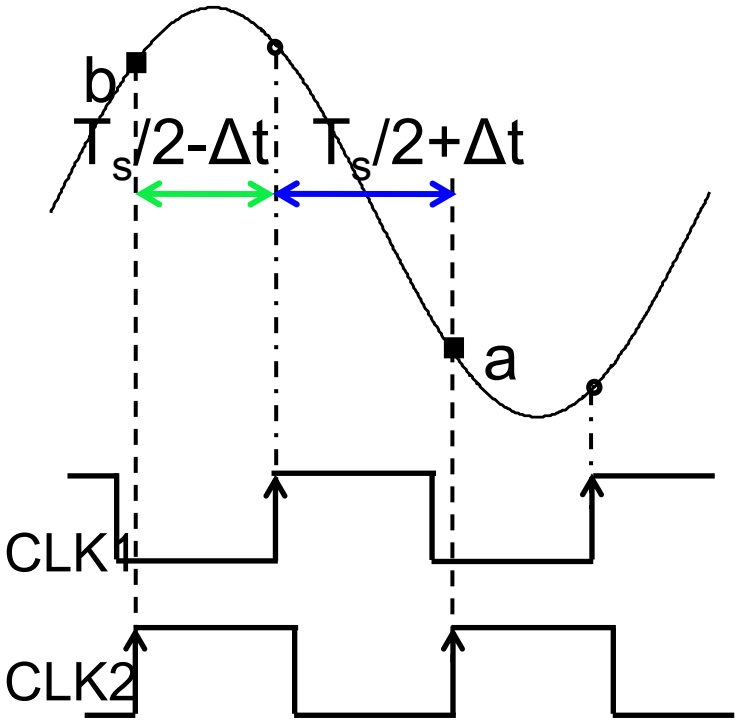
Timing skew Δt

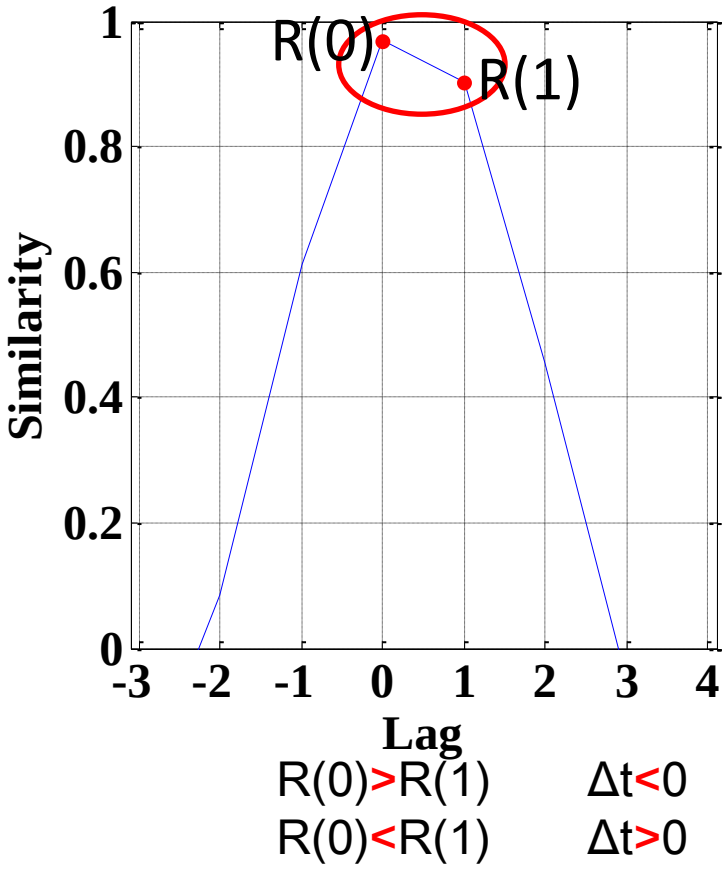
Cross-Correlation without Timing Skew





Cross-Correlation with Timing Skew





R(0)>R(1) Δt<0

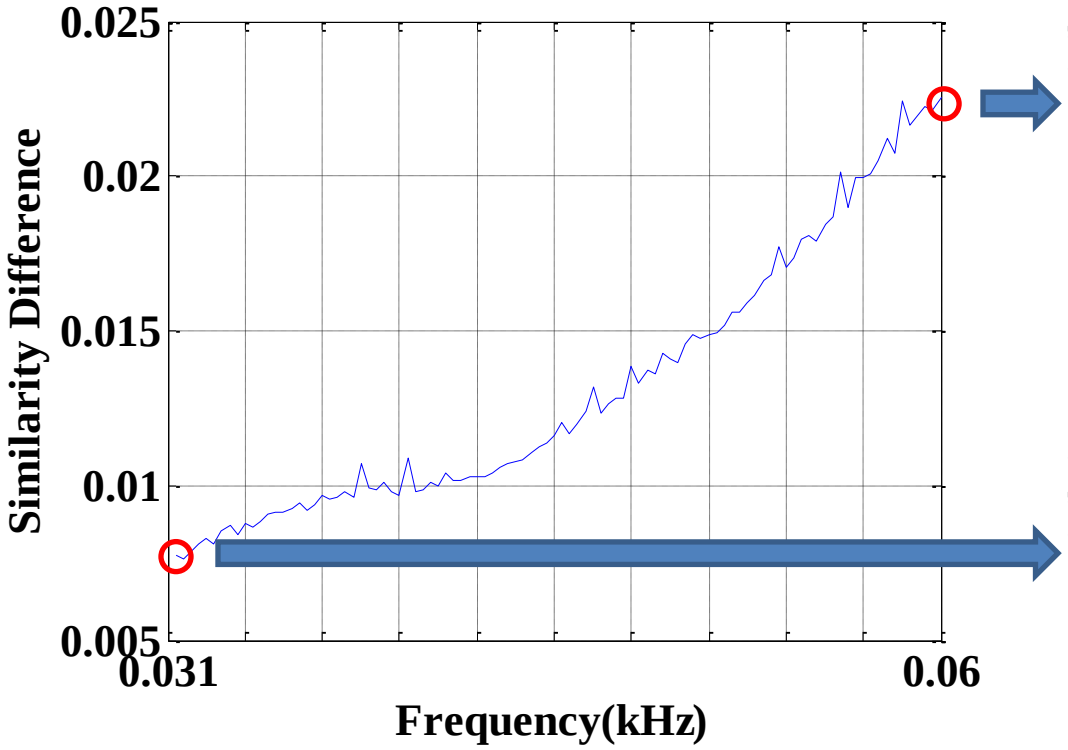
R(0)<R(1) Δt>0

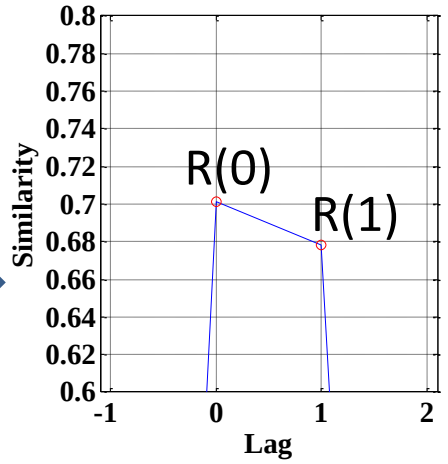
cross-correlation value ⇒ Sign of Δt (Δt >0 or Δt <0)

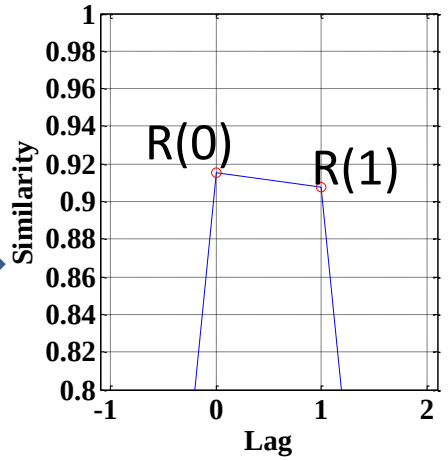
Magnitude of |Δt|

Calibration Input Frequency & Correlation Sensitivity

Δt=-0.02Ts



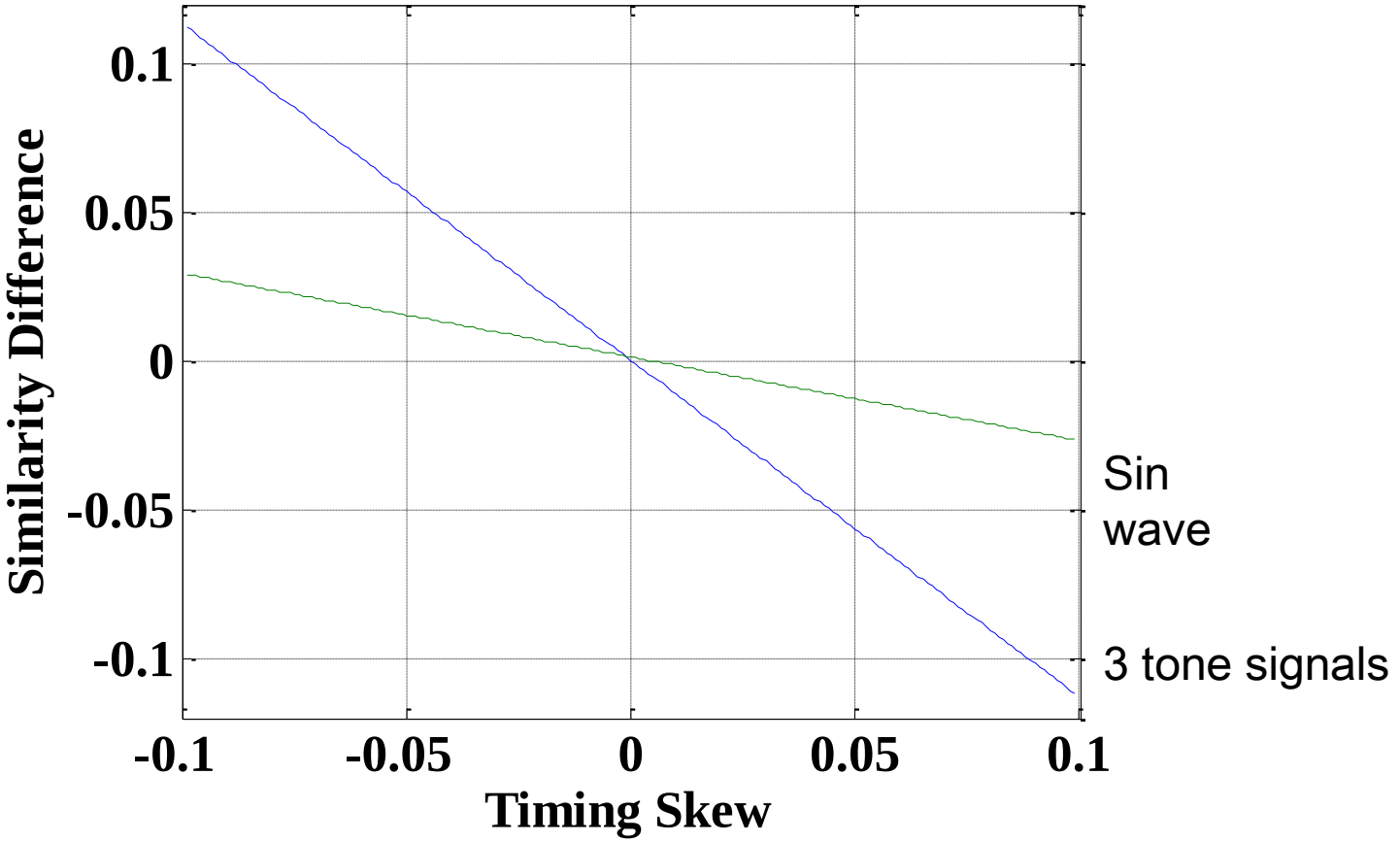




Frequency ⬆ ➡ Difference between R(0) and R(1) ⬆

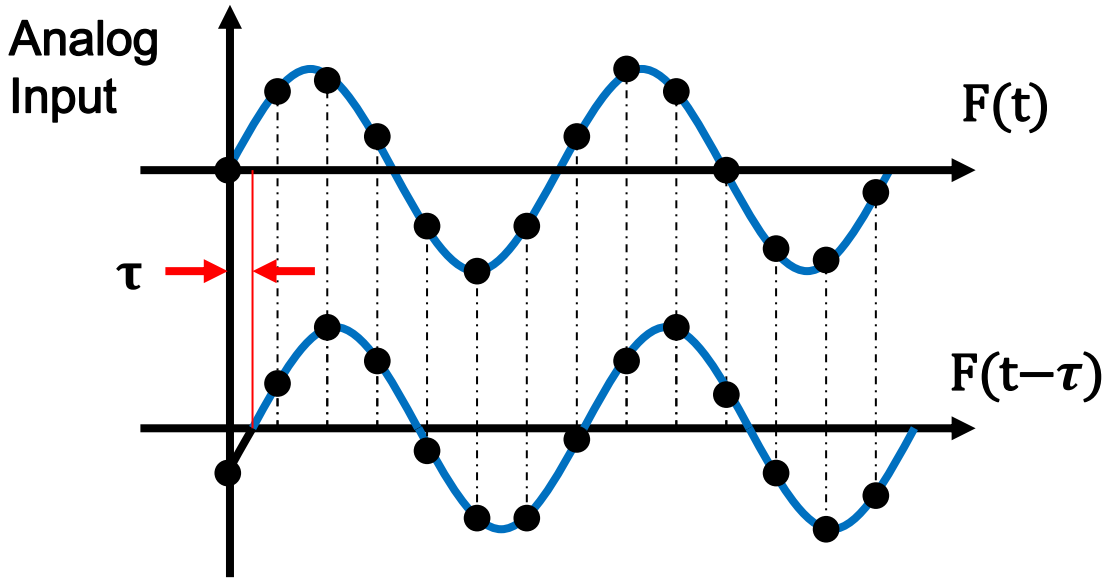
Timing Skew Detection

Calibration Input Signal & Correlation Sensitivity



- 3-tone is more sensitive than 1-tone.
- For 3-tone, minimize random phase and crest factor

Linear Phase Delay Digital Filter



Linear phase ⇒ maintain time-domain waveform

Conventional Linear-Phase Digital Filter :

Group delay time resolution $T_s/2$

Proposed Linear-Phase Delay Digital Filter [1] :

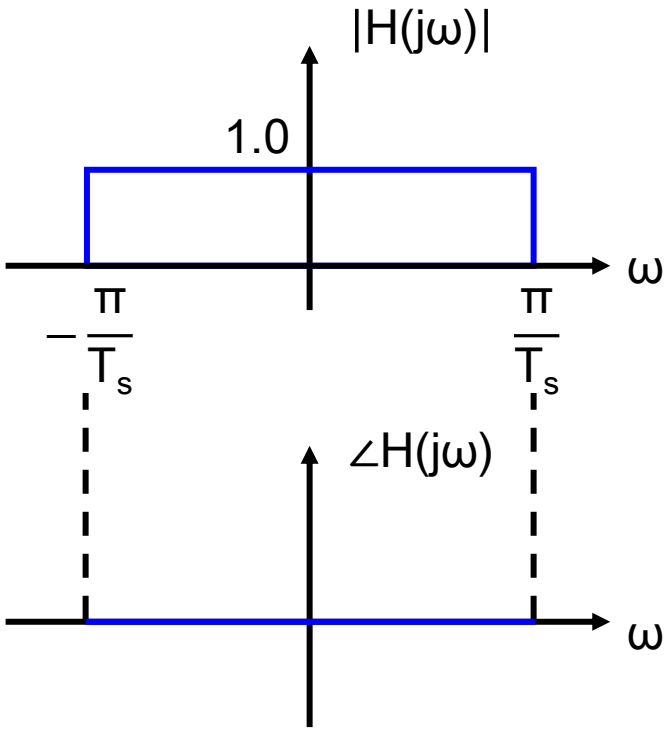
Arbitrary small time resolution τ

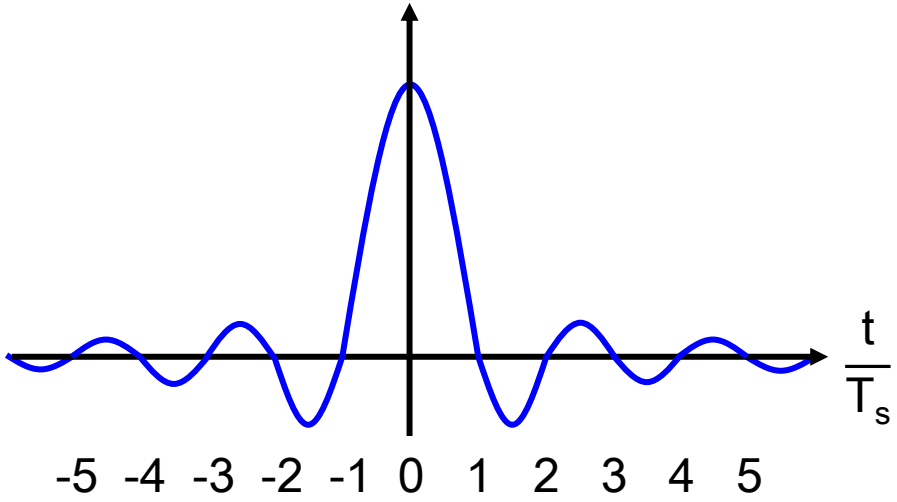
[1] K. Asami, et. al., "Timing Skew Compensation Technique using Digital Filter with Novel Linear Phase Condition," IEEE International Test Conference (Nov. 2010).

Ideal Filter

Inverse Fourier Transform

Frequency response → Impulse response



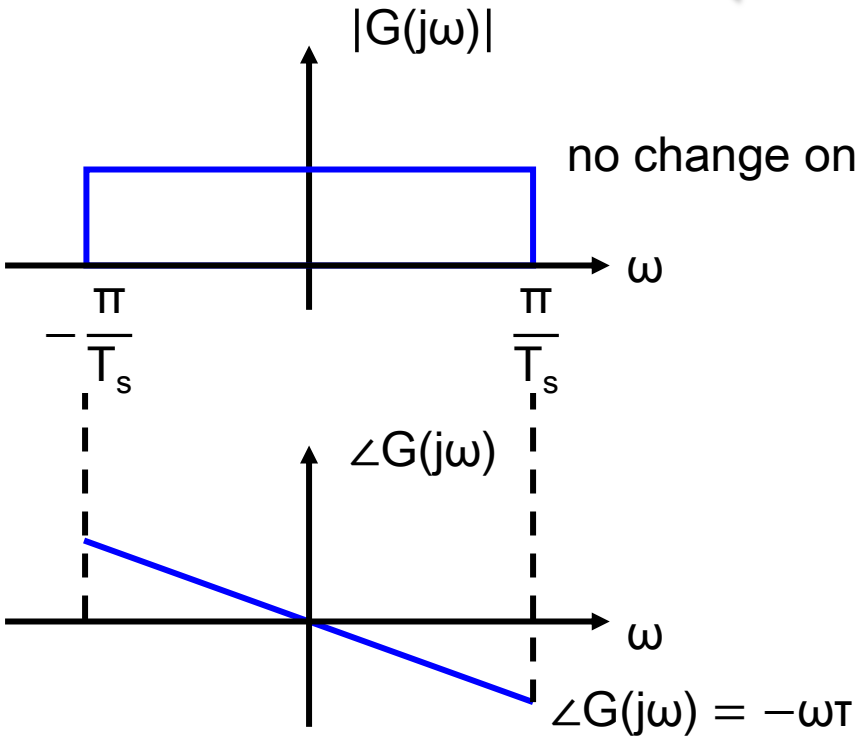


$$h(t)=\frac{1}{T_s}\,\mathrm{sinc}\left(\pi\frac{t}{T_s}\right)$$

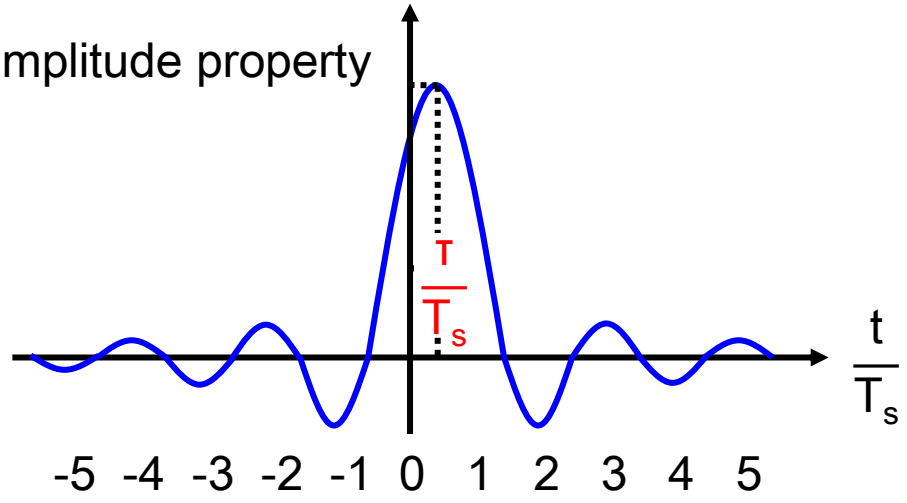
Time Shift of Ideal Filter

Fourier transform

Frequency response ⟵ Impulse response



no change on amplitude property



$$g(t) = h(t-\tau)$$
$$= \frac{1}{T_s}\mathrm{sinc}\left(\pi\frac{t-\tau}{T_s}\right)$$

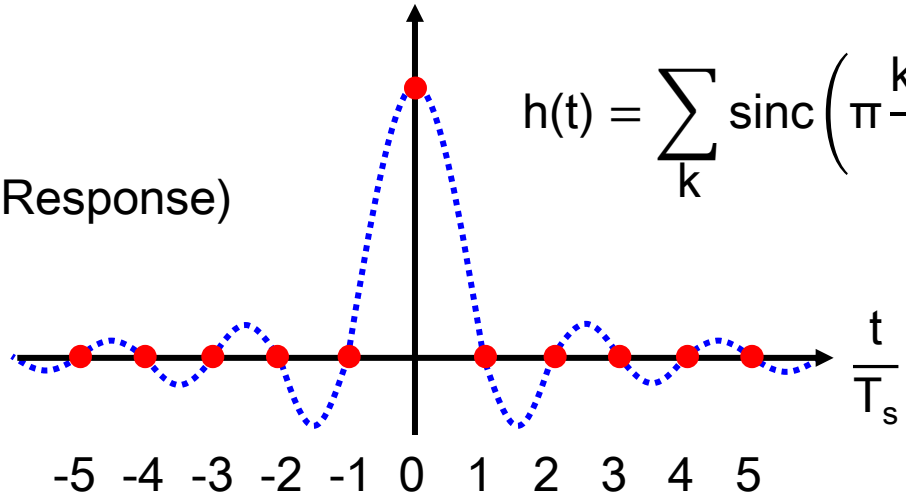
Linear phase is maintained.

Impulse response is time-shifted by, τ

Delay Digital Filter Coefficients

FIR(Finite Impulse Response) Filter

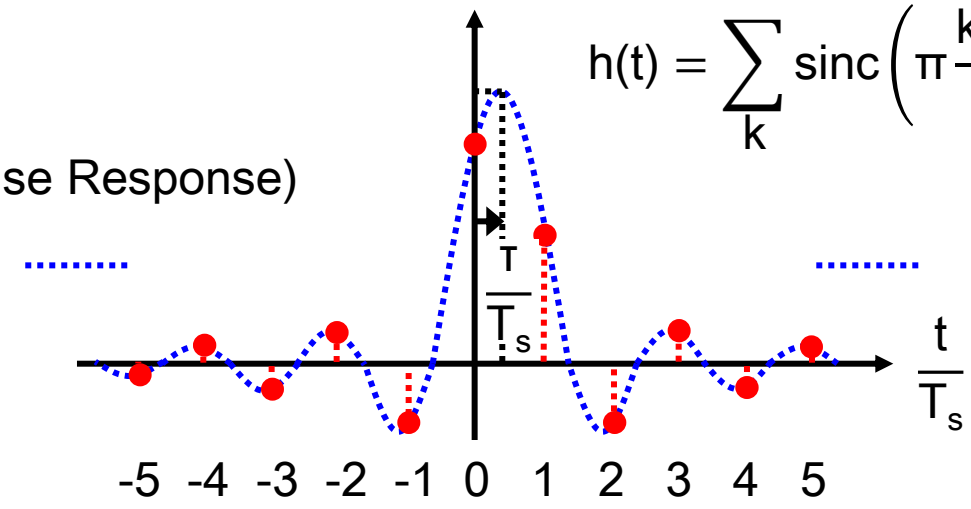
$$h(t) = \sum_k \mathrm{sinc}\left(\pi \frac{k \cdot T_s}{T_s}\right) \delta\left(t - k \cdot T_s\right)$$



Time-shift

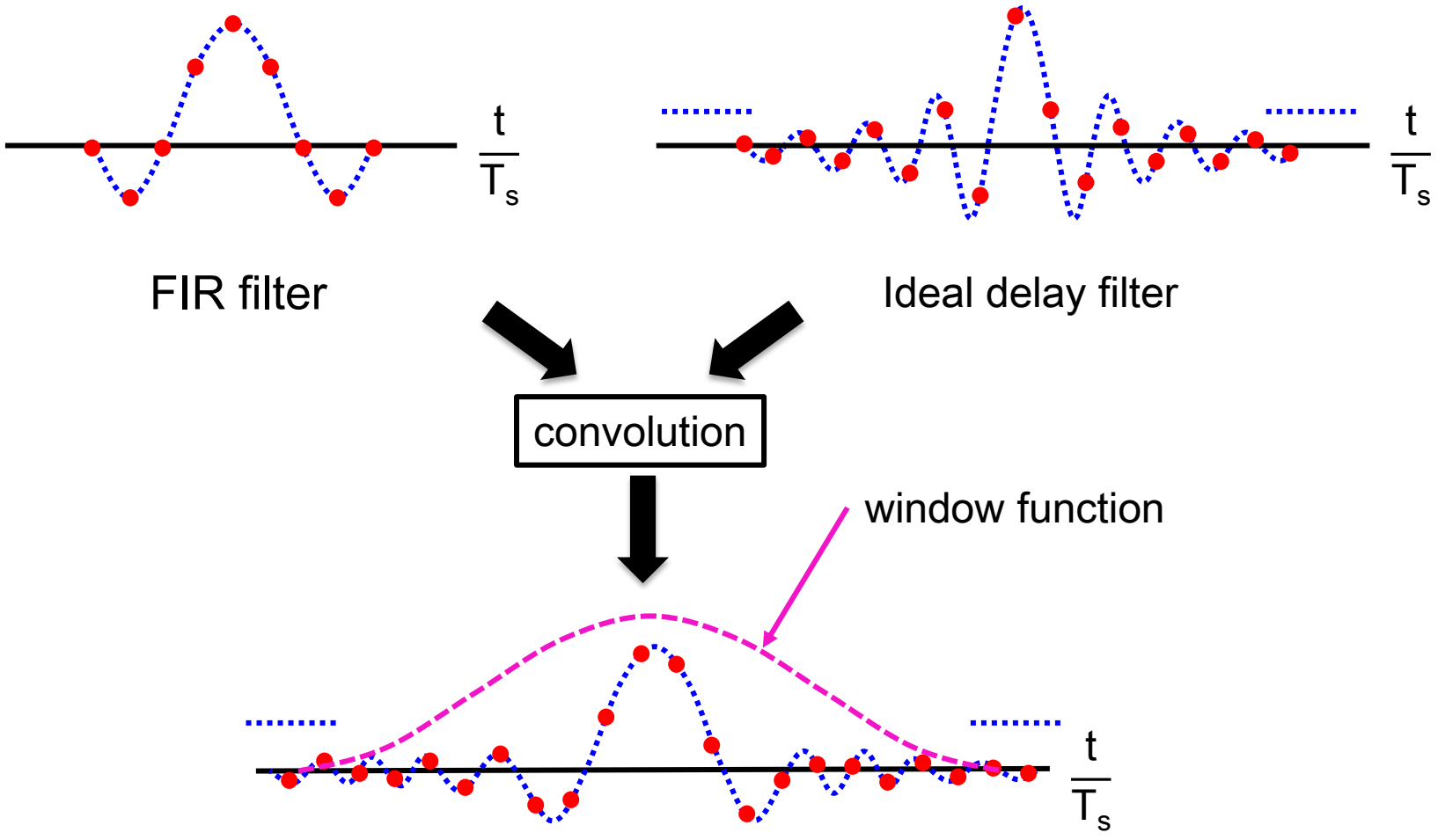
IIR(Infinite Impulse Response) Filter

$$h(t) = \sum_k \mathrm{sinc}\left(\pi \frac{k \cdot T_s - \tau}{T_s}\right) \delta\left(t - k \cdot T_s\right)$$



Ideal delay filter

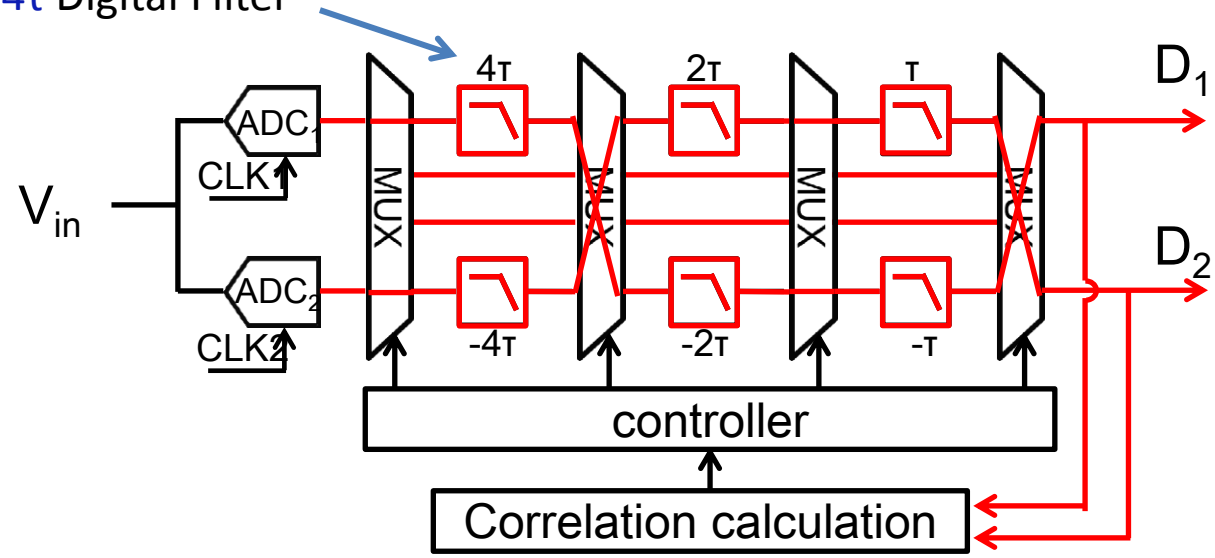
Design of Linear-Phase Delay Digital Filter

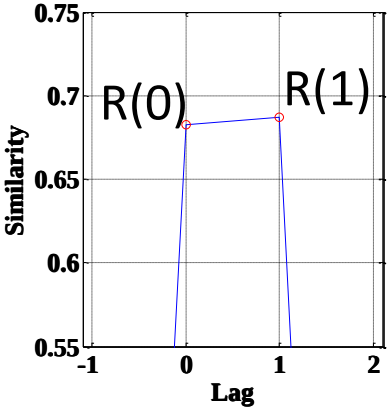


Linear phase Digital Delay Filter

Proposed System

Delay 4τ Digital Filter

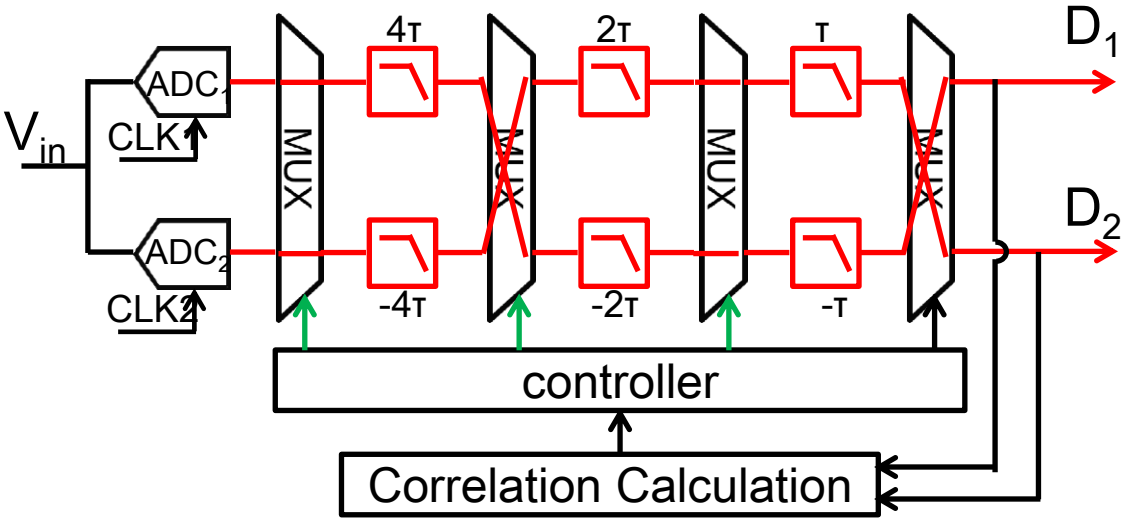




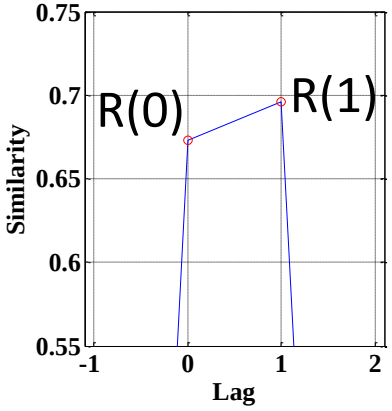
compare the correlation value of the lag 1 and lag 0
R(0)≠R(1)
Δt≠0

delay CH1 -4τ
delay CH2 -4τ

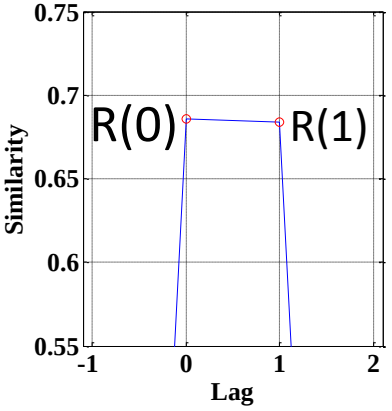
Calibration Done



before calibration



after calibration

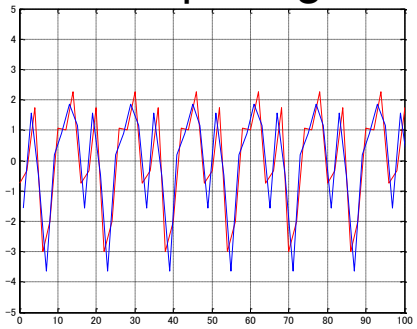


Binary-search, successive approximation

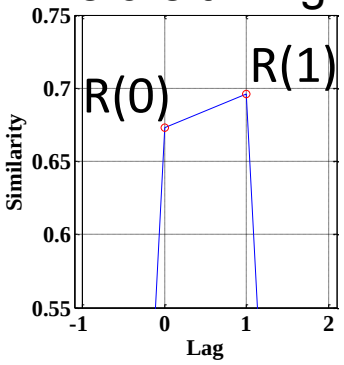
Contents

Simulation Results (1)

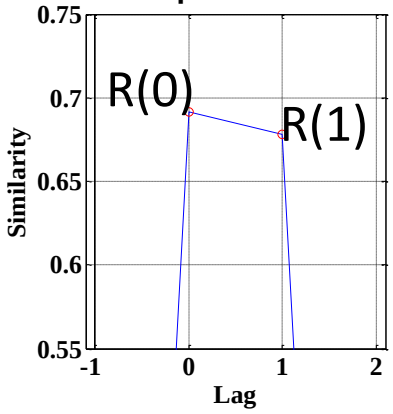
3-tone Input signal



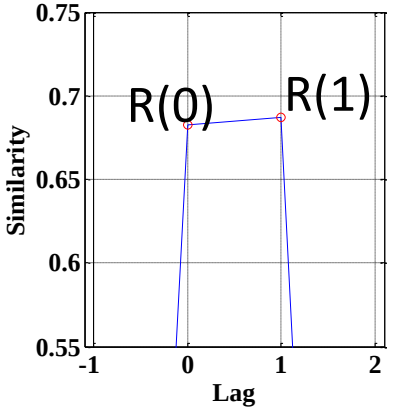
Before timing skew calibration



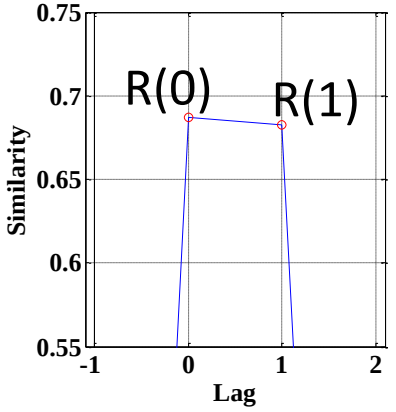
After step1 calibration



After step2 calibration



After step3 calibration

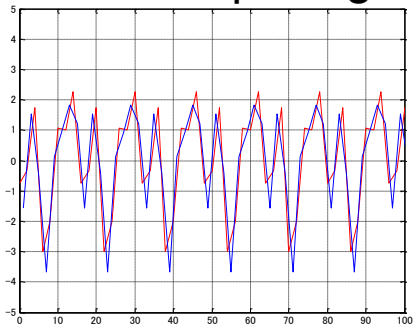


Confirm the performance of timing skew calibration

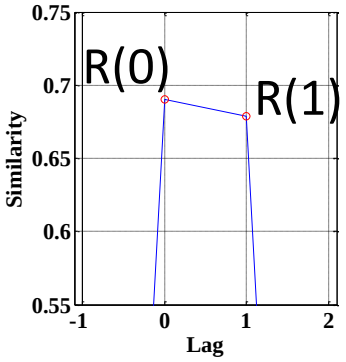
timing skew	+ 0.02 Ts
filter tap	21
window function	Blackman
T	0.001 Ts

Simulation Results (2)

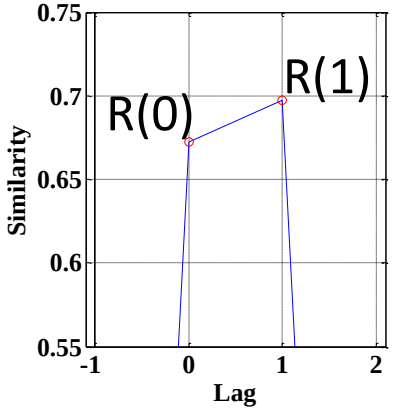
3-tone Input signal



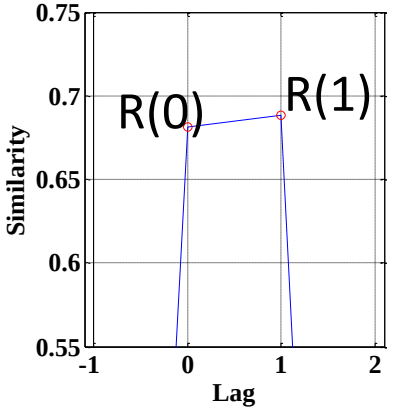
Before skew calibration



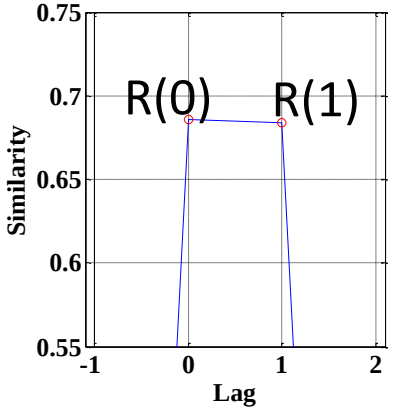
After step1 calibration



After step2 calibration



After step3 calibration

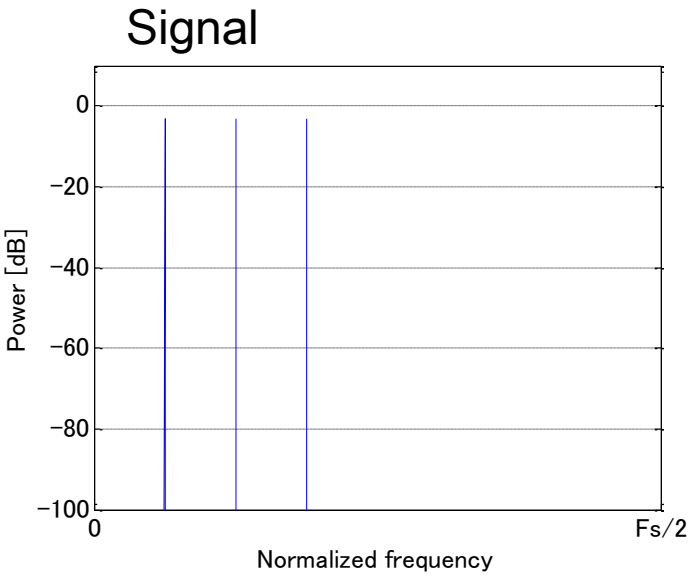


Confirm the performance of timing skew calibration

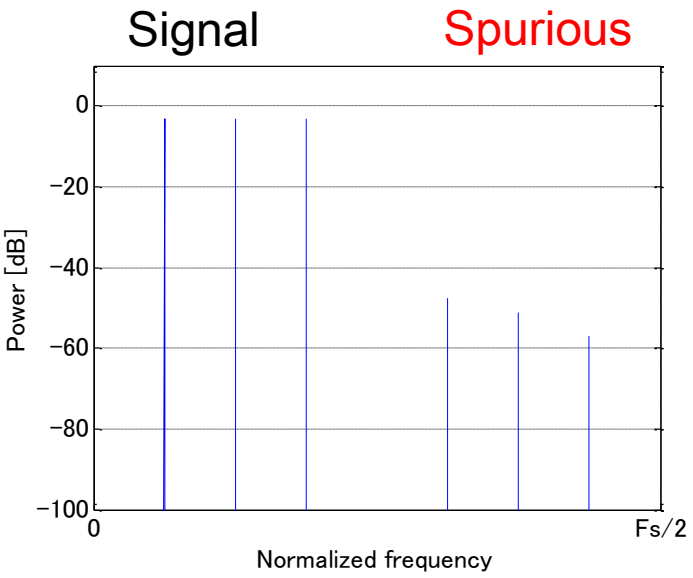
timing skew	- 0.01 Ts
filter tap	21
window function	Blackman
T	0.001 Ts

Power Spectrum of Interleaved ADC Output without/with Timing Skew

3-tone signal without skew

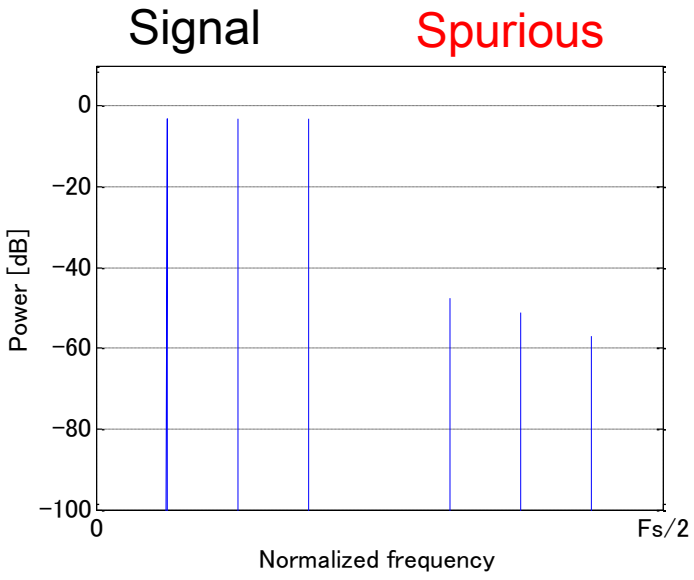


3-tone signal with skew

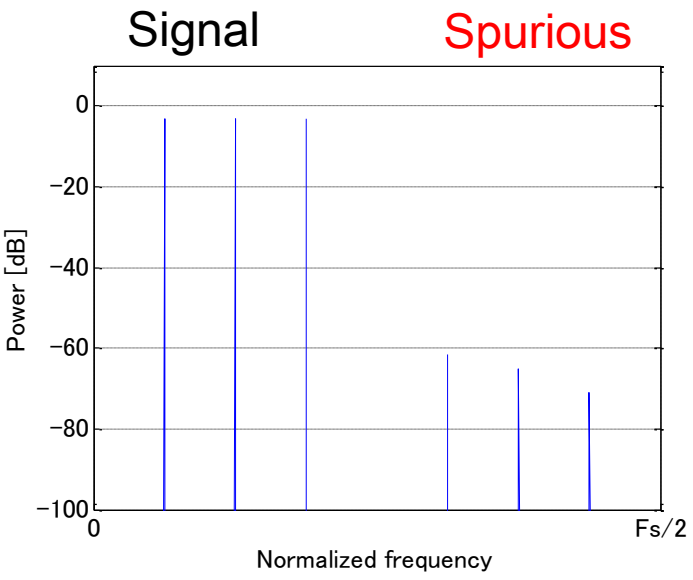


Power spectrum before/after Calibration

Before skew calibration



After skew calibration



Spurious components are reduced by proposed calibration

Contents

- Research Background and Objective
- Time Interleaved ADC System
- Proposed Calibration System
- Simulation Results
- Extension to 4ch Interleaved ADCs
- Conclusion

4-Channel Case Extension Method

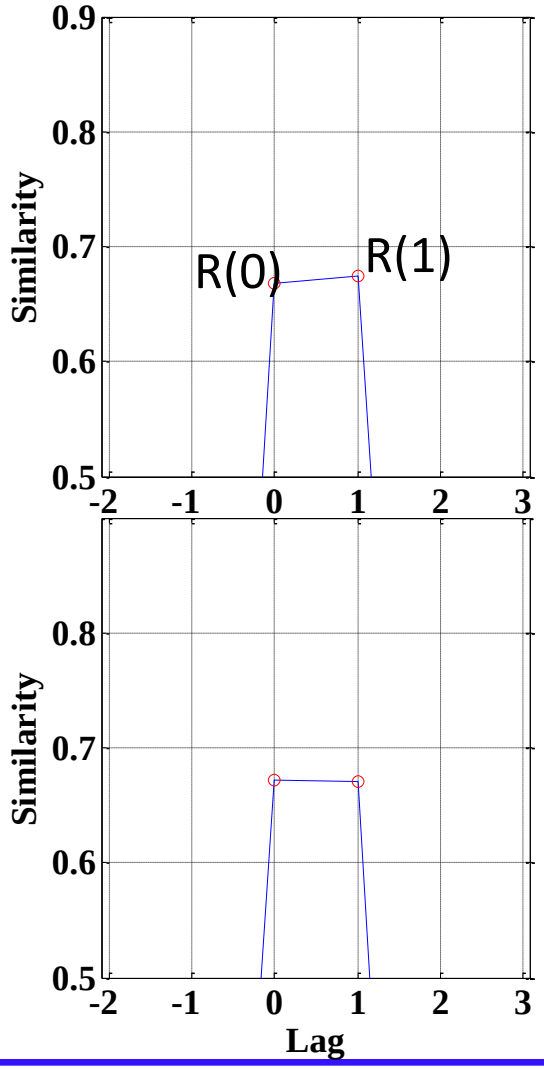
Ch1/ch3 calibration

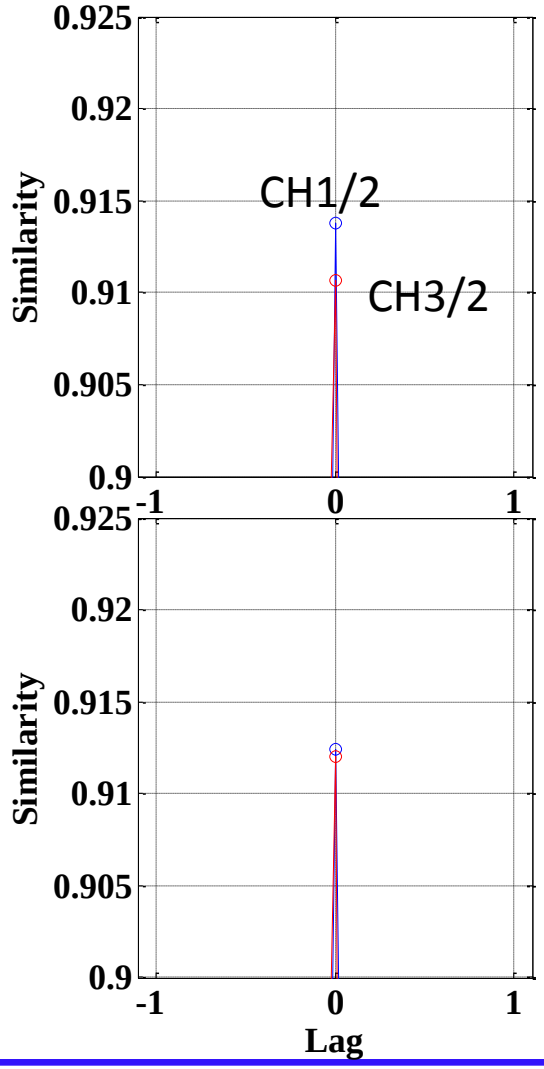
Ch2 calibration

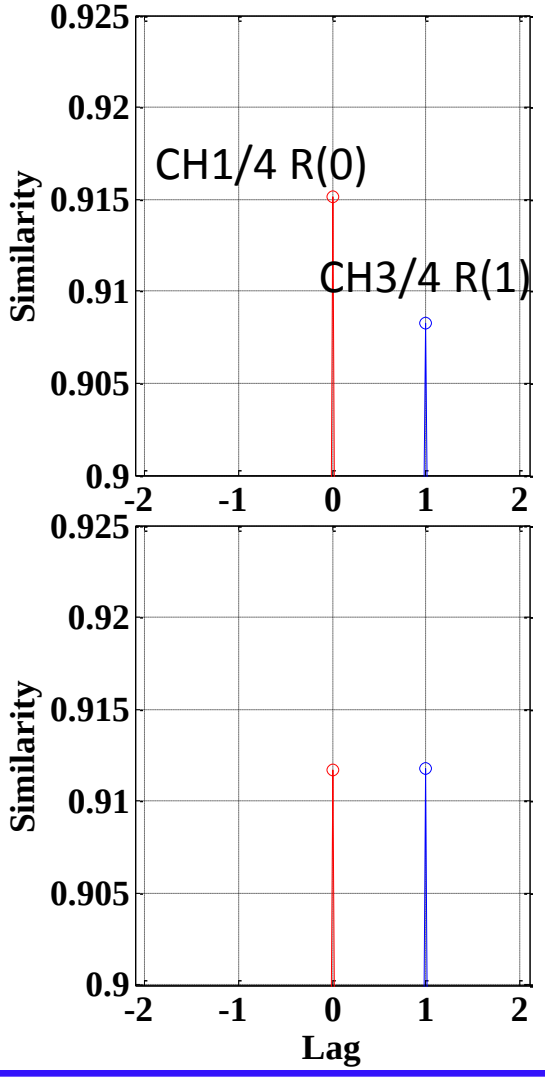
Ch4 calibration

Before calibration

After calibration

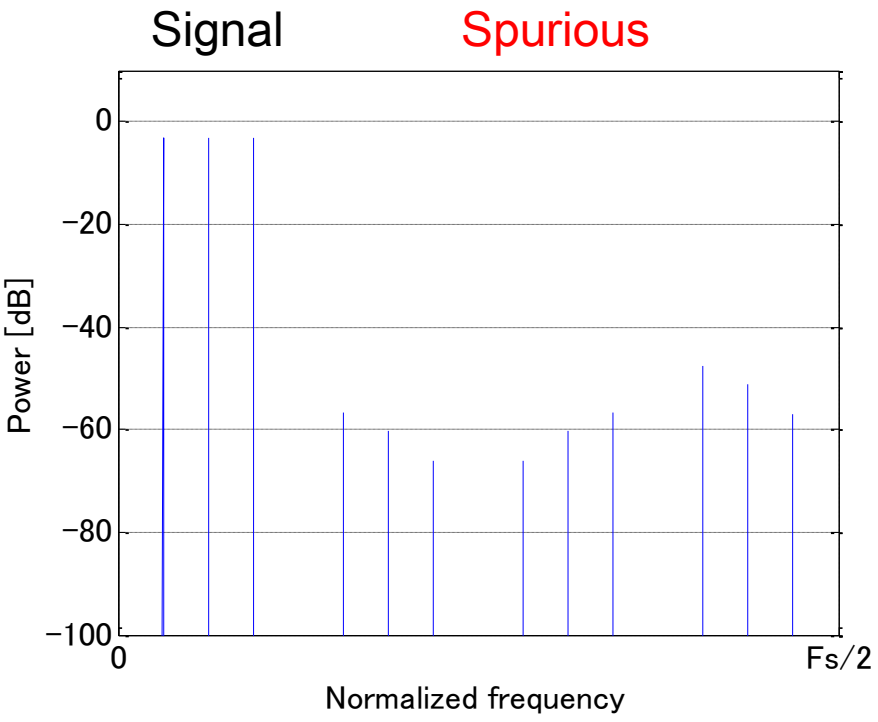




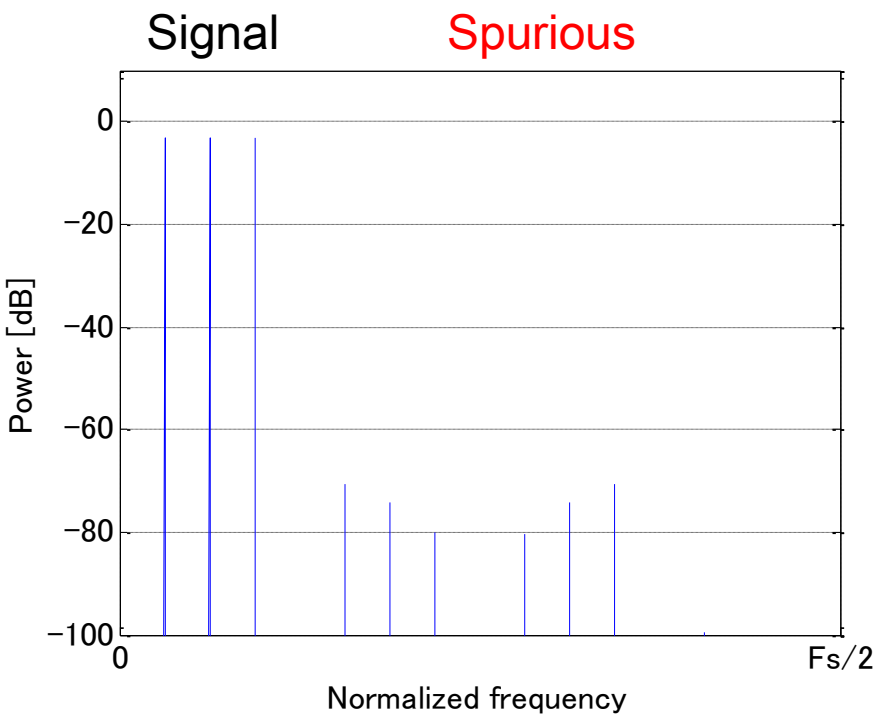


Simulation Results - Power Spectrum

Before calibration



After calibration



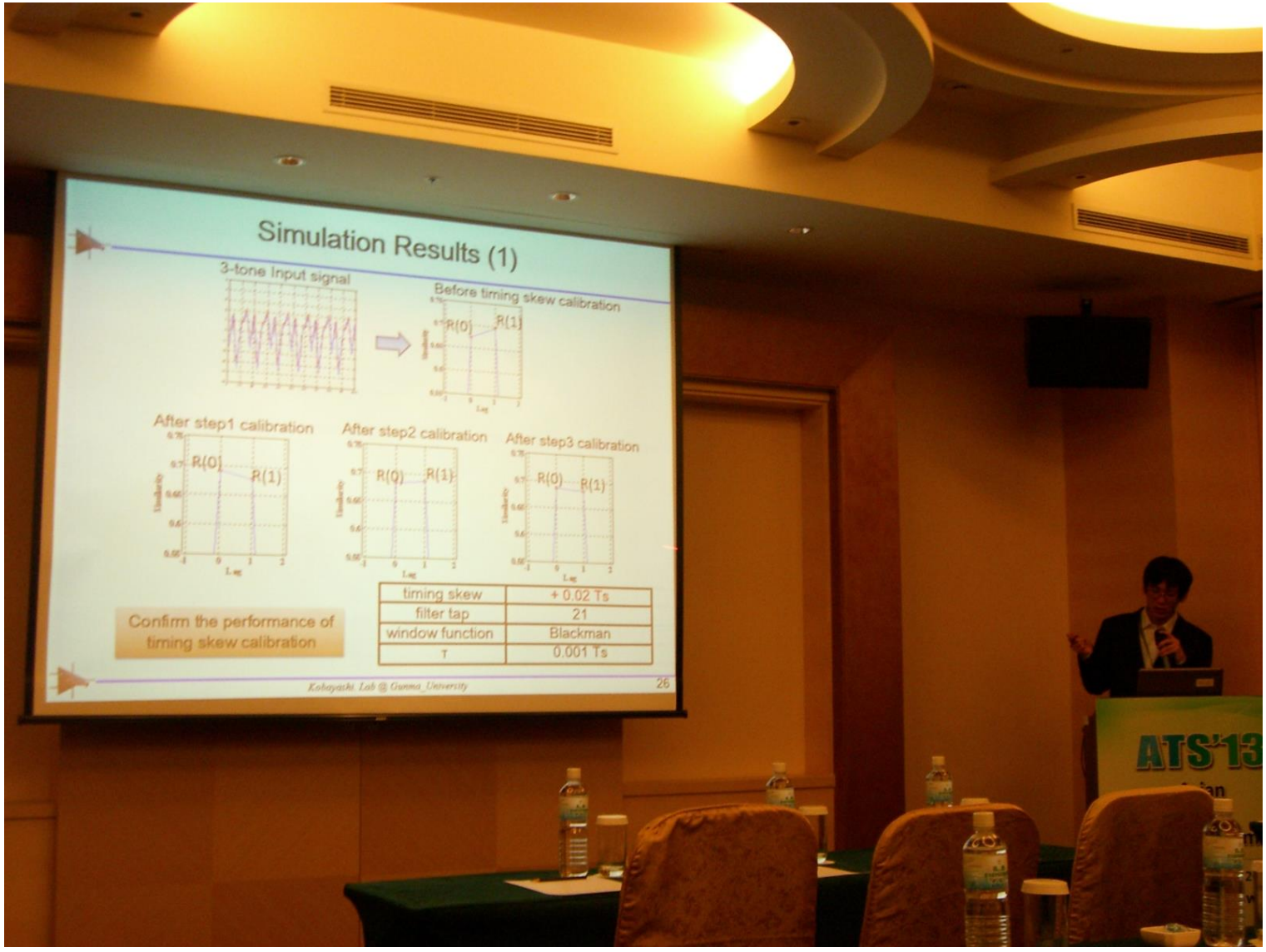
Contents

Conclusion

Proposal of timing skew calibration in interleaved ADC

- Full digital
- Timing Skew Detection
  - Cross-correlation of two channel ADC outputs
  - Effective for high frequency, multi-tone input
- Timing Skew Effect Compensation
  - Delay linear–phase digital filter
- Calibration Control
  - Successive approximation algorithm
  - Foreground calibration
- Verified with MATLAB simulation in 2-channel, 4-channel cases.

Presented by呉明輝（Minghui Wu）




ATS'13


ATS'13