26 Oct. 2022 (Wed)
15:45-16:15

Session D2: Mixed-Signal Circuit I

ICSICT-2022
2022 IEEE 16th International Conference on Solid-State and Integrated Circuit Technology
Oct. 25-28, 2022
Nanjing Platinum Hanjue Hotel Nanjing, China.

Invited

Challenges for Waveform Sampling and Related Technologies

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Gunma University

Self-Introduction

Haruo KOBAYASHI

Professor

Gunma University, Japan

Analog/Mixed-Signal IC Design and Test

Signal Processing Algorithm

B.S. from U. Tokyo, Information Physics

M.S. from U. Tokyo, Information Physics

M.S. from UCLA, Electrical Engineering

Ph.D. from Waseda U. Electrical Engineering

OUTLINE

- Introduction
- Equivalent-Time Sampling Time-Base
- Metallic Ratio Sampling
  - AMS IC Testing Applications
  - ADC Histogram Test Application
  - TDC Linearity Self-Calibration Application
  - Pseudo Random Signal Generation
- Proactive Use of Finite Aperture Time
- Conclusion

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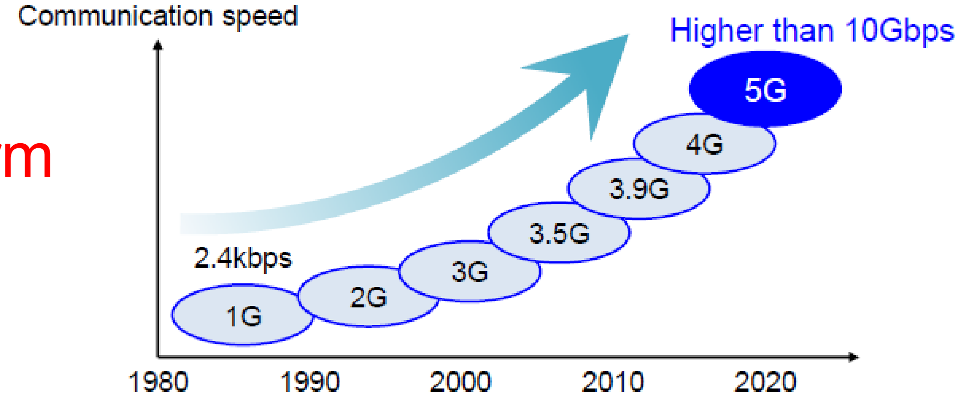
Research Motivation (1)

Next Generation Communication System "5G"

High frequencies
in communication systems

Electronic components
for high frequency bands

Their testing technology
"High frequency waveform sampling"
should be developed



Research Motivation (2)

IoT systems prevail

A lot of sensors

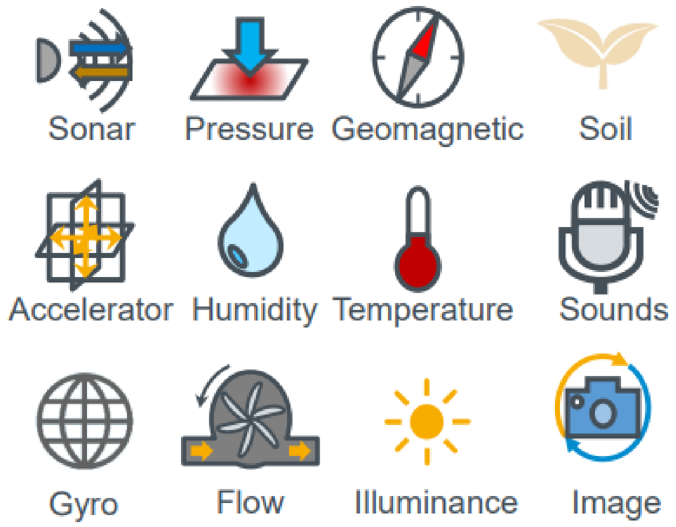
low frequency signals

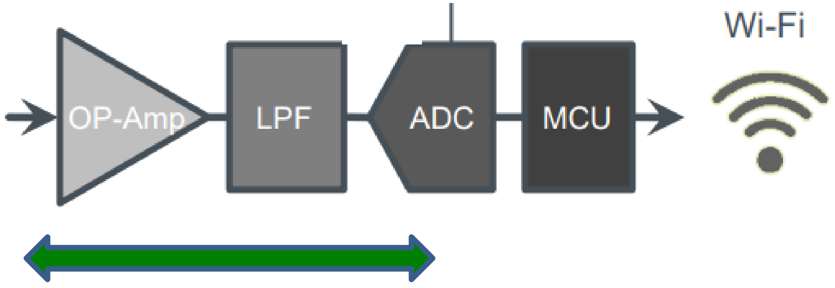
Analog interface circuit

low power, miniature size

Proactive use of finite aperture time in sampling circuit

Sensor

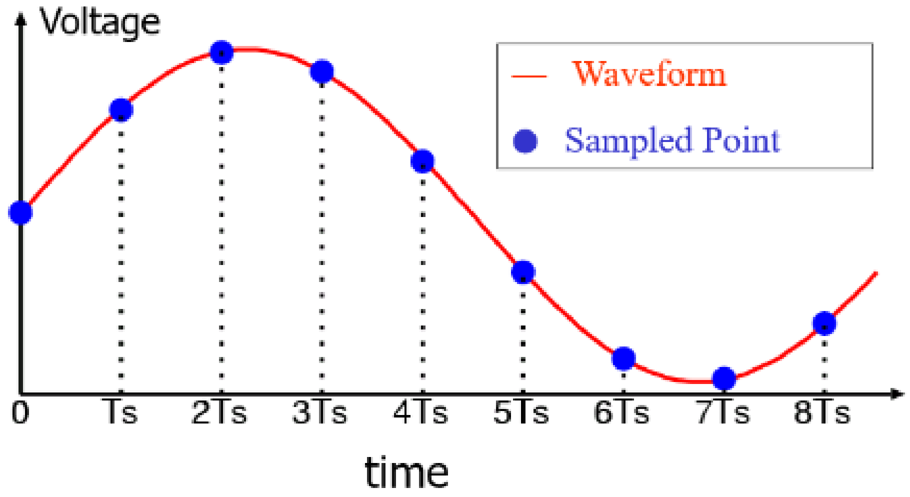




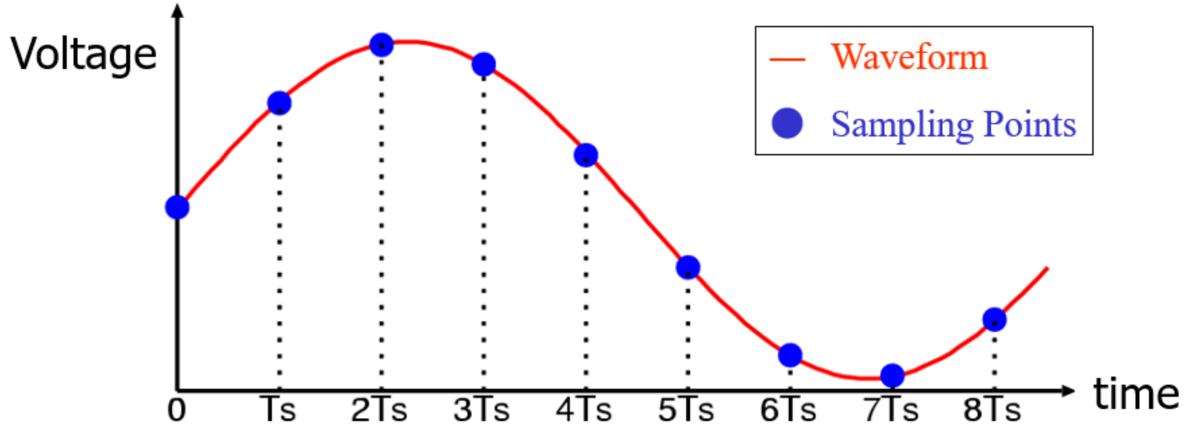
Analog interface circuit

Varieties of Sampling Technologies

Sampling Circuit
Anti-Aliasing Filter
Sampling Theorem
Subsampling
Spectrum Folding
Oversampling
Equivalent-Time Sampling
Metallic Ratio Sampling
Residue Sampling
Coherent Sampling
Frequency Conversion by Sampling
Quadrature Sampling
Non-uniform Sampling
Sampling Clock Jitter, phase jitter
Timing skew
Finite Aperture Time



Sampling for Waveform Acquisition

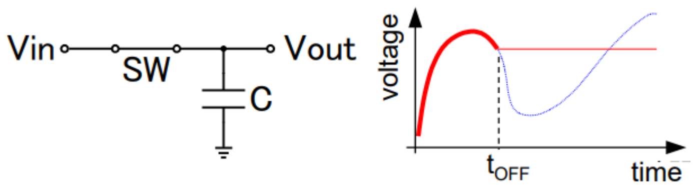


Track/Hold Circuit

- SW : ON

  $Vout(t) = Vin(t)$

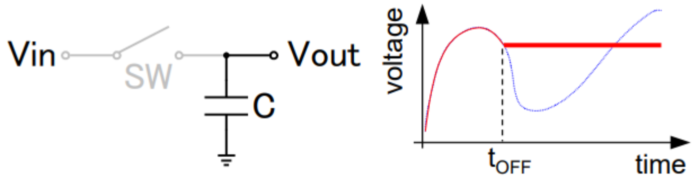
  Track mode



- SW : OFF

  $Vout(t) = Vin(t_{OFF})$

  Hold mode



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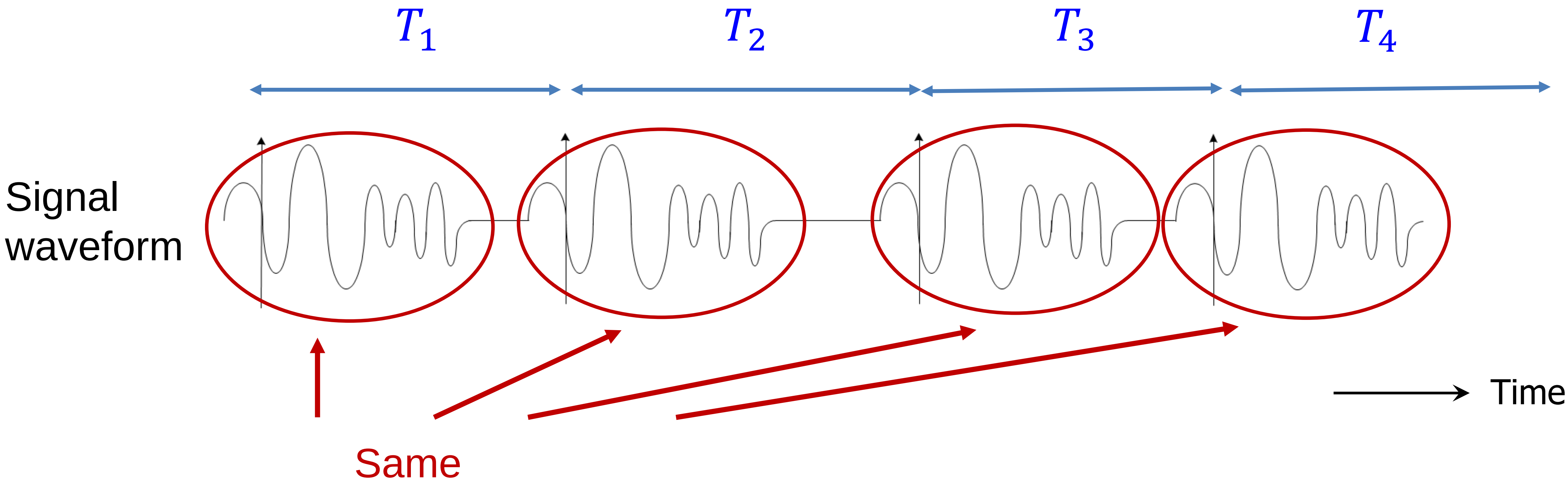
Sampling Oscilloscope

Wideband Repetitive Signal

In general $T_1 \neq T_2 \neq T_3 \neq T_4$ Non-periodic



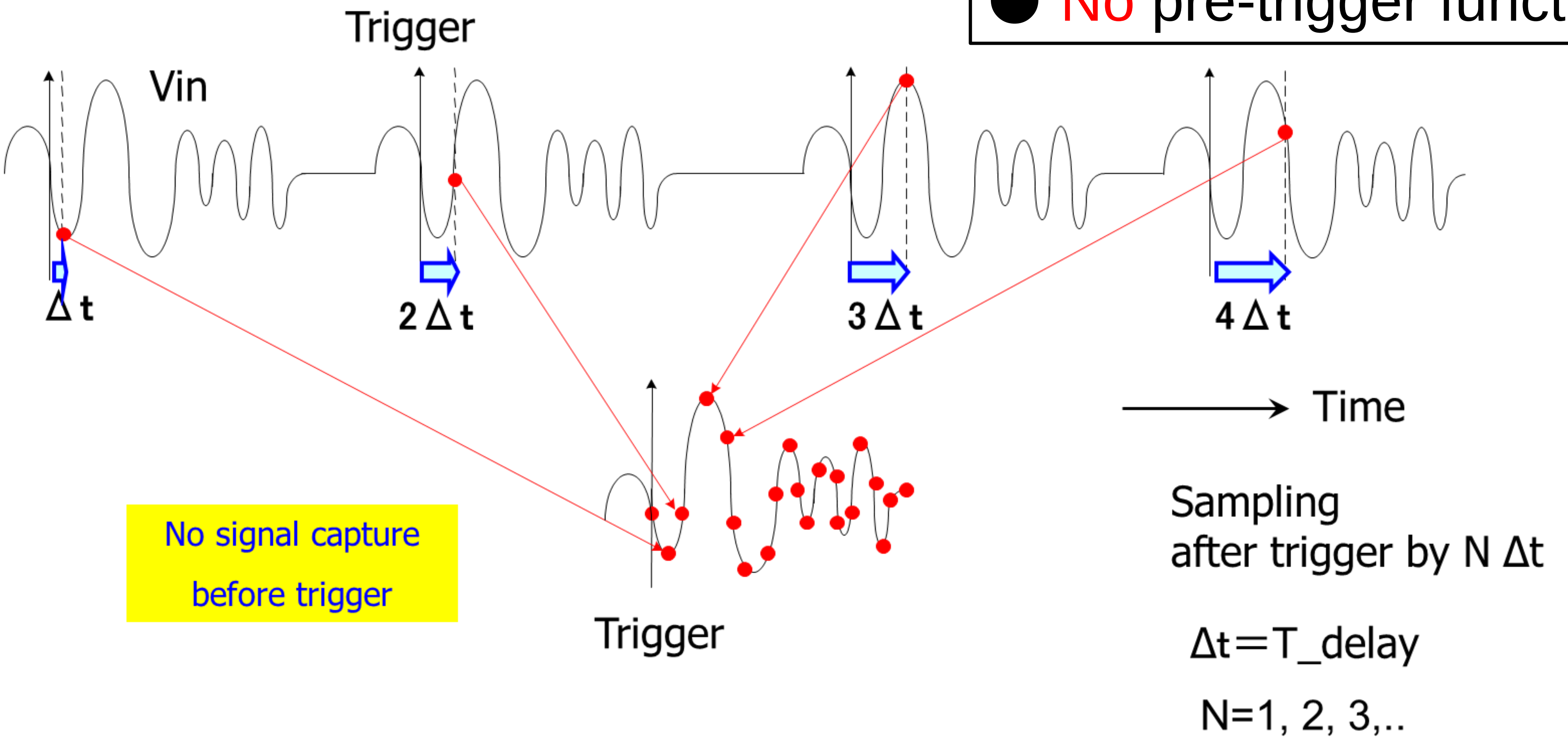
Repetitive ⇒ Equivalent-time sampling is applicable.

Sequential Sampling

Input signal: repetitive, need NOT periodic

Sampling clock: synchronous to trigger

- Used for measurement
- Effective acquisition
- No pre-trigger function

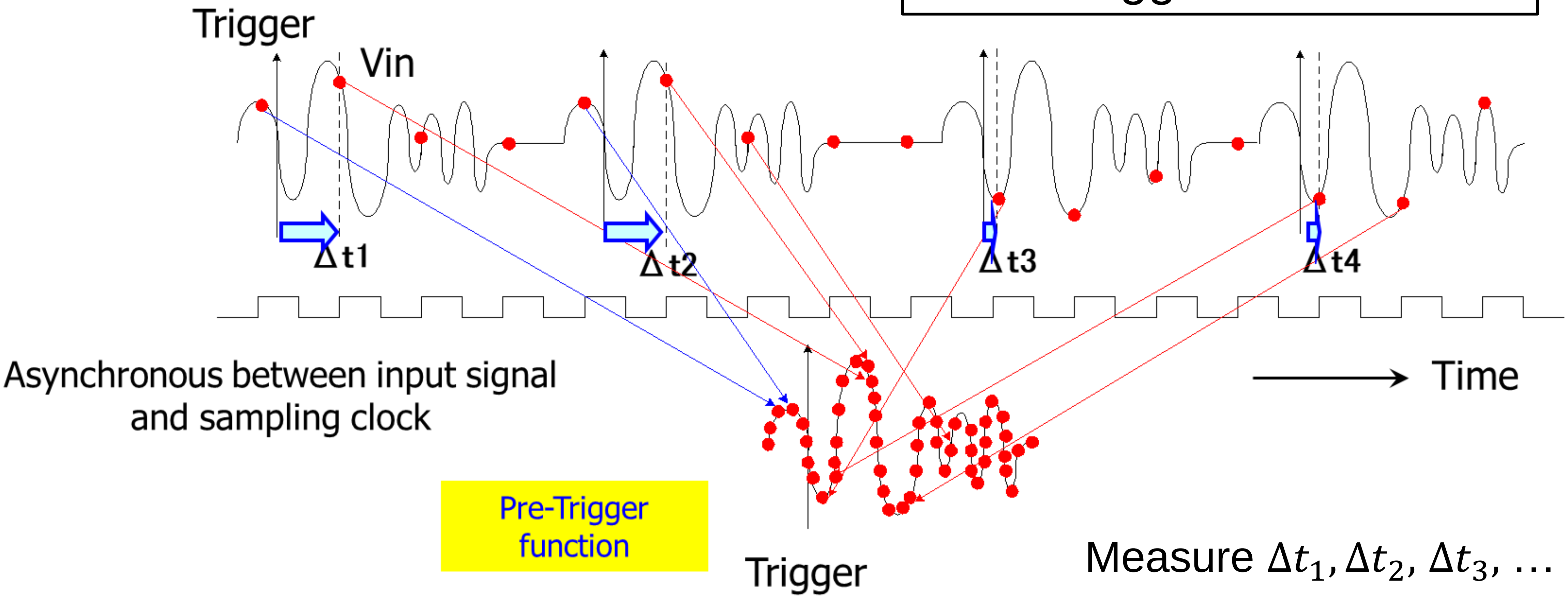


Random Sampling

Input signal: repetitive, need NOT periodic

Sampling clock: NOT synchronous to input

- Used for measurement
- Not effective acquisition
- Pre-trigger function



Measure $\Delta t_1, \Delta t_2, \Delta t_3, \ldots$

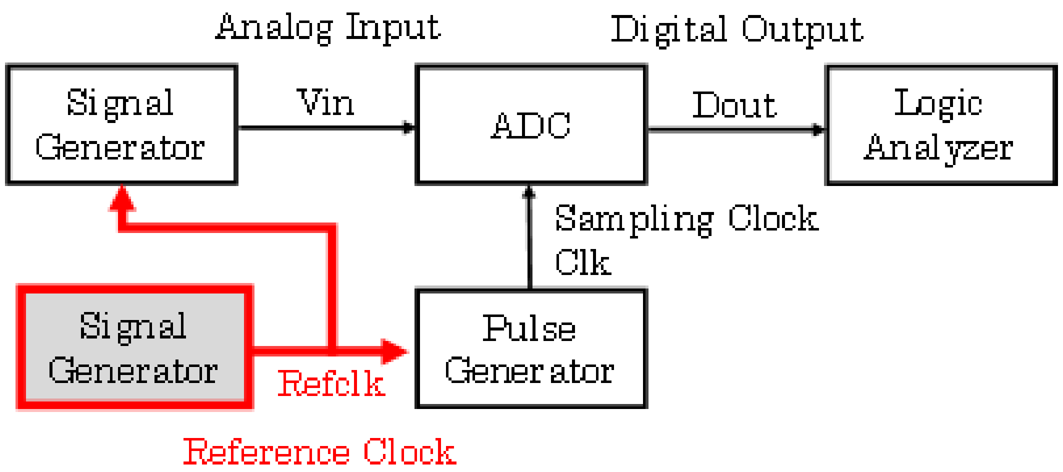
Coherent Sampling

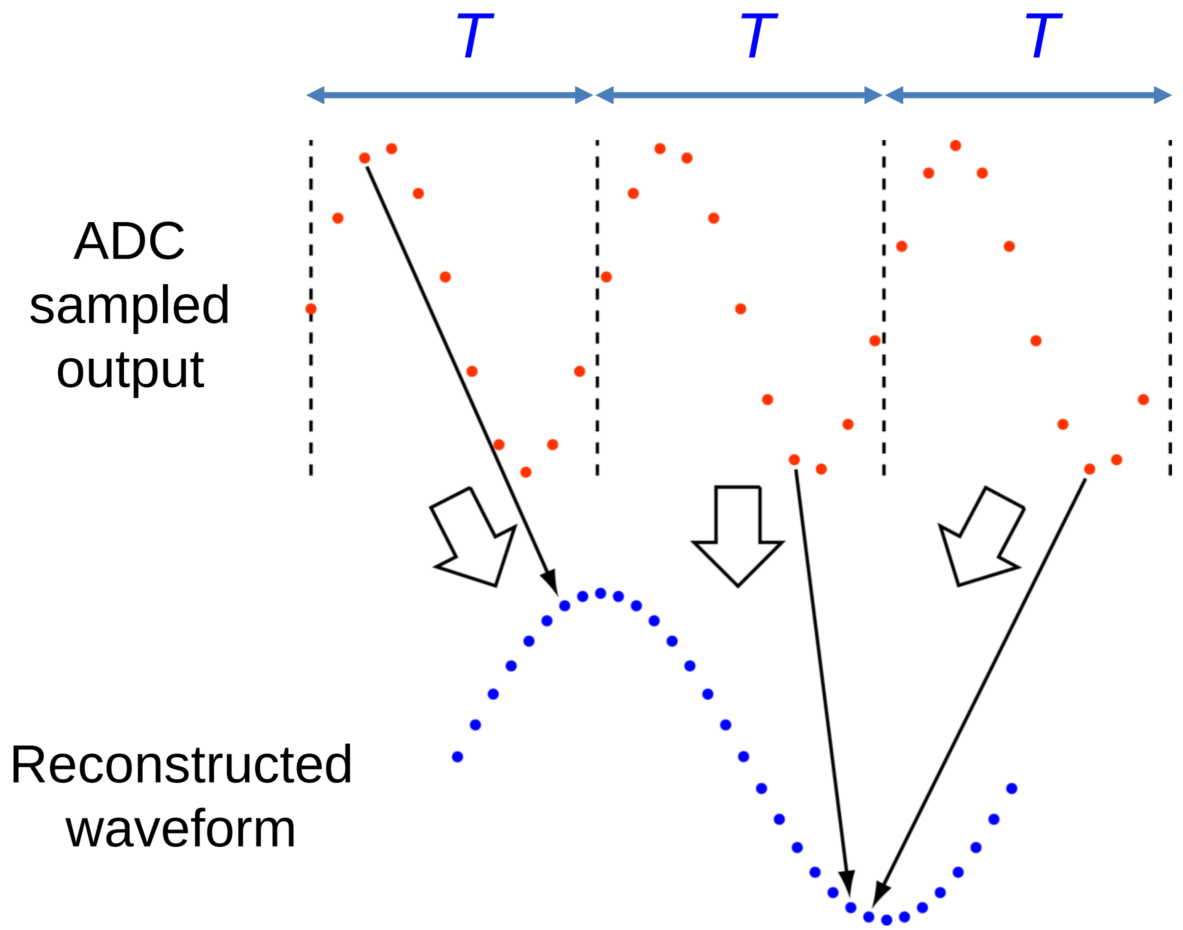
Input signal: repetitive, periodic

Sampling clock: synchronous to input

Used for LSI Testing

Coherent sampling
ADC test system





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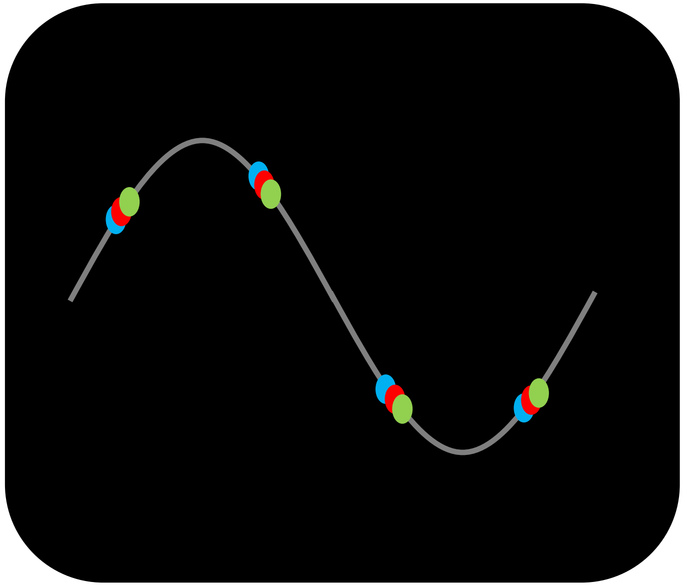
AMS: Analog and Mixed-Signal

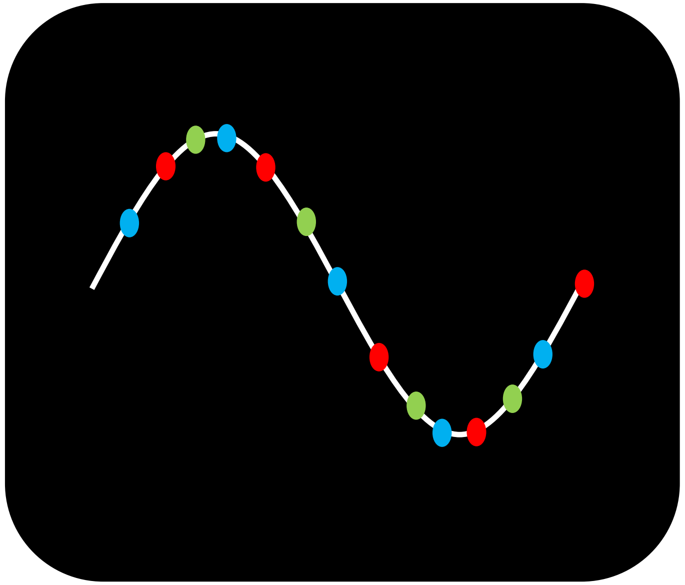
[1] S.Yamamoto, H. Kobayashi, et. al., "Metallic Ratio Equivalent-Time Sampling and Application to TDC Linearity Calibration" IEEE Trans. Device and Materials Reliability（Mar. 2022)

Research Objective

Objective: For efficient IC testing,
high efficiency waveform acquisition
with equivalent-time sampling.



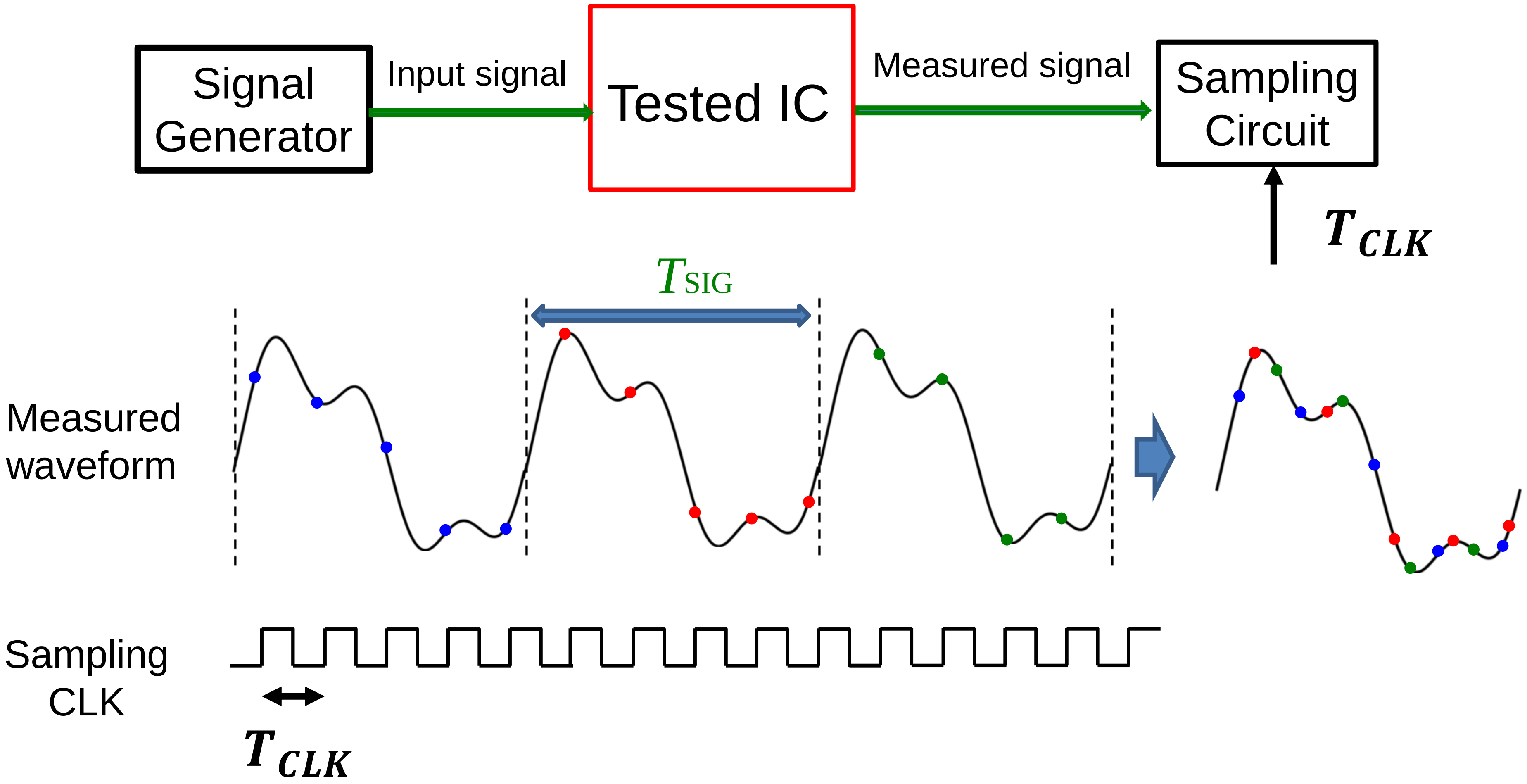
Sampling points: localized



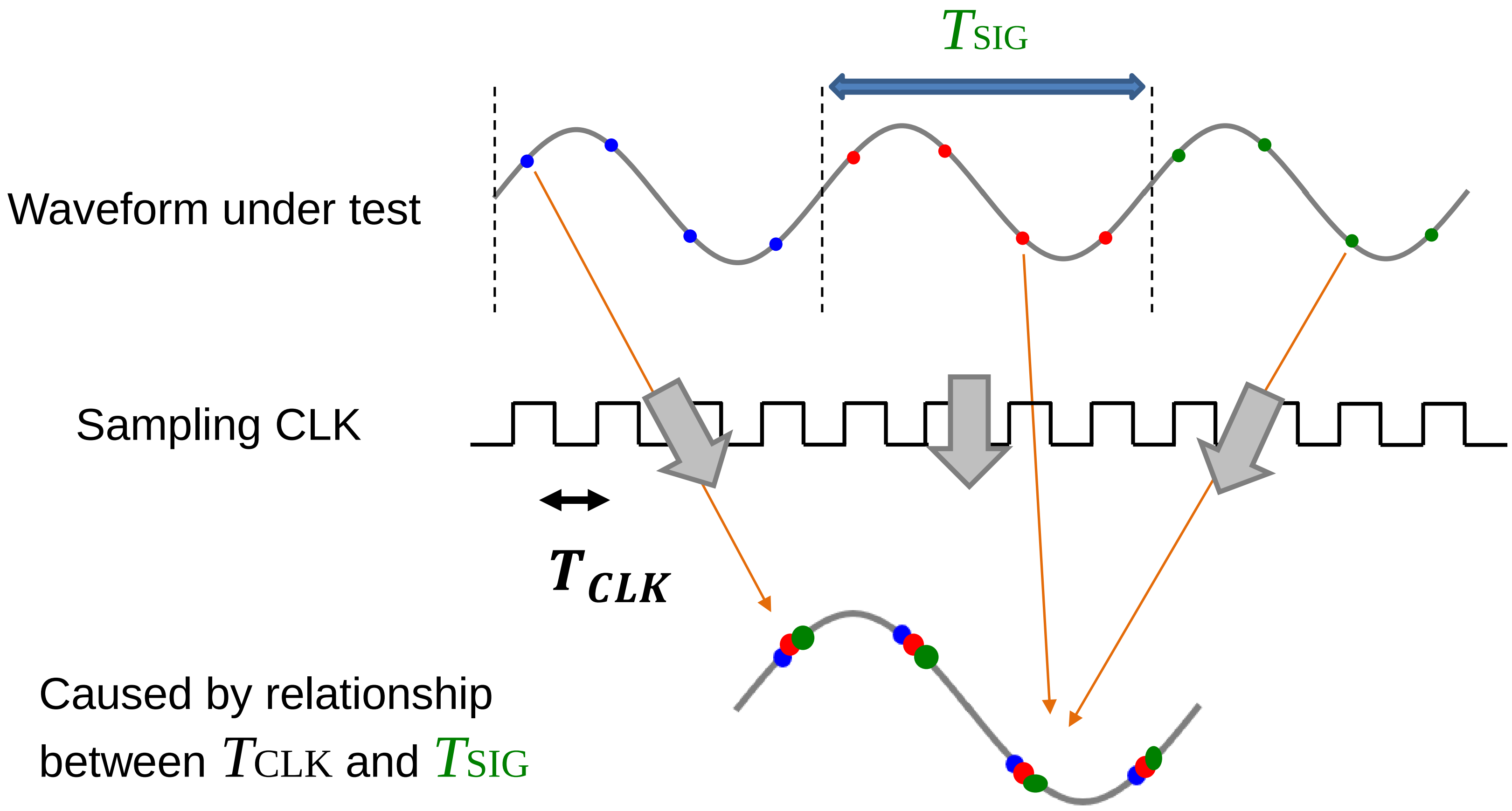
Sampling points: distributed

IC Testing and Equivalent-Time Sampling

- Input signal → Controlled during IC testing
  Input signal period T_{SIG} → Output signal period T_{SIG}



Waveform Missing Phenomena



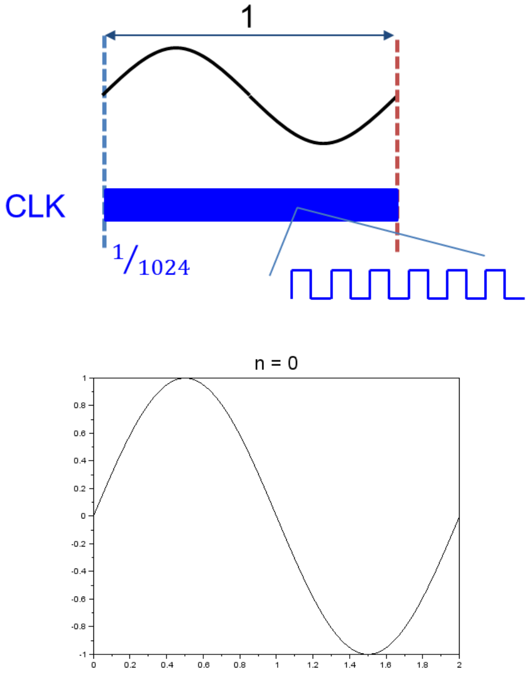
Caused by relationship between T_{CLK} and T_{SIG}

A lot of data → reconstruct one period

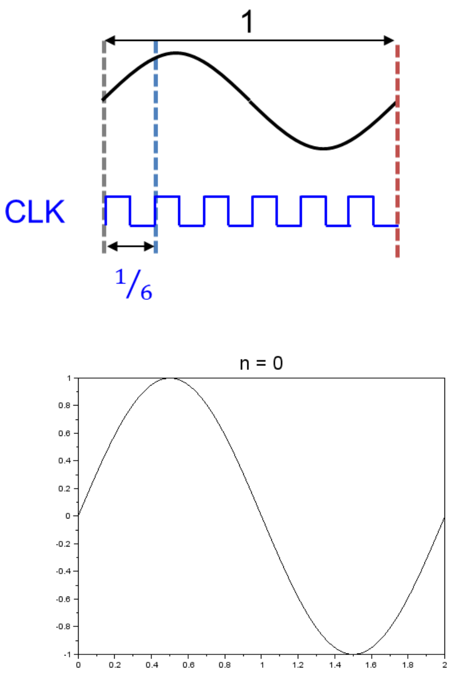
Test time : LONG

Waveform Missing Conditions

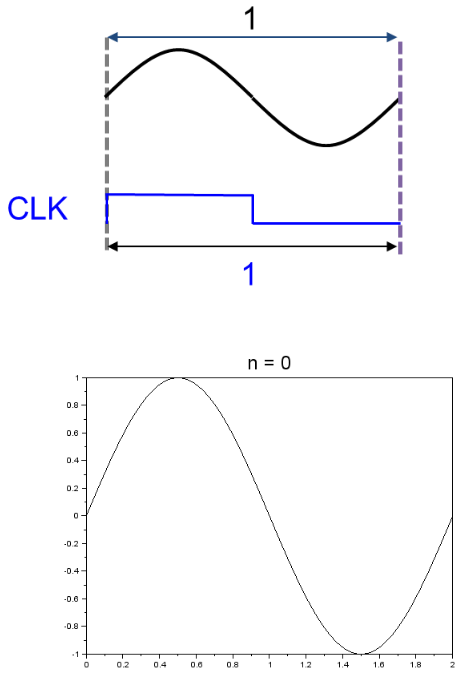
$f_{CLK} \gg f_{sin}$



$f_{CLK} \approx \frac{1}{\alpha} f_{sin} \quad \left(\alpha = 1, \frac{1}{2}, \frac{1}{3}, \frac{2}{3}, \cdots, \frac{1}{6}, \cdots\right)$



$f_{CLK} \approx f_{sin}$



Sampling points: Localized

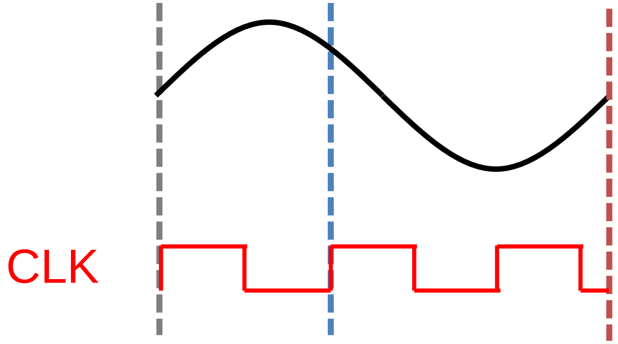
➡ One-period reconstruction time : Long ☹

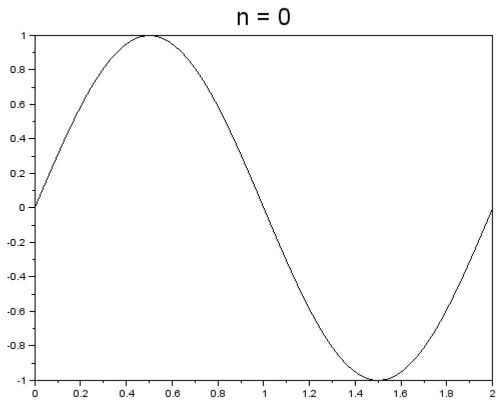
Efficient Waveform Acquisition Condition

Proper CLK

Sampling points: distributed

High efficiency waveform acquisition





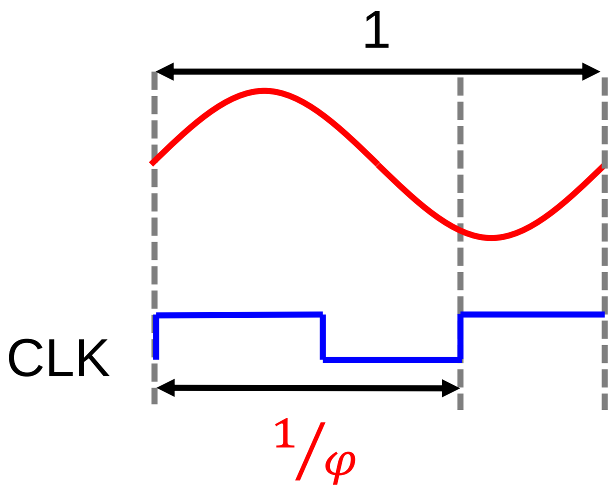
Sampling points: Distributed

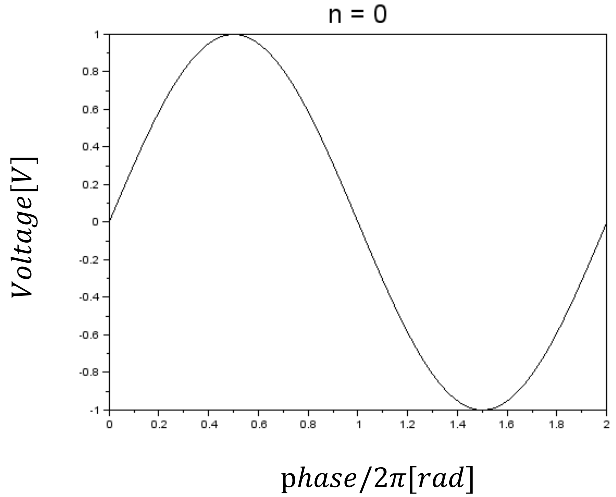
One-period reconstruction time Short

Golden Ratio Sampling

$$f_{CLK} = \varphi \times f_{sig}$$

φ : golden ratio (= 1.6180339887…)

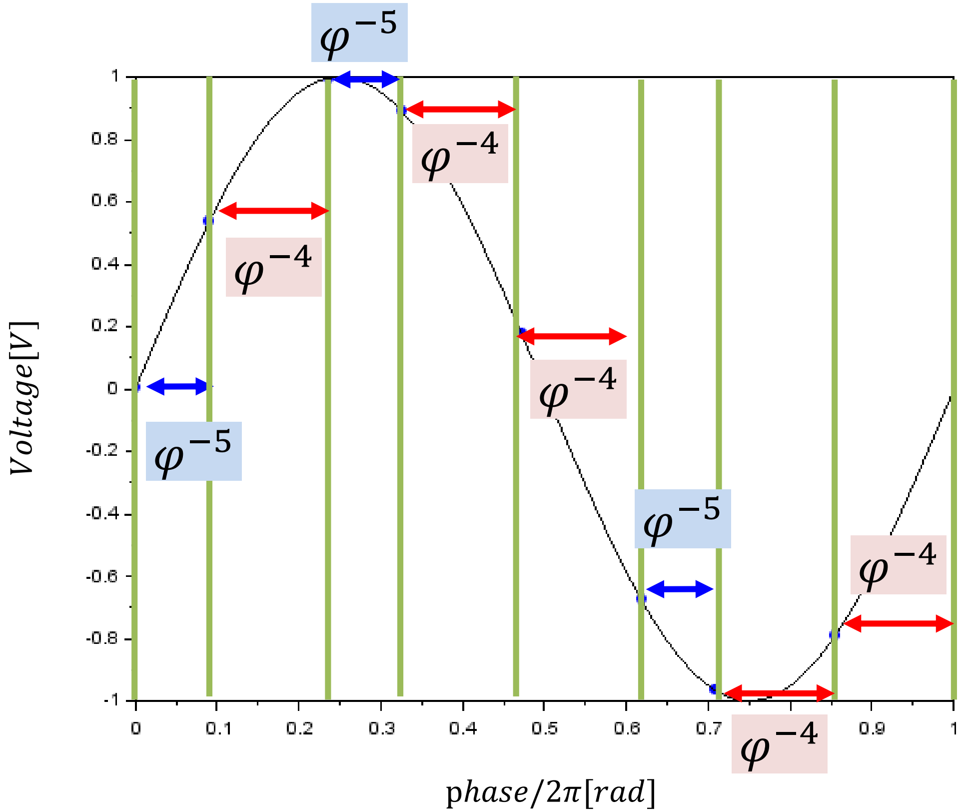




Sampling points ➡ Uniformly distributed

[2] Y. Sasaki, H. Kobayashi, et. al., "Highly Efficient Waveform Acquisition Condition in Equivalent-Time Sampling System", 27th IEEE Asian Test Symposium (Oct. 2018)

Distance of Adjacent Sampling Points



$\boldsymbol{\varphi}$: golden ratio (= 1.6180339887…)

Maximum distance／Minimum distance $= \varphi$ or φ^2

➡ Sampling points : Not too close & Not too far

Metallic Ratio

Metallic ratio

$$1 : \frac{n + \sqrt{n^2 + 4}}{2} \qquad (n = 1, 2, 3 \cdots)$$

M : Metallic number

n=1 : Golden ratio (M =1.6180…)

n=2 : Silver ratio (M = 2.4142…)

n=3 : Bronze ratio (M = 3.3027…)

⋮

n=m : 1 : M

Difference from reciprocal

$$M - \frac{1}{M} = \text{Natural Number}$$

Continued fraction

$$M = n + \cfrac{1}{n + \cfrac{1}{n + M}}$$

Limit of adjacent term ratio

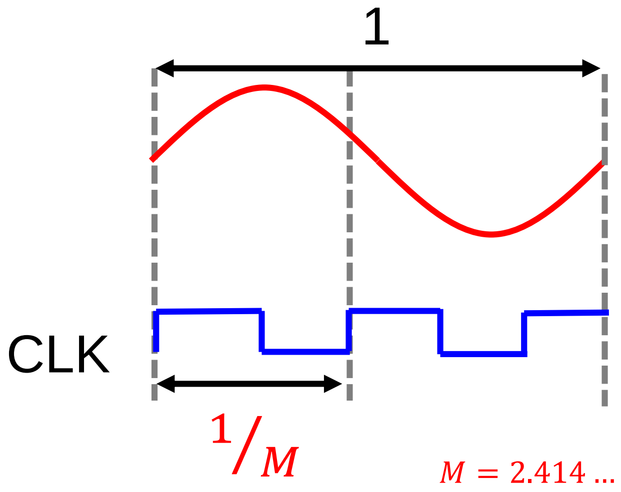
$$F_0 = 0, F_1 = 1, F_{n+2} = nF_{n+1} + F_n$$

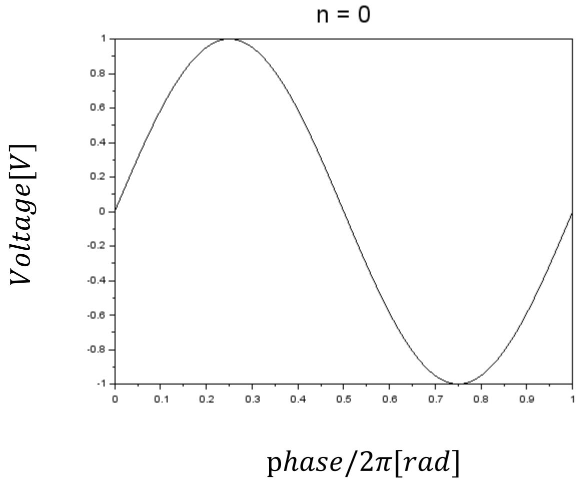
Metallic Ratio Sampling

Fixed f_{CLK} → Test ADC with various f_{sig}

$$f_{CLK} = M \times f_{sig}$$

M : Metallic ratio





In the case of silver ratio

Sampling points ➡ Always distributed evenly in phase

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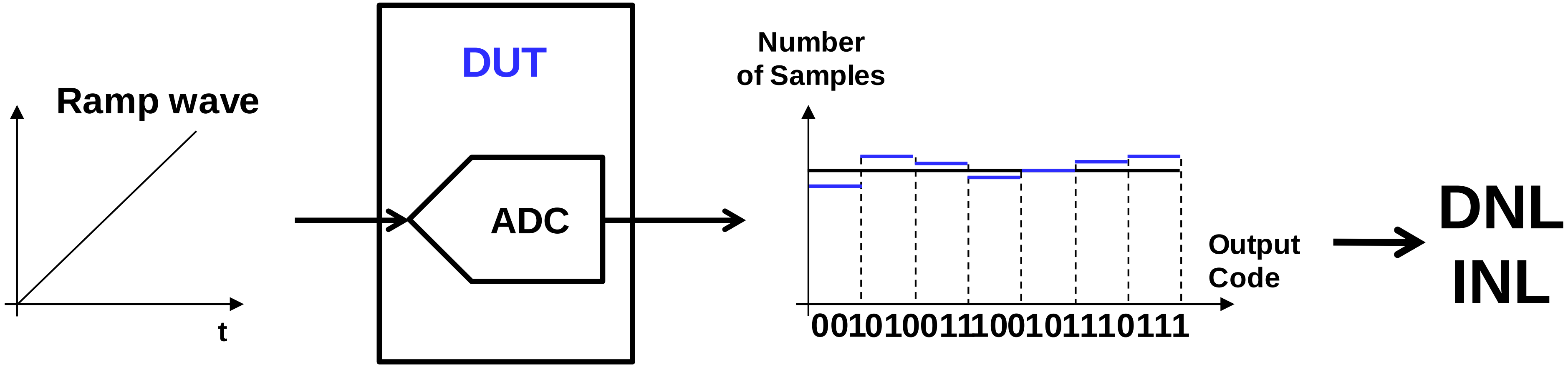
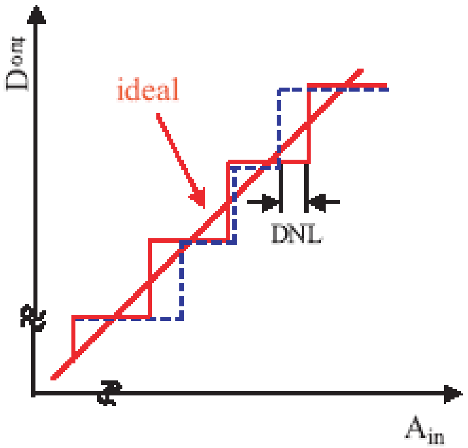
[3] Y. Zhao, H. Kobayashi, et al. "Revisit to Histogram Method for ADC Linearity Test: Examination of Input Signal and Ratio of Input and Sampling Frequencies", Journal of Electronic Testing (Mar. 2022)

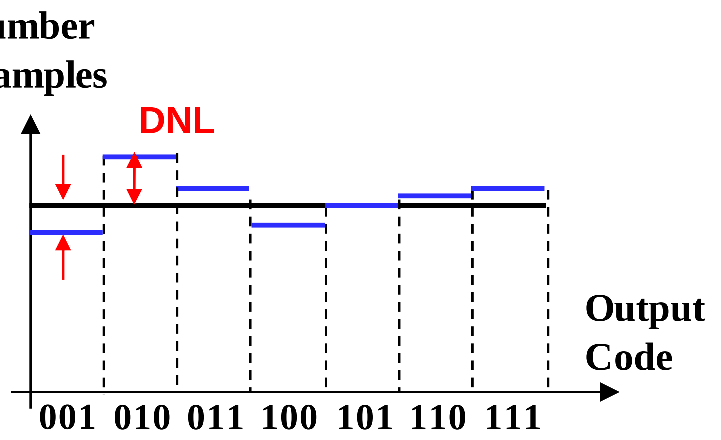
ADC Test Using Histogram with Ramp Input

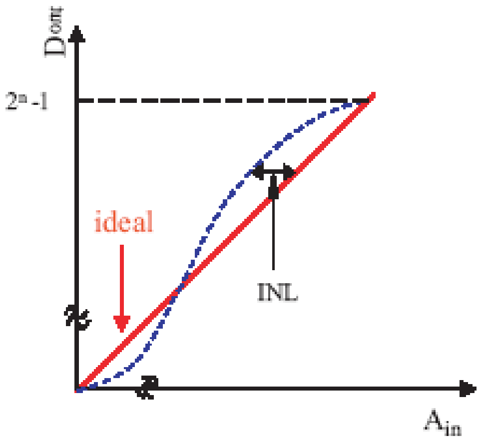


- ADC output histograms for all bins are equal if ADC is perfectly linear

DNL & INL Calculation







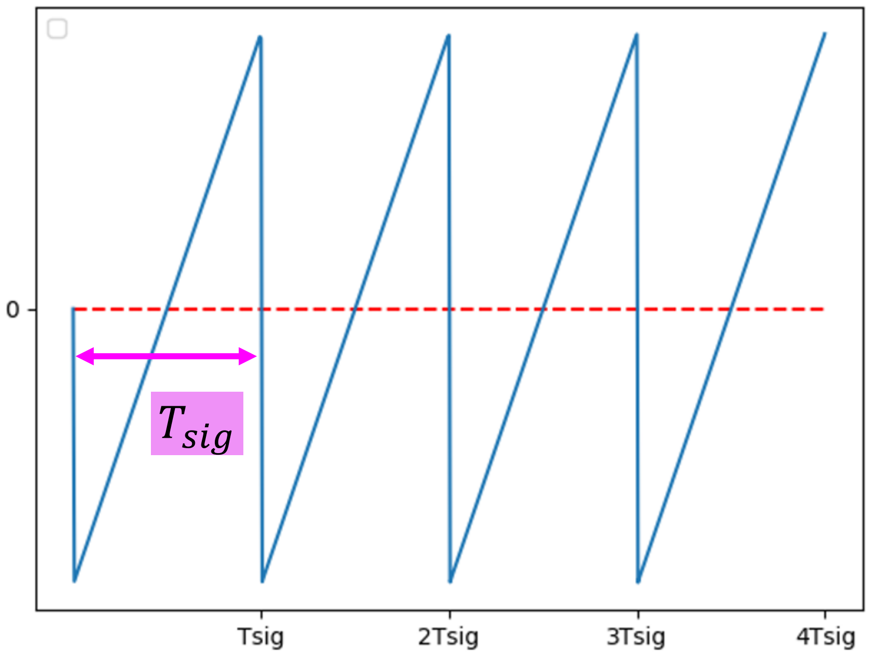
- Important ADC testing items

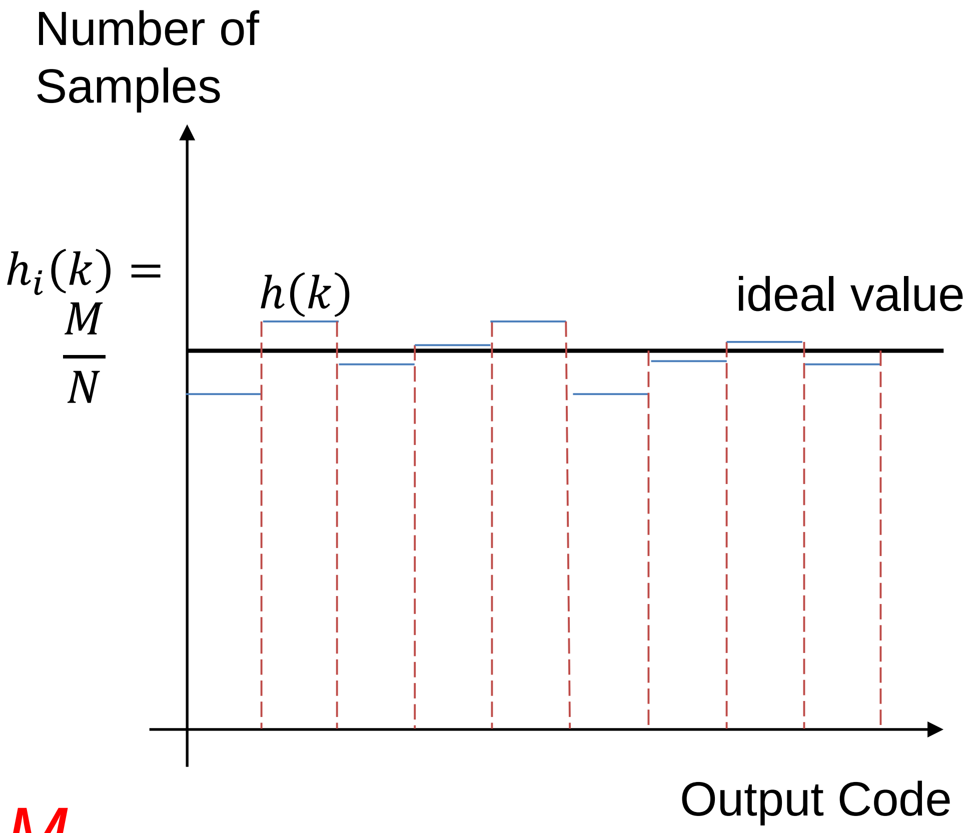
DNL : Difference between
actual step width and ideal value

INL : Deviation from ideal conversion line

$$INL(k) = \sum_{i=1}^{k} DNL(i)$$

Histogram of Ramp Signal



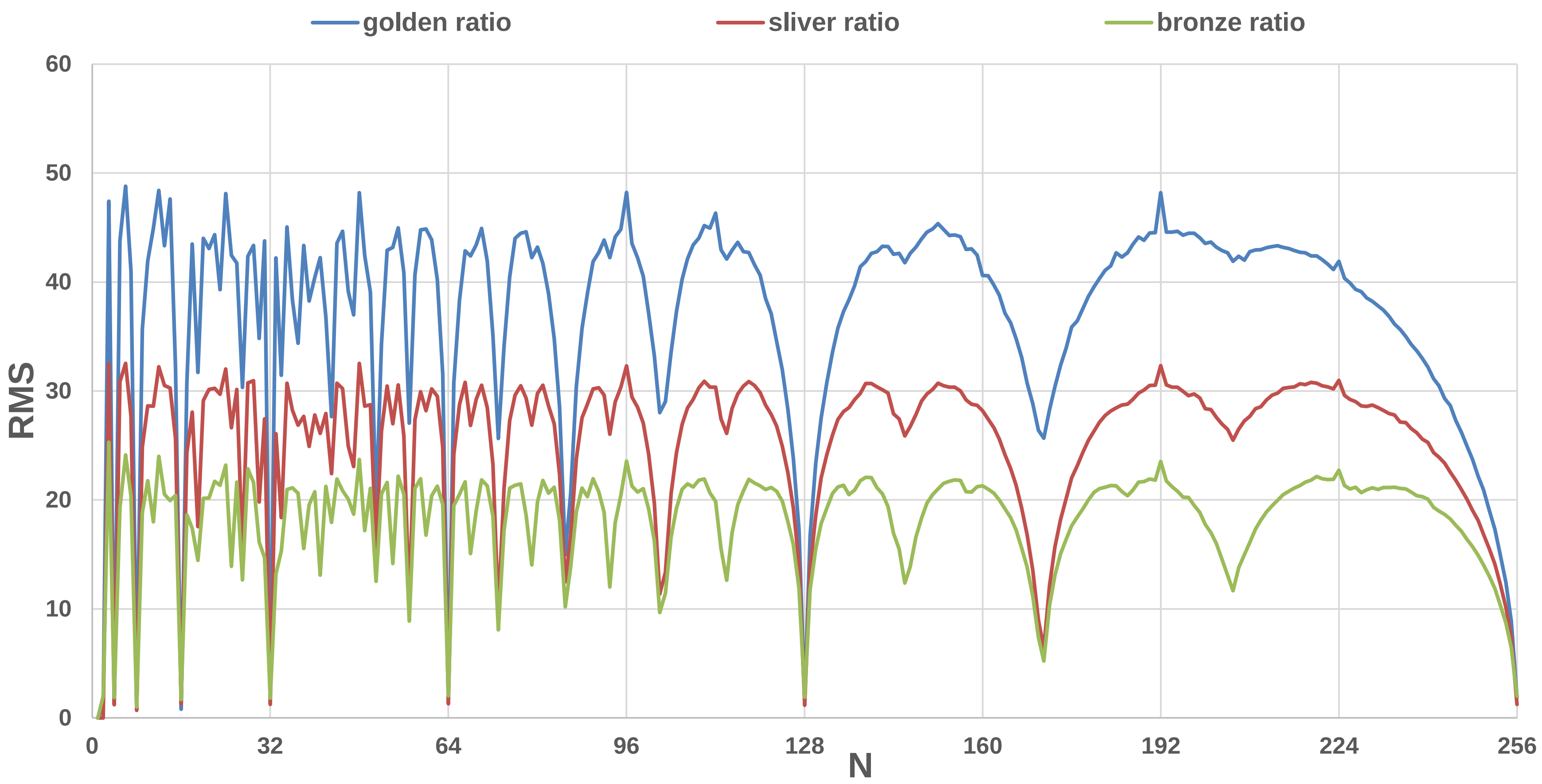


Total number of samples: *M*
ADC resolution :*N*.

ideal value $h_i(k) = \frac{M}{N}, k = 1,2,3,\ldots,N$ error $e(k) = \frac{N \cdot h(k)}{M} - 1$

RMS Error Calculation

Total number of samples: M=65536



RMS error is finite even for ideal ADC

Histogram is accurate with bronze ratio sampling

fs: sampling freq.
fin: ramp input frequency

fs : fin = 3.302 : 1

Root mean square error
between actual and ideal histograms

$$RMS = \sqrt{\frac{\sum\left(e(k)\right)^2}{N}}$$

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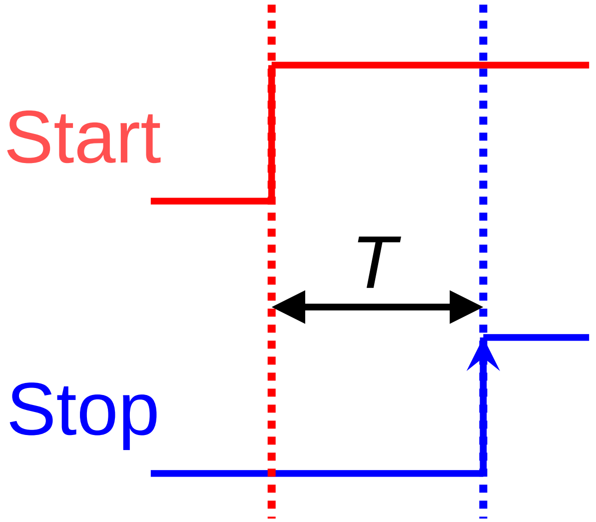
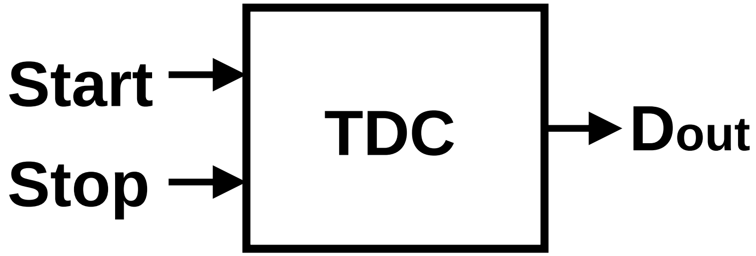
[1] S.Yamamoto, H. Kobayashi, et. al., "Metallic Ratio Equivalent-Time Sampling and Application to TDC Linearity Calibration" IEEE Trans. Device and Materials Reliability（Mar. 2022)

Time to Digital Converter（TDC）

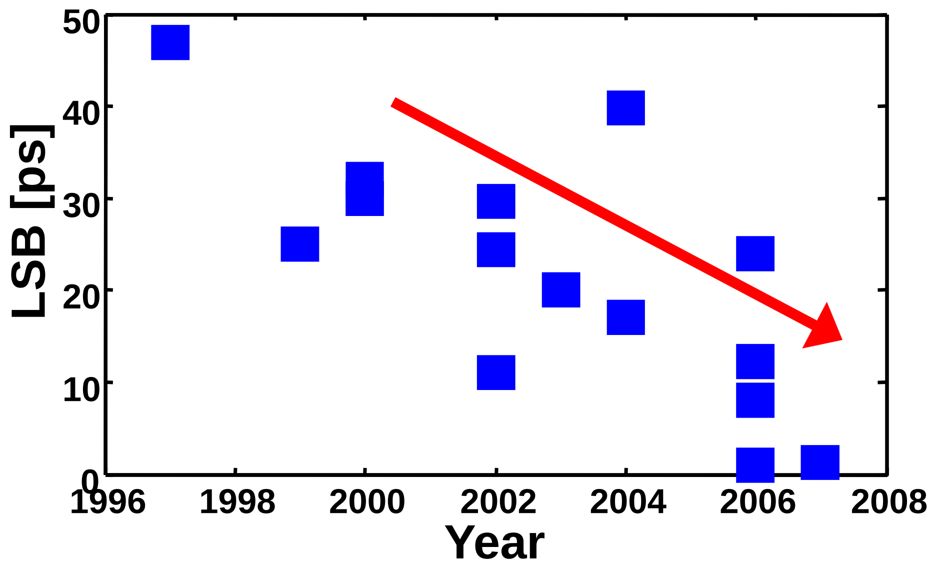
- time interval → Measurement → Digital value



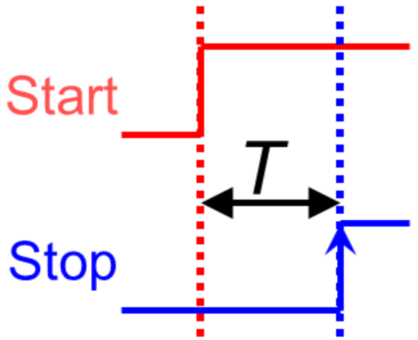


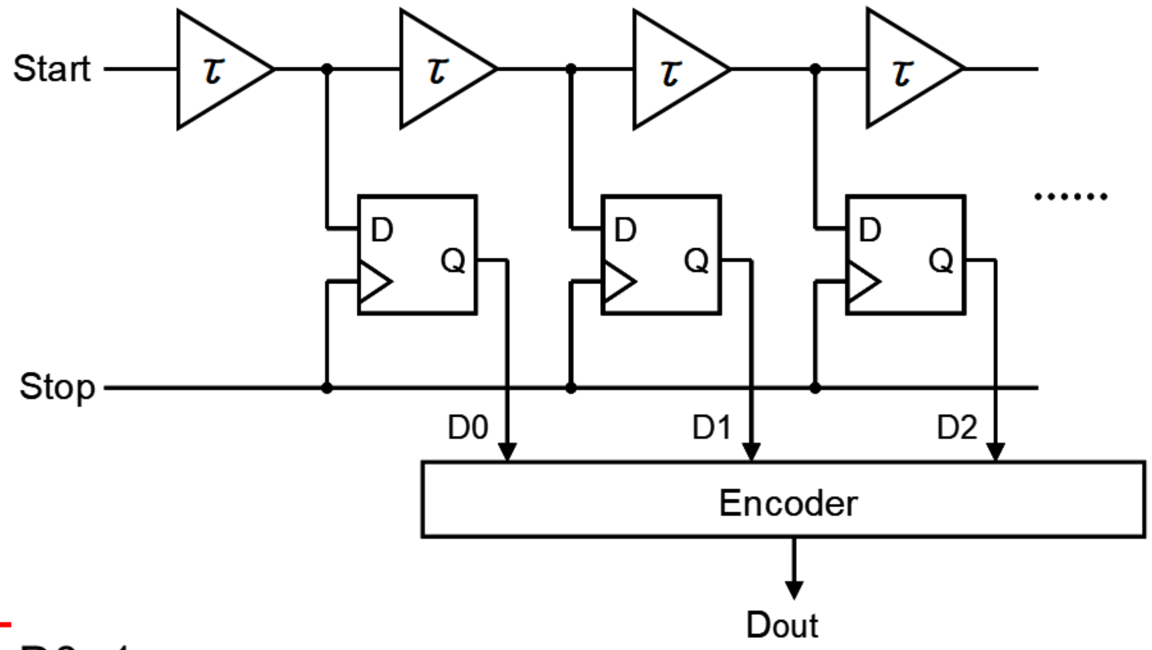
- Key component of Time-domain analog circuit
- Higher resolution can be obtained with scaled CMOS

Higher resolution with CMOS scaling

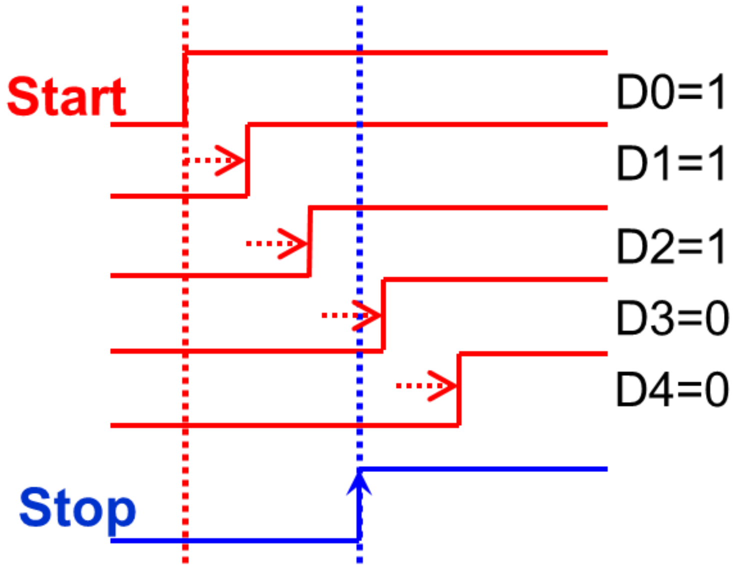


Time-to-Digital Converter（TDC）





Timing chart



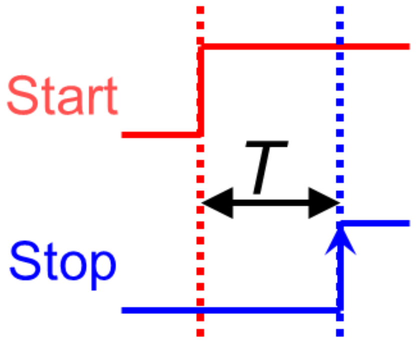
Encoder

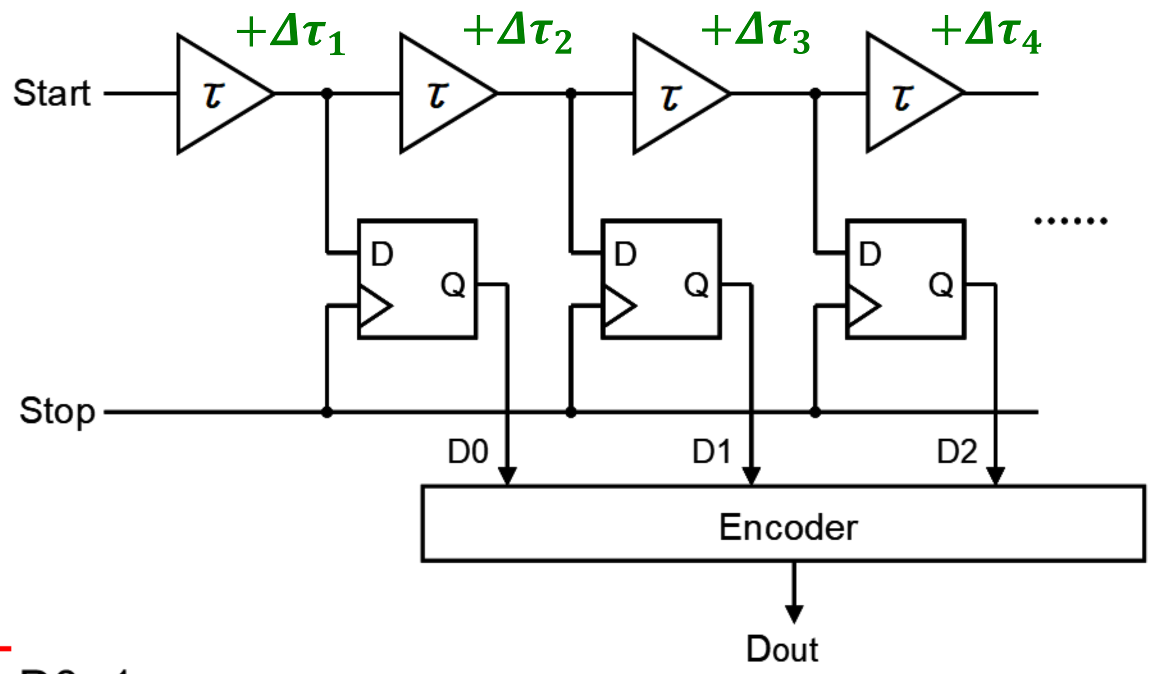
Thermometer code

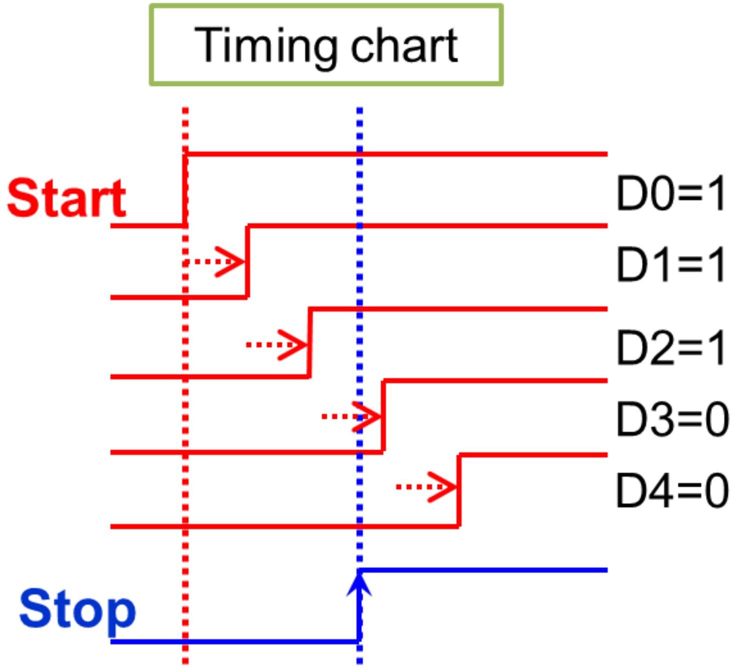
▼

binary code

Time-to-Digital Converter（TDC）





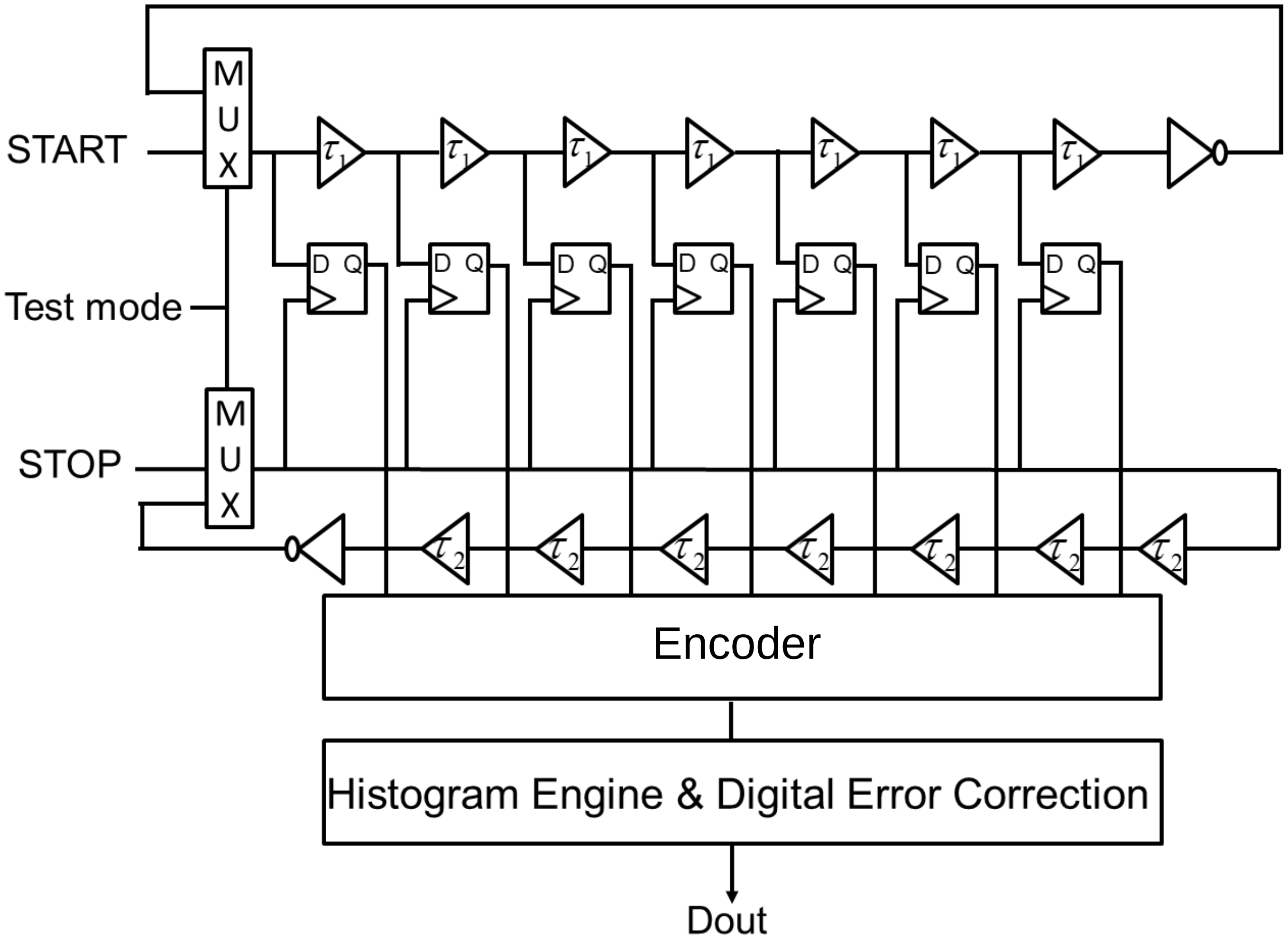


Encoder

Thermometer code

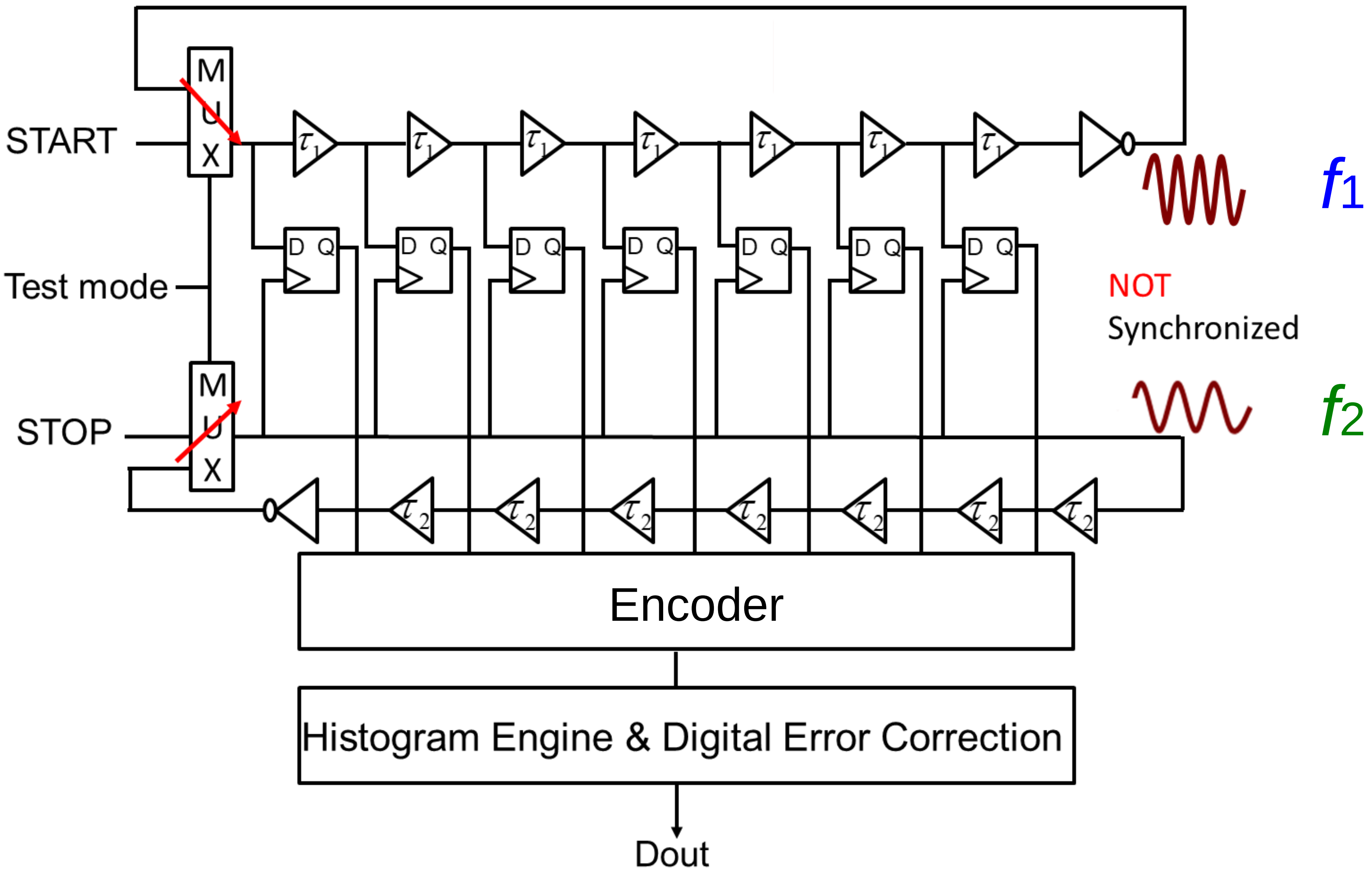
binary code

TDC Linearity Self-Calibration with Histogram

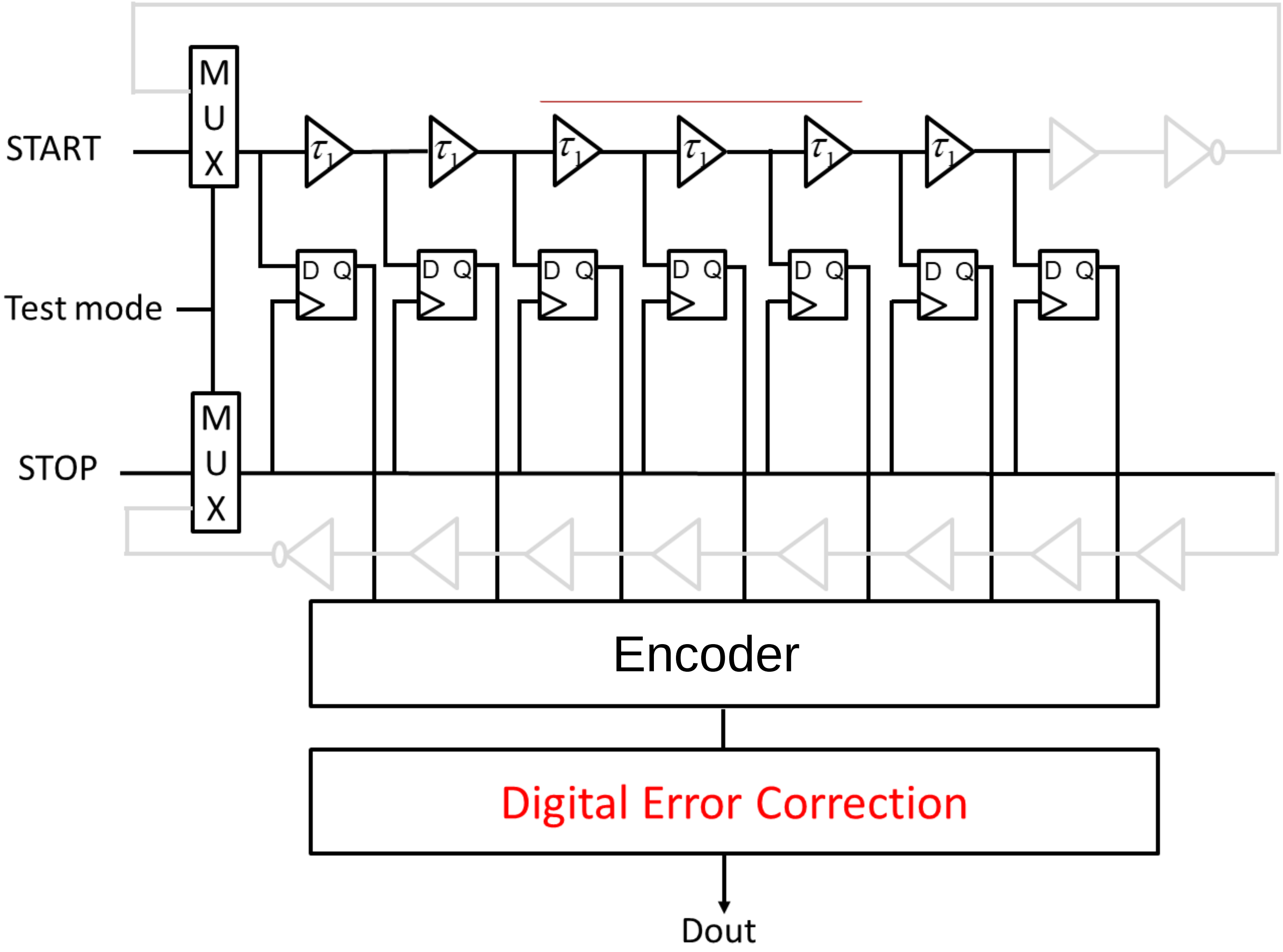


[4] S. Ito, H. Kobayashi, et al. “Stochastic TDC Architecture with Self-Calibration,” IEEE Asia Pacific Conference on Circuits and Systems (Dec. 2010)

Self-Calibration Mode



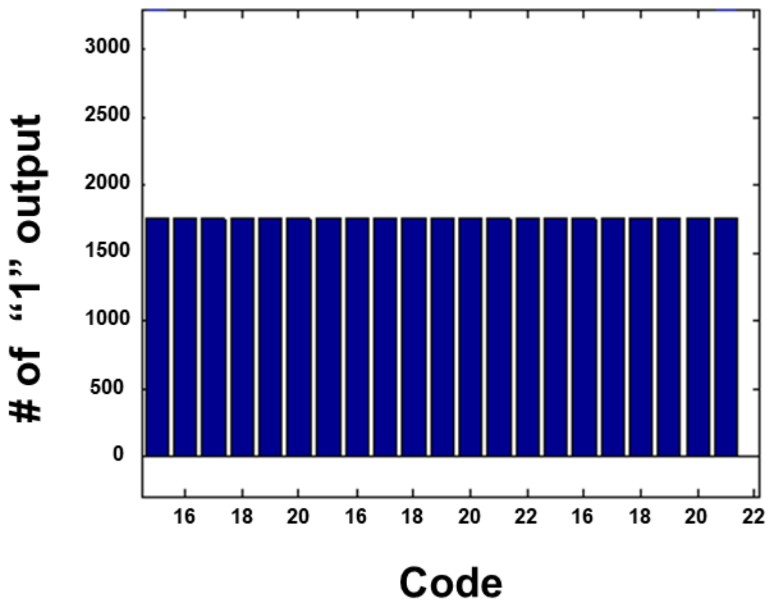
Normal Operation Mode



Histogram for Ideal TDC

Self-Calibration Mode

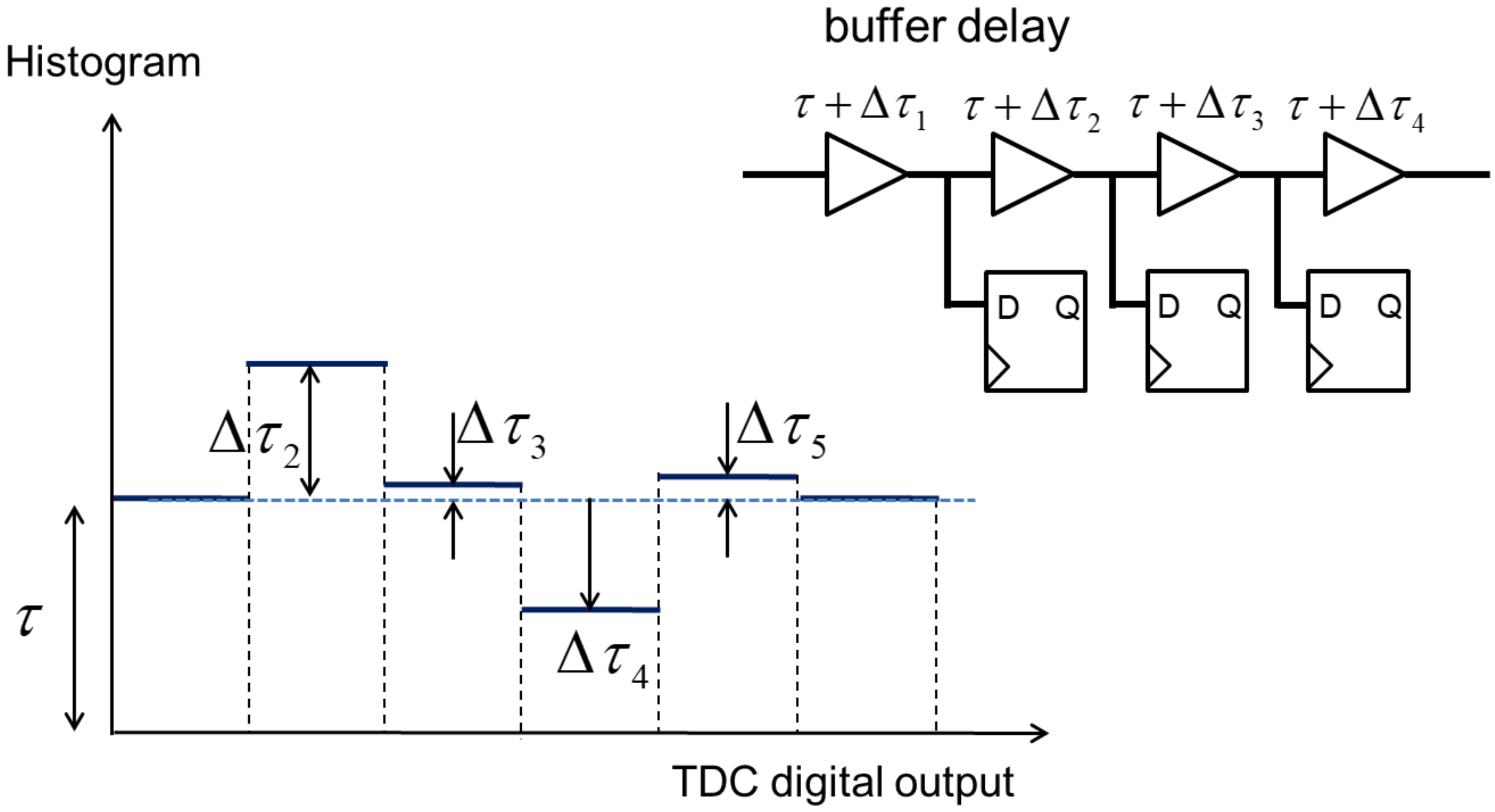
The two oscillators are different from each other and not synchronized



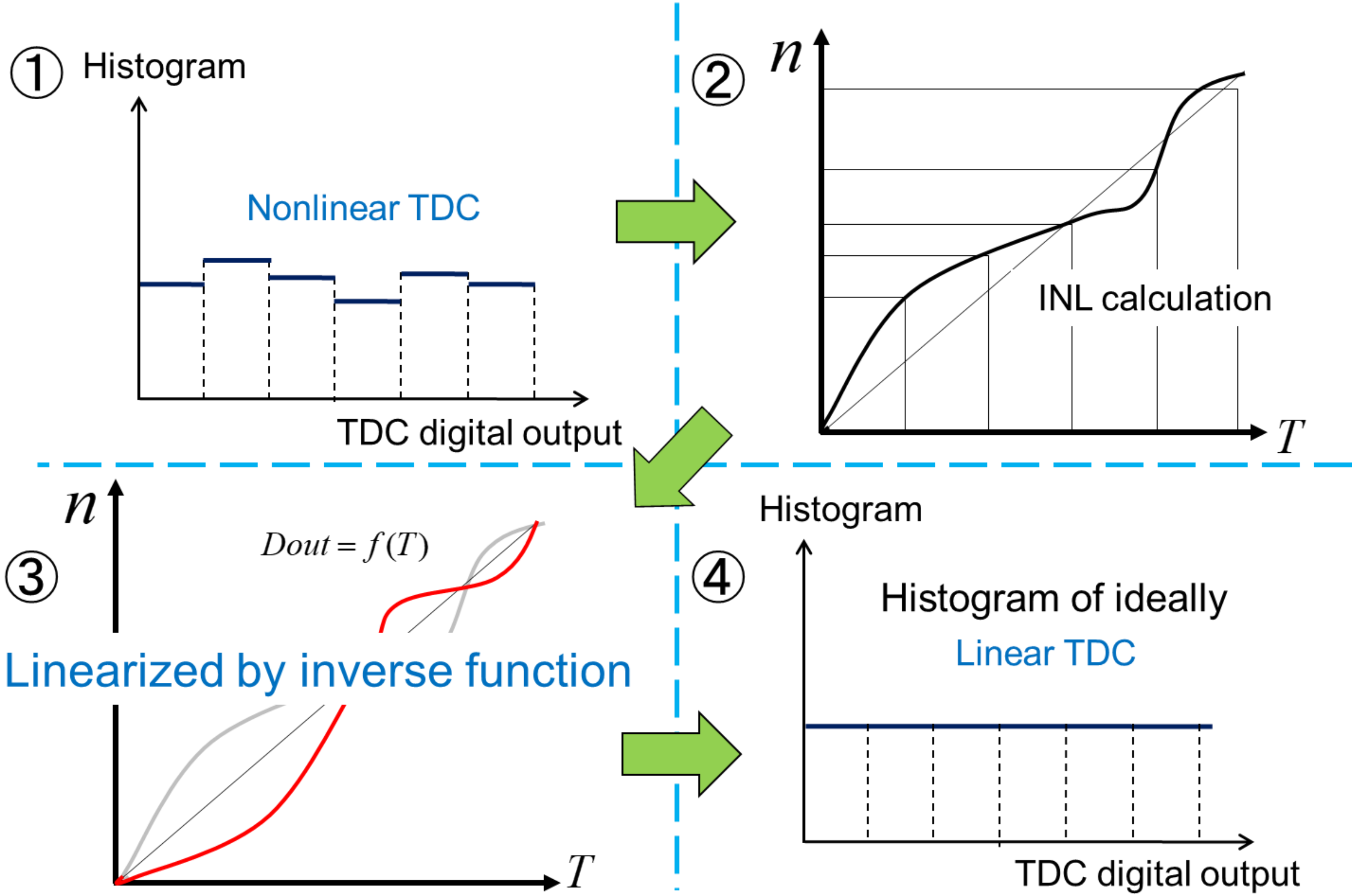
The histograms in all bins will be equal, after collection of a sufficiently large number of data, if the TDC has perfect linearity

Histogram for Delay Mismatches

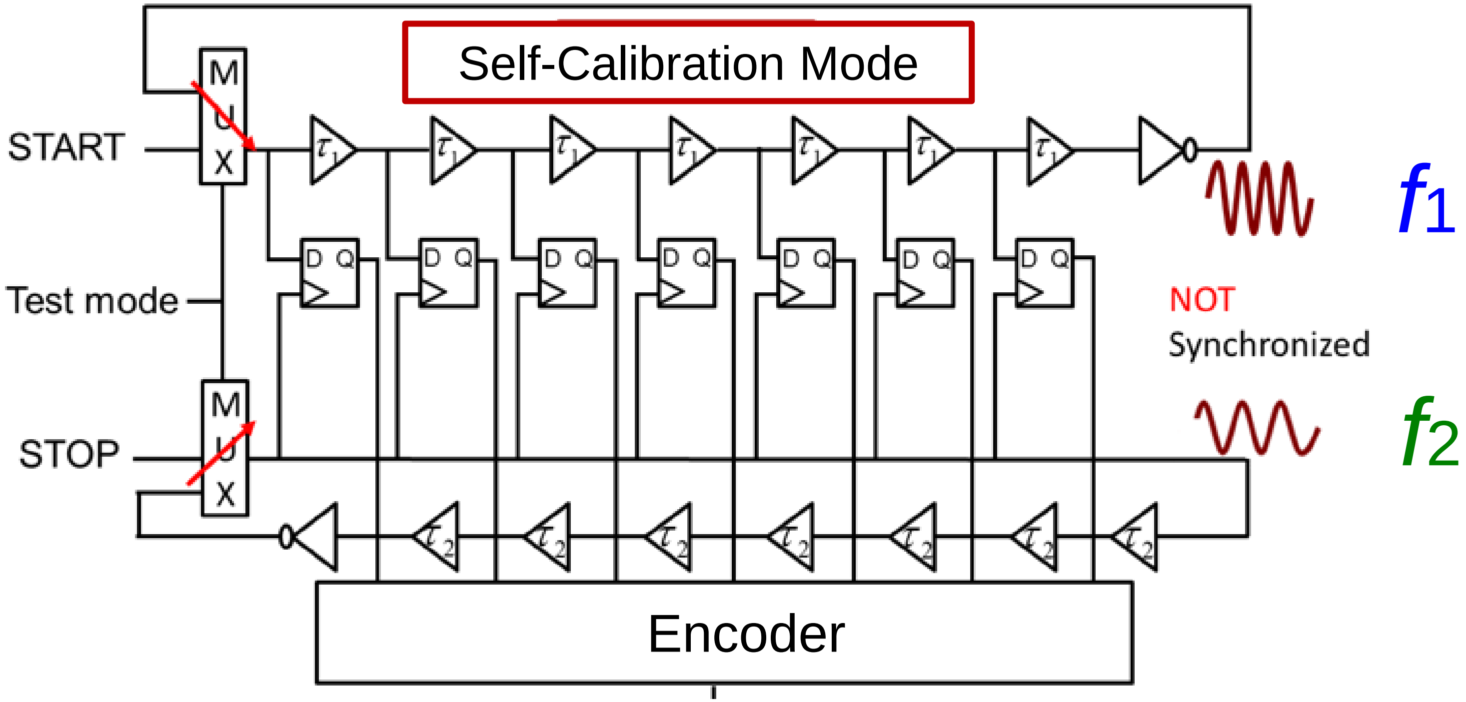
TDC is non-linear



Principle of Linearity Self-Calibration



Effective Self-Calibration Condition



Our new finding

f_1 : f_2 Metallic ratio ⇨ Accurate calibration with small number of data

[1] S. Yamamoto, H. Kobayashi, et. al., "Metallic Ratio Equivalent-Time Sampling and Application to TDC Linearity Calibration" IEEE Trans. Device and Materials Reliability (Mar. 2022)

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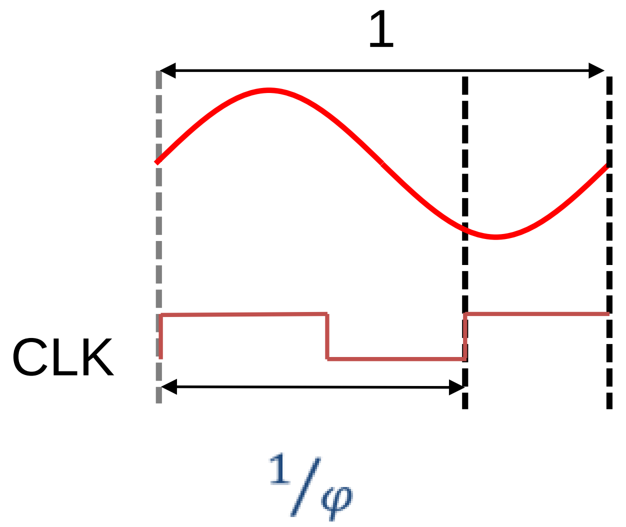
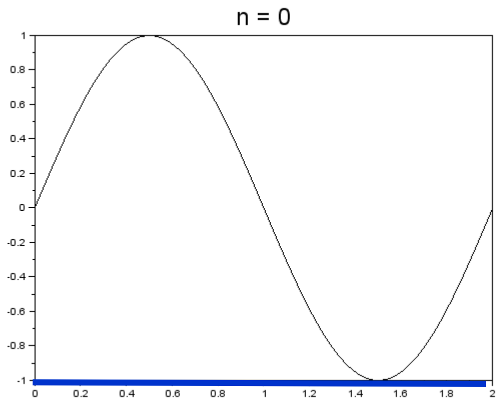
Pseudo Random Signal Generation

$$f_{CLK} = \varphi \times f_{sig}$$

φ : Golden ratio (= 1.6180339887…)





⇨ **Our proposal:**
Pseudo Random Signal
With Uniform Distribution

Sampling points disperse uniformly

[7] R. Ohta, A. Kuwana, et al., "Pseudo Random Number Generation Algorithms with Fibonacci Sequence“, 31st International Workshop on Post-Binary ULSI Systems ((May 2022)

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- Equivalent-Time Sampling Time-Base
- Metallic Ratio Sampling
  - AMS IC Testing Applications
  - ADC Histogram Test Application
  - TDC Linearity Self-Calibration Application
  - Pseudo Random Signal Generation
- <u>Proactive Use of Finite Aperture Time</u>
- Conclusion

[5] Y. Yan, H. Kobayashi, et al., "Proactive Use of Finite Aperture Time in Sampling Circuit for Sensor Interface“, 5th International Conference on Technology and Social Science (Dec. 2021)

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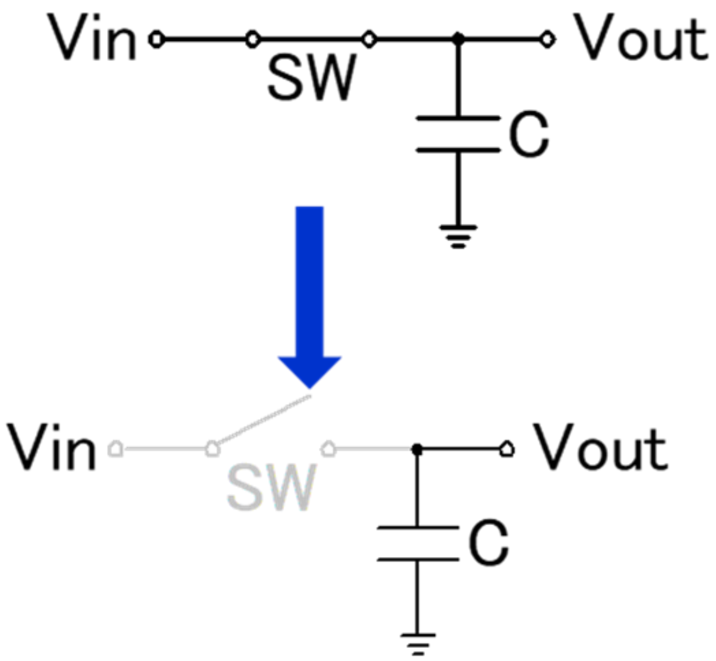
Finite Aperture Time

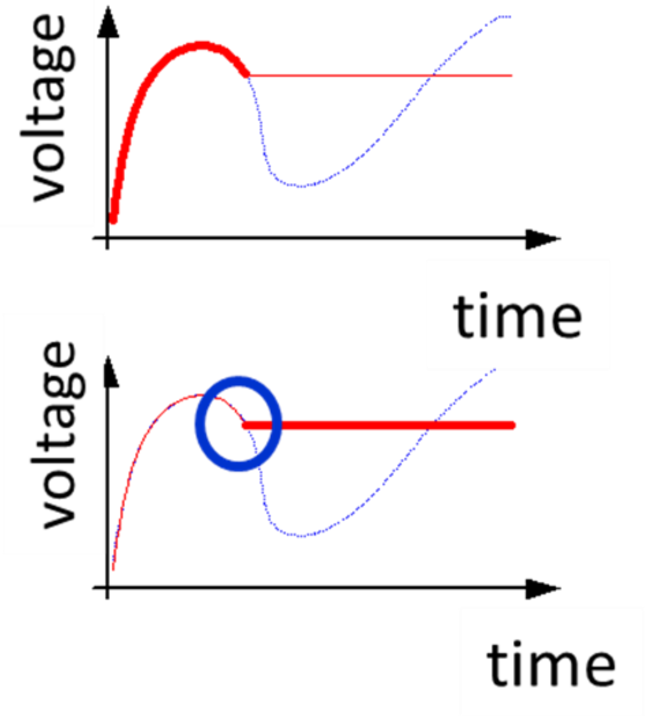


- SW: ON
  - $V_{out}(t) = V_{in}(t)$

  Track mode

- SW: OFF
  - $V_{out}(t) = V_{in}(t_{OFF})$

  Hold mode



Finite transition time from track to hold modes

Analogy with Camera Shutter Speed

Camera: Finite Shutter Speed

Moving Object

Blurred

Sampling Circuit:
Finite Aperture Time

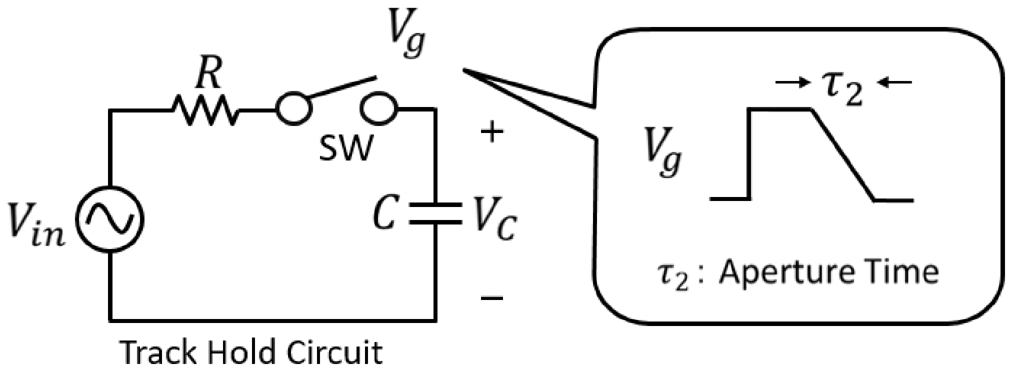
Input Signal

High frequency

Acquired Signal

Low pass filtered

Low Pass Filtering Effect of Aperture Time



Explicit transfer function

$$\frac{V_C}{V_{in}} = \frac{sinc(\omega\tau_2)}{sinc(\omega\tau_2) + j\omega\tau_1}$$

Here τ_1= RC.

Finite aperture time τ_2 ➡ Lowpass filter action

- Bad for high frequency signal sampling
- Good for low frequency signal sampling

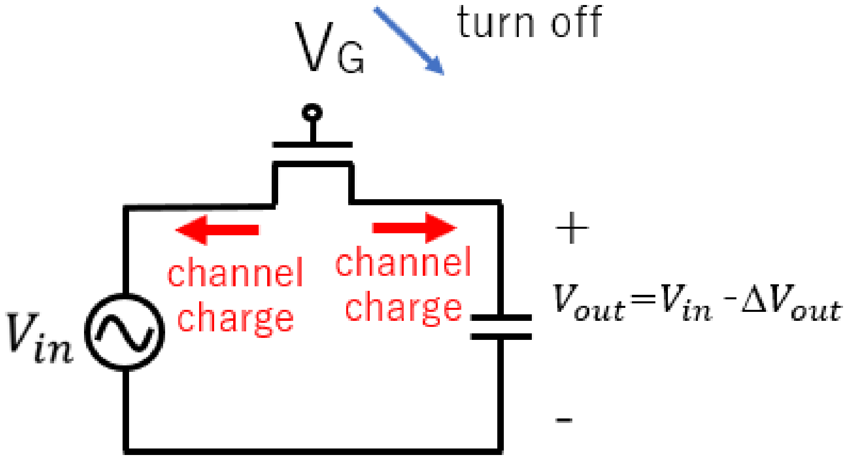
➡ Lowpass filter simplification

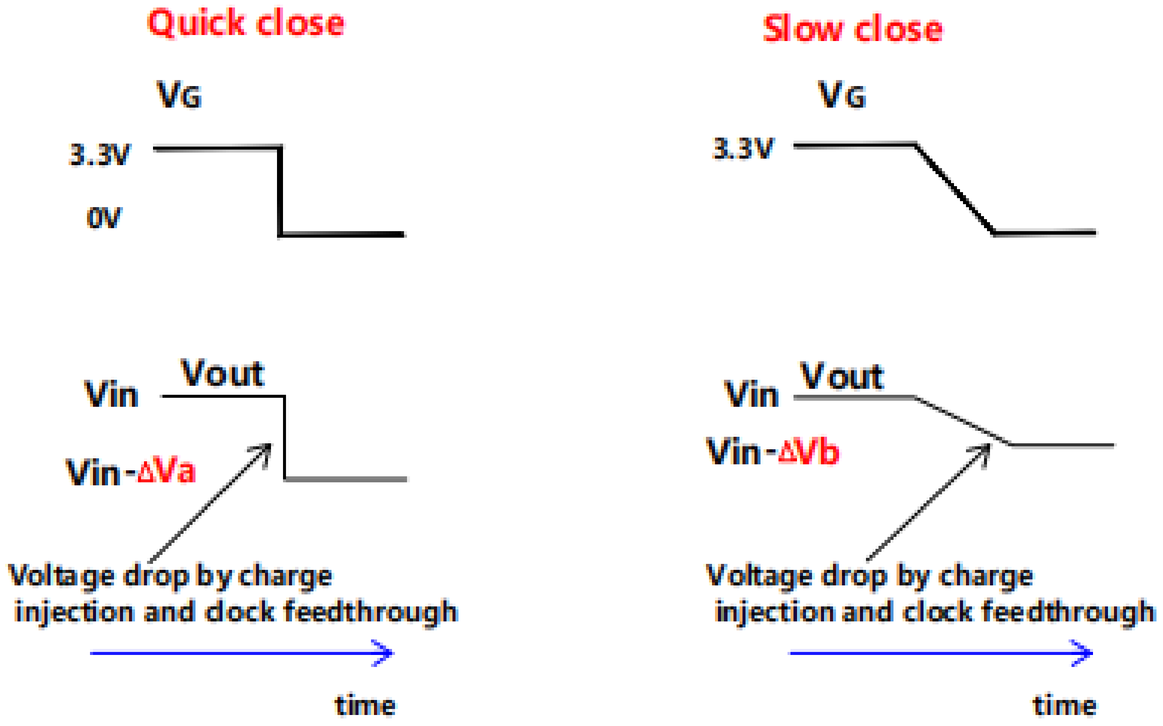
[6] M. Arai, H. Kobayashi , et. al. “Finite Aperture Time Effects in Sampling Circuit,” IEEE 11th International Conference on ASIC (Nov. 2015).

Long Finite Aperture Time

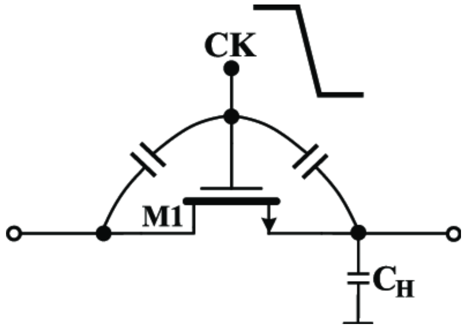
Small pedestal error

- Small charge injection





- Small clock feedthrough



Proactive Use of Finite Aperture Time

- Finite aperture time in sampling circuit:

  Integral time from hold start to switch opening end.

- High frequency signal acquisition:

  ➡ Performance deterioration

- Low frequency signal acquisition:

  ➡ Proactive use for lowpass filtering

  Explicit transfer function

  ➡ Used for sensor interface analog circuit

- Pedestal error in sampling circuit

  ➡ Caused by charge injection and clock feedthrough.

- Pedestal error reduction for long aperture time.

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Conclusion

- Varieties of waveform sampling related technologies
- Equivalent-time sampling
  - Three time-bases
  - Metallic ratio sampling
  - Application to ADC histogram test
  - Application to TDC linearity self-calibration
  - Application to pseudo random signal generation
- Proactive use of finite aperture time
  - Useful for sensor interface analog circuit
- Still many challenges