21st IEEE International Mixed-Signal Testing Workshop
Catalunya, Spain

July 5, 2016
9:00-9:30am

Conference Room: Goya

Timing Measurement BOST Architecture with Full Digital Circuit and Self-Calibration Using Characteristics Variation Positively for Fine Time Resolution

Congbing Li, Junshan Wang, Haruo Kobayashi
Ryoji Shiota

Gunma University, Socionext Inc.

Kobayashi Laboratory

群馬大学 GUNMA UNIVERSITY

Outline

- Introduction
- Time to Digital Converter（TDC）
- Encoder Circuit
- Self-Calibration
- Stochastic TDC Structure
- RTL Simulation
- Conclusions

Outline

- Introduction
- Time to Digital Converter（TDC）
- Encoder Circuit
- Self-Calibration
- Stochastic TDC Structure
- RTL Simulation
- Conclusions

Introduction

“Fine time resolution” and “high linearity” TDC is essential for jitter, timing BOST

- High linearity TDC

  →Self-calibration circuit

- Fine time resolution TDC

  →Stochastic architecture

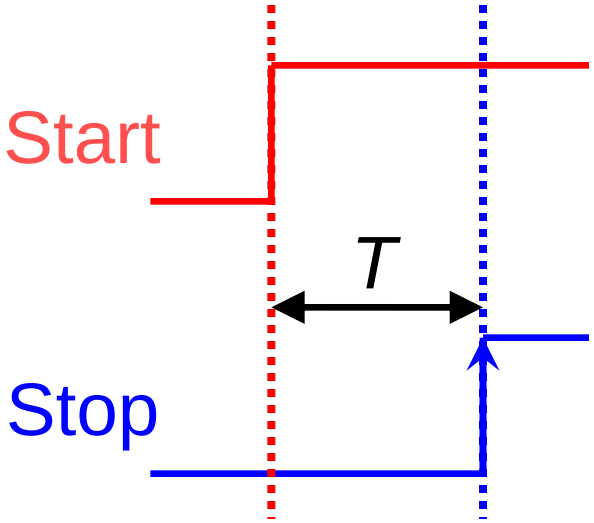
TDC: Time-to-Digital Converter
BOST: Built-Out Self-Test

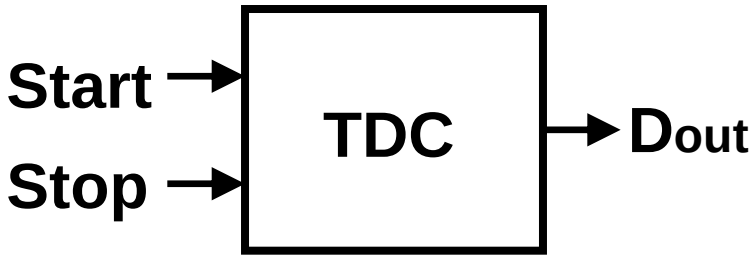
Outline

- Introduction
- Time to Digital Converter（TDC）
- Encoder Circuit
- Self-Calibration
- Stochastic TDC Structure
- RTL Simulation
- Conclusions

Time to Digital Converter（TDC）

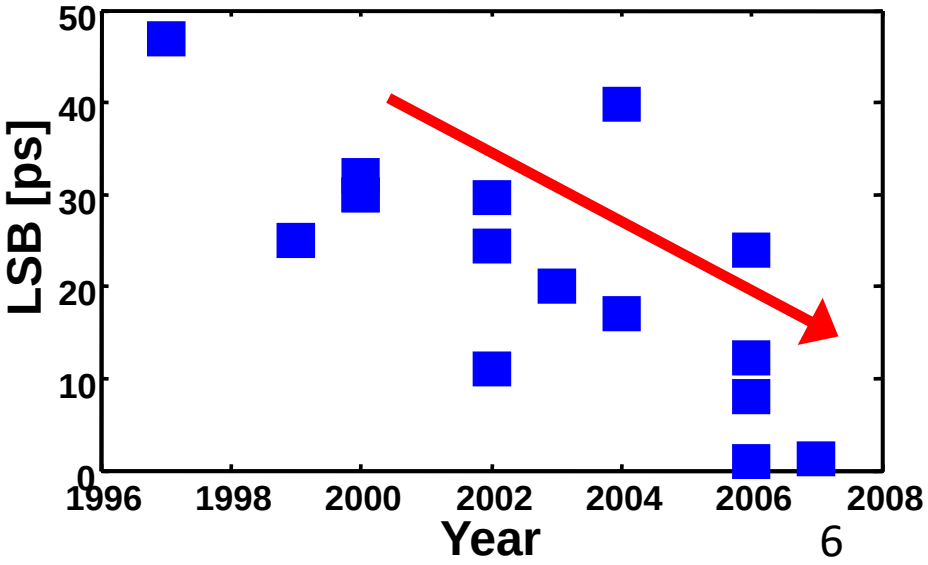
- time interval → Measurement → Digital value



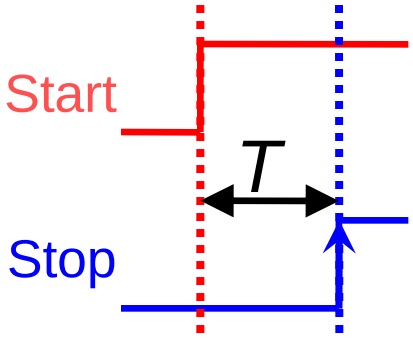


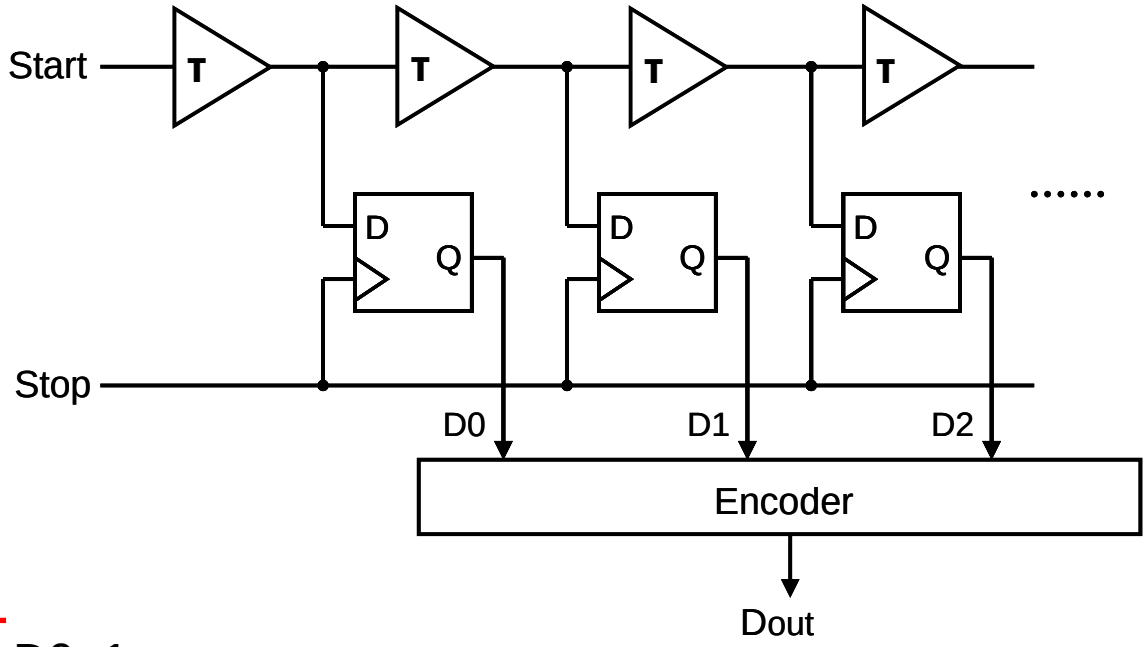
- Key component of time-domain analog circuit
- Higher resolution can be obtained with scaled CMOS

Higher resolution with CMOS scaling

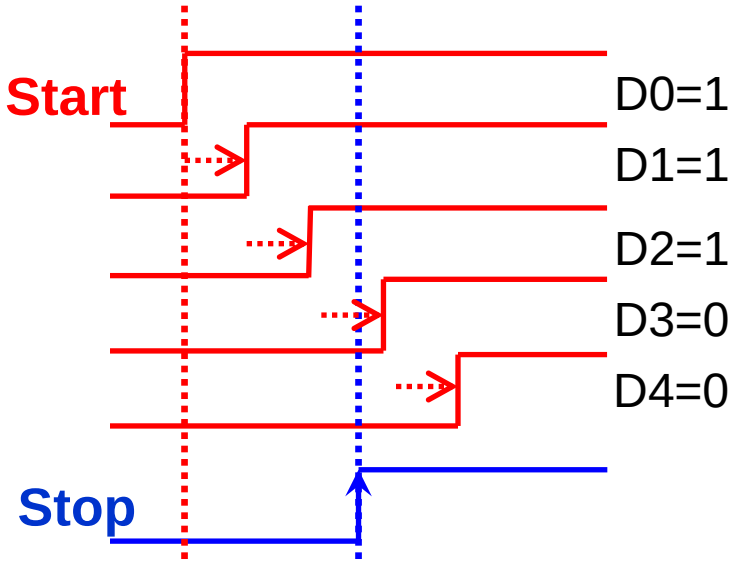


Time to Digital Converter（TDC）





Timing chart



Encoder

Thermometer code

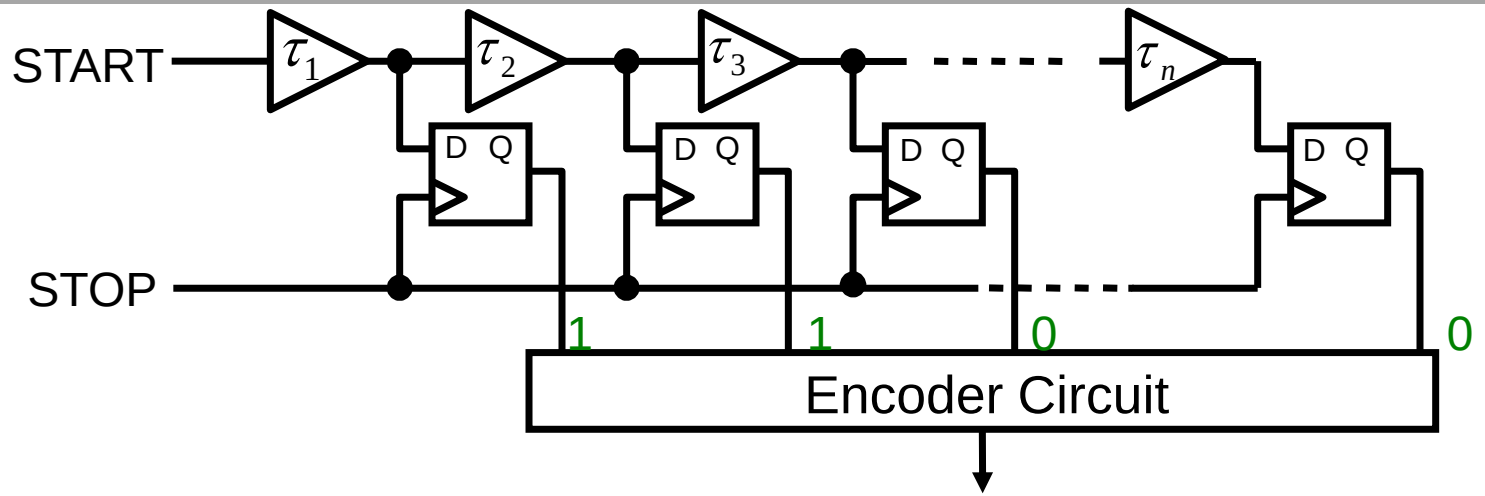
▼

binary code

Outline

- Introduction
- Time to Digital Converter（TDC）
- Encoder Circuit
- Self-Calibration
- Stochastic TDC Structure
- RTL Simulation
- Conclusions

Encoder Circuit

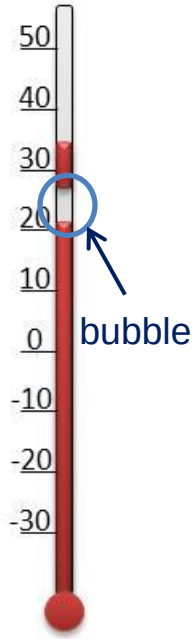


DFF outputs	Dout
0 0 0 0 0 0 0 0	0
1 0 0 0 0 0 0 0	1
1 1 0 0 0 0 0 0	2
1 1 1 0 0 0 0 0	3
1 1 1 1 0 0 0 0	4
1 1 1 1 1 0 0 0	5
1 1 1 1 1 1 0 0	6
1 1 1 1 1 1 1 0	7
1 1 1 1 1 1 1 1	8

1 0 1 0 0 0 0 0	2
1 1 1 0 0 0 0 0	3
1 1 1 0 1 0 0 0	4
1 1 1 0 1 0 1 0	5
1 1 1 0 1 0 1 1	6

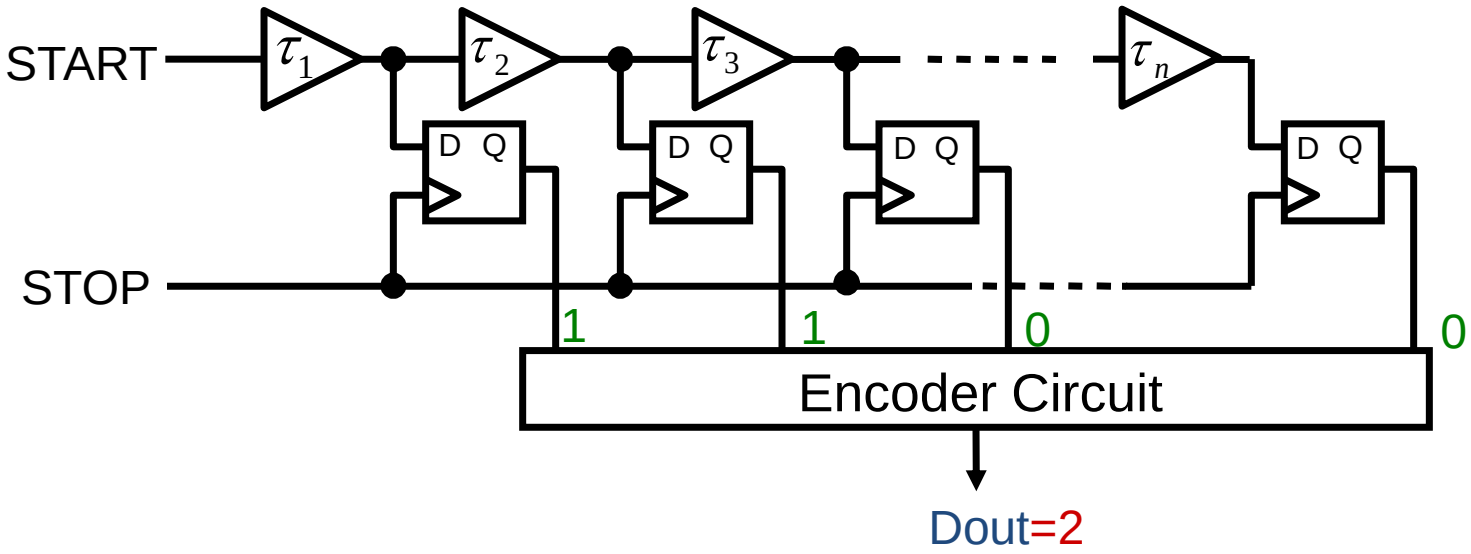
Buffer delay
DFF offset mismatch

Bubble error



thermometer

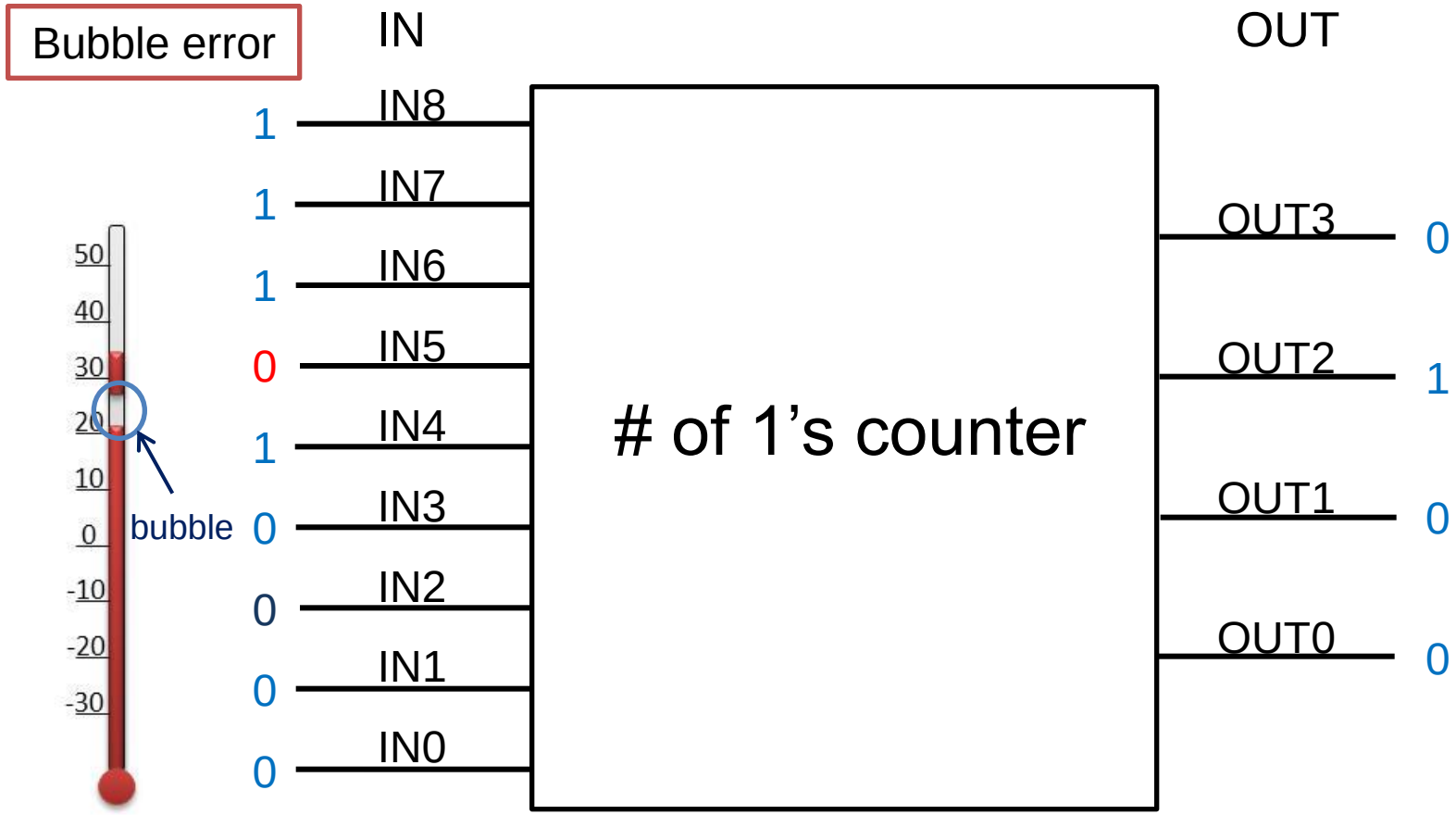
Encoder Circuit



Count the number of “1” outputs from DFFs

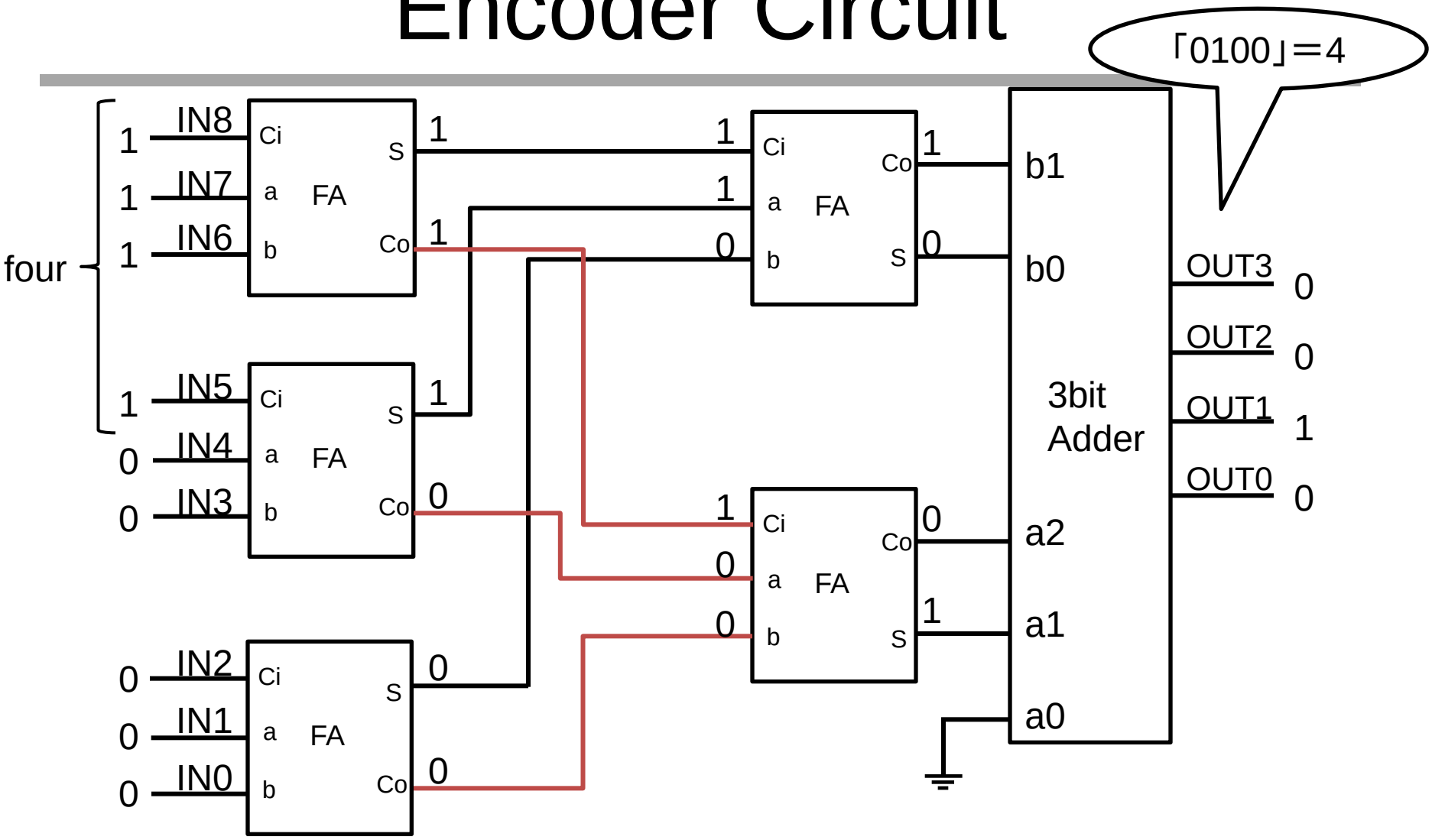
To ensure monotonicity of the TDC

Encoder Circuit



Bubble error effects are suppressed.

Encoder Circuit

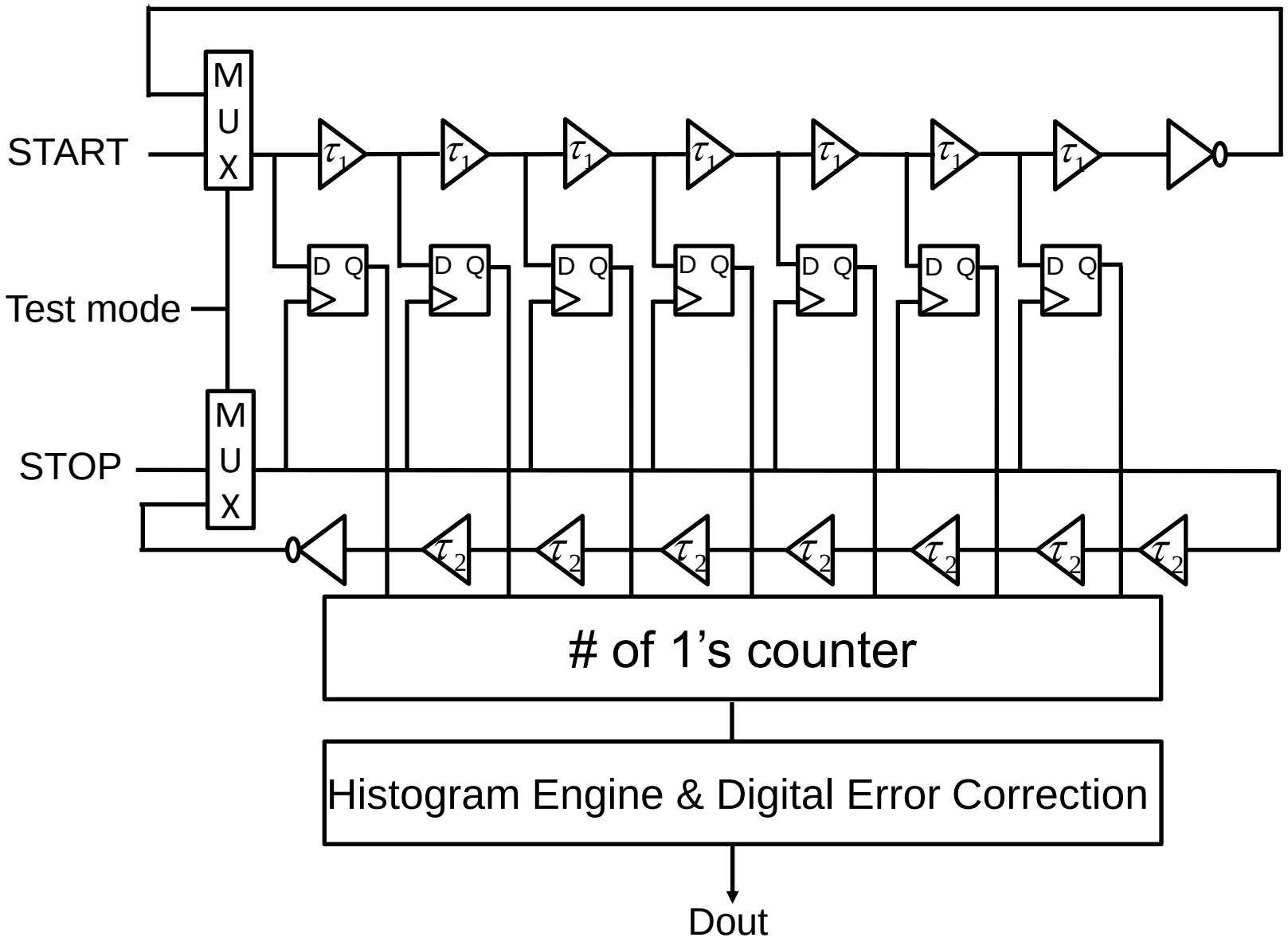


Designed the encoder using an array of full adders

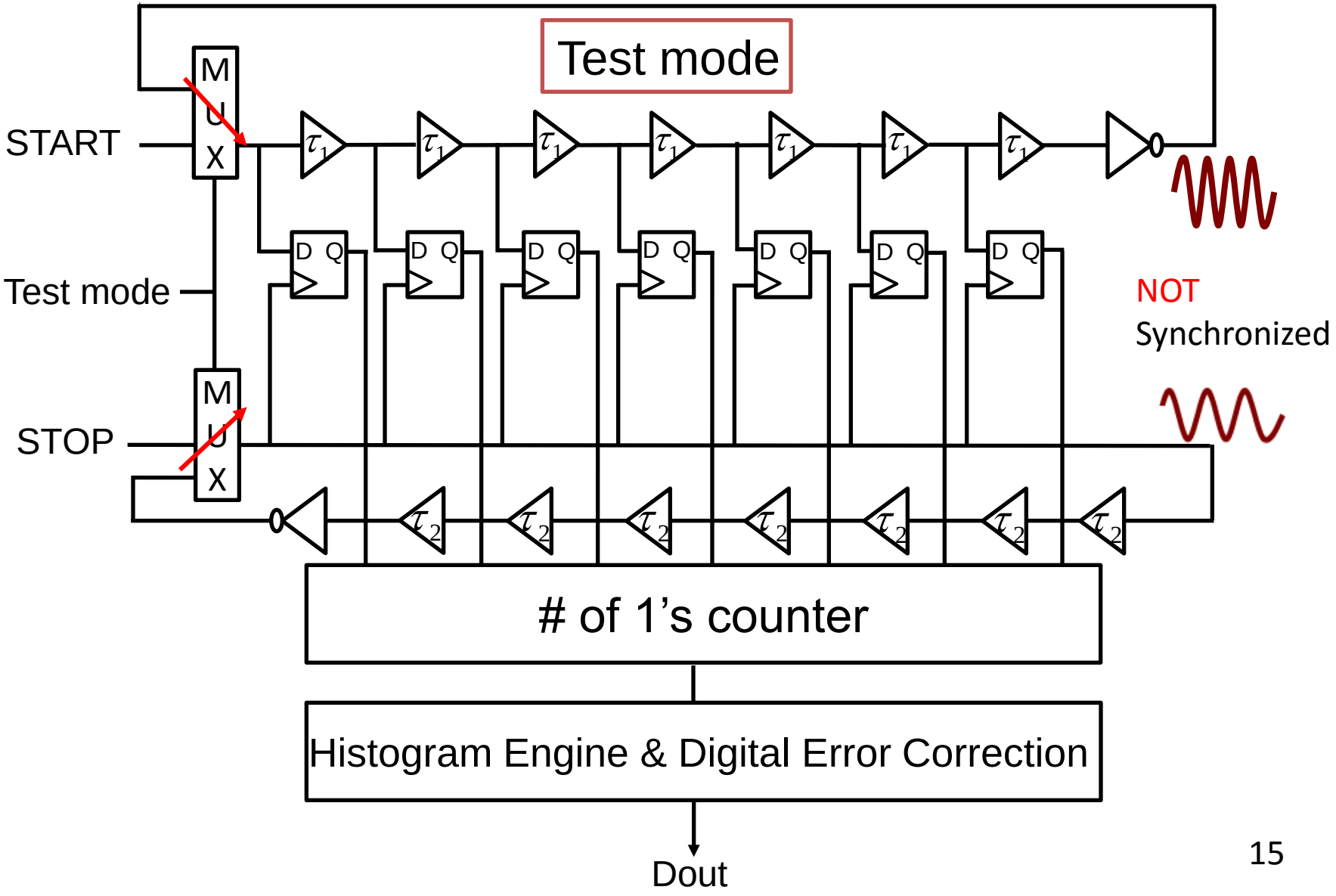
Outline

- Introduction
- Time to Digital Converter（TDC）
- Encoder Circuit
- Self-Calibration
- Stochastic TDC Structure
- RTL Simulation
- Conclusions

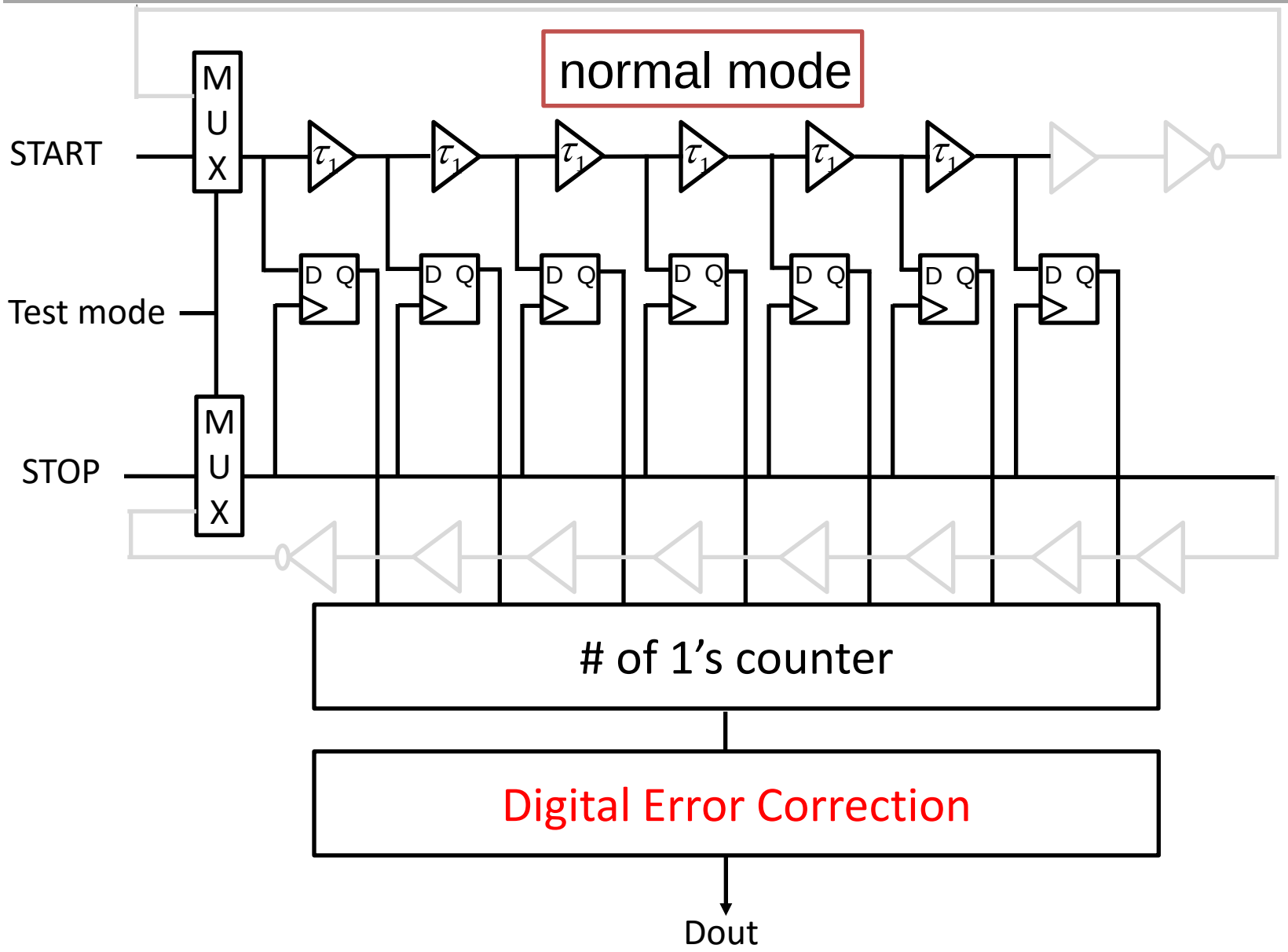
TDC Architecture with Self-Calibration



Self-Calibration Mode

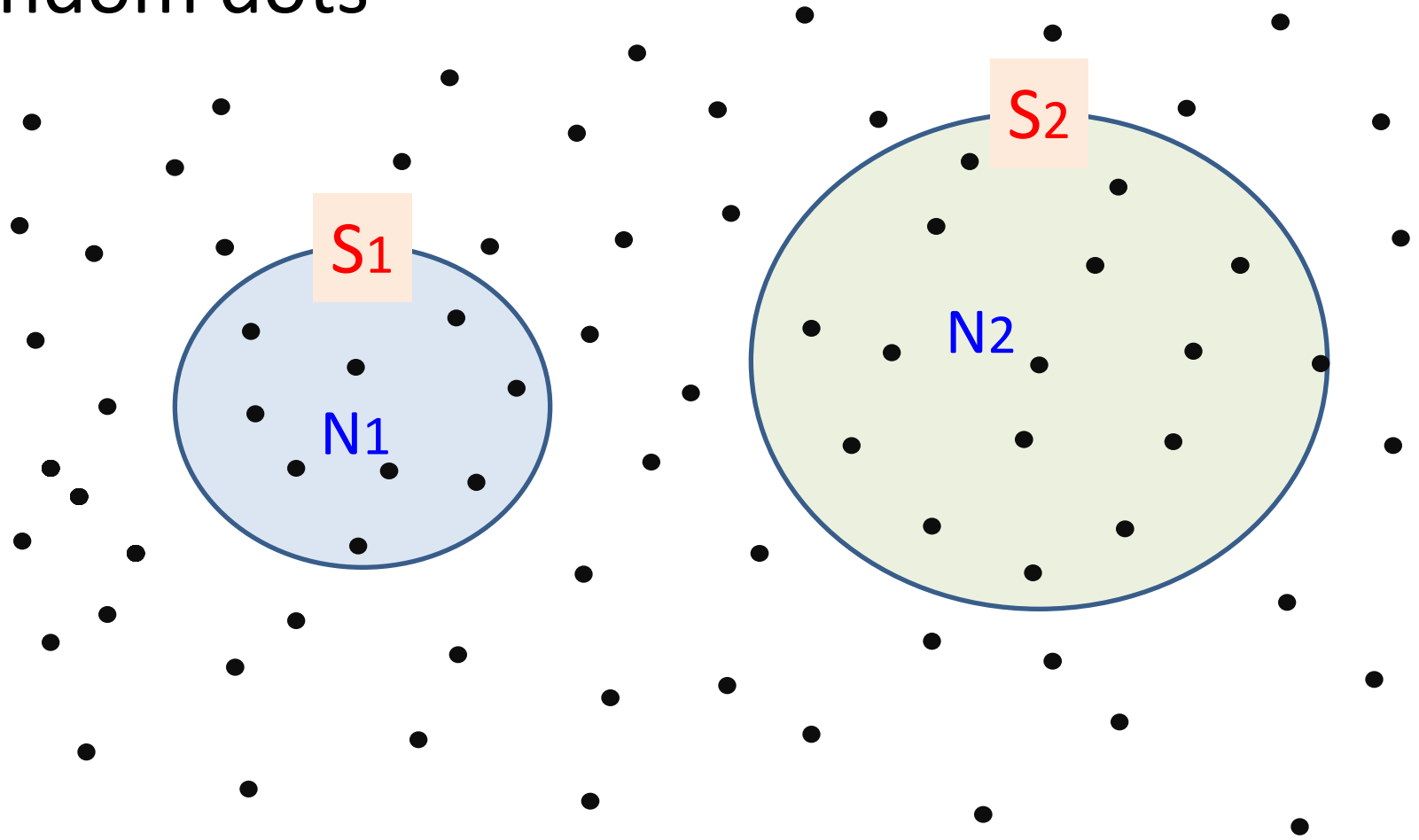


Normal Operation Mode



Measurement with Histogram

Random dots

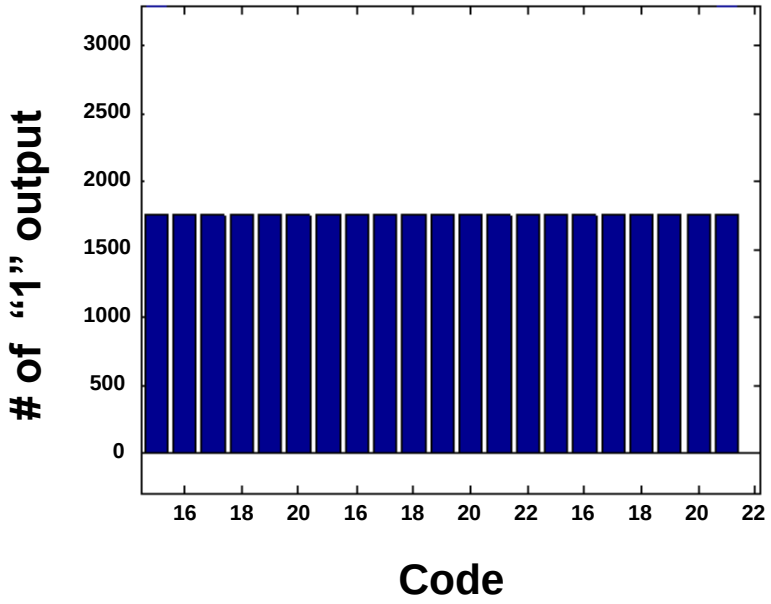


# of dots ratio $\frac{N1}{N2}$ ⇒ Area ratio $\frac{S1}{S2}$

Histogram in Ideal Case

Test mode

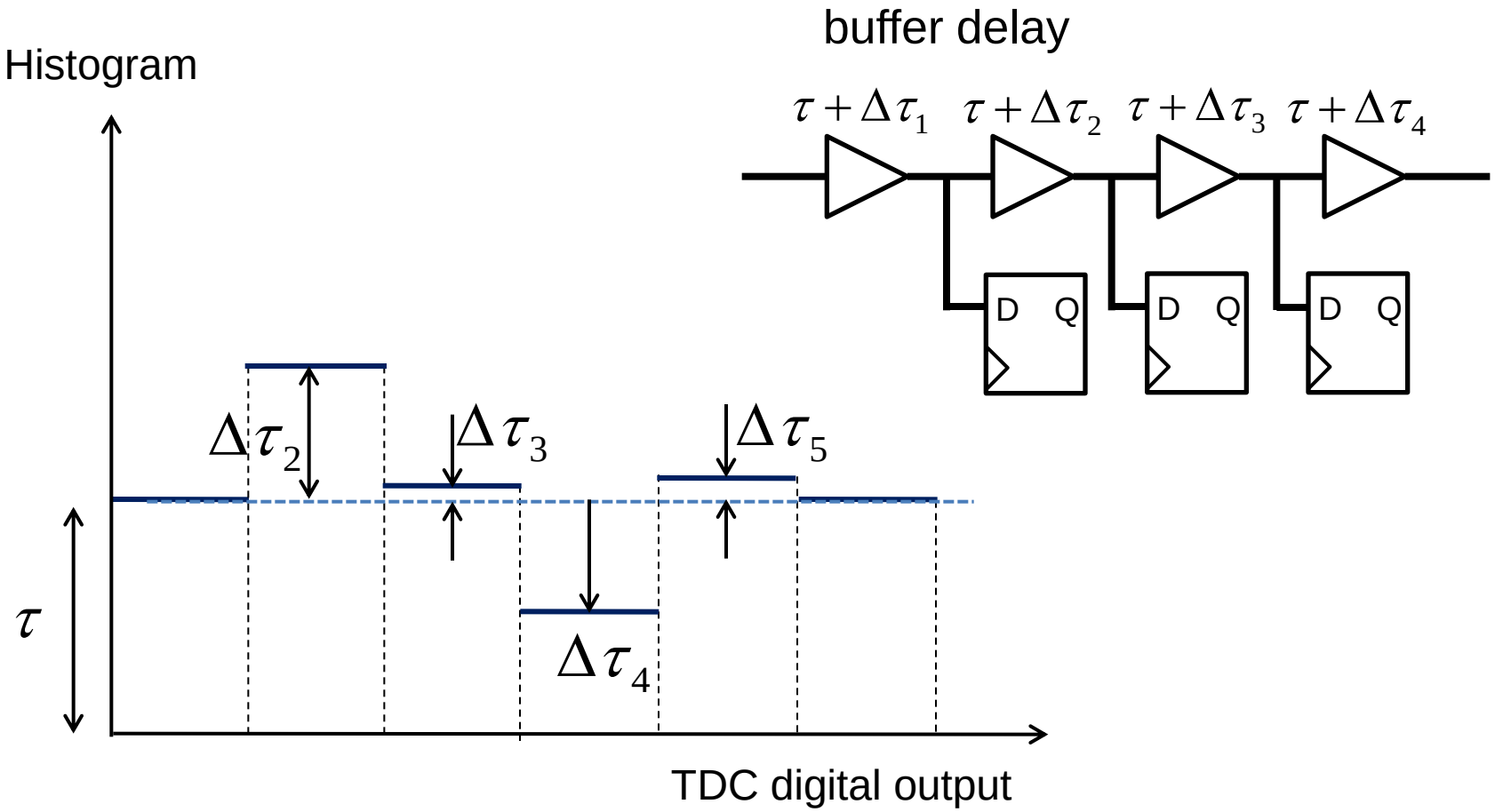
The two oscillators are different from each other and not synchronized



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

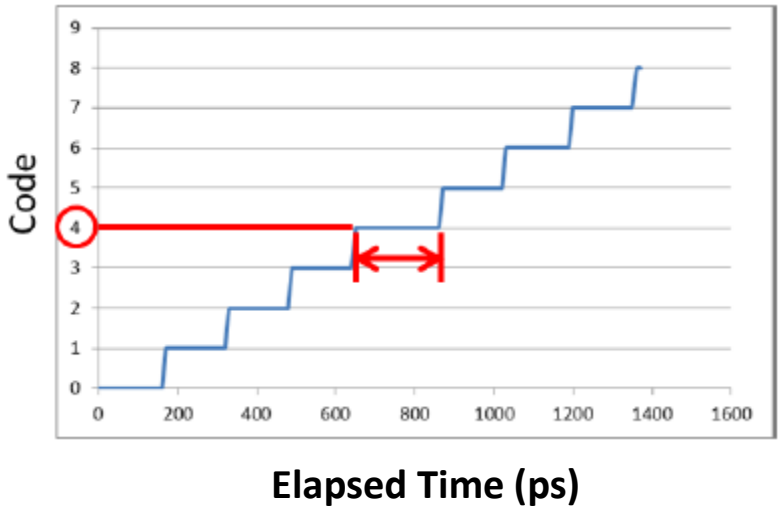
Delay Variation Measurement

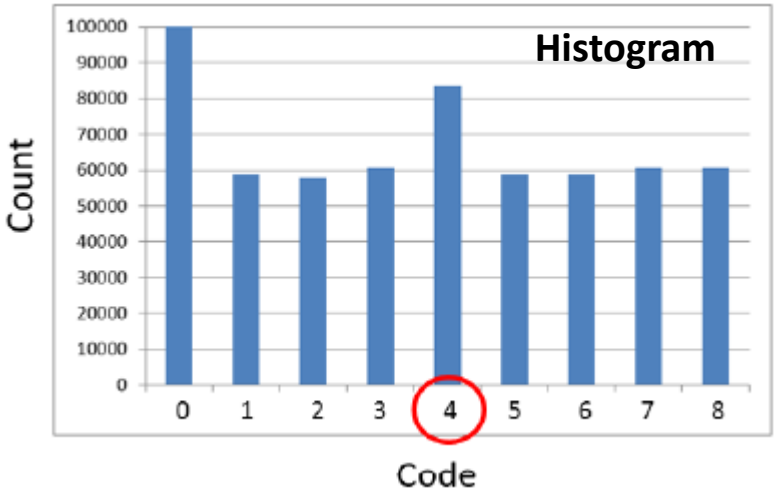
TDC is non-linear

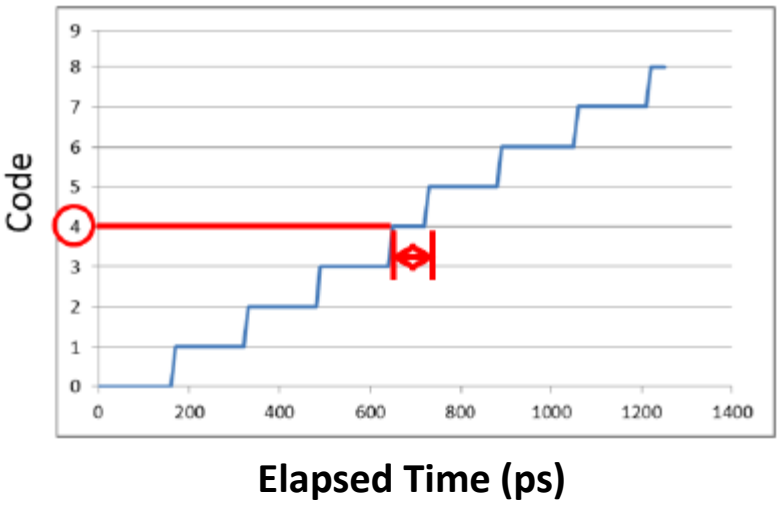


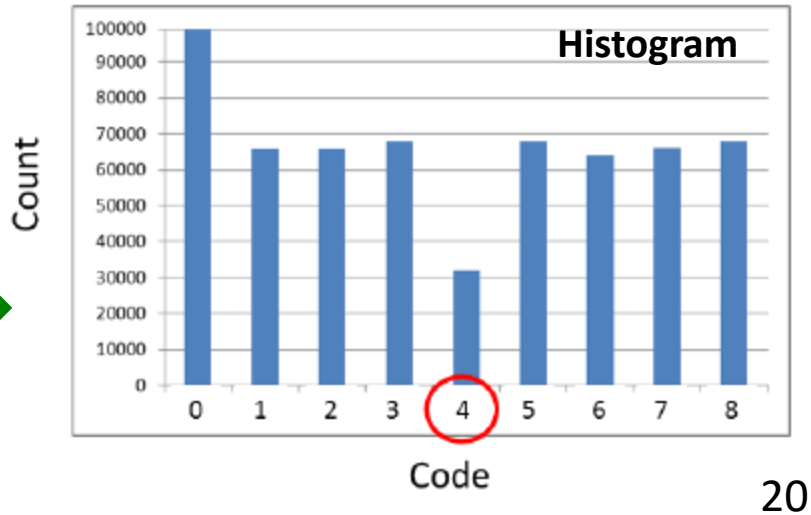
Histogram Data is Proportional to Delay Value

Histogram bin of digital code with large delay is high.
Histogram bin of digital code with small delay is low.

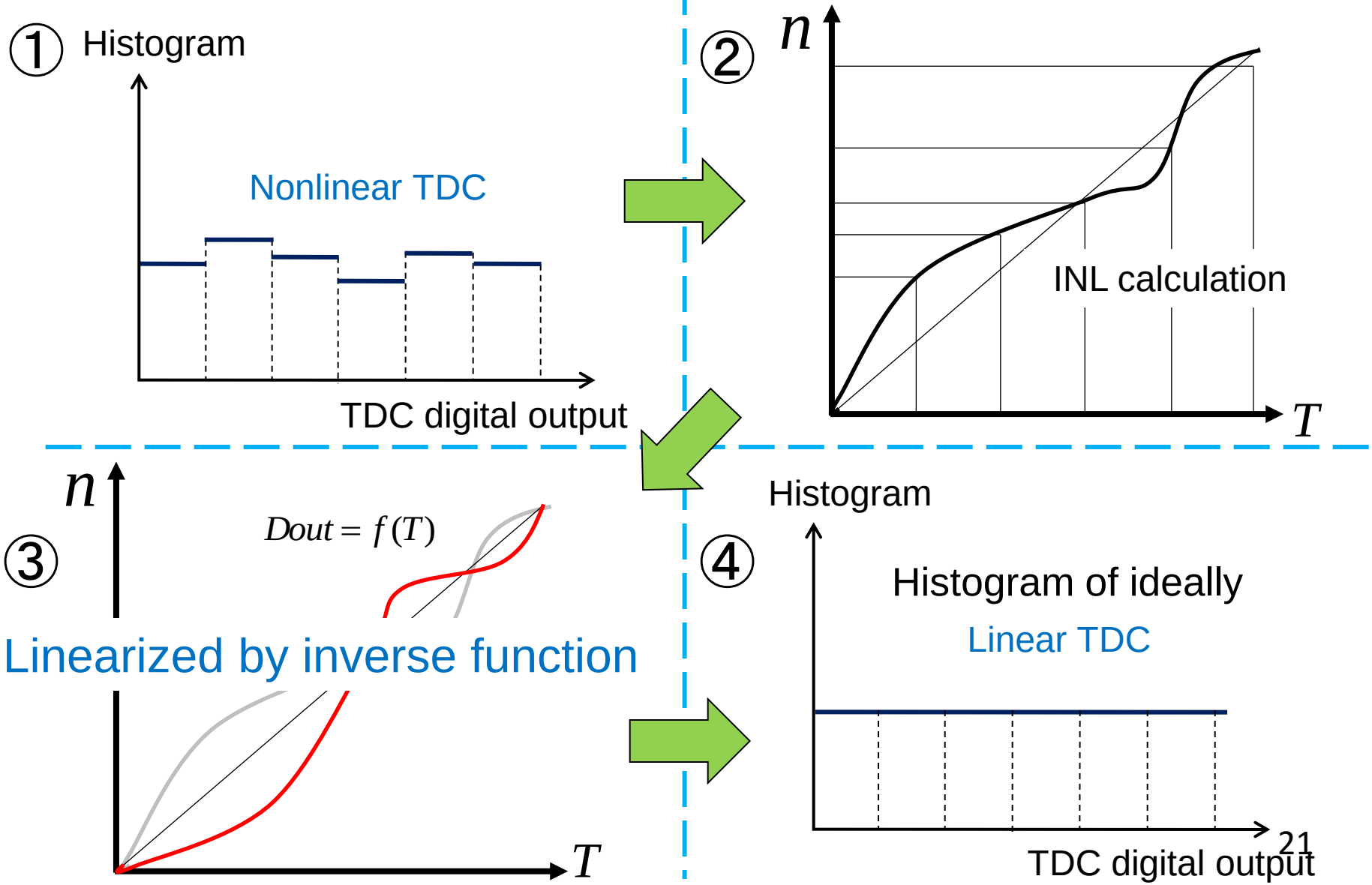








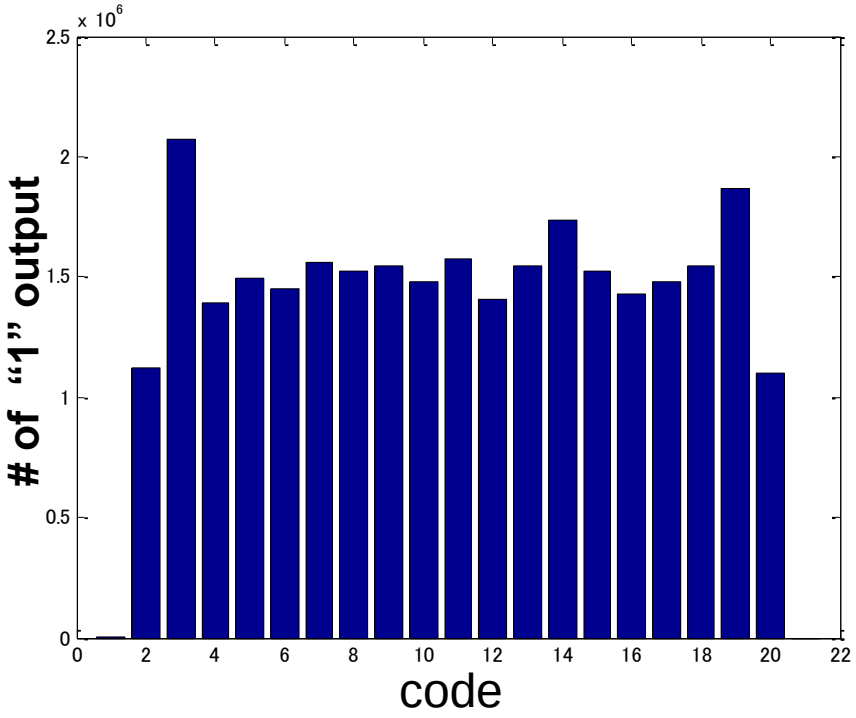
Principle of Self-Calibration



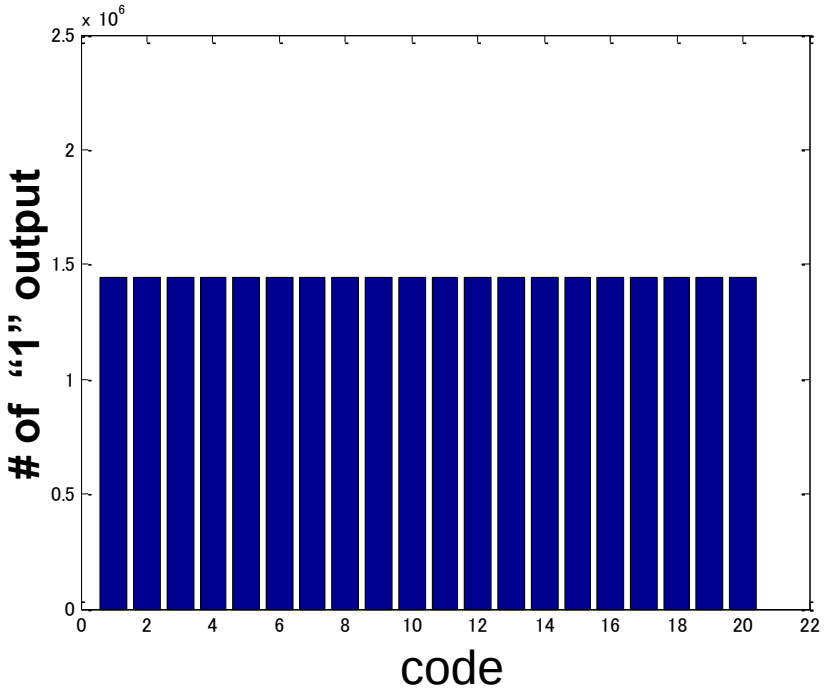
Simulation Result of Self-Calibration

MATLAB

before calibration



after calibration



Sampling points 28,848,432

$\tau_1 = 60 \sim 69 ps$

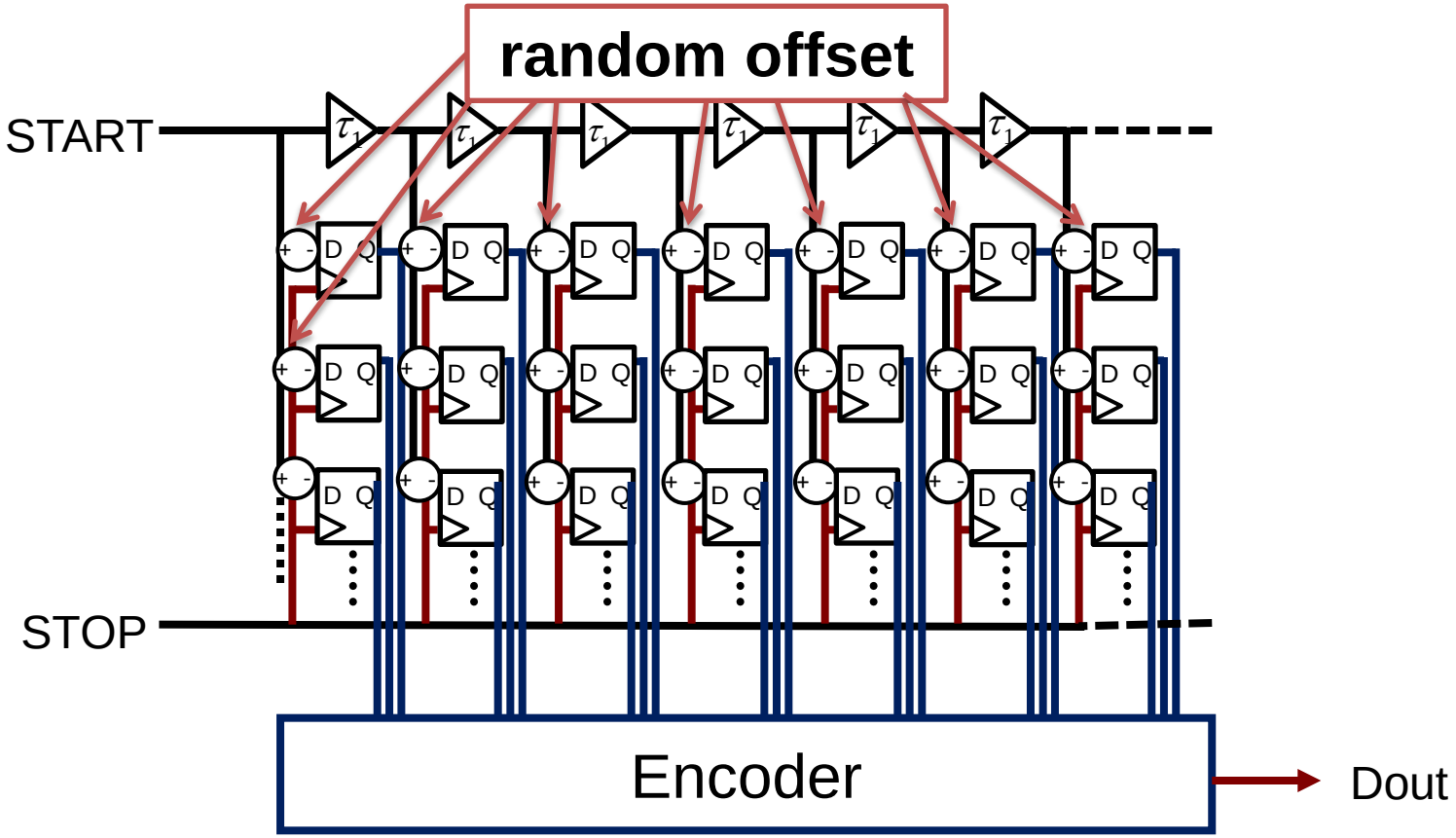
$\tau_2 = 10 ns$

Histogram for each bin is the same when the TDC is linear.

Outline

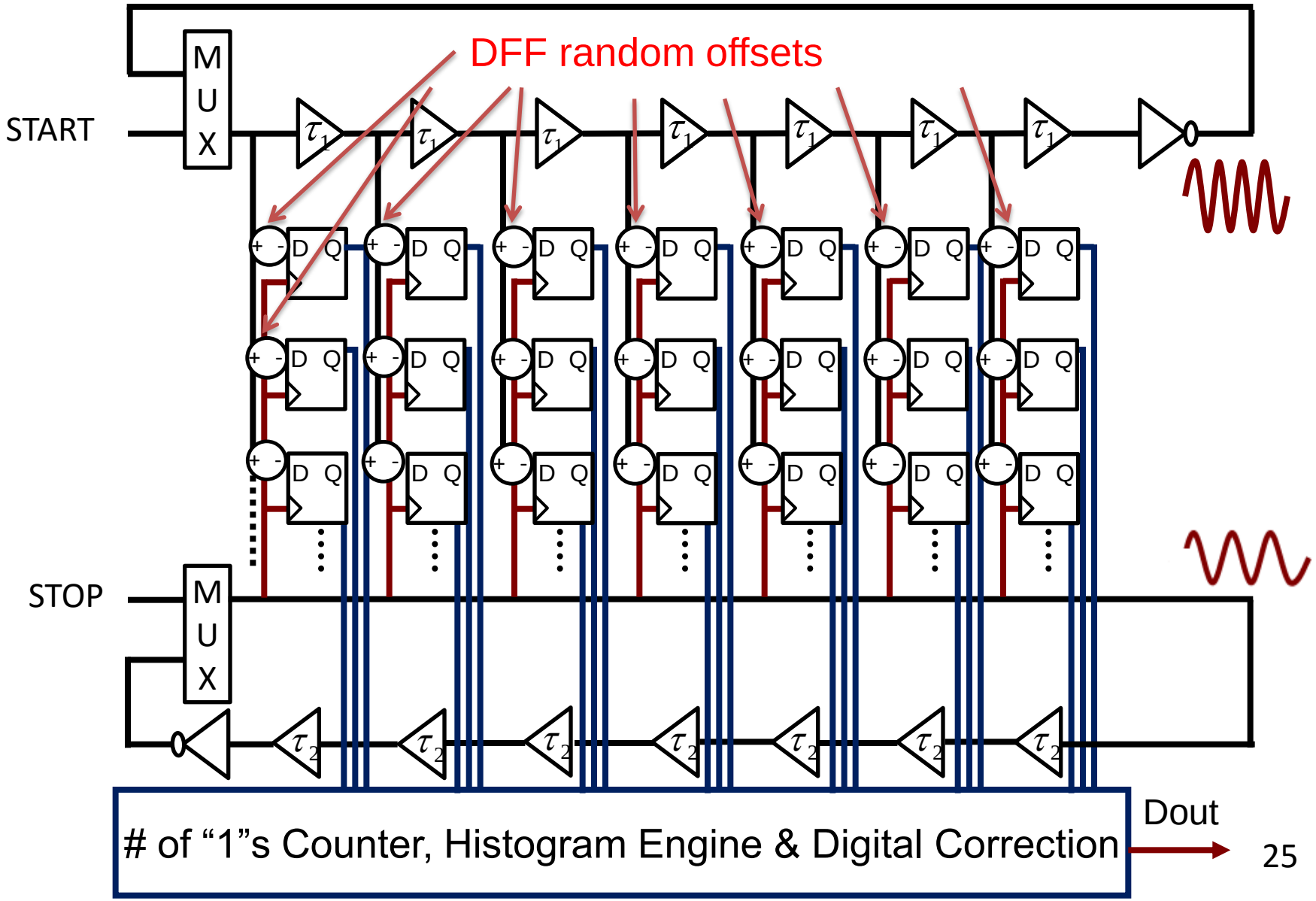
- Introduction
- Time to Digital Converter（TDC）
- Encoder Circuit
- Self-Calibration
- Stochastic TDC Structure
- RTL Simulation
- Conclusions

Stochastic TDC Structure



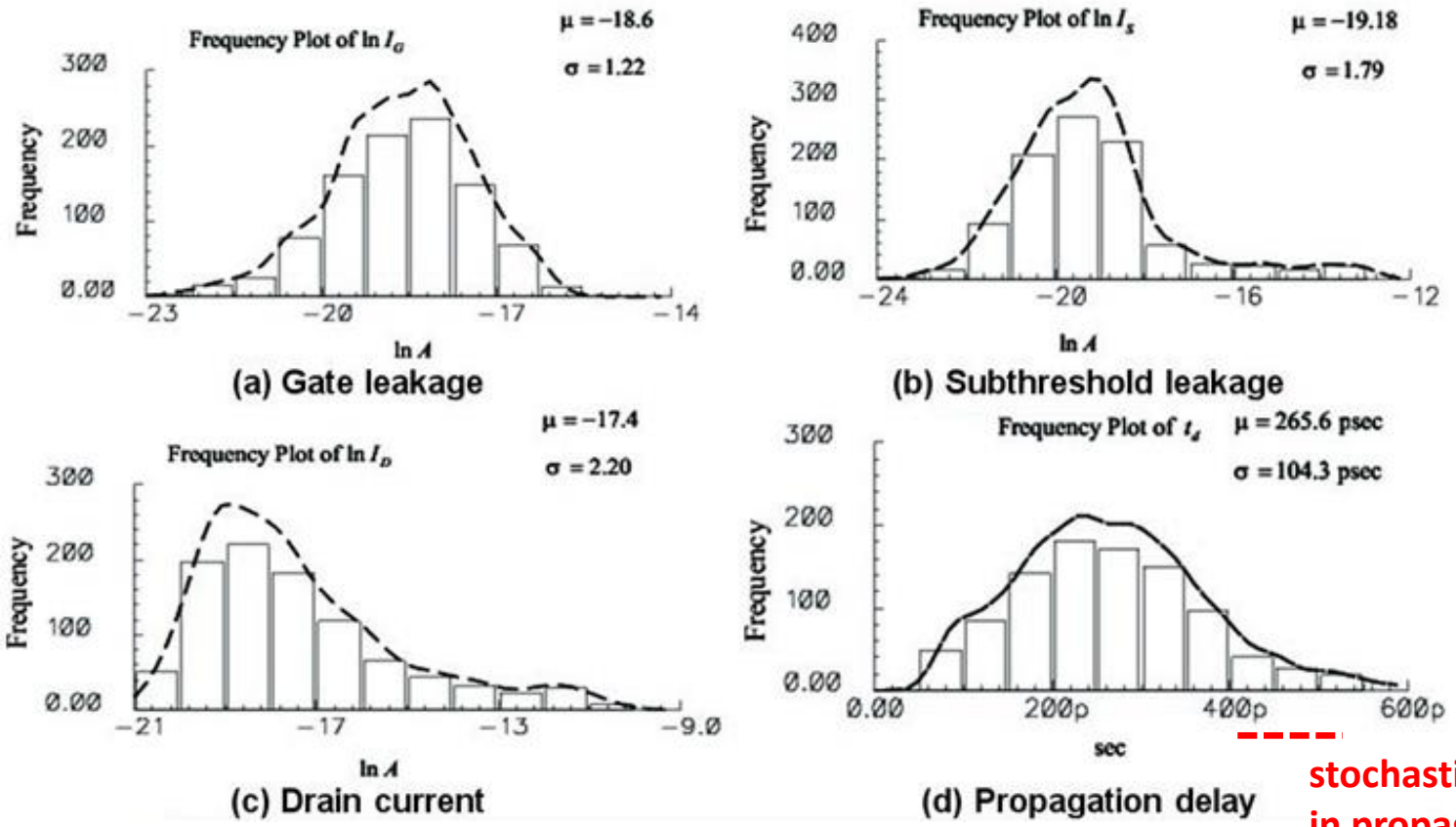
Use the random offset proactively

Stochastic TDC for Fine Time Resolution



Stochastic Variation of Delay at Sub-Picosecond Level

Circuit performance characteristics like voltage, delay, slew and power are stochastic processes.



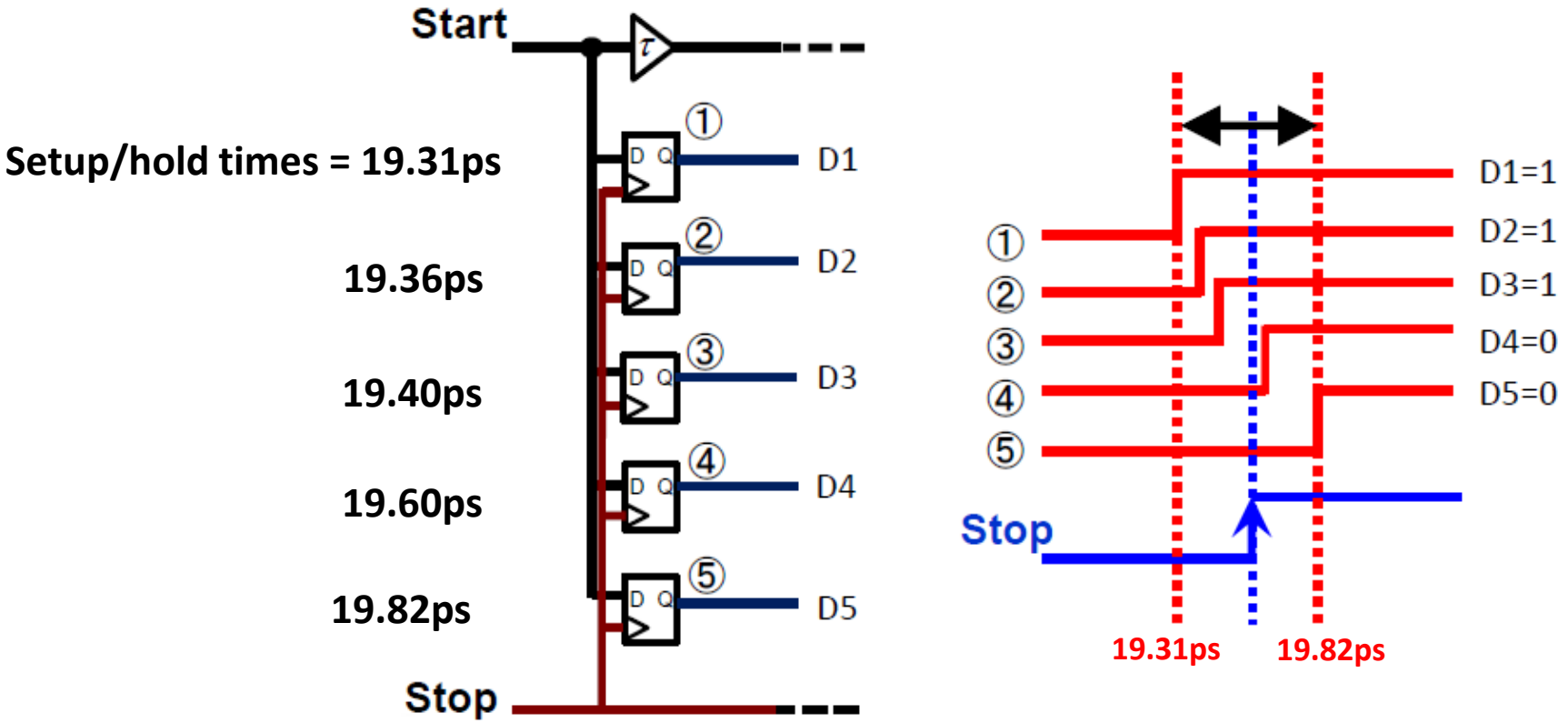
stochastic variation in propagation delay is at sub-picosecond level

Example:
Statistical process variation on gate leakage, subthreshold leakage, dynamic power and propagation delay in a 2-input NAND gate

(source: http://www.cse.unt.edu/~smohanty/Projects/CCF_0702361/CCF_0702361.html)

Delay Variation in Stochastic TDC

Setup /hold times of each DFF are different due to stochastic variation



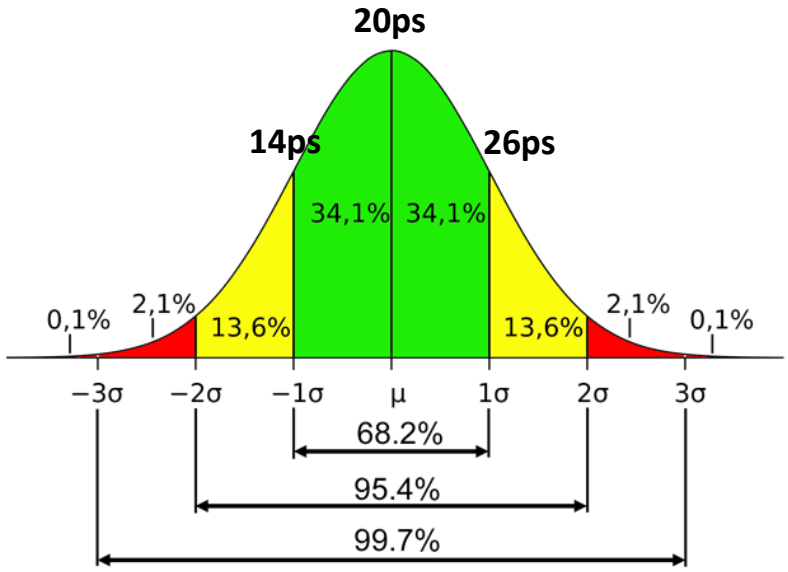
Input-Output Characteristics of Stochastic TDC

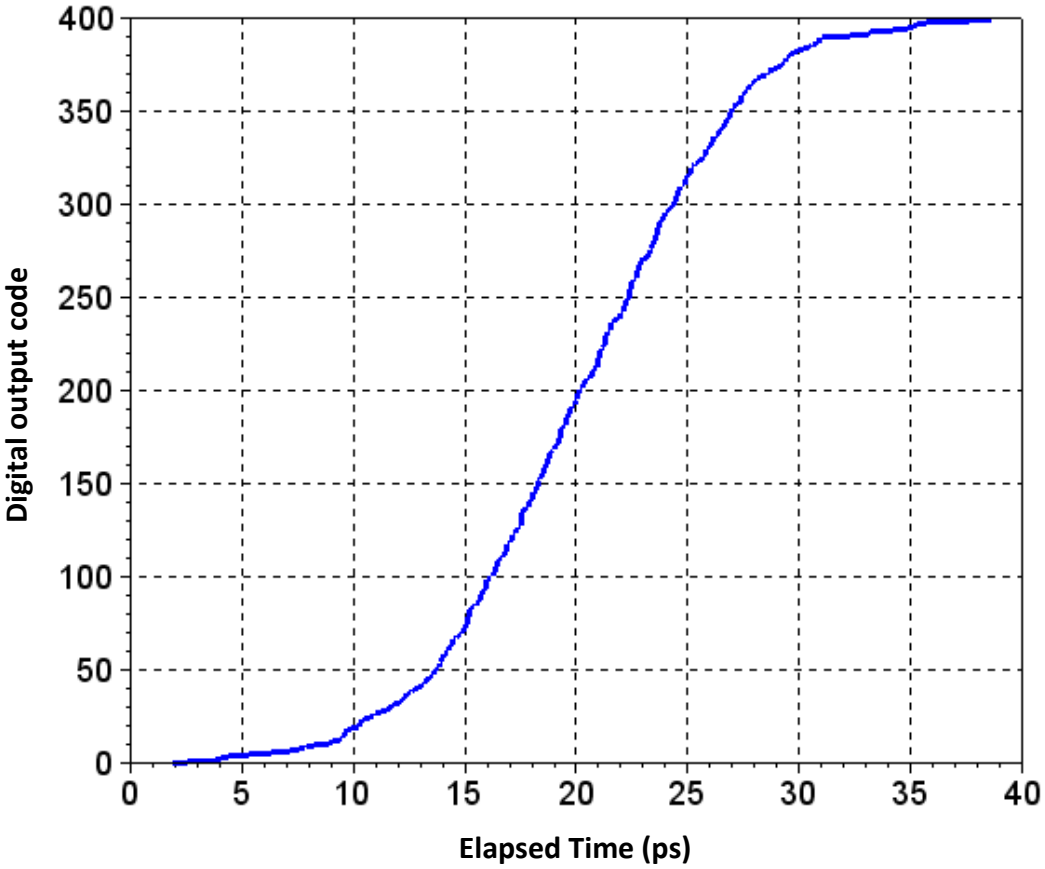
Ex.

DFF number = 400

Setup/hold times of 400 DFFs are normally distributed

Mean = 20ps, standard deviation = 6ps

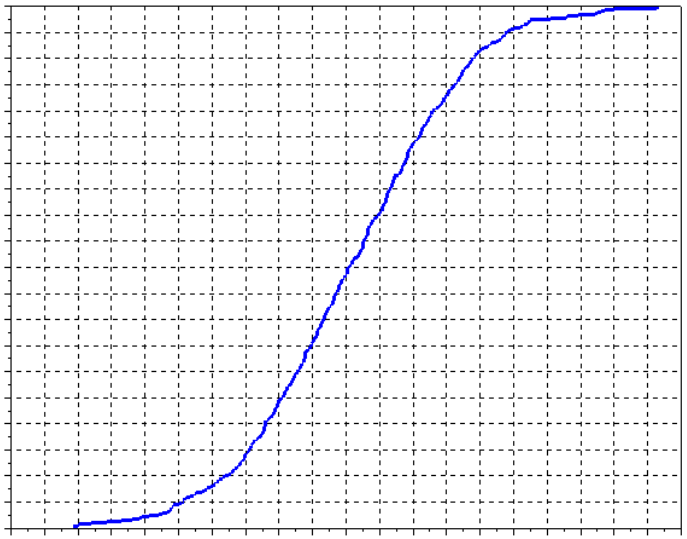




Time resolution = 0.08ps

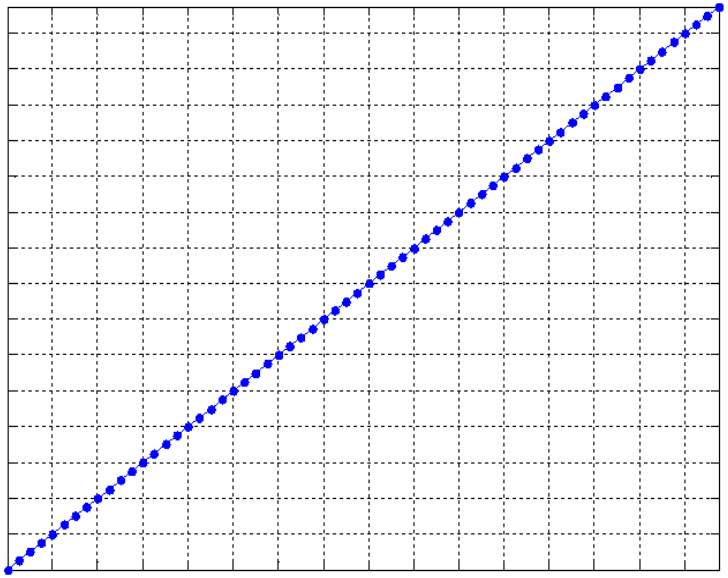
But nonlinear !!

How to Convert a Nonlinear TDC into a Linear TDC?



nonlinear TDC

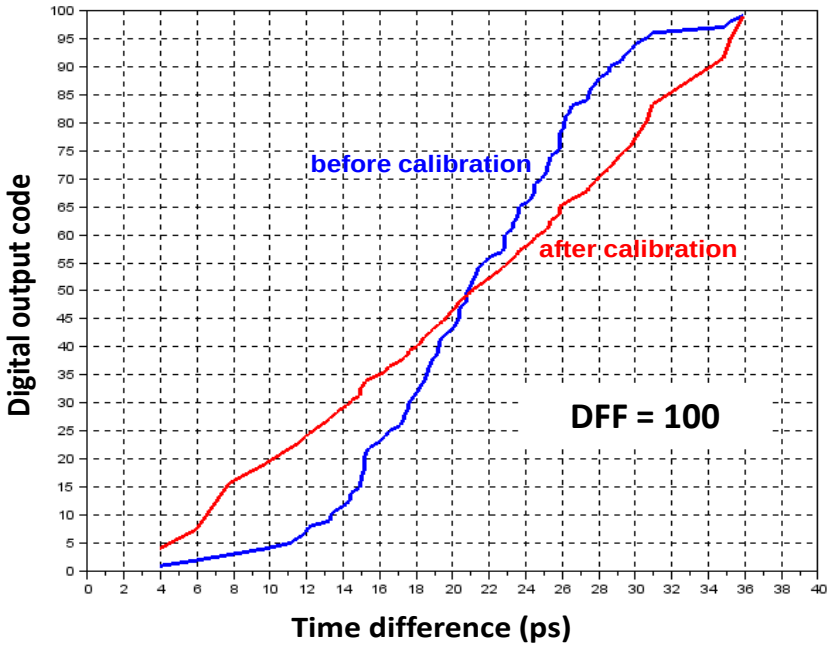
Convert

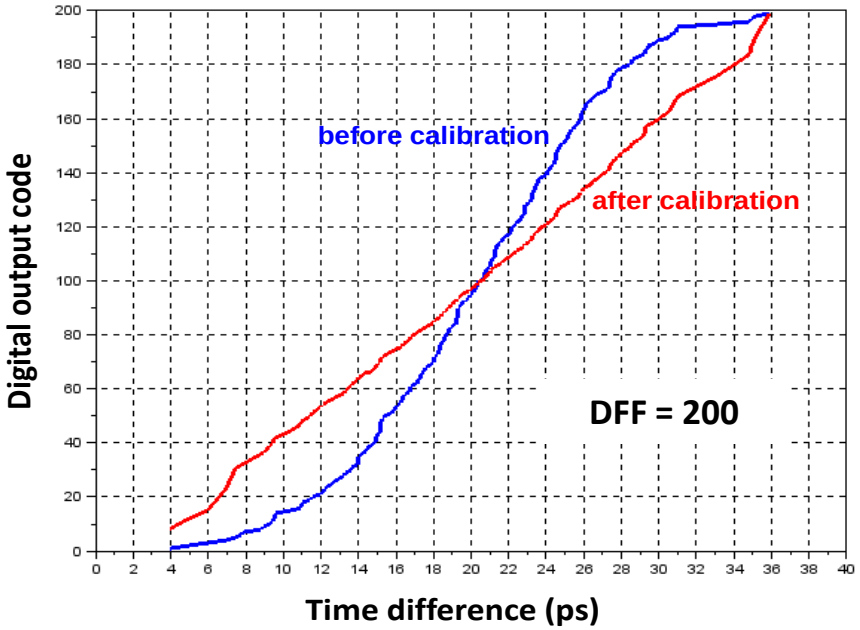


linear TDC

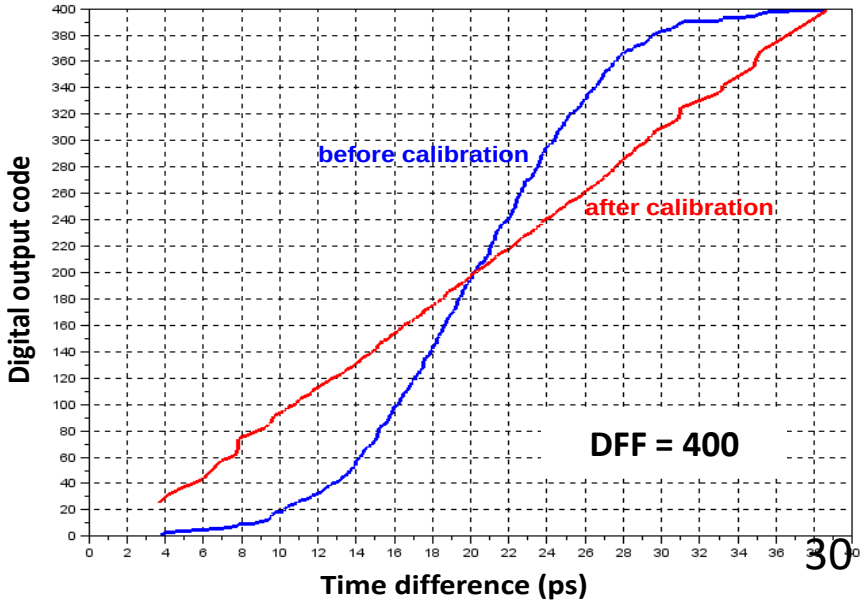
Self-calibration is applied to improve linearity !!

Input-output Characteristics Before and After Calibration

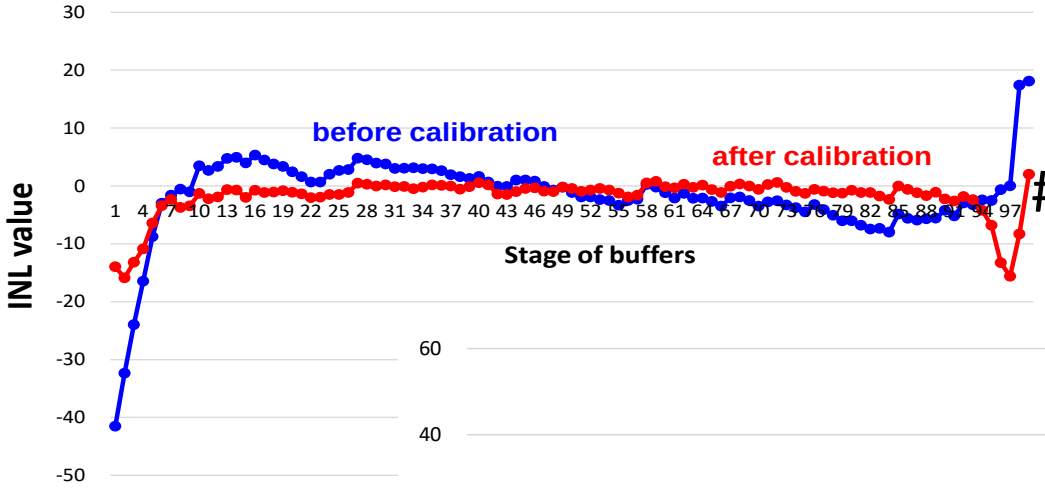




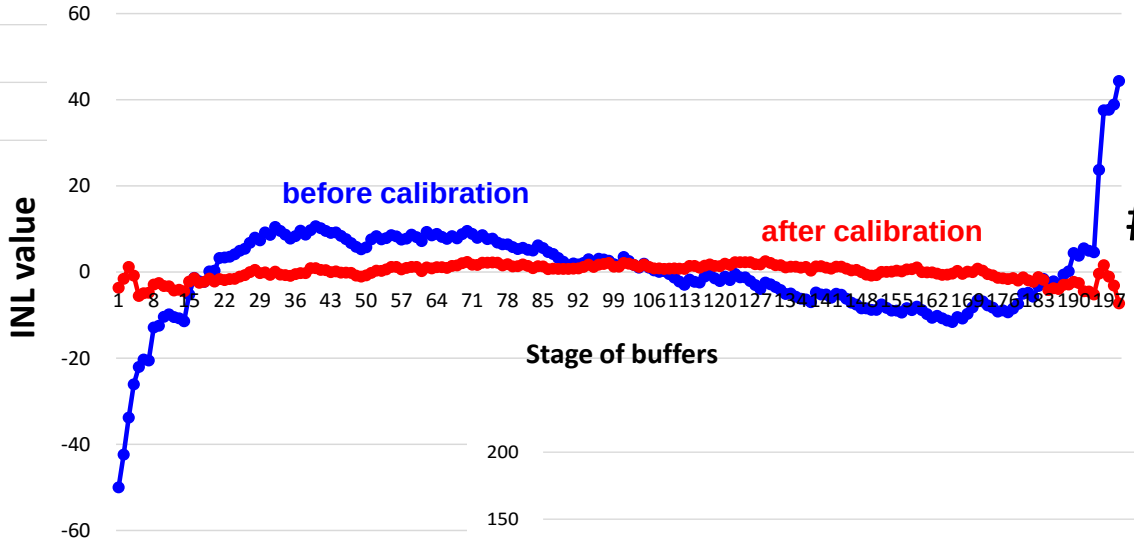
TDC linearity is improved after calibration !!



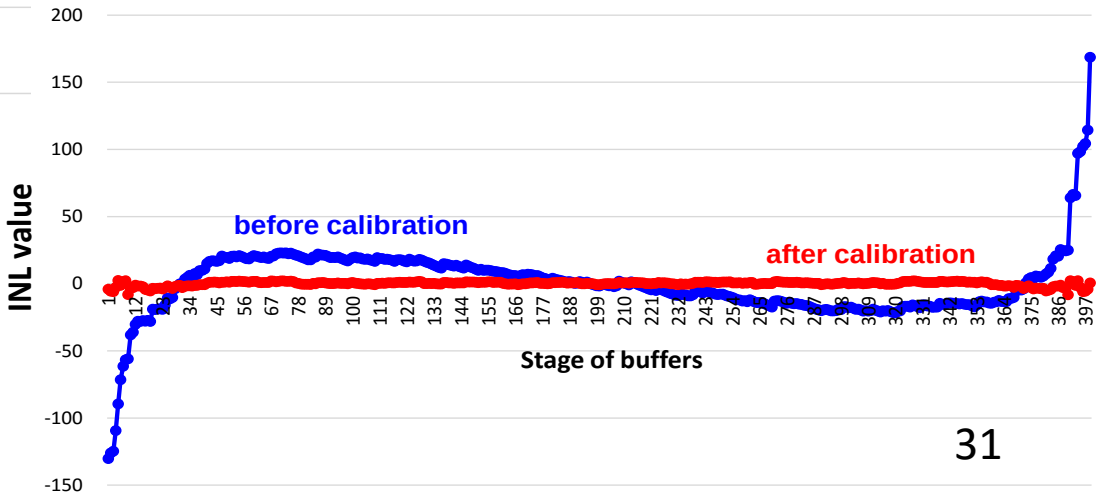
INL Reduction After Calibration



# of DFFs = 100



# of DFFs = 200



# of DFFs = 400

Measurement Time Resolution

DFF Number	Time Resolution
100	0.3258ps
200	0.1613ps
400	0.0876ps

Time resolution after calibration can reach sub-picosecond level !!

Comparison with other TDC architectures

TDC architecture	Time resolution
This work	0.0876ps
Freeze Vernier [11]	4.88ps
Vernier gated ring oscillator [12]	3.2ps
Delay line [13]	6.25ps
2D Vernier [14]	4.8ps
Local passive interpolation [15]	4.7ps
Inverter-chain [16]	80.0ps
Two-step [17]	3.75ps

Outline

- Introduction
- Time to Digital Converter（TDC）
- Encoder Circuit
- Self-Calibration
- Stochastic TDC Structure
- RTL Simulation
- Conclusions

Conclusions

- High linearity TDC
  →Self-Calibration circuit
- Fine time resolution TDC
  →Stochastic architecture

Note: Stochastic ADC linearity calibration is NOT easy.

■ Fine digital CMOS implementation

- Verification
- Self-calibration
- Consists of digital cells
  (FPGA implementation is possible)

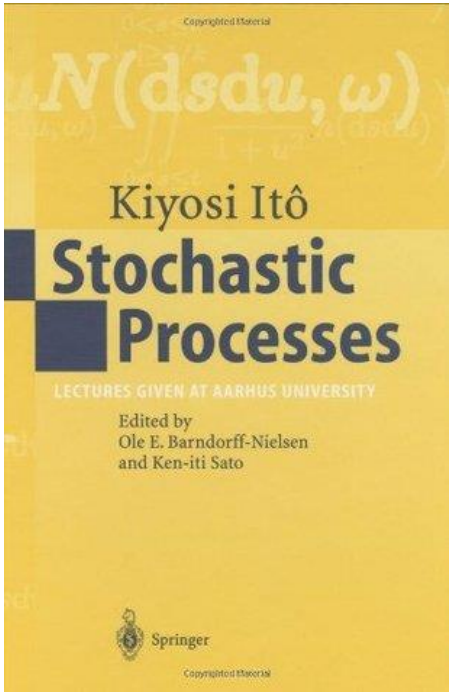
Final Statement

Stochastic process theory advances

precise timing measurement technology.

Prof. Kiyoshi Ito (1915-2008)

Japanese Mathematician



Great contribution to

- Stochastic calculus
- Stochastic differential equation