Effect of Delay Element Variation on Time-to-Digital Converter Linearity

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OUTLINE

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- Time to Digital Converter（TDC）
- Simulation
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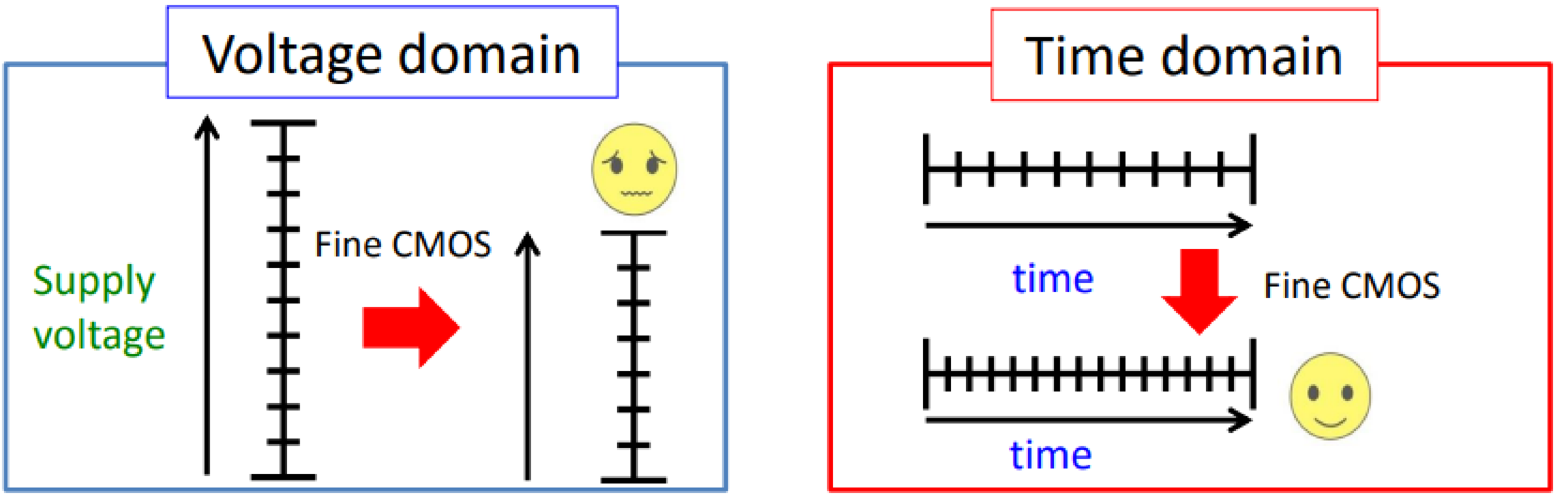
Research Background

Advanced CMOS VLSI

- Low power-supply voltages
- Fast switching speeds



A Time-to-Digital Converter (TDC) provides a digital output proportional to the time between two clock transitions.

The TDC is a key component in time-domain analog circuits,

(e.g. Sensor Interfaces, All-Digital PLLs, ADCs, ..)

Research Objective

"**Fine time resolution**" and "**high linearity**"
Time-to-Digital Converter (TDC) measures the time difference between two digital signals into a digital value

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Variations among buffer delays

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Input time signal → Output digital signal
accurate (linear) or not

Clarification of how they affect TDC linearity

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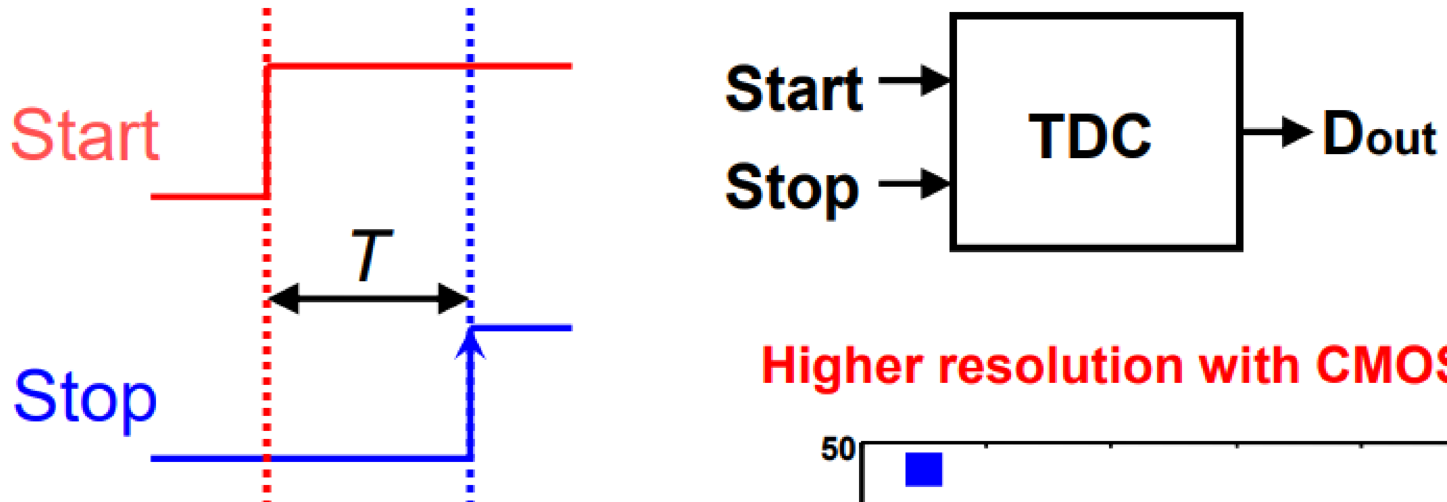
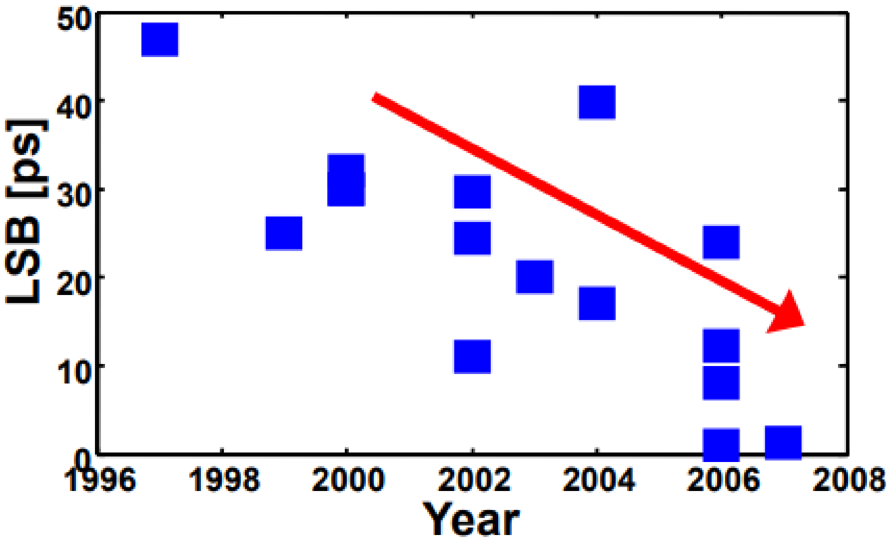
Time to Digital Converter（TDC）: Role

- time interval → Measurement → Digital value



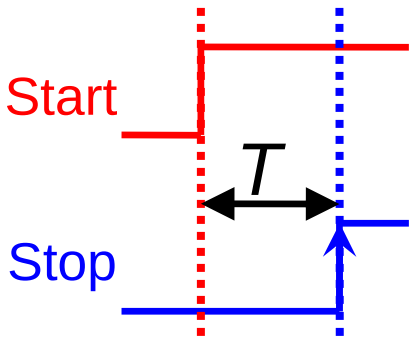
Higher resolution with CMOS scaling

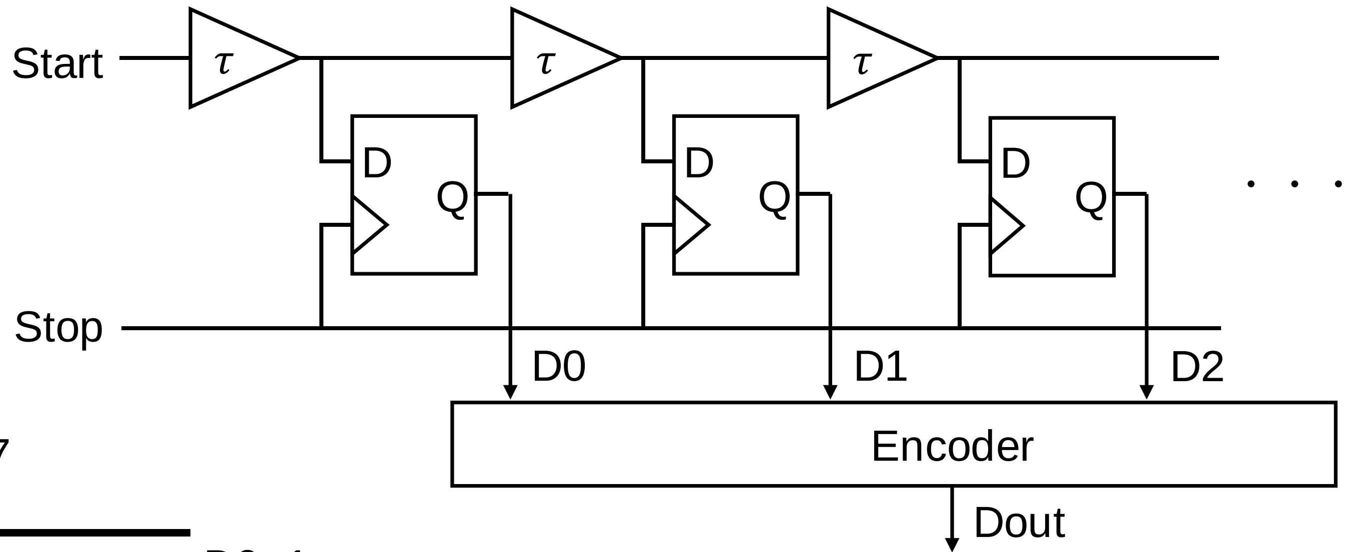


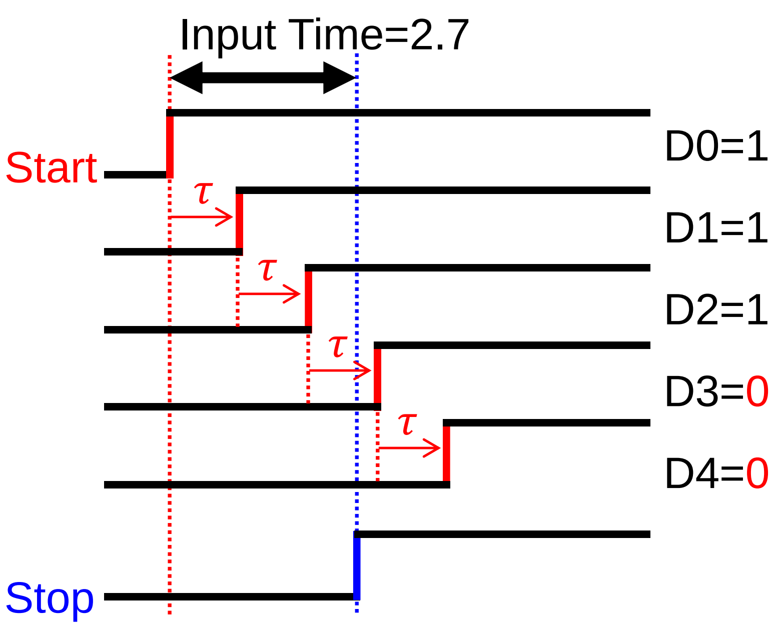
- Key component of Time-domain analog circuit
- Higher resolution can be obtained with scaled CMOS

Time to Digital Converter（TDC）: Principle

Time interval → Measurement → Digital value



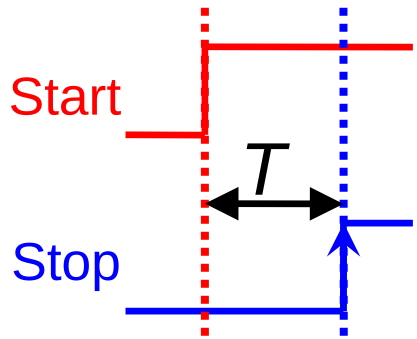


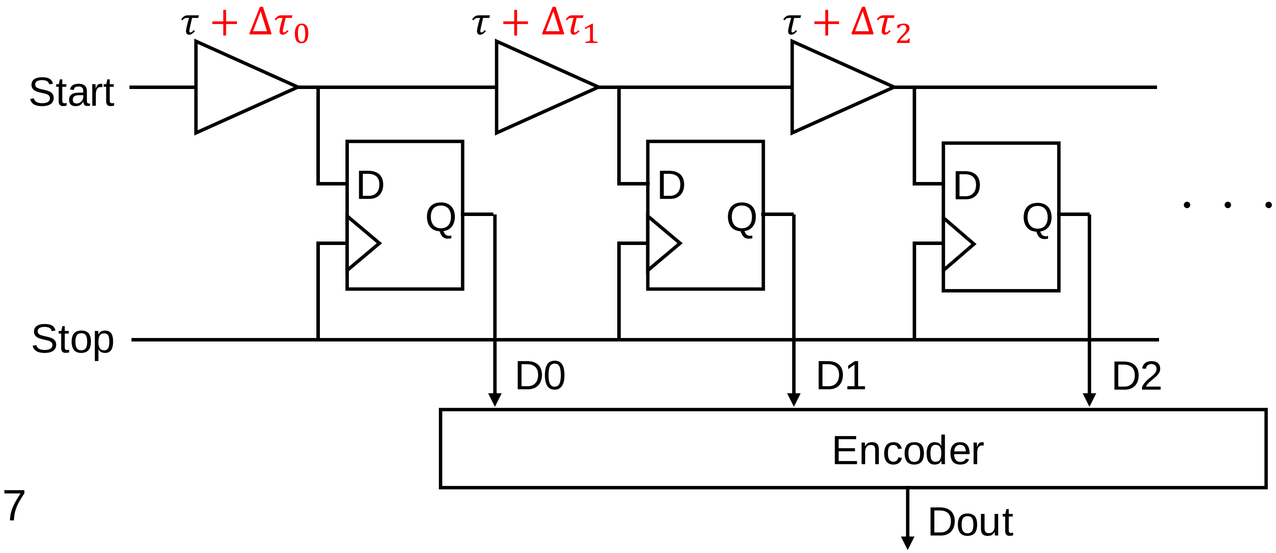


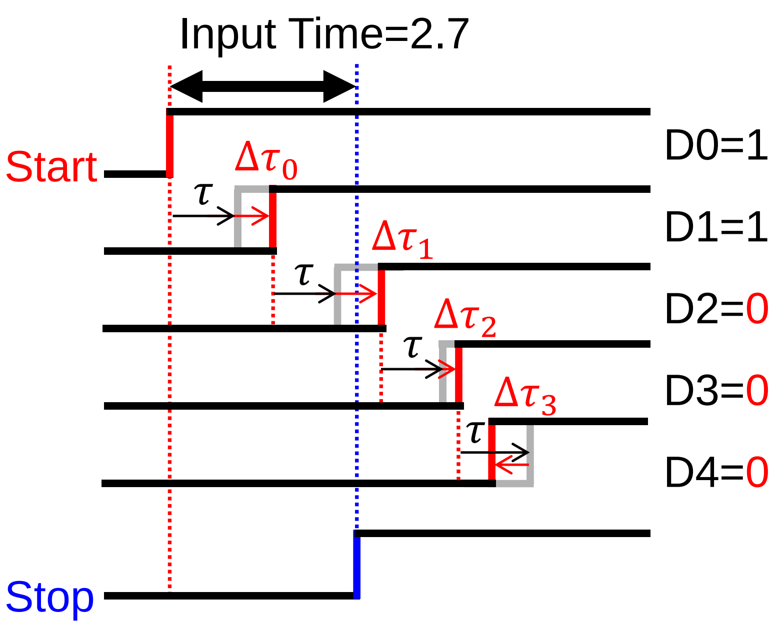
Digital Output
Thermometer code: 00111
↓ Encoder
Binary code: 10 (2 in decimal number)

TDC with Delay Element Variation

Delay variation Δτ causes non-linearity







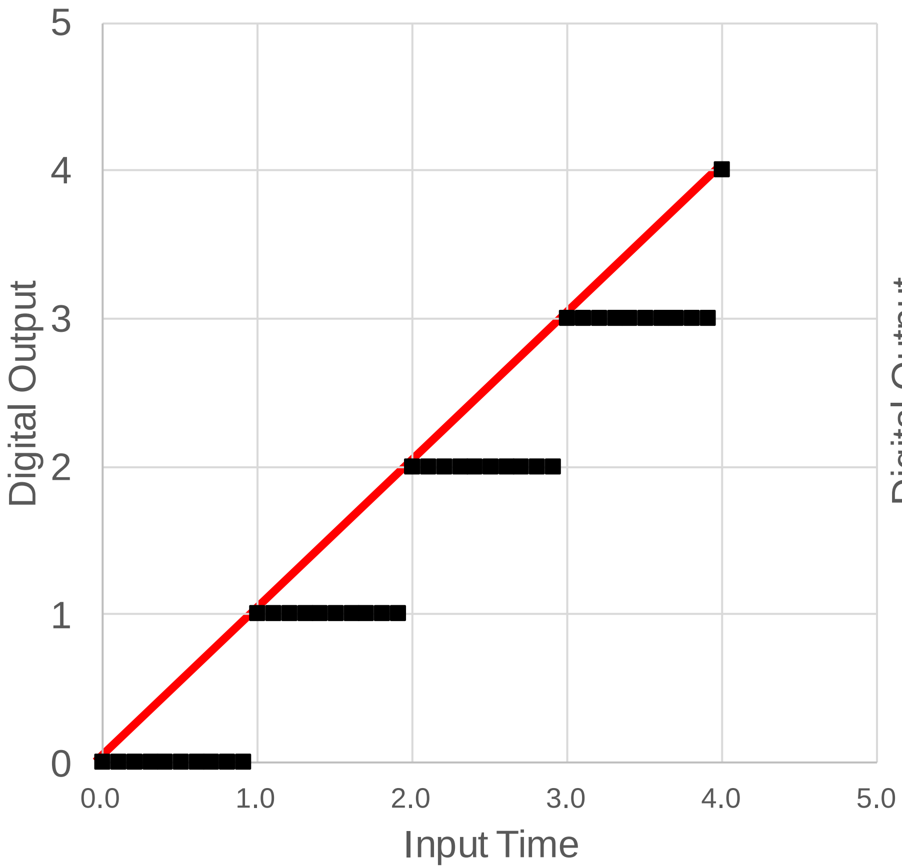
Digital Output

Thermometer code: 00011

↓ Encoder

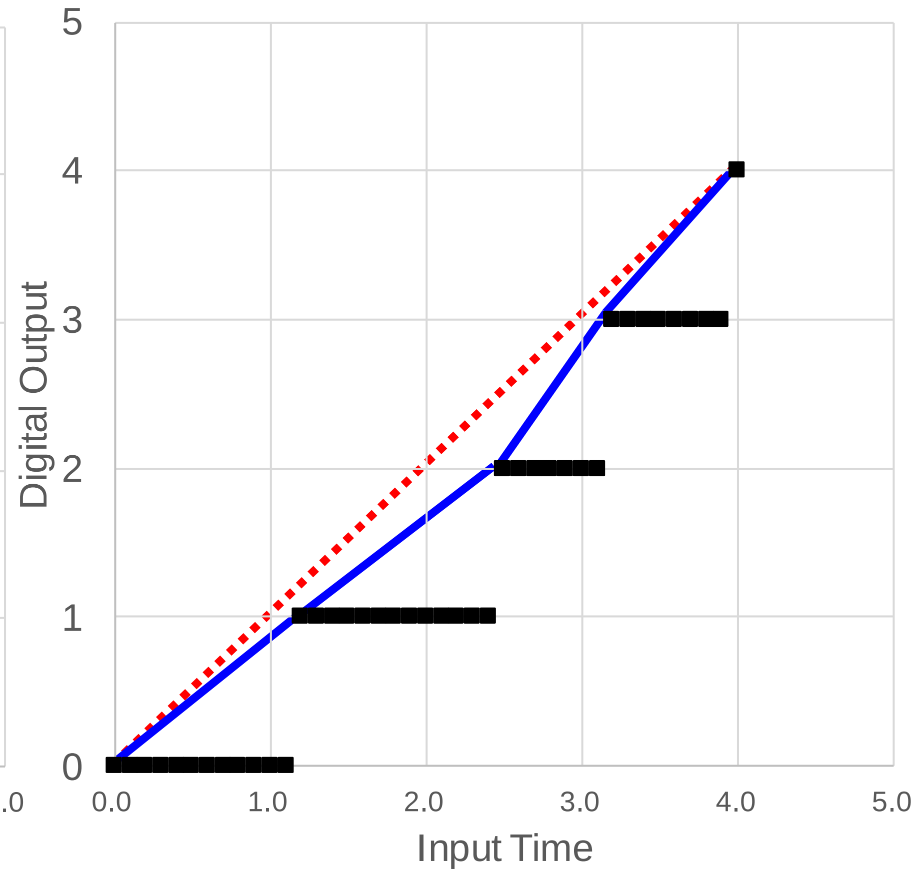
Binary code: 1 (1 in decimal number)

Comparison Without/With Delay Variation



Without delay element variation

Linear



With delay element variation

Non-linear

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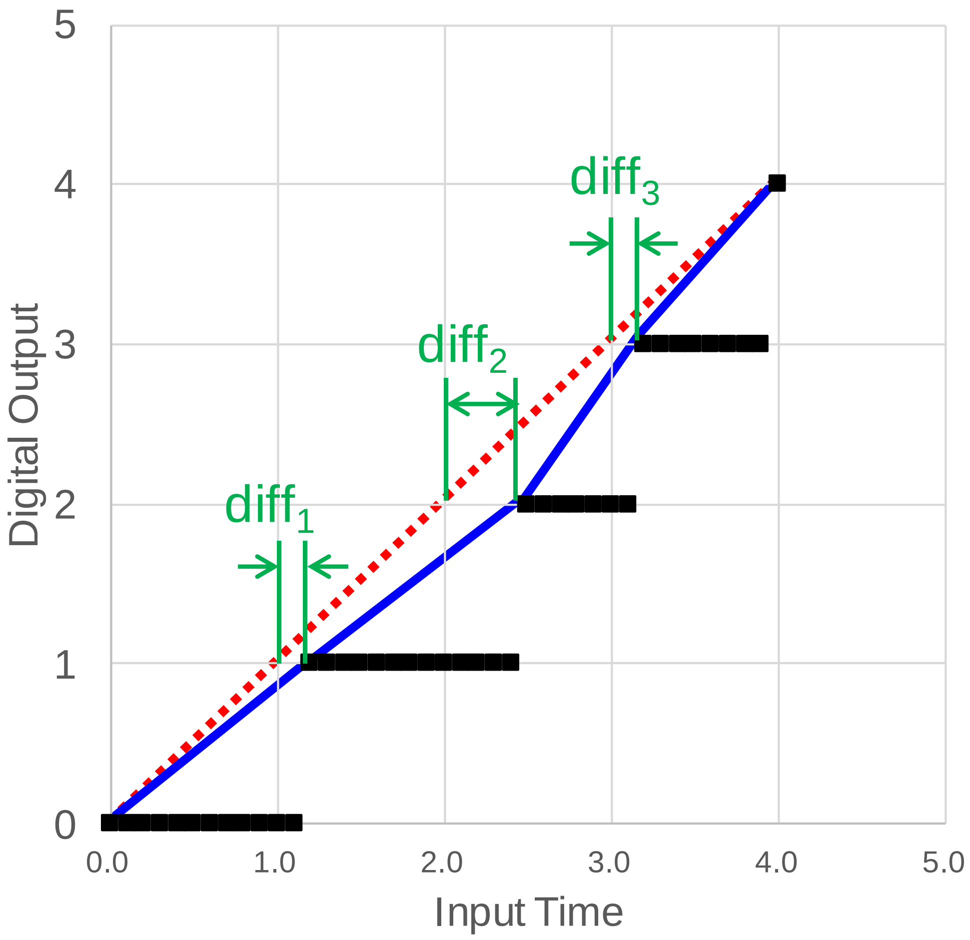
Problem Settings

Error RMS as measure of non-linearity :

$$\mathrm{RMS} = \sqrt{\frac{\sum_{i=0}^{N} (\mathrm{diff}_i)^2}{N}}$$



$$\mathrm{diff}_i = \mathrm{Minimum}\left(\text{Input time}|_{\text{Digital Output}=i}\right) - i$$

Parameters Settings

- Number of delay elements: 8
- $\tau = 1.0, \ \ |\Delta\tau_i| = 0.01$
- Total delay element variation is set to zero

$$\sum_{i=0}^{N} \Delta\tau_i = 0$$

- Number of patterns: 70

Delay Element Variation Patterns

Delay element variation patterns considered in simulation

	$\Delta\tau_0$	$\Delta\tau_1$	$\Delta\tau_2$	$\Delta\tau_3$	$\Delta\tau_4$	$\Delta\tau_5$	$\Delta\tau_6$	$\Delta\tau_7$
Patten 0	-0.01	-0.01	-0.01	-0.01	0.01	0.01	0.01	0.01
Patten 1	-0.01	-0.01	-0.01	0.01	-0.01	0.01	0.01	0.01
Patten 2	-0.01	-0.01	-0.01	0.01	0.01	-0.01	0.01	0.01
Patten 3	-0.01	-0.01	-0.01	0.01	0.01	0.01	-0.01	0.01
Patten 4	-0.01	-0.01	-0.01	0.01	0.01	0.01	0.01	-0.01
Patten 5	-0.01	-0.01	0.01	-0.01	-0.01	0.01	0.01	0.01
Patten 6	-0.01	-0.01	0.01	-0.01	0.01	-0.01	0.01	0.01
Patten 7	-0.01	-0.01	0.01	-0.01	0.01	0.01	-0.01	0.01
Patten 8	-0.01	-0.01	0.01	-0.01	0.01	0.01	0.01	-0.01
...								
Patten 68	0.01	0.01	0.01	-0.01	0.01	-0.01	-0.01	-0.01
Patten 69	0.01	0.01	0.01	0.01	-0.01	-0.01	-0.01	-0.01

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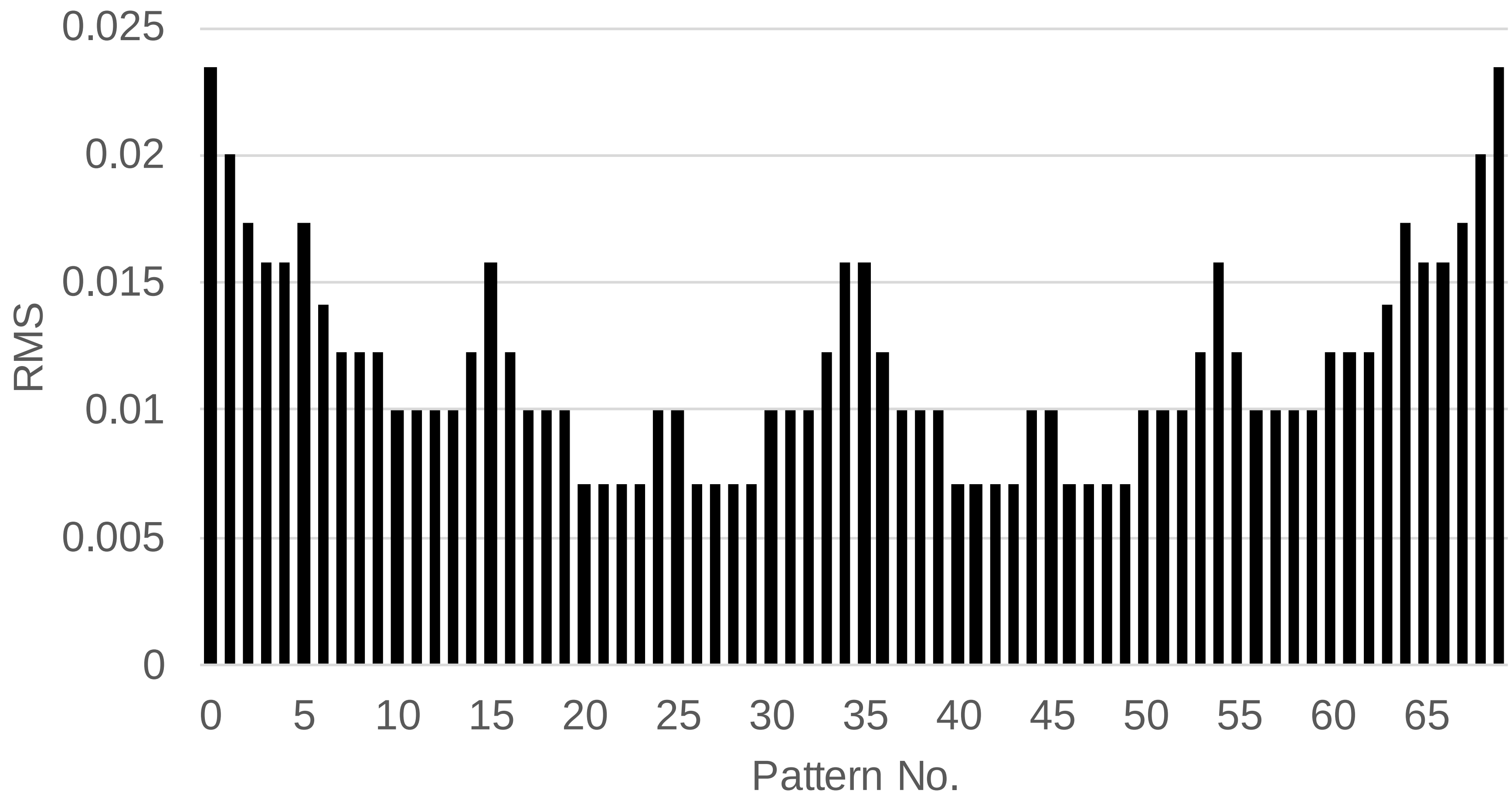
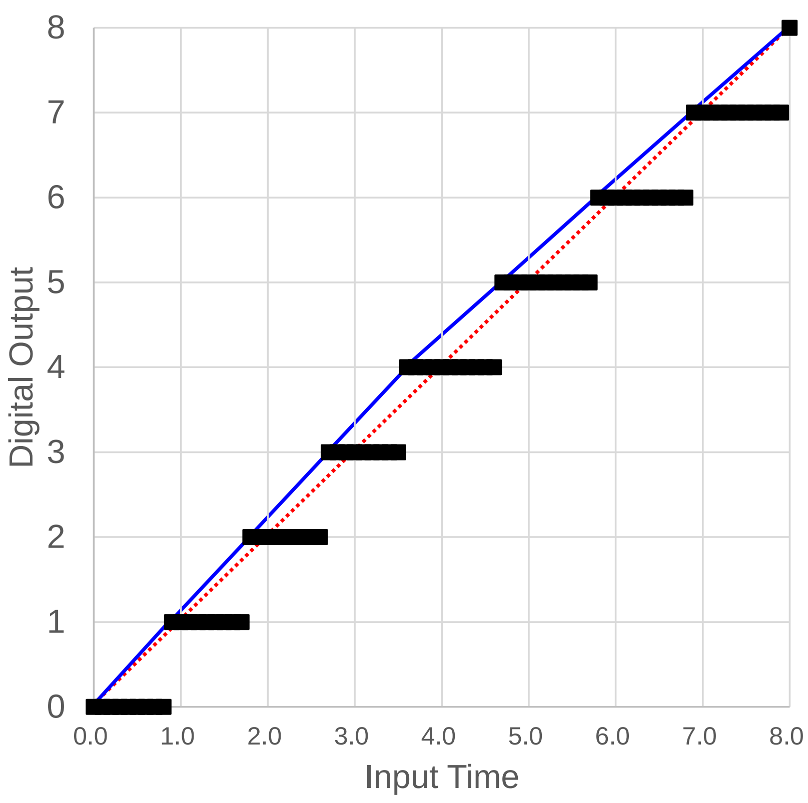
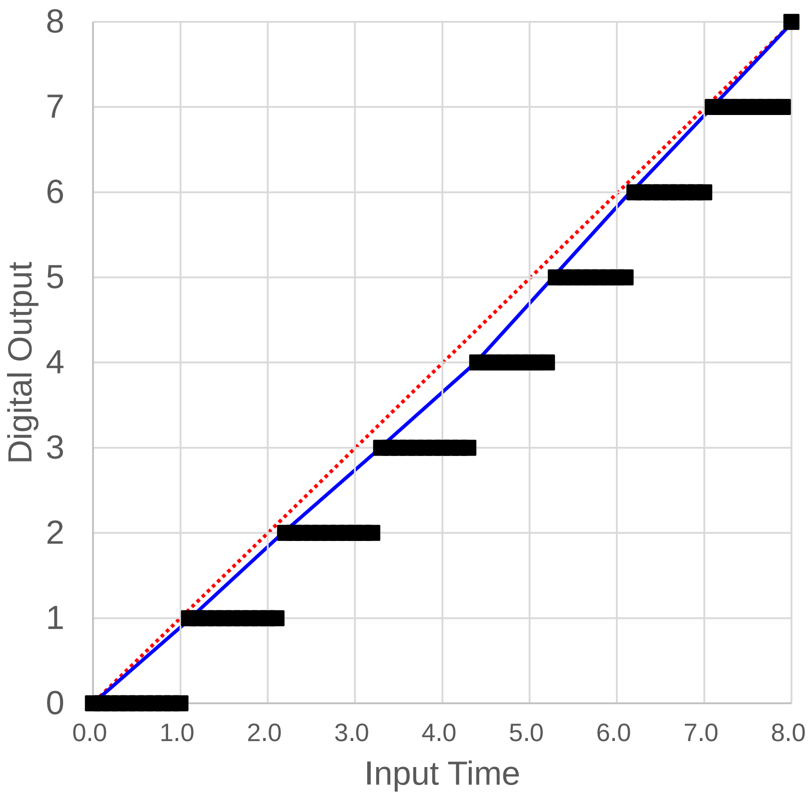
Simulation Results for All Patterns



Simulation Results: Patterns #0, #69



Patten #0



Patten #69

Large RMS Case

Delay element variation patterns with large RMS

	$\Delta\tau_0$	$\Delta\tau_1$	$\Delta\tau_2$	$\Delta\tau_3$	$\Delta\tau_4$	$\Delta\tau_5$	$\Delta\tau_6$	$\Delta\tau_7$
Patten 0	-0.01	-0.01	-0.01	-0.01	0.01	0.01	0.01	0.01
Patten 1	-0.01	-0.01	-0.01	0.01	-0.01	0.01	0.01	0.01
Patten 2	-0.01	-0.01	-0.01	0.01	0.01	-0.01	0.01	0.01
Patten 3	-0.01	-0.01	-0.01	0.01	0.01	0.01	-0.01	0.01
Patten 4	-0.01	-0.01	-0.01	0.01	0.01	0.01	0.01	-0.01
Patten 5	-0.01	-0.01	0.01	-0.01	-0.01	0.01	0.01	0.01
Patten 15	-0.01	0.01	-0.01	-0.01	-0.01	0.01	0.01	0.01
Patten 34	-0.01	0.01	0.01	0.01	0.01	-0.01	-0.01	-0.01

Pattern 2 as an example

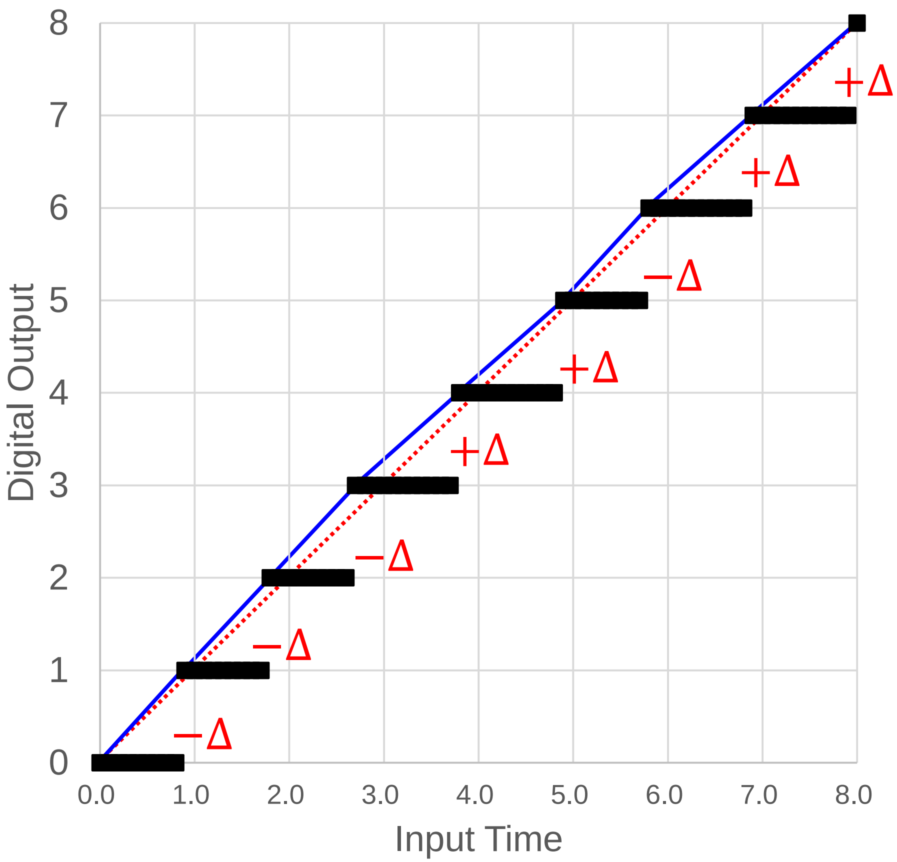
Small RMS Case

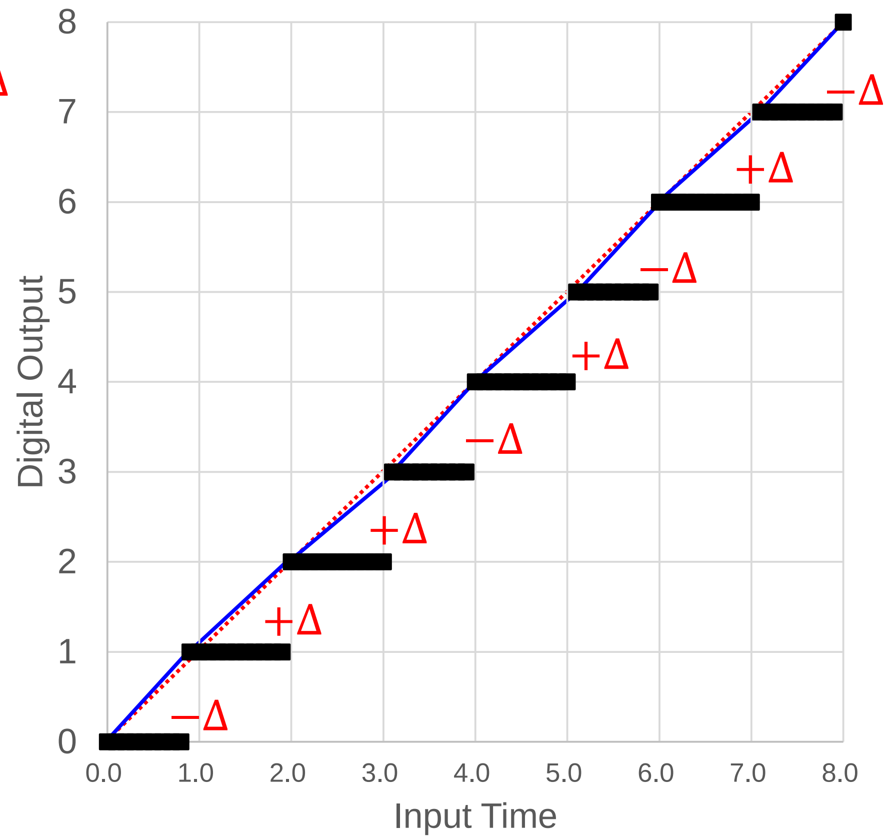
Delay elements variation patterns with small RMS

	$\Delta\tau_0$	$\Delta\tau_1$	$\Delta\tau_2$	$\Delta\tau_3$	$\Delta\tau_4$	$\Delta\tau_5$	$\Delta\tau_6$	$\Delta\tau_7$
Patten 20	-0.01	0.01	-0.01	0.01	-0.01	0.01	-0.01	0.01
Patten 21	-0.01	0.01	-0.01	0.01	-0.01	0.01	0.01	-0.01
Patten 22	-0.01	0.01	-0.01	0.01	0.01	-0.01	-0.01	0.01
Patten 23	-0.01	0.01	-0.01	0.01	0.01	-0.01	0.01	-0.01
Patten 26	-0.01	0.01	0.01	-0.01	-0.01	0.01	-0.01	0.01
Patten 27	-0.01	0.01	0.01	-0.01	-0.01	0.01	0.01	-0.01
Patten 28	-0.01	0.01	0.01	-0.01	0.01	-0.01	-0.01	0.01
Patten 29	-0.01	0.01	0.01	-0.01	0.01	-0.01	0.01	-0.01

Pattern 29 as an example

Input-Output Characteristics





RMS-pattern #2

Large RMS

RMS-pattern #29

Small RMS

Small RMS Case Consideration

Delay element variation patterns with small RMS

	$\Delta\tau_0$	$\Delta\tau_1$	$\Delta\tau_2$	$\Delta\tau_3$	$\Delta\tau_4$	$\Delta\tau_5$	$\Delta\tau_6$	$\Delta\tau_7$
Patten 20	-0.01	0.01	-0.01	0.01	-0.01	0.01	-0.01	0.01
Patten 21	-0.01	0.01	-0.01	0.01	-0.01	0.01	0.01	-0.01
Patten 22	-0.01	0.01	-0.01	0.01	0.01	-0.01	-0.01	0.01
Patten 23	-0.01	0.01	-0.01	0.01	0.01	-0.01	0.01	-0.01
Patten 26	-0.01	0.01	0.01	-0.01	-0.01	0.01	-0.01	0.01
Patten 27	-0.01	0.01	0.01	-0.01	-0.01	0.01	0.01	-0.01
Patten 28	-0.01	0.01	0.01	-0.01	0.01	-0.01	-0.01	0.01
Patten 29	-0.01	0.01	0.01	-0.01	0.01	-0.01	0.01	-0.01

$$\Delta\tau_0 + \Delta\tau_1 = \Delta\tau_2 + \Delta\tau_3 = \Delta\tau_4 + \Delta\tau_5 = \Delta\tau_6 + \Delta\tau_7 = 0$$

are satisfied.

RMS becomes smaller
as a result of cancelation local variations

Larger RMS Case Consideration

Delay elements variation patterns with slightly larger RMS

	$\Delta\tau_0$	$\Delta\tau_1$	$\Delta\tau_2$	$\Delta\tau_3$	$\Delta\tau_4$	$\Delta\tau_5$	$\Delta\tau_6$	$\Delta\tau_7$
Patten 10	-0.01	-0.01	0.01	0.01	-0.01	0.01	-0.01	0.01
Patten 11	-0.01	-0.01	0.01	0.01	-0.01	0.01	0.01	-0.01
Patten 12	-0.01	-0.01	0.01	0.01	0.01	-0.01	-0.01	0.01
Patten 13	-0.01	-0.01	0.01	0.01	0.01	-0.01	0.01	-0.01
Patten 17	-0.01	0.01	-0.01	-0.01	0.01	0.01	-0.01	0.01
Patten 18	-0.01	0.01	-0.01	-0.01	0.01	0.01	0.01	-0.01
Patten 19	-0.01	0.01	-0.01	0.01	-0.01	-0.01	0.01	0.01
Patten 24	-0.01	0.01	-0.01	0.01	0.01	0.01	-0.01	-0.01
Patten 25	-0.01	0.01	0.01	-0.01	-0.01	-0.01	0.01	0.01
Patten 30	-0.01	0.01	0.01	-0.01	0.01	0.01	-0.01	-0.01
Patten 31	-0.01	0.01	0.01	0.01	-0.01	-0.01	-0.01	0.01
Patten 32	-0.01	0.01	0.01	0.01	-0.01	-0.01	0.01	-0.01

$$\Delta\tau_0 + \Delta\tau_1 < 0,\ \Delta\tau_2 + \Delta\tau_3 > 0,\ \Delta\tau_4 + \Delta\tau_5 = \Delta\tau_6 + \Delta\tau_7 = 0$$

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Conclusions

TDC: Delay variation and Non-linearity

- Even if sum of delay variations is the same, deviation from the ideal becomes larger when order of variations is different.

- Sequence of delay elements with positive or negative deviations results in larger RMS.

- If positive and negative deviations of delay elements locally cancel each other, RMS becomes smaller.

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