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I-Q Signal Generation Techniques for Communication IC Testing and ATE Systems

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Research Objective

- To develop usage of complex multi-band signals for LSI testing applications
- To develop digital centric design of complex multi-band signal generator
  - Multi-bit ΔΣ DA modulator
  - Linearity enhancement algorithms

Outline

- Background to This Research
- Complex Multi-Band Signals
- Complex Multi-BP ΔΣ DA Modulators
- DWA Algorithm
- Self-Calibration
- Combination of DWA and Self-Calibration
- Conclusions

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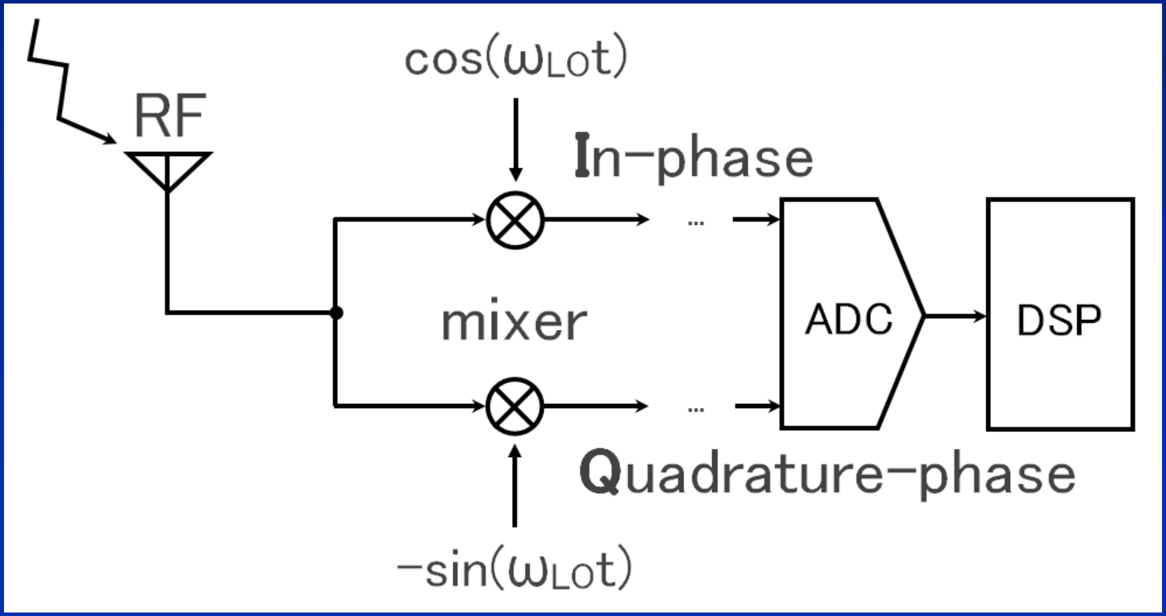
Research Goal

Demand for low cost testing of communication IC

High quality I,Q test signal generation for receiver IC with low cost



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Complex Signal

2 Real signals $\mathbf{I_{in}}$, $\mathbf{Q_{in}}$

⇩

Complex signal $\mathbf{I_{in} + j\, Q_{in}}$ $\mathbf{j = \sqrt{-1}}$

Complex signal processing is NOT complex.

- Prof. Ken Martin, Toronto Univ.

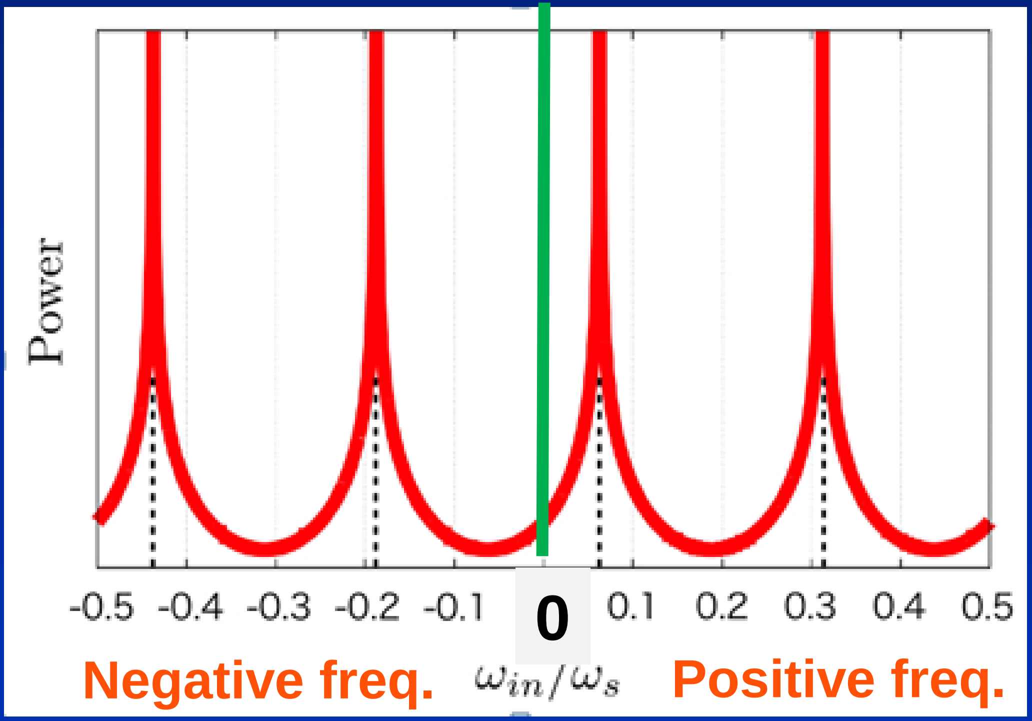
Complex Signal in Frequency Domain

Complex signal $I_{in} + j\, Q_{in}$

After Fourier transform $I_{in}(j\,\omega) + j\, Q_{in}(j\,\omega)$

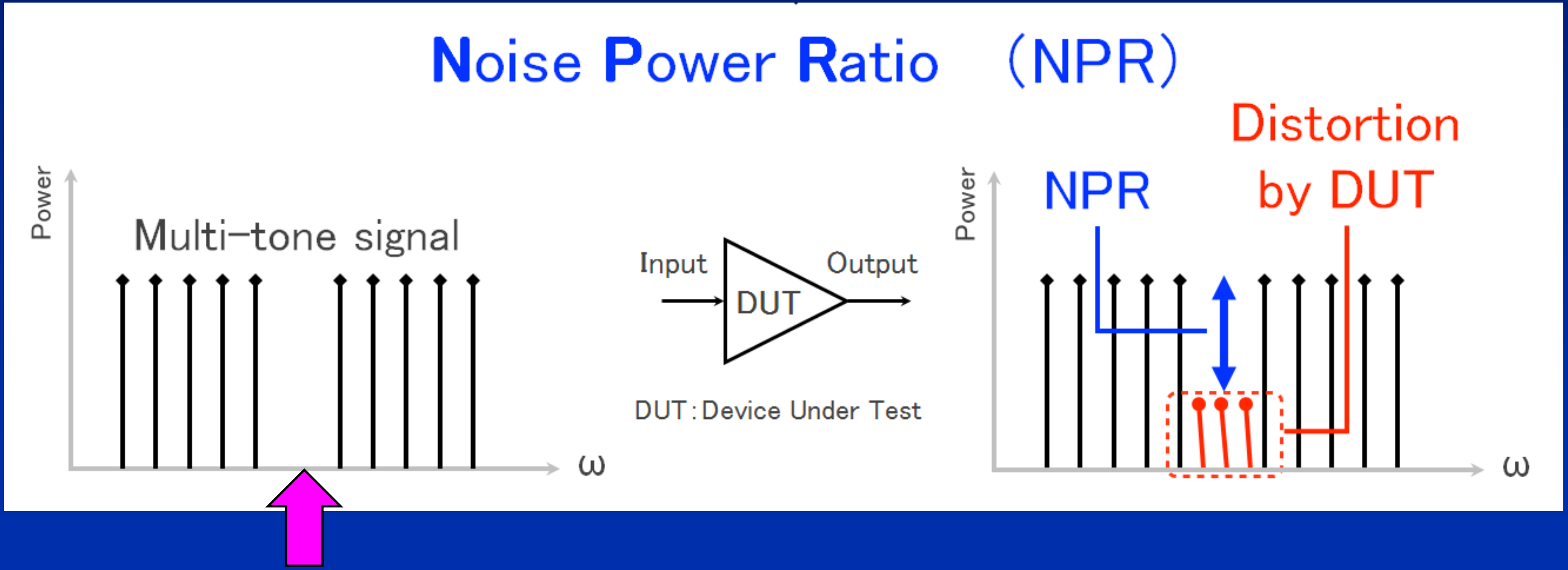
Asymmetric

Complex



IC Testing with Multi-tone Signal

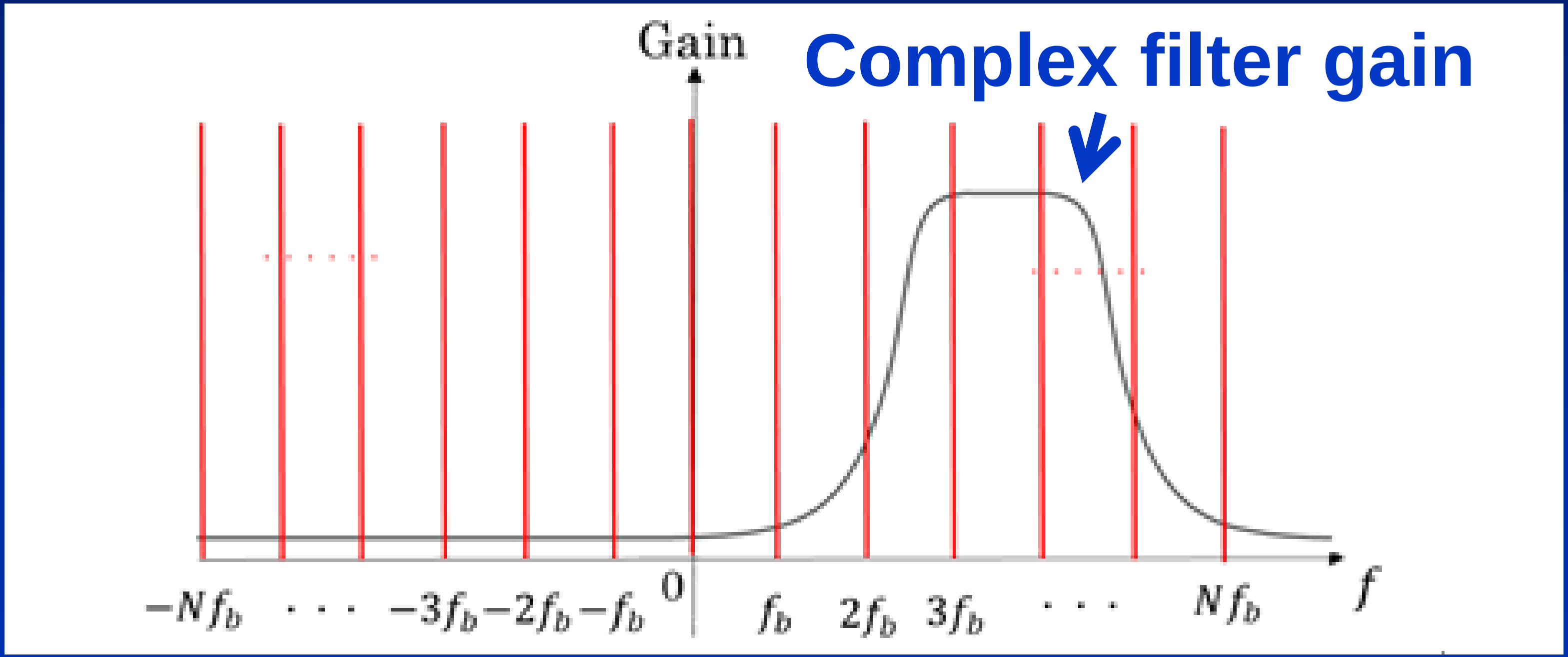
ADSL ADC Testing



empty

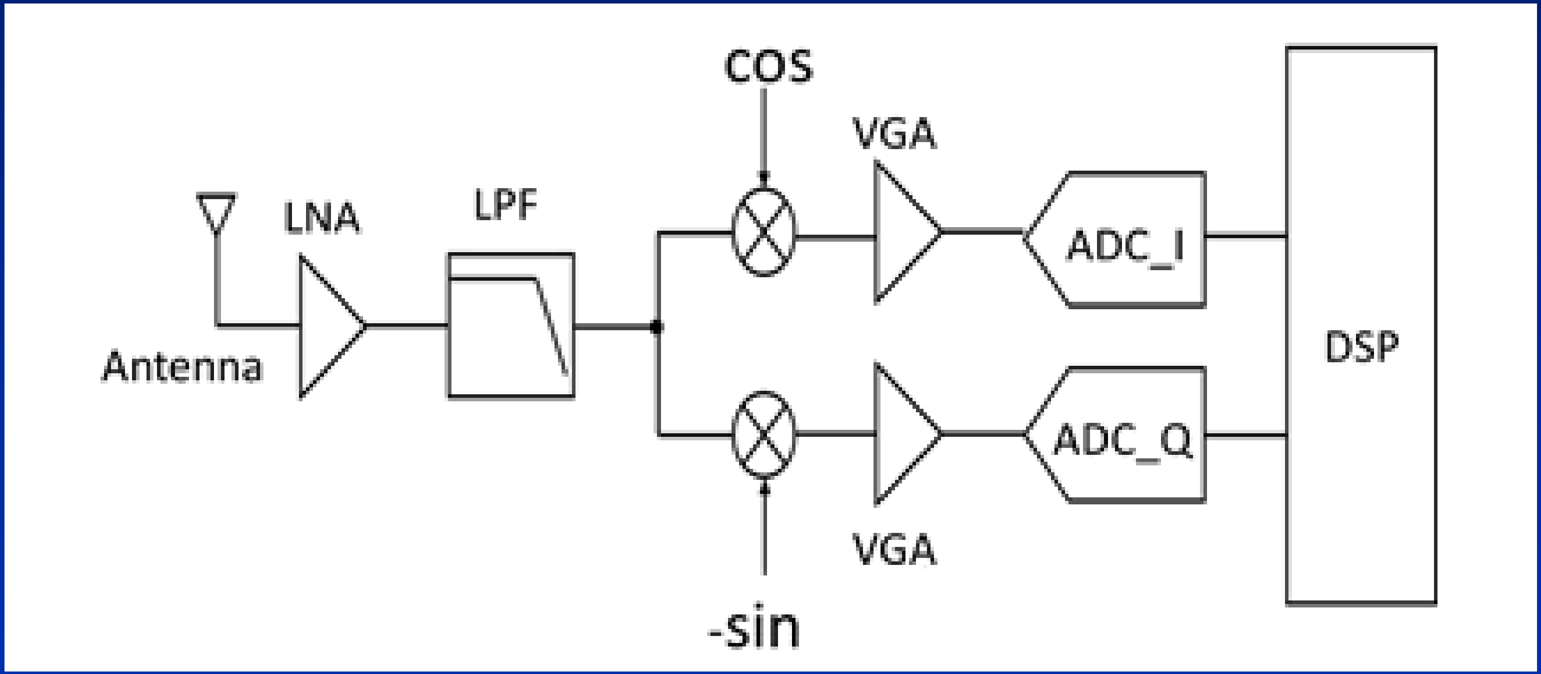
IC Testing with Complex Multi-tone Signal

Complex Analog Filter Testing



IC Testing with Complex Multi-tone Signal

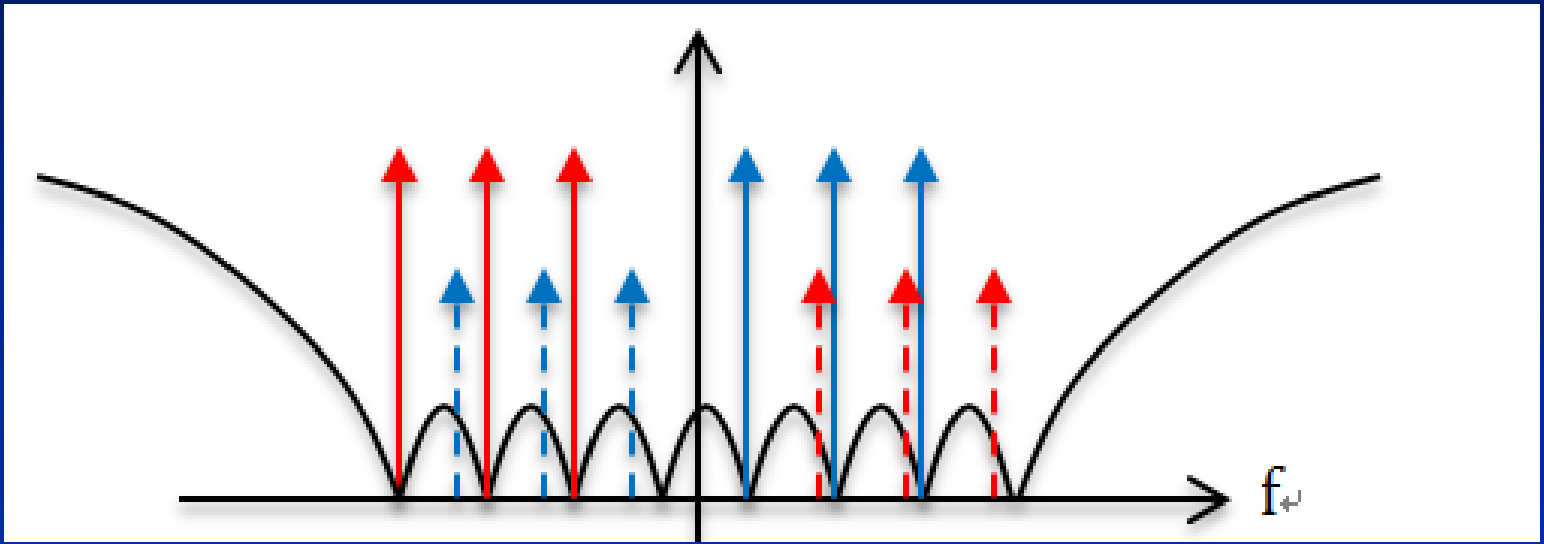
I-Q ADCs Testing



I-Q ADCs in receiver circuit

IC Testing with Complex Multi-tone Signal

Image Rejection Ratio Testing of Communication ICs



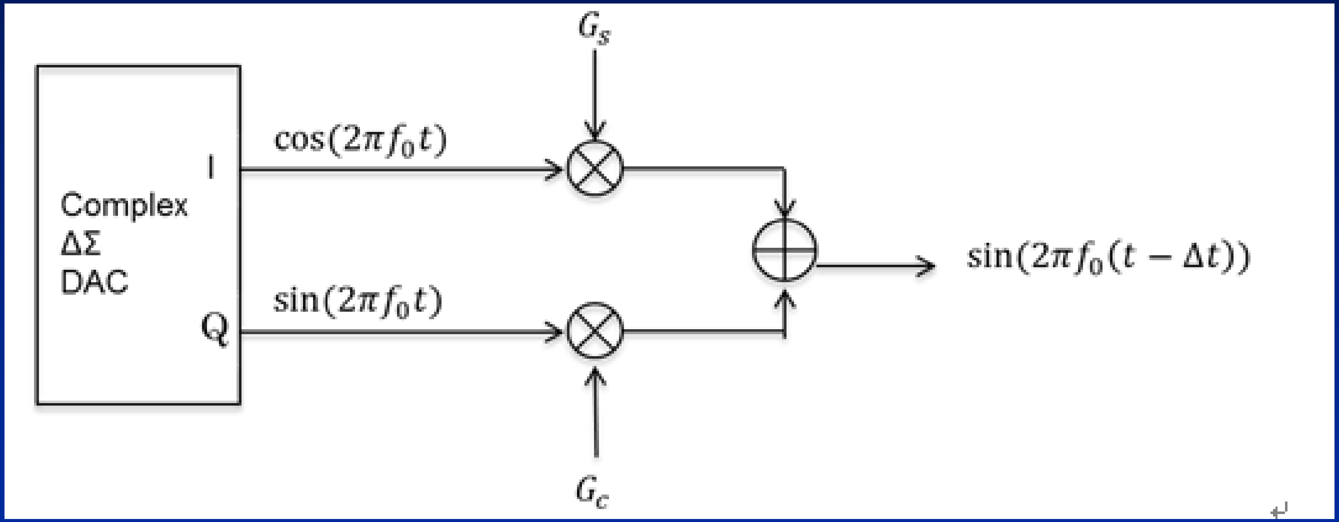
I, Q imbalance ➡

Negative freq. (input) ➡ Positive freq. (output)

Suggested by an ATE vendor

IC Testing with Complex Signal

Clock phase fine adjustment system using complex signal

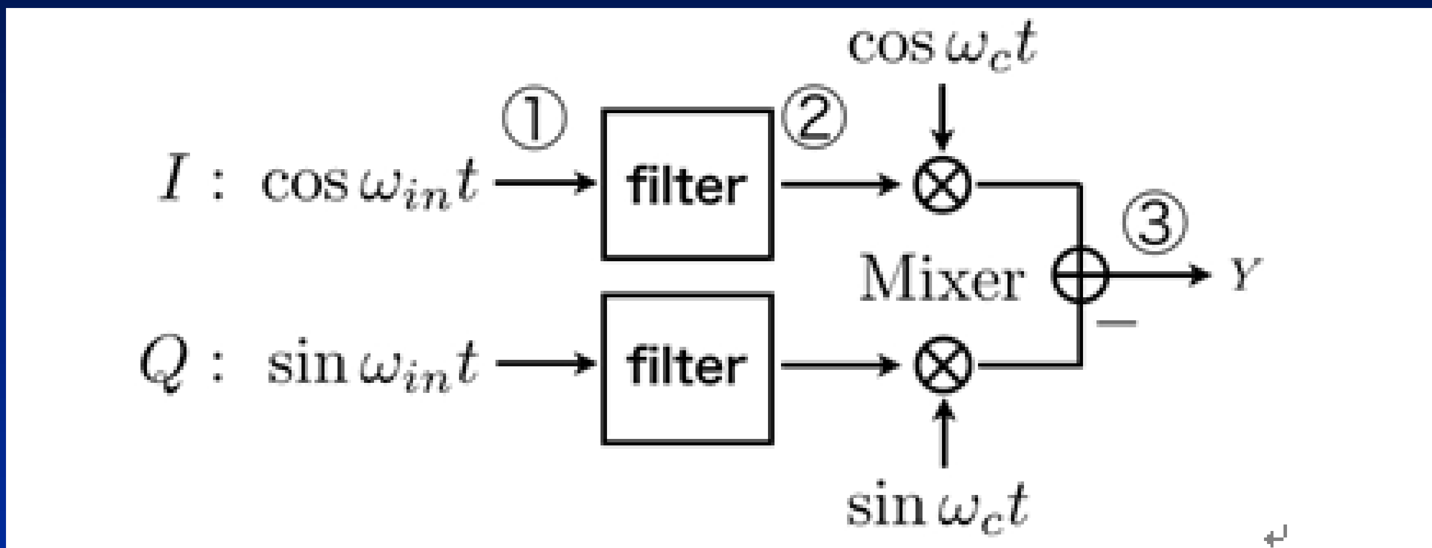


$$
\begin{aligned}
&\sin\left(2\pi f_0(t - \Delta t)\right) \\
&= \cos(2\pi f_0 \Delta t)\sin(2\pi f_0 t) - \sin(2\pi f_0 \Delta t)\cos(2\pi f_0 t) \\
&= G_c \sin(2\pi f_0 t) + G_S \cos(2\pi f_0 t)
\end{aligned}
$$

Suggested by an ATE vendor

IC Testing with Complex Signal

High frequency signal generation



③

$$
\begin{aligned}
Y &= \cos\omega_{in}t \cdot \cos\omega_c t - \sin\omega_{in}t \cdot \sin\omega_c t \\
&= \cos(\omega_{in} + \omega_c)t.
\end{aligned}
$$

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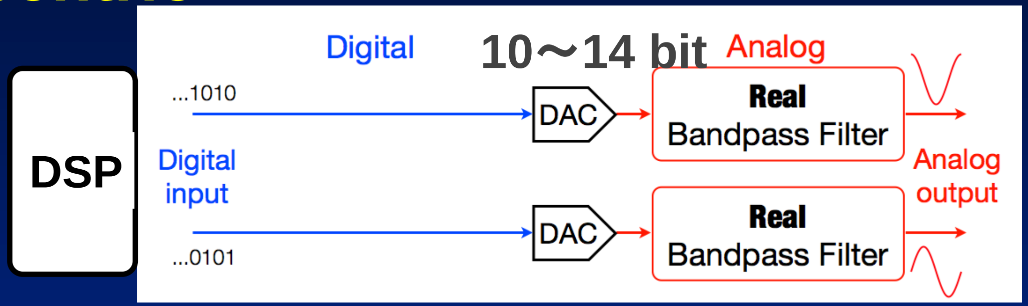
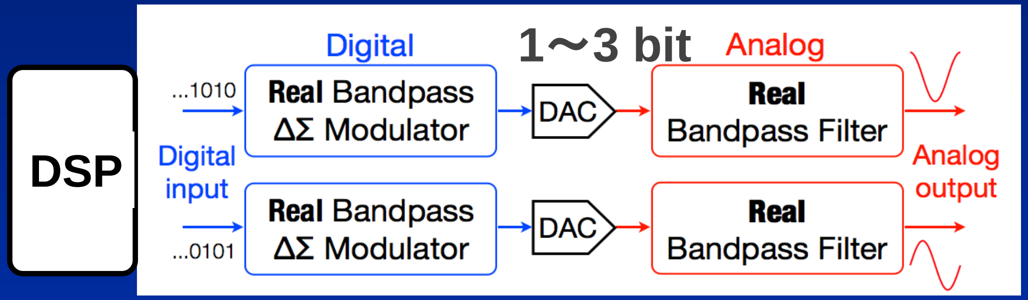
I,Q Signal Generation

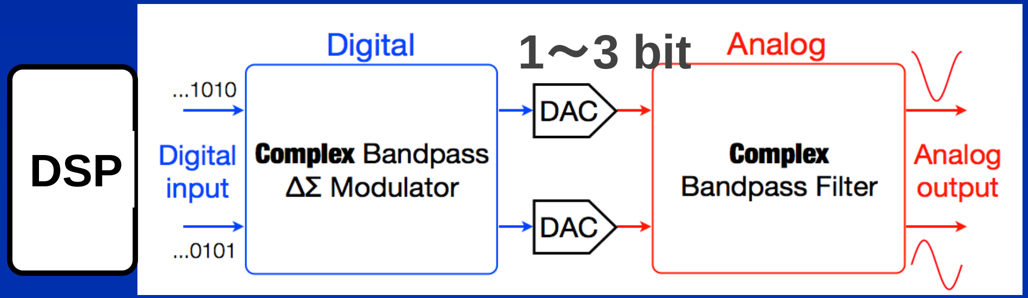
① Analog centric



② Digital centric（1）

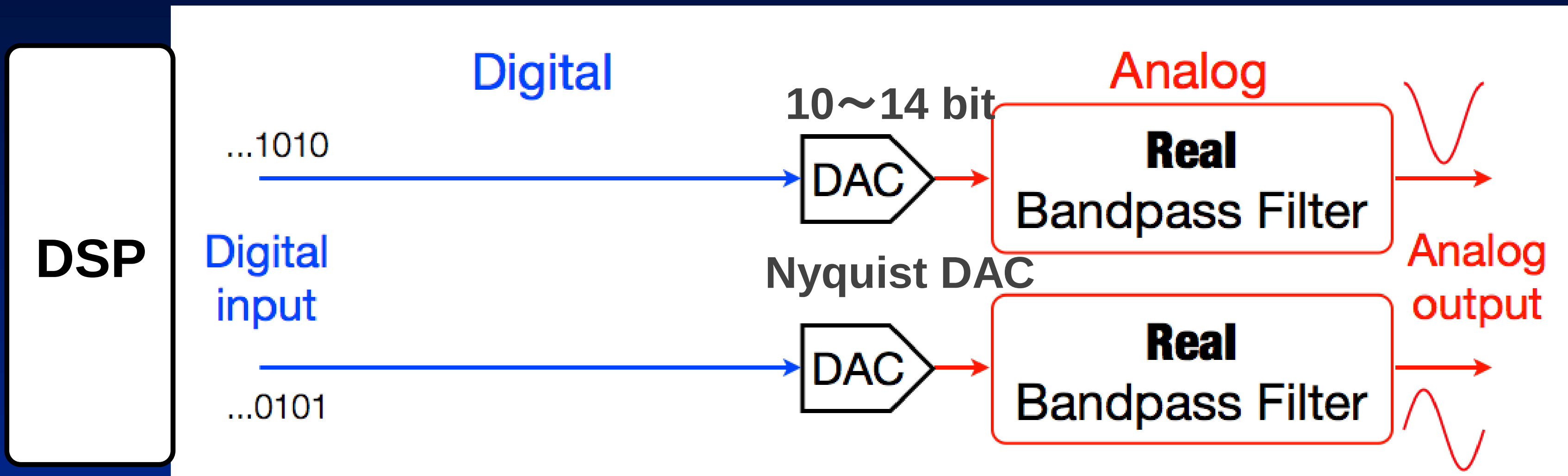


③ Digital centric（2）



Proposed

① Analog Centric



Large Nyquist-rate DACs

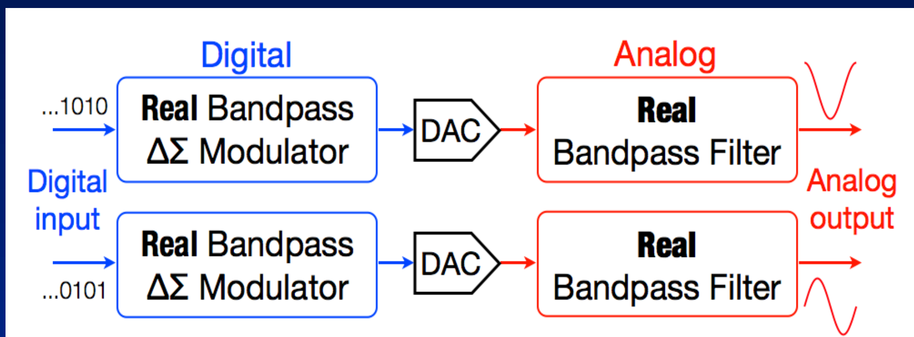
and

Steep analog filters

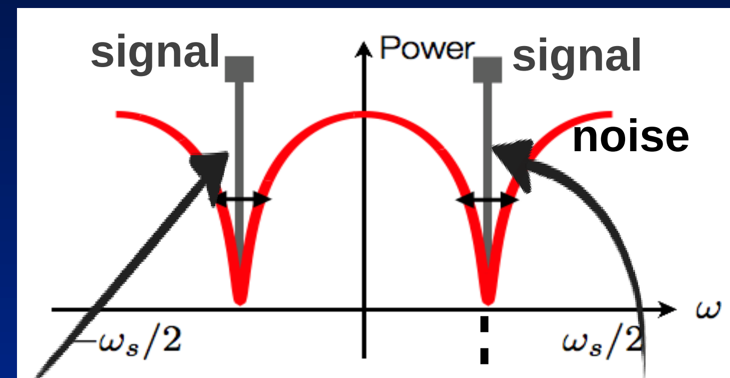
Delta Sigma DA Converter

Real vs Complex

② 2 Real-BP ΔΣ DACs



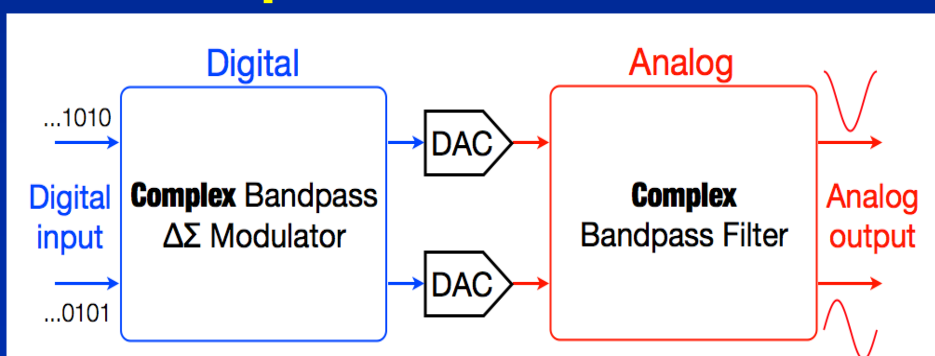
1～3 bit DAC



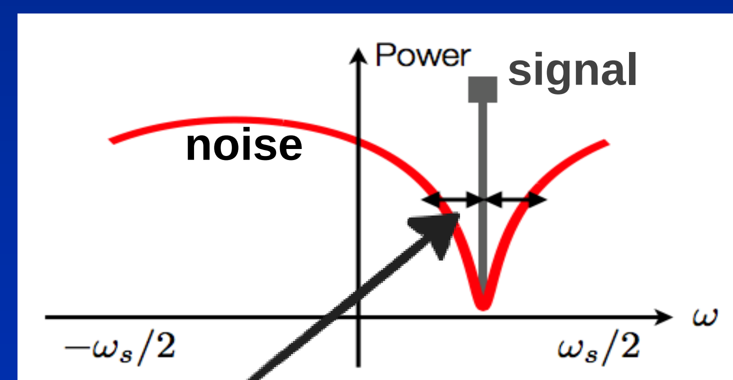
Unused band

Signal band

③ 1 Complex-BP ΔΣ DAC

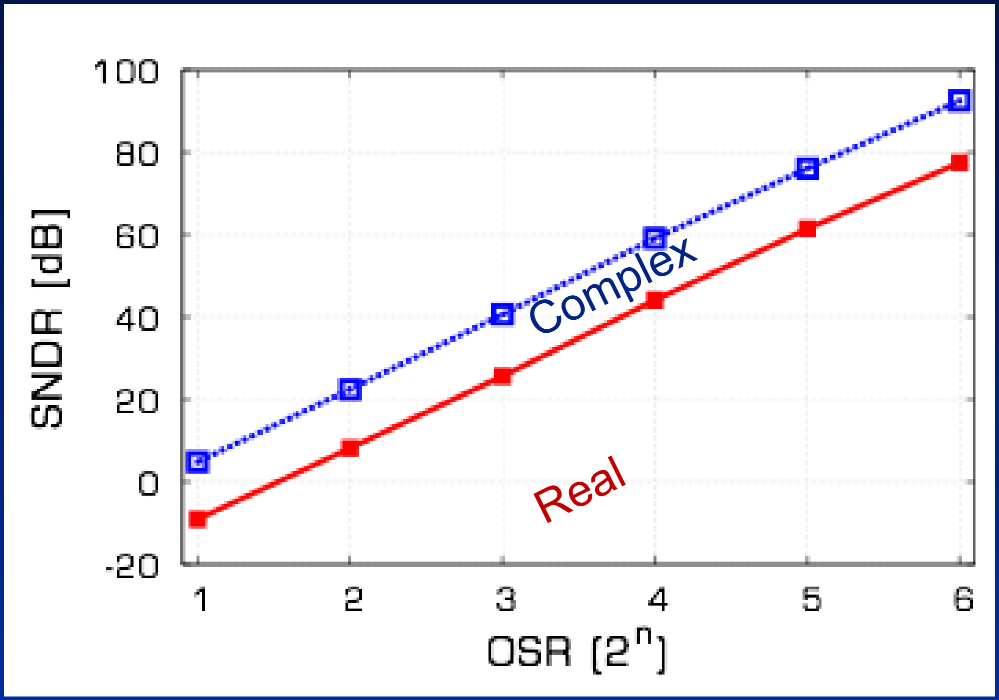


1～3 bit DAC

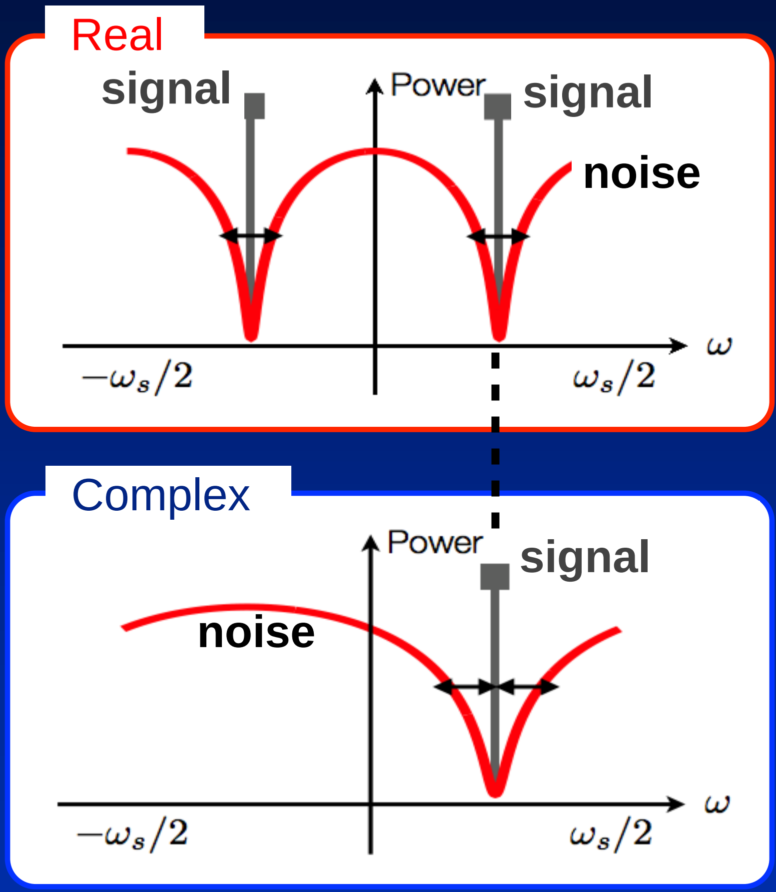


Wider signal band, High SNR

Complex Delta Sigma is Superior



OSR : Oversampling Ratio



15 dB better SNDR
for complex BP ΔΣ modulator

High quality I, Q signals

I,Q Signal Generation

DSP

+

ΔΣ DAC

+

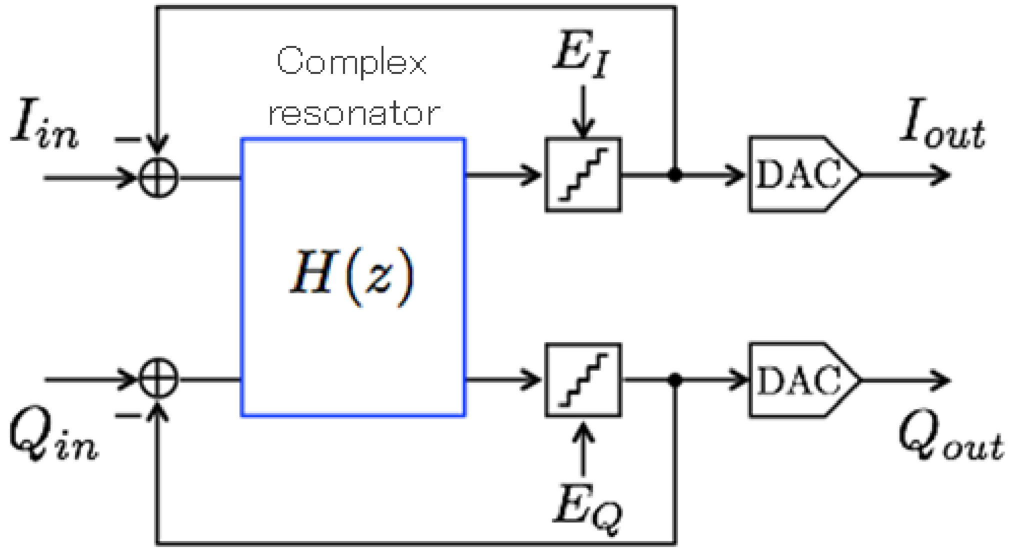
Complex

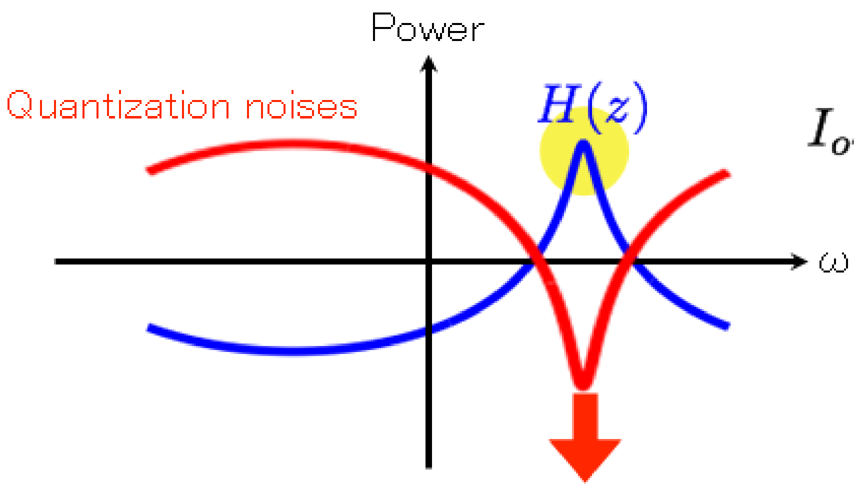
||

Low cost, high quality signal !

Digital rich !

Principle of Complex BP Noise Shape



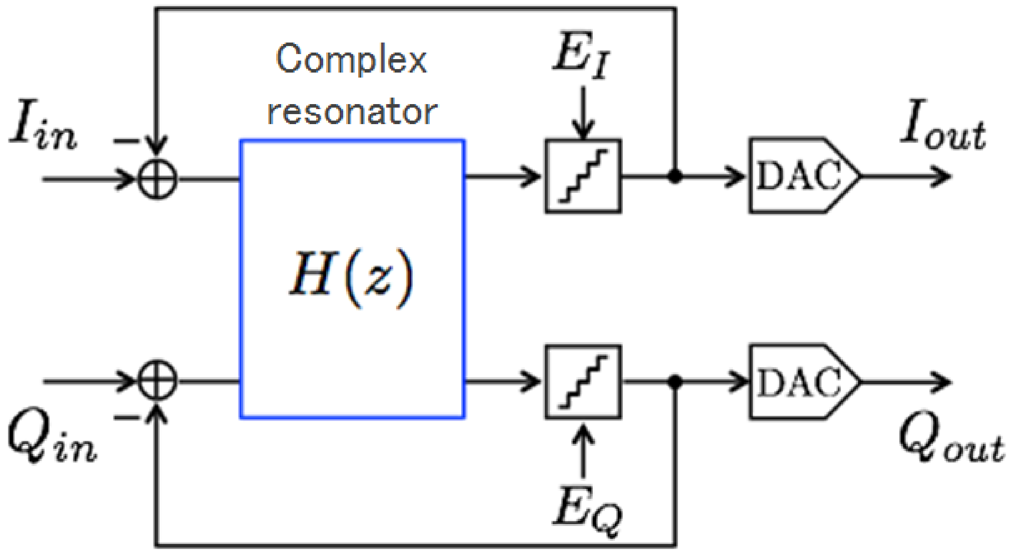


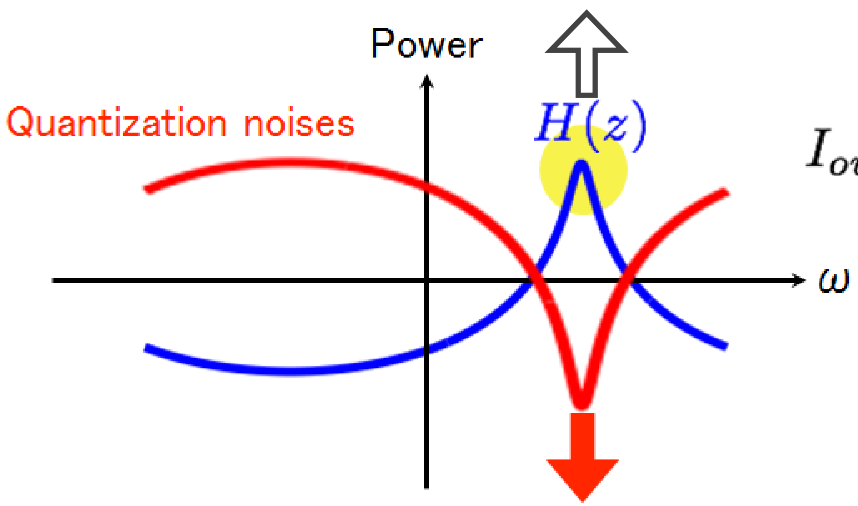
Signal Transfer Function

$$I_{out} + jQ_{out} = \frac{H(z)}{1+H(z)}(I_{in} + jQ_{in}) + \frac{1}{1+H(z)}(E_I + jE_Q)$$

Noise Transfer Function

Principle of Complex BP Noise Shape





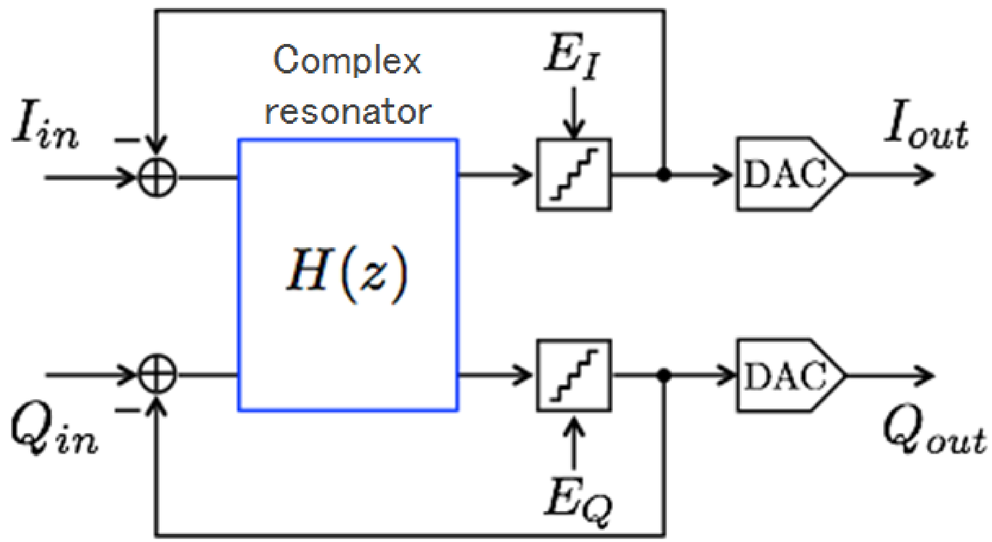
Signal Transfer Function = 1

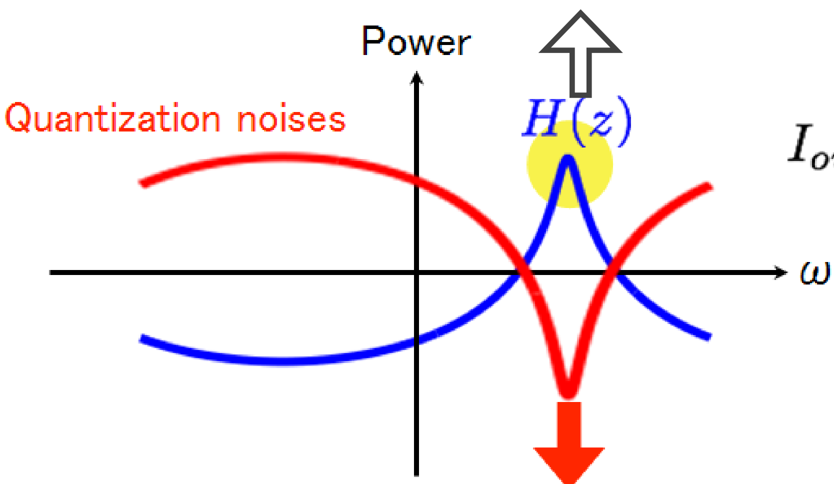
$$I_{out} + jQ_{out} = \frac{H(z)}{1+H(z)}(I_{in} + jQ_{in})$$

$$+\frac{1}{1+H(z)}(E_I + jE_Q)$$

Noise Transfer Function = 0

Principle of Complex BP Noise Shape





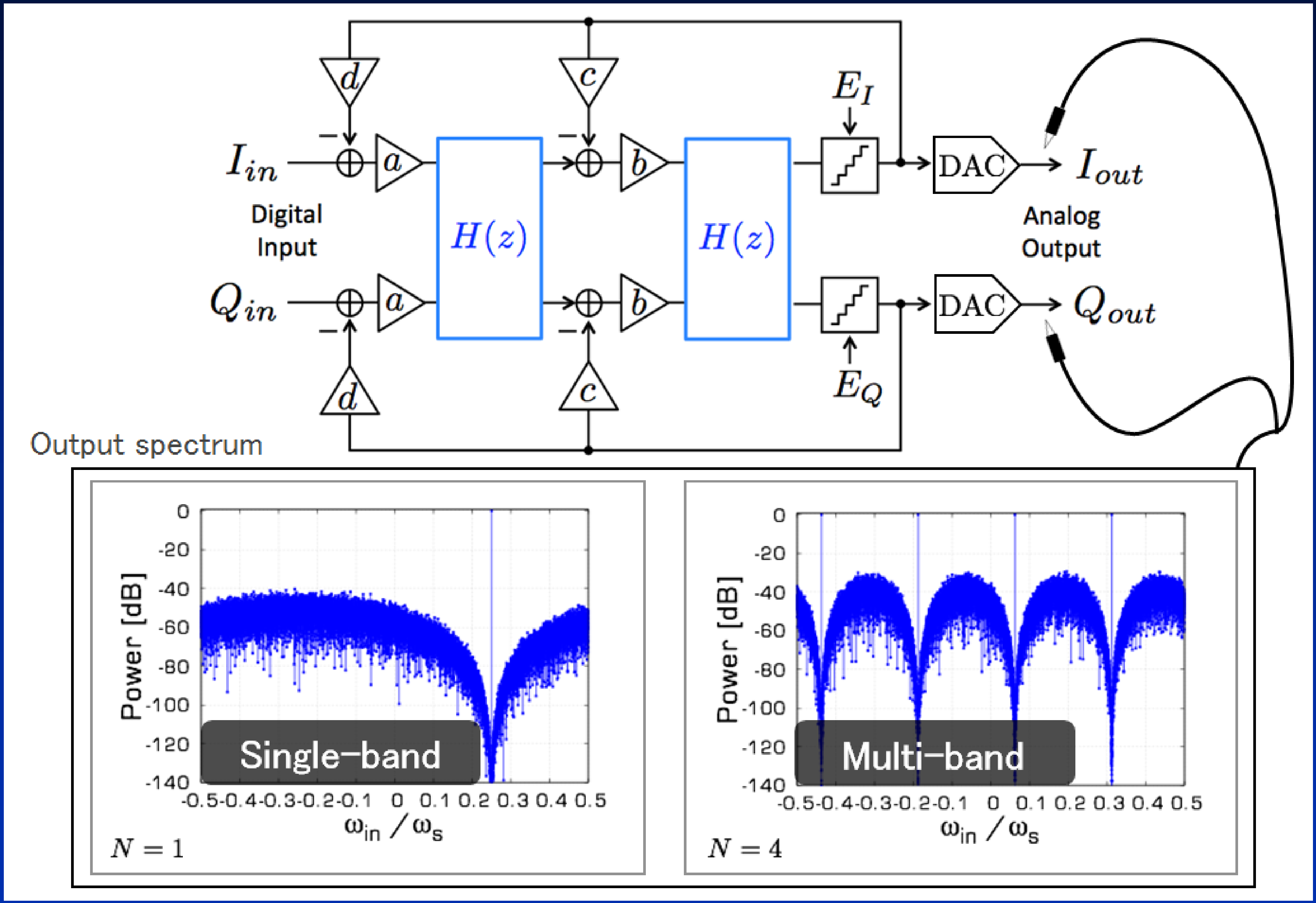
Signal Transfer Function = 1

$$I_{out} + jQ_{out} = \boxed{1}\,(I_{in} + jQ_{in})$$

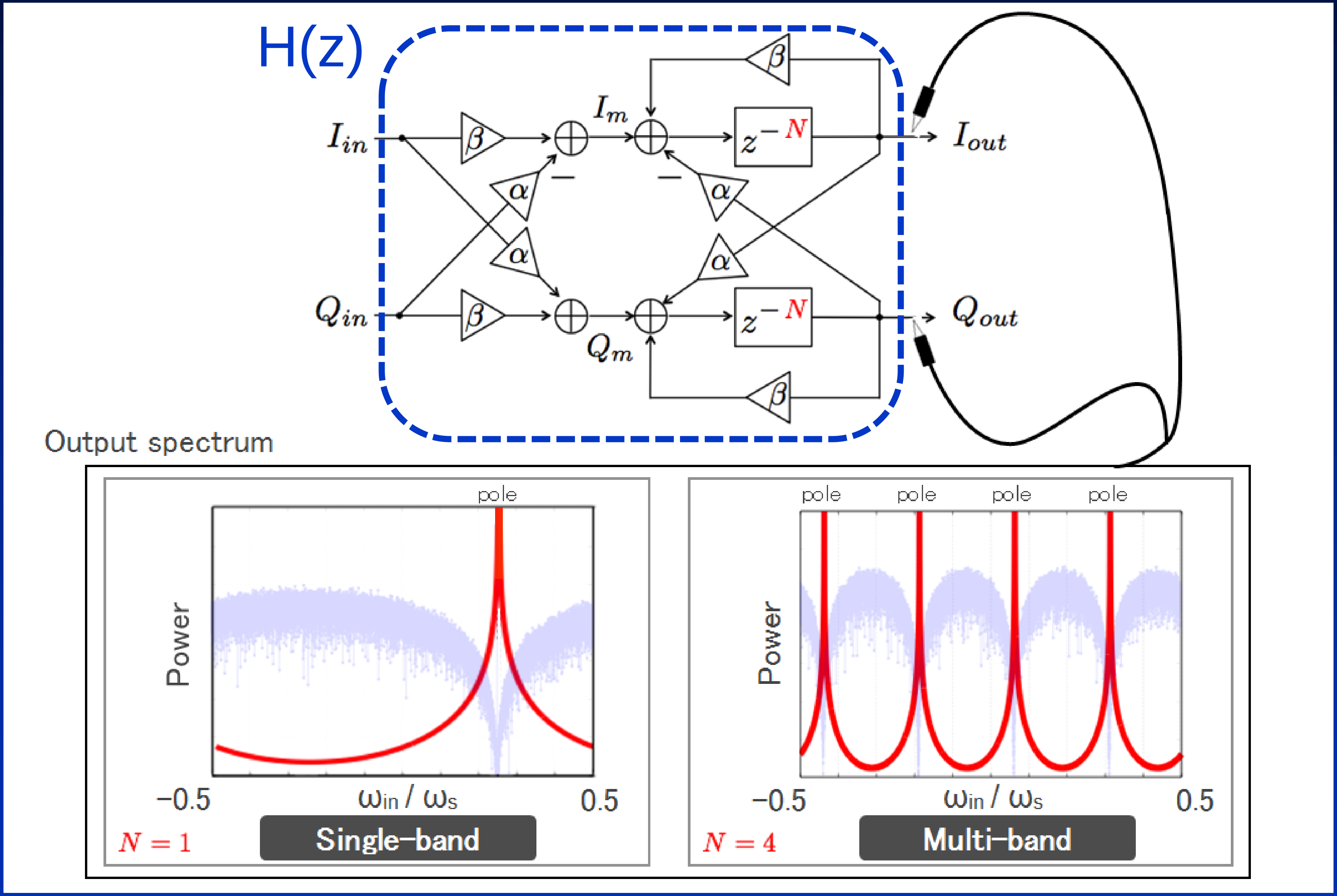
$$+ \boxed{0}\,(E_I + jE_Q)$$

Noise Transfer Function = 0

2nd-order Complex Multi-BP ΔΣ DAC



N^{th}-order Complex Resonator



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- Background to This Research
- Complex Multi-Band Signals
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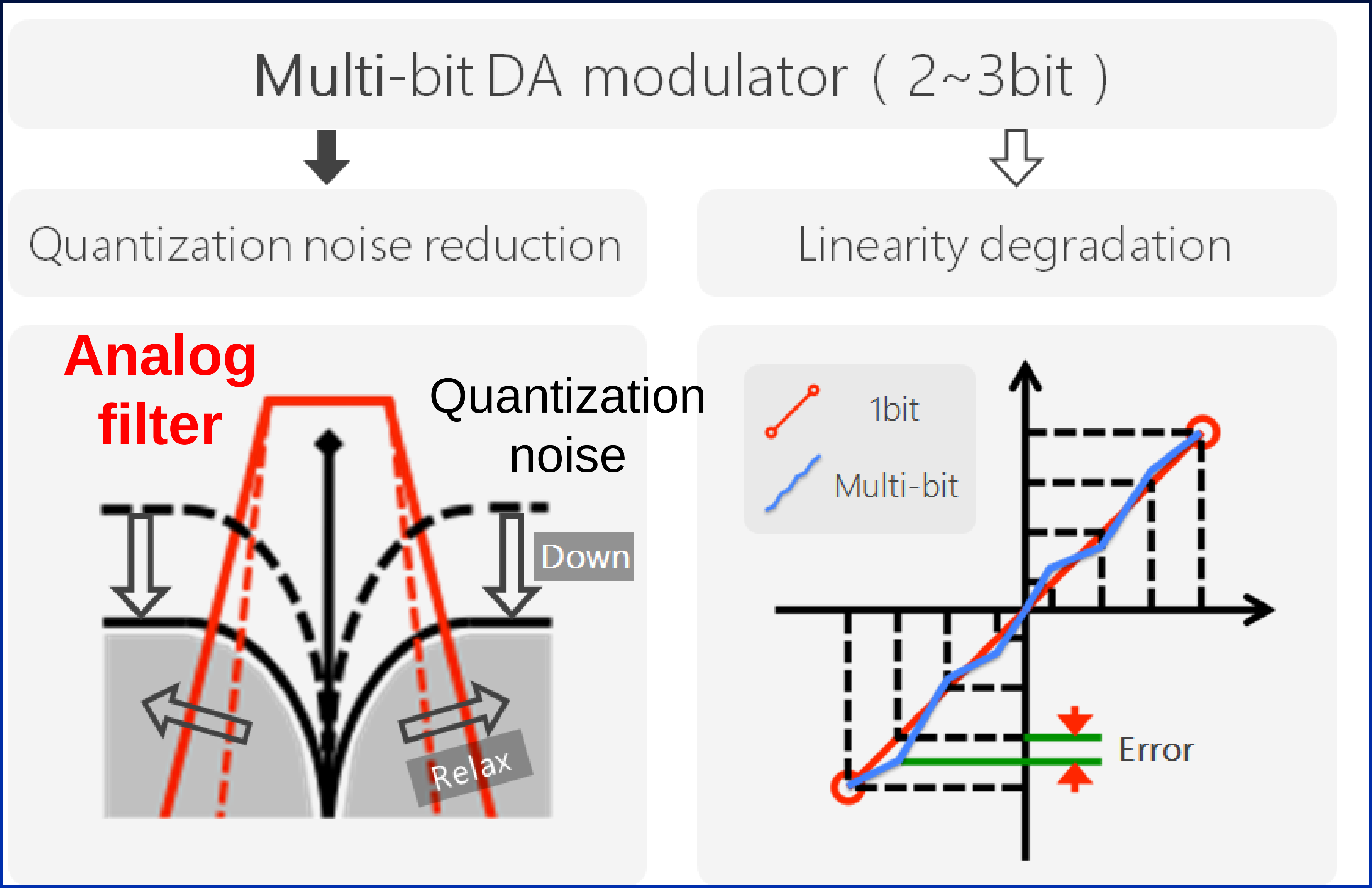
- DWA Algorithm

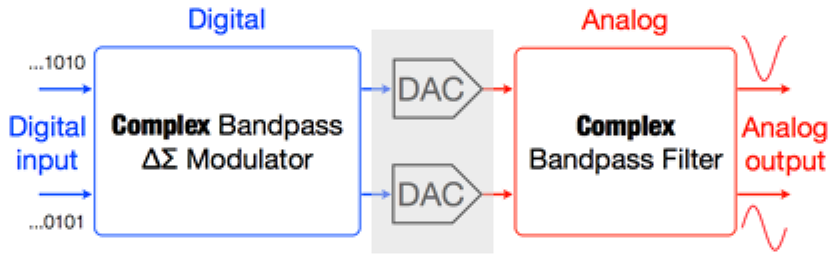
DWA: Data Weighted Averaging

One of
Dynamic Element Matching (DEM) algorithms

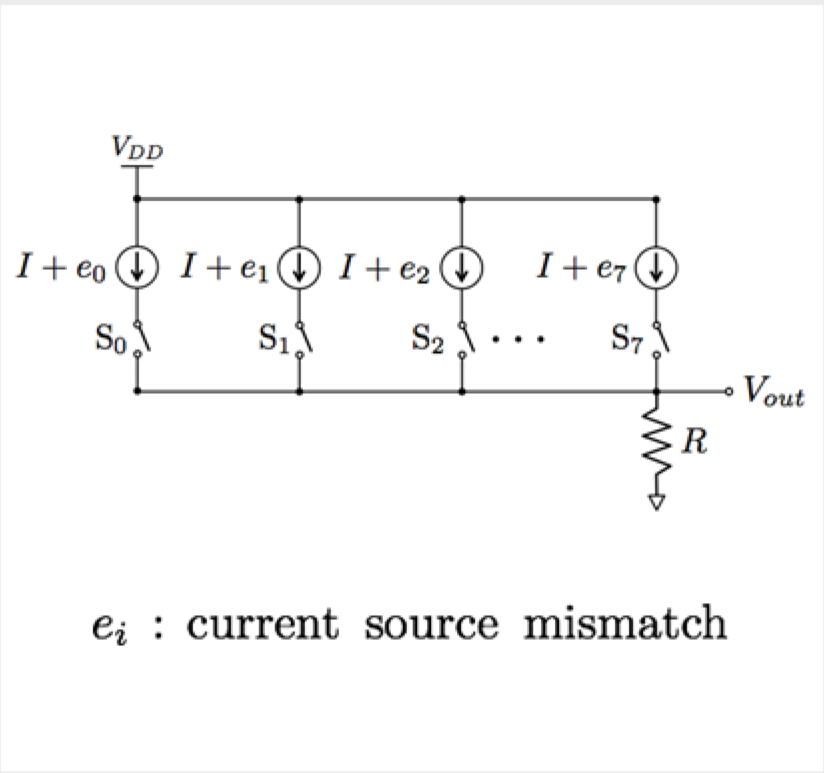
Multi-bit DA Modulator

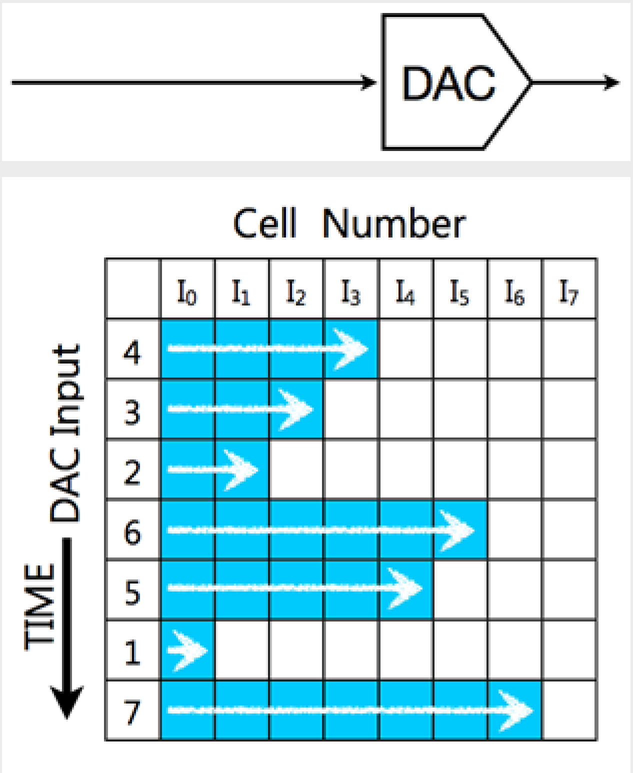


Multi-bit DAC



Normal unary DAC

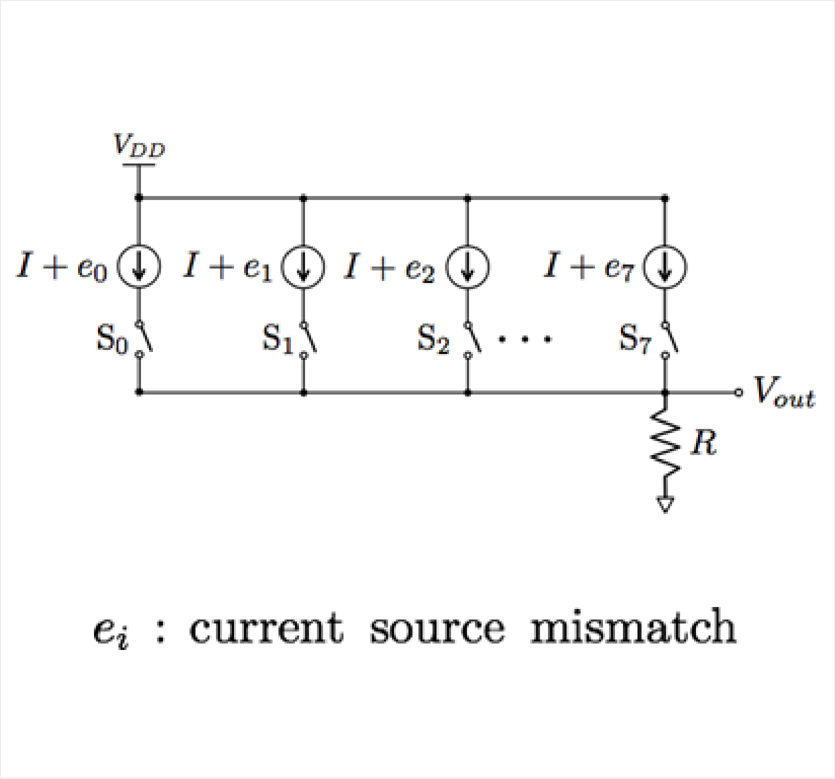


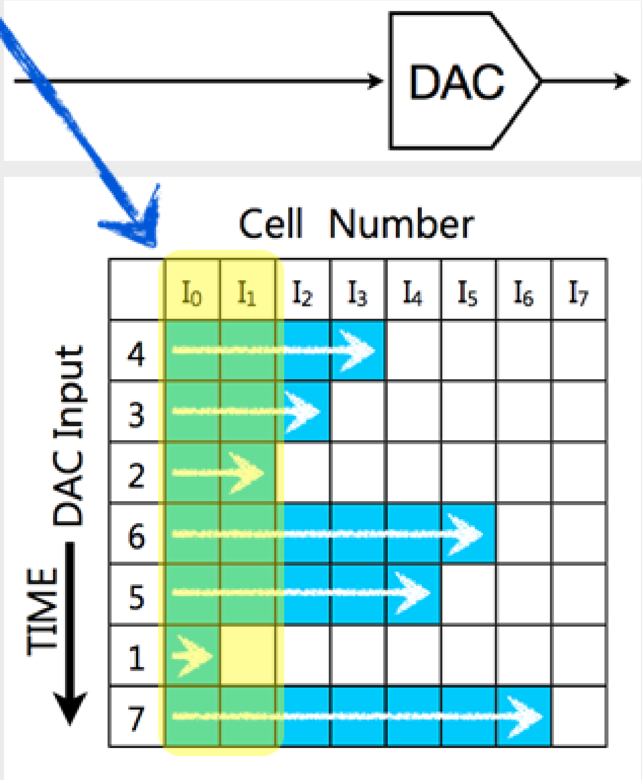


Multi-bit DAC

Accumulate mismatch of particular cell

Normal unary DAC



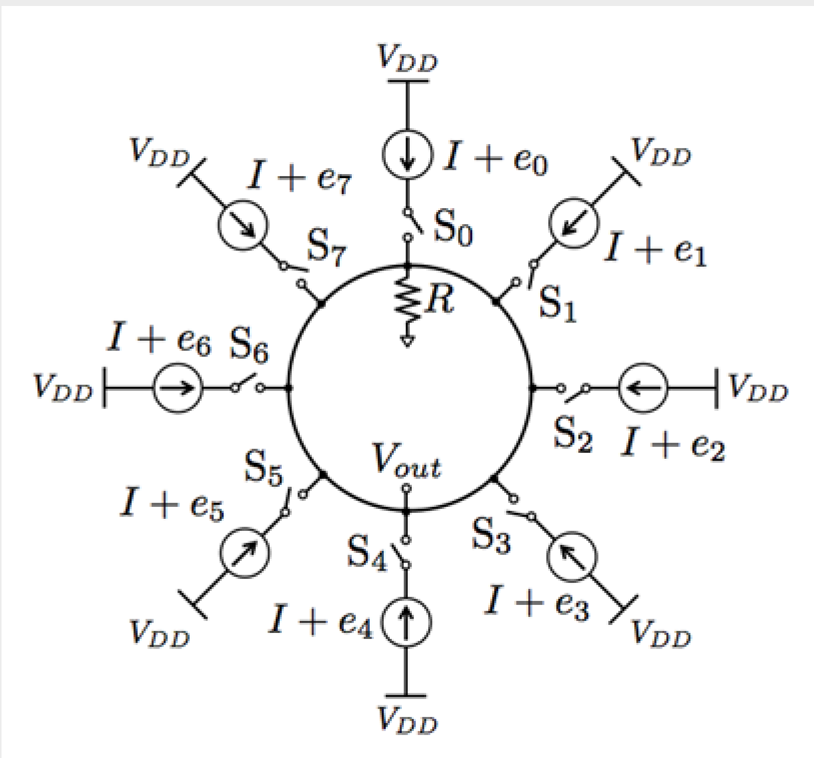


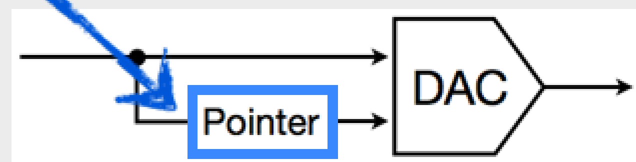
Multi-bit DAC + DWA

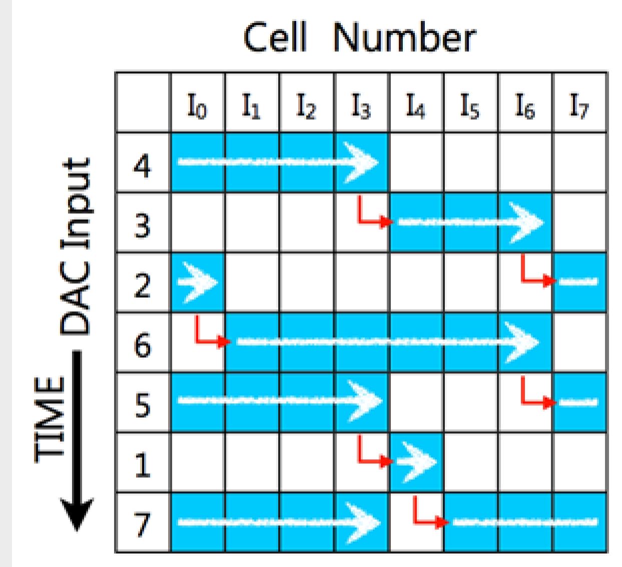
Memorize next cell selection start point

DWA* DAC

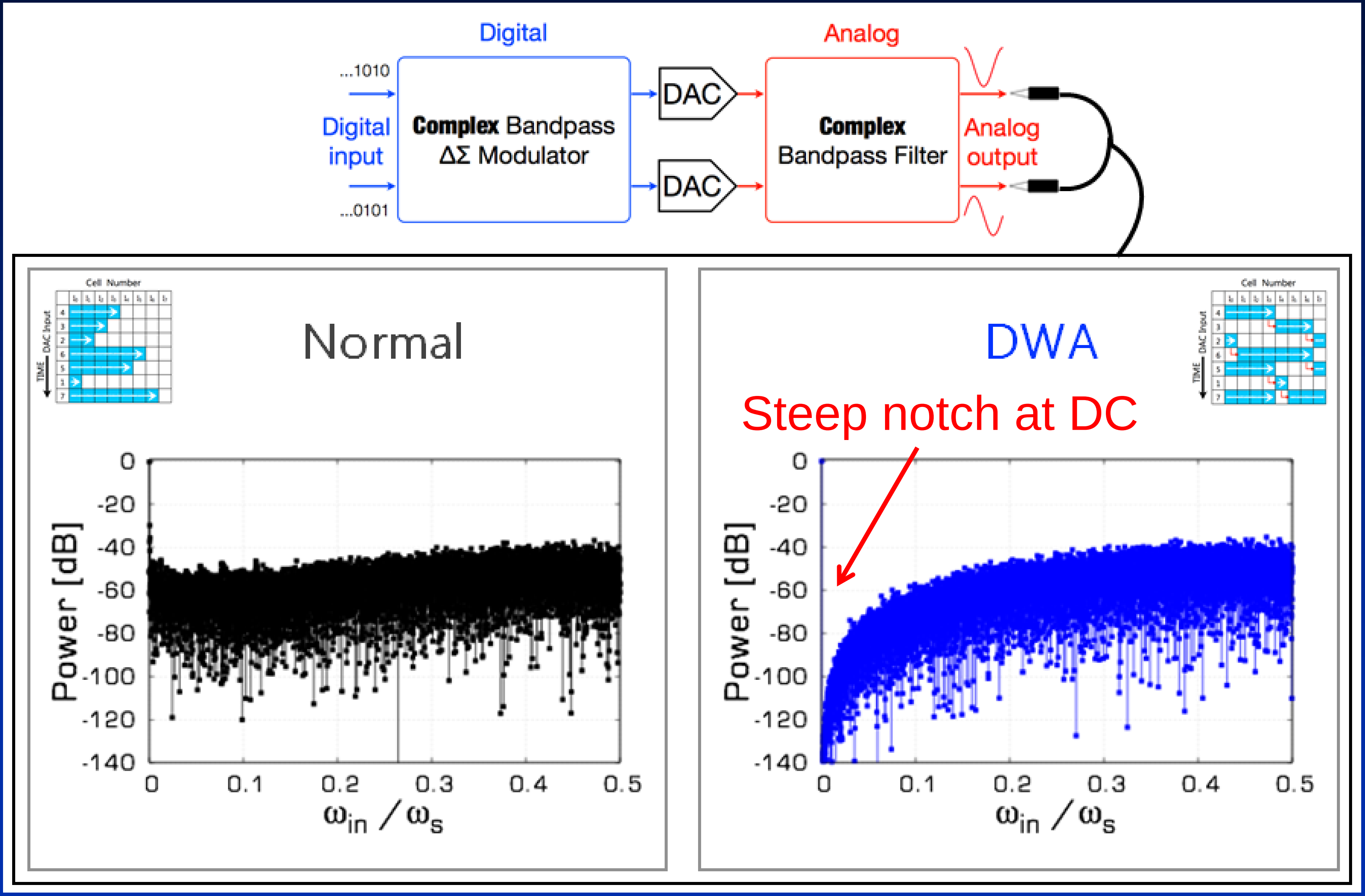
*Data Weighted Averaging | Select the element with DSP algorithm



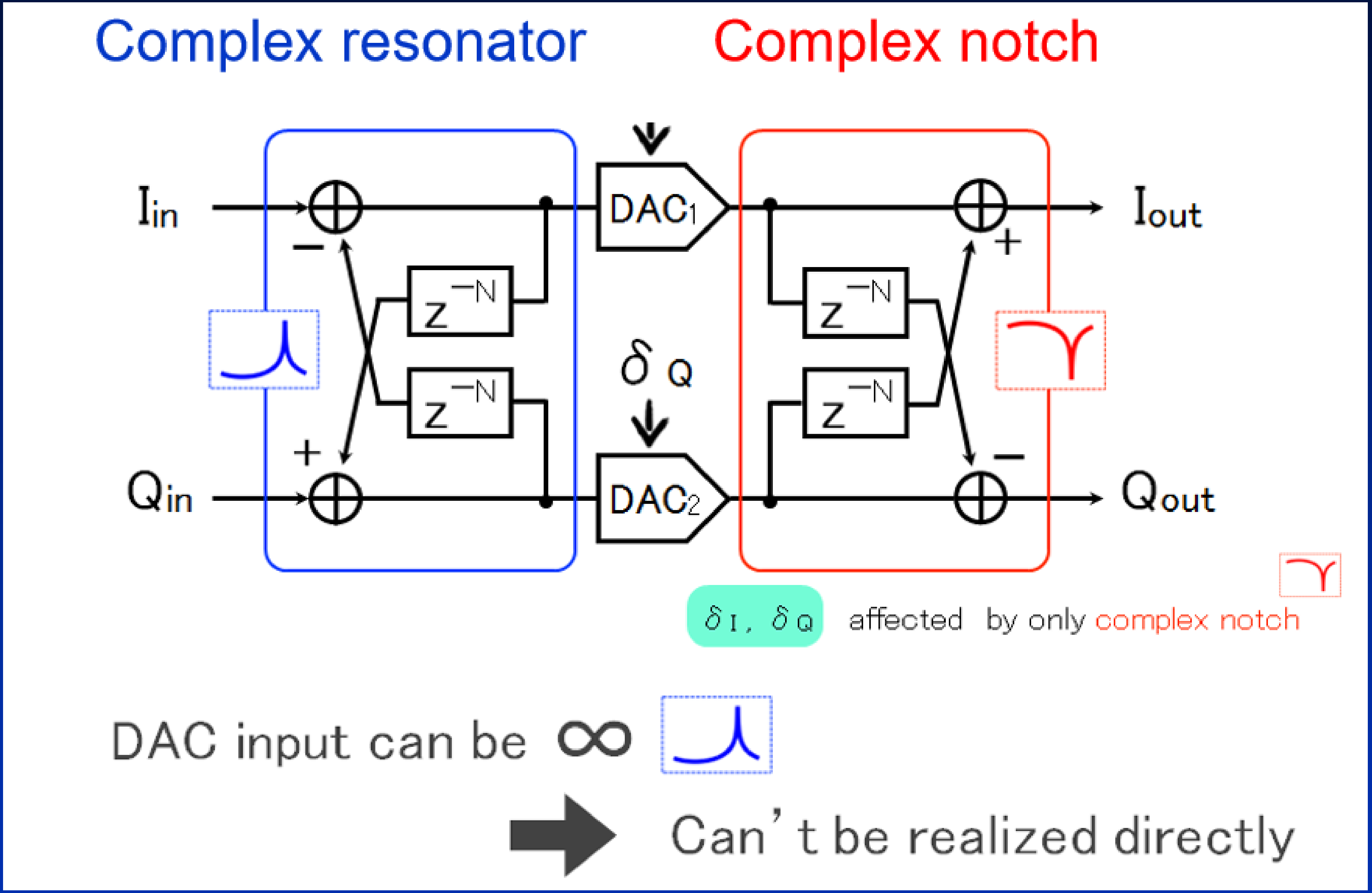




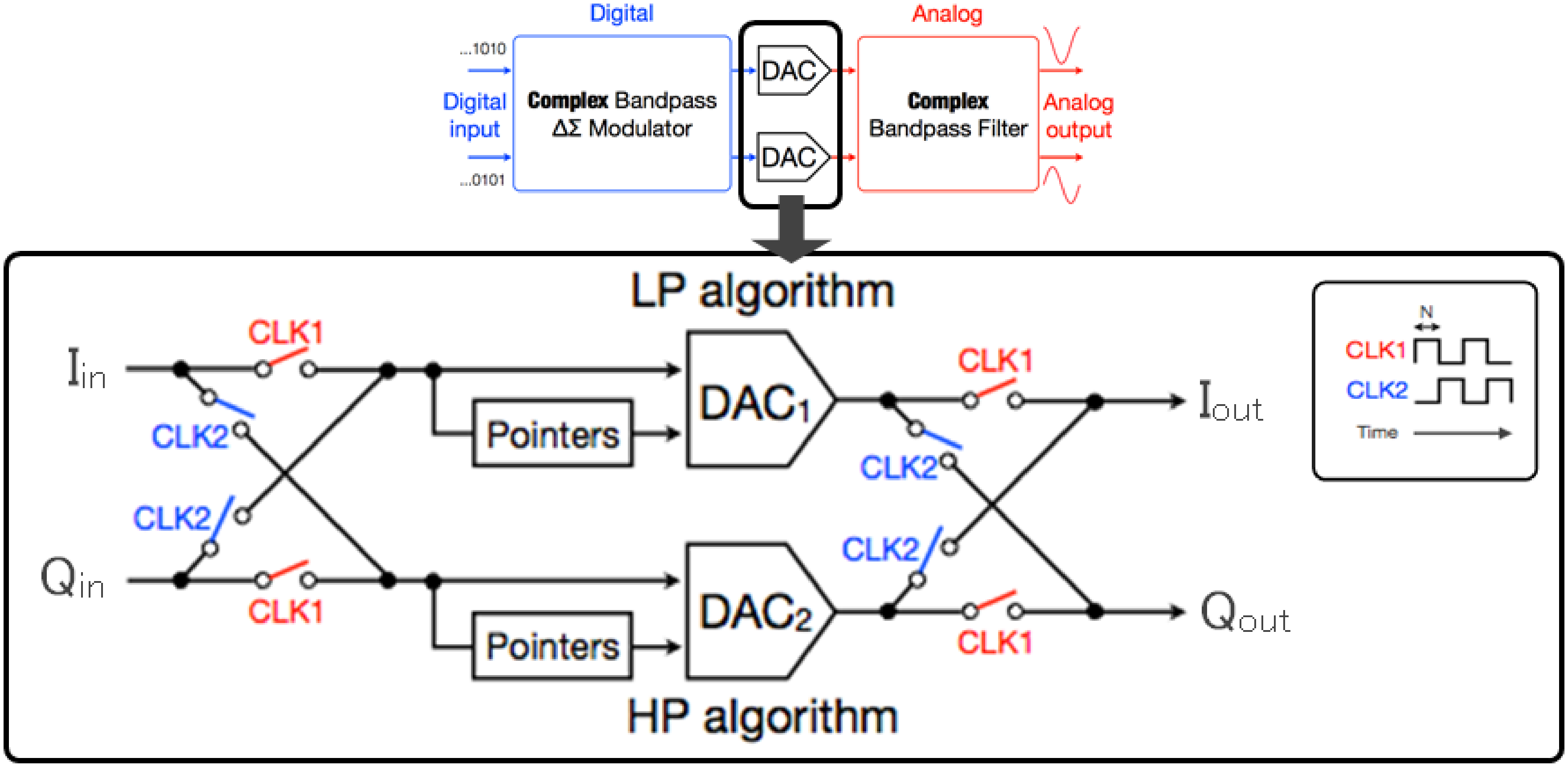
Effect of DWA



Equivalent Circuit of Complex DWA



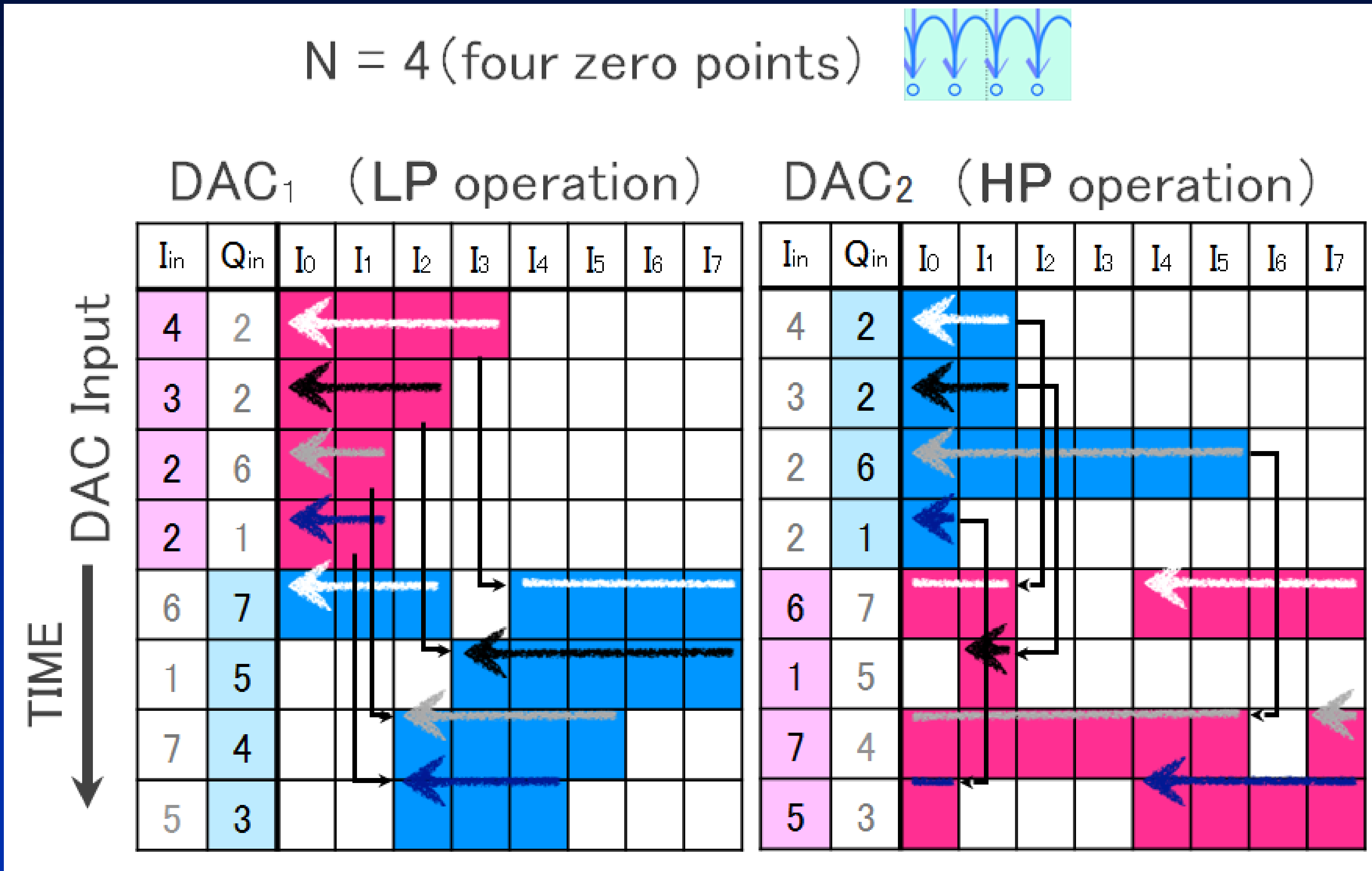
Equivalent Circuit Implementation



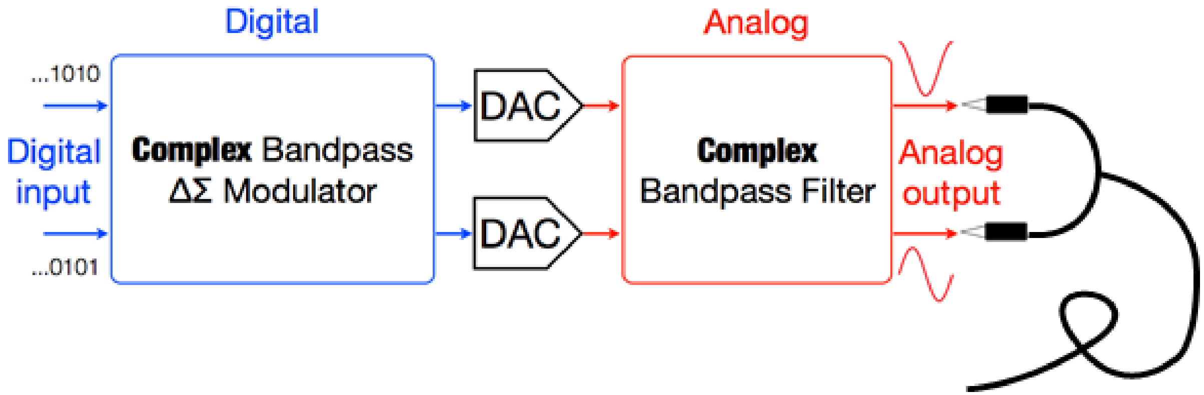
- Attach pointers
- Exchange upper–path and lower–path every N clock

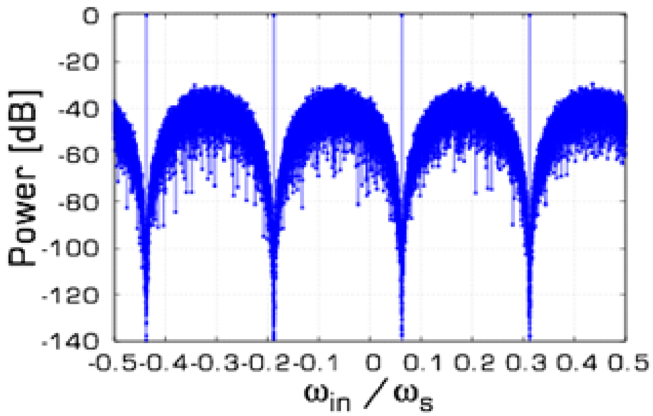
→ Complex DWA is realized.

Complex Multi-Bandpass DWA Algorithm

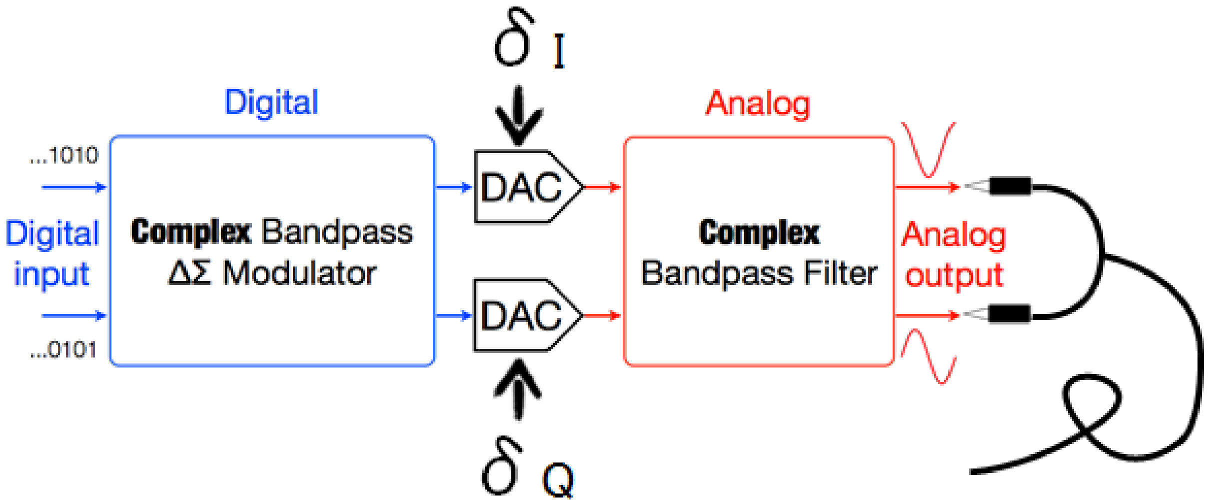


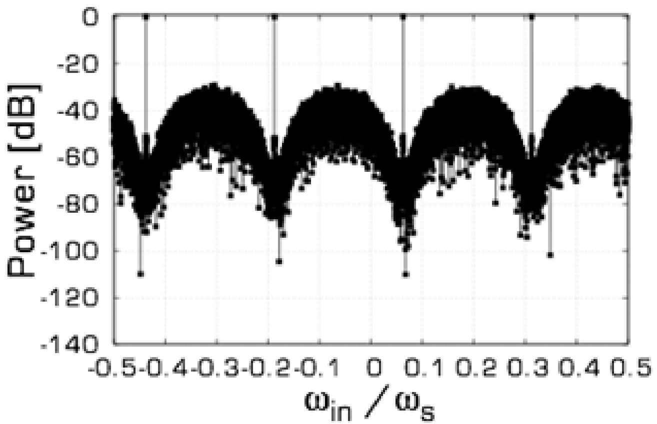
Simulation Result ~Ideal Linear DAC~





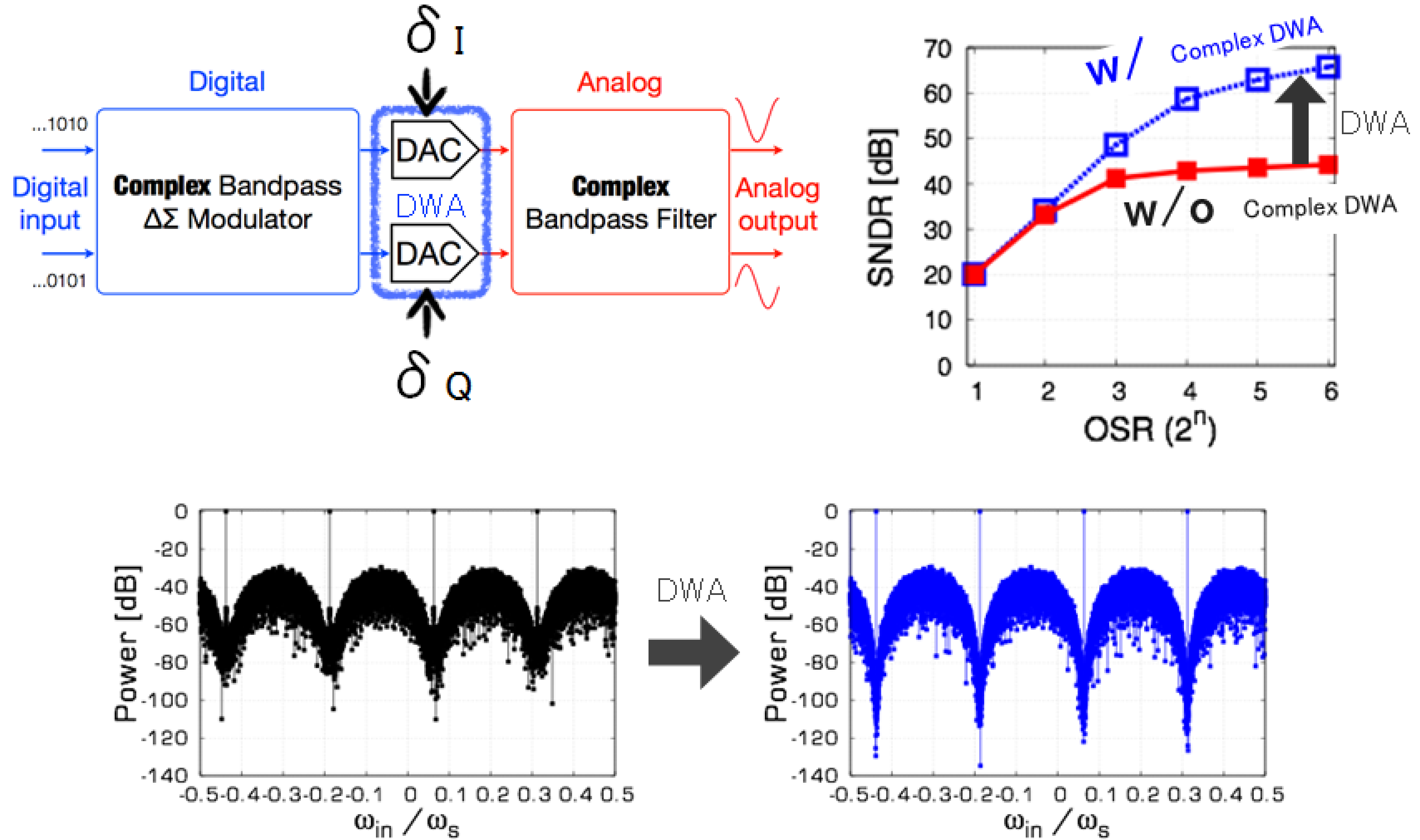
Simulation Result ~Actual Nonlinear DAC~





Notches filled with noise

Simulation Result
~ Actual Nonlinear DAC + DWA ~



Notches filled with noise → Steep Notches

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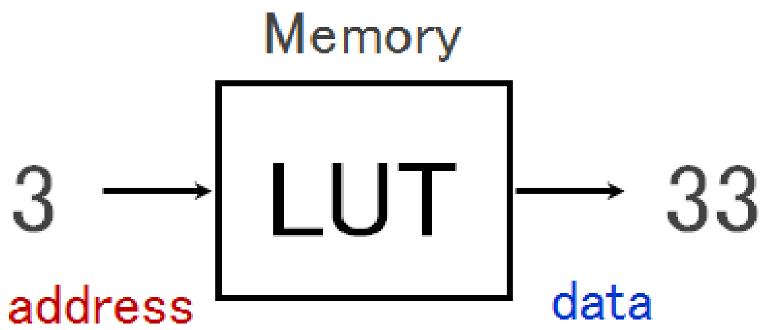
Look Up Table

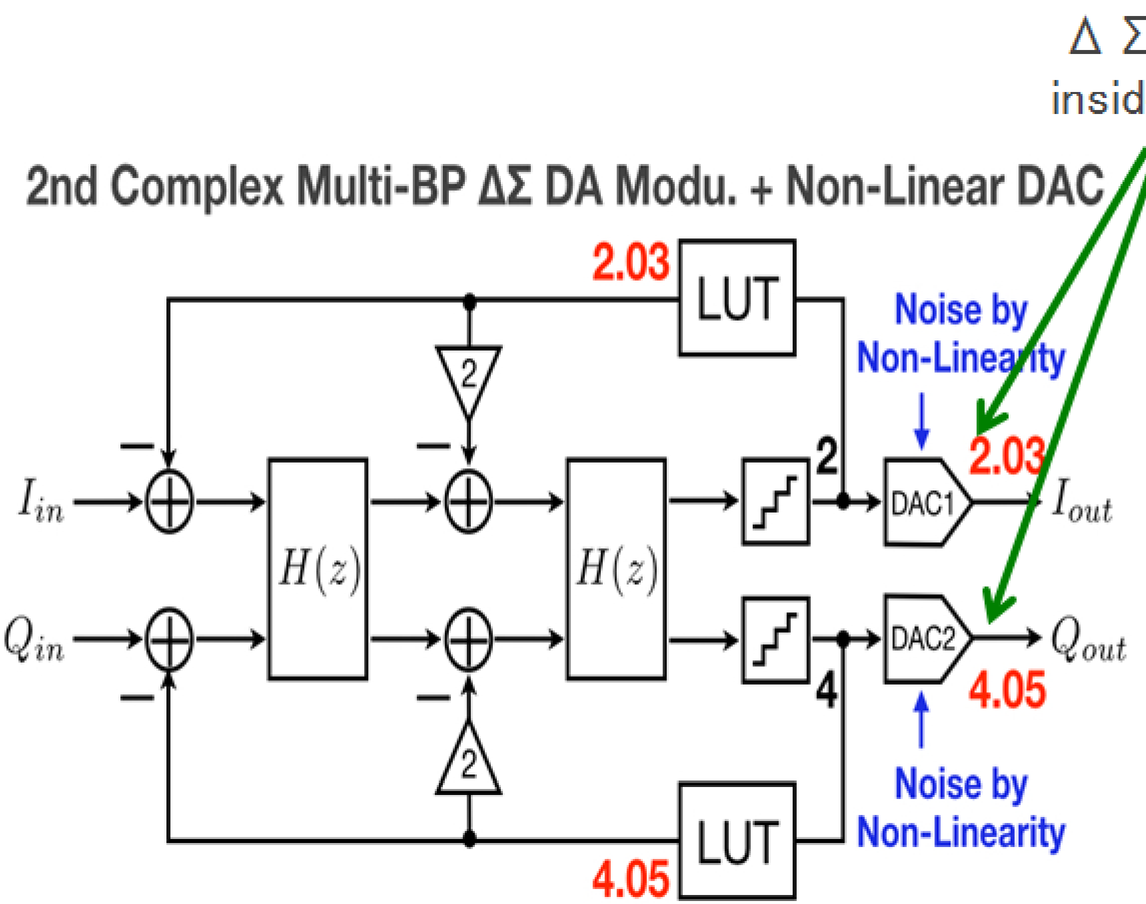
Example 

Cat Age	Human Age
1	20
2	27
3	33
4	39
5	45
6	50
7	55
8	60



DAC Nonlinearity Measurement

Results are stored in LUTs

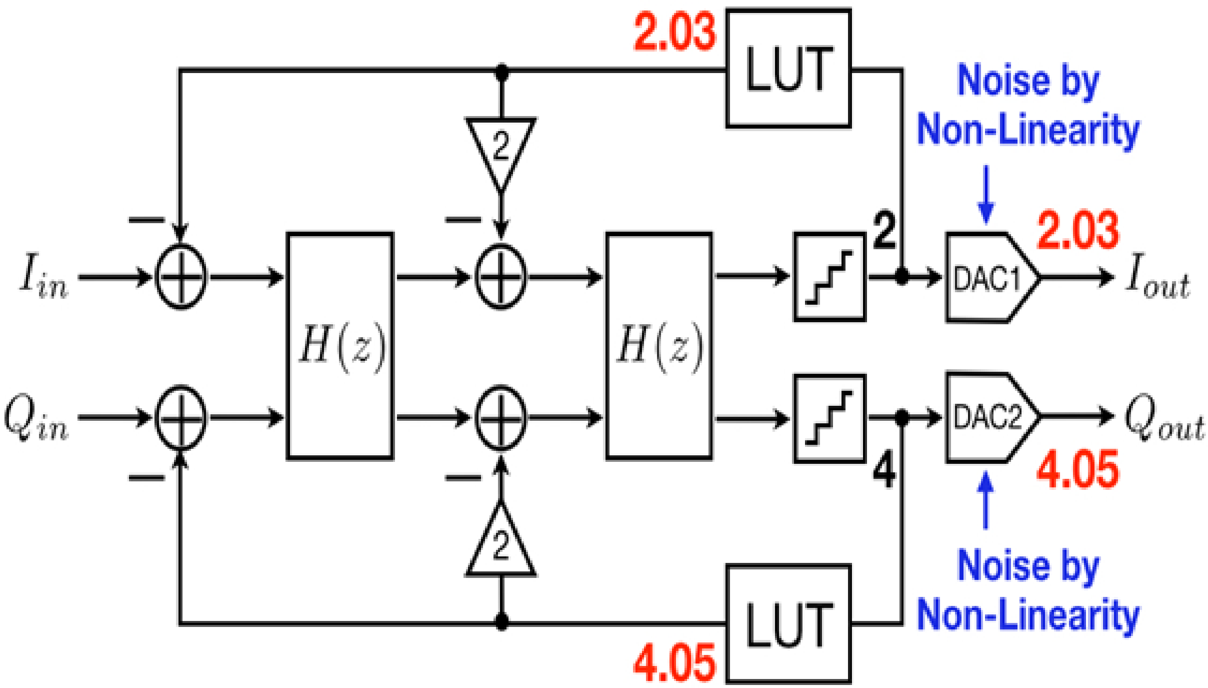


LUT

Address	I	Q
0		
1		
2	**2.03**	
3		
4		**4.05**
⋮		

ΔΣ DAC with Self-Calibration of DAC1, DAC2

CLK(1)



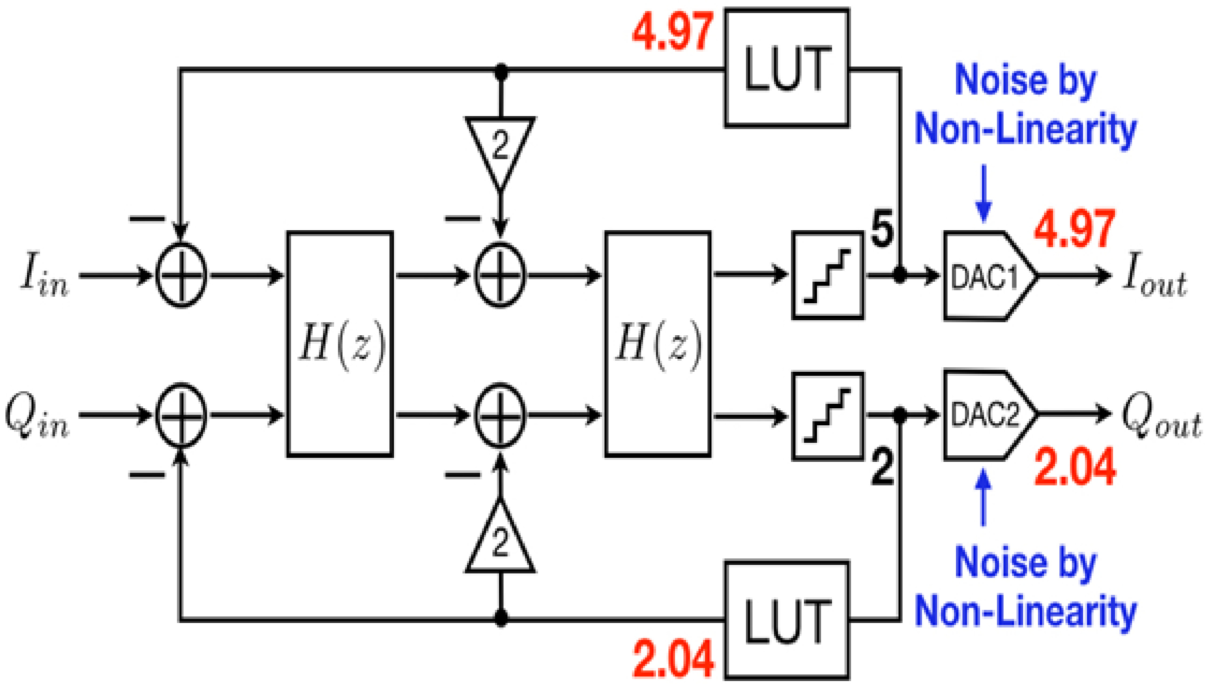
LUT

Address	I	Q
0	0.00	0.00
1	1.05	0.97
2	**2.03**	2.04
3	2.99	3.01
4	4.02	**4.05**

⋮

ΔΣ DAC with Self-Calibration of DAC1, DAC2

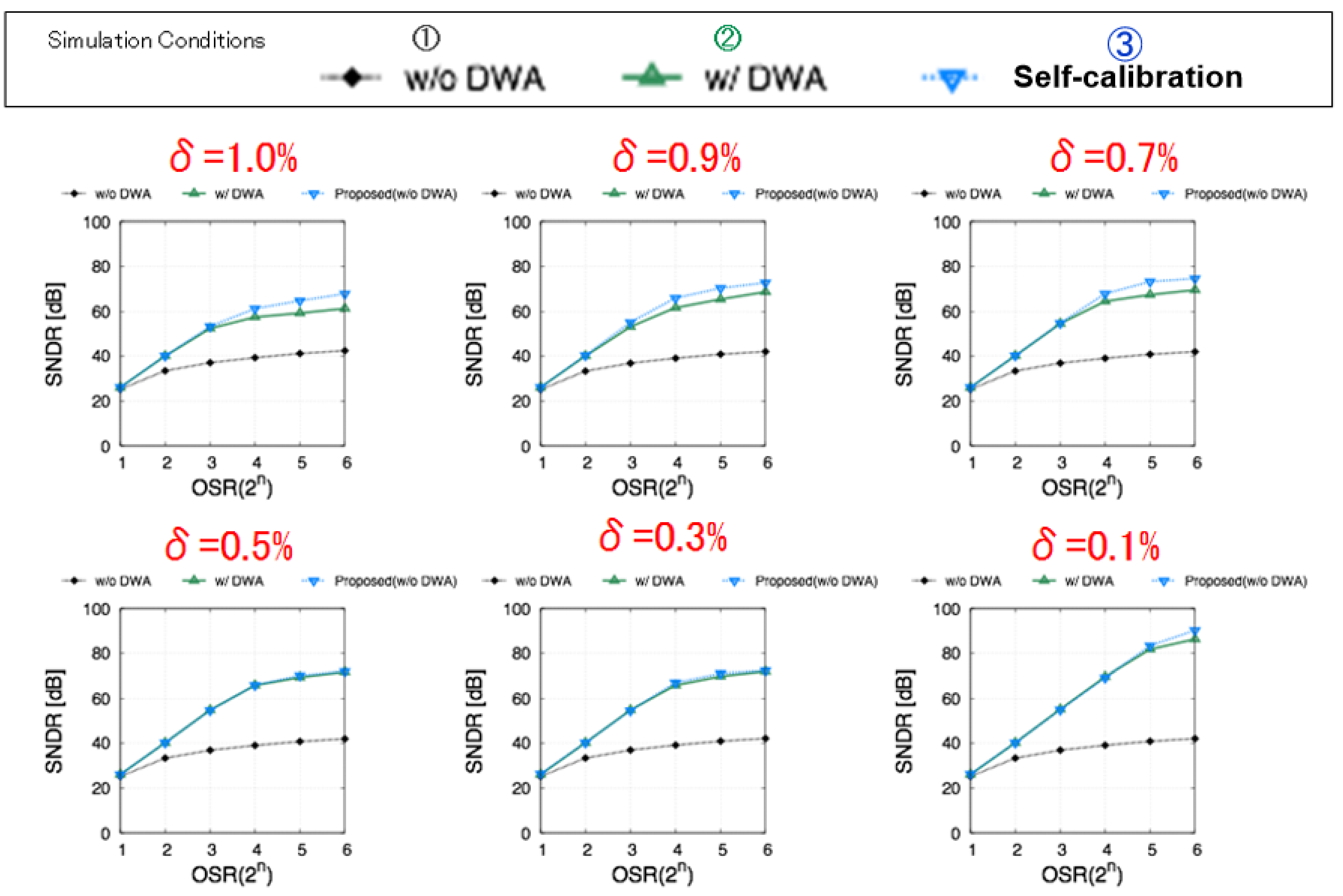
CLK(2)



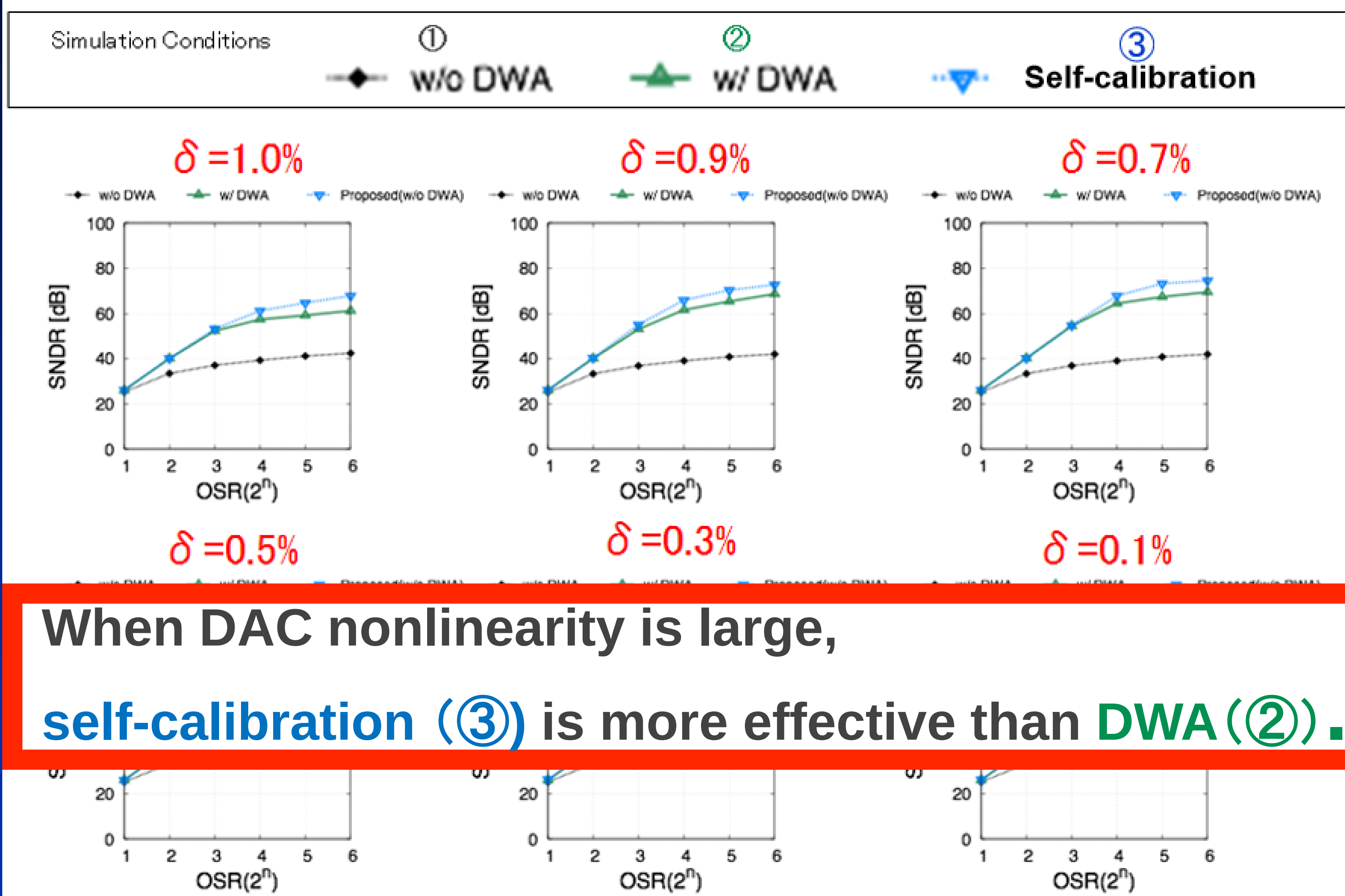
LUT

Address	I	Q
0	0.00	0.00
1	1.05	0.97
2	2.03	**2.04**
⋮		
5	**4.97**	5.03
⋮		

Simulation Results



Simulation Results



When DAC nonlinearity is large,

self-calibration (③) is more effective than DWA (②).

Pros and Cons of Self-Calibration

Pros

	DWA	Self-Calibration
DAC Nonlinearity Noise Shaping	Specific Bands	All Bands

- Better SNDR than DWA is obtained.

Cons

- DAC nonlinearity measurement with delta-sigma ADC is required.

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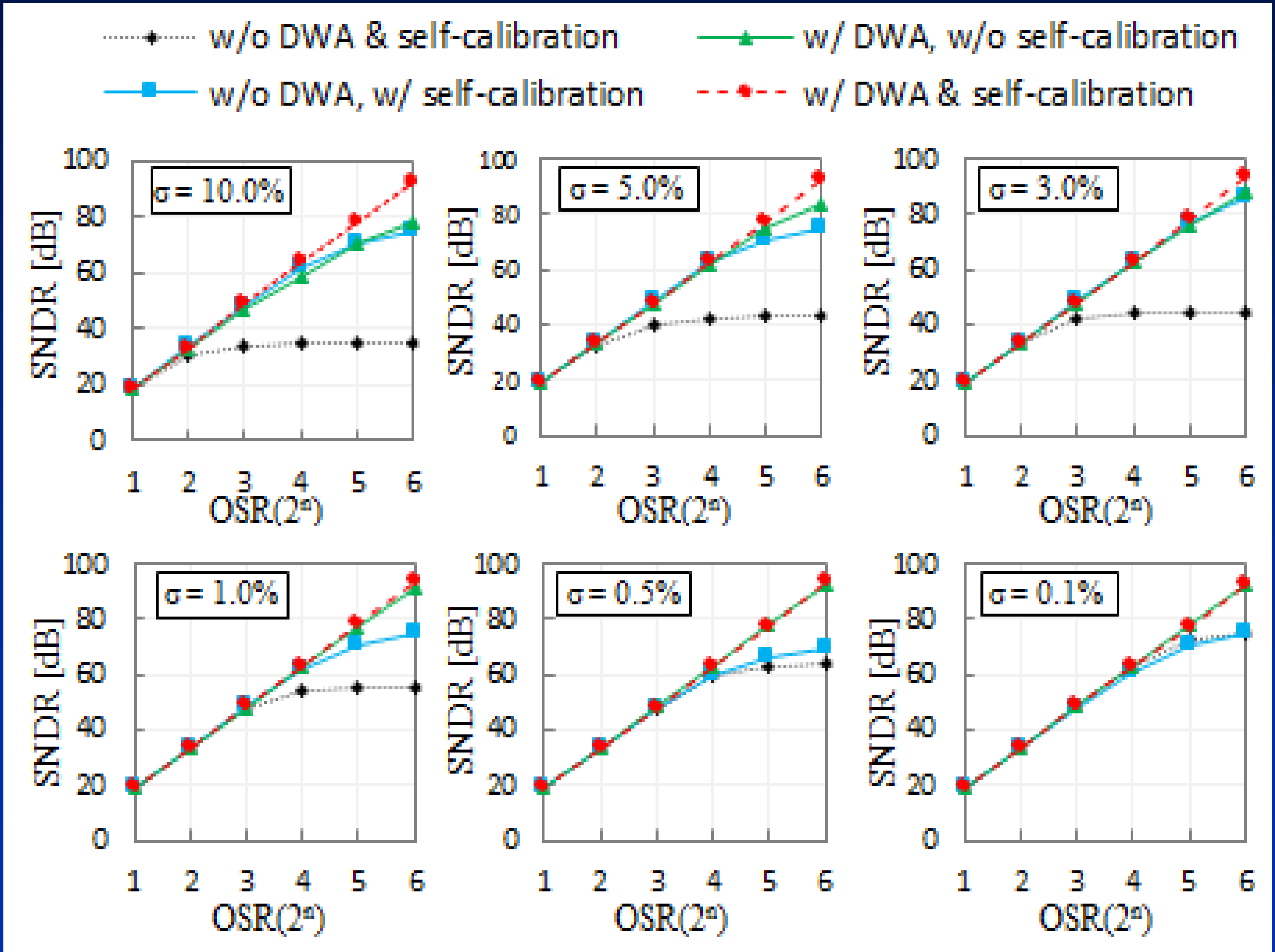
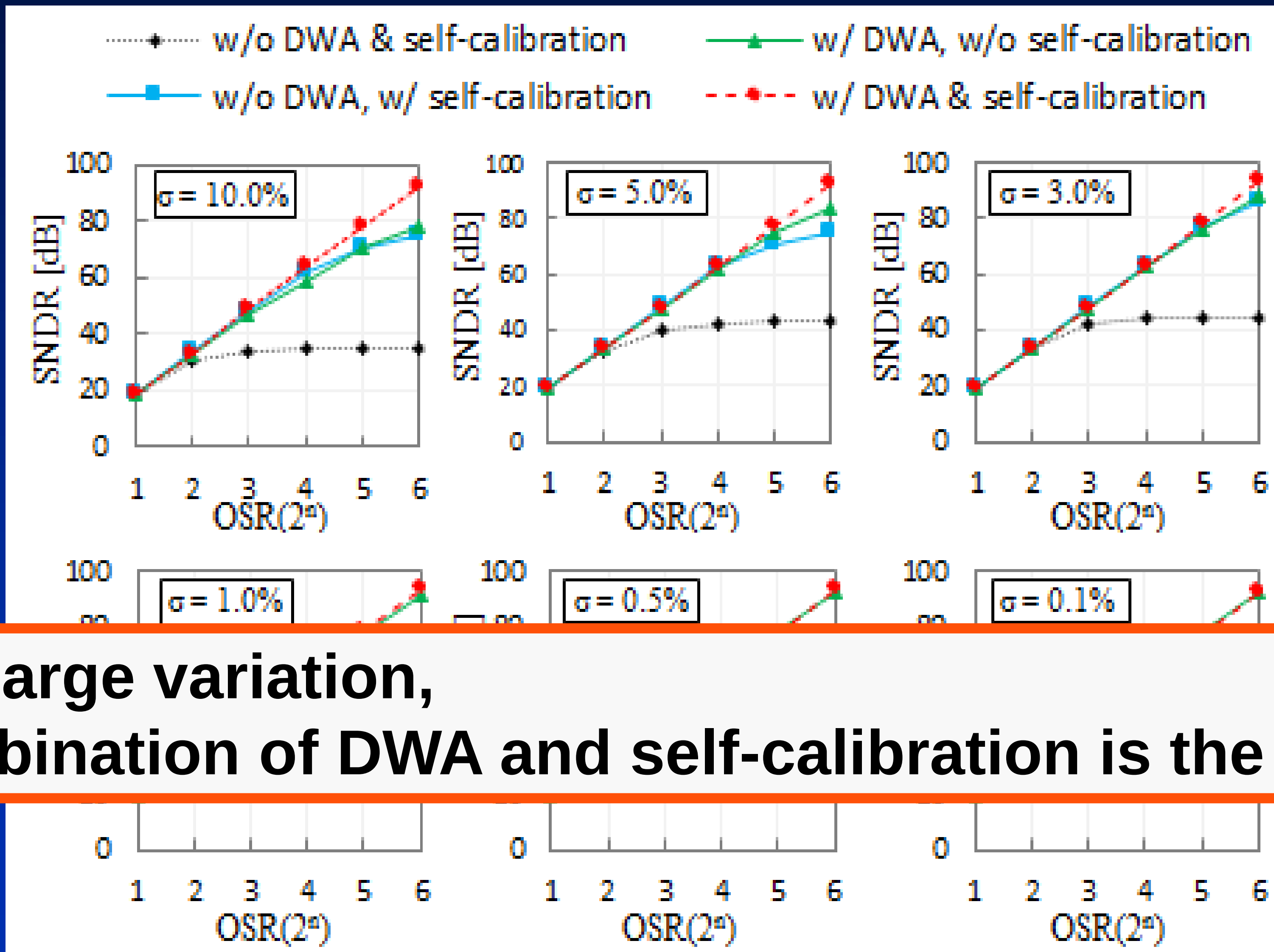
Combination of DWA and Self-Calibration

LP case



Combination of DWA and Self-Calibration

LP case



For large variation,
combination of DWA and self-calibration is the best.

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Conclusion

- I-Q signal generation with digital centric
- Complex multi-BP ΔΣ DAC
- Multi-bit DAC

○ Relaxes analog filter requirements

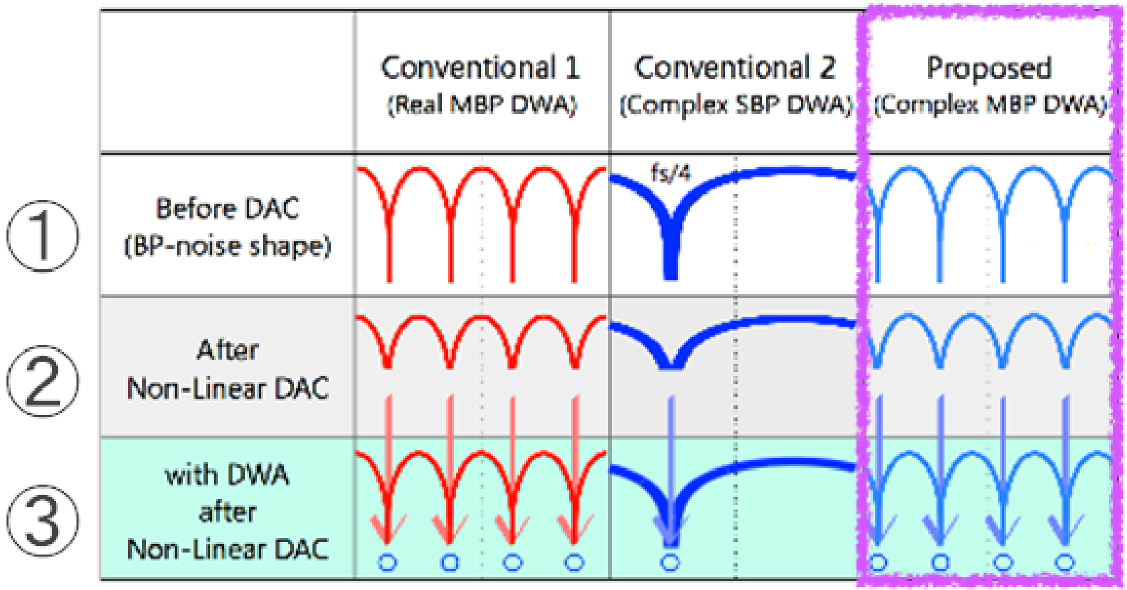
x Degrades system linearity

➡ DWA algorithm
Self-calibration algorithm
Their combination

Low cost, high quality I-Q signal generation.

Back Up

Type of DWA



DWA

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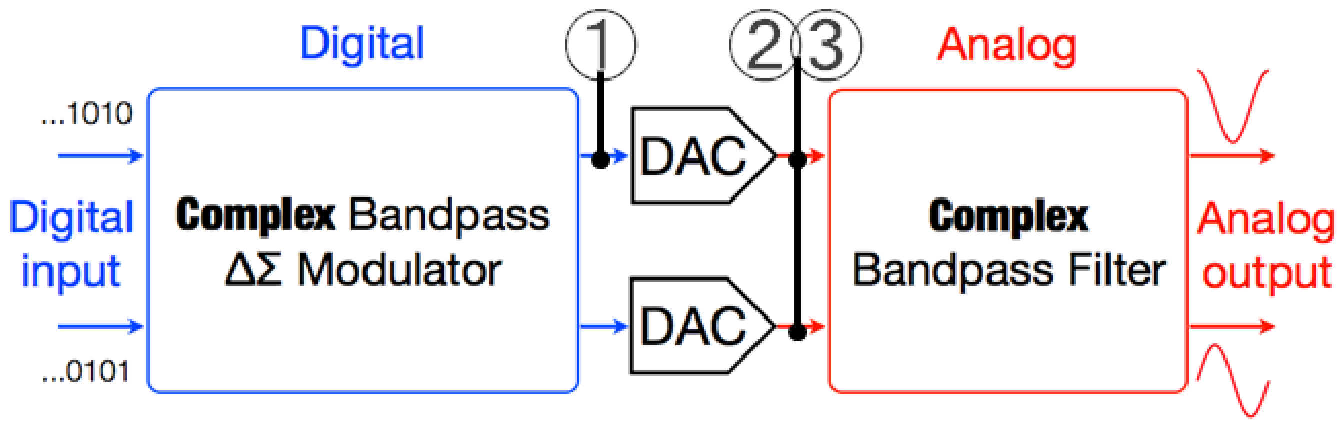
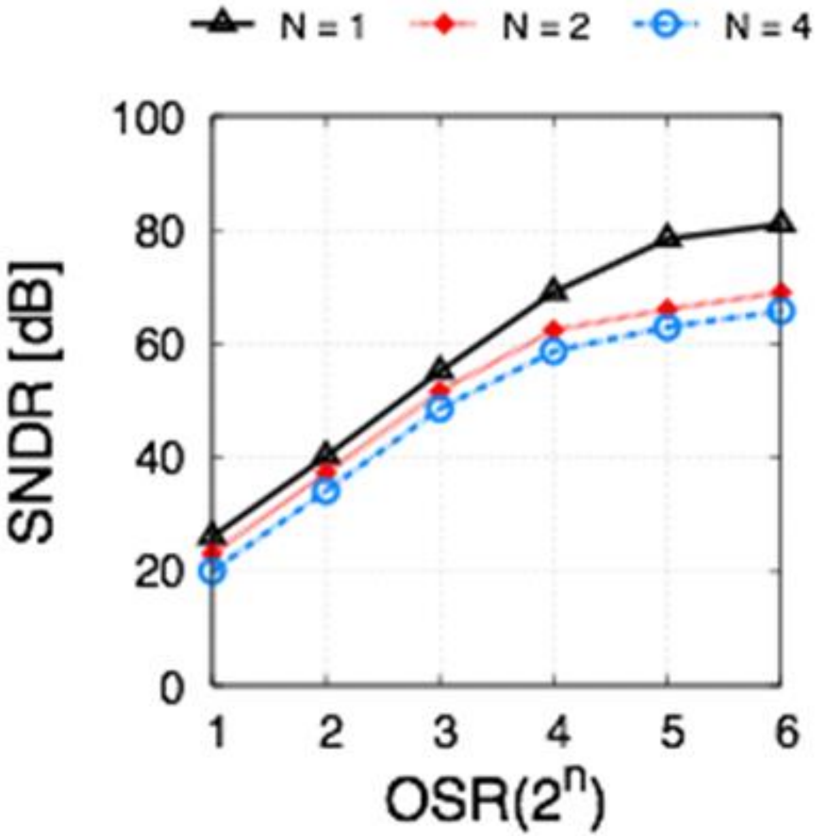
DSP algorithm



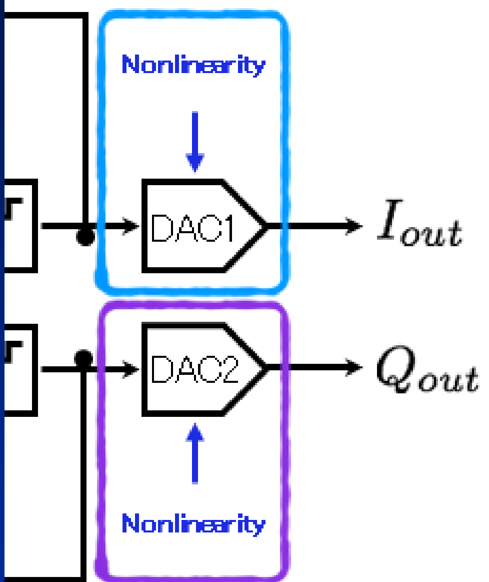
Simulation Result
~ Actual Nonlinear DAC + DWA ~

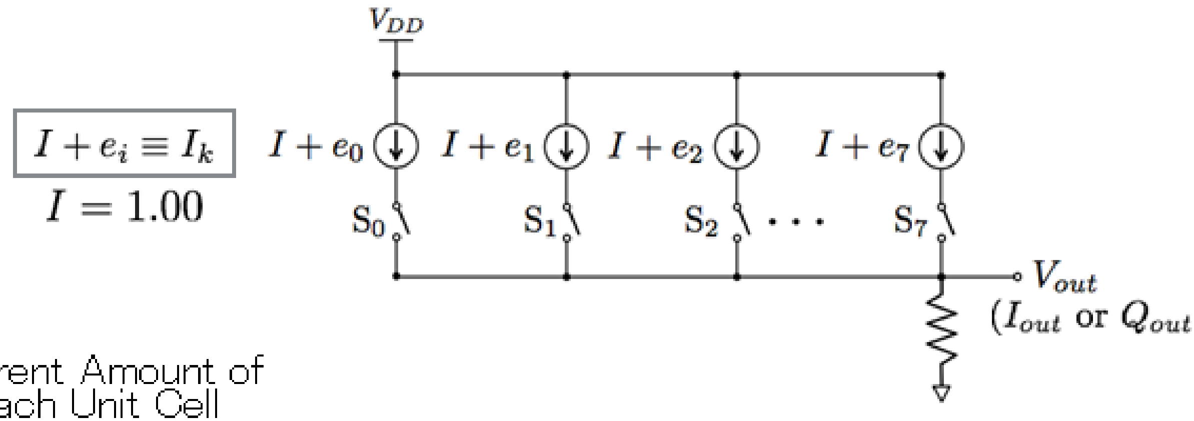
N (number of notches)

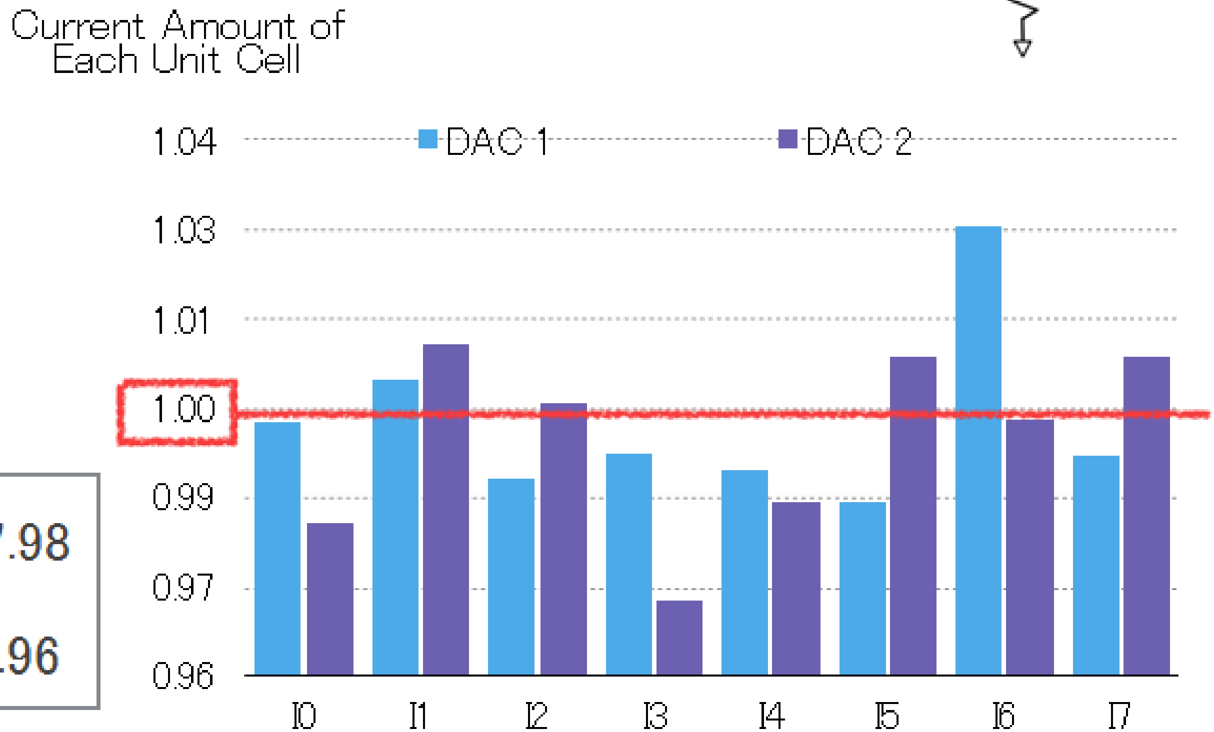


N increases ➡ SNDR decreases

Simulation Conditions :
DAC unit cell variation　Standard deviation 1.0%



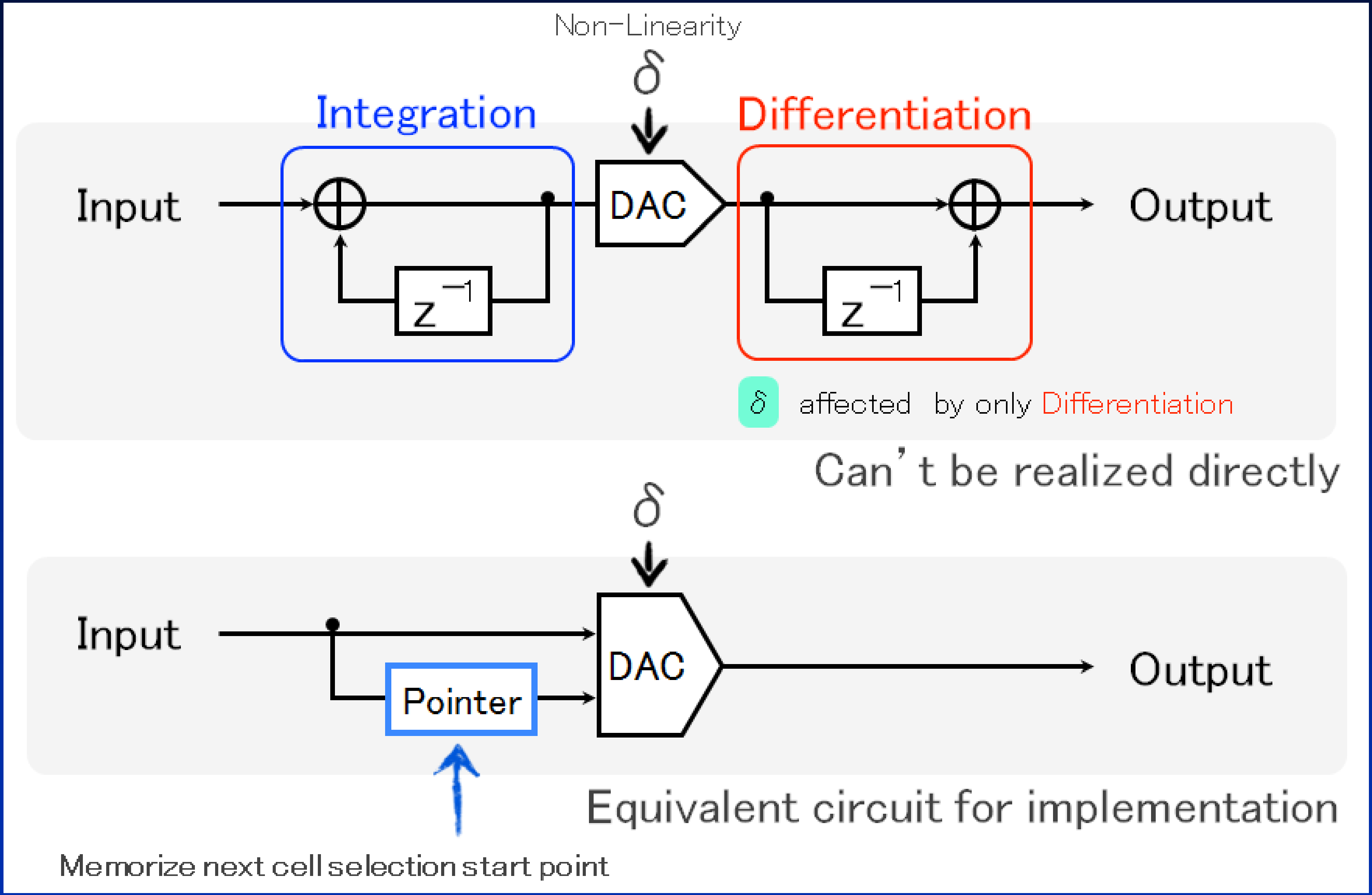




DAC1 Total Current : 7.98

DAC2 Total Current : 7.96

DWA = ΔΣ



Non-Linearity
δ
Integration
Differentiation
Input
DAC
Output
z^{-1}
z^{-1}
δ affected by only Differentiation
Can't be realized directly
δ
Input
Pointer
DAC
Output
Equivalent circuit for implementation
Memorize next cell selection start point