IEEE International Mixed-Signals,
Sensors, and Systems Test Workshop

May 2011

Digitally-Assisted Compensation for Timing Skew in ATE Systems

K. Asami T. Tateiwa T. Kurosawa
H. Miyajima H. Kobayashi

Advantest Corporation

Gunma University

Contents

- <u>Research Goal</u>
- Conventional Linear Phase Digital Filter Condition
- New Linear Phase Digital Filter Condition
  - Time-Shift, Impulse Response of Ideal Filter
  - New Linear Phase Digital Filter
- MATLAB Simulation
- Design Considerations
  - Window
  - Gain Adjustment
- Application
- Conclusion

Research Goal

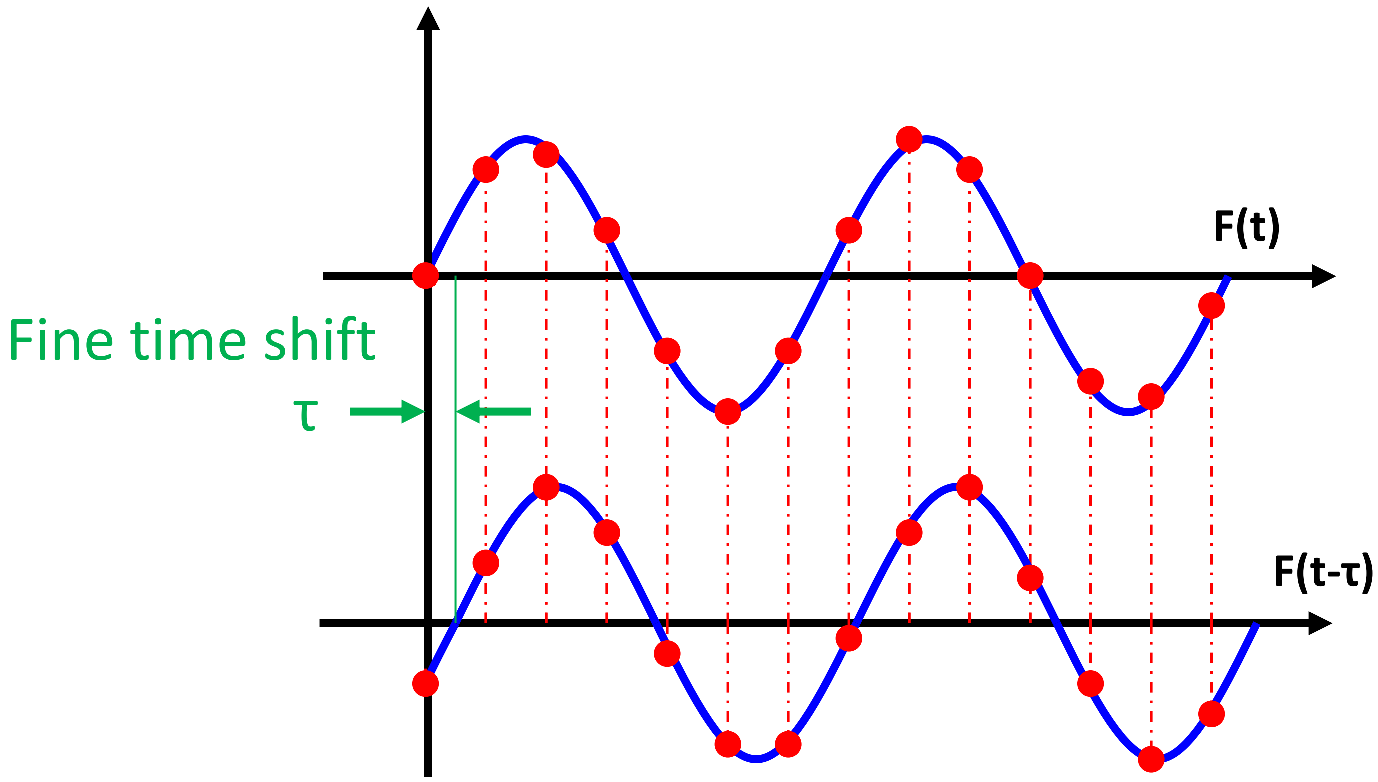
Timing skew is a major problem in ATE systems

Digital compensation for timing skew
⇒ Linear phase is important

Conventional linear-phase digital filter ⇒ coarse timing adjustment

Proposed linear-phase digital filter ⇒ fine timing adjustment

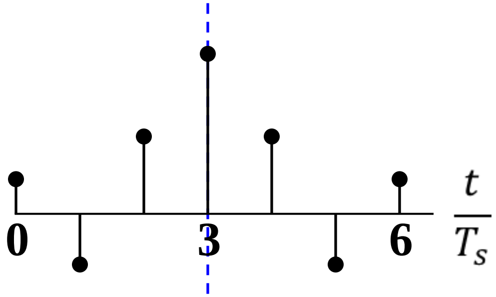
Features of Proposed Digital Filter



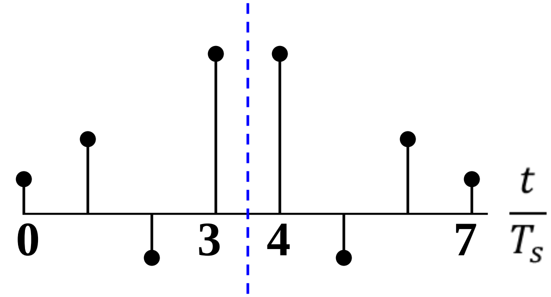
- **Fine time resolution**
- **Linear phase**
- **Applicable to bandpass signal**

Contents

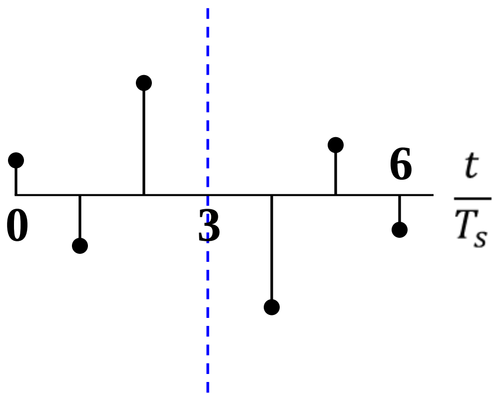
Linear Phase FIR Filter Impulse Response



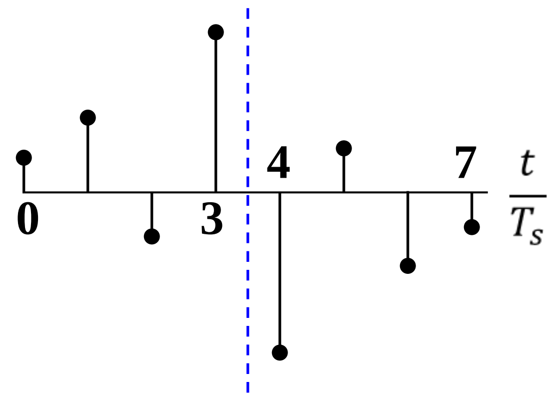
(1)Case 1
odd # of taps・even symmetry



(2) Case 2
even # of taps・even symmetry



(3) Case 3
odd # of taps・odd symmetry



(4) Case 4
even # of taps・odd symmetry

Frequency Characteristics

$h(nT)$	$H(e^{j\omega T})$
Case 1	$e^{-j\omega(N-1)T_s/2} \sum_{k=0}^{(N-1)/2} a_k \cos[\omega k T_s]$
Case 2	$e^{-j\omega(N-1)T_s/2} \sum_{k=1}^{N/2} b_k \cos[\omega(k-1/2)T_s]$
Case 3	$e^{-j(\omega(N-1)T_s/2-\pi/2)} \sum_{k=0}^{(N-1)/2} a_k \sin[\omega k T_s]$
Case 4	$e^{-j(\omega(N-1)T_s/2-\pi/2)} \sum_{k=1}^{N/2} b_k \sin[\omega(k-1/2)T_s]$

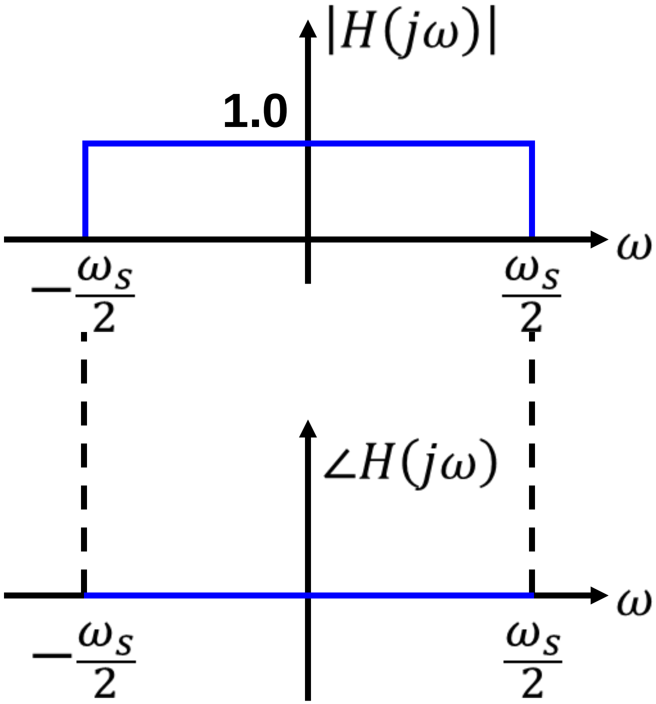
Phase : proportional to ω (linear phase)

Time resolution of group delay Ts/2

Contents

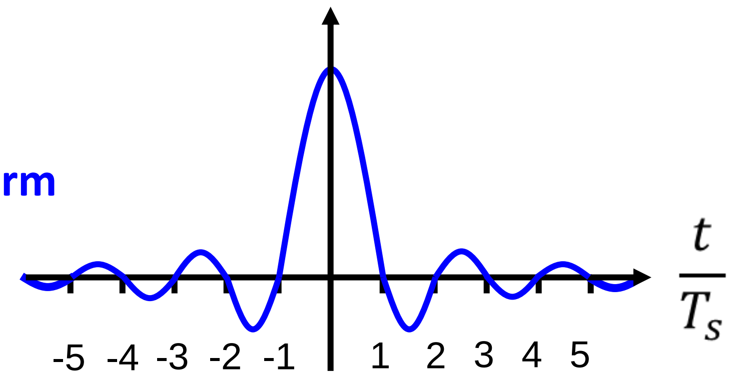
Ideal LPF

Frequency Characteristics



Fourier Transform

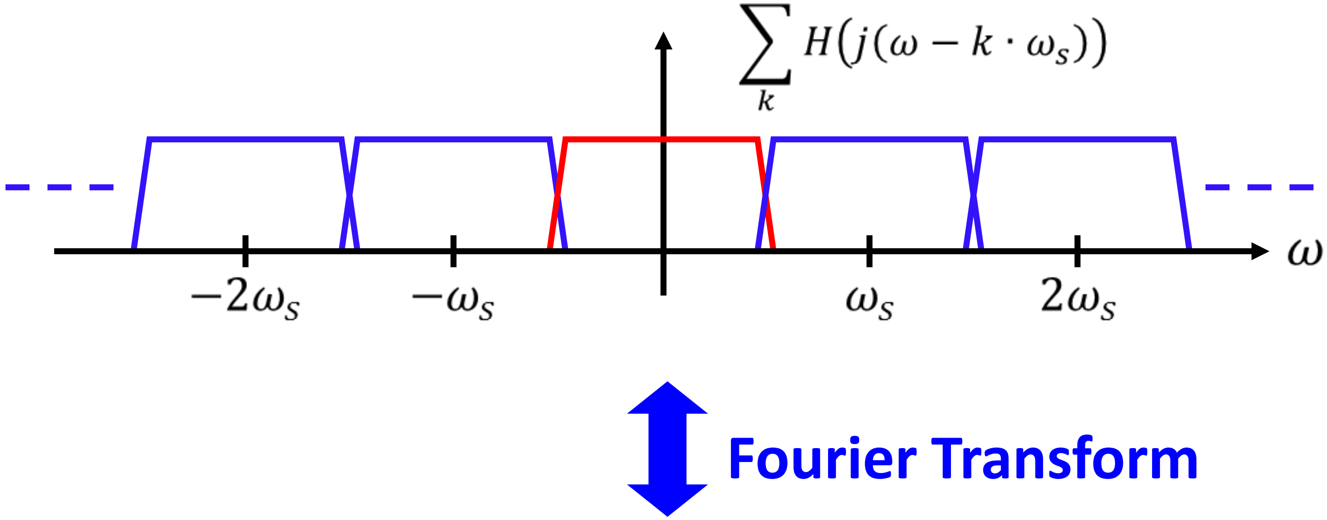
Impulse Response



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

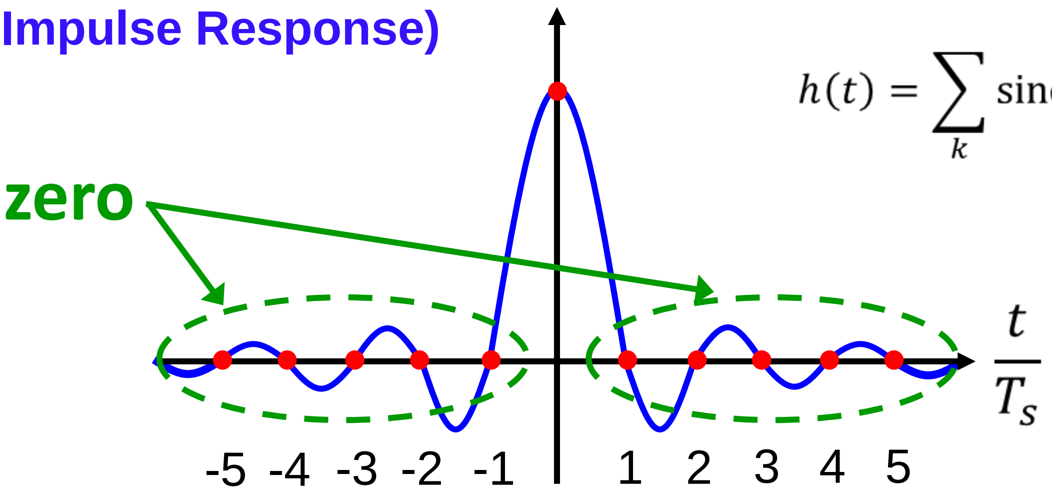
$$\omega_s = \frac{2\pi}{T_s}$$ **: Sampling Frequency**

Discrete-Time Representation of Ideal LPF

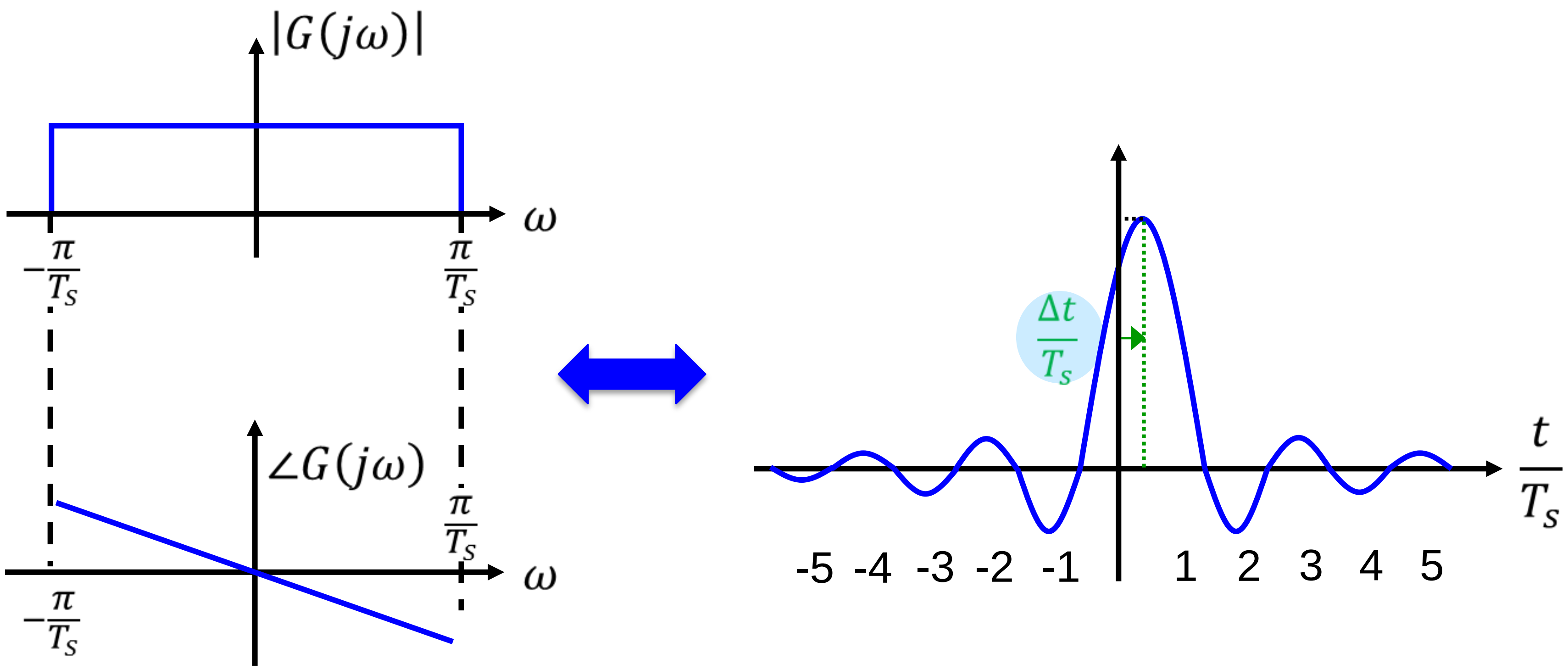


FIR (Finite Impulse Response)

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



Impulse Response Time-Shift



$\angle G(j\omega) = -\omega\Delta t$

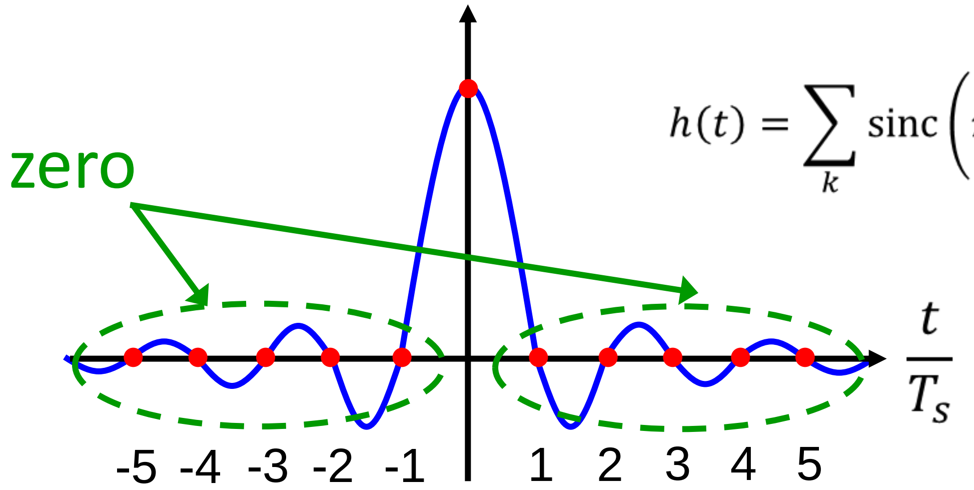
Δt time-shift of impulse response

No change of Gain

Time-Shift and Filter Coefficients

FIR filter

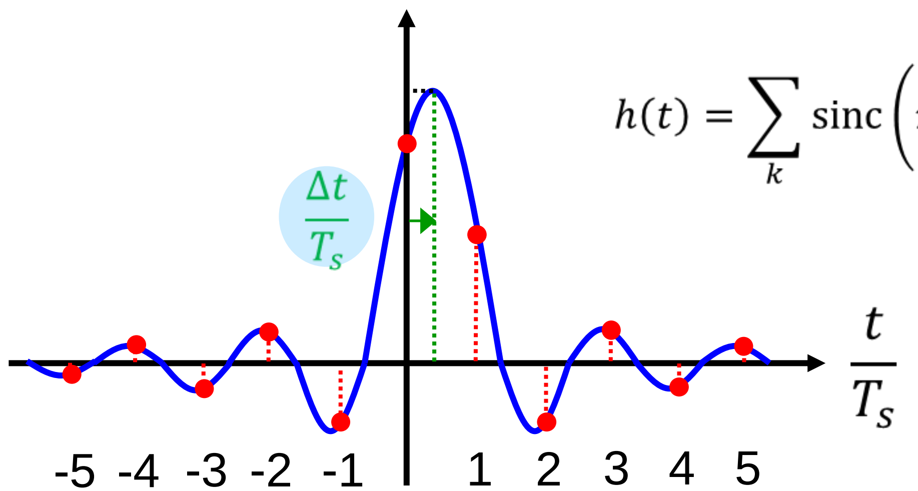
$$h(t) = \sum_{k} \mathrm{sinc}\left(\pi \frac{k \cdot T_s}{T_s}\right) \delta(t - k \cdot T_s)$$



Time Shift

IIR Filter

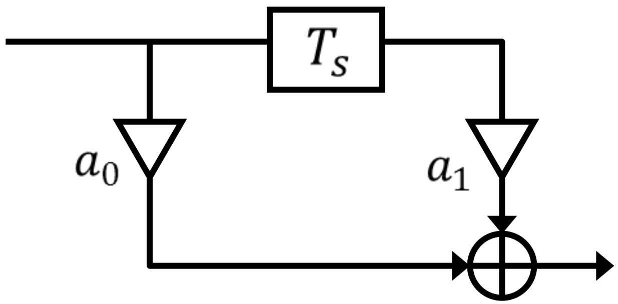
$$h(t) = \sum_{k} \mathrm{sinc}\left(\pi \frac{k \cdot T_s - \Delta t}{T_s}\right) \delta(t - k \cdot T_s)$$

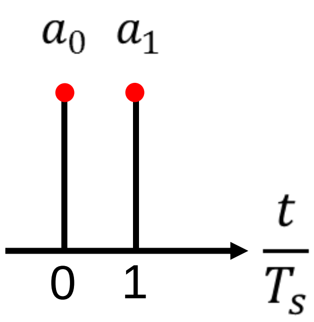


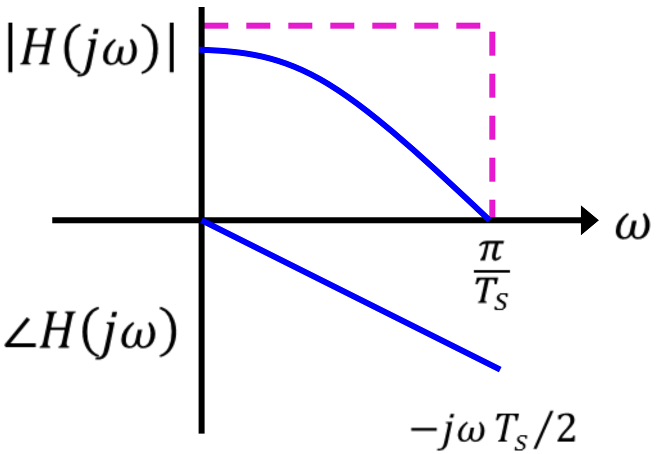
Ideal Delay-Filter

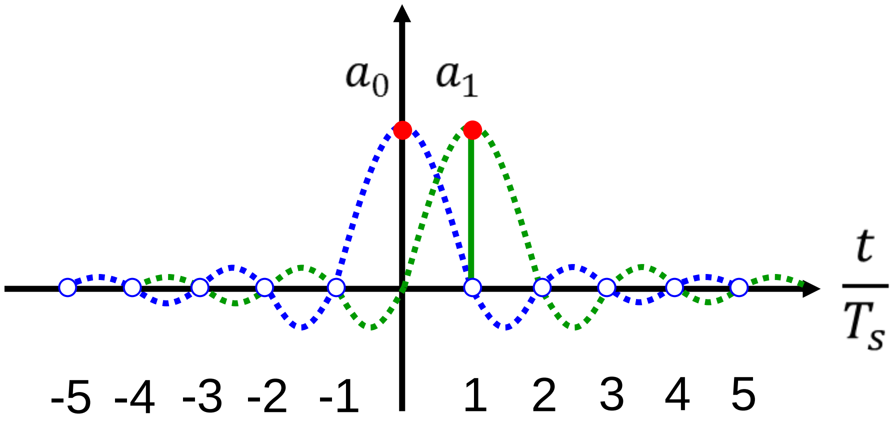
Contents

2-Tap Filter: Model

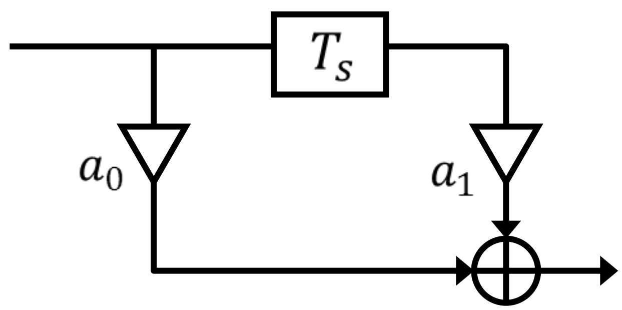


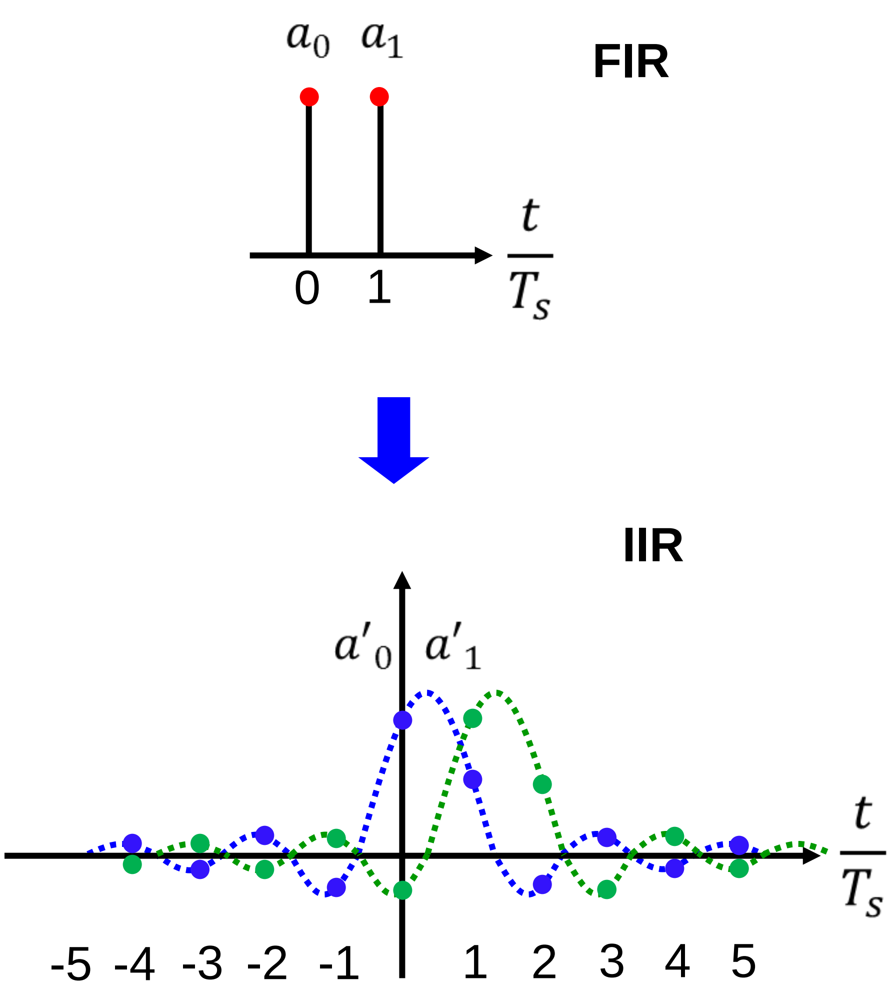


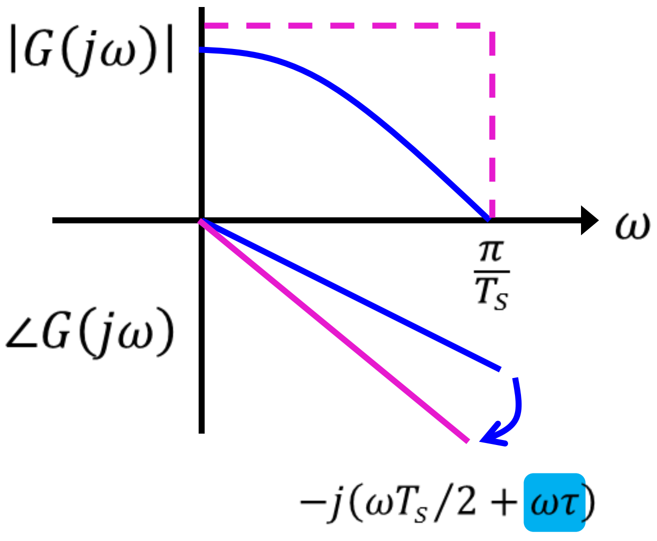




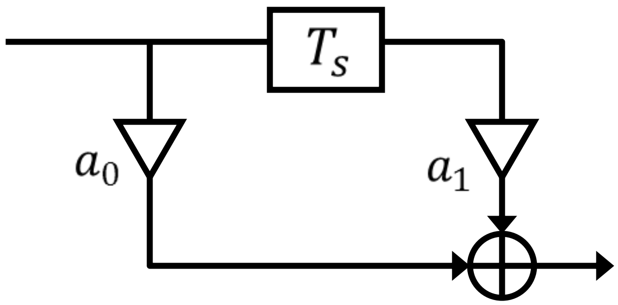
2-Tap Filter: Delay Model

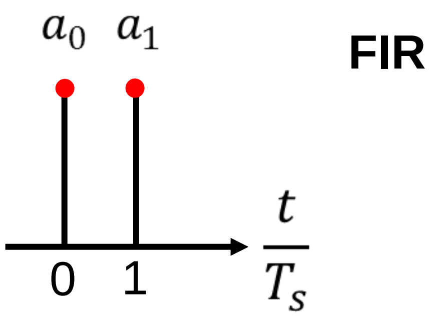


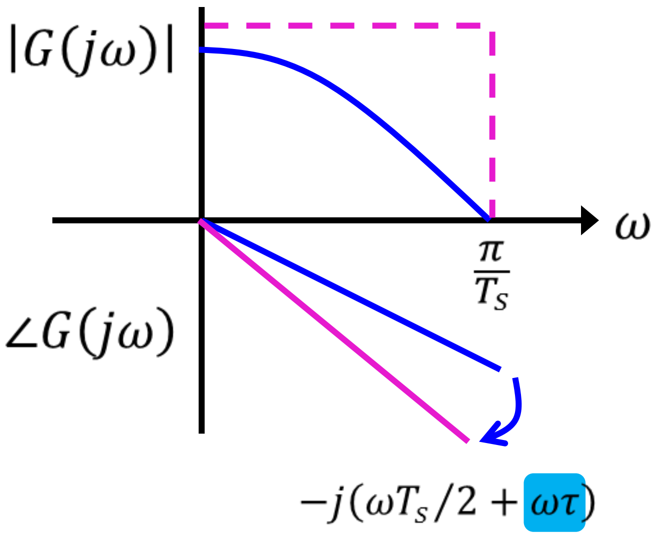


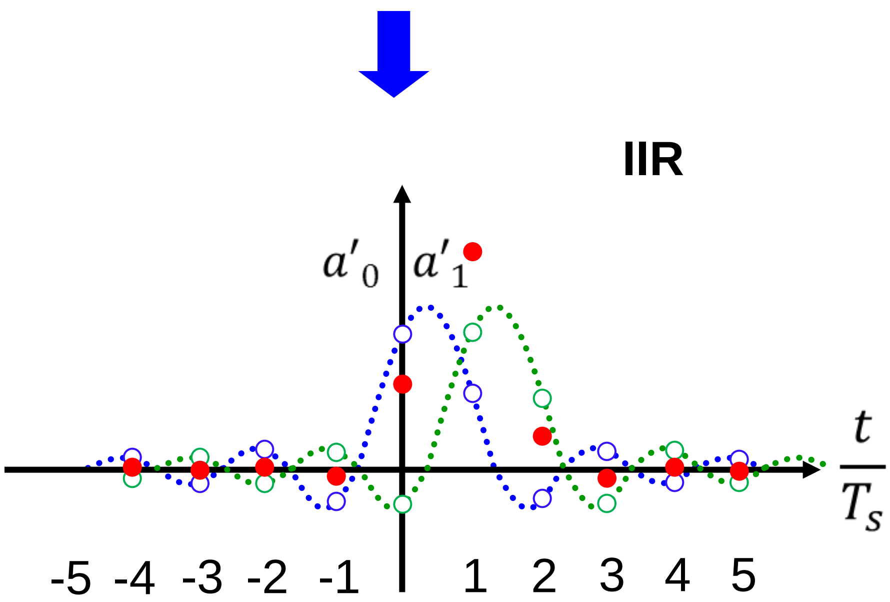


2-Tap Filter: Delay Model

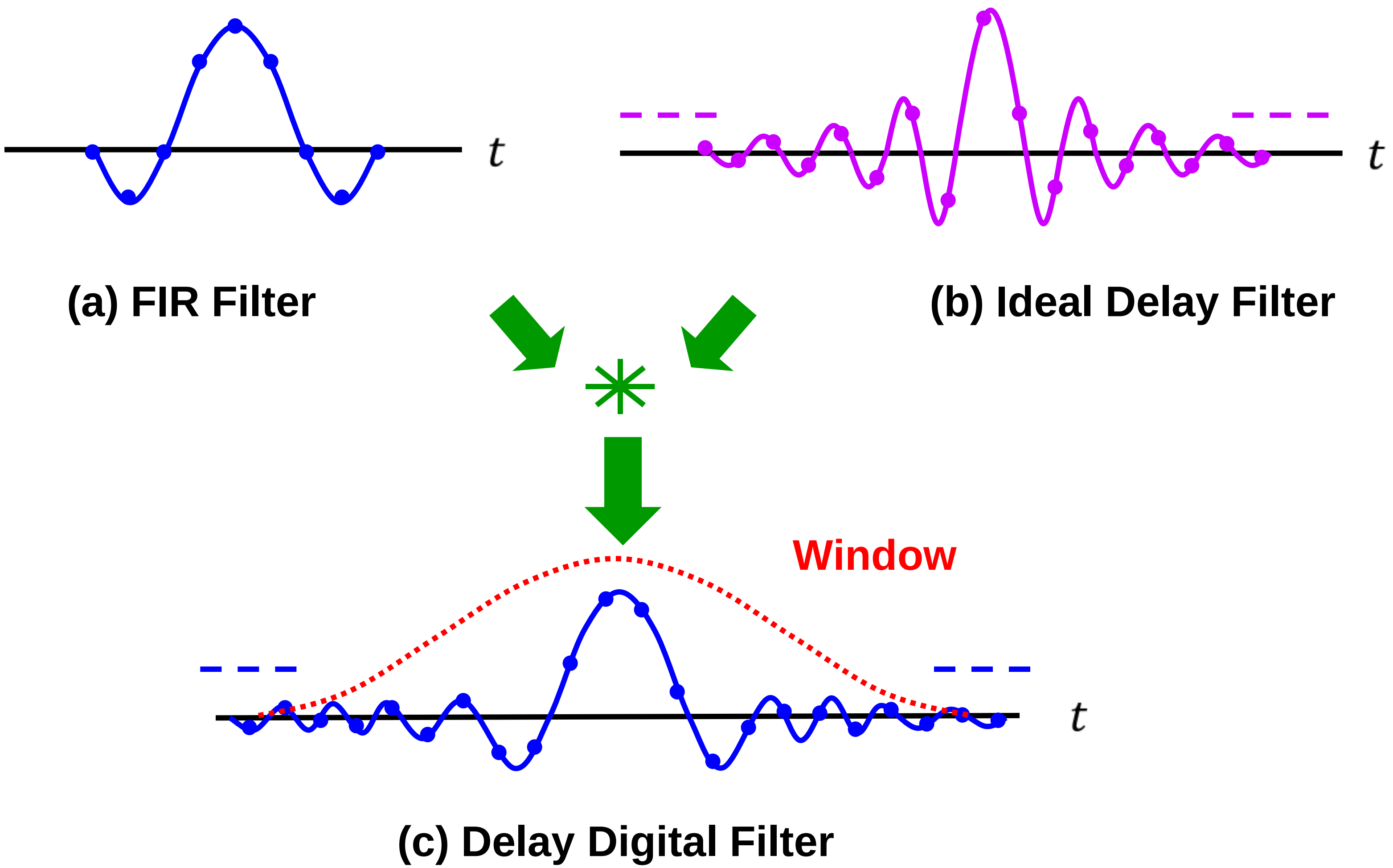








Proposed Delay Digital Filter



Frequency Characteristics of Proposed Delay Digital Filter

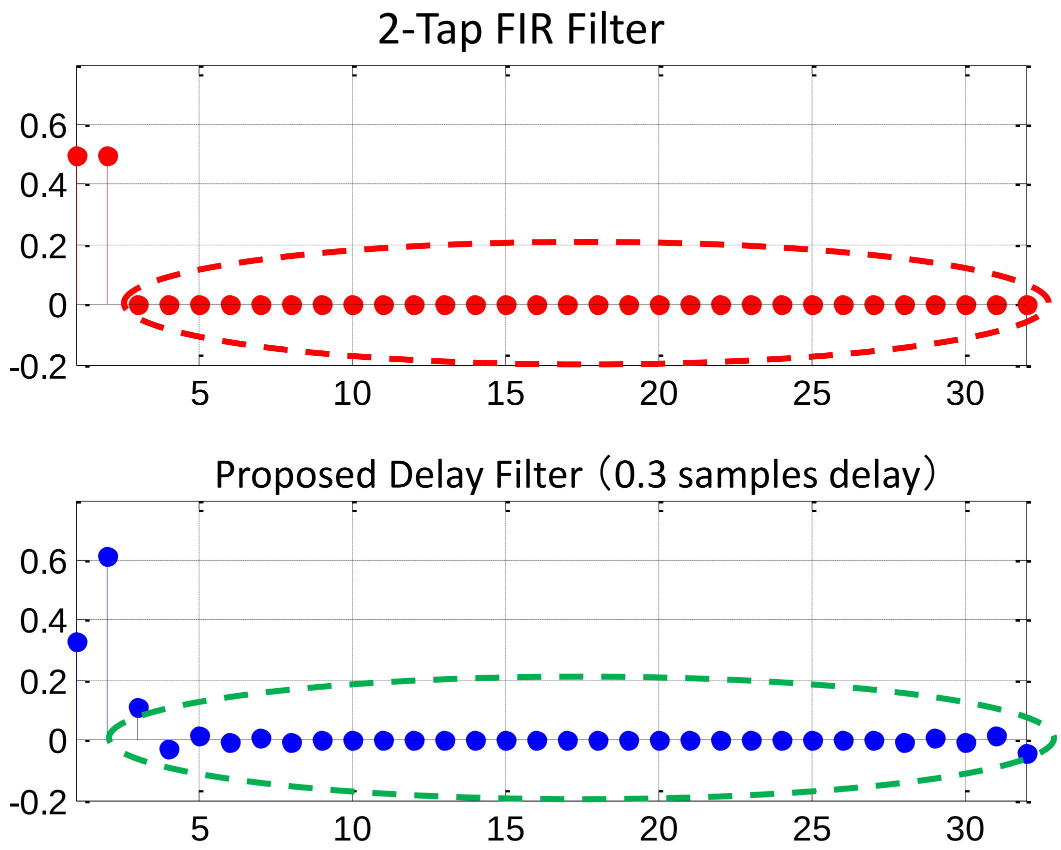
$g(nT)$	$G(e^{j\omega T})$
Case 1	$e^{-j\omega(N-1)T_s/2+\omega\tau} \sum_{k=0}^{(N-1)/2} a_k \cos[\omega k T_s]$
Case 2	$e^{-j\omega(N-1)T_s/2+\omega\tau} \sum_{k=1}^{N/2} b_k \cos[\omega(k-1/2)T_s]$
Case 3	$e^{-j(\omega(N-1)T_s/2-\pi/2+\omega\tau)} \sum_{k=0}^{(N-1)/2} a_k \sin[\omega k T_s]$
Case 4	$e^{-j(\omega(N-1)T_s/2-\pi/2+\omega\tau)} \sum_{k=1}^{N/2} b_k \sin[\omega(k-1/2)T_s]$

Phase : proportional to ω（linear phase）

Group delay time resolution τ : Arbitrary small

Contents

Comparison of 2-Tap Filter Impulse Responses



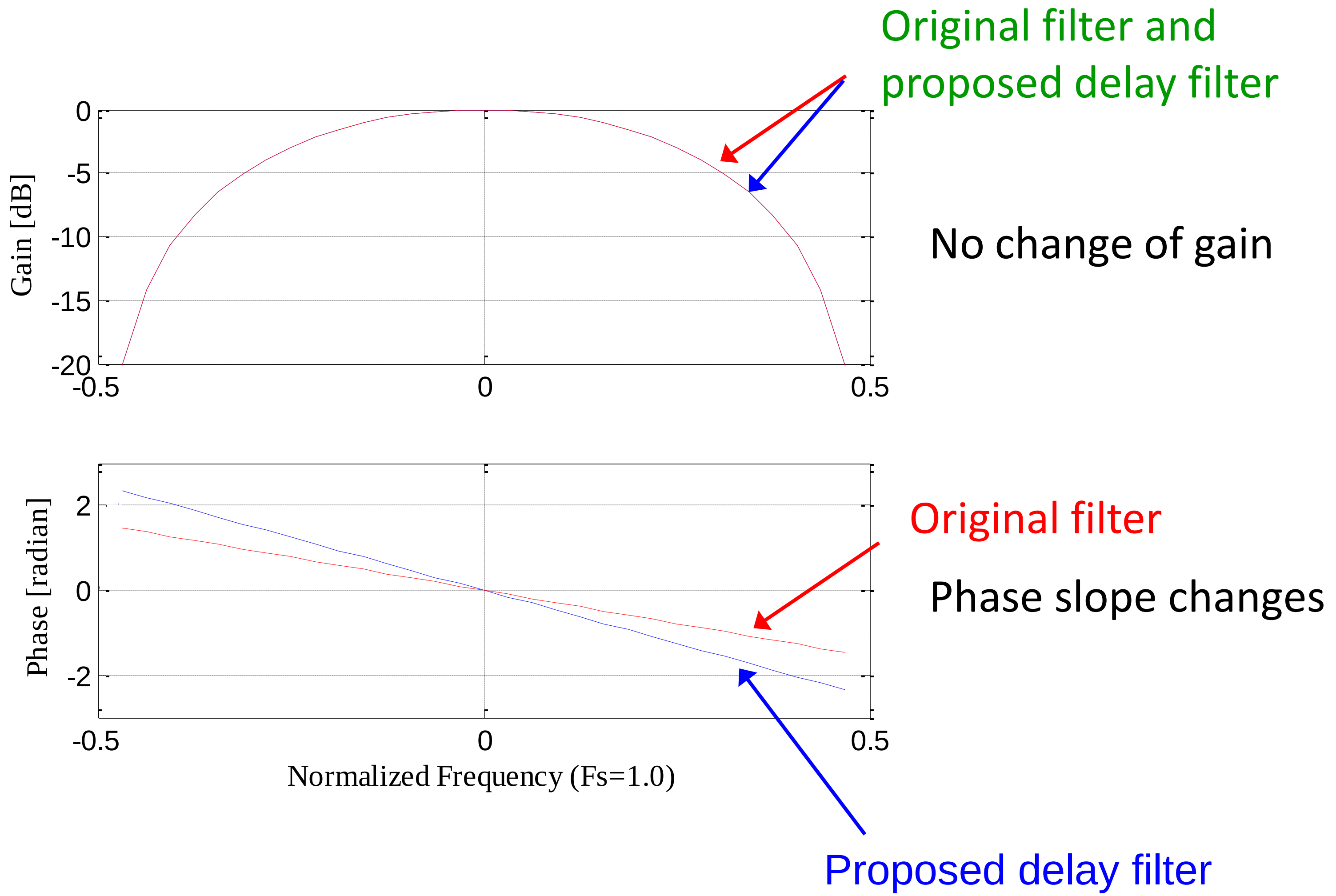
2-tap FIR coefficients

zero

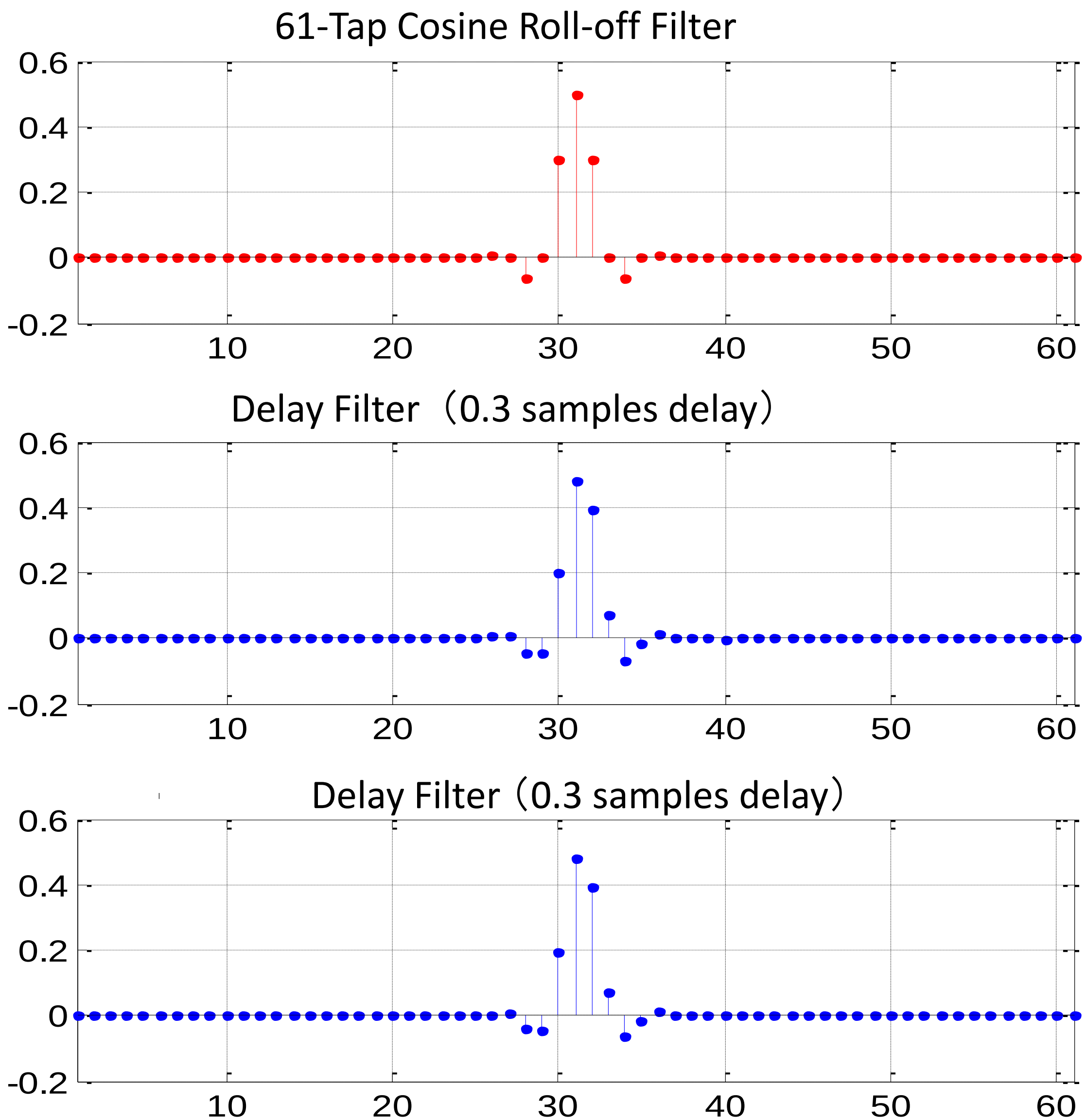
Impulse response changes.

Non-zero

Comparison of 2-Tap Filter Frequency Characteristics



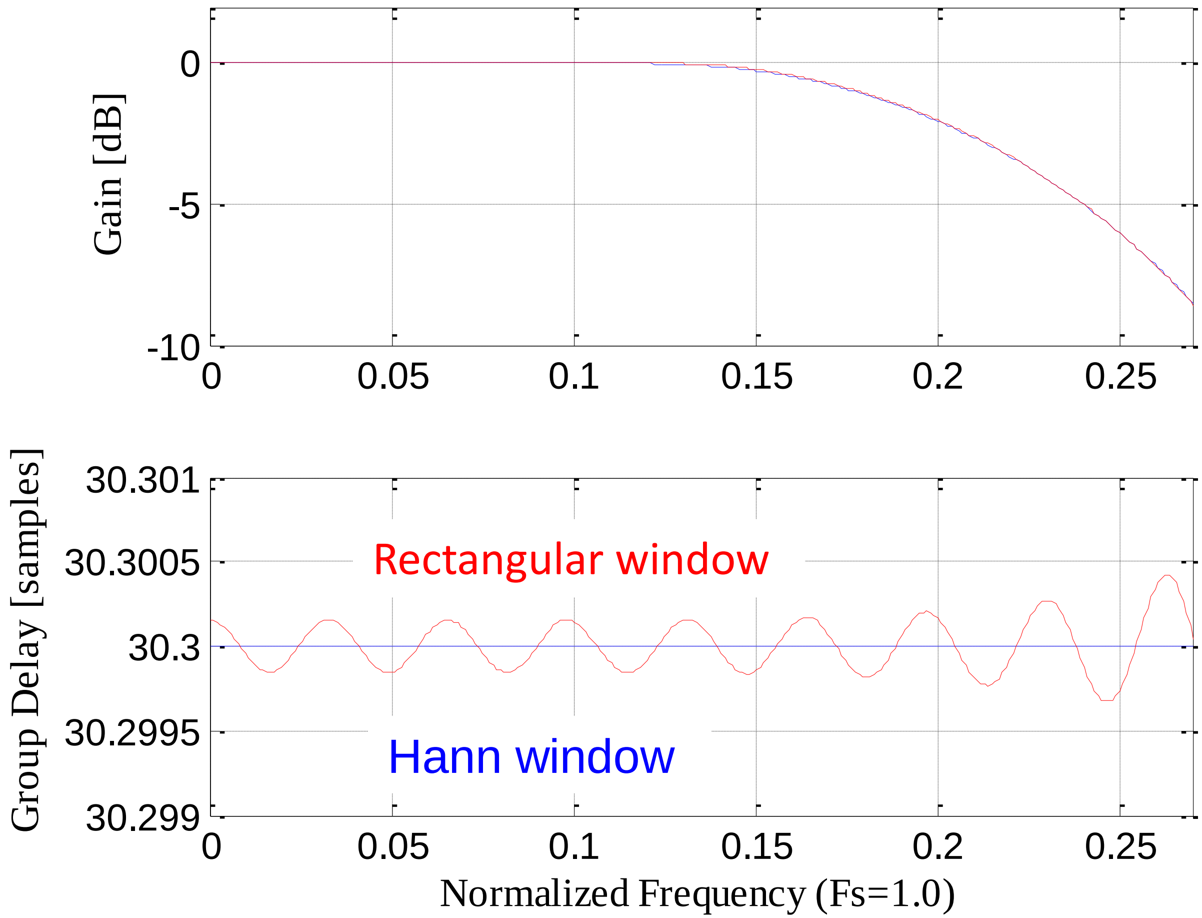
Finite Tap Truncation of Proposed Delay Filter



Rectangular window

Hann window

Effects of Window



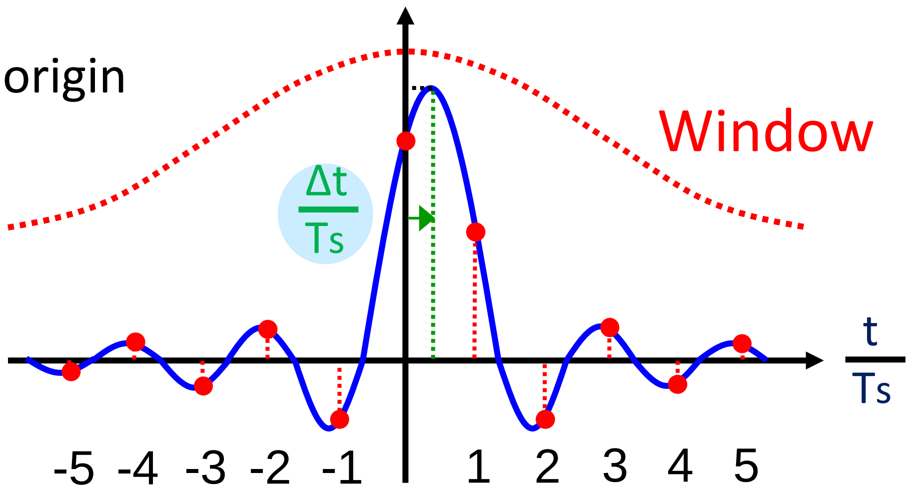
Gibbs oscillation of group delay

Frequency characteristics of delay filter with 61-tap truncation

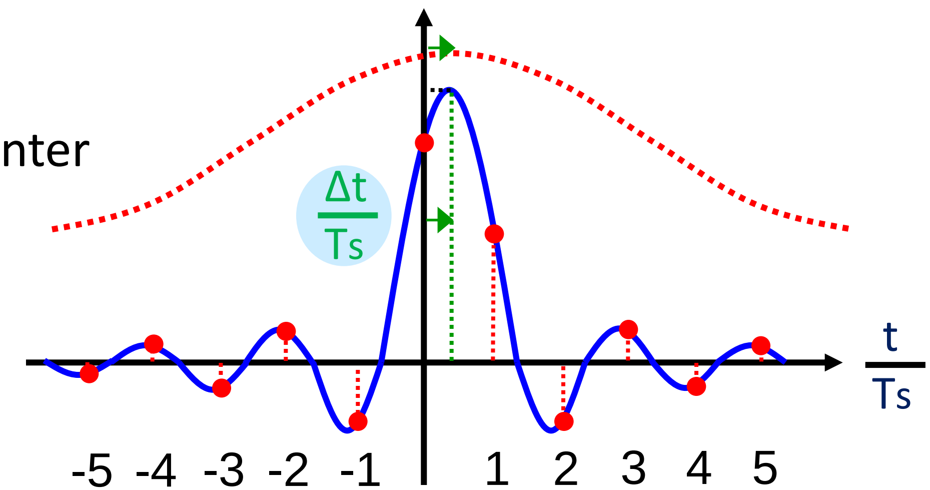
Contents

How to Apply Window

Centered at origin

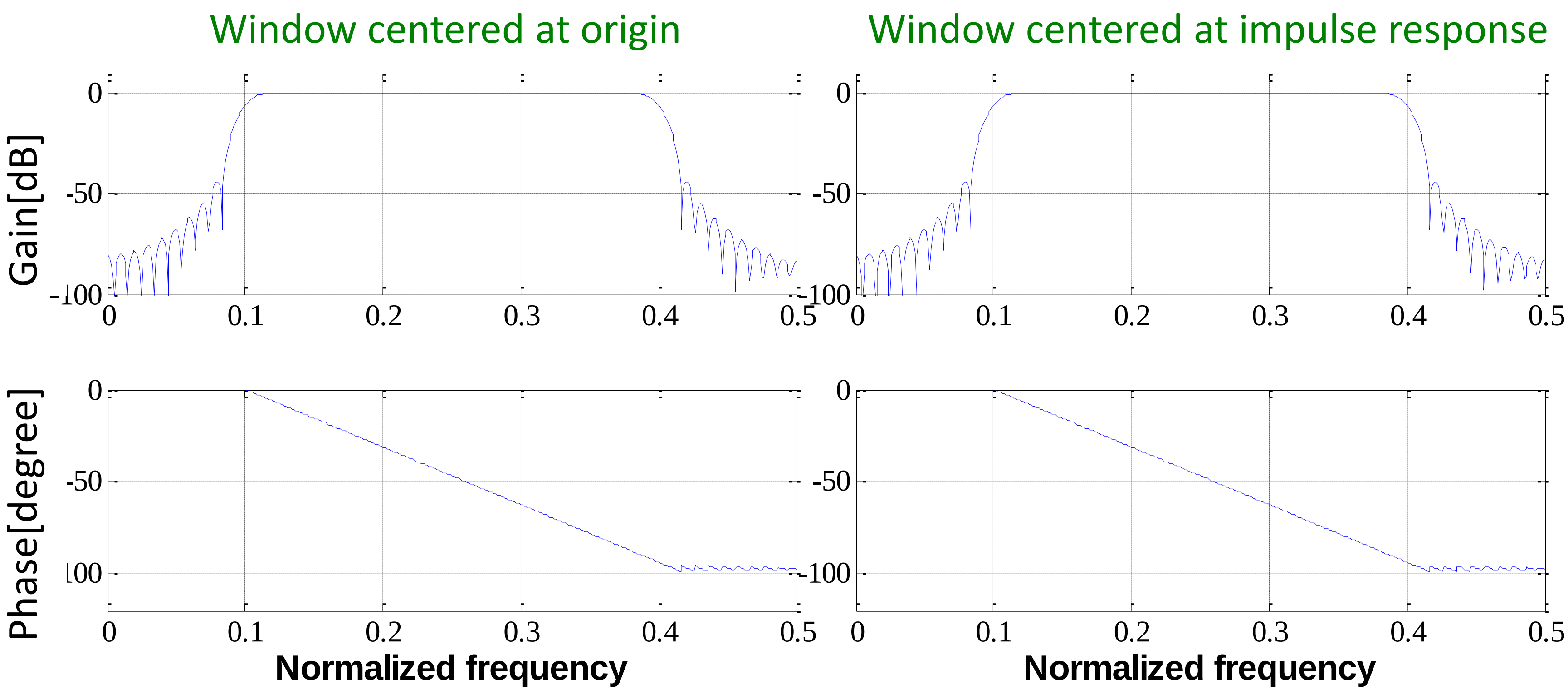


Centered at
impulse response center



Window center shifted by Δt

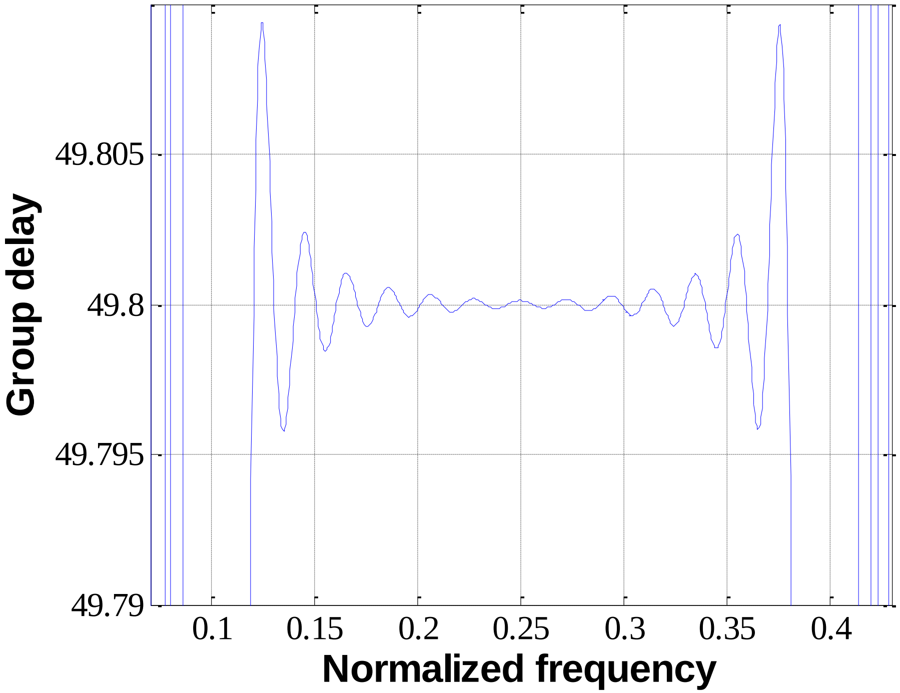
Frequency Characteristics of Delay Filter after Applying Window



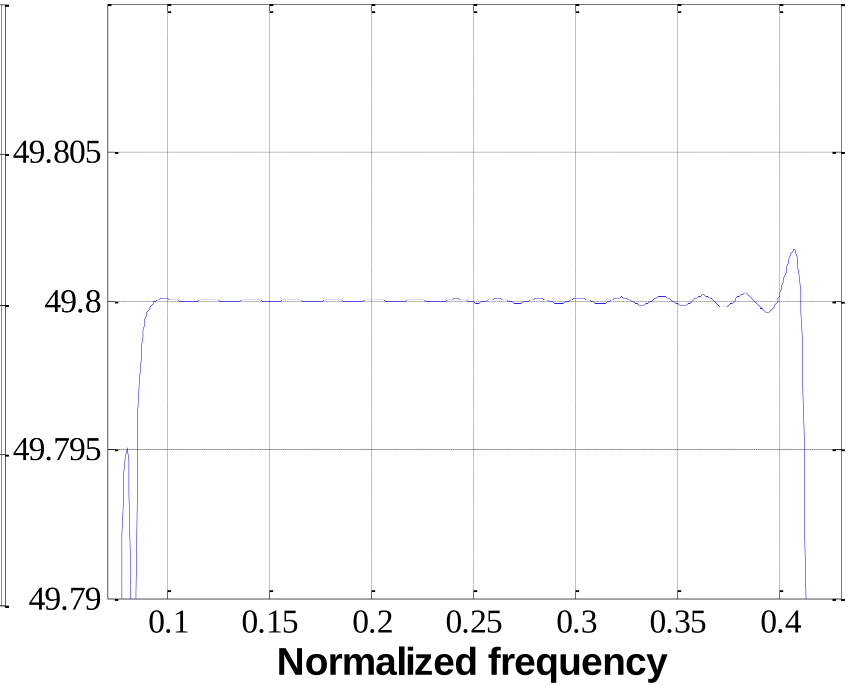
Delay	0.3 samples
Filter Tap	100 taps
Window	Han
Pass band	(0.1～0.4)･Fs
FFT points	1024 points

Group Delay Characteristics of Delay Filter after Applying Window

Window centered at origin

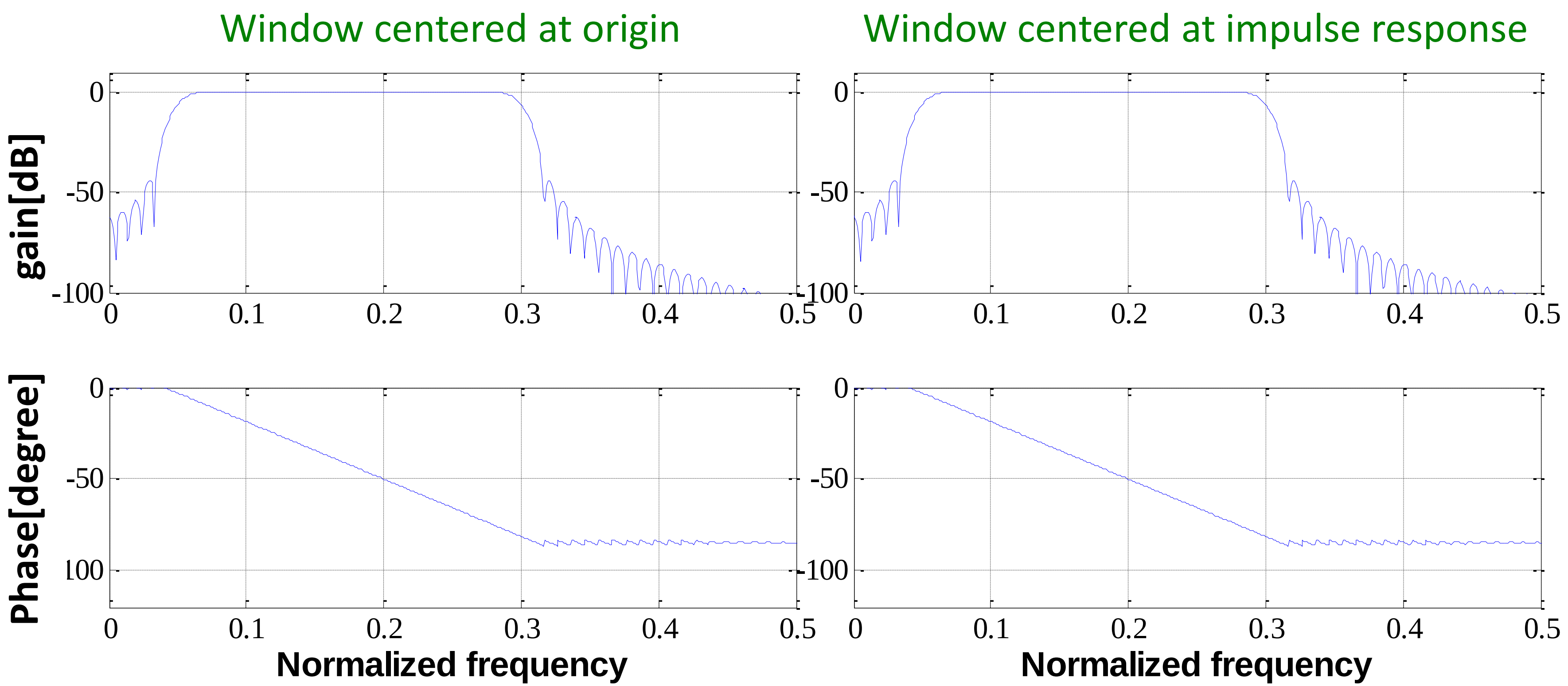


Window centered at impulse response



Delay	0.3 samples
Filter Tap	100 taps
Window	Han
Pass band	(0.1～0.4)･Fs
FFT points	1024 points

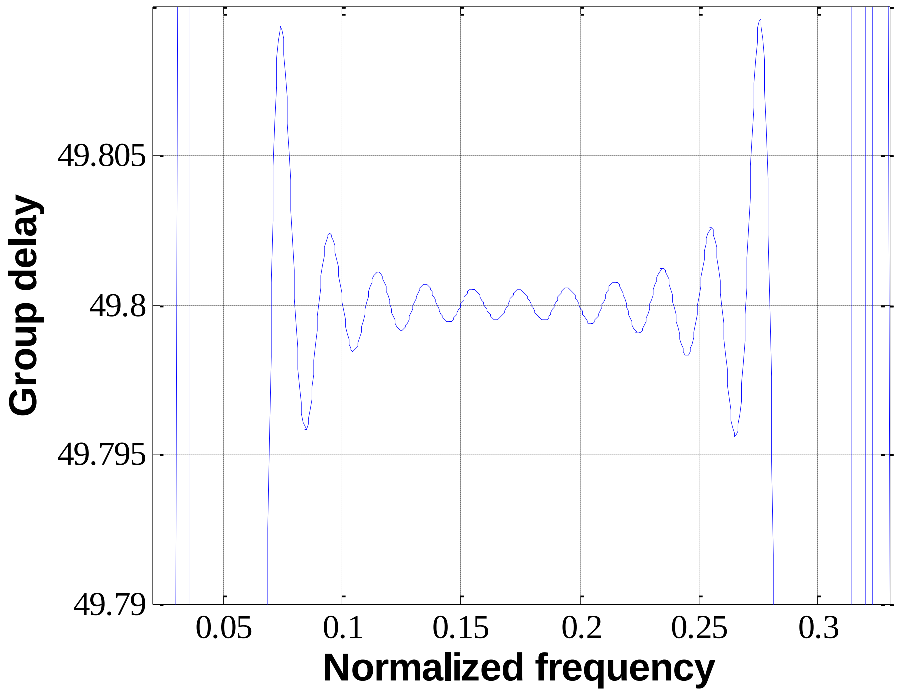
Frequency Characteristics of Delay Filter after Applying Window



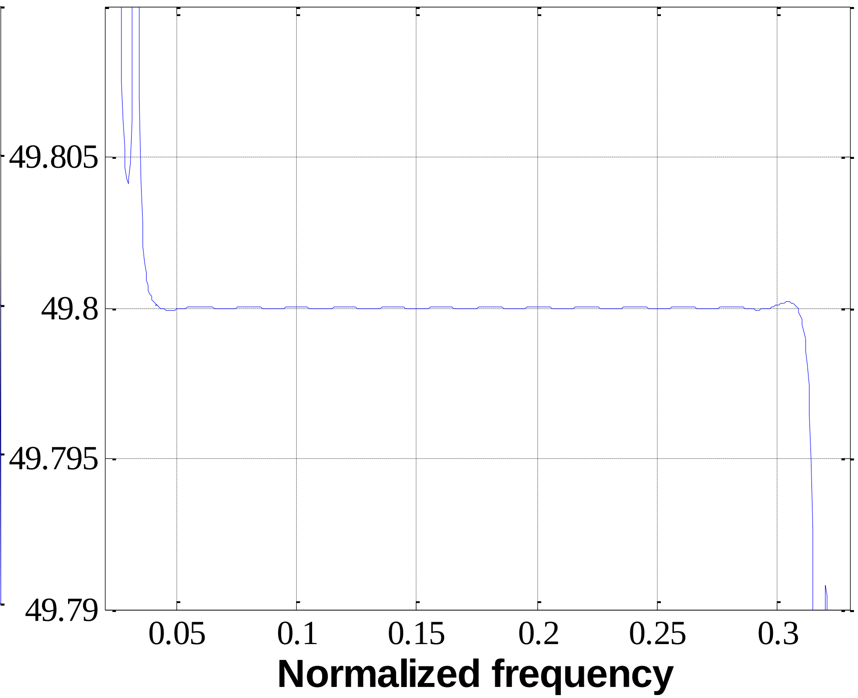
Delay	0.3 samples
Filter Tap	100 taps
Window	Han
Pass band	(0.05～0.3)・Fs
FFT points	1024 points

Group Delay Characteristics of Delay Filter after Applying Window

Window centered at origin



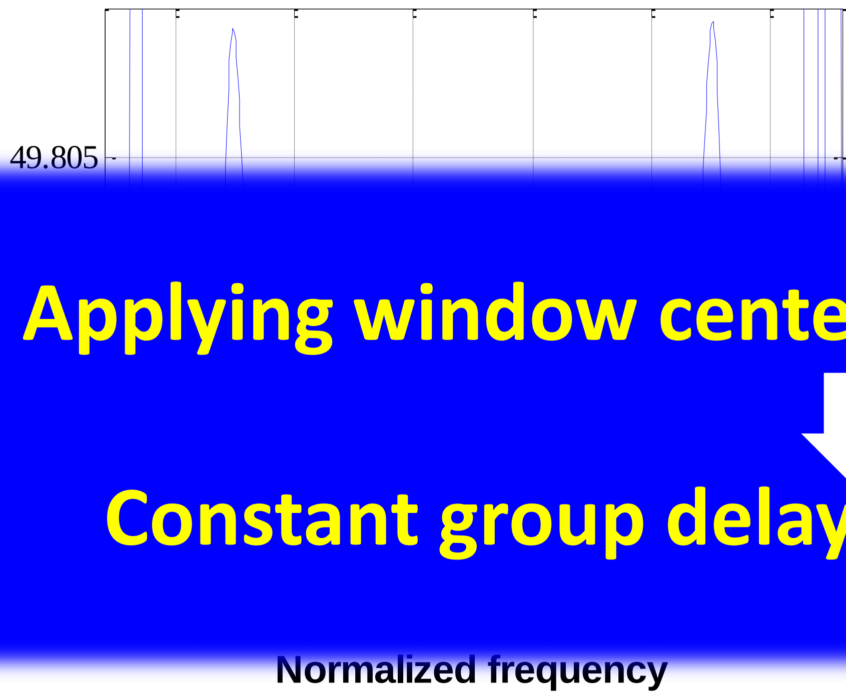
Window centered at impulse response



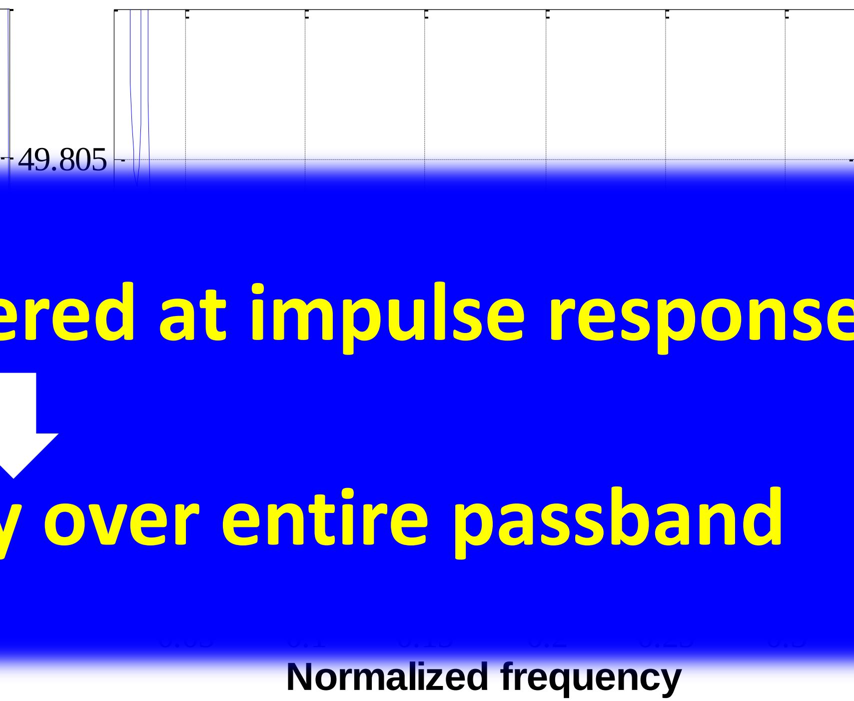
Delay	0.3 samples
Filter Tap	100 taps
Window	Han
Pass band	(0.05～0.3)･Fs
FFT points	1024 points

Group Delay Characteristics of Delay Filter after Applying Window

Window centered at origin



Window centered at impulse response



Applying window centered at impulse response

⬇

Constant group delay over entire passband

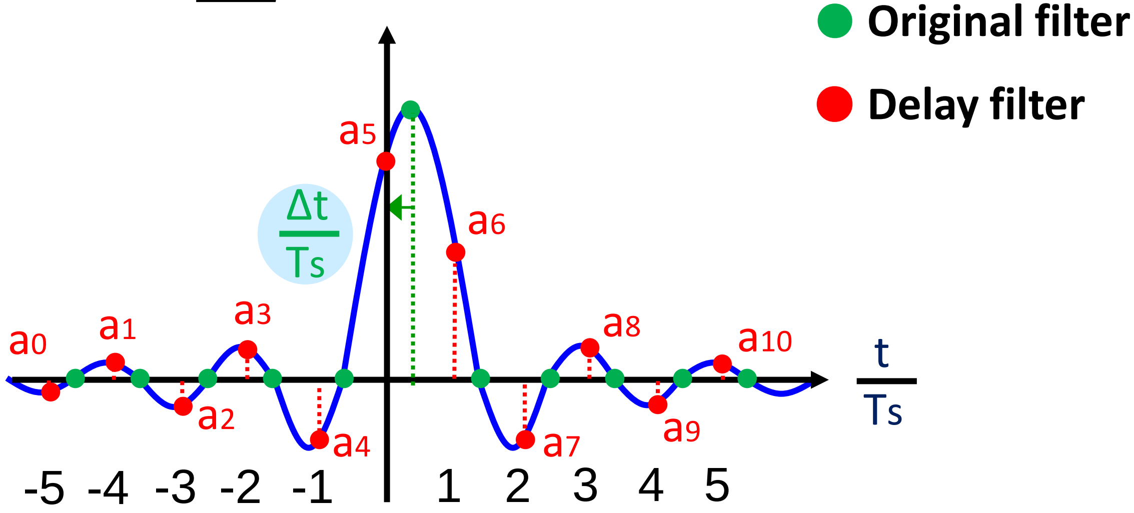
Delay	0.3 samples
Filter Tap	100 taps
Window	Han
Pass band	(0.05～0.3)・Fs
FFT points	1024 points

Contents

- Research Purpose
- Conventional Linear Phase Digital Filter Condition
- New Linear Phase Digital Filter Condition
  - Time-Shift, Impulse Response of Ideal Filter
  - New Linear Phase Digital Filter
- MATLAB Simulation
- Design Consideration
  - Window
  - Gain Adjustment
- Application
- Conclusion

Proposed Filter DC Gain Adjustment

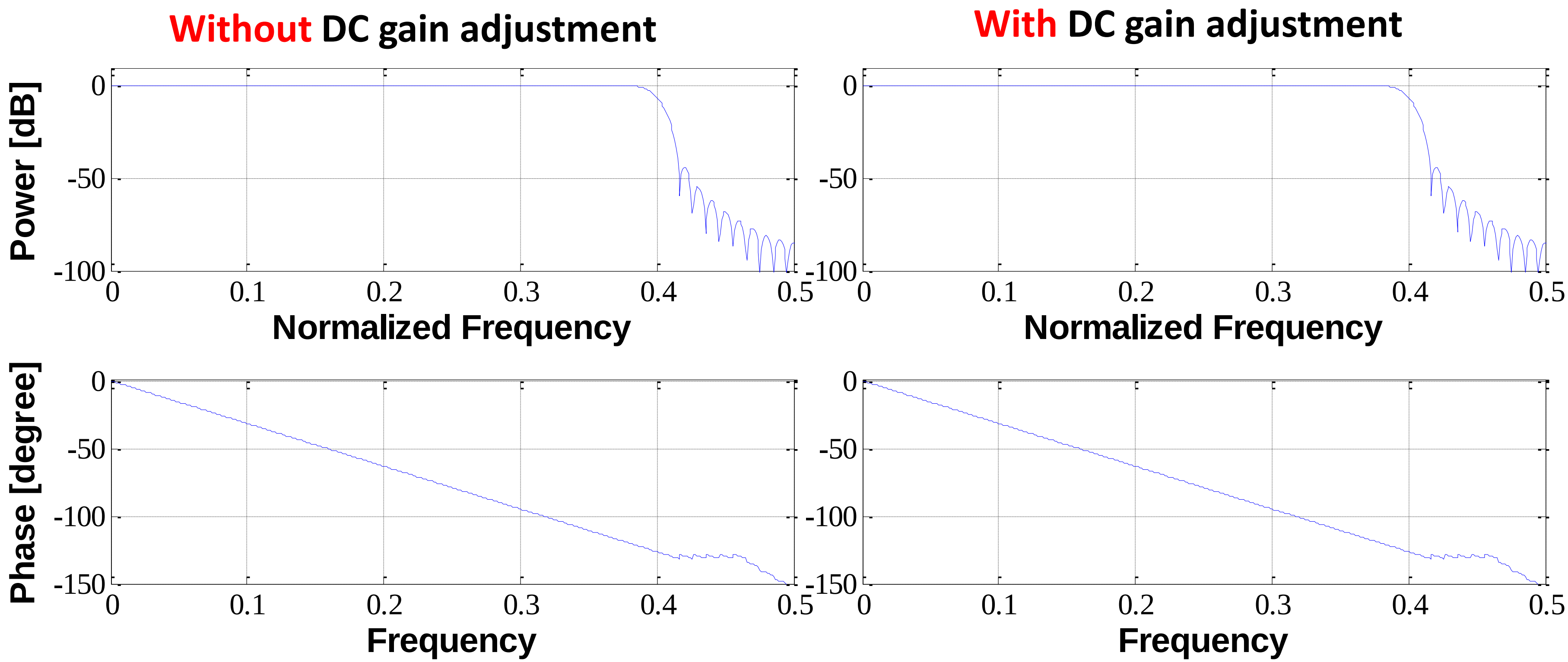
Digital filter DC gain : $\sum a_n$



DC gain adjustment due to finite tap truncation is required

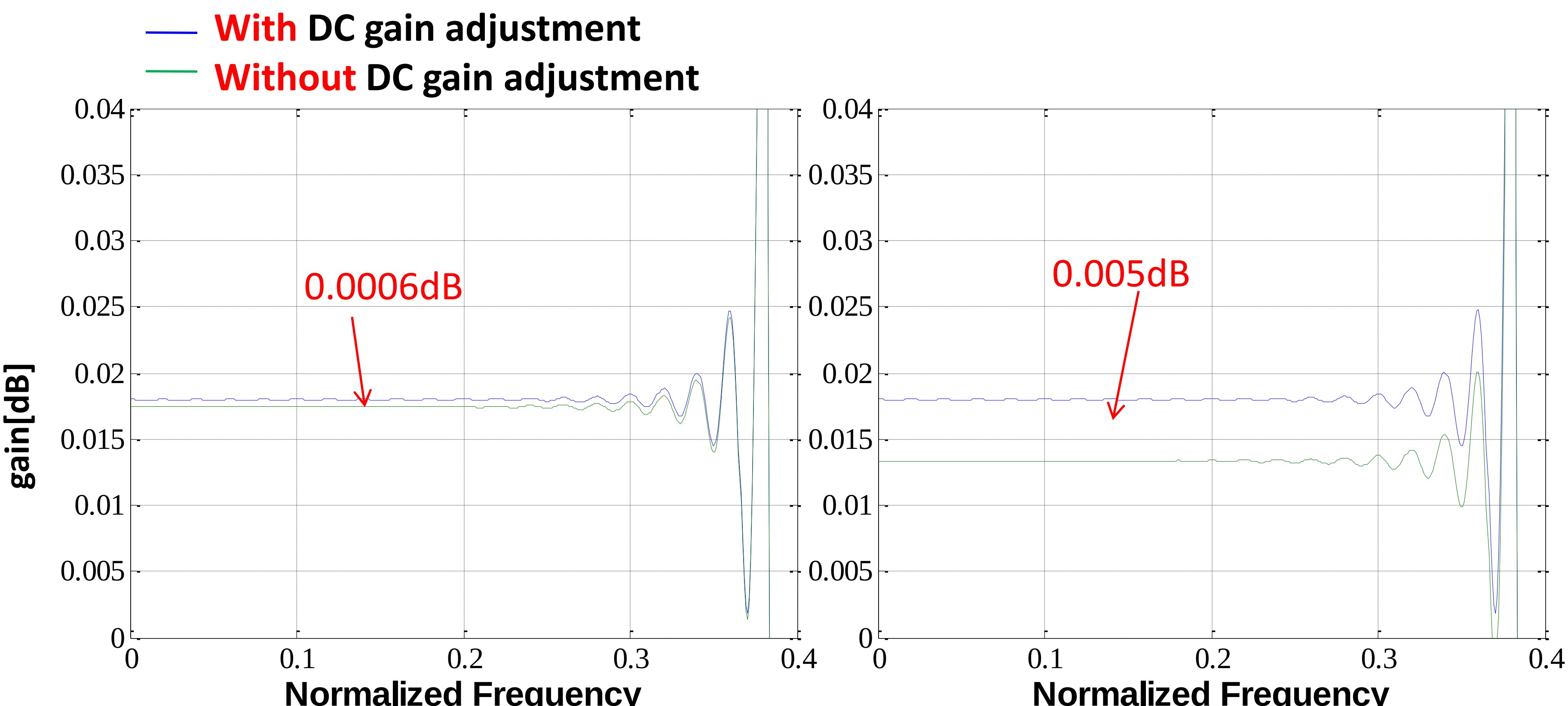
$$\sum_{n=0}^{N} a'_n = \text{DC gain of original FIR filter}$$

Frequency Characteristics of Proposed Delay Filter



Delay	0.3 samples
Filter Tap	101 taps
Window	Han
Cut-off Freq.	0.4・Fs
FFTpoints	1024 points

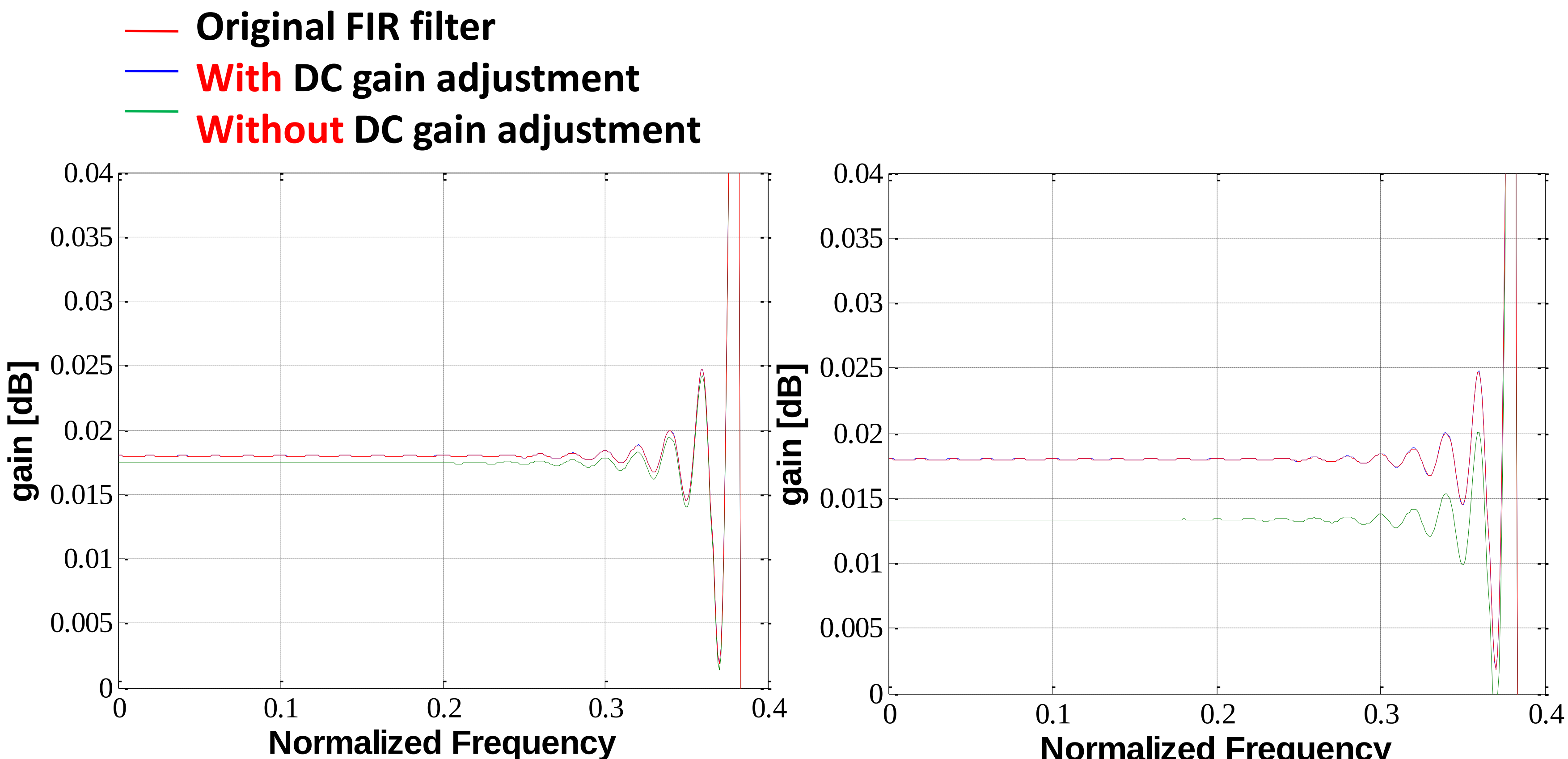
Gain Characteristics of Proposed Delay Filter



Delay	0.1samples
Filter Tap	101 taps
Window	Han
Cutoff Freq.	0.4･Fs
FFTpoints	1024 points

Delay	0.3 samples
Filter Tap	101 taps
Window	Han
Cutoff Freq.	0.4･Fs
FFT points	1024 points

Gain Characteristics of Proposed Delay Filter

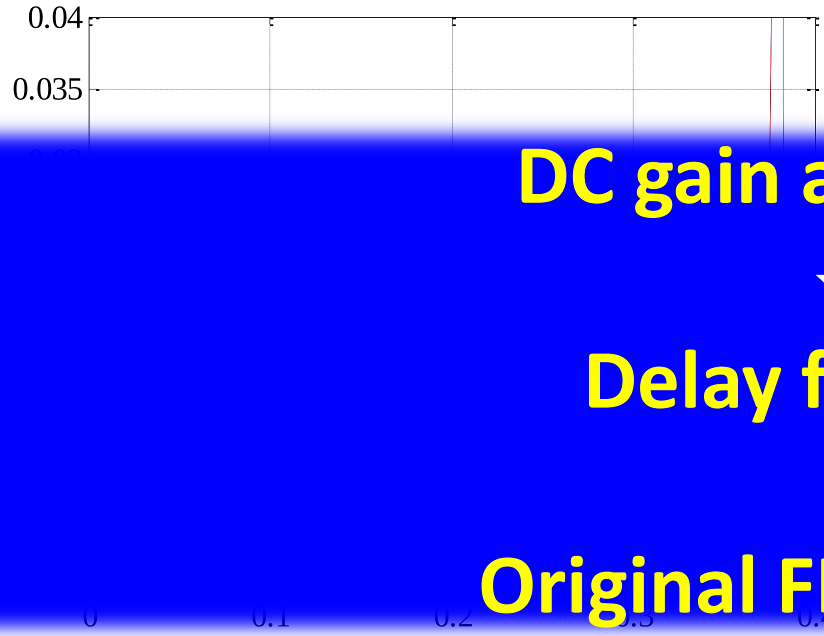


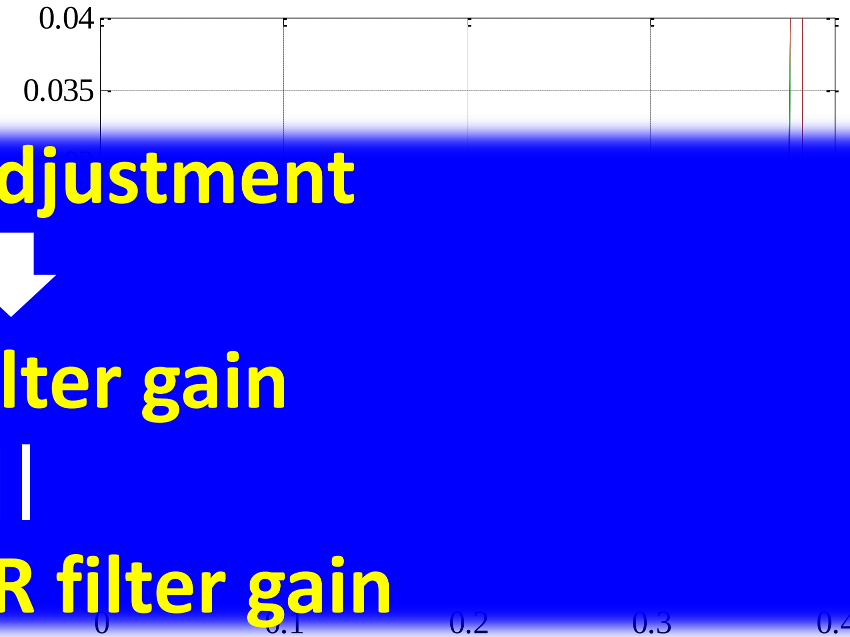
Delay	0.1samples
Filter Tap	101 taps
Window	Han
Cutoff Freq.	0.4･Fs
FFTpoints	1024 points

Delay	0.3 samples
Filter Tap	101 taps
Window	Han
Cutoff Freq.	0.4･Fs
FFT points	1024 points

Gain Characteristics of Proposed Delay Filter

— Original FIR filter
— With DC gain adjustment
— Without DC gain adjustment





DC gain adjustment

⇩

Delay filter gain

||

Original FIR filter gain

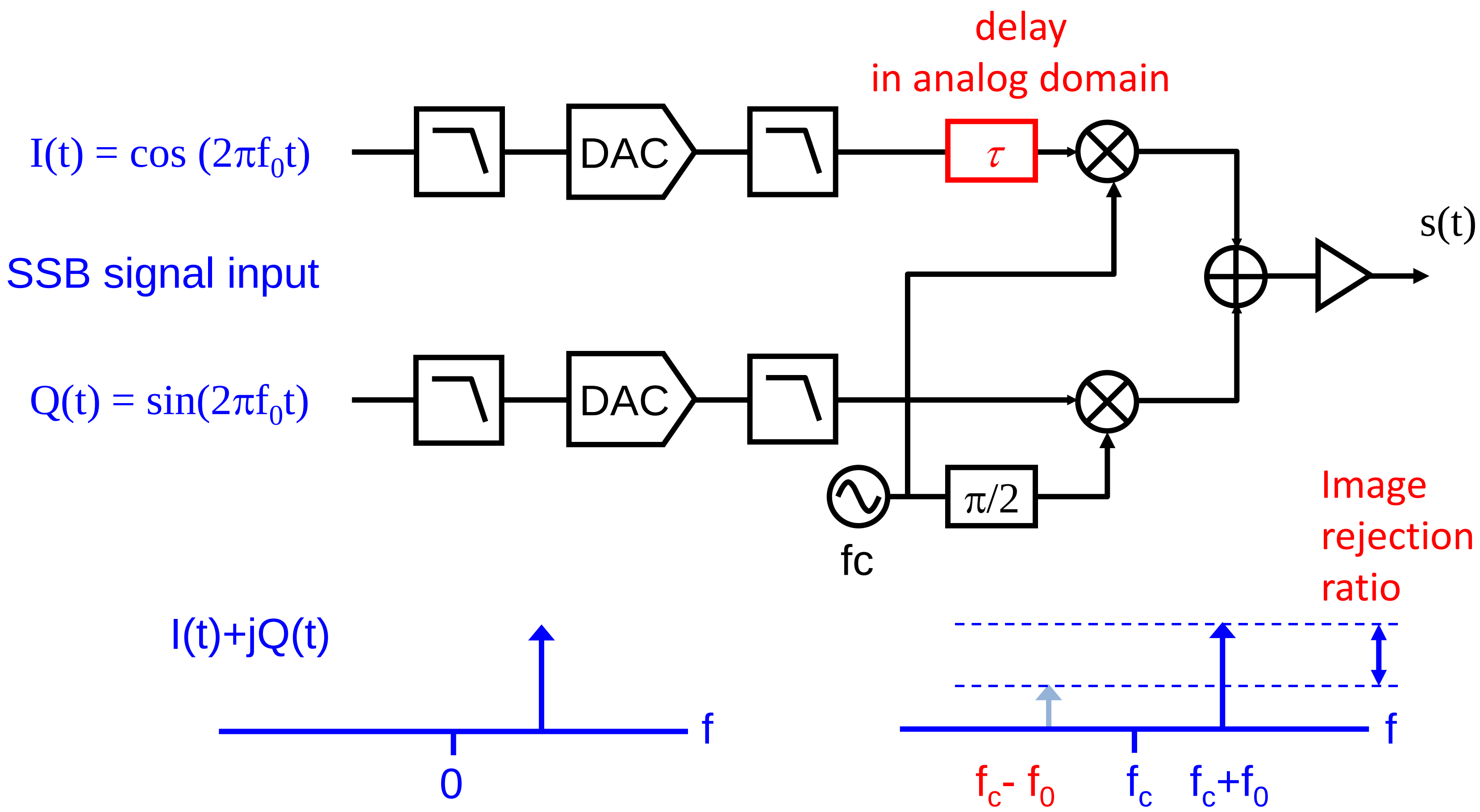
Delay	0.1samples
Filter Tap	101 taps
Window	Han
Cutoff Freq.	0.4･Fs
FFTpoints	1024 points

Delay	0.3 samples
Filter Tap	101 taps
Window	Han
Cutoff Freq.	0.4･Fs
FFT points	1024 points

Contents

- Research Purpose
- Conventional Linear Phase Digital Filter Condition
- New Linear Phase Digital Filter Condition
  - Time-Shift, Impulse Response of Ideal Filter
  - New Linear Phase Digital Filter
- MATLAB Simulation
- Design Consideration
  - Window
  - Gain Adjustment
- <u>Application</u>
- Conclusion

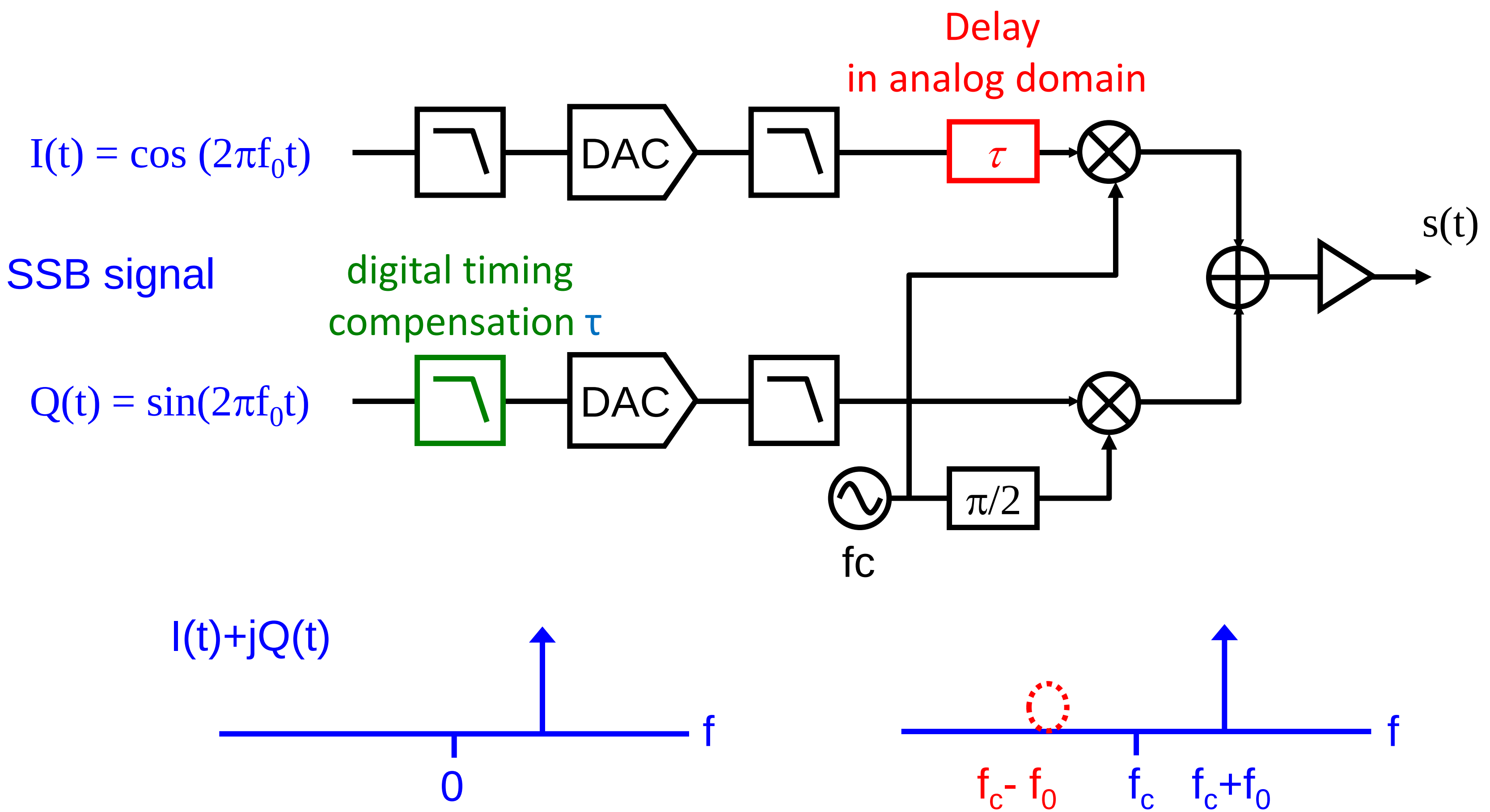
I/Q Delay Mismatch in Quadrature Modulator



SSB：single side band

DAC：digital-to-analog converter

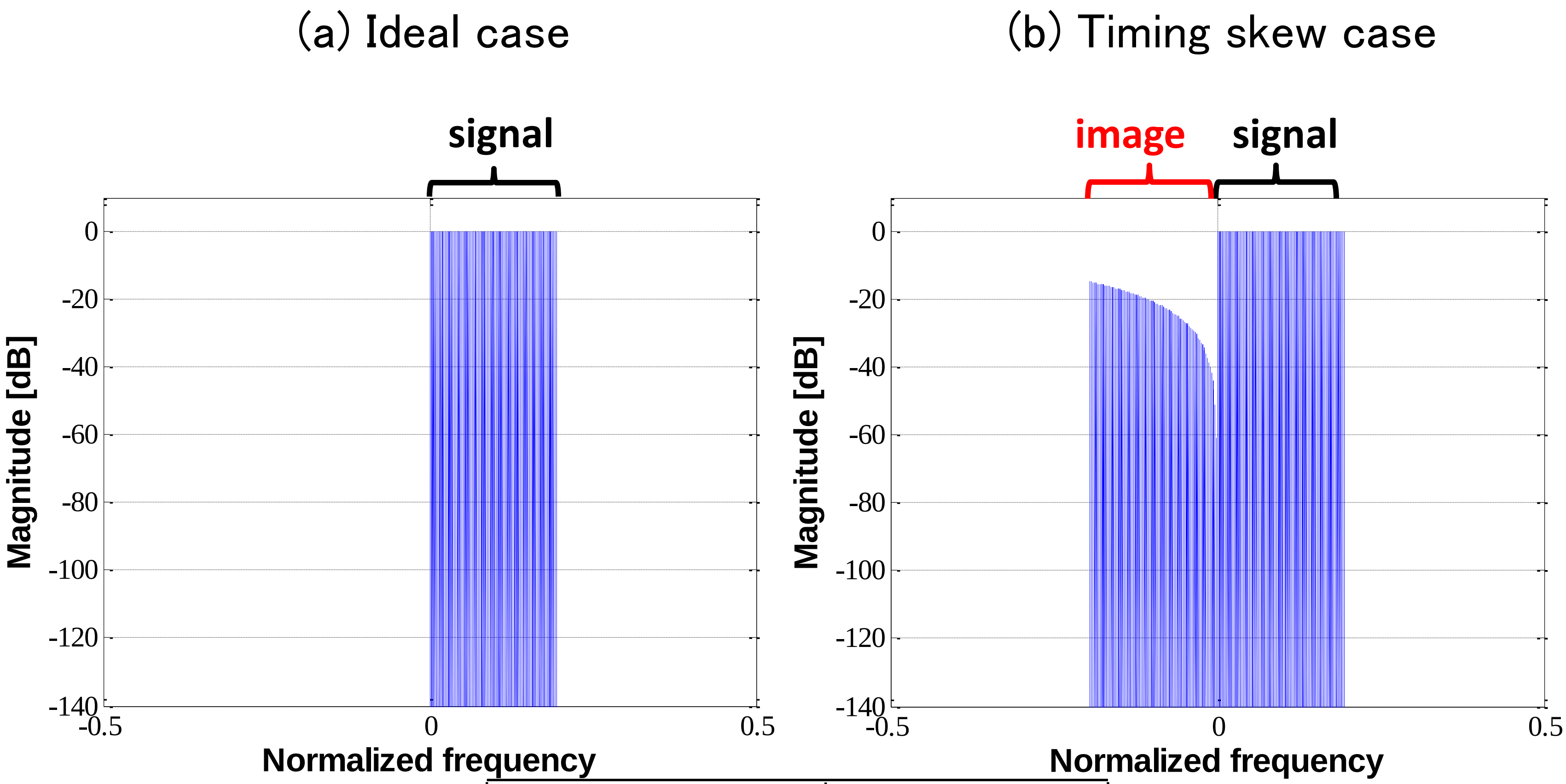
I/Q Delay Mismatch Compensation in Quadrature Modulator



SSB : single side band

DAC : digital-to-analog converter

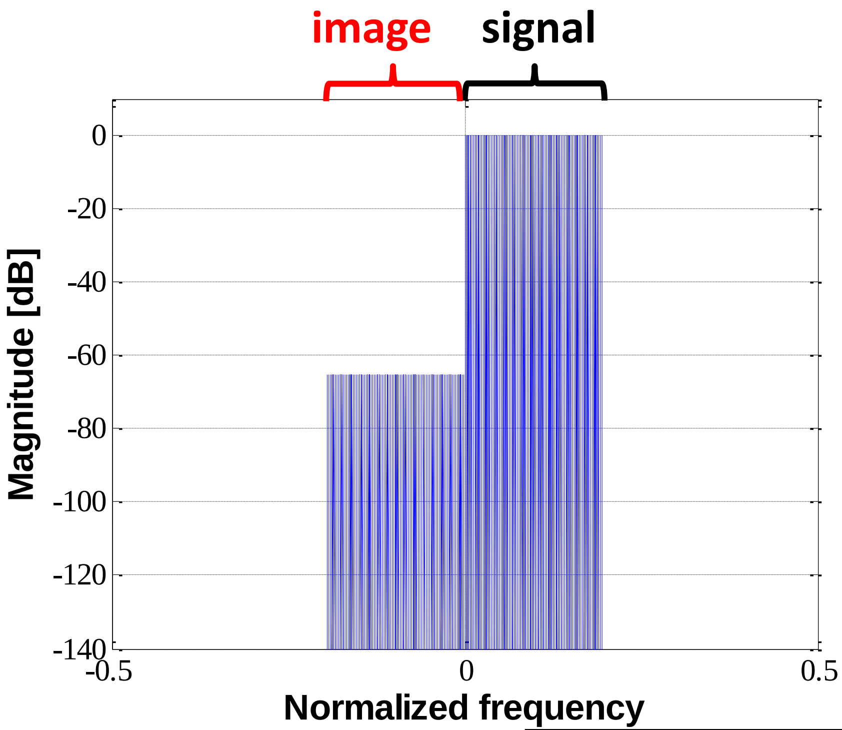
Matlab Simulation Results



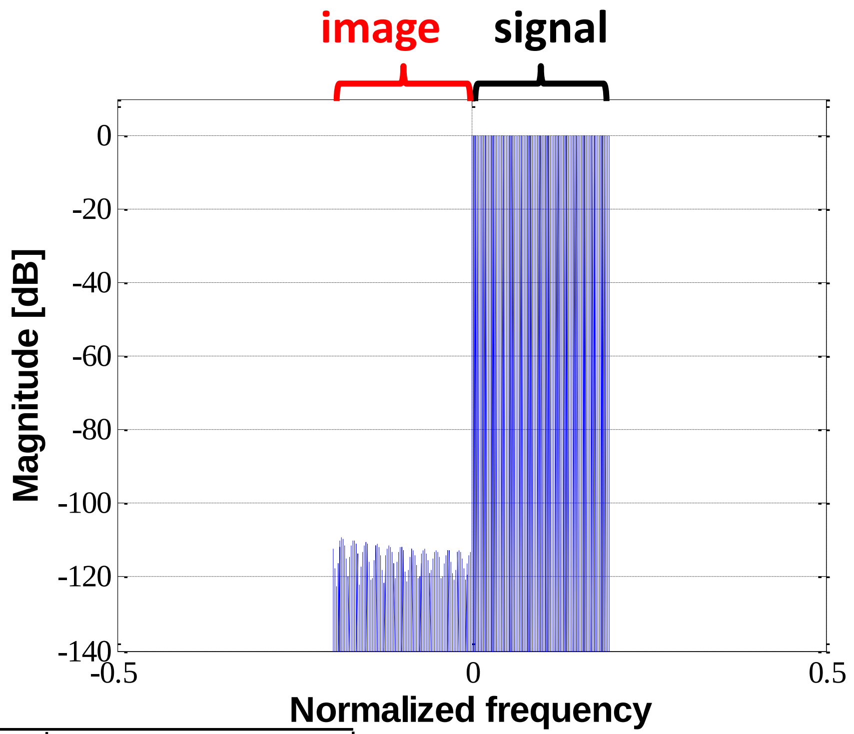
Delay	0.3 samples
Filter tap #	61 taps
Window	Han
FFT points	1024 points

Matlab Simulation Results

(c) Compensation using delay filter
Without adjustment of window, gain



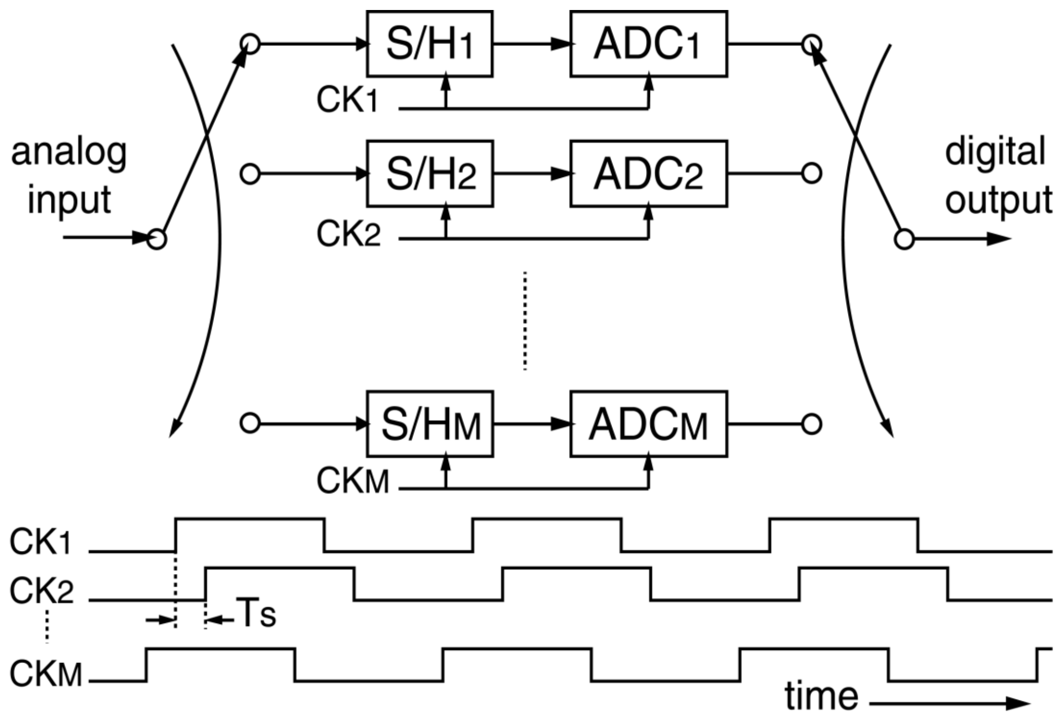
(d) Compensation using delay filter
With adjustment of window, gain



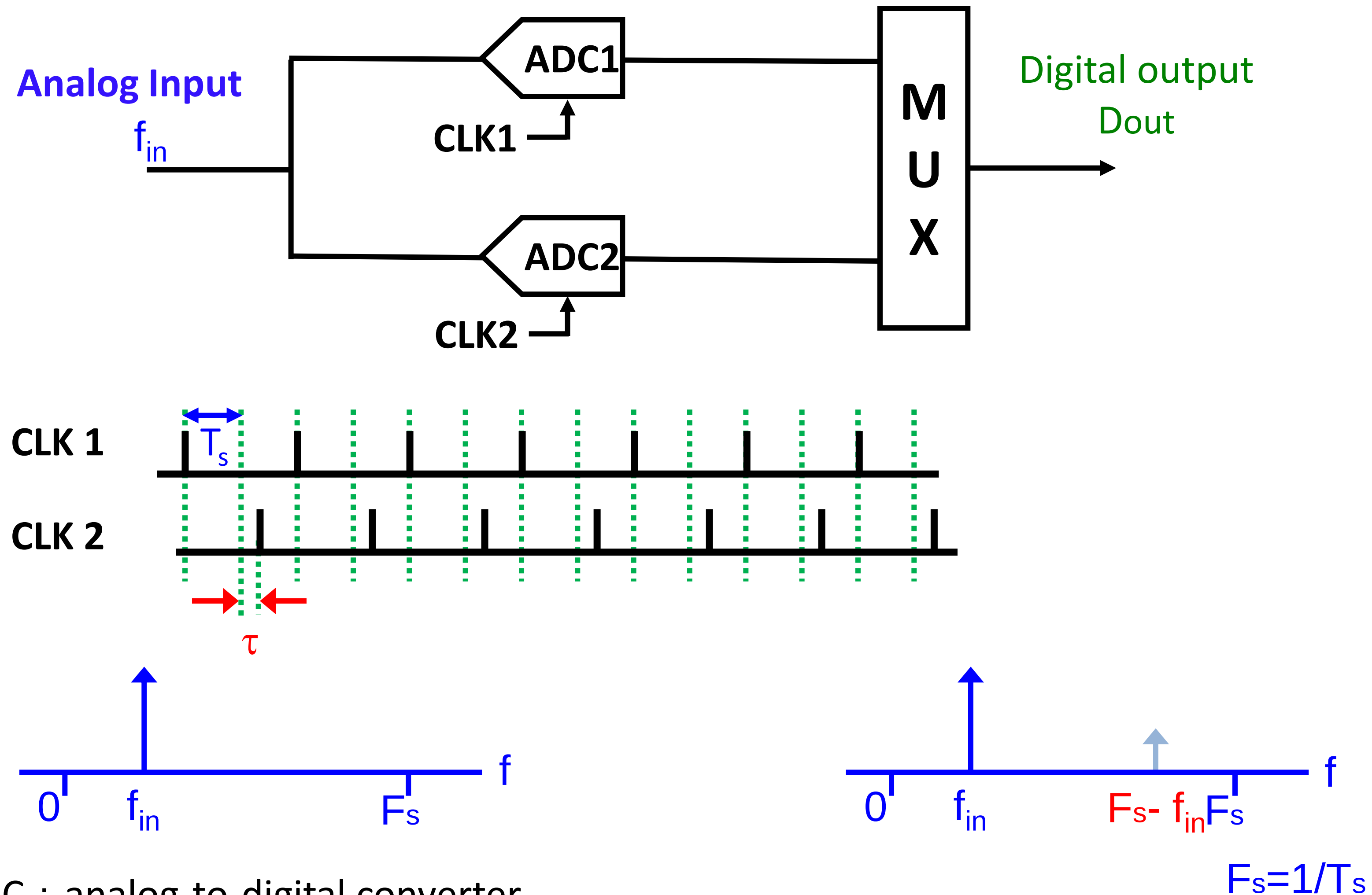
Delay	0.3 samples
Filter tap	61 taps
Window	Han
FFT points	1024 points

Interleaved ADC System

- M channel ADCs ➡ M-times sampling rate

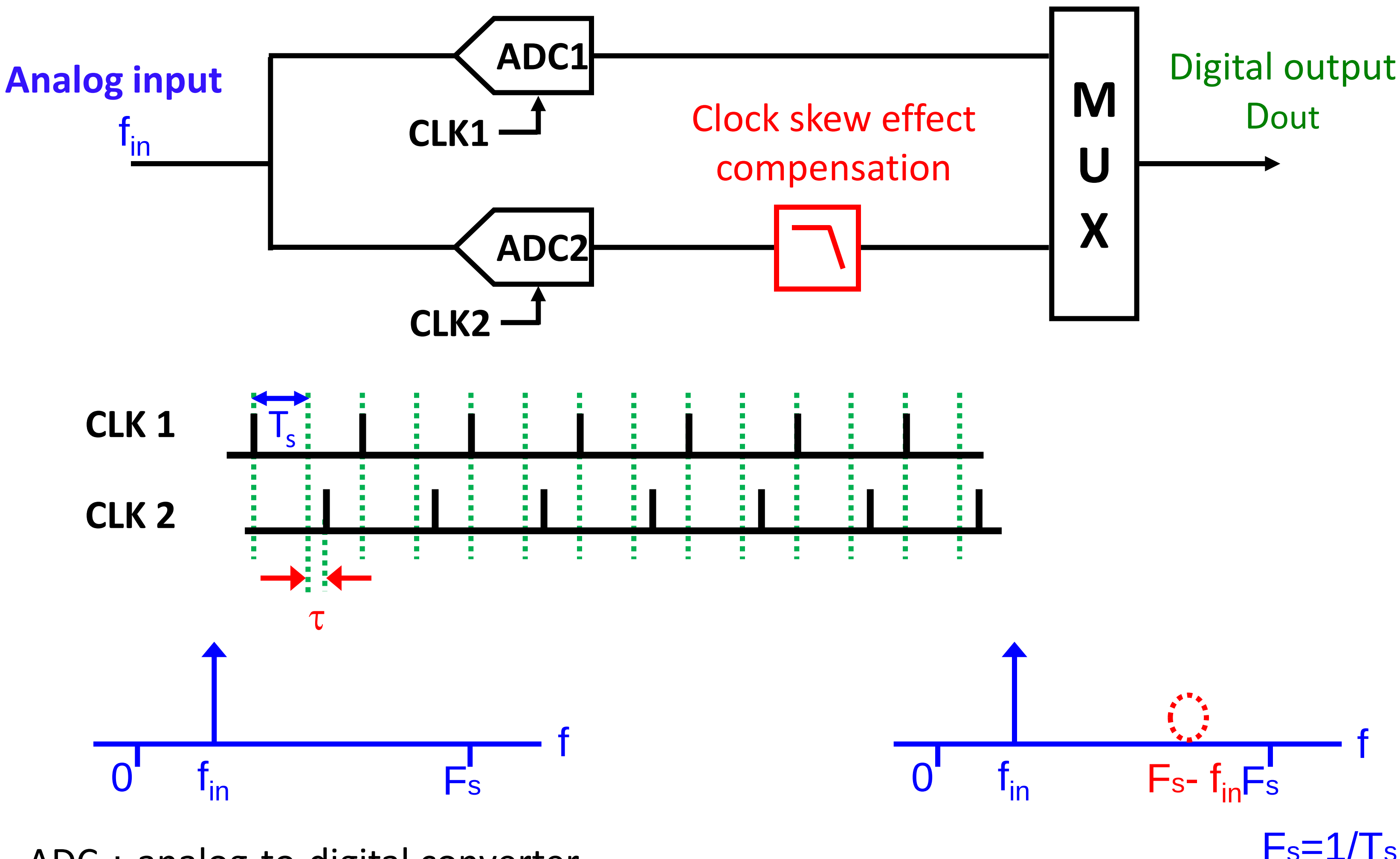


Timing Skew in Interleaved ADC System



ADC：analog-to-digital converter

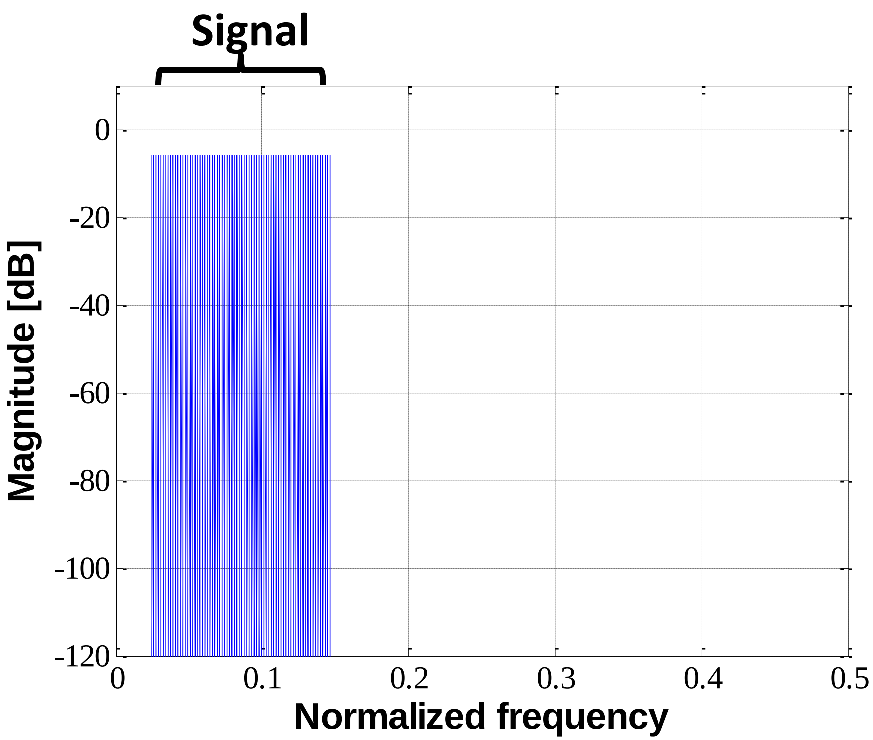
Timing Skew Compensation in Interleaved ADC System



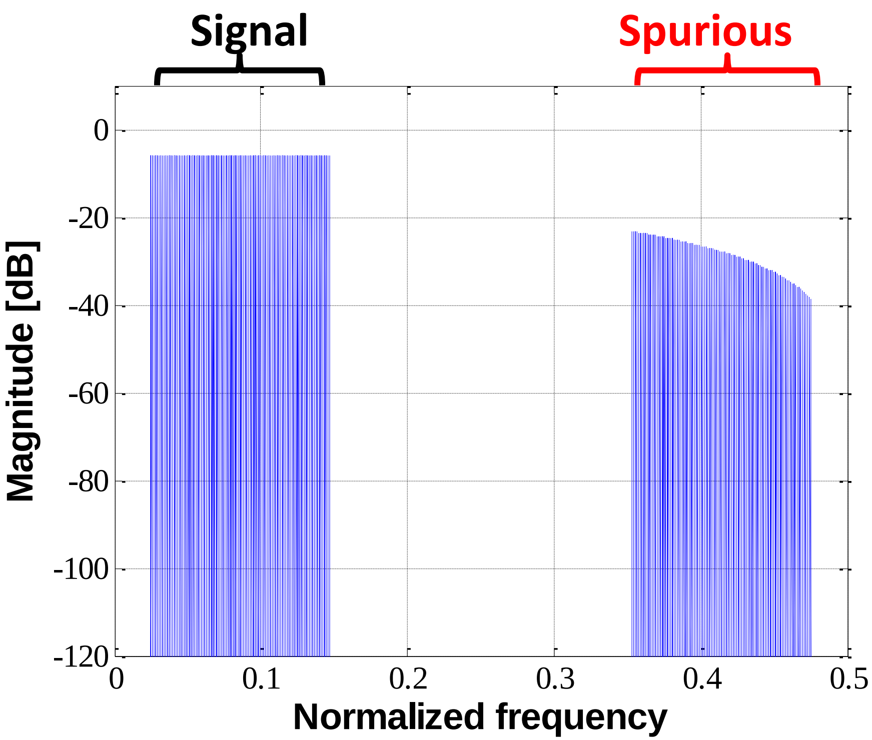
ADC：analog-to-digital converter

Matlab Simulation Results

(a) Ideal case



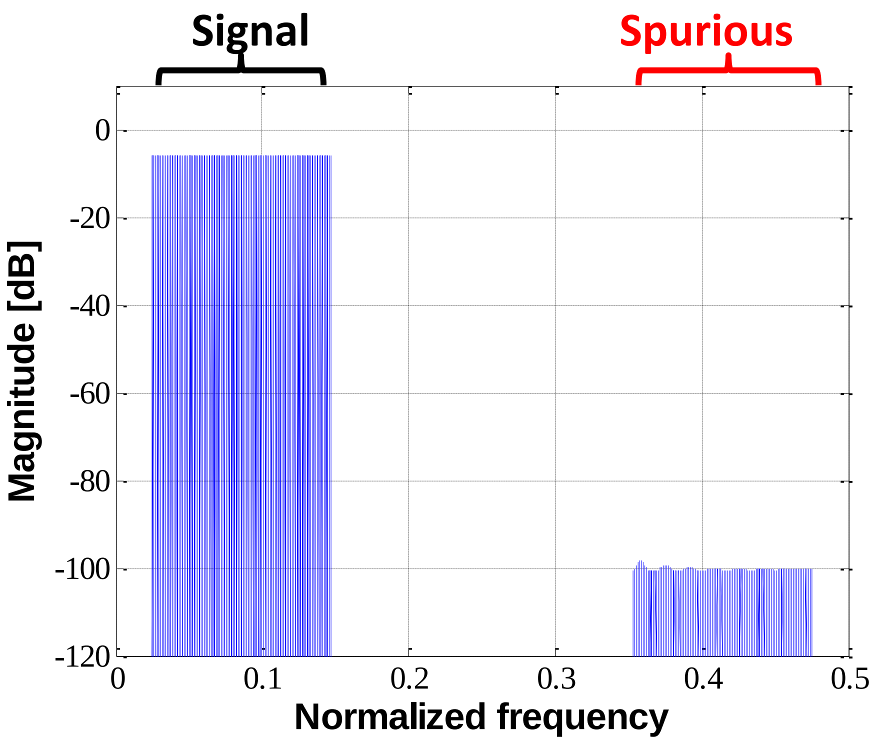
(b) Timing skew case



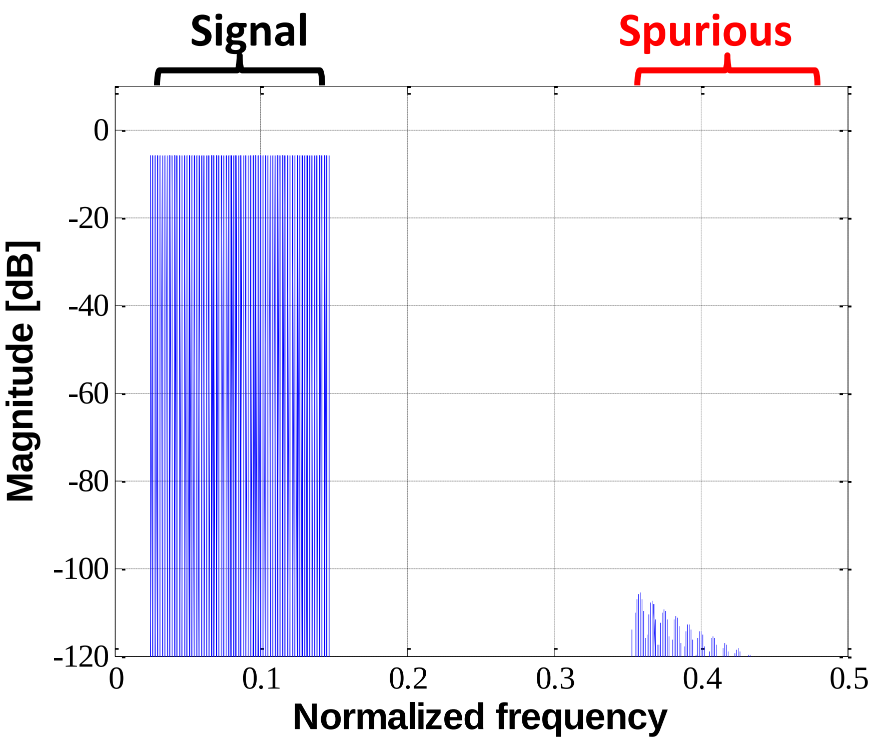
Delay	0.3 samples
Filter tap	61 taps
Window	Han
FFTpoints	1024 points

Matlab Simulation Results

(c) Compensation using delay filter
Without adjustment of window, gain



(d) Compensation using delay filter
With adjustment of window, gain



Delay	0.3 samples
Filter tap	61 taps
Window	Han
FFTpoints	1024 points

Conclusion

- Linear phase digital filter
  with fine time resolution of group delay
- Design consideration
  - How to apply window
  - DC gain adjustment
- Application Examples
  - I/Q delay mismatch compensation
    in quadrature modulator
  - Timing skew compensation in interleaved ADC system

Future work

- Implementation issues
  – Finite word length, finite tap effects
  – LSI implementation