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Frequency Estimation Sampling Circuit Using Analog Hilbert Filter and Residue Number System

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OUTLINE

1. Research Background and Goal
2. Chinese Remainder Theorem
3. Proposed Waveform Sampling Circuit
4. Simulation Verification
5. Summary and Challenge

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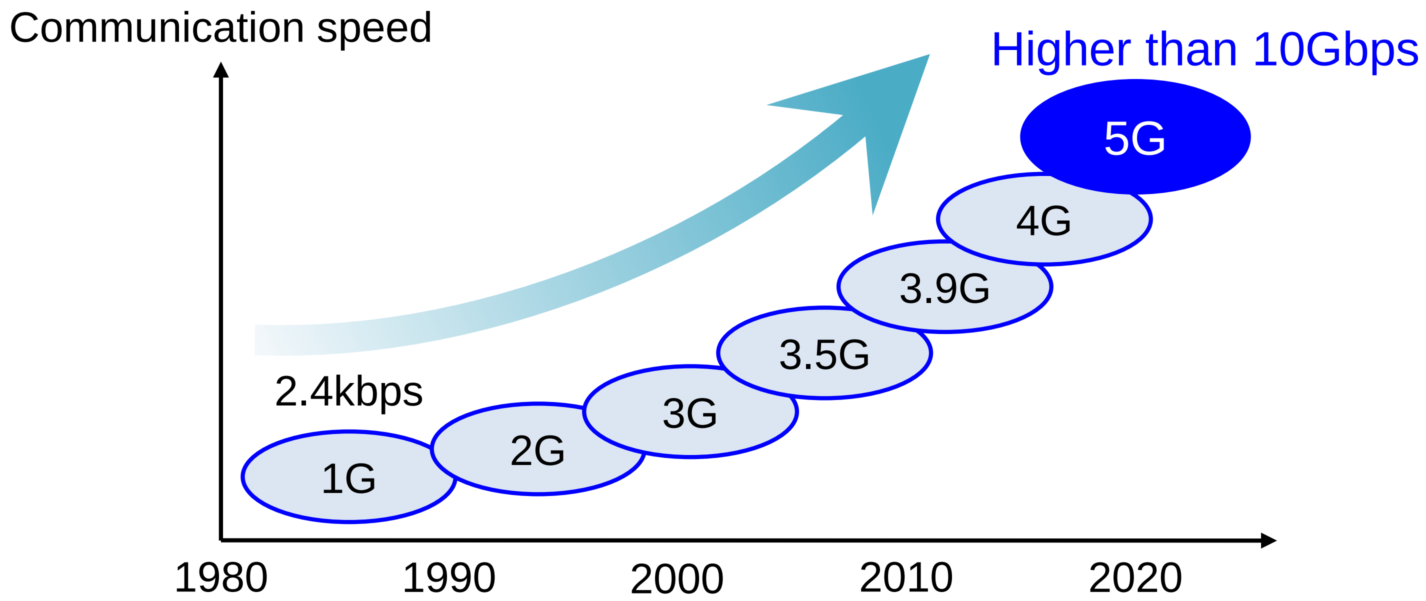
Research Background

Next Generation Communication System "5G"

High frequencies
in communication systems

Electronic components
for high frequency bands



Our Research Goal

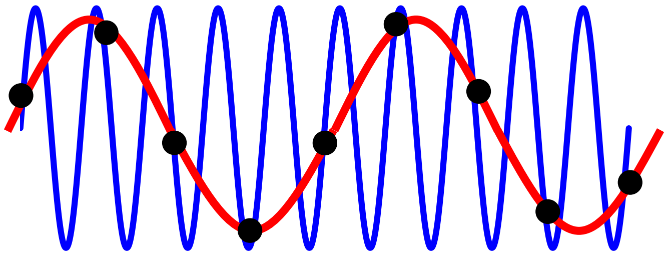
Estimate high-frequency input signal
with multiple low-frequency clock sampling circuits

High-frequency sampling circuit is difficult to realize

Our Approach :

Sampling high frequency signal with multiple low frequency clocks

Use Aliasing proactively



Analog Hilbert filter and residue number system

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Chinese Remainder Theorem

Sun Tzu

孫子算經卷上

唐朝議大夫行太史令上輕車都尉臣李淳風等奉勅注釋

度之所起起於忽欲知其忽蠶吐絲爲忽十忽

爲一絲十絲爲一毫十毫爲一氂十氂爲一分

十分爲一寸十寸爲一尺十尺爲一丈十丈爲

一引五十尺爲一端四十尺爲一疋六尺爲一

步二百四十步爲一畝三百步爲一里

稱之所起起於黍十黍爲一絫十絫爲一銖二

十四銖爲一兩十六兩爲一斤三十斤爲一鈞

Sun Tzu calculation

Chinese arithmetic book 'Sun Tzu calculation'

孫子算経

"When dividing by 3, its residue is 2,
dividing by 5, its residue is 3,
dividing by 7,its residue is 2.
What is the original number ?"

Answer 23

Generalization

Chinese Remainder Theorem

How to use the Chinese remainder theorem

He used to quickly find out how many soldiers there are.

Sun Tzu

“How many soldiers are there?”

“Divide into 3 people.”

...

How to use the Chinese remainder theorem

He used to quickly find out how many soldiers there are.

Sun Tzu

"Divide into 5 people."

Remainder : 2

...

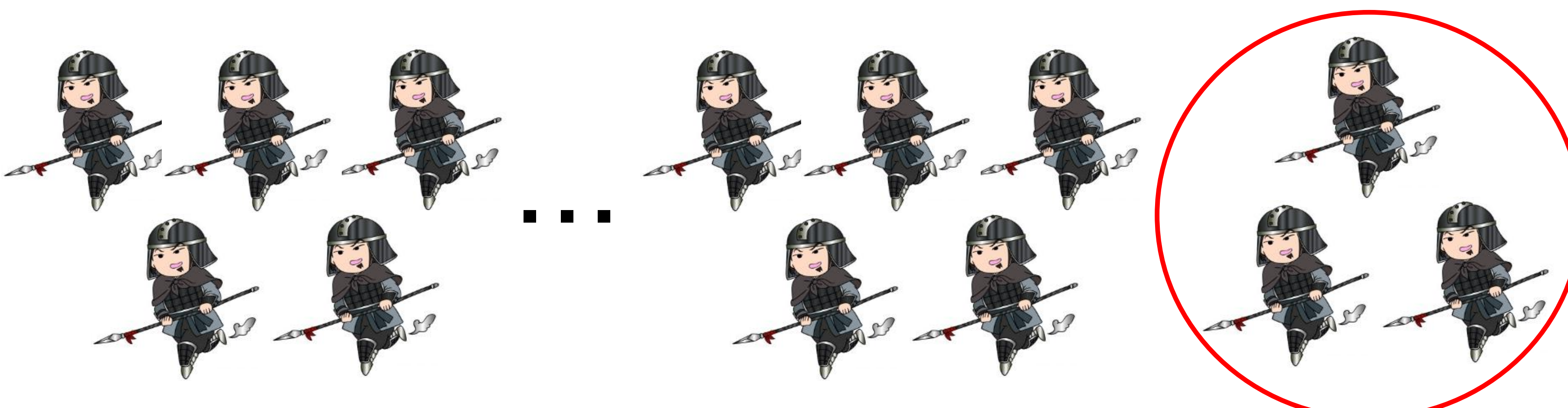
How to use the Chinese remainder theorem

He used to quickly find out how many soldiers there are.

Sun Tzu

“Divide into 7 people.”

Remainder : 3



How to use the Chinese remainder theorem

He used to quickly find out how many soldiers there are.

Sun Tzu

"Divide into 7 people."

"There are 23 people in all."

Remainder : 2

Example of Residue Number System

23 % 3 = 2, 23 % 5 = 3, 23 % 7 = 2

- Natural numbers
  3, 5, 7 (relatively prime)
  N=3 × 5 × 7=105
- k (0 <= k <= N-1 (=104))

a : Remainder of k dividing by 3 a=mod3(k)
b : Remainder of k dividing by 5 b=mod5(k)
c : Remainder of k dividing by 7 c=mod7(k)

k ⟷ (a, b, c)

one to one

Chinese remainder theorem

a	b	c	k
0	0	1	15
1	1	2	16
2	2	3	17
0	3	4	18
1	4	5	19
2	0	6	20
0	1	0	21
1	2	1	22
2	**3**	**2**	**23**
0	4	3	24
1	0	4	25
2	1	5	26
0	2	6	27
1	3	0	28
2	4	1	29

Residue number system

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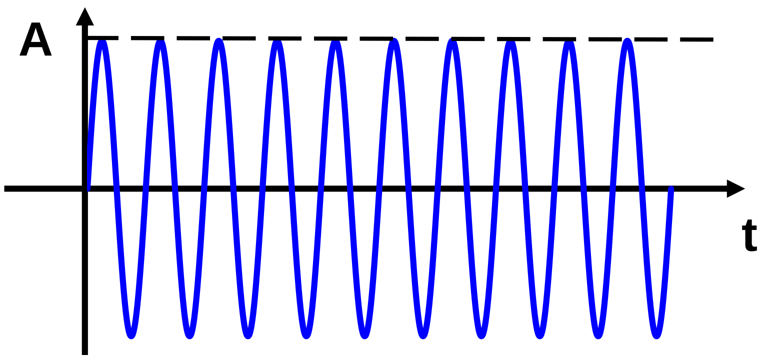
Aliasing Phenomenon

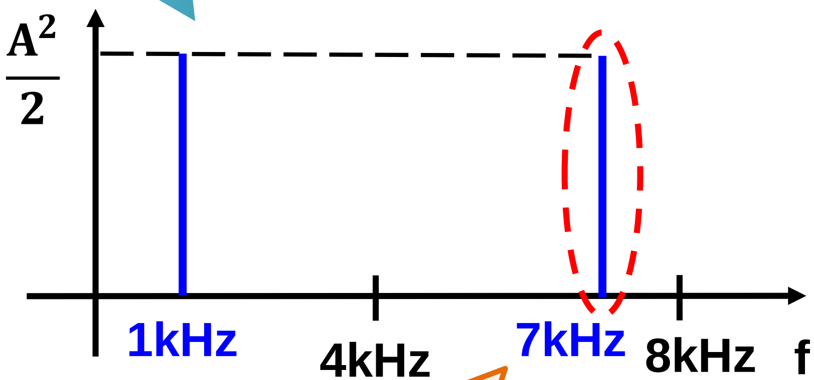
Sampling frequency : 8 kHz

FFT

Spectrums are folded
within the sampling frequency band
(sampling theorem)

Waveform frequency : 31kHz

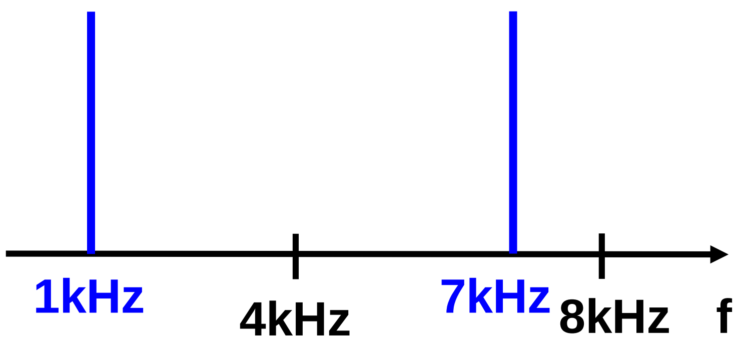




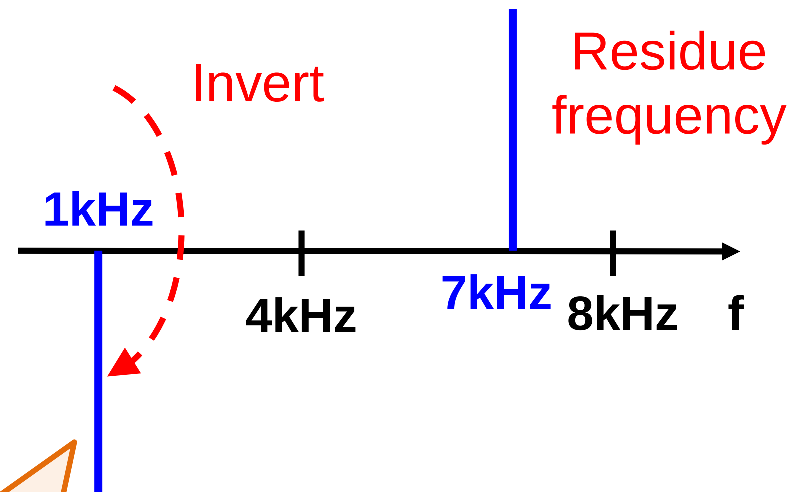
Residue frequency
(7 is the remainder of 31 divided by 8)

Complex FFT of $j \times \sin(2\pi f_{in} t)$

Complex FFT
Input frequency : 31 kHz
Sampling frequency : 8 kHz



$\cos(2\pi f_{in} t)$

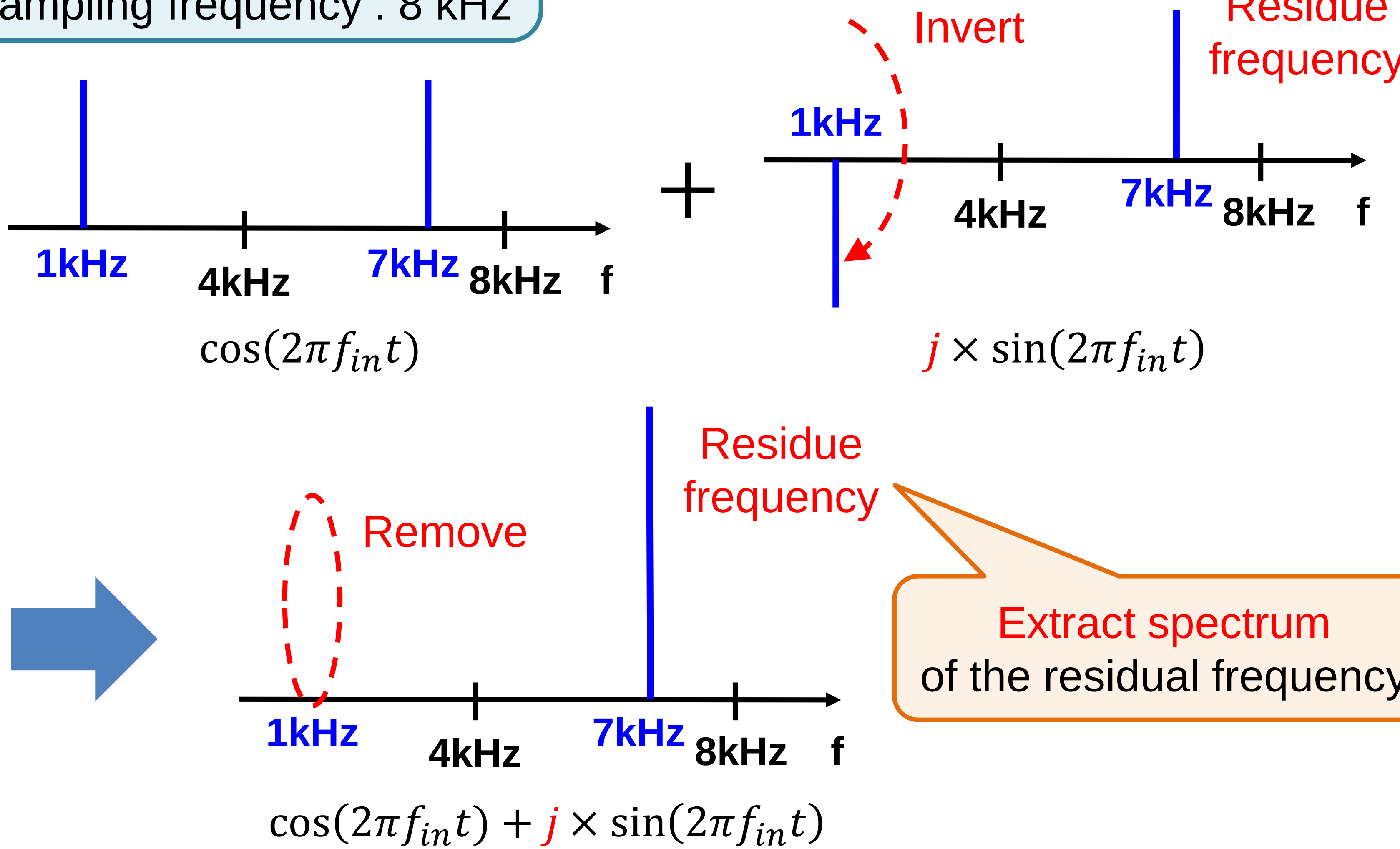


$j \times \sin(2\pi f_{in} t)$

Inverted spectrum
anti-symmetric at Nyquist frequency

Complex FFT of $\cos(2\pi f_{in}t) + j \times \sin(2\pi f_{in}t)$

Complex FFT
Input frequency : 31 kHz
Sampling frequency : 8 kHz



Extract spectrum
of the residual frequency

How Generate $j \times \sin(2\pi f_{in} t)$

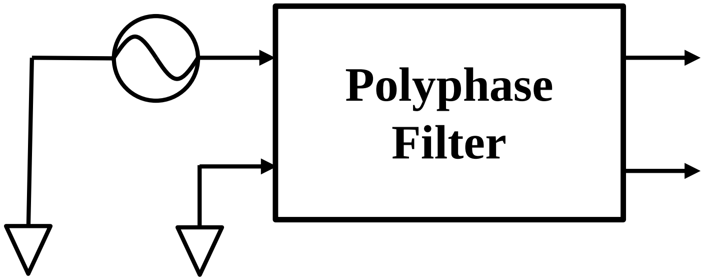
Use Analog Hilbert filter

↓

RC polyphase filter

David Hilbert
(German mathematician)
1862-1943

$\mathbf{I_{in} = \cos(\omega t)}$



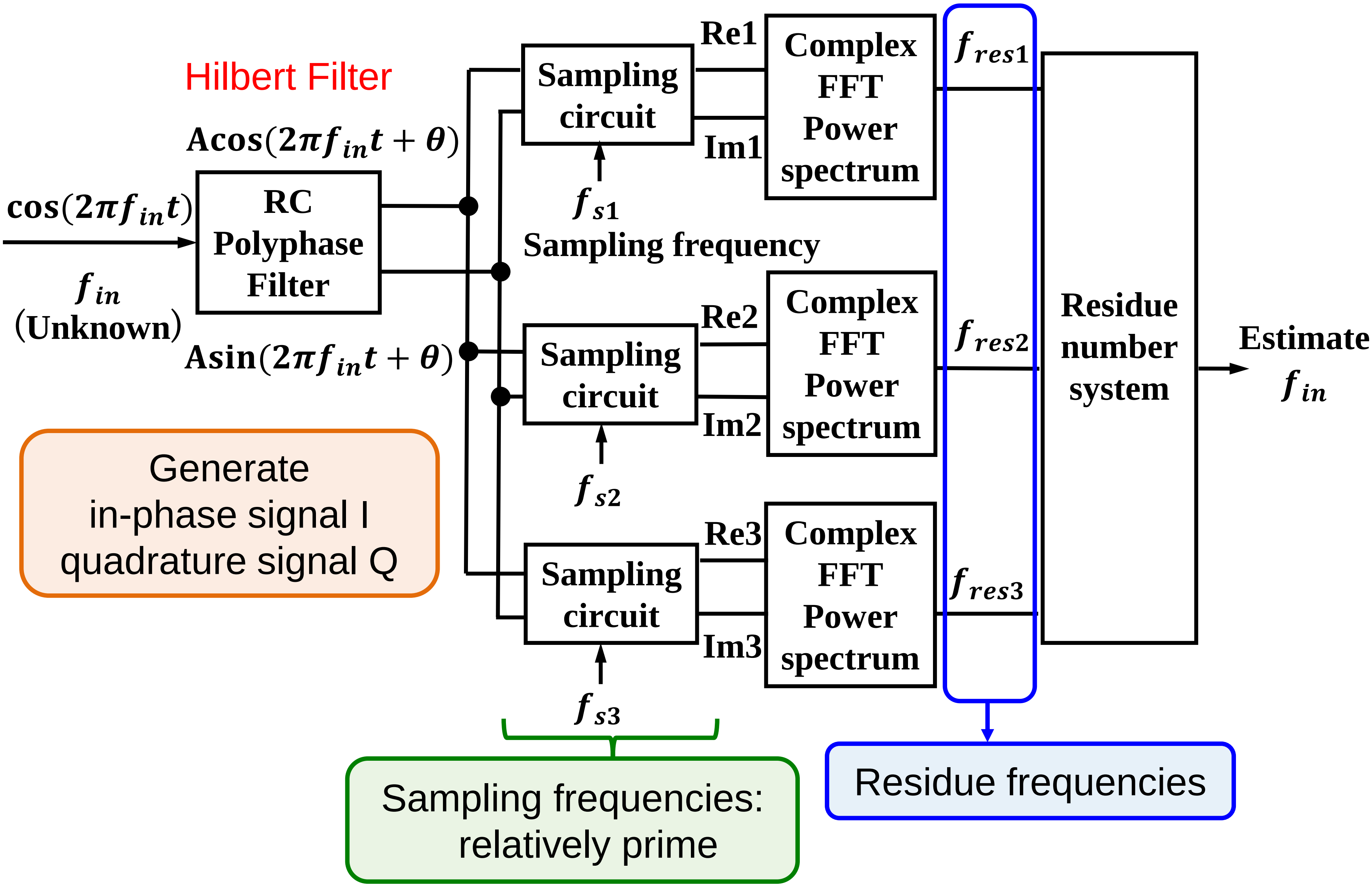
$\mathbf{I_{out} = A\cos(\omega t + \theta)}$

$\mathbf{Q_{out} = A\sin(\omega t + \theta)}$

$\mathbf{Q_{in} = 0}$

Generate in-phase and quadrature waves
from a single cosine wave

Proposed Sampling Circuit



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Simulation Settings

Complex FFT

- Input frequency : 12 GHz
- Frequency resolution : 1 kHz
- Sampling frequency : 229 kHz, 233 kHz, 239 kHz
  (Relatively prime)
- Range of measurement : 0~2080622 kHz
  (Note: $229 \times 233 \times 239 = 2080623$)

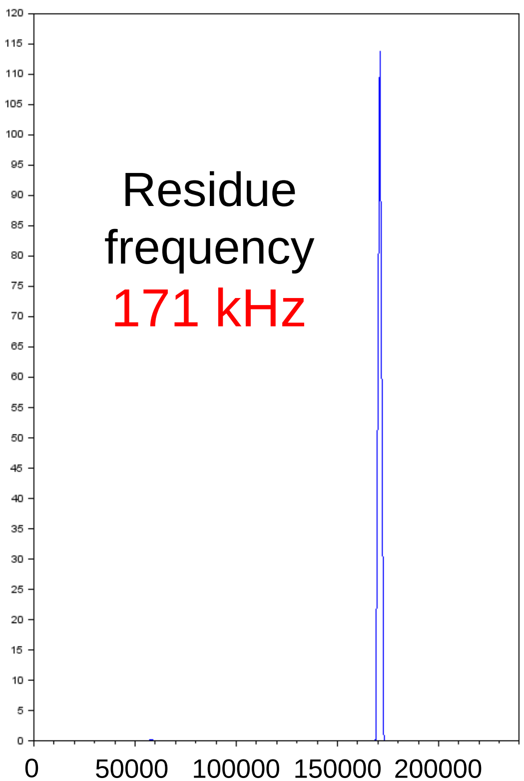
Measurement at 20 GHz
using sampling frequencies of ≒ 200 kHz

Simulation Results

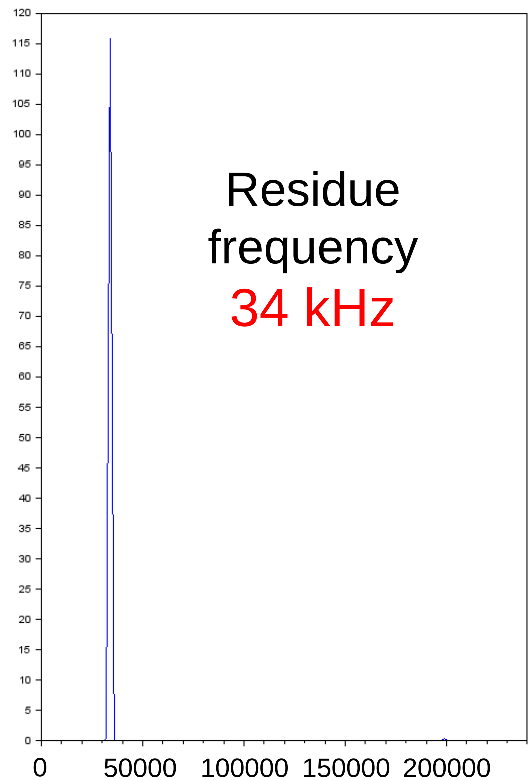
Complex FFT : $\cos(2\pi f_{in} t) + j \times \sin(2\pi f_{in} t)$

- Input frequency : 12 GHz
- Frequency resolution : 1 kHz
- Sampling frequency : 229 kHz 233 kHz 239 kHz

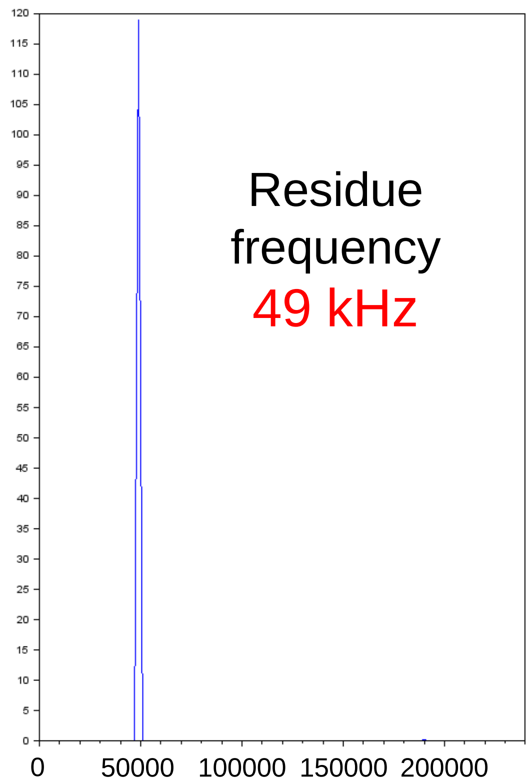
229 kHz Sampling



233 kHz Sampling



239 kHz Sampling



Frequency Estimation by Residue Number System

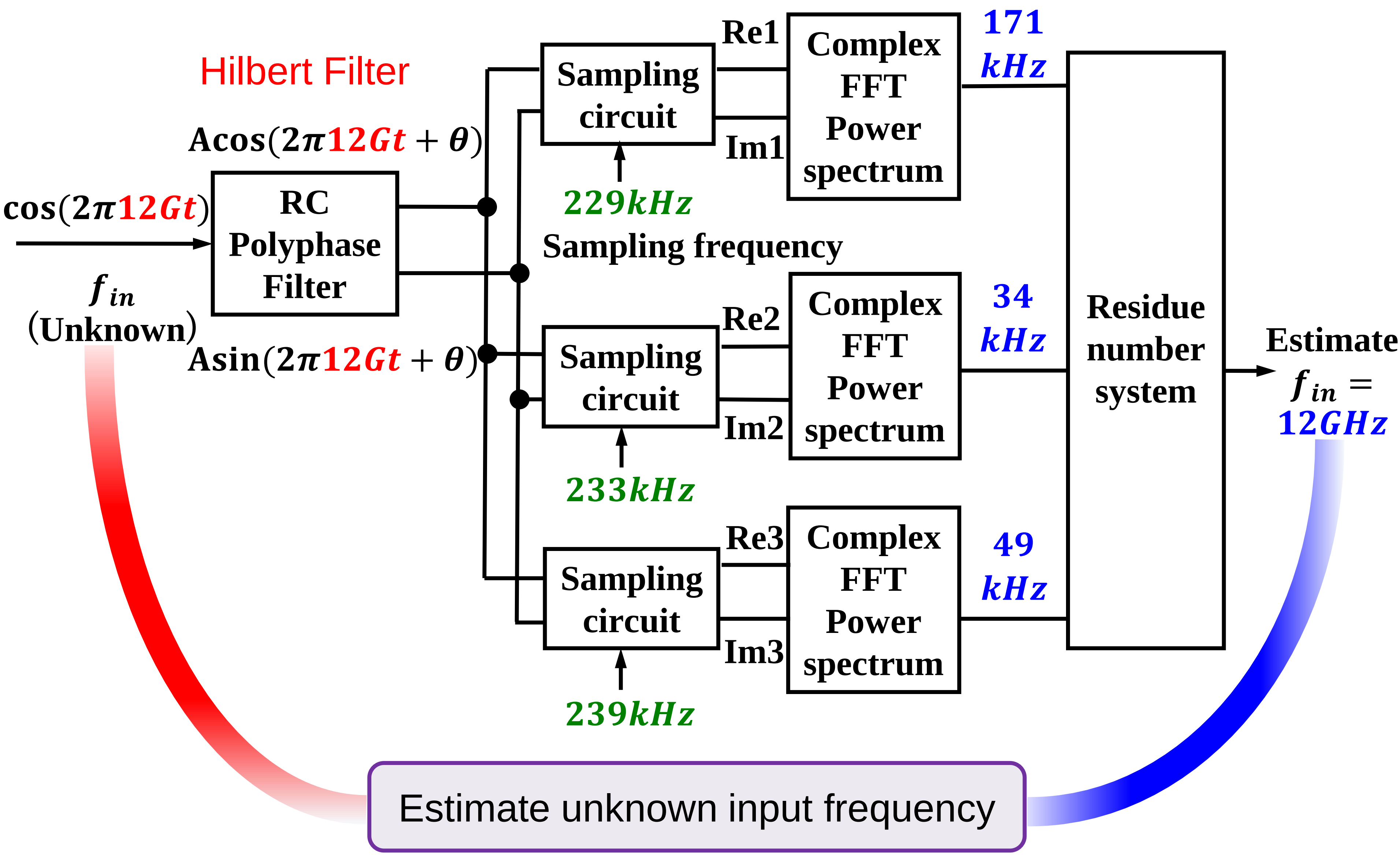
Residue frequencies
171 kHz, 34 kHz, 49 kHz

Input frequency estimation
using residue frequencies
and residue number system

Estimate input frequency 12GHz

a [kHz]	b [kHz]	c [kHz]	k [kHz]
0	0	0	0
1	1	1	1
2	2	2	2
⋮	⋮	⋮	⋮
169	[illegible]	47	11999998
170	[illegible]	48	11999999
171	**34**	**49**	**12000000**
172	35	50	[illegible]
173	36	51	[illegible]
⋮	⋮	⋮	⋮
226	230	[illegible]	12752320
227	231	237	12752321
228	232	238	12752322

Simulation Result Overview



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Summary and Challenge

Summary

- Proposed a method to estimate high-frequency signal using multiple low-frequency sampling circuits.
- Confirmed its operation by theory and simulation.
- Measurable range is wide:
  proportional to multiplication of multiple sampling frequencies.

Challenge

- Estimated input frequency is discrete

→ Consider estimation with fine frequency resolution

Thank you for your attention