Application of Real Zero Concept to Coherent Detector for Quadrature Amplitude Modulation

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Outline

- Background
- Conventional concept: Baseband real zero process
- Proposed concept: Extension to RF signals
- Coherent detector employing real zero
- Simulation results
- Conclusion

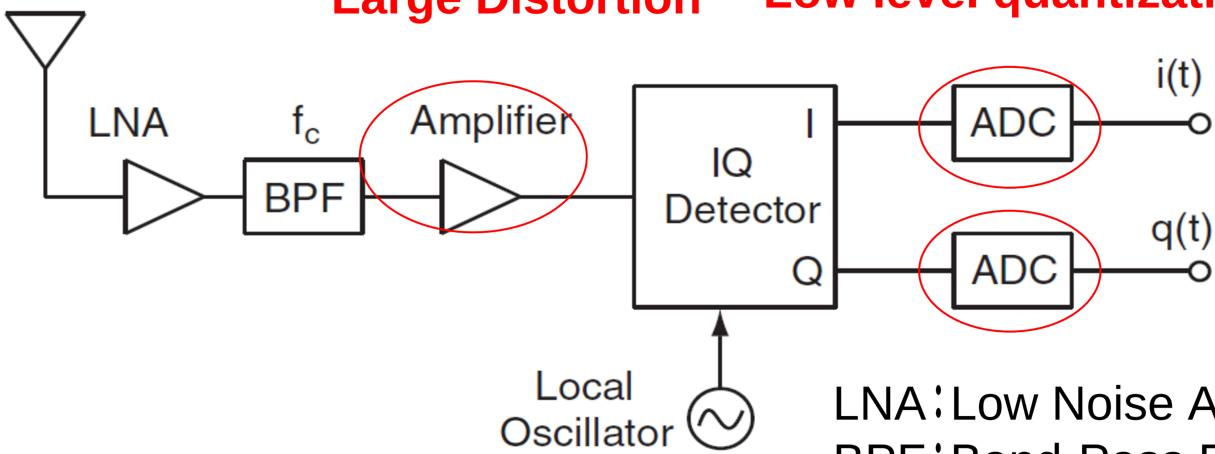
Background

The Si-CMOS IC technology is rapidly advancing:

- 60 GHz Si-CMOS elements will be commercially available soon.
- Analog RF and digital baseband circuits will be integrated on a single chip.
- **Low-voltage design** will, however, degrade the analog circuit performance.

Lower dynamic-range in analog circuit

Large Distortion **Low level quantization**



LNA：Low Noise Amplifier
BPF：Band-Pass Filter
ADC：Analog to Digital Converter

We apply Real Zero (RZ) concept to the coherent detection.

Concept of Baseband Real Zero (1)

Fourier series expansion of a periodic baseband signal r(t) is given by

$$r(t) = \sum_{k=-K_m}^{K_m} c(k) e^{j2\pi f_0 k t}$$

$$= z^{-K_m} c(K_m) \sum_{k=0}^{2K_m} \frac{c(k-K_m)}{c(K_m)} z^k$$

$$= z^{-K_m} c(K_m) \prod_{k=1}^{2K_m} (z - e^{j2\pi f_0 t_k})$$

T : Period

$f_0 = 1/T$: Fundamental frequency

$K_m f_0$: Maximum frequency

$c(k)$: Fourier coefficients

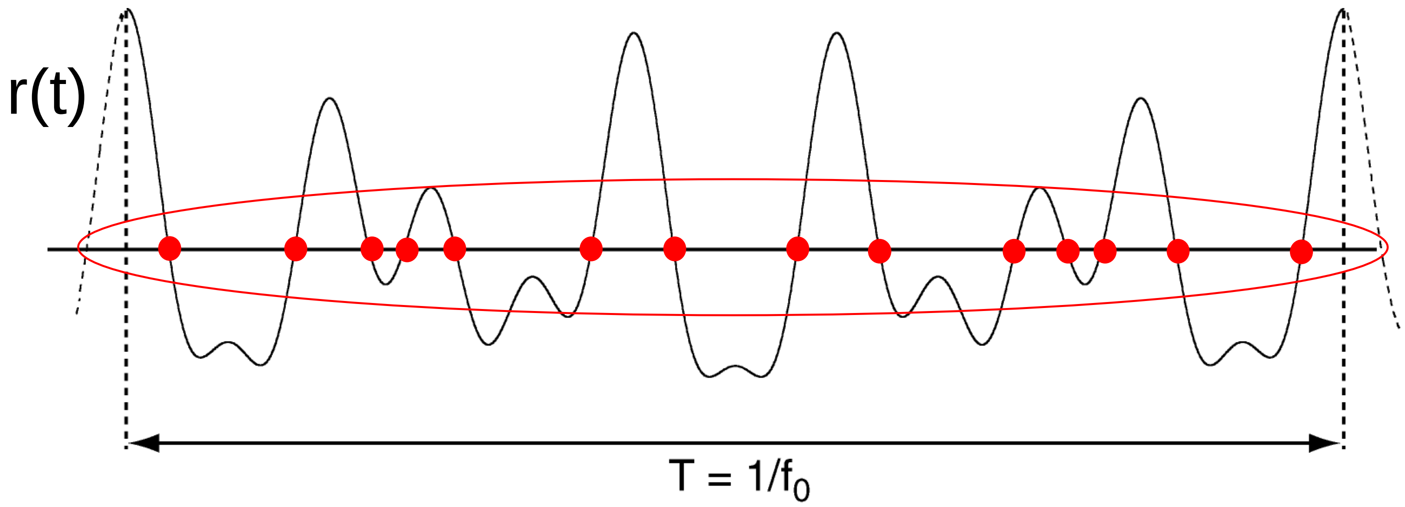
$z = e^{j2\pi f_0 t}$

$2K_m$–th order polynomial with respect to z

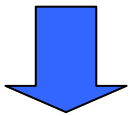
$2K_m$ roots can be classified into

- $2K_r$ real roots：Real Zeros (RZ)
- $2(K_m - K_r)$ complex roots

Concept of Baseband Real Zero (2)



When all the roots are real zero, r(t) can completely be recovered from them



Real Zero conversion : all the roots are transformed into RZs

Real Zero Conversion

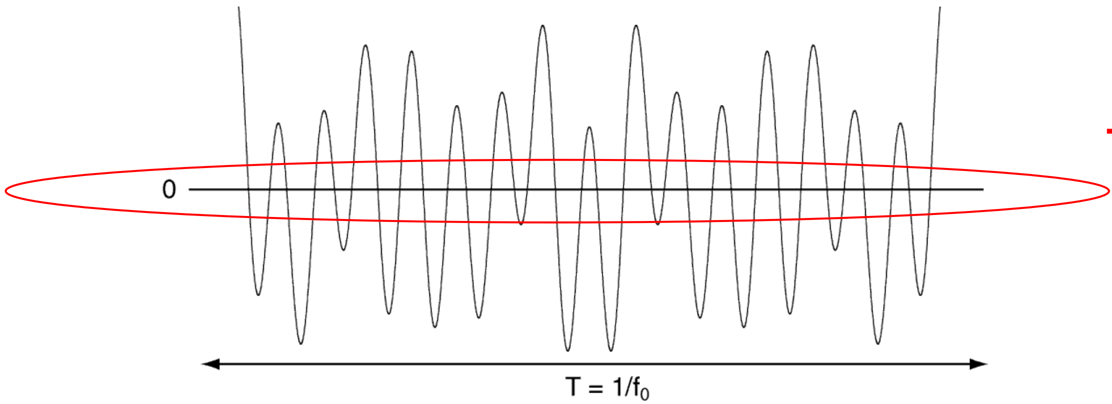
Add a sinusoidal wave to r(t)

$$r_z(t) = r(t) + A_u \cos(2\pi K_a f_0 t + \theta_a)$$
$$= z^{-K_a} 2^{-1} A_u e^{j2\theta_a} \prod_{k=1}^{2K_a} (z - e^{j2\pi f_0 t_k})$$

$K_a f_0$: **frequency of the wave ($K_a f_o > K_m f_0$)**

A_u : **amplitude of the wave**

If $A_u > \max[|r(t)|]$, $r_z(t)$ crosses the level zero $2K_a$ times.



There are $2K_a$ RZ

All roots are RZ

Real zero is expressed by t_k

$$r_z(t) = A_u 2^{2K_a - 1} \prod_{k=1}^{2K_a} \sin[\pi f_0 (t - t_k)]$$

Remove the additional sinusoidal wave by LPF

Summary of Baseband Real Zero

Input r(t)

↓

Add a sinusoidal wave to r(t)

↓ $$r_z(t) = r(t) + A_u \cos(2\pi K_a f_0 t + \theta_a)$$

Sample RZ timings

↓ $\{t_k\}$

Recover the waveform from RZ timings

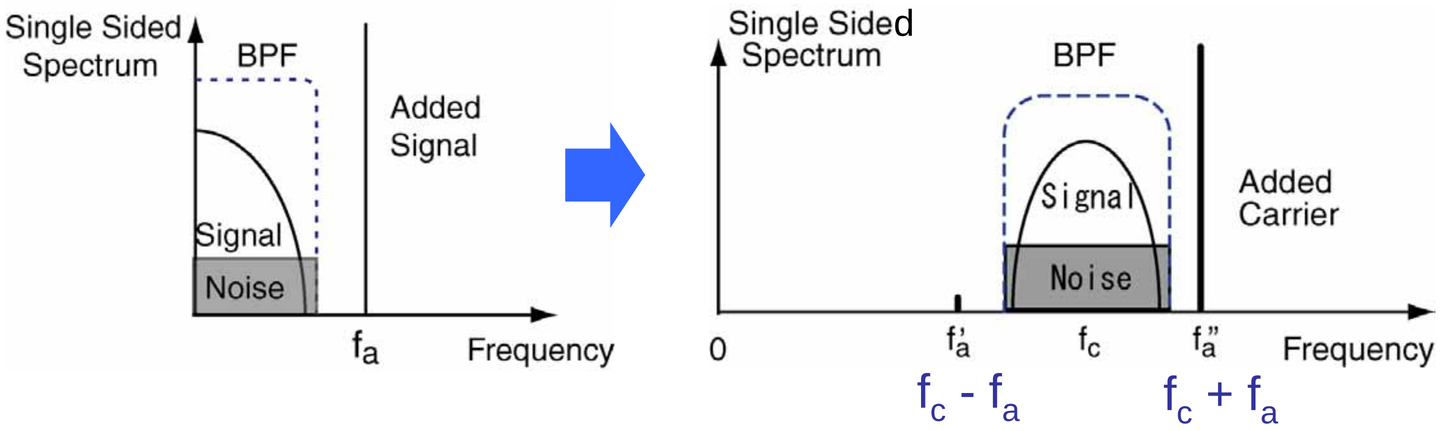
↓ $$r_z(t) = A_u 2^{2K_a - 1} \prod_{k=1}^{2K_a} \sin[\pi f_0 (t - t_k)]$$

Remove the additional sinusoidal wave

↓

Recover r(t)

Extension to RF Signals



Either frequency is allowed for the added carrier

$$r(t) = i(t)\cos(2\pi f_c t) - q(t)\sin(2\pi f_c t)$$

Add a sinusoidal wave outside BPF-band.

$$\begin{aligned} r_z(t) &= r(t) + A_u \cos(2\pi f_a'' t) \\ &= \{i(t) + A_u \cos(2\pi f_a t)\}\cos(2\pi f_c t) \\ &\quad - \{q(t) + A_u \sin(2\pi f_a t)\}\sin(2\pi f_c t) \end{aligned}$$

All the roots of the in-phase and quadrature components become RZs.

A conventional method：RZ-SSB ➡ Only for SSB

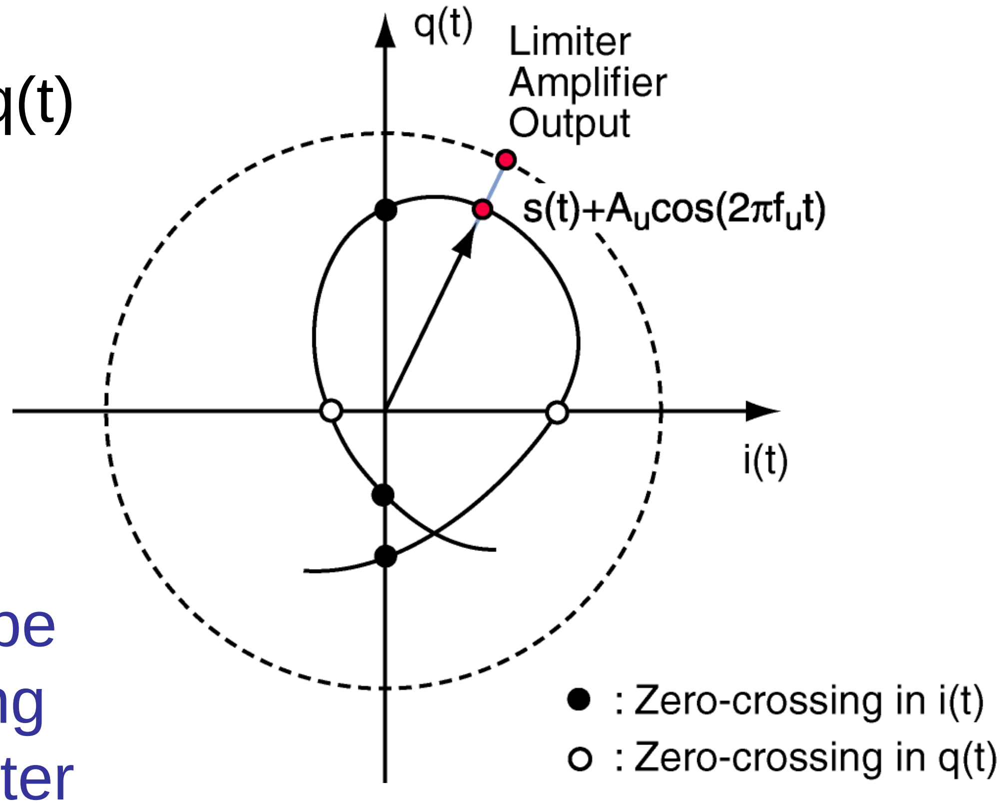
Proposed method ➡ Applicable to PSK，QAM

RZ Property Conservation

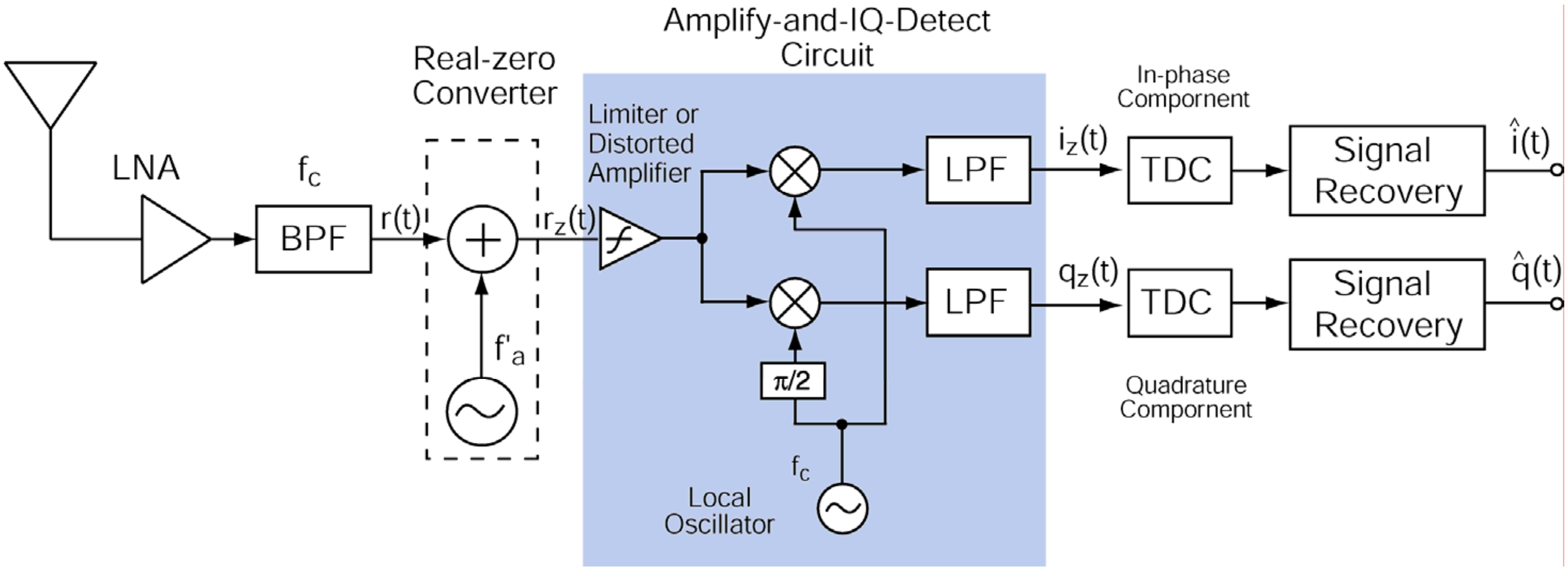
The RZ property in i(t) and q(t) does not change after the nonlinear amplification

⬇

The transmitted signal can be recovered from the RZ timing sequences of i(t) and q(t) after nonlinear amplification.



Coherent Detector Employing RZ

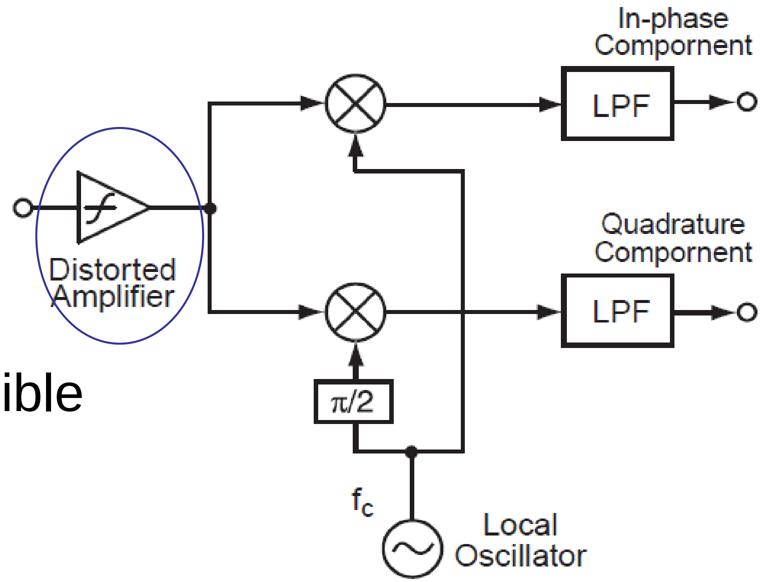


TDC：Time to Digital Converter

- Add the sinusoidal wave in RF region
- Limiter amplify and extract IQ baseband wave
- Generate RZ sequences in baseband region

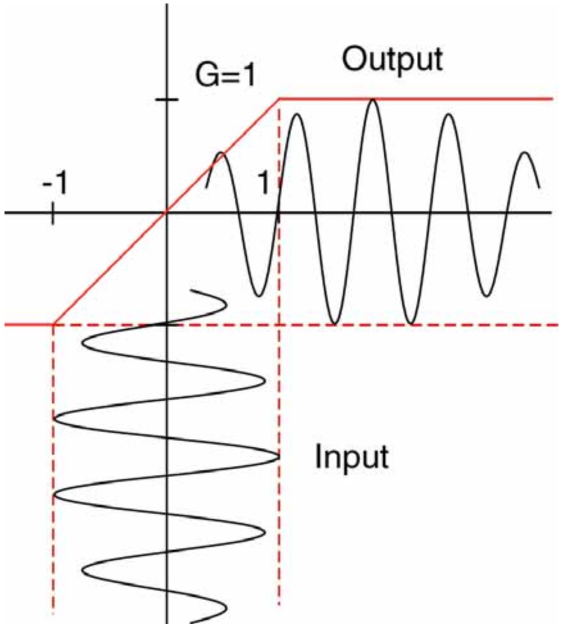
Robust to distortion in RF region.

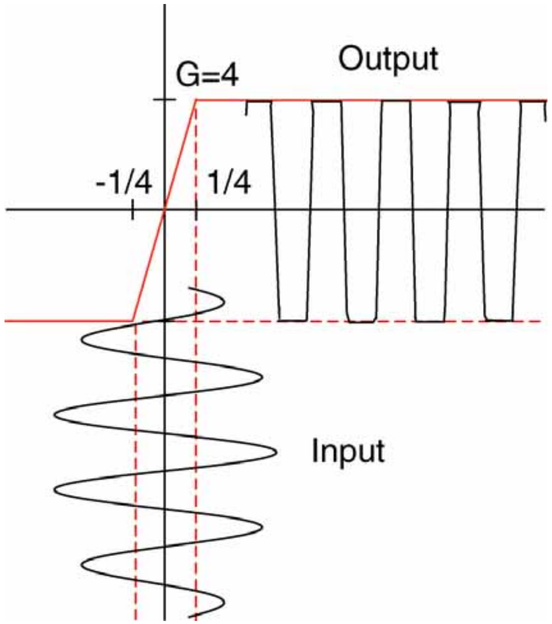
Nonlinear Distortion of Amplifier



- Power gain (dB)： $20\log_{10} G$
- AM-PM conversion is assumed to be negligible

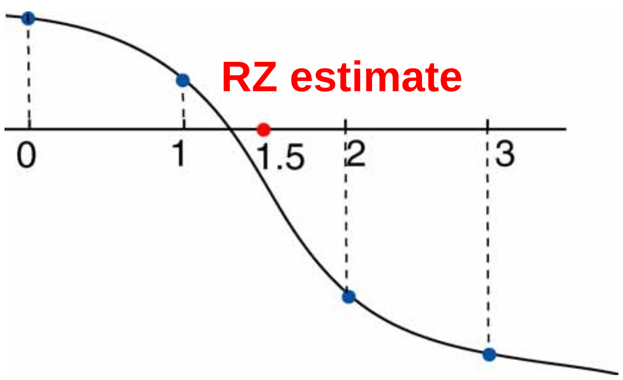
Input peak power： Normalize to 1



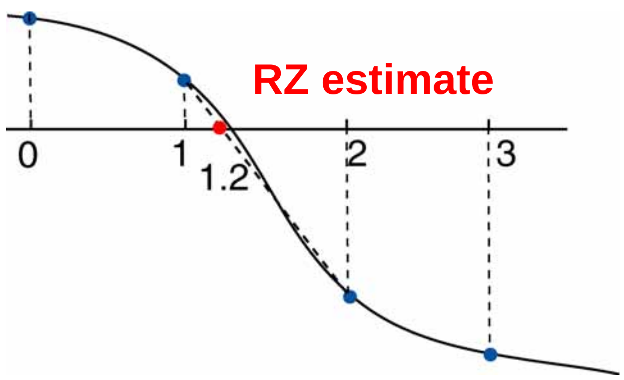


Time to Digital Converter

Simple quantization



Linear interpolation

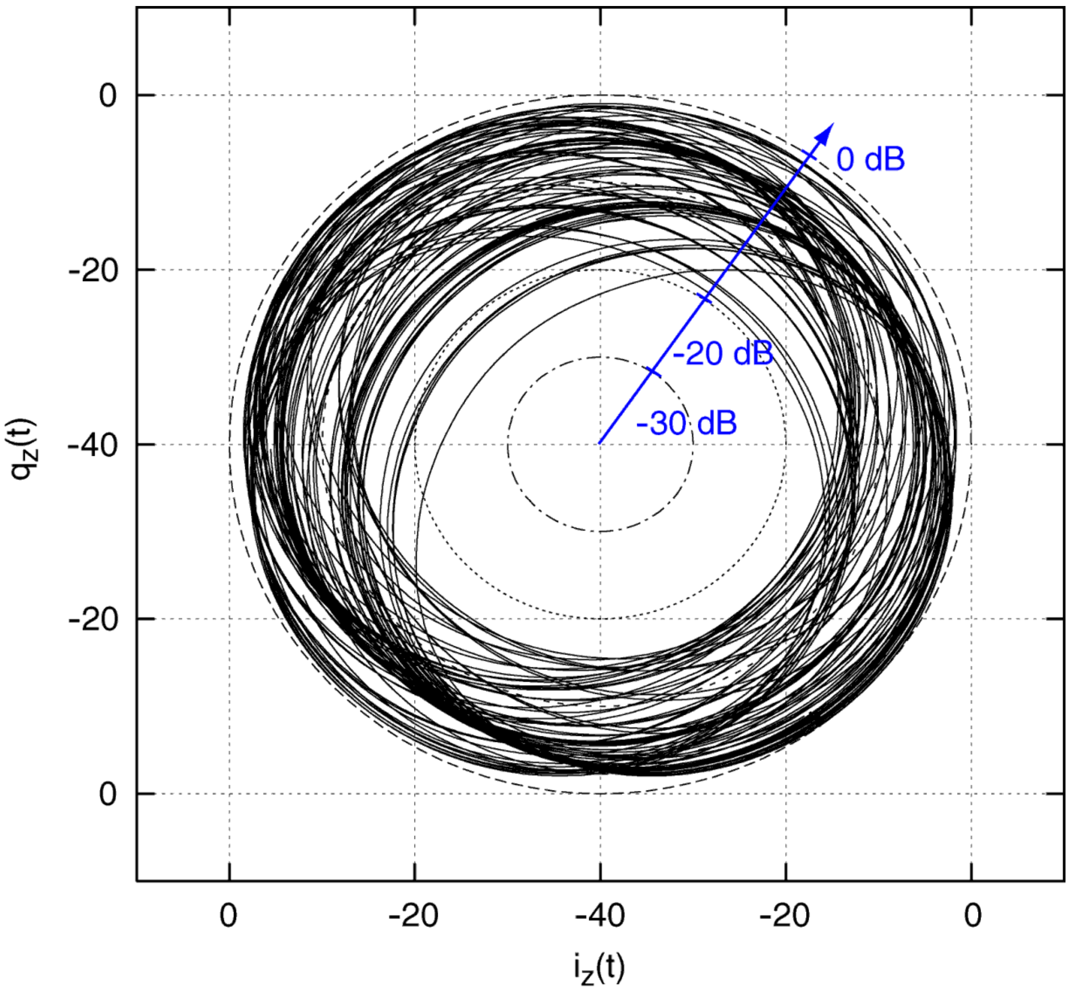


Simulation Conditions

Received signal: $r(t)$	Modulated signal
Modulation scheme	QPSK
Amplitude of constellation	1
Symbol duration	T_s
f_c/f_s	75
Roll-off	Raised cosine
Roll-off factor α	0.5
Added sinusoid: $r_a(t)$	$A_u \cos[2\pi(f_c + f_a)t]$
$f_a T_s$	2, 4
A_u	1.5
Amplifier gain: $G_p = 20 \log_{10} G$	from 0 to 65 dB
LPF	Two stages
Impulse response shape	Triangular pulse
Pulse width	$1.0\tau_c, 0.33\tau_c$
TDC	Linear interpolation
Digital sampling per symbol: p_d	40
Simulation	
Precision	Floating point (double)
Analog sampling per symbol: p_a	$3, 840$

Envelope of Input Received Signal

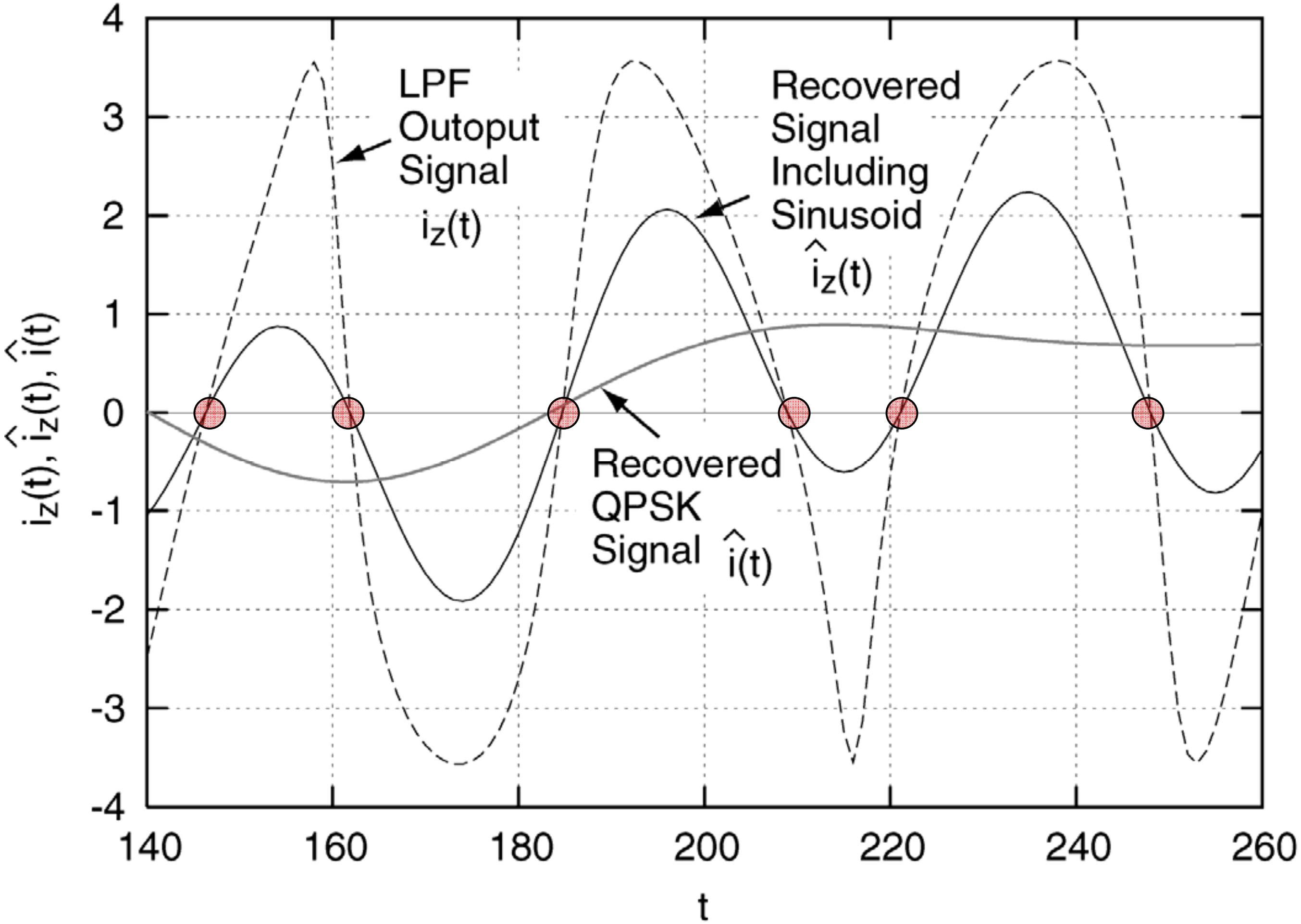
Polar (dB) representation



In 30 dB gain amplification

- From -30 dB to 0 dB：
  Limiter amplification
  to 0 dB
- Lower than -30 dB：
  Linear amplification

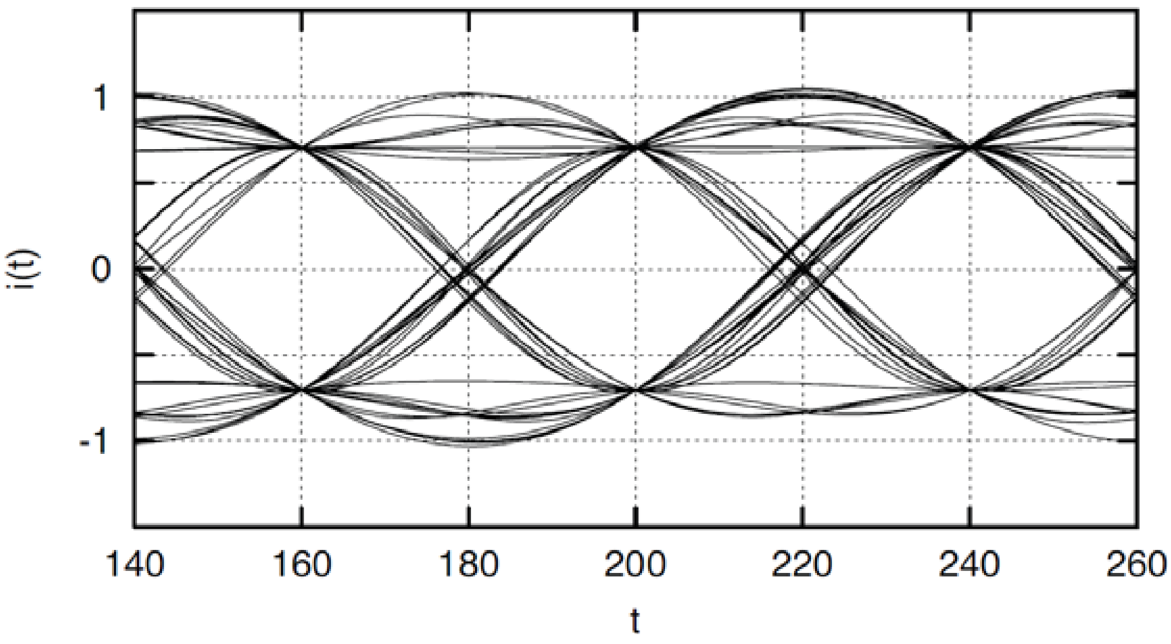
Detected and Recovered Signals

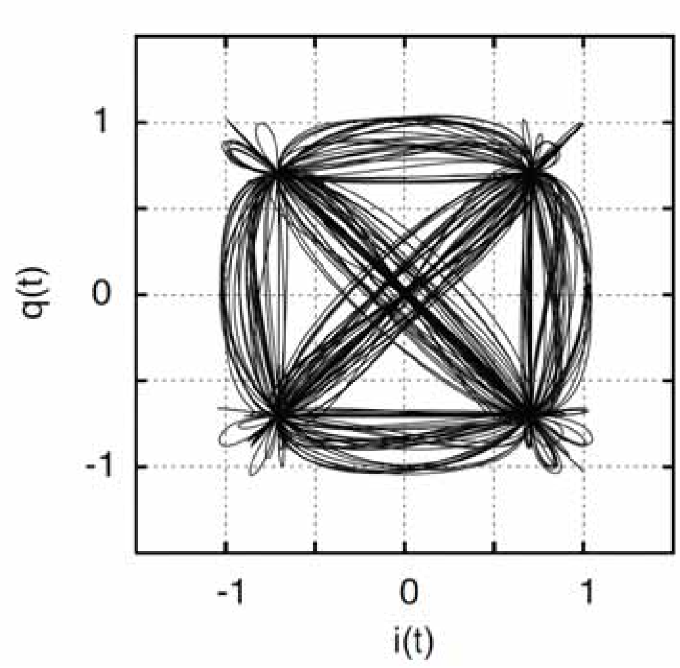


: RZ

Gain: 30 dB, $f_a T_s = 2$

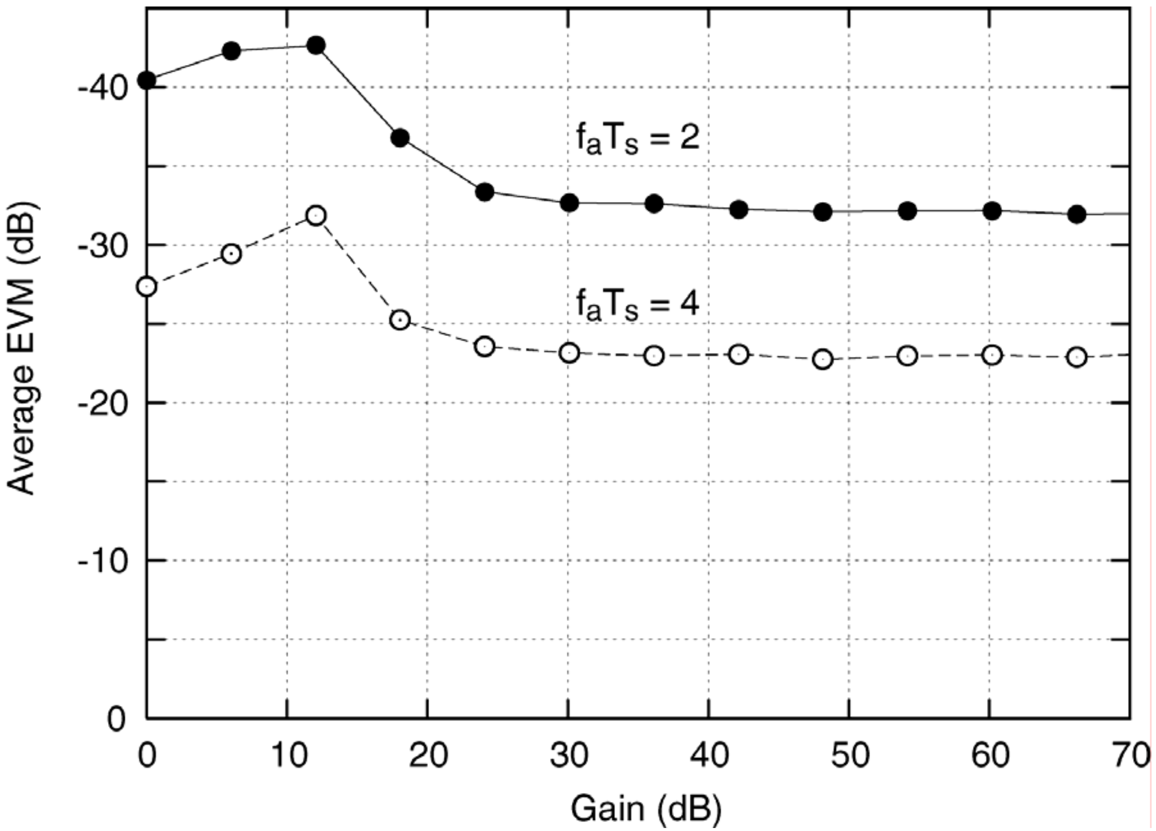
Eye Pattern and Constellation of Recovered signal





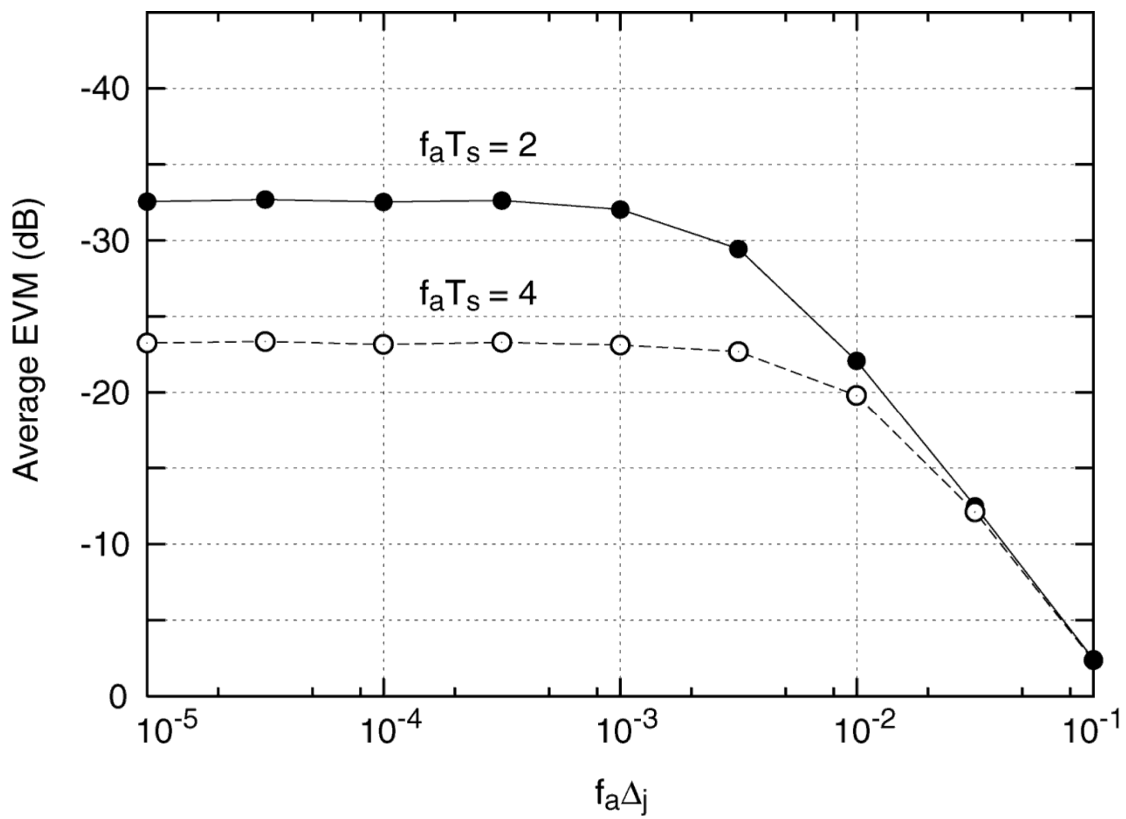
Gain: 30 dB, $f_a T_s = 2$

Average EVM Versus Gain



- Large f_a results in decrease in the average EVM.
- EVM becomes constant in gain more than 25 dB.

Average EVM vs. Sampling Jitter



Gain: 30 dB

A random jitter that uniformly distributes in the range $[-\Delta_j, \Delta_j]$ is added to the RZ timing.

➡ $f_a\Delta_j \leq 10^{-3}$ is necessary for small impairment in average EVM.

Conclusion

- A coherent detector employing RZ has been proposed.
  - The baseband RZ concept is extended to RF signal (modulated signals).
  - The RZ concept requires the RZ conversion which adds a sinusoidal wave to outside of the modulated band before limiter amplification.
  - Nonlinear amplification is applicable even to the linear modulation schemes (QAM, OFDM).

- Computer Simulation
  - Conditions
    - Raised cosine roll off QPSK signal, $f_a T_s = 2$
  - Results
    - Gain 30 dB: Recovered signal EVM = - 32 dB
    - Sampling jitter should be $f_a \Delta_j \leq 10^{-3}$