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.

We apply Real Zero (RZ) concept to the coherent detection.
Fourier series expansion of a periodic baseband signal \( r(t) \) is given by

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

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

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

2\(K_m\)-th order polynomial with respect to \( z \)

2\(K_m\) roots can be classified into

\[
\begin{align*}
2K_r & \text{ real roots : Real Zeros (RZ)} \\
2(K_m - K_r) & \text{ complex roots}
\end{align*}
\]
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 \( r(t) \)

\[
R_z(t) = r(t) + A_u \cos(2\pi K_a f_0 t + \theta_a)
\]

\[
= z^{-K_a 2^{-1}} A_u e^{j2\theta_a} \prod_{k=1}^{2K_a} (z - e^{j2\pi f_0 t_k})
\]

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

1. **Input r(t)**
2. **Add a sinusoidal wave to r(t)**
   \[ r_z(t) = r(t) + A_u \cos(2\pi K_a f_0 t + \theta_a) \]
3. **Sample RZ timings**
   \[ \{t_k\} \]
4. **Recover the waveform from RZ timings**
   \[ r_z(t) = A_u 2^{2K_a-1} \prod_{k=1}^{2K_a} \sin[\pi f_0(t - t_k)] \]
5. **Remove the additional sinusoidal wave**
6. **Recover r(t)**
### Extension to RF Signals

Add a sinusoidal wave outside BPF-band.

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

Either frequency is allowed for the added carrier.

\[ r_z(t) = r(t) + A_u \cos(2\pi f_a' t) \]
\[ = \{i(t) + A_u \cos(2\pi f_a t)\} \cos(2\pi f_c t) \]
\[ - \{q(t) + A_u \sin(2\pi f_a t)\} \sin(2\pi f_c t) \]

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

- 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

RZ estimate
## Simulation Conditions

<table>
<thead>
<tr>
<th>Received signal: ( r(t) )</th>
<th>Modulated signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation scheme</td>
<td>QPSK</td>
</tr>
<tr>
<td>Amplitude of constellation</td>
<td>1</td>
</tr>
<tr>
<td>Symbol duration</td>
<td>( T_s )</td>
</tr>
<tr>
<td>( f_c/f_s )</td>
<td>75</td>
</tr>
<tr>
<td>Roll-off</td>
<td>Raised cosine</td>
</tr>
<tr>
<td>Roll-off factor ( \alpha )</td>
<td>0.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Added sinusoid: ( r_a(t) )</th>
<th>( A_u \cos[2\pi(f_c + f_a)t] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_a T_s )</td>
<td>2, 4</td>
</tr>
<tr>
<td>( A_u )</td>
<td>1.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Amplifier gain: ( G_p = 20\log_{10} G )</th>
<th>from 0 to 65 dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPF</td>
<td>Two stages</td>
</tr>
<tr>
<td>Impulse response shape</td>
<td>Triangular pulse</td>
</tr>
<tr>
<td>Pulse width</td>
<td>1.0( \tau_c ), 0.33( \tau_c )</td>
</tr>
<tr>
<td>TDC</td>
<td>Linear interpolation</td>
</tr>
<tr>
<td>Digital sampling per symbol: ( p_d )</td>
<td>40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Simulation</th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Precision</td>
<td>Floating point (double)</td>
<td>3, 840</td>
</tr>
<tr>
<td>Analog sampling per symbol: ( p_a )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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

Gain: 30 dB, $f_a T_s = 2$

- LPF Output Signal $i_z(t)$
- Recovered Signal Including Sinusoid $\hat{i}_z(t)$
- Recovered QPSK Signal $\hat{i}(t)$

$\circ$: RZ
Eye Pattern and Constellation of Recovered signal

Gain: 30 dB, $f_a T_s = 2$
• Large $f_a$ results in decrease in the average EVM.
• EVM becomes constant in gain more than 25 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.

Gain: 30 dB
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, $f_aT_s = 2$
- Results
  - Gain 30 dB: Recovered signal $EVM = -32$ dB
  - Sampling jitter should be $f_a \Delta j \leq 10^{-3}$